SAND74-0092
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Printed November 1975

COMPILATION OF

SANDIA LABORATORIES TECHNICAL CAPABILITIES

MASTER

ABSTRACT

This report is a compilation of individual documents that together summarize the technical capabilities of Sandia Laboratories. Each document in this compilation contains details about a specific area of capability. Examples of application of the capability to research and development problems are provided.

CONTRACT NO. AT(29-1)-789

SAND74-0073A
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SANDIA LABORATORIES TECHNICAL CAPABILITIES

MATERIALS AND PROCESSES

ABSTRACT

This report characterizes the materials and processes capabilities at Sandia Laboratories. Selected applications of these capabilities are presented to illustrate the extent to which they can be applied in research and development programs.

Issued by Sandia Laboratories, operated for the United States Energy
Research and Development Administration by Sandia Corporation.

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115
and Livermore, California 94550 for the United States Energy Research
and Development Administration under Contract AT(29–1)-789

FOREWORD

Sandia Laboratories, a multiprogram laboratory of the Energy Research and Development Administration (ERDA), is located in Albuquerque, New Mexico, and Livermore, California, with a remote testing facility at Tonopah, Nevada. In fulfilling its responsibilities to ERDA in the fields of national security, energy, and other programs, Sandia has acquired extensive capabilities in research, development, testing, and evaluation, and has made numerous contributions in scientific and engineering fields. These technical capabilities are integrated by management for the definition and solution of scientific and engineering problems.

A series of reports has been written describing these capabilities and showing typical applications. The reader will find the capabilities summarized in a separate paper, or may choose any of the 17 separate reports, or, if he wishes a compendium, can find all the reports and the summary compiled in a single publication. Identifying numbers for the entire series are given below.

C. Donald Lundergan, Technical Editor
P. L. Mead, Publication Editor

TECHNICAL CAPABILITIES OF SANDIA LABORATORIES

Summary
(SAND74-0091)

Aerosciences	SAND74-0075	**Instrumentation and Data Systems**	SAND74-0083
Applied Mathematics	SAND74-0079	**Materials and Processes**	SAND74-0073A
Biosciences	SAND74-0076	**Measurement Standards**	SAND74-0077
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Design Definition and Fabrication	SAND74-0084	**Safety and Reliability Assurance**	SAND74-0090
Earth Sciences	SAND74-0085	**Systems Analysis**	SAND74-0089
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		Information Sciences	

Compilation of
Sandia Laboratories Technical Capabilities
(SAND74-0092)

SAND74-0091

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SUMMARY

Summary of

Sandia Laboratories Technical Capabilities

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SUMMARY OF

SANDIA LABORATORIES TECHNICAL CAPABILITIES

ABSTRACT

The technical capabilities of Sandia Laboratories are detailed in a series of companion reports. In this summary the use of the capabilities in technical programs is outlined and the capabilities are summarized.

CONTENTS

INTRODUCTION

In this summary the technical capabilities of Sandia Laboratories and their application to national security, energy, and other federal programs are briefly described. These capabilities are the basic scientific and engineering disciplines and technologies currently in use at these laboratories. They are the tools used to define and solve scientific and engineering problems and to conduct research, development, testing, and evaluation of advanced systems.

The reason for describing these technical capabilities is so that they can be more efficiently brought to bear upon two major areas of national concern - national security and energy. The reports associated with this summary:

- Provide an inventory of resources that will allow overall program planning in relation to national problems.
- Furnish information needed by Sandia management to balance project requirements with technical capabilities.
- Supply an additional basis for communication among federal agencies, laboratories, universities, industries, and the Laboratories' own staff.
- Provide source material for reports, proposals, presentations, and recruiting purposes.

A breakdown of the managerial and technical capabilities is given on the following page.

OPERATIONAL STRUCTURE

The technical capabilities of these laboratories are located in functional organizations dedicated to individual disciplines and technologies. Responsibility for individual projects is assigned to project organizations which rely upon the functional organizations for support. The project/functional relationship is advantageous because responsibility for a project is assigned to a single manager and his staff, and continuity of control over the assigned system is assured. This control is necessary to assure the integration of complex designs having stringent requirements for performance, reliability, safety, and longevity. The relationship also permits detailed technical direction to be concentrated at the level where primary technical competence exists.

The use of the most recent scientific and engineering advances on the various projects is assured through the interaction of the technical staff with the general technical community. This interaction includes publication in technical journals, participation in national and international conferences, and personal exchanges of information with peers. The continuing challenge of interesting and important problems and the resulting long-term continuity of personnel provides stability of the essential technical staff.

The technical staff is utilized by the project managers in the major areas of national security, energy, and work for other federal programs.

SUMMARY

MANAGERIAL CAPABILITIES

SYSTEM ENGINEERING AND MANAGEMENT
- Technical Management
- Fiscal Controls
- Program Direction

COMPONENT DEVELOPMENT
- Electronic
- Electrochemical
- Explosives
- Electromechanical
- Mechanical

QUALITY ASSURANCE
- Technical Management
- Analysis
- Testing
- Evaluation

TECHNICAL CAPABILITIES

SCIENCE AND ENGINEERING

PHYSICAL SCIENCES
- Physics of Surfaces and Thin Surface Layers
- Physics of Solids
- Solid Dynamics
- Interaction of Radiation with Matter
- Laser Physics
- Relativistic Electron Beam Research
- Research Reactors

APPLIED MATHEMATICS
- Development of Computer Codes
- Discrete Mathematics
- Mathematical Physics
- Theoretical Mathematics
- Statistical Analysis

EXPLOSIVES, ELECTROCHEMISTRY, AND ELECTROMECHANISMS
- Explosives
  - Detonation Physics
  - Explosives Chemistry
- Electrochemical Power Sources
- Electromechanisms

MATERIALS AND PROCESSES
- Metallurgy
- Composites
- Surface Characterization and Film Deposition
- Polymers
- Ceramics
- Glass and Glass Ceramics
- High-Temperature Characterization of Materials
- Laboratory Analysis

EARTH SCIENCES
- Numerical Methods
- Terradynamics
- Underground Physics
- Drilling, Magma, and Diagnostic Technologies

ELECTRONICS
- Active Semiconductors
- Hybrid Microcircuits
- Vacuum Tubes
- Pulsed High Energy Technology

AEROSCIENCES
- Aeroballistics
- Aerodynamics
- Atomic and Fluid Physics
- Aerothermodynamics
- Aerophysics
- Atmospheric Environments
- Fluid Dynamics
- Aeromechanical Design

SAFETY AND RELIABILITY ASSURANCE
- Safety Assessment
- Safety Assurance
- System Safety
- Reliability Assessment
- Statistical Design and Analysis
- Human Factors
- Quality Control

BIOSCIENCES
- Environmental Biology
- Applied Biology
- Analytical Biology

ANALYSIS AND TESTING

INSTRUMENTATION AND DATA SYSTEMS
- Data Acquisition
  - Transducers
  - Communications
  - Optical Recording
  - Mobile and Transportable Instrumentation
- Special Instrumentation
  - Meteorological
  - Photometric
  - Quality Assurance
  - Radiation Analysis
- Data Reduction Systems
  - Magnetic Tape
  - Optical Data

SYSTEMS ANALYSIS
- Problem Definition and Assessment
- Concept Formulation
- System Evaluation
- Concept Optimization

ENGINEERING ANALYSIS
- Structural Mechanics
- Stress Wave Analysis
- Explosive Technology
- Heat Transfer
- Aerospace Engineering
- Mechanism Analysis
- Environment Analysis
- Controls Engineering
- Electrical Engineering
- Nuclear Engineering
- Reactor Safety Analysis

TESTING
- Environment Simulation
  - Mechanical Loading
  - Radiation Loading
- Development and Evaluation
  - Aerosciences
  - Material Response
  - Nondestructive Testing
- Field Testing
  - Tonopah Test Range
  - Nevada Test Site
  - Kauai Test Facility
  - Mobile and Remote Ranges

SUPPORT FUNCTIONS

DESIGN DEFINITION AND FABRICATION
- Design
- Metals
- Glasses and Ceramics
- Composites and Plastics
- Electrical Components
- Heat Treating and Finishing

INFORMATION SCIENCE
- Information Management
- Information Dissemination
- Reference and Translation

COMPUTATION SYSTEMS
- System Planning, Development, and Support
- Central Computing
- Time-Sharing System
- Interactive Graphics
- Computer-Based Special-Purpose Systems

MEASUREMENT STANDARDS
- ERDA Standardization Program Management
- Direct-Current Electrical Quantities
- Microwave Quantities
- Radiation
- Mechanical
- Environmental

ENVIRONMENTAL HEALTH
- Hazard Control
- Radiation Dosimetry
- Radiation Counting
- Effluent Documentation

APPLICATIONS OF CAPABILITIES

NATIONAL SECURITY PROJECTS

The responsibilities of the Laboratories in national security missions are to develop and maintain the scientific and engineering expertise that will assure viability of the nation's nuclear ordnance; to conduct research that will generate new weapon concepts; to design and develop nuclear ordnance in conjunction with other national laboratories; to verify that the weapon stockpile remains a credible deterrent through continual assessment of safety and reliability; to modify weapons as necessary to meet new requirements; and to develop and apply advanced technologies to the protection of nuclear materials from theft.

It is upon these responsibilities that the technical capabilities are concentrated, as shown in the schematic on the following page. While most national security projects are classified and cannot be discussed here, a few representative examples are described below.

* * * * * * * * * * *

System Integration

The application of Sandia's technical capabilities to problems of system integration led to major advances in the design and development of small reentry vehicles. These advances were in response to a national security problem, which was to find a way to preclude possible exhaustion of the U.S. missile force by ballistic missile defense systems then being developed by potential adversaries.

A solution to the problem involved the deployment of decoys, which the enemy could not discriminate from actual warheads and therefore could not dismiss. Another alternative led to an intensive study of lightweight reentry vehicles, resulting in the development of smaller, lighter warheads containing miniaturized components (Figure 1).

This technology was based upon a number of basic capabilities, including: systems analysis to establish optimal designs; engineering analysis by multidimensional computer programs to determine shock and structural loads; materials studies to determine and apply dynamic properties; physical sciences to determine the response of materials to radiation; electronics and electromechanics for the miniaturization and design of electrical components; and extensive use of testing facilities.

The technology has since been applied to the development of integrated arming, fuzing, and firing systems such as the Navy's Poseidon and Trident missiles. Components developed for these systems include integrating accelerometers, radar fuzes, electromechanical and electronic timers, and thermal batteries.

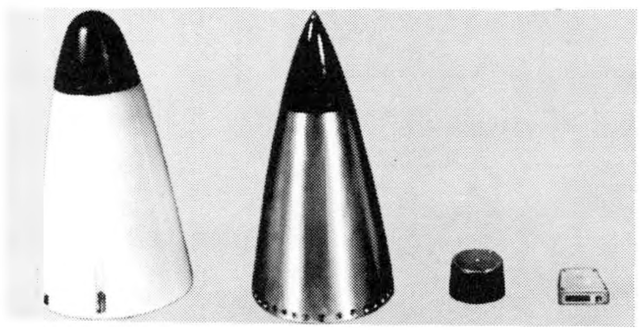
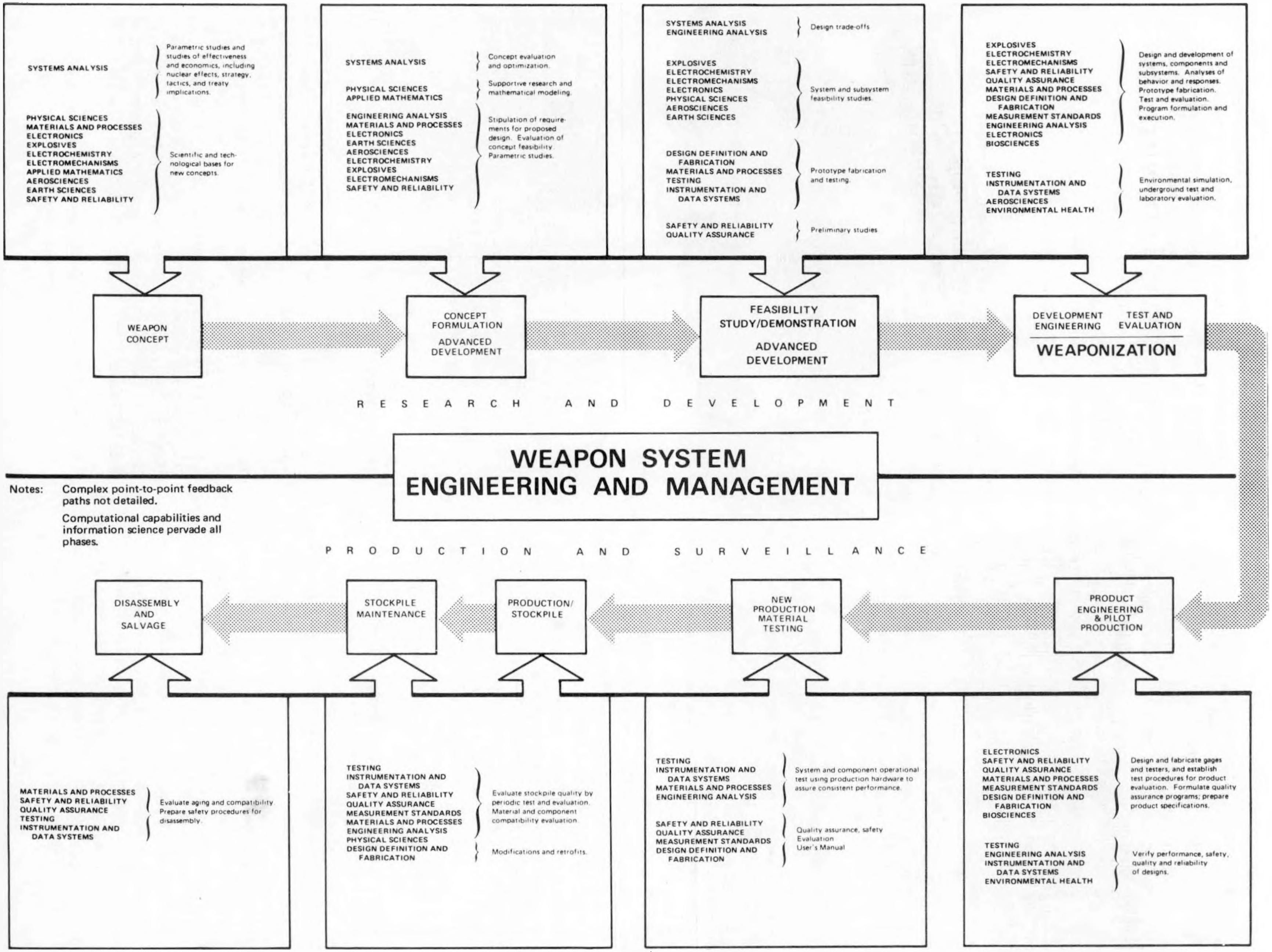


Figure 1. Continuing improvements in miniaturization are illustrated by these periodic reductions in the size of a radar fuzing component.

Nuclear Weapon Security

Sandia pioneered concepts for inhibiting the unauthorized use of nuclear weapons. Security locks containing sophisticated logic have become small enough to be embedded in critical weapon components. Newer technology provides the capability to destroy or disable the weapon. A storage vessel has been designed to contain all the products of an explosion, including fissionable material. Other techniques for disabling a weapon include rendering the radioactive material useless by chemical, physical, or isotopic means (Figure 2).

Use of these techniques has raised confidence levels in the security of nuclear weapons deployed overseas.



EXAMPLES OF CAPABILITIES REQUIRED FOR A TYPICAL WEAPON PROJECT

APPLICATIONS OF CAPABILITIES

Figure 2. Cross section of special nuclear material that has been chemically altered into slag and metallic components, both of which contain uranium, but in dilute, unusable form.

Safety: The Weak-Link/Strong-Link Concept

Without safety devices, the electrical system of a nuclear weapon would be vulnerable to fire, deep water, lightning, crushing impacts, or high-velocity projectiles. Design features of weapon electrical systems have been combined to obtain predictably safe responses in such environments. In a special exclusion region of the electrical system, selected "weak links," which are vital to weapon operation, are interrupted by open contacts from "strong links," which are accident-resistant switches that respond only to unique signals (Figure 3). Electrical elements are so combined and sequenced that the weapon system will not operate if premature signals from any source arrive at the exclusion region, because the weak links will always fail before the strong links can do so.

This designed response does not require a detailed understanding of the complex environments encountered in accidents. Use of this conept also eliminates the need for lengthy evaluations of power supplies and wiring outside the exclusion region. Consequently, system safety can be economically verified by relatively simple analyses and tests.

Earth-Penetrating Weapons

Nuclear weapon systems that penetrate deeply into the earth before detonating can be used to create barriers or craters to impede troop advances; to destroy targets that are vulnerable to burial or sensitive to ground shock, and to reduce the spread of radioactive contamination. Such penetrating warheads were made possible because of an extensive terradynamics research and development program carried on by Sandia over the past decade, and because of development of a superior heat treatment that makes a steel alloy highly resistant to fracture (Figure 4). A mobile vertically fired recoilless gun (Figure 5) was used for extensive testing, and instrumentation was developed to withstand resultant high-impact loadings.

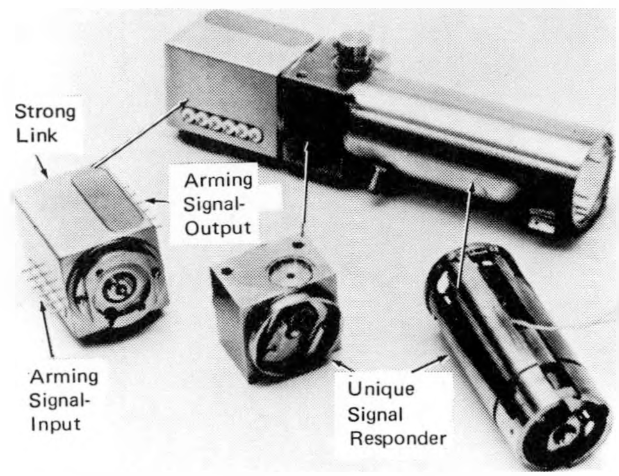


Figure 3. Strong link and unique-signal detector of a weapon safety component.

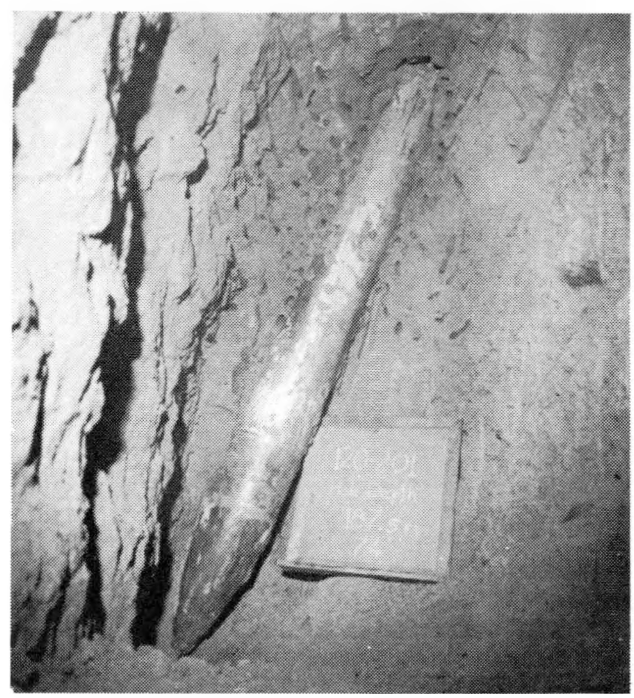


Figure 4. Unfractured penetrator recovered at a depth of 57 metres.

Penetrators have also been used to measure thicknesses and properties of sea ice (Figure 6), have been designed to measure the surface properties of Mars, have formed the basis for innovative deep-drilling designs and for ways of implanting instruments to locate fossil-fuel deposits, and are being designed to make geotechnical measurements of ocean-bottom sediments for locating offshore drilling platforms.

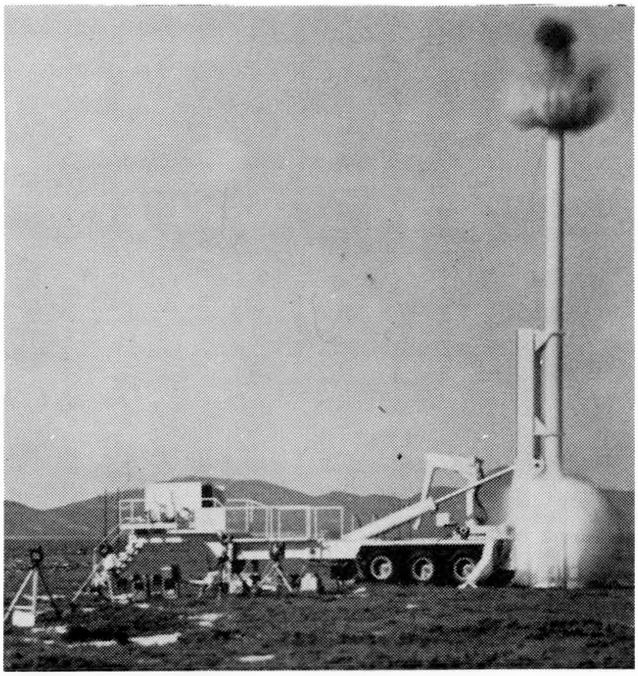


Figure 5. Recoilless gun used to fire penetrators vertically into soils.

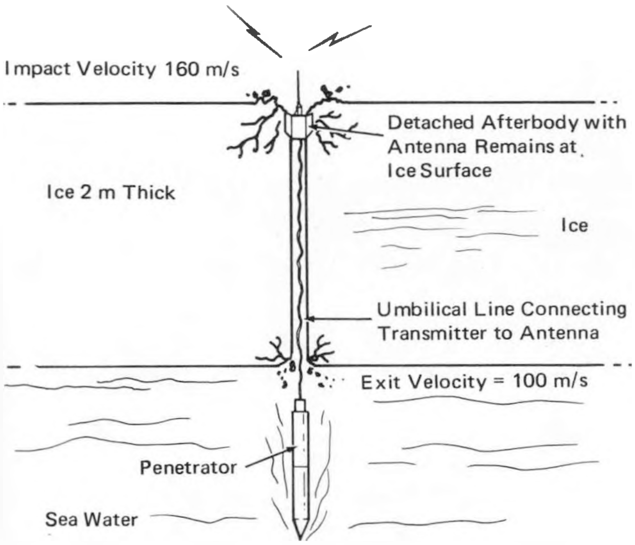


Figure 6. Method by which an instrumented penetrator is used to measure sea ice properties and thickness.

APPLICATIONS OF CAPABILITIES

ENERGY PROJECTS

It is a policy of these Laboratories to apply its capabilities to problems of national concern. Consequently, existing projects aimed at increasing the supply of domestic energy and developing methods of conservation of energy resources have been accelerated and additional projects are being undertaken. Representative examples follow.

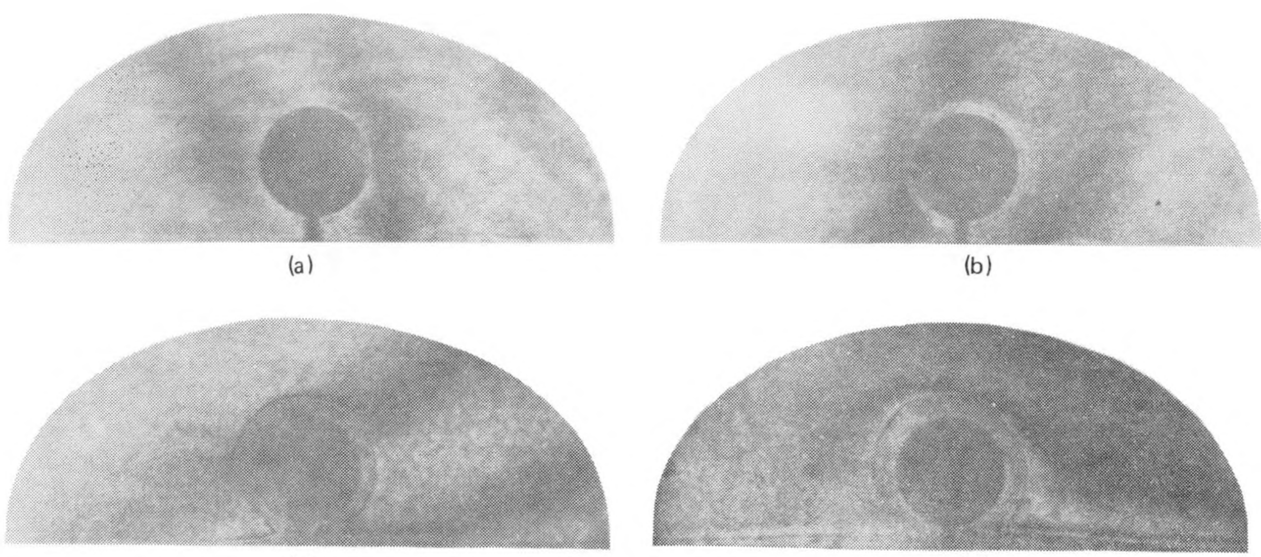
* * * * * * * * * * *

Electron-Beam Fusion

The electron-beam fusion program is a study of mechanisms involved in the production of fusion by inertial compression of thermonuclear fuel, and development of the technology for producing the physical conditions necessary for this process. The near-term goal is to provide an in-house capability to study the physics of small-scale thermonuclear explosions. Over a longer period, this capability could lead to a fusion power source or a fissile material breeder. Radiation produced by these explosions can also be used to test the ability of weapon components to function in a nuclear countermeasure environment.

The program involves systematic attempts to scale early results to increasingly higher levels of input power. Recent experiments illustrate satisfactorily symmetrical energy deposition on a spherical target (Figure 7).

Now under construction is one of the world's highest-power electron-beam accelerators, developed expressly for use in fusion studies. The accelerator (Figure 8) will subject a fusion pellet to two 400,000-amp beams for 25 billionths of a second. Total power will be about 2 trillion watts.



(a) (b) (c) (d)

Figure 7. Sequence illustrating how material ablates (concentric outer rings) from surface of spherical target in electron-beam fusion experiment.

APPLICATIONS OF CAPABILITIES

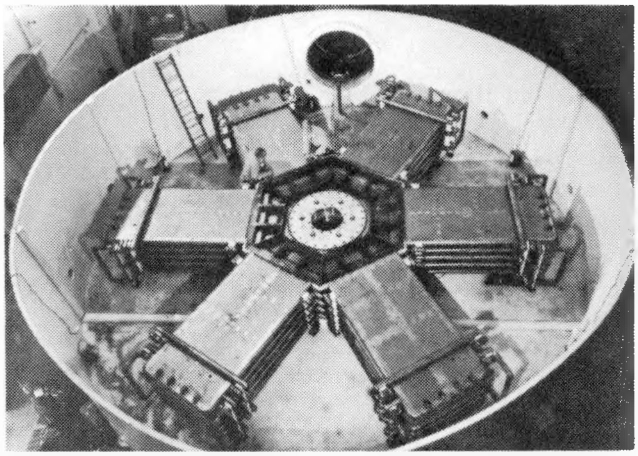


Figure 8. The world's largest electron-beam accelerator under construction. Shown are six voltage multipliers which receive their charge from a large capacitor bank and direct their energy into two diodes that will occupy the space in the center.

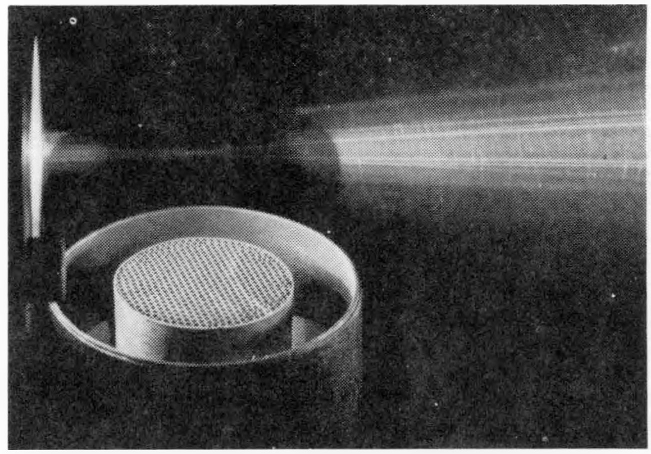


Figure 9. In an experiment involving combustion analysis by lasers, spatial and time-resolved specie concentrations and temperatures of gaseous combustion products are measured using Raman scattering techniques.

Combustion Research

The ERDA Assistant Administrator for Conservation is establishing a National Combustion Research Center at these Laboratories. The underlying analytical and experimental capability was first developed to study gas dynamics for the weapon program and was then extended to the study of combustion processes. Activities include the use of high-powered lasers for analyzing combustion processes (Figure 9), the study of turbulent reacting flows, applied research emphasizing automotive propulsion, and advanced coal-burning power cycles and coal processing.

Solar Energy

Sandia Laboratories is the technical manager of the Solar Central Receiver project for ERDA. The goal of this project is the design and construction of a 10-megawatt (electric) pilot plant. As a part of this project, a 5-megawatt (thermal) test facility will be constructed primarily to test and evaluate solar receivers.

Another major project in Sandia's energy effort is the Solar Total Energy Program. This is an energy cascading concept in which solar energy is used to generate electrical power and the normally wasted heat from electrical power generation is used for heating and cooling buildings and for domestic hot water (Figure 10).

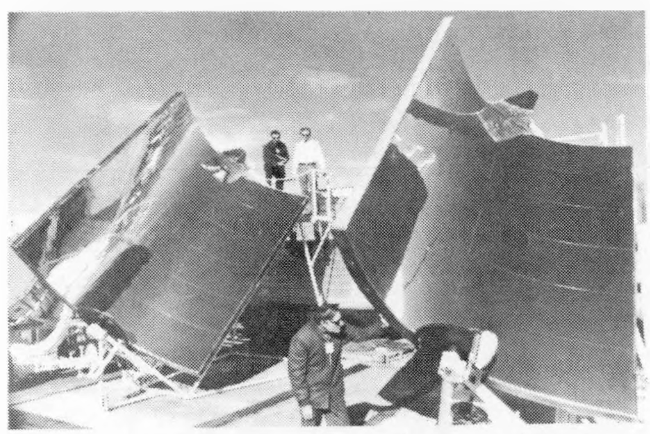


Figure 10. Two parabolic line-focusing reflectors, measuring 2.7 x 3.7 metres, of the type to be used in the Solar Total Energy System, are shown mounted for testing and evaluation. In operation, solar radiation is reflected and focused on receiver tubes through which a heat-transfer fluid is pumped.

APPLICATIONS OF CAPABILITIES

PROGRAMS FOR OTHER FEDERAL AGENCIES

Much of the work done for federal agencies other than the Energy Research and Development Administration is performed for the Department of Defense and is classified. An example is the design and development of satellite-carried nuclear burst detectors. Nondefense work includes studies of the environmental effects of supersonic aircraft on the atmosphere for the Department of Transportation and the development of instrumentation for monitoring fissionable materials for the Arms Control and Disarmament Agency. Other sponsoring organizations include the National Aeronautics and Space Administration, the National Science Foundation, and the National Institutes of Health. An example of work for the Nuclear Regulatory Commission is described below.

* * * * * * * * * * *

Safety and Security Studies

In work related to the nuclear fuel cycle, activities consist of the technical evaluation of systems and components designed to protect against the release of radioactivity. Experiments and system studies are conducted to elucidate the behavior of reactor components and nuclear fuels under accident conditions, and to determine the nature and degree of hazards associated with other segments of the nuclear fuel cycle. Of particular concern are risks attendant upon transportation of fuel materials and radioactive wastes. Here the objective is to safeguard the material from diversion by terrorist groups, and to prevent its dispersal in the event of accident or sabotage. Because of the high toxicity of plutonium and its potential for use in nuclear weapons, its shipment is under very close scrutiny. As part of this investigation, containers used for shipping plutonium are being tested to see how well they withstand severe impact and explosion environments. Figure 11 shows such a container after being driven into any unyielding steel surface at 120 metres per second. In this end-on impact, the outer container was breached, but the inner container remained intact. It was found that other impact conditions are more likely to breach both containers.

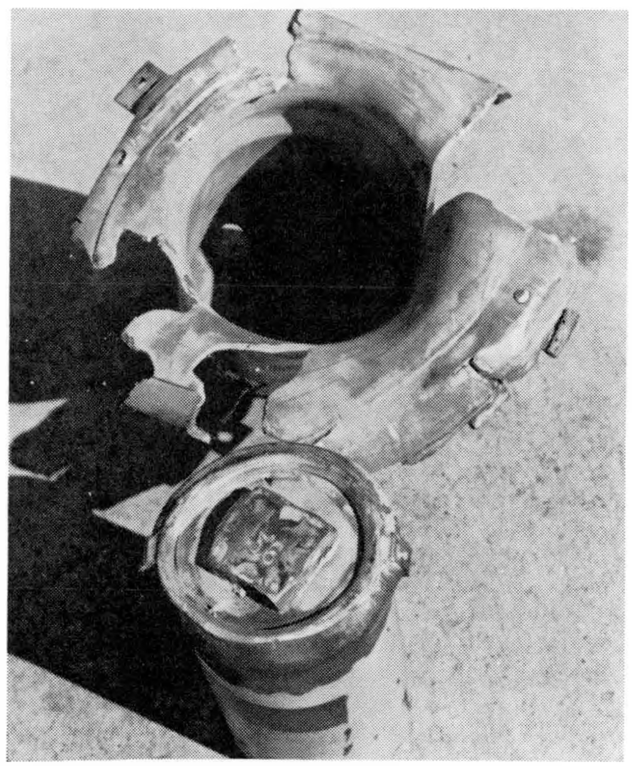


Figure 11. Components of a shipping container for plutonium that was driven into a steel surface by a rocket sled.

MANAGERIAL CAPABILITIES

The form of direction provided by Sandia technical management is directly dependent upon the number of technical capabilities required to complete a project. Extensive projects, such as weapon programs, require essentially all of the capabilities and are directed by a program manager and his staff. Smaller projects, such as research, are centered in a particular discipline and are managed by the technical staff of the organization specializing in that capability.

SYSTEM ENGINEERING AND MANAGEMENT

Individual projects for national security, energy, and other federal programs are directed by the System Engineering and Management staff. Their function is to provide technical direction, control expenditures, and direct the progress of engineering programs. The system staff consists of some 580 engineers and scientists (from a total of 1743 in the Laboratories) of diversified interests and backgrounds. The system staff defines the objectives of a system and the environments in which it must function, and evaluates cost and associated trade-offs needed to attain cost effectiveness.

COMPONENT DEVELOPMENT

The component development activity uses various technical capabilities to design special components for nuclear weapons, nuclear-material security, and energy applications. These components are characterized by exceptional reliability, ruggedness, and precision. The reliability requirements are imposed by the consequences of failure of the systems on which they are used. The requirements for ruggedness stem from the severe use environments that could be encountered, and timing requirements are imposed by the inherent physics of the systems and the necessity for accuracy.

QUALITY ASSURANCE

Quality assurance programs assure predictable and satisfactory behavior of engineering systems and components. The primary responsibility of this activity is to the nuclear weapon research and development program and to surveillance of the quality of deployed weapons.

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TECHNICAL CAPABILITIES

SCIENCE AND ENGINEERING

PHYSICAL SCIENCES

Research in the physical sciences is directed toward understanding basic phenomena, enhancing physical characteristics, and developing predictive capabilities for practical applications. Studies in the physics of solids, surfaces, and thin surface layers are leading to improvements in solid-state devices. Work on the dynamics of stress and shock waves is directed toward generating computer codes to augment or replace costly and time-consuming hardware testing. Investigations into the interaction of radiation with matter are resulting in techniques to ameliorate radiation-induced damage in solid-state components. Research in laser fusion and electron-beam fusion constitutes an essential part of the nation's program to harness thermonuclear fusion as a future energy source, and also provides nearer-term radiation sources for weapon-effects studies. Fission reactor activities are aimed at developing improved fuels and enhanced safety for commercial power reactors.

The major facilities for conducting research in the physical sciences include several high-energy Van de Graaff

SUMMARY

accelerators, heavy-ion and high-current accelerators, ultra-high vacuum facilities, gas-gun installations, high-intensity lasers, intense pulsed electron accelerators, and pulse reactors. (Item 1)*

MATERIALS AND PROCESSES

Materials and process activities maintain a balance between research and development to provide materials compatible with the extreme environments and performance requirements associated with nuclear ordnance.

Specific technical areas that have continuing emphasis include metallurgy, composites, surface characterization, thin film deposition, polymers, ceramics, and high-temperature characterization. Complete processing and fabrication facilities assure a capability for early evaluation and use of tailored materials. Efforts are focused on material applications involving structural and electronic materials, thermal and electrical insulation, radiation shields, and shock mitigation. Key elements in these efforts are functionability, reliability, and longevity.

This interdisciplinary approach to scientific materials engineering results from the recognition that many disciplines are required to understand, characterize, and apply materials, and from the fact that material design is an essential element in meeting the objectives of quality, functionality, and life. (Item 2)

APPLIED MATHEMATICS

Research in numerical mathematics provides support for scientific computing and typically leads to the development of new or improved computer programs. Many problems associated with the command and control of nuclear weapons and with the reliability and security of communication networks require mathematical research in the related disciplines of graph theory, combinatorics, and coding theory. Research in mathematical physics is resulting in a better understanding of material properties and wave propagation. Research on the theoretical foundations of a number of mathematical tools used by scientists and engineers is delineating more clearly the range and usefulness of these tools. Statistical research is carried out in support of reliability studies, system analysis, the design of experiments, and data analysis. (Item 3)

*See Highlights below.

EARTH SCIENCES

The earth sciences are directed principally toward an understanding of the response of the upper layers of the earth (soil and rock) to dynamic loading. The disciplines of geology, soil mechanics, fluid dynamics, and engineering mechanics have been combined to solve specific earth-response problems that fall outside the scope of any one technical area. Penetration, drilling, and measuring the response of the earth to explosions and earthquakes are of prime importance. In problem areas encountered at these Laboratories, earth-material motions and strain rates are appreciably greater than are found in more classical studies of soil motion. Specific technical areas on which continuing emphasis is placed include dynamic stress analysis (as related to earth materials), terradynamics (phenomena attendant upon earth penetration by high-velocity projectiles), underground physics (the study of earth-material motions resulting from underground detonations), drilling technology, magma research, and the development of diagnostic instrumentation. The key element in each of these areas is the effort to understand the dynamic behavior of earth materials so that they can be characterized well enough to make specific problems solvable. Soil and rock are complex materials in terms of engineering properties, particularly during high loading rates and at high temperatures, and consequently there is a strong reliance upon empirical results.

AEROSCIENCES

Aeroscience activities represent a balance between applied research and the aeroengineering required to support technical programs. Studies are directed toward a greater understanding of mechanisms encountered in extreme flight environments that include velocities up to 8000 metres per second, altitudes from below sea level to over a million metres, and vehicle surface temperatures up to 4500 K. Areas of interest include aeroballistics, rocket aerodynamics, decelerator technology, experimental aerodynamics, atomic and fluid physics, aerothermodynamics, experimental aerophysics, atmospheric environmental studies, applied fluid dynamics, and aeromechanical design.

Research and development are supported by analytical techniques including computer modeling, and by laboratory facilities such as analog and hybrid computers, motion simulators, trisonic and hypersonic wind tunnels, arc jets, shock tubes, water tunnels, and parachute fabrication and testing equipment. (Item 4)

SUMMARY

BIOSCIENCES

Biological programs are directed toward an understanding of the effects of environmental conditions upon living systems. Emphasis is on incorporating physical, chemical, and engineering principles, theories, and techniques into the resolution of biological problems. Results from this effort include models of the lethal effects of heat and ionizing radiation on microbiological systems, new microbiological sampling devices and techniques, new sterilization processes, computerized systems representing man's interaction with a plutonium-contaminated environment, new information about the effect of heat upon radiation-induced mutation, the behavior of bacteria on surfaces to be sterilized, and the usefulness of heat/radiation combinations in vaccine development. (Item 5)

EXPLOSIVES, ELECTROCHEMISTRY, AND ELECTROMECHANISMS

A demand for components made to high standards of reliability, safety, and longevity for use in nuclear weaponry has required research and development to make possible an understanding of the mechanisms that control component operation, and to use these mechanisms for practical purposes.

Most of the components either generate or are actuated by electrical signals. Operational constraints have necessitated miniaturization, long-term material compatibility, and an ability to withstand severe environments.

Studies in explosives, particularly detonation physics and the chemistry of explosives, have led to reliable ways to use the sudden release of chemical energy. Chemical and thermal-conversion processes are used to release the energy stored in batteries. Studies in electromechanisms have resulted in miniaturized components for environment sensing, electrical switching, and timing.

The major facilities for conducting research and advanced development of electrochemical and electromechanical components are chemical laboratories, gas guns, fabrication facilities, and environmental testing and firing sites.

ELECTRONICS

The aim of electronics activities is to acquire an understanding of the physical properties of elements used in electronic circuits and the effects of fabrication and processing on these properties. Reliability is a basic requirement, and predictable response is necessary under extreme environments such as mechanical shock, intense radiation, and large temperature excursions. Studies of the properties of silicon as influenced by processing variables result in reliable and innovative active elements. Work on various methods of discrete component attachment aids in the miniaturization of hybrid circuits. Substrate and thin-film studies are leading to new electronic materials and providing improved assembly methods.

Vacuum tubes are designed that allow the rapid transfer of electrical energy and the generation of high-energy neutrons. Pulses of high-current, high-voltage electrical discharges are generated by the controlled depolarization of ferromagnetic and ferroelectric materials.

Facilities exist for building hybrid microcircuits and for evaluating prototype designs. There are large modern clean-room facilities for the fabrication of active semiconductor elements and large-scale integrated circuits. A laboratory area is available for fabricating neutron generator tubes and high-energy switching tubes. (Item 6)

SAFETY AND RELIABILITY ASSURANCE

Safety and reliability responsibilities have necessitated the development of analytical and measurement techniques for evaluating system behavior in normal and abnormal environments. As a result of these evaluations, designs are sometimes modified or new design concepts introduced. Assessment technologies emphasize extensive use of computational models and data from simulation experiments and tests at subassembly and lower levels. This is necessary because full-scale demonstrations in anticipated final-use conditions are often forbidden by international agreements, or by ecological or economic conditions.

Safety and reliability studies are performed on such projects as nuclear weapons, conventional weapon subassemblies, nuclear power reactors, special transport vehicles, and ground-based and satellite sensor systems.

Both safety and reliability investigations are conducted by specialists outside the project groups to encourage an independent assessment approach.

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Electron-Beam-Ignited Chemical Laser*

The REBA accelerator (Figure 1), developed by Sandia in 1967 for weapon-effects studies, is used in the exploration of methods to develop high-power lasers. In one experiment a magnetic field is used to guide electrons in a drift chamber filled with hydrogen and fluorine. The gas mixture is ignited, producing the most intense laser pulse ever recorded: 5000 joules for 20 billionths of a second.

Item 2. *Melting and Solidification Laboratory*

A melting and solidification laboratory has been established for the pilot-scale production of homogeneous alloys of unique chemistries. Specific alloy chemistries are prepared in a 500-pound-capacity vacuum-induction furnace and cast into electrode feedstock for the vacuum-arc remelt furnace shown in Figure 2. Ingots up to 10 inches in diameter can be produced by the consumption of feed electrodes in a low-pressure, 15,000-ampere arc. These highly instrumented furnace systems provide significant quantities of well-characterized material for alloy-development studies, demonstrating how superior structural materials can be produced through enhanced process controls.

Item 3. *Advanced Numerical Techniques*

Stress- and shock-wave-propagation computer programs are developed for a more complete understanding of stress-wave mechanics. Codes are used to analyze system and component designs, reducing reliance on expensive experiments. The ability of two-dimensional computer codes to solve difficult problems accurately is illustrated in Figure 3. A 1.27-cm-thick steel armor plate is impacted by a 0.95-cm-diameter nylon sphere at 5182 m/s. The 13-GPa polymorphic phase change in iron, the correct spall strength, an accurate material failure model, and a high degree of numerical resolution were required in the solution.

Studies of high-velocity impacts include predictions of damage to nuclear reactor vessels from fragments such as turbine blades dispersed in an internal accident, and from tornado-borne debris.

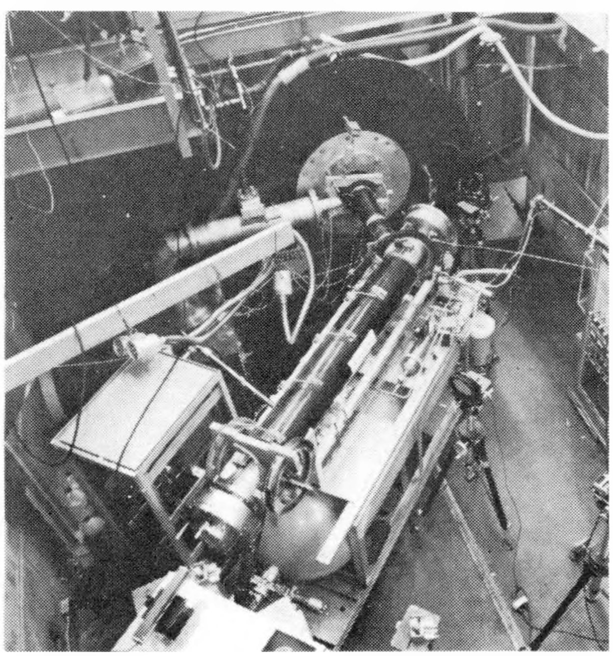


Figure 1. Relativistic electron beam accelerator (REBA).

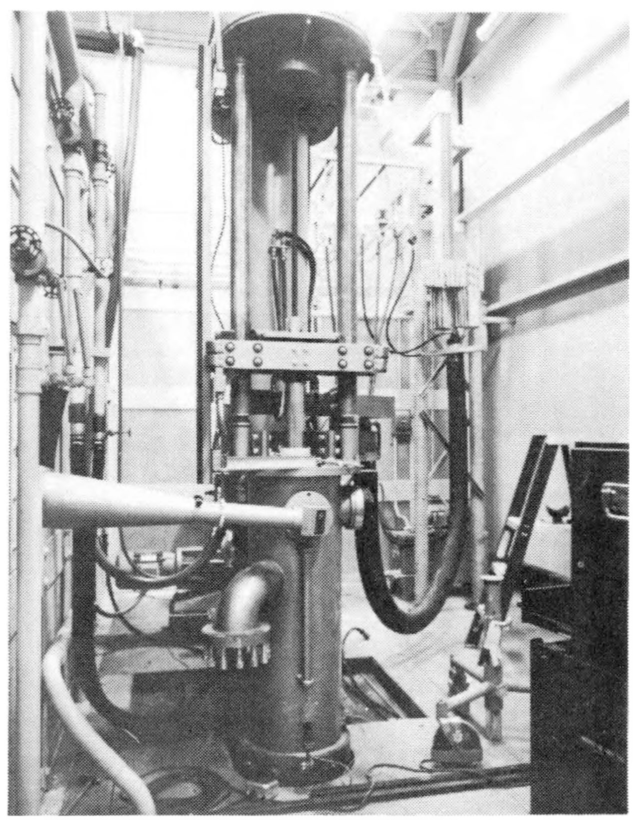
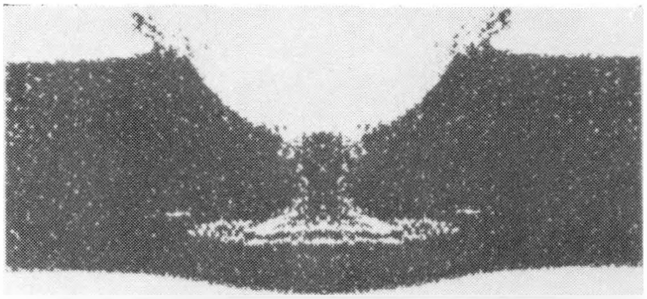
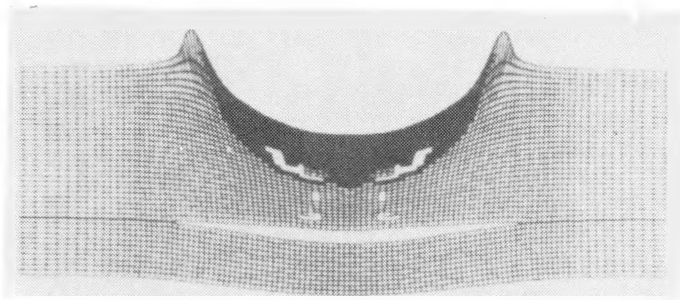


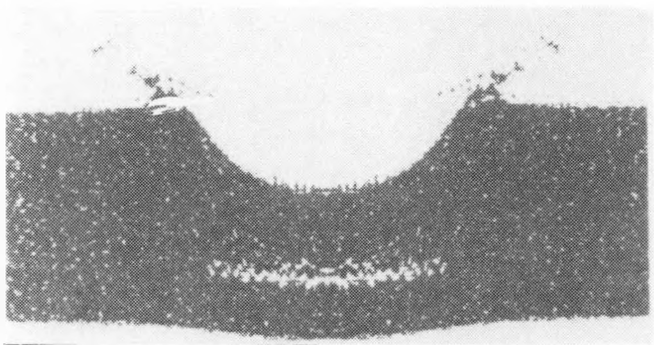
Figure 2. Vacuum-arc remelt furnace.



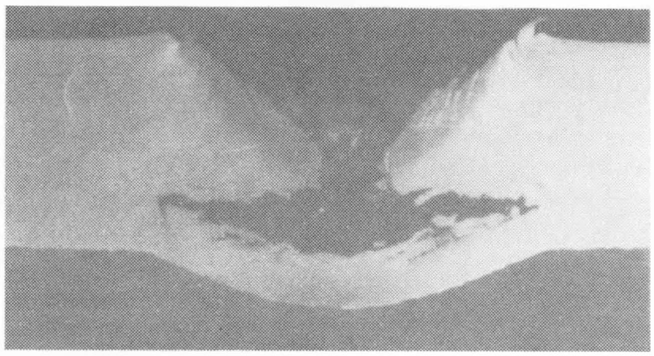
Eulerian code solution with
13-GPa phase transition



Eulerian code solution without
13-GPa phase transition



Lagrangian code solution with
13-GPa phase transition



Experiment

Figure 3. Comparison of code predictions with results of hypervelocity impact experiment

Item 4. *Hypersonic Wind Tunnel*

The hypersonic wind tunnel (Figure 4) is used for aerodynamic testing of scaled models of high-performance flight vehicles, and for applied-research studies in fluid dynamics. Flow Mach numbers of 3.5, 5, 8, 11, and 14 can be obtained in a 45-cm-diameter test section. The facility includes comprehensive instrumentation and data-acquisition systems.

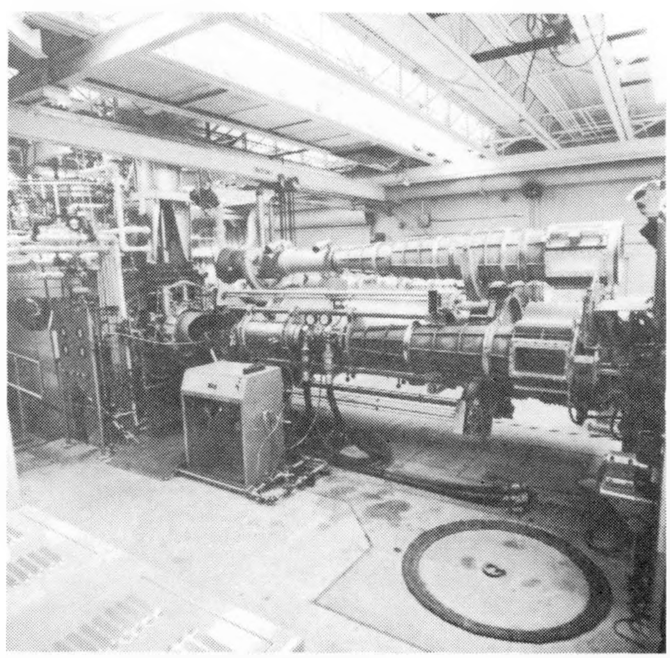


Figure 4. Hypersonic wind tunnel.

Item 5. *Bacteria Inactivation*

A biosciences project has as one of its objectives the development of a technology to use radioisotopic by-products from reactor fuel rod reprocessing to deactivate municipal sewage sludge. A potentially beneficial use of heat combined with radiation from cesium is the eradication of pathogenic organisms so that the sludge may be used on crop-producing land or in livestock feeding. The optimal combination of radiation and heat is being sought through studies of the inactivation of polio virus, adenovirus, coliform bacteria, fecal streptococci, Salmonella species, and Ascaris ova. Figure 5 depicts typical coliform inactivation data. Modification of the physical and chemical characteristics of sludge (such as filterability, odor, and chemical and biological oxygen demand) by heat and radiation combinations is also being studied. The activity includes experimental system design and fabrication, pilot plant design, determination of cost factors, the study of sludge uses and accruing benefits, and safety analyses.

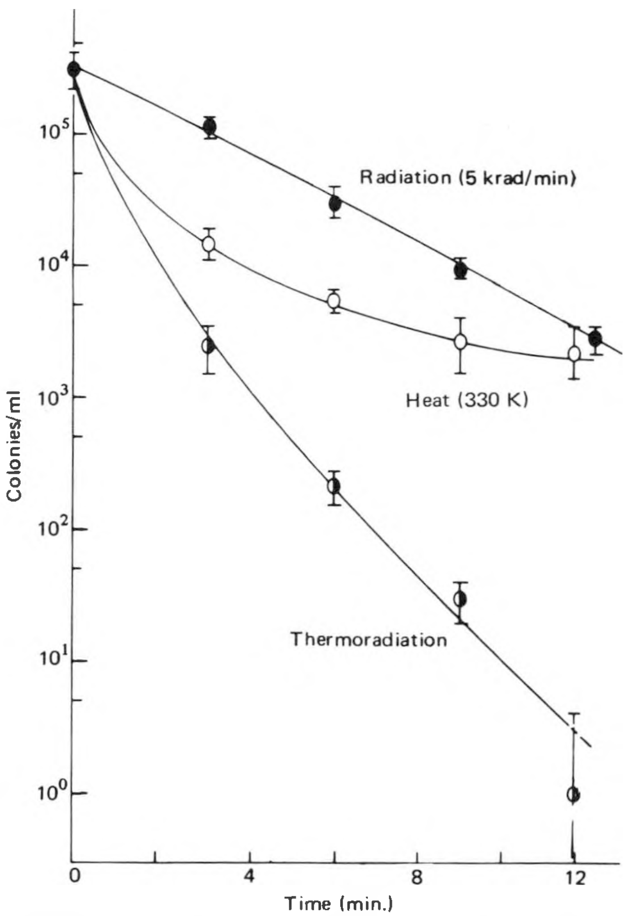


Figure 5. Inactivation curves for heat, radiation, and their combination (thermoradiation) in the treatment of coliforms in sewage sludge.

Item 6. *Hybrid Microcircuit Technology*

A continuing effort to advance thin film and hybrid-circuit techniques provides a foundation for fabrication, materials, and the interconnections of discrete components. As an example, the hybrid microcircuit shown in Figure 6 is used in locking mechanisms to protect nuclear materials from unauthorized use. Hybrid microcircuit technology is highly developed and has found application in other protective components and intrusion detectors for special nuclear materials, satellites, radars, and applications requiring rugged, compact circuits such as earth penetrators, new drilling techniques, and underground test instrumentation.

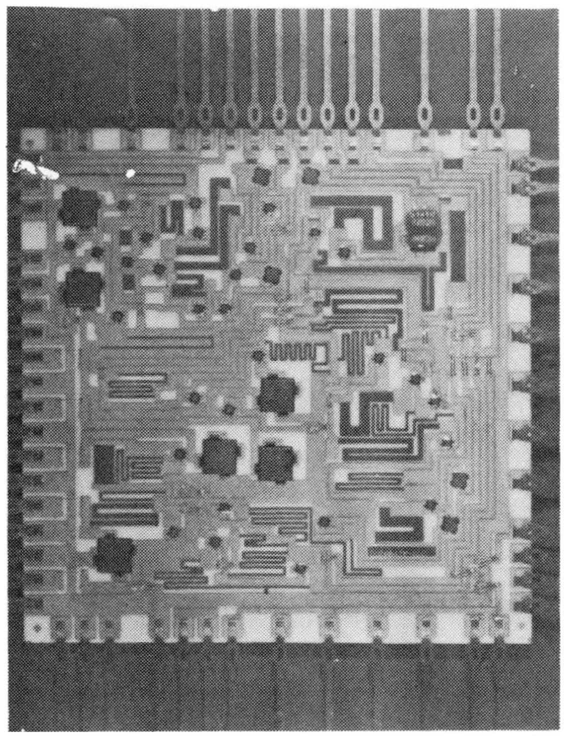


Figure 6. A hybrid microcircuit. The actual size is 6 square centimetres.

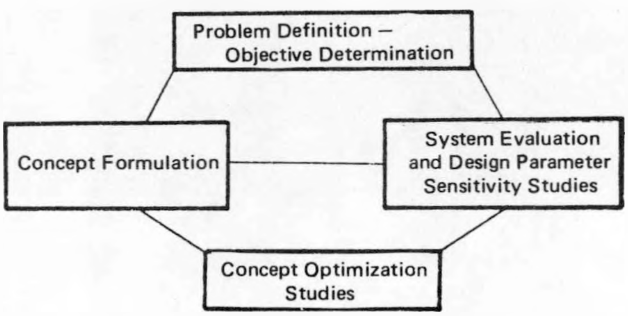
SUMMARY

ANALYSIS AND TESTING

SYSTEMS ANALYSIS

The objective of systems analysis activities is to aid in deciding among alternative systems and concepts. This is accomplished by evaluating the relative utility and costs of competing options within the appropriate environment. Areas of active study include nuclear and conventional weapon systems, energy extraction and conversion, environment analyses, security systems for weapons and materials in nuclear fuel cycles, and biological systems. Typically, the studies seek to evaluate the relative worth of new concepts and to provide an understanding of parameter sensitivities that can lead to system improvements.

The outline below describes the major steps in almost every system study.



The systems analysis function may begin at any point in this schematic and feed forward or back to previous steps, as indicated. The object of such iterations is to formulate, evaluate, and/or optimize a system or alternative systems on the basis of a common set of objectives. In addition to identifying system options or alternatives the studies provide early insight into critical technology requirements. (Item 1)*

ENGINEERING ANALYSIS

This function is concerned with calculating the responses of designs to their environments. Structural mechanics is used to aid in determining a design configuration and in choosing materials suitable for the loads to be encountered in practice, particularly in severe dynamic environments.

Stress-wave analysis centers on the propagation of stress waves arising from impact, explosions, transient radiation, and other extreme environments. Chemical analysis is used to determine the initiation and detonation characteristics of explosives. Heat-transfer studies confirm the performance of heat-exchange systems, thermal protection materials, and rotating machinery based on various thermal cycles and phase changes. Aerodynamic calculations predict the behavior of vehicles in free and propelled flight. Environment analysis is used to define the conditions a product might encounter during its lifetime. The analysis of control systems comes into play when environment-sensing devices, control mechanisms, and decision-making and guidance functions are combined. The design of electronic packages relies on circuit analysis. Nuclear engineering analyses are directed toward pulsed reactor development, design, and operation. Reactor safety analysis relates to hypothetical disruptions of nuclear reactor operations.

As a necessary adjunct to successful engineering computations, both mechanical and thermal material properties are determined.

The major facilities used in engineering analysis are large digital and analog computers, static test facilities, wind tunnels, and vibration test facilities. Numerous pieces of equipment are used to determine material properties. (Item 2)

TESTING

Extensive test facilities have been developed to simulate mechanical, thermal, hydrodynamic, electromagnetic, and radiation environments. Research, development, and evaluation testing facilities are used to explore new concepts and to evaluate proposed and existing designs. Environments simulated include shock, vibration, surface impulse, blast loads, thermal, aerodynamic, underwater, and electromagnetic. Radiation sources have been developed to simulate nuclear effects tests. Pulse reactors provide a mixed neutron-gamma exposure. Steady-state neutron and gamma irradiation are provided by a neutron generator and cobalt and cesium radiation sources. Bremsstrahlung x-ray and electron-beam exposures are performed using pulse accelerators. Test facilities used primarily in support of exploratory research and development are wind tunnels, plasma jets, shock tubes, and flight simulators to support aerodynamic testing, and high-velocity gas guns and explosively and magnetically driven flyer plate facilities

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*See Highlights below.

to support materials characterization in solid dynamics and structural studies. Materials, structures, components, and entire integrated systems are evaluated using a wide variety of nondestructive testing techniques such as flash x-ray, acoustic emission, laser holometry, ultrasonics, and x-ray and neutron radiography. Field-testing capabilities include mobile instrumentation vans that can be deployed worldwide, a rocket-launching facility at Kauai in Hawaii, an isolated area at the Nevada Test Site for underground nuclear testing, and the Tonopah Test Range for a wide variety of aerodynamic testing.

In addition to providing test facilities for engineering programs, the responsibility of the testing function includes anticipating future test requirements and integrating test plans with project, research, and advanced development organizations for the design of meaningful test programs. (Item 3)

INSTRUMENTATION AND DATA SYSTEMS

An extensive instrumentation and data-reduction activity is maintained. Many advanced designs now in development must operate in extreme environments such as those encountered in space, in high radiation fields, or under severe mechanical, thermal, and electromagnetic loads. The instrumentation activity provides instruments that measure characteristics of environments, measure responses and performance of materials and systems operating in them, and locate accurately the position of systems in the environment. To fulfill these tasks, new instrumentation systems are developed and existing techniques modified. Instrumentation is fielded in conjunction with design and testing activities.

Data processing and data reduction are integral activities that provide test information in various forms, including charts, graphs, photos, movies, or special forms, depending upon needs. (Item 4)

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Nuclear Material Security*

A concept has been developed that involves drilling and casing a deep hole of reasonably small diameter to create a secure underground vault for weapons or nuclear materials (Figure 1). Access to the vault is controlled through the use of a security door operated by a buried coded switch. All other features necessary for a complete security system were conceptually designed and evaluated.

A study of this and other alternative storage concepts was prompted by increasing concern about terrorist threats and by the desirability for reducing readily available, full-time guard force, such as is demanded by present storage methods.

Critical factors that were studied relating to weapon storage included potential security threats, safety, initial and operating costs, vulnerability, logistics, and future flexibility.

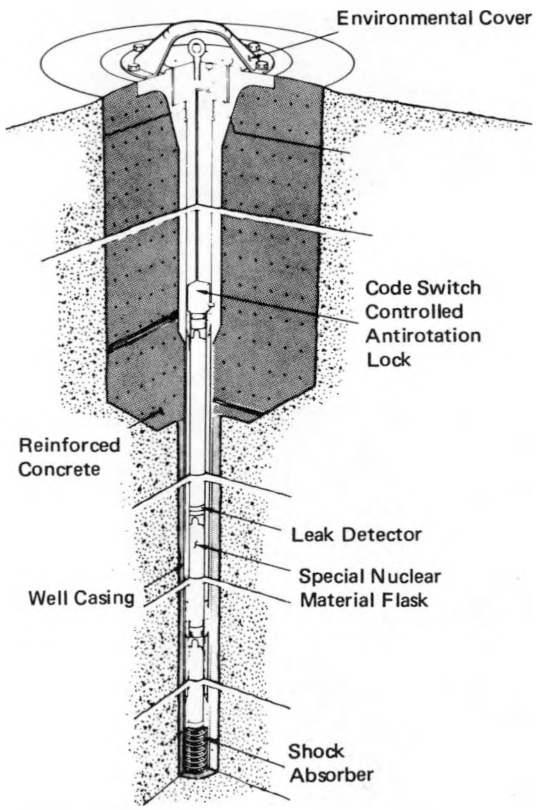

Figure 1. Underground vault for storing nuclear materials.

Item 2. *Three-Dimensional Static Stress Analysis*

Analytical capability has been developed to perform three-dimensional static stress analyses of shells and solid structures subjected to mechanical and thermal loading. Analyses are based on assumptions of infinitesimal strain and linear elastic material behavior. A capability exists to perform elastic-plastic three-dimensional calculations. Implied in this capability is the use of input and output data processors, which are essential in three-dimensional analyses. This type of analysis finds application in structural, electrical, and electromechanical components. As an example of the technology, Figure 2 shows the three-dimensional finite-element idealization of an encapsulated electrical component. When subjected to a combination of mechanical loads, the top surface deforms as shown in Figure 3. Calculated stress contours on a particular plane can also be plotted, as shown in Figure 4.

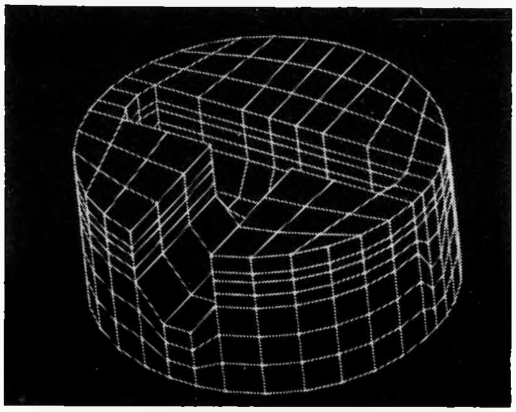

Figure 2. A three-dimensional finite-element mesh idealization of an encapsulated electrical component.

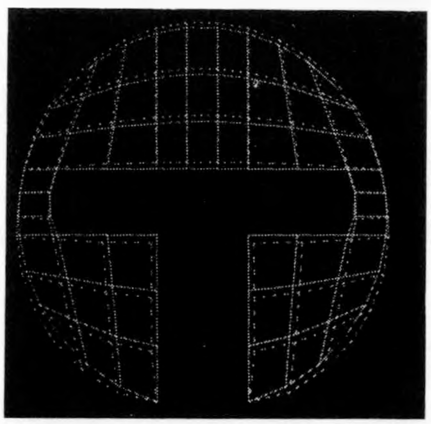

Figure 3. Deformed shape of the mesh on a plane through the structure.

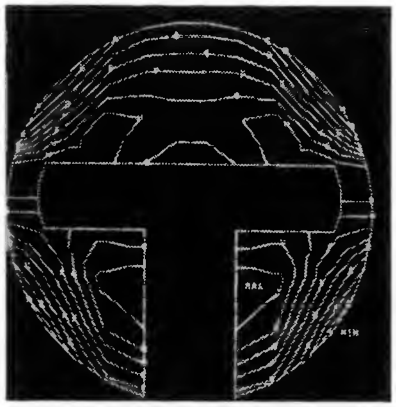

Figure 4. Maximum principal stress contours on a plane through the structure.

Item 3. *Nuclear Weapon Test and Evaluation*

Testing and evaluation of materials, components, and systems play key roles in the research and development of nuclear ordnance. Extensive facilities for environment simulation, research, development, evaluation, and field testing, and associated instrumentation and data analysis systems have been developed. Figures 5 through 7 show examples of test facilities.

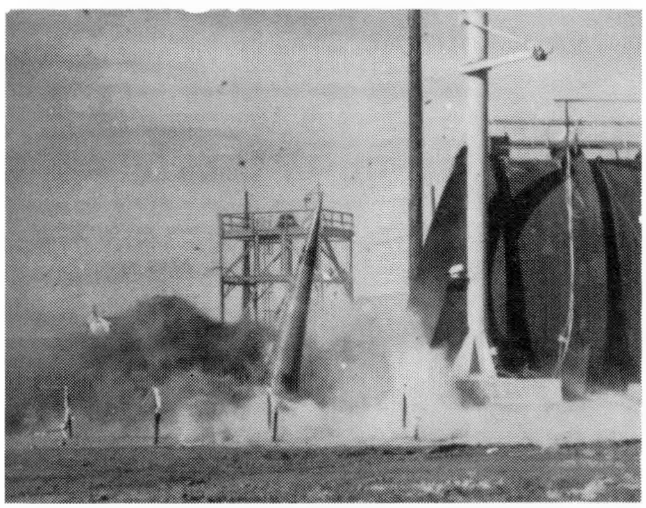

Figure 5. An explosively driven shock tube is used to evaluate the response of a vehicle to blast loading.

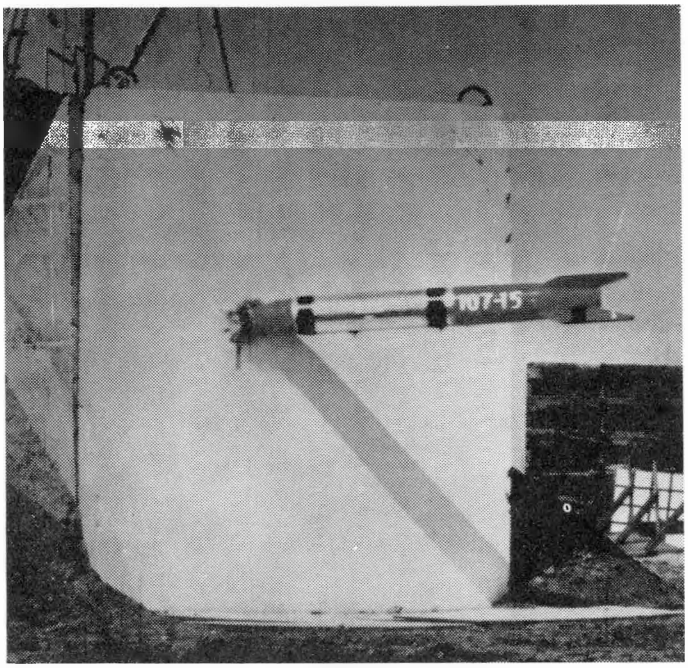

Figure 6. A rocket-propelled sled drives a test vehicle into a concrete target. Impact angle was 45 degrees. The structural response of the vehicle and the timing sequence of the components operation were evaluated.

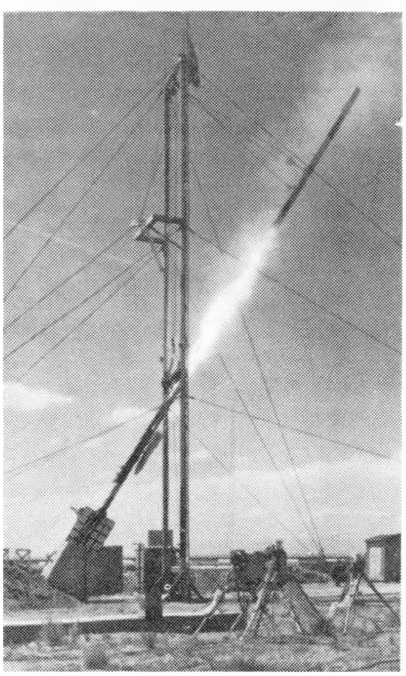

Figure 7. A rocket is used to accelerate a prototype nuclear bomb into a hard target. Behavior of weapon components and structure is measured using optical and electronic instruments.

Item 4. *Atmospheric Research*

Concern about atmospheric pollution has been intensified with the realization that potentially serious deleterious effects on the earth's protective ozone layer may be caused by stratospheric aircraft, fluorocarbon chemicals, and atmospheric testing of nuclear weapons. The long-term Sandia atmospheric research program has become of central importance to solution of the stratospheric problems; it is the principal correlated multi-instrument national study of the stratosphere and troposphere. The program is carried out in cooperation with research teams from twelve university, federal, and industrial laboratories, with Sandia providing project engineering and scientific coordination in addition to scientific experiments. Other atmospheric environmental programs include lower-atmosphere pollution studies from aircraft and manned balloons (Figure 8), and rocket-based studies of the ionosphere and mesosphere.

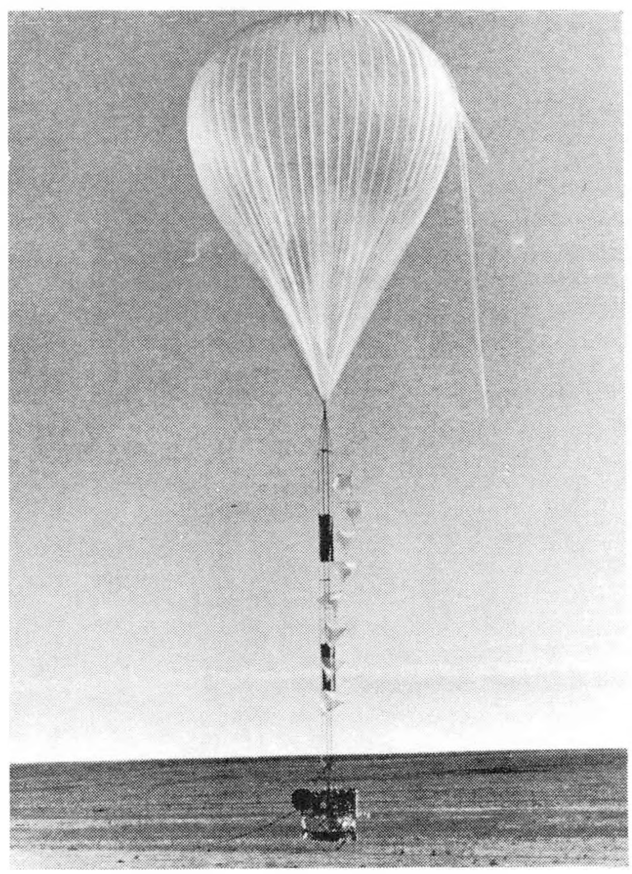

Figure 8. Termination of a scientific manned balloon flight. The tropospheric balloon carried instruments for studying the chemical evolution of air pollutants.

SUMMARY

SUPPORT FUNCTIONS

DESIGN DEFINITION AND FABRICATION

Research and development programs are supported by developing and applying computerized design and record-keeping systems; maintaining records of designs, specifications and changes, and coordinating with contractors who produce parts of systems; and maintaining drawings of designed systems.

Processes are developed and hardware fabricated to provide experimental vehicles and models required by engineering and scientific organizations. Complementing the fabrication and development facilities are inspection, equipment repair, and process engineering services, as well as calibration services which interact with Sandia's Primary Standards Laboratory.

COMPUTATION SYSTEMS

The computing centers and their associated technical support organizations at both Albuquerque and Livermore have the responsibility of planning, adapting, and operating large-scale digital computer facilities in general support of the scientific and engineering community of the Laboratories. Such modern, large-scale computers have become essential to the solution of such problems as the modeling of complex systems, component design and development, and the detailed simulation of physical phenomena. A growing number of smaller digital computers are integrated into specialized facilities supporting specific areas of research and development such as activities in experiment control, data acquisition, and test monitoring. A few main-line computers are devoted to management information and business data processing.

The central computing facilities are presently based on Control Data Corporation scientific computer systems. The Albuquerque facility consists of three CDC-6600's sharing a common mass-storage subsystem as well as extended core storage. A CDC-7600 is scheduled for operation in January 1976. The Livermore facility contains an additional CDC-6600, also with an extended core capability. Remote job entry and interactive computation are increasingly emphasized. Time-sharing is accommodated at both centers but is represented more extensively at Albuquerque where a PDP-10 computer system is devoted exclusively to that function.

MEASUREMENT STANDARDS

The aim of this activity is to assure measurement agreement among participating research, development, design, production, acceptance, and quality assessment groups and agencies. To this end it promotes a common administrative and technical base of procedure and capability, embodied in physical references and practices of high accuracy and sophistication. When possible, values are referred to those defined by the National Bureau of Standards.

The ERDA Primary Standards Laboratory, which is managed by Sandia Laboratories, is oriented to the development and maintenance of primary reference standards and their application to the calibration of other reference standards in the overall standards system. A research and development program in measurement technology provides new standards and accuracy levels when required. Program and measurement activities of participating groups and agencies are examined continuously to assure balance and compatibility in standards efforts. Consultation service is provided on measurement and standardization problems, and technical audits and surveys of contractor standards laboratories are conducted regularly.

ENVIRONMENTAL HEALTH

The primary responsibility of the environmental health function is the evaluation and control of hazardous materials and conditions. The evaluation and control of toxic materials, nonionizing radiation such as laser beams and microwaves, and ionizing radiation from radiation machines and radioactive sources, are examples of the activities of environmental health programs. A chemical laboratory is operated for the analysis of toxic and radioactive substances and to provide an index of internal exposure of personnel to toxic and radioactive materials. Instrumentation is developed and maintained for environmental health activities. A dosimetry program measures personnel exposure to external ionizing radiation. Reentry safety control and effluent documentation support are provided for underground nuclear tests.

INFORMATION SCIENCE

The information science activity functions within the framework of the technical library, and is oriented toward the efficient dissemination of information to technical and administrative personnel. Computerized systems are used to collect, process, and circulate books, reports, and other literature. Current awareness, reference, translation, and literature-search services are also provided.

APPENDIX

APPENDIX

FACILITIES

The administrative, laboratory, shop, storage, and special facilities maintained by Sandia at its three locations include:

Location	Acres	Number Buildings	Thousand Sq. Ft.	Cost $ Million*
Albuquerque, NM	2,835**	285	2,233	247.5
Livermore, CA	161	45	161	48.3
Tonopah, NV	369,280***	39	60	20.3

*Includes facilities, equipment, land, and utilities

**An additional 47,000 acres are available on co-use agreement with the Air Force

***Used by permit from and operating agreement with the Air Force

Major Technological Assets

Over 25 years of operation, Sandia has acquired a wide range of specially designed and constructed facilities for ordnance engineering. Recently, some of these, together with new facilities being developed, have been applied to energy problems. Some individual facilities are among the largest in the country, but it is the broad scope of special facilities and equipment that makes the activities in engineering, testing, and basic sciences particularly effective. Because of the specialized demands most of the equipment and facilities were either designed or modified by the Laboratories.

Testing facilities at the three locations represent an investment of more than $106 million, providing capabilities for environment and radiation simulation, aerodynamic and material characterization, nondestructive testing and quality-assurance evaluation, and field assessments of components, weapons, and delivery modes. Special facilities include some of the nation's largest centrifuges and shock tubes, a radiant-heat facility, a transonic wind tunnel, a sled track, and aerial cable facilities on which test specimens are accelerated downward by rocket sleds. Facilities for the investigation of aerodynamic and material characteristics of components and full-scale flight vehicles represent a further investment of $27 million. Nondestructive and quality-assurance testing equipment and facilities total $30 million in acquisition cost. A new advanced Tritium Research Laboratory will provide capability to handle safely a variety of experiments with tritium compounds.

In the physical sciences, several Van de Graaff and Cockroft-Walton accelerators are used in surface physics research and microelectronics development; three pulsed reactors (one of which can deliver 4×10^{15} neutrons per square centimetre in a 4.7 millisecond pulse) are employed for reactor development and reactor safety research; and the nation's most intense relativistic electron beam accelerators are being used in pulsed fusion research, in laser excitation, in nuclear effects studies, and in collective acceleration of ions to ultrahigh energies. These accelerators are also used in the laser fusion program to excite large-volume laser media to record levels. One of the reactors has been used to pump a carbon-monoxide laser of Sandia design. Investment: $19 million.

Computation facilities at all locations represent an investment of $32 million. Scientific computing is currently done with four CDC-6600 computers, with a CDC-7600 soon to be added, including batch processing and interactive graphics capabilities and an off-line computer output microfilm system that can also generate motion pictures in color. Business and management information needs are handled by a dual-processor UNIVAC 1108 and a CDC-3600. Requirements for unclassified computation in a time-sharing mode are satisfied by an 80-terminal PDP-10. Instrumentation and data needs at the test sites are handled by a CDC-6400, a CDC-3100, two PDP-124's, and an XDS-930. Flight-simulation facilities include several analog and hybrid computers. Other computers are used to control device testers and acquire and reduce data in the microelectronics laboratory, for laser diagnostics, and for numerically controlled machine tools.

Investment in facilities dedicated to design, fabrication, and process development exceeds $12 million. Included are computers to aid in design; a complete machine shop whose conventional equipment is supplemented by five-axis numerically controlled milling facilities, and a miniaturization shop; a welding and joining laboratory (including microwelding); a specialized glass-fabrication shop; a ceramics fabrication laboratory; a combustion laboratory, including equipment for laser-based Raman spectroscopy; a plastics and composites (such as carbon-carbon) fabrication and processing facility; a laboratory for melting special alloys; and heat-treating and finishing facilities for flame and plasma spraying, plating, and coating.

Sandia maintains for ERDA a Primary Standards Laboratory wherein technical procedures and capabilities are reflected in physical references and practices of high accuracy and sophistication. A hierarchy of standards laboratories and calibration stations carries the units of measurement to the working level among all prime contractors in the nationwide weapon-production complex. Facilities and equipment valued at $4.5 million are used to maintain measurement standards in direct and alternating current, microwave, electrical pulse, radiation, mechanical, and environmental areas.

A laboratory is maintained for conducting research on the mechanisms that control the response of electronic elements and for studying the processing techniques involved in hybrid microcircuitry and semiconductor development. Hybrid microcircuitry developed at Sandia has found application in the protection of nuclear weapons and materials, weapon electronic components (resulting in significant reductions in size and weight), and in providing down-hole power for advanced drilling techniques.

APPENDIX

EDUCATIONAL RESOURCES

	BA BS	MA MS	PhD	Total
ENGINEERS				
Chemical	14	6	14	34
Civil	27	19	11	57
Electrical and Electronics	376	254	78	708
Mechanical	235	164	93	492
Nuclear and Reactor	2	14	15	31
Metallurgical	4	7	8	19
Petroleum			1	1
Other	55	30	24	109
Total	713	494	244	1451
MATHEMATICIANS				
Mathematicians	66	41	35	142
Information Science		6	1	7
Systems Analysis		8	4	12
Total	66	55	40	161
PHYSICAL AND EARTH SCIENTISTS				
Chemists	51	12	65	161
Geologists and Geophysicists	5	6	5	16
Physicists	46	46	180	272
Metallurgists	3	6	30	39
Other	4			4
Total	109	70	280	459
LIFE SCIENTISTS				
Biological	5	3		8
Medical	2		3	5
Health	1	5	2	8
Total	8	8	5	21
BUSINESS AND MANAGEMENT				
Administration	129	73	4	206
Finance	2	1		3
Accounting	52	10	1	63
Management Science	20	23		43
Personnel	2	7		9
Other	19	5		24
Total	224	119	5	348
SOCIAL SCIENTISTS				
Sociology	7	3	4	14
Psychology	6	4	1	11
Economics	17	6	1	24
Other	37	17	4	58
Total	67	30	10	107
TOTALS	1187	776	584	2547

BUDGETARY INFORMATION

Sandia Laboratories is operated by the Bell System for ERDA on a no-fee, no-profit contract with Western Electric Company.

The estimated FY 1976 budget is $299.5 million, of which $201.5 is committed to nuclear weapons, $8.6 million to laser and electron-beam fusion, $5.0 million to nuclear-material security, and $23.4 million to energy. Reimbursable funding of projects performed for other federal agencies totals $61.0 million. Estimated expenditures for construction and capital equipment are $23.4 million. The total estimated laboratory budget for FY 1976 is $322.9 million.

The Laboratories staff at the beginning of FY 1976 was 6405; of these 5500 were in Albuquerque, 866 in Livermore, and 39 in Tonopah.

The capital investment for FY 1976 is $322 million.

BREAKDOWN OF OPERATING EXPENSES

Actual for FY 1975 and Estimated Cost for FY 1976*
($ in Thousands)

	FY 75	FY 76
NATIONAL SECURITY		
Weapon Research and Development	$130,865	$143,700
Weapon Production	29,984	30,300
Weapon Testing	26,699	27,500
Total Weapons	187,548	201,500
Electron Beam Fusion and Lasers	7,728	8,600
Nuclear Material Security	1,399	5,000
Total	196,675	215,100
SOLAR, GEOTHERMAL, AND ADVANCED ENERGY		
Solar Energy	2,164	7,700
Geothermal Energy	503	2,000
Physical Research	377	500
Fusion Research and Development	411	400
Total	3,455	10,600
CONSERVATION RESEARCH AND DEVELOPMENT		
Energy Storage	256	200
Improved Conversion Efficiency		1,600
Total	256	1,800
FOSSIL ENERGY		
Coal Conversion	599	800
Natural Gas Stimulation		700
Diagnostics and Rock Mechanics		600
Advanced Instrumentation		400
In Situ Technology	262	1,400
Total	861	3,900

*Compiled December 1975

APPENDIX

Actual for FY 1975 and Estimated Cost for FY 1976*
($ in Thousands)

	FY 75	FY 76
NUCLEAR ENERGY		
Reactor Research and Development	$ 98	$ 500
Applied Nuclear Energy Systems	562	1,700
Nuclear Fuel Cycle	1,264	2,600
Total	1,924	4,800
ENVIRONMENTAL AND SAFETY RESEARCH		
Biomedical and Environmental Research	142	400
Operational Safety	148	100
Environmental Control Technology		1,700
Total	290	2,200
INDUSTRIAL AND GOVERNMENT RELATIONS		
Technology Utilization	65	100
Total	65	100
TOTAL ERDA	$203,526	$238,500

OTHER FEDERAL AGENCIES

	FY 75	FY 76
NUCLEAR REGULATORY COMMISSION		
Regulation	$ 781	$ 2,600
Reactor Safety Research	694	2,200
Total	1,475	4,800
OTHER AGENCIES		
Weapon Development	13,118	19,000
Instrumentation Sensors and Data Handling	5,430	10,300
Satellite Systems	3,155	4,400
Intelligence Analysis and Monitoring	820	1,100
Vulnerability and Nuclear Testing	1,516	2,600
Environmental and Performance Testing	6,353	3,700
Material and Process Development	429	300
Weapon Production	901	700
Miscellaneous	3,974	11,300
Anticipated		2,800
Total	35,696	56,200
TOTAL OPERATING EXPENSES	240,697	299,500
Plant and Capital Equipment	20,179	21,400
Construction	2,505	2,000
TOTAL LABORATORY BUDGET	$263,381	$322,900

*Compiled December 1975

SAND74-0075
Unlimited Release

AEROSCIENCES

Sandia Laboratories Technical Capabilities

Aerosciences

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115
and Livermore, California 94550 for the United States Energy Research
and Development Administration under Contract AT(29-1)-789

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SANDIA LABORATORIES TECHNICAL CAPABILITIES

AEROSCIENCES

ABSTRACT

This report describes the aeroscience capabilities at Sandia Laboratories. Selected applications of these capabilities are presented to illustrate how they can be used in research and development programs.

AEROSCIENCES*

Aerosciences activities represent a balance between applied research and the aero engineering required to support the Laboratories' technical programs. Studies are directed toward a greater understanding of mechanisms encountered in extreme flight environments that include velocities up to 8000 meters per second, altitudes from below sea level to over a million meters, and vehicle surface temperature of up to 4500 K. Areas of interest include aeroballistics, rocket aerodynamics, decelerator technology, experimental aerodynamics, atomic and fluid physics, aerothermodynamics, experimental aerophysics, atmospheric environmental studies, applied fluid dynamics, and aeromechanical design.

Research and development are supported by analytical techniques including computer modeling, and by laboratory facilities such as analog and hybrid computers, motion simulators, trisonic and hypersonic wind tunnels, arc jets, shock tubes, water tunnels, and parachute fabrication and testing equipment.

Aerosciences Technical Staff
and Investment in Equipment

	Professional Staff	Investment in Equipment (in $1000)
Aeroballistics	28	1400
Rocket Aerodynamics	7	
Decelerator Technology	10	500
Experimental Aerodynamics	9	3000
Atomic and Fluid Physics	10	
Aerothermodynamics	12	
Experimental Aerophysics	12	5600
Atmospheric Environmental Studies	12	1100
Applied Fluid Dynamics	9	200
Aeromechanical Design	8	

*Compiled January 1975.

AEROBALLISTICS

Aeroballistics studies are directed toward the development of computation methods and simulation techniques for determining the flight characteristics of a variety of shapes, at velocities ranging from subsonic through hypersonic. Areas under continuing study include vehicle aerodynamics, stability, guidance and control, separation dynamics, and problems in flight simulation. Investigations are conducted also on the interaction of objects with blast waves, and on phenomena associated with internal ballistics.

Hybrid (analog/digital) computers, interfaced with three-axis angular-motion devices, are used in support of this work. This equipment permits flight simulations to be made in real time, and guidance and control hardware can be subjected to the angular rates and velocities experienced in full-scale flight.

Aerodynamic Analysis

Programs are aimed at developing analytical and numerical methods of predicting aerodynamic characteristics. Included are studies of forces operating on vehicles in flight and of shapes best suited for various flight conditions.

Current Activities

Configuration definition
Determination of force and moment coefficients
Pressure-distribution studies
Analysis of flow-field interactions

Stability Analysis

Vehicle geometry, weight, and inertia characteristics are investigated to provide designs that will maintain specified flight conditions. (Items 1,2)*

Current Activities

Static characteristics
Dynamic phenomena
Nonlinear effects

Guidance and Control

Fins and other control surfaces, as well as basic vehicle shapes, are studied for optimum aerodynamic control. Guidance systems are designed to produce various flight characteristics.

Current Activities

Configuration response
Flight characteristics
Guidance techniques

Separation Dynamics

A complex interactive flow field exists between two vehicles in close proximity such as with an aircraft and a drop vehicle, or a rocket and its ejected missile. Numerical-analysis techniques and experimental simulation methods are developed to predict the motion of the separating body. (Item 3)

Current Activities

Aircraft/store flow-field interaction studies
Separation trajectory analysis
Determination of aerodynamic loads on store during carriage

Flight Simulation

Analog and hybrid computer equipment is used to obtain simulations of vehicle flight characteristics. Three-axis angular-motion simulators interfaced to the computer equipment are used to test guidance and control system hardware. (Item 4)

Current Activities

Guidance and control system development
Six-degree-of-freedom flight simulations
Tricyclic angular-motion studies
Point-mass trajectory calculations
Aerodynamic heating investigations
Component testing in real time

*See Highlights below.

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Reentry Vehicle Resonance Test Vehicle*

The Reentry Vehicle Resonance Test Vehicle (RVRTV) is shown in Figure 1 as the conical payload attached to a two-stage Nike-Nike booster mounted on a rocket launcher at the Tonopah Test Range. The RVRTV program is a study of trim-angle behavior and its effect on roll rate. Trim-induced roll torques can produce large roll-rate excursions, including the sometimes catastrophic condition of persistent roll resonance. Theoretical research was aimed at describing the effects of RV asymmetries on trim-angle behavior; the individual effects of mass, aerodynamic, and inertia trim-producing asymmetries were analytically isolated for the first time. Wind-tunnel and RVRTV flight tests were conducted with built-in asymmetries to verify the analysis.

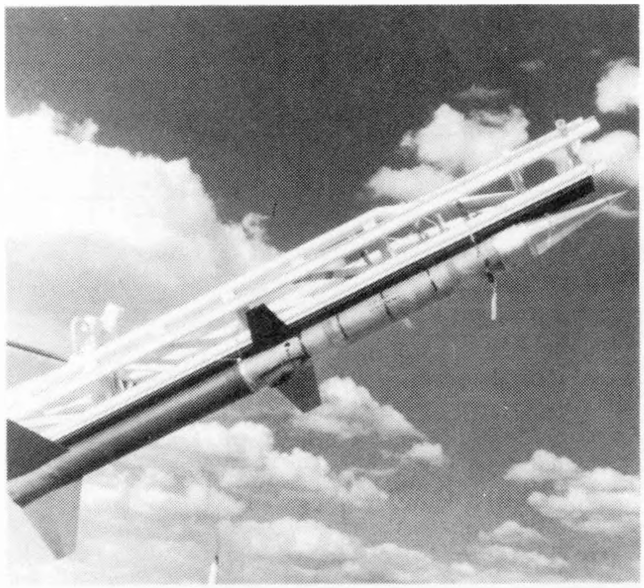

Figure 1. RV resonance test vehicle

Item 2. *Ballistic Match of Projectiles*

A linearized theory of ballistics, which describes projectile motion relative to the local velocity vector (Figure 2), has been used to demonstrate that projectiles with different mass properties can be ballistically matched (i.e., projectiles with different characteristics successively launched from the same gun under the same launch conditions will impact at the same location within a specified dispersion). This can be accomplished by matching the ratio of lift to drag and the ratio of roll moment of inertia to the distance between center of pressure and center of gravity.

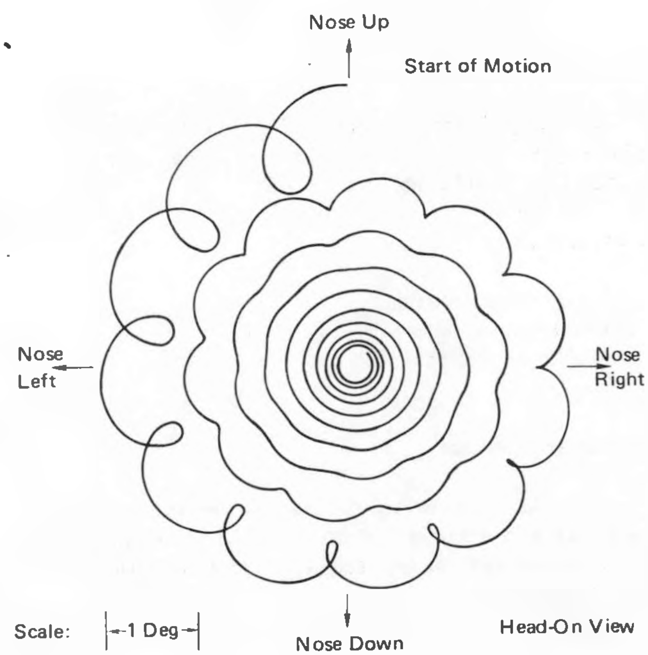

Figure 2. Angular motion of a projectile in flight

Item 3. *Vehicle Release and Separation*

Computer programs including visual documentary output have been developed to simulate the separation trajectories of canard*controlled missiles ejected from an F-4D aircraft through its complex flow field. Computer-generated pictures (Figure 3) and computer-generated color movies are made rapidly and economically. Using this approach, control-system parameters were investigated and modifications were made to achieve optimum separation characteristics. The good agreement between these simulations and full-scale tests greatly reduced the scope and expense of full-scale testing required. Limited full-scale testing, supplemented by the computer simulations, was found adequate.

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*Canards – small, movable fins on the forebody, used for guidance.

AEROBALLISTICS

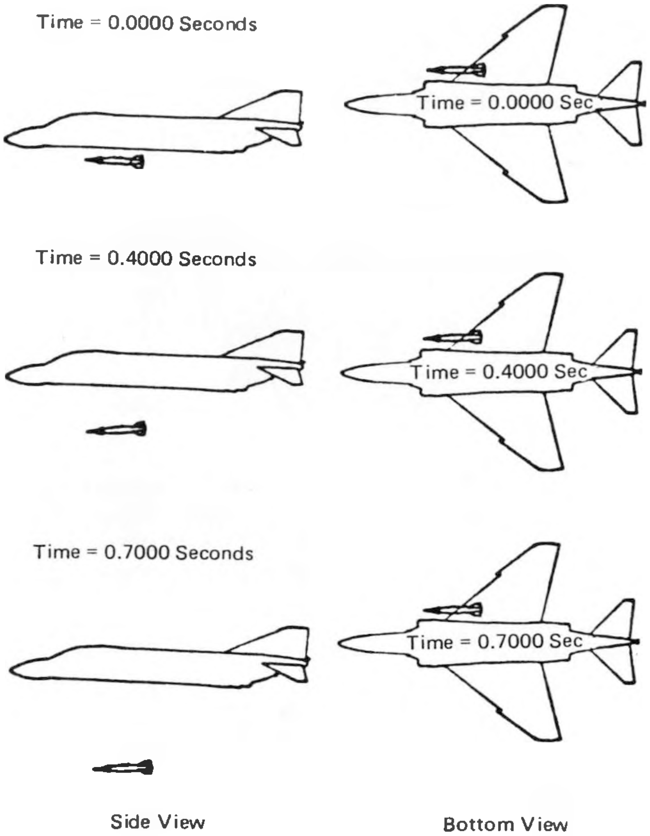


Figure 3. Computer-generated documentation of missile-separation characteristics

Item 4. *Simulator Facilities*

Complete multi-degree-of-freedom motion can be simulated on each of two hybrid computer installations. Simulation is achieved by interfacing analog and digital machines, which in turn are interfaced with a three-axis motion simulator (Figure 4). Control-system hardware can be mounted and subjected to the angular rates and displacements encountered in full-scale flight. An example of simulator results compared with flight-test data on a roll-controlled vehicle is shown in Figure 5.

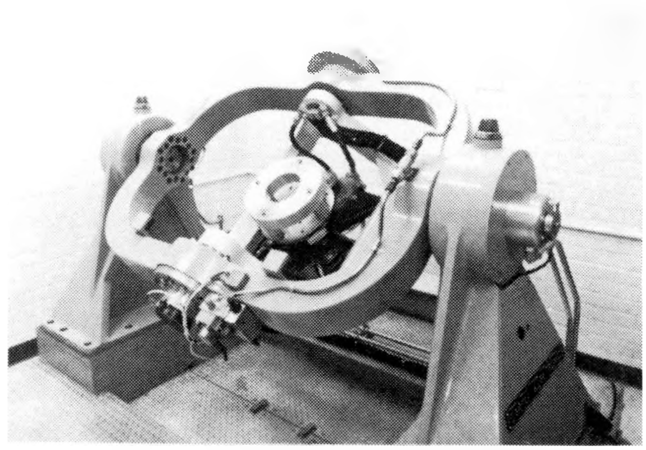


Figure 4. Carco three-axis motion simulator

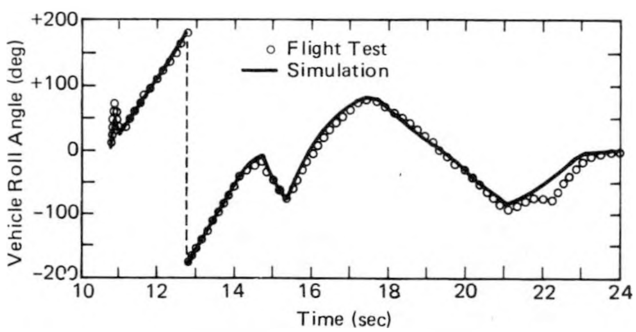


Figure 5. Comparison of simulation with flight data on a roll-controlled reentry vehicle

ROCKET AERODYNAMICS

Objectives are to determine trajectory characteristics of rockets (e.g., apogee, range, and velocity) and to provide ballistic data for use in range safety analysis and launch criteria. Aeroelasticity and aerodynamic heating studies are conducted to provide information on rocket stability. Stability analyses are made before each flight, assuring adequate static margin and dynamic response for the rocket.

Stability

Analytical studies and experimental investigations are conducted to determine the aerodynamic coefficients used in evaluating vehicle stability and to investigate phenomena that adversely affect stability.

Current Activities

Drag and axial force characteristics
Lateral force and moment coefficients
Static stability
Dynamic stability
Roll pitch resonance

Performance

Computers are used to analyze trajectories to determine vehicle flight characteristics (e.g., velocity, altitude, and range). Vehicle response to atmospheric variations (density, temperature, wind) is considered in the evaluation of ballistic accuracy. (Item 1)*

Current Activities

Six-degree-of-freedom computer programs
Point mass computer programs
Atmospheric models and gravity fields

*See Highlights below.

Aeroelasticity

Aerodynamic loading of a vehicle, coupled with its mechanical characteristics, is used to determine elastic deformation of the vehicle during flight. The flexed body is studied to assure that aerodynamic stability and structural integrity are maintained.

Current Activities

Weight and stiffness distribution
Aerodynamic load distribution
Vehicle joint characteristics
Flight environment and vehicle geometry

Range Safety

When all flight characteristics have been determined, they are used as the bases for flight safety studies. Using the standard deviation of the vehicle's mechanical and aerodynamic characteristics, analyses are conducted to ensure that the vehicle and its components will fall within predicted geographical areas, to avoid personal injury or damage to private property. (Item 2)

Current Activities

Ballistic factors and unit wind effects
Coriolis effects
Launcher errors (dynamics and tipoff)
Rocket-motor variations (thrust, impulse, and weight)
Weight and drag asymmetries
Wind variations
Impact area definition

ROCKET AERODYNAMICS

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Rocket Aerodynamic Research Support*

Rocket vehicles are developed for nuclear weapon and diagnostic instrumentation carriers for high-altitude tests; reentry vehicle tests; high-velocity tests of reentry vehicle components and materials; parachute and weapon-system tests; high-altitude barium release for field-line mapping and effects studies; and aerodynamic research studies. Table I lists some of the rocket vehicles currently in use, with typical performance characteristics.

TABLE I

Some Rocket Vehicles Currently in Use

Rocket System	Payload Weight (kg)	Apogee Altitude (km)	Impact Range (km)	Maximum Velocity (m/s)
Nike-Tomahawk 23-cm*	57	325	114	2438
Nike-Tomahawk 30-cm	116	178	46	1839
Terrier-Sandhawk 33-cm	91	427	157	2701
Terrier-Sandhawk 43-cm	408	150	61	1631
Sandhawk-Tomahawk 23-cm	73	539	258	3058
Terrier-Tomahawk 23-cm	79	387	150	2363
Terrier Recruit	32	14	37	2637
Talos-Terrier-Recruit	32	14	57	3170
Strypi II (XM-33/2 Recruits)	600	207	146	1848
Strypi IV (TX354/2 Recruits-TE-442)	408	595	448	3216
Strypi VII (TX354/2 Recruits-ALCOR-1B-BE3A)	48	213	688	6139

*Payload diameter.

Item 2. *Dispersion Calculation Summary*

Impact dispersion calculations are made for each stage of rocket vehicle configurations. This is done by determining tolerances for each of the various parameters affecting dispersion and using a six-degree-of-freedom computer program to calculate deviations from the norm. An example of this work is shown in Table II, where calculations are summarized for the payload of the Terrier-Sandhawk 43-cm* rocket system.

*Payload diameter.

TABLE II

Terrier-Sandhawk 43 cm
Dispersion at Payload Impact
408 kg Gross Payload Weight
Quadrant Elevation = 85 Degrees

Dispersion Item	Item 3σ Value	Dispersion Downrange (m)	Dispersion Crossrange (m)
First Stage			
Thrust misalignment			
Angular	0.1 deg	±16,877	±16,848
Offset	0.457 cm	± 9,253	± 9,023
Fin misalignment	0.2 deg	± 1,304	± 1,304
Drag	10%	± 250	0
Inert weight	2%	± 908	0
Motor total impulse	3%	± 1,139	0
Second Stage			
Second stage ignition	1.5 sec	± 2,421	0
Drag	10%	± 2,465	0
Inert weight	2%	± 3,437	0
Motor total impulse	3%	± 3,571	0
Ballistic Wind	3.05 m/s	±19,607	±20,561
Elevation angle	0.5 deg	± 7,089	0
Azimuth angle	0.5 deg	0	± 639
3σ Dispersion Radius		±28,078	±28,109

DECELERATOR TECHNOLOGY

The objective of deceleration technology is to reduce the velocity of vehicles to predictable levels. The reduced velocity is essential in some weapon systems, and reduces damage to recoverable instrumentation packages in experimental vehicles. Ribbon parachutes from 0.3 to 40 meters in diameter have been designed to decelerate vehicles weighing from 2 to 20,400 kilograms. Over-water recovery systems have been designed for rocket payloads weighing up to 540 kilograms. Prototype parachutes are fabricated and tested in a 370-square-meter laboratory and shop.

Decelerator Design

Emphasis is placed on development of new analytical techniques for the design of fabric parachutes. In addition, effort is directed toward designing decelerators to withstand extreme dynamic pressures.

Current Activities

- Parachute configurations
  - Ribbon
  - Guide-surface
  - Solid-canopy
  - Ringsail
  - Lifting and guided
- Clustering of parachutes
- Special-design rigid decelerators

Fabric Development

Detailed information on parachute material properties is acquired to facilitate optimum system design. New high-strength fabrics are developed to reduce parachute weight and volume.

Current Activities

- Nylon
  - High-strain properties
  - Hysteresis effects
- KELVAR-29®
  - Fiber development
  - Mechanical properties

Flotation Devices

Over-water recovery of sounding rocket payloads requires development of reliable flotation gear and locator beacons. Emphasis is placed on reducing the weight and volume of the system, and extending its life. (Item 1)*

Current Activities

- Sonic seaming of urethane-coated fabrics
- Low-temperature chemical-gas generation for inflation
- Small, lightweight locator aids

Analysis and Test

Computer codes are developed to predict parachute deployment and inflation loads, structural response, and dynamic stability. Methods are developed to measure loads and pressure distribution on parachute canopies during inflation. (Item 2)

Current Activities

- Deployment and inflation dynamics
- Dynamic stability
  - Two-body mathematical models
- Parachute fluid mechanics
  - Two-body flow-field models
- Material response
- In-flight pressure and stress measurement

*See Highlights below.

DECELERATOR TECHNOLOGY

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Over-Water Recovery System for 450-kg Payload*

The recovery system shown in Figure 1 is designed for 450-kg rocket payloads. The payload is suspended from the main parachute, with the patented ram-air flotation bag attached to the top of the parachute canopy. Similar systems have demonstrated 94 percent parachute reliability in 121 flight tests. Eight separate recovery systems have been developed for payload weights from 20 to 550 kilograms. In addition to those developed for Sandia requirements, recovery systems have also been developed for the National Aeronautics and Space Administration, the Naval Ordnance Laboratory, the Los Alamos Scientific Laboratory, the Lawrence Livermore Laboratory, Cambridge Research Laboratory, and West Germany.

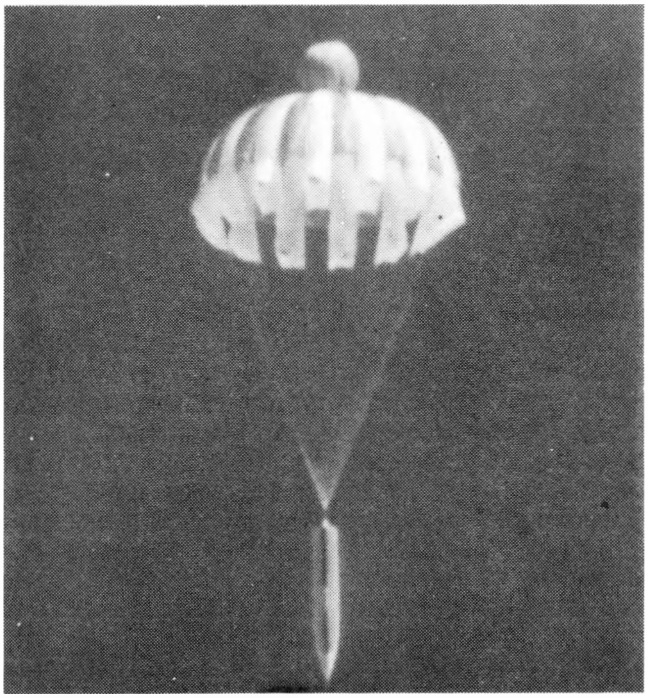


Figure 1. Over-water recovery system for 450-kg payload

Item 2. *Deceleration Prediction*

Deceleration computed by one of the inflation codes is compared in Figure 2 to experimental data from a drop test. In this prediction method the parachute is divided into two finite masses, one concentrated at the skirt and the other at the maximum radius point. The sum of the rates of change of axial and radial momentum for the parachute mass points and for the payload is equated to the sum of the aerodynamic and gravitational forces. Quasi-steady axial and radial aerodynamic forces are approximated in drag and radial force coefficient form. Parachute internal forces are modeled as nonlinear springs.

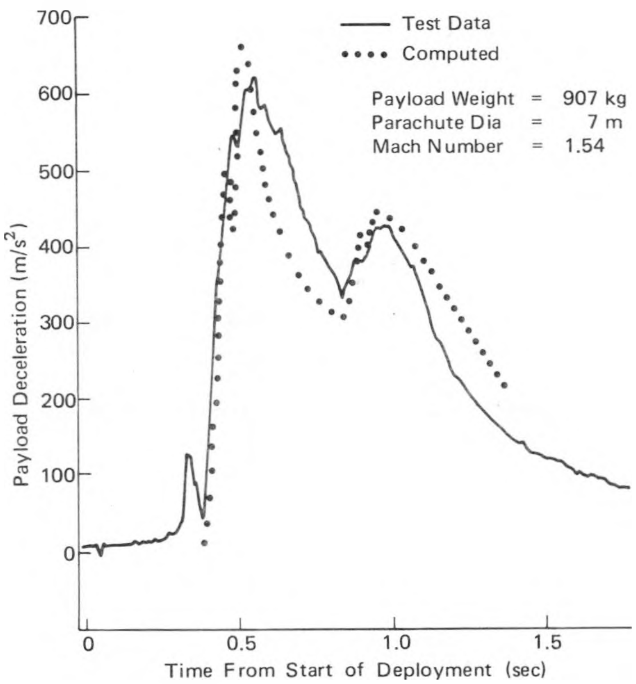


Figure 2. Computed vs measured payload decelerations

EXPERIMENTAL AERODYNAMICS

Some aerodynamics problems are solved experimentally because the complex geometries and extreme flow environments of flight vehicles often exceed the current capabilities of the theoretical and numerical prediction techniques available for aerodynamic design. Both in-house and external wind-tunnel test facilities are used to verify aerodynamic analyses conducted in support of aerospace projects.

Wind-Tunnel Testing of Scaled Models

Scaled models are tested on a continuing basis in support of design and development projects for which data are needed on such factors as flow fields, heat transfer, pressure distributions, and static and dynamic stability. (Items 1,2)*

Current Activities

- Three- and six-component force measurements
- Heat-transfer measurements
- Model pressure-distribution tests
- Flow-field surveys
- Low-temperature ablation tests
- Roll-damping measurements
- Dynamic stability tests
- Free-flight tests (drag and stability)

Wind-Tunnel Flow Diagnostics

Measurements are made to define the flow field around wind-tunnel models. Such studies contribute to an understanding of the physical consequences of interactions between the air and the aerodynamic shape being studied.

Current Activities

- Flow visualization
- Pressure probes
- Temperature probes
- Hot-wire probes for unsteady flow measurements
- Laser diagnostics to measure velocity
- Electron beam measurements of density and temperature

Experimental Aerodynamics Research

The objective is to study areas pertinent to the experimental process so that proper techniques and facilities can be provided. Areas of immediate interest include flow characteristics, particulate propagation, and vehicle stability. (Item 3)

Current Activities

- Low-speed particle deposition/resuspension
- Hypersonic boundary-layer characteristics
- Transonic flow noise problems
- Reentry vehicle stability analyses
- Refinement of experimental aerodynamic facilities

*See Highlights below.

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Wind-Tunnel Facilities*

Shown in Figure 1 are the Mach-number and Reynolds-number ranges of existing wind-tunnel facilities at Sandia Laboratories. The Mach-number range of the 30 x 30 cm trisonic wind tunnel can be varied continuously from 0.7 to 1.3, and specific Mach numbers of 1.6, 2.0, and 2.5 are available through the use of interchangeable nozzle blocks. Models are mounted on precision strain-gage balances that measure the forces and moments imposed on the body by the airstream. Data are obtained at several angles of attack during each run. All data are automatically recorded, digitized, and analyzed on a high-speed data acquisition and control system. Similar procedures for obtaining vehicle performance data are used in the 45-cm* hypersonic wind tunnel (Figure 2) at Mach numbers of 5.0, 7.3, 11.3, and 14.0. Modifications now being made to the hypersonic tunnel will markedly improve the test Reynolds-number capability; nozzles will provide flows at Mach numbers of 3.5, 5, 8, 11, and 14.

*Internal diameter of test section.

EXPERIMENTAL AERODYNAMICS

Item 2. *Flow-Field Studies*

The shadowgraph in Figure 3, taken in the trisonic wind tunnel, shows the flow field about a flight vehicle moving at the speed of sound. Complex interactions exist between the shock waves, the boundary layer, and the near wake. Phenomena such as these, occurring in many flight regimes, are under continual investigation to achieve optimum design of flight vehicles.

Item 3. *High-Speed Turbulent Boundary-Layer Research*

New propulsion and guidance systems have made it possible for the present generation of reentry vehicles to travel extremely fast at low altitudes, giving rise to hypersonic turbulent boundary layers on their surfaces. Present analytical techniques are incapable of accurately predicting the properties of these boundary layers for calculation of vehicle performance. Consequently, hypersonic turbulent boundary-layer profiles have been experimentally measured to improve the accuracy of analytic techniques and to provide empirical engineering data for design purposes. Figure 4 shows experimental velocity, temperature, and Mach-number boundary-layer profiles obtained in Sandia's Mach 14 hypersonic wind tunnel. They are representative of profiles that exist on actual reentry vehicles.

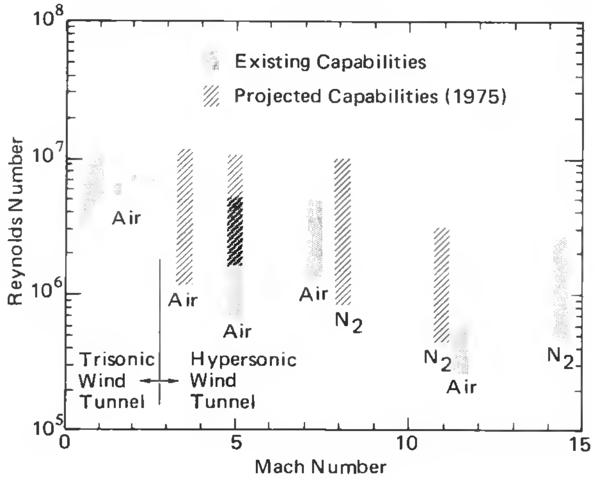


Figure 1. Test capabilities

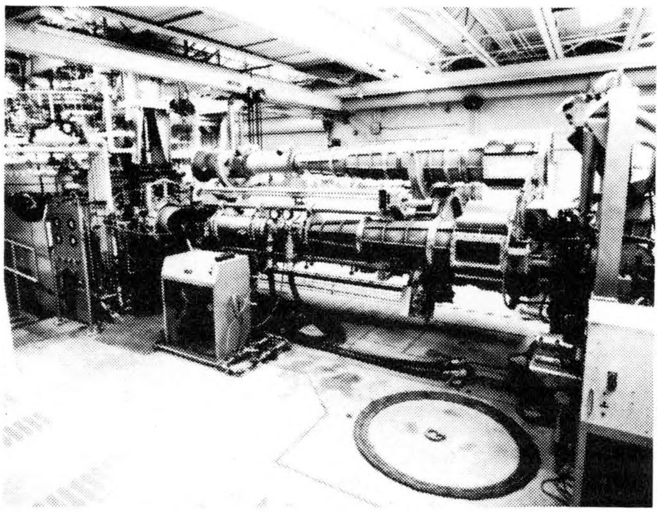


Figure 2. Hypersonic wind tunnel

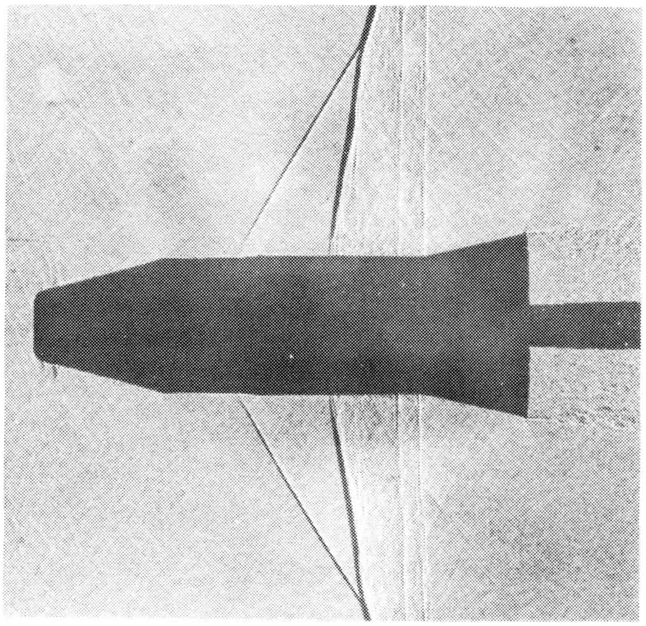


Figure 3. Shadowgraph of flow field

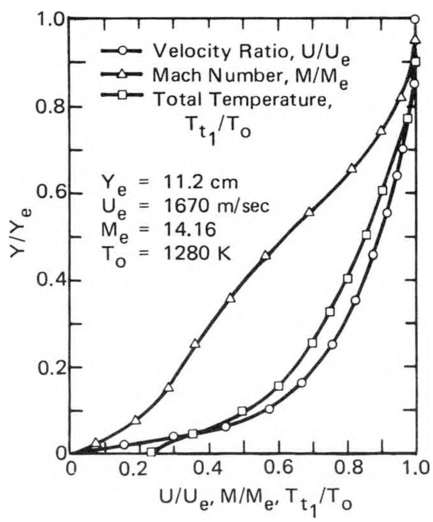


Figure 4. Experimental high-speed turbulent boundary-layer profiles

ATOMIC AND FLUID PHYSICS

This function includes capabilities for theoretical modeling of fluid or gas-phase systems at both the macroscopic and microscopic levels. Flow simulations that can be performed include two- and three-dimensional boundary layers, the viscous shock layer on bodies at incidence, unsteady flows in diagnostic pipes used to transport radiation from detonated nuclear devices, and coupled energy-transfer and radiation-transport processes in gas lasers. Hydrodynamic stability theory techniques are employed to study stability of liquid layers and of boundary-layer flows with nonparallel effects. A distribution-function approach is being used to develop a turbulence theory for compressible and reacting gas mixtures. Atomic and molecular structures are investigated and the results used to compute cross sections for collisions of atoms or ions with high-energy electrons, photons, or low-energy atoms.

Boundary-Layer Flows

Prediction of the boundary layer and its interaction with the adjacent inviscid flow field are made to obtain the parameters required for system design. Computer codes have been developed to predict boundary-layer characteristics. Efforts continue on the development and application of numerical methods to boundary-layer analyses. (Item 1)*

Current Activities

- Two-dimensional boundary-layer computation
  - Compressible multicomponent gas mixtures
  - Finite-rate chemical reactions
  - Arbitrary body geometry
  - Ablation and mass transfer at surface
- Three-dimensional boundary-layer computation
  - Incompressible perfect gas
  - Blunt bodies
  - Angle of attack
- Turbulent flow predictions
- Parabolic viscous flow predictions

Viscous Shock Layers

Classical fluid-flow analysis methods are used to match flow parameters at the boundary between the inviscid flow and the viscous boundary layer. Another useful method, particularly for nonzero angle of attack, is used to calculate the viscous shock-layer flow using a single set of equations. A computer code has been developed to obtain solutions along the symmetry plane of sharp or blunt bodies at angle of attack in laminar or turbulent flow. Effort is being directed toward expanding the capabilities to include real-gas effects and complete three-dimensional flow.

Current Activities

- Hypersonic flow
- Compressible perfect gas
- Plane of symmetry for angle of attack
- Real-gas effects
- Three-dimensional flows

Unsteady Flows

The purpose of this area of investigation is to solve unsteady-flow equations, both for the analysis and design of devices based on transient dynamics, and as a useful method of obtaining results for complicated steady-state phenomena. Two-dimensional codes have been developed for the solution of multi-component flows in geometries that can be represented in spherical or cylindrical coordinates. These computer codes can be applied to a wide variety of flow problems including internal and external flows, inviscid and viscous flows, and laminar and turbulent flows.

Current Activities

- Underground nuclear tests
  - Line-of-sight flow
  - Muffler effects
  - Wall interactions
- Rain erosion
  - Particle acceleration device
- Separation
  - Nozzle flow
  - Colliding jets

*See Highlights below.

ATOMIC AND FLUID PHYSICS

Stability and Turbulence

Research is conducted to determine the mechanisms that initiate instabilities and turbulence. Analyses are made of turbulence found in boundary layers over aircraft and reentry vehicles; flow in ducts and pipes; fluid mixing, and the dispersing of gases and aerosols in the atmosphere. In the stability area, studies are made of the growth or attenuation of waves or other disturbances generated by liquid/gas interactions, convective instabilities, and boundary-layer stability where the flow undergoes a transition from laminar to turbulent. (Items 2,3)

Current Activities

- Isotropic turbulence
  - Evolution of correlations and spectra
  - Mixing and chemically reacting flows
  - Closure analysis
- Shear flows
  - Free shear layer
  - Couette flow
  - Flow over flat plate
- Compressible flows
  - Development of characteristic equations
  - Chemically reacting fluids
- Liquid-layer stability
  - Analysis of nonlinear disturbances on liquid-gas interfaces
  - Experiments involving air flow over liquid layers
- Boundary-layer stability
  - Analysis of nonparallel effects for incompressible case
  - Analysis of nonparallel effects on supersonic boundary layers
  - Experiments on the stability of supersonic boundary layers

Energy Processes in Gas Lasers

The object of this study is to gain an understanding of the complex interplay among energy-transfer processes in gaseous lasers. Comprehension of these processes is vital to their optimization and scaling. Numerical models are developed that are useful in guiding and interpreting scaling, optimization, and other experiments.

Current Activities

- Electron-beam-initiated super-radiant H_2-F_2 laser
- Implicit techniques for large systems of hyperbolic partial differential equations

Atomic and Molecular Collision Phenomena

Effort is aimed at improving the current theory of atomic and molecular processes and the techniques for applying theory to individual systems. Nonequilibrium models of the atmosphere, gas discharge tubes, plasma containment devices, and gas lasers all depend for their predictive utility on the accuracy and completeness of the rate coefficient and cross-section data included in the models. Thus, to the extent to which the models are intended to go beyond the correlation of data from past experiments, it is essential to deal with the dominant microscopic processes quantitatively. (Item 4)

Current Activities

- Elastic and inelastic ion-atom and atom-atom collisions at low energies
- Scattering of energetic electrons and atoms by molecules
- Photon-molecule interactions
- Molecule formation processes

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Flow-Field Determination*

Shock-wave location and boundary-layer displacement thickness (δ^*) for a reentry-vehicle configuration at zero angle of attack at Mach number 14.3 are shown in Figure 1. It can be seen that the values predicted from inviscid and boundary-layer computer codes compare favorably with results from hypersonic wind-tunnel tests. The numerical solutions also provide information on electron density in the vehicle's flow field. For vehicles at angle of attack, a code has been developed for predicting the complete viscous shock-layer flow in the plane of symmetry.

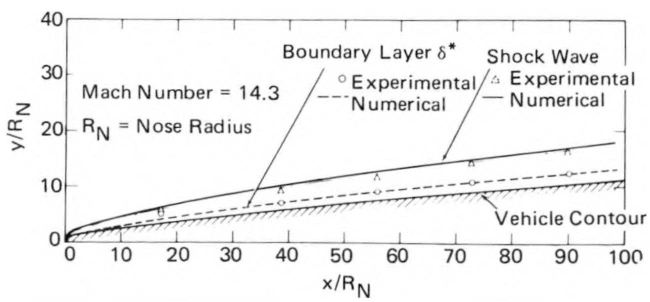


Figure 1. Shock wave and boundary layer δ^* on a reentry vehicle

Item 2. *Turbulence Study*

The simplest type of fluid turbulence is obtained in wind-tunnel experiments by inserting a grid into the flow. The dynamic behavior of the turbulence is then measured at various test stations downstream of the grid. In Figure 2, the theoretical distribution of turbulent energy among the variously sized eddies is compared with wind-tunnel measurements of grid-generated turbulent flow. The spectrum tensor, from which the energy distribution is obtained, is sufficient to determine the turbulent contribution to the mean flow field and thus permit the calculation of fluid motion by methods analogous to those used in laminar flow. The analytical solution also provides other flow parameters that have been used to evaluate existing semi-empirical methods such as eddy viscosity and mixing-length models.

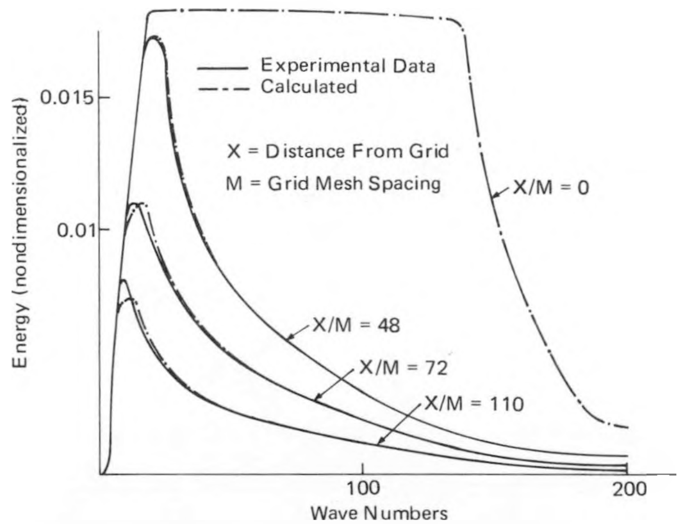


Figure 2. Turbulent energy distribution

Item 3. *Stability of Liquid Films*

The stability of liquid films adjacent to compressible streams has been investigated analytically as well as experimentally. Linear theories predict that films adjacent to supersonic streams are much more unstable than those adjacent to subsonic streams. This is in qualitative disagreement with experimental observations. Although stability parameters were matched in subsonic and supersonic experiments, it was found that films adjacent to supersonic streams are stable while those adjacent to subsonic streams are unstable, as evidenced by entrainment of the liquid by the gas. These experimental observations can be explained by nonlinear theories which predict that linear unstable disturbances achieve steady-state amplitudes in the supersonic case and continue to be unstable in the subsonic case.

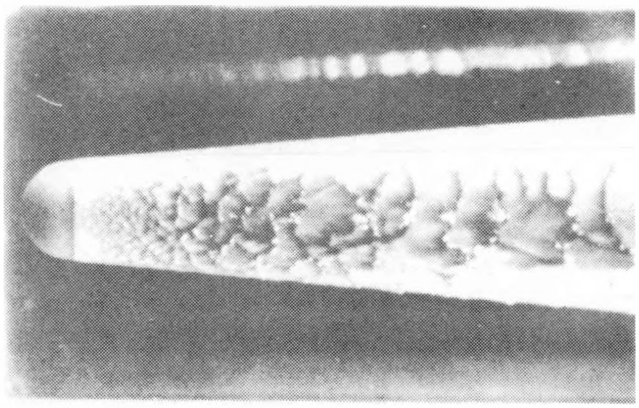


Figure 3. Supersonic flow over liquid film

Item 4. *Molecule Formation: Dissociation and Association Mechanisms*

Plasmas containing molecular species involve the study of dissociation and association mechanisms. Shape resonances or, equivalently, quasibound rotation-vibration states can play an important role in both processes. Accordingly, theoretical techniques have been developed for the characterization and enumeration of such states occurring in diatomic molecules. The use of these procedures to analyze high-resolution mass-spectrometer data for the HeH^+ and H_2^+ ions has resulted in identification of most of the important experimentally observed features.

One of the important molecule formation mechanisms in tenuous media is radiative association. A completely quantum-mechanical investigation of H_2^+ formation by this process in hydrogenic plasmas has been started. To date, the low-temperature formation rate has been shown to be almost an order of magnitude larger than predicted by semi-classical arguments. Smaller quantum-mechanical effects were found in the region of very high temperatures. The low-temperature result may prove of importance to the study of the interstellar medium.

AEROTHERMODYNAMICS

Aerothermodynamics studies are conducted in support of thermal protection system design for high-performance rocket and reentry vehicles. Extensive analytic and test capabilities have been developed that allow the prediction and understanding of nosetip and aft-heatshield response to the extreme temperatures, pressures, and heating rates imposed during reentry. The aerothermodynamics analysis capability has also been applied to such diverse fields as coal gasification, the analysis of possible causes of fire that could abort a rocket mission, liquid-droplet vaporization, planetary-probe entry analysis, metal ablation, and rocket-motor failure studies.

Flow-Field Definition

The objective of this study area is to define the vehicle flow field, which covers a broad spectrum of fluid dynamic problems through hypersonic speeds. Such definition is fundamental to aerothermodynamic analysis. (Item 1)*

Current Activities

- Inviscid flow
  - Shock wave shape prediction
  - Entropy layer effects
  - Pressure distribution prediction
  - Shock-shock interaction phenomena
- Viscous flow
  - Laminar boundary layer
  - Turbulent boundary layer
  - Separation and reattachment phenomena
  - Base flows and wakes
- Chemically reacting flow
  - Equilibrium
  - Nonequilibrium
- Ionized plasma flow
  - Electromagnetic attenuation studies
- Transport phenomena
  - Heat transfer
  - Mass transfer
- Boundary-layer transition

*See Highlights below.

Heatshield Response

Interaction of a vehicle heatshield with its flow field is predicted through simultaneous or iterative solutions of the energy and mass-balance equations describing the coupled flow field, surface chemistry, and heatshield-material response. Of primary interest is the prediction of material ablation, temperature, and thermal stress. (Item 2)

Current Activities

- Heatshield concepts
  - Heat sink
  - Subliming
  - Charring, noncharring
  - Transpiration cooling
- Thermal modeling
  - One-dimensional
  - Two-dimensional (axisymmetric)
  - Three-dimensional (nonaxisymmetric)
  - Multilayered composites
- Heat transfer
  - Convection
  - Radiation
  - Conduction
  - Chemical generation
- Surface recession
  - Thermochemical
  - Mechanical
  - Hypervelocity particle impact
- Material studies
  - Ablation performance
  - Structure
  - Properties

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Reentry-Vehicle Flow Fields*

Inherent to the reentry-vehicle flow field shown in Figure 1 is a wide variety of fluid-dynamics problems. Within the bow shock wave are flows that extend from subsonic to hypersonic speeds and that may be either inviscid or viscous, and chemically reacting in equilibrium or nonequilibrium. Analysis techniques have been developed that allow solutions to these problems as well as definition of the flow-field-generated pressure, temperature, and heating environments surrounding the vehicle during reentry. Predicted vehicle responses, both mechanical and thermal, depend upon the accuracy of these predicted environments. Communication between vehicle and ground is in large part dependent upon electromagnetic attenuation of telemetered signals. This attenuation can be predicted only when the extent of ionization in the plasma sheath is accurately known.

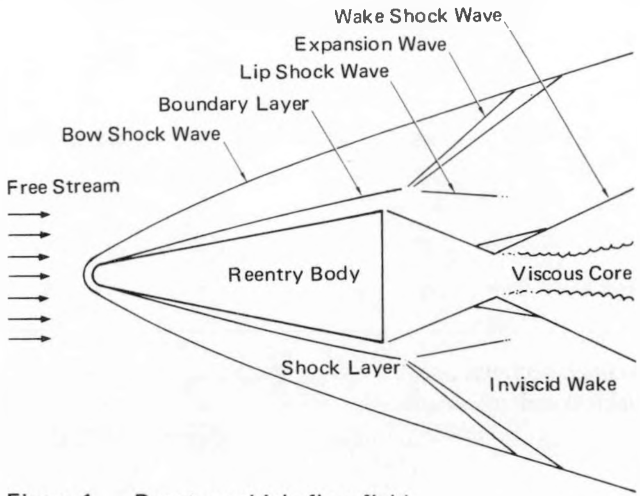


Figure 1. Reentry vehicle flow field

Item 2. *Heatshield Thermal Analyses*

The objective of these analyses is to arrive at accurate predictions of the ablation, temperature, and thermal-stress response of thermal-protection systems. Such predictions are of primary importance to the design of successful reentry vehicles. Shown in Figure 2 is an example of this prediction capability, where computed aft-heatshield backface temperatures (which may reach values of 1500 to 2500 K) are compared with measured flight data obtained from three thermal sensors mounted in a carbon-carbon heatshield. Many state-of-the-art thermal-protection materials are graphitic or carbonaceous in nature and hence are very susceptible to thermal-stress failure. Accurate thermal analysis thus becomes vital in optimization of system design.

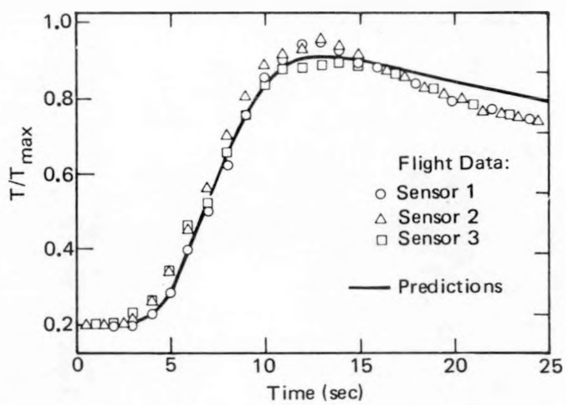


Figure 2. Heatshield temperature comparison

EXPERIMENTAL AEROPHYSICS

Programs are directed at understanding and describing the aerothermodynamic environment encountered by reentry vehicles. The reentry environment is simulated with 5-megawatt, 2-megawatt, and 160-kilowatt arc-heated plasmajets, a 500-kilojoule arc-heated shock tube (30 cm ID) and a conventional pressure-drive shock tube (5 cm ID). These facilities are used to support development of vehicle nosetips, aft heatshields, and radar-antenna windows, and to carry out research in high-temperature chemical kinetics and plasma diagnostics.

Nosetip and Heatshield Ablation Testing

Ablation tests on nosetips, aft heatshields, and antenna windows are carried out in the 5- and 2-megawatt plasmajets in support of diverse exploratory development projects. (Item 1)*

Current Activities

Material ablation and development tests
- Nosetip
- Aft heatshield
- Antenna windows

Facility development for extended capability
Radio frequency propagation studies

Plasma and Gas-Flow Diagnostics

New diagnostic techniques are developed for measuring plasma properties, e.g., electron density, electron temperature, heavy-particle temperature, plasma velocity, etc., to obtain more accurate plasmajet test conditions, and to give a better understanding of the physics of ionized flow. New techniques are developed to measure temperature, density, and velocity in cold nozzle flows, continuous high-powered lasers, and combustion processes. (Items 2,3)

Current Activities

Fabry-Perot interferometry
Electron-beam-excited fluorescence
Laser Raman scattering
Laser Doppler velocimetry
Infrared absorption spectroscopy

Shock-Tube Research

The 500-kJ arc-driven shock tube provides capabilities for shock-wave research at extreme conditions; shock-wave velocities of 15 km/sec into 1-torr test gas are obtained. Fast rise-time end-wall pressure instrumentation provides a sensitive measurement of density in the end-wall region for molecular vibrational relaxation and dissociation studies. Used as a conventional pressure-driven shock tube, the apparatus is available for studies of shock-wave interactions with water sheets, and novel techniques for producing spherical and cylindrical blast waves are being developed.

Current Activities

Nozzleless water-jet development
Blast-wave physics
Population inversions for pulsed lasers

*See Highlights below.

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Two-Megawatt Plasmajet Facility*

The 2-megawatt facility (Figure 1) is operated with either of two heaters. A tandem hollow-cylinder-electrode high-pressure arc heater provides enthalpies of 5 kJ/g with stagnation-point pressures of 50 atm on 0.76-cm-diameter nosetip models. The available enthalpy increases to a maximum of ~15 kJ/g at stagnation-point pressures of 1 atm on 2.5-cm-diameter nosetips. A constricted arc heater provides enthalpies of 50 kJ/g at stagnation-point pressures of 1 atm on 1.3-cm-diameter nosetips.

The facility is equipped with a computer-controlled Ferguson injector to accurately position nosetip models in the jet, and a laser-controlled drive system to maintain the ablating nosetip at a fixed position in the jet. A channel flow device, where the test specimen occupies one wall of the channel, is used for aft-heatshield and antenna-window ablation tests.

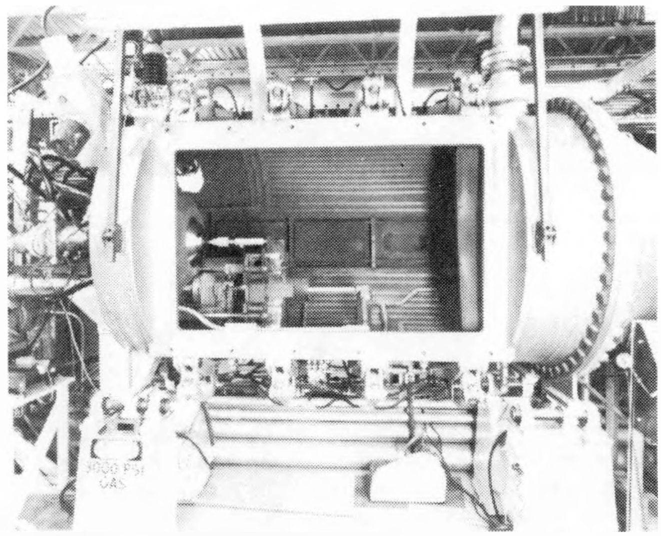


Figure 1. The 2-megawatt plasmajet

Item 2. *Diagnostics with a Fabry-Perot Interferometer*

A Fabry-Perot interferometer is being used to measure Doppler-broadened, Doppler- and Stark-shifted emission-line profiles in a supersonic arc-heated argon plasmajet. These data determine the atom temperature T_a, plasma velocity U, and electron density N_e, respectively. The electron temperature T_e is determined by a Boltzmann plot of argon emission-line intensities. An Abel inversion of these data results in radial profiles of these quantities that are used with the static pressure to calculate radial profiles of atom density N_a, Mach number M, and enthalpy H, as shown in Figure 2.

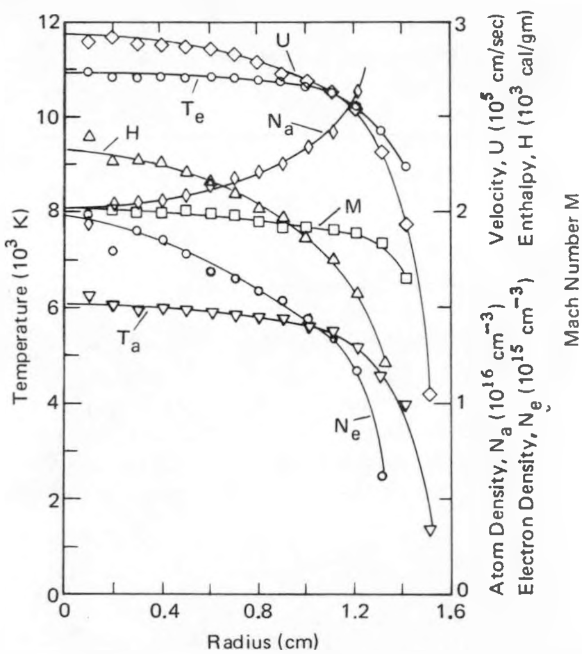


Figure 2. Radial profiles of plasmajet properties

Item 3. *Optical Cell for Raman Spectroscopy*

In low- to moderate-density gas flows (number densities $\sim 10^{14}$ cm^{-3}), Raman scattering requires a large flux of incident photons to obtain sufficient signal levels because the relevant scattering cross sections are exceedingly small ($\sim 10^{-29}$ cm^2/steradian). An optical cell designed for Raman scattering experiments is shown in Figure 3; it consists of an ellipsoidal mirror (on the left) and a coaxial flat-spherical mirror (on the right) positioned at the minor axis of the ellipsoid. A laser beam, introduced at the far right, is reflected repeatedly through the focus of this cell, providing a large flux of photons in the focal region. Gains of ~100 in Raman signal intensity have been obtained with this optical cell. The technique has been used to measure both density and temperature in combustion experiments.

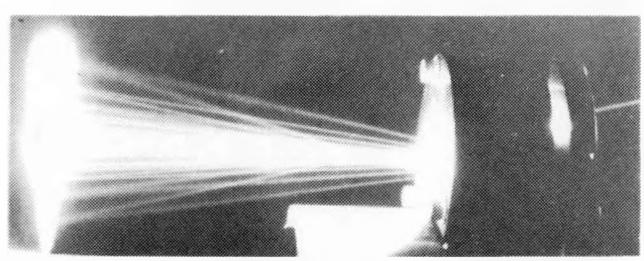


Figure 3. Optical cell for Raman scattering experiments

ATMOSPHERIC ENVIRONMENTAL STUDIES

Atmospheric studies are directed toward development of theoretical, experimental, and field-operational methods for learning the physics, chemistry, and dynamics of normal and perturbed atmosphere in the altitude range of 1 to 120 kilometers. Theoretical studies emphasize atomic, molecular, and charged-particle collisions, and mathematical simulation of the complex chemistry and dynamics of the atmosphere. Laboratory studies have been concerned with characterization of atmospheric species and their interactions, and with study of sensors of potential use in atmospheric measurements. Instrumentation programs result in development of prototype instruments for remote and in-situ atmospheric measurement, adapted to the environmental extremes and operational limitations encountered. Field experiments are the core of the program, providing the fundamental data on atmospheric parameters required to develop understanding of atmospheric processes as well as predictive capability.

Instrumentation packages may be on the ground or carried on rockets, parachutes, stratospheric and tropospheric balloons, or aircraft. Field studies are frequently conducted jointly with other laboratories* to provide integrated correlation of measurements. Sandia is central to the planning and management, and provides payload engineering in addition to scientific experiments.

*Recent Sandia partners include the Atmospheric Sciences Laboratory/WSMR; Air Force Cambridge Research Laboratories, University of Texas at El Paso; New Mexico State University, National Center for Atmospheric Research, Pennsylvania State University, Denver University, Johns Hopkins University, and Battelle Northwest Laboratory, among others.

Theoretical, Analytical, and Modeling Studies

Studies range from quantum-mechanical through system analysis, including direct analytical support for planning of field experiments and interpretation of results.

Current Activities

- Quantum-mechanical calculations
- Modeling of atmospheric transport on local, meso, and global scales
- Chemical kinetic modeling of normal and chemically perturbed atmsophere
- Modeling of the atmospheric effects of nuclear weapons
- Analytical studies for planning of stratospheric (balloon-based) and mesospheric (rocket-based) experiments

Laboratory Experiments

The aim of this activity is to study the physical and chemical properties and behavior of atmospheric species. This includes locating or developing sensors suitable for detecting and measuring desired atmospheric parameters.

Current Studies

- Laser excitation of atmospheric species, and relaxation characteristics
- Characteristics of tunable diode lasers
- Characteristics of heterodyne lasers for detection of atmospheric species
- Use of the tunable laser in radar applications for measurement of meteorological parameters

Instrumentation Development

Studies are directed toward development of flight-qualified instruments for use on rockets, balloons, aircraft, and parachutes.

ATMOSPHERIC ENVIRONMENTAL STUDIES

Current Activities

Quadrupole mass spectrometer and associated cryogenic pumping system for the study of densities of neutral and ionized particles
Quadrupole mass spectrometer for studying mesopheric neutral and ionized particles
Filter-wheel photometers for measurement of solar ultraviolet flux
Spectrometer systems for measurement of solar ultraviolet spectra
Tunable-diode laser for atmospheric composition studies
Heterodyne lasers for detection and measurement of certain stratospheric species

Field Experimental Studies

The purpose of this activity is to determine the relationships between pertinent parameters under a range of normal and perturbed atmospheric conditions in order to define the role of the important atmospheric processes and ultimately to allow prediction of atmospheric behavior. Ground, balloon, aircraft, and rocket-based experiments involving multiple correlated measurements of atmospheric parameters are used. (Item 1)*

Current Activities

Mass spectrometric measurement of neutral species among particle densities in the stratosphere
Mass spectrometric measurement of ionized species among particle densities in the mesosphere
Spectrometric measurement of particle densities of nitric oxide and excited oxygen molecules in the mesosphere
Heterodyne laser measurements of particle densities of nitric oxide and other species in the stratosphere
Spectrometric measurement of solar ultraviolet spectra in stratosphere and troposphere
Photometric measurement of solar ultraviolet flux in selected bands
Measurement of atmospheric diffusion and relative transport in balloon-based studies
LIDAR (laser radar) study of aerosol particle densities in the troposphere and stratosphere

*See Highlights below.

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Stratosphere and Troposphere Studies*

In September 1972, a balloon-borne payload of 22 instruments measuring dynamic, thermodynamic, solar flux, and compositional parameters gathered 6 hours of data, including sunrise, at 48 kilometers altitude. In studies related to stratospheric behavior and pollution in the ozone layer, in October 1973 and May 1974, payloads of 22 to 25 instruments, weighing about 4500 pounds, gathered nighttime, sunrise, and daytime data at 28 kilometers altitude for periods of 15 and 23 hours respectively.

In November 1974, a balloon carrying an on-board scientist and a 25-instrument payload for measuring meteorological parameters gathered 12 hours of nighttime and sunrise data at altitudes of 1 to 4 km. Ground-based instrumentation aided in data correlation. The scientific goal was to determine relationships among various measurements of atmospheric parameters in a single parcel of air in its natural diurnal transit over varying terrain. The operational goal was to develop a methodology for such complex low-altitude studies as climatology, weather, and pollution problems.

Mathematical models simulating the complex chemical kinetics and dynamics of these parts of the atmosphere provided a methodology for selecting the most pertinent parameters and conditions for the experiments, together with a structure for relating measurements and for optimizing the interpretive value of the data.

From 4 to 12 other laboratories participated in or provided experiments on the four successful flights. Although much remains to be learned about the stratosphere, the flights considerably increased Sandia's capabilities for making all types of atmospheric measurements.

APPLIED FLUID DYNAMICS

Applied research in fluid dynamics includes studies of the erosion of materials caused by high-speed impact of rain, snow, ice, or dust; of the steady flow of two-phase homogeneous mixtures of gas and liquid through pipes; of water entry and underwater performance of projectiles; of boundary-layer transition from laminar to turbulent flow on reentry vehicles; of acoustic-wave propagation through real atmospheres with varying winds and temperatures; and of the atmospheric dispersion of particulate debris by explosions, fires, and stratospheric aircraft. Instrumented water tunnels and wave tanks are available to support hydronautical studies. A special low-speed wind tunnel (< 14 m/s) is available for studying atmsopheric wind effects, such as the deposition and resuspension of particles. Field experiments are performed in support of these fluid dynamic studies.

Particulate Impact Erosion

This area has to do with the loss and degradation of materials resulting from impacts by small liquid or solid particles. Of particular concern is the erosion of exposed surfaces on high-speed vehicles which encounter rain, snow, ice, or dust particles. Excessive loss of nosetip or heatshield material can cause increased drag, instability, and even vehicle destruction. (Item 1)*

Current Activities

Rocket test flights through natural meteorological environments
Single-particle impact studies using a light gas gun
Development of semi-empirical methods for predicting erosion

Transitional and Two-Phase Flows

Research is conducted on boundary-layer transition and two-phase flow phenomena. Transition of boundary-layer flow from laminar to turbulent over a high-speed vehicle markedly increases skin friction drag and the heating rate of the vehicle's surface. Two-phase flows through ducts are of concern in the design of power-generating equipment; e.g., flashing of a liquid coolant reduces the efficiency of heat transfer and the flow capacity of the piping system.

*See Highlights below.

Current Activities

Determination of boundary-layer transition from flight-test data
Analysis of boundary-layer transition data acquired in wind tunnels
- Vehicle nose bluntness effects
- Free-stream unit Reynolds-number effects
- Wall to free-stream temperature-ratio effects

Computer-code development for two-phase fluid flows

Atmospheric Acoustics

This study deals with the manner in which acoustic waves behave while moving through the atmosphere. Gradients in air temperature and wind can cause the atmosphere to act like an acoustic lens, refocusing or dispersing acoustic waves. Specific phenomena being investigated are blast waves from explosives and sonic booms from aircraft. (Item 2)

Current Activities

Prediction of acoustic-wave overpressures
Participation in explosive field tests
Sonic-boom studies using supersonic sleds
Determination of parameters affecting amplification

Atmospheric Particulate Dispersion

Techniques are developed to predict the extent of particulate dispersal on both local and global scales. Particulate matter released in the atmosphere, such as through explosion, fire, or vehicular emission, will be transported and dispersed by winds and turbulence and ultimately deposited on the ground. Later winds can resuspend these particles and disperse them further. It is important to learn the approximate geographical extent of this dispersion, and particulate density as a function of distance from the source. (Item 3)

Current Activities

- Computer codes for prediction of debris dispersion
- Safety analyses for weapon systems
- Studies of aerosols produced by pyrophoric materials
- Studies of ozone production by stratospheric aircraft
- Support of municipal studies of vehicular pollution

Meteorology

Analyses are made of the climatic, synoptic, and local weather. Results of these studies are important in siting and conducting field operations and in designing apparatus that must function when exposed to the environment. (Item 4)

Current Activities

- Determining sites for wind-powered generators
- Analyzing meteorological data from erosion research vehicle tests

Hydronautics

Studies in process deal with the water entry and submerged performance of various projectile configurations. Wind and water tunnels and wave tanks, in addition to analytical and numerical methods, are used to determine force and moment coefficients, cavity characteristics, and other effects for each projectile configuration. (Item 5)

Current Activities

- Projectile water-entry studies
  - Configuration design criteria and parametric studies
  - Projectile entry and underwater stability and performance
  - Cavity dimensions and pressures
  - Supercavitating flow phenomena
- Instrumentation development
  - Digital memory system
  - Trailing-line telemetry
  - Radio frequency transmission
  - Acoustic tracking
  - Facility development
    - Blow-down water tunnel with velocities to 180 meters per second
    - Rocket-sled track for high-speed water-impact tests
    - Hydroballistics tank
  - Buoy/mooring-line systems
    - Configuration design
    - Dynamic simulation

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Nosetip Erosion*

Figure 1 shows how a reentry vehicle nosetip was eroded during hypersonic flight through a light snowstorm, demonstrating how the impact of particles such as dust, ice, and water can cause significant damage to the surface of a high-speed vehicle. A computer code has been developed for the study of surface erosion. Behind the shock wave is a gas layer that envelops the vehicle and will cause particles to be deflected and/or decelerated, and dissipated by evaporation and/or breakup. The code accounts for these effects on a sphere-cone vehicle and, with proper modeling for impact erosion, can predict surface recession. This code has been coupled with a one-dimensional aerothermal ablation code to compute the total mass removed from a nosetip material by particle impact and aerodynamic heating.

Item 2. *Blast Study*

At Tooele Army Depot, Utah, obsolete and defective munitions must occasionally be destroyed. As shown in Figure 2, these 2300-kg high-explosive demolitions can send window-breaking 600-Pa waves into neighboring communities at distances of 11 to 15 km under adverse weather conditions. The problem is that the atmosphere acts as an acoustic lens to refract airblast waves, depending quantitatively on vertical gradients of wind and temperature (sound speed). In consequence, at a fixed distance from an explosion, a wave may cause damage on one day and pass undetected on another.

Because of Sandia's work in the peaceful applications of nuclear devices, its experience in evaluating airblast from atmospheric nuclear testing, and its continuing surveillance

APPLIED FLUID DYNAMICS

of controlled explosions at mining and other locations, the Laboratories was called upon to study the Tooele problem and recommend procedures.

A simplified method was developed for evaluating atmospheric conditions at Tooele to help minimize propagation, using only local wind and temperature observations plus morning balloon data from the National Weather Services in Salt Lake City. The principles and procedures are applicable to mining and quarrying operations as well as to a variety of ordnance-disposal situations.

Item 3. *Global Diffusion Model*

A diffusion code developed previously for analyzing the dispersion of radioactive particles produced by reentry burnup of satellite isotopic power generating systems has been recently applied to the problem of supersonic transport (SST) emissions in the stratosphere. Common to both problems is the very small gravitational fall rate, which implies a very long residence time in the atmosphere. By modifying the previous code to accommodate the continuous character of SST emissions, it was possible to simulate the long-term buildup of SST exhaust products on a global scale, while accounting for diffusion effects as well as appropriate wet and dry removal processes. Figure 3 shows the projected buildup of one pollutant with time (based on projected 1980 traffic) as a function of altitude for a latitude at which most SST traffic will occur. Similar but somewhat smaller buildups are predicted for all latitudes.

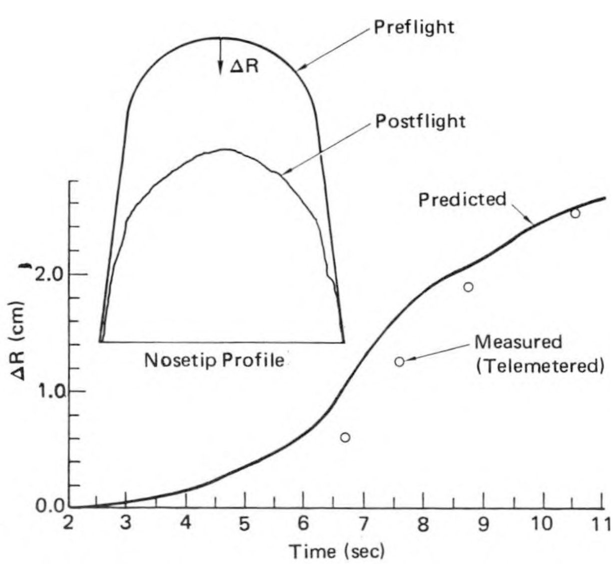
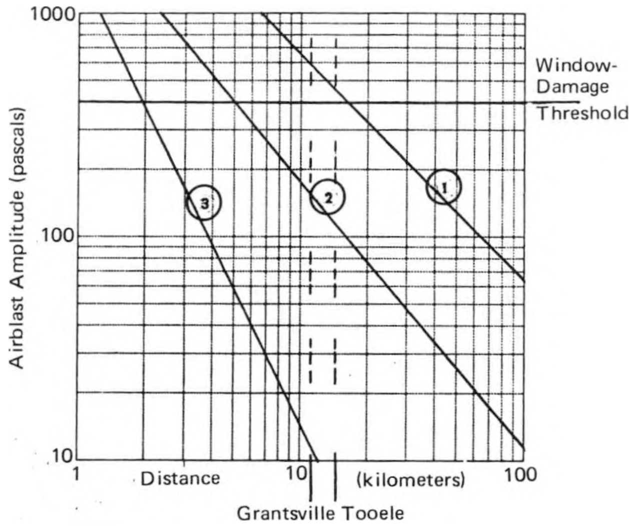


Figure 1. Erosion on a reentry vehicle nosetip



1 Maximized propagation, atmospheric ducting, focusing

2 Standard propagation, spherical wave expansion

3 Minimized propagation, strong sound velocity gradient with height

Figure 2. Airblast pressure-distance curves for 2300 kg high explosives (surface burst)

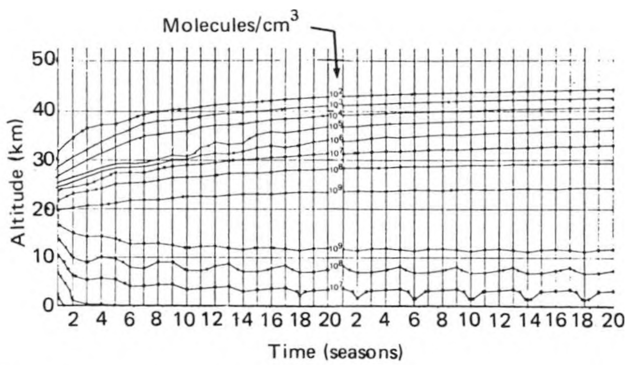
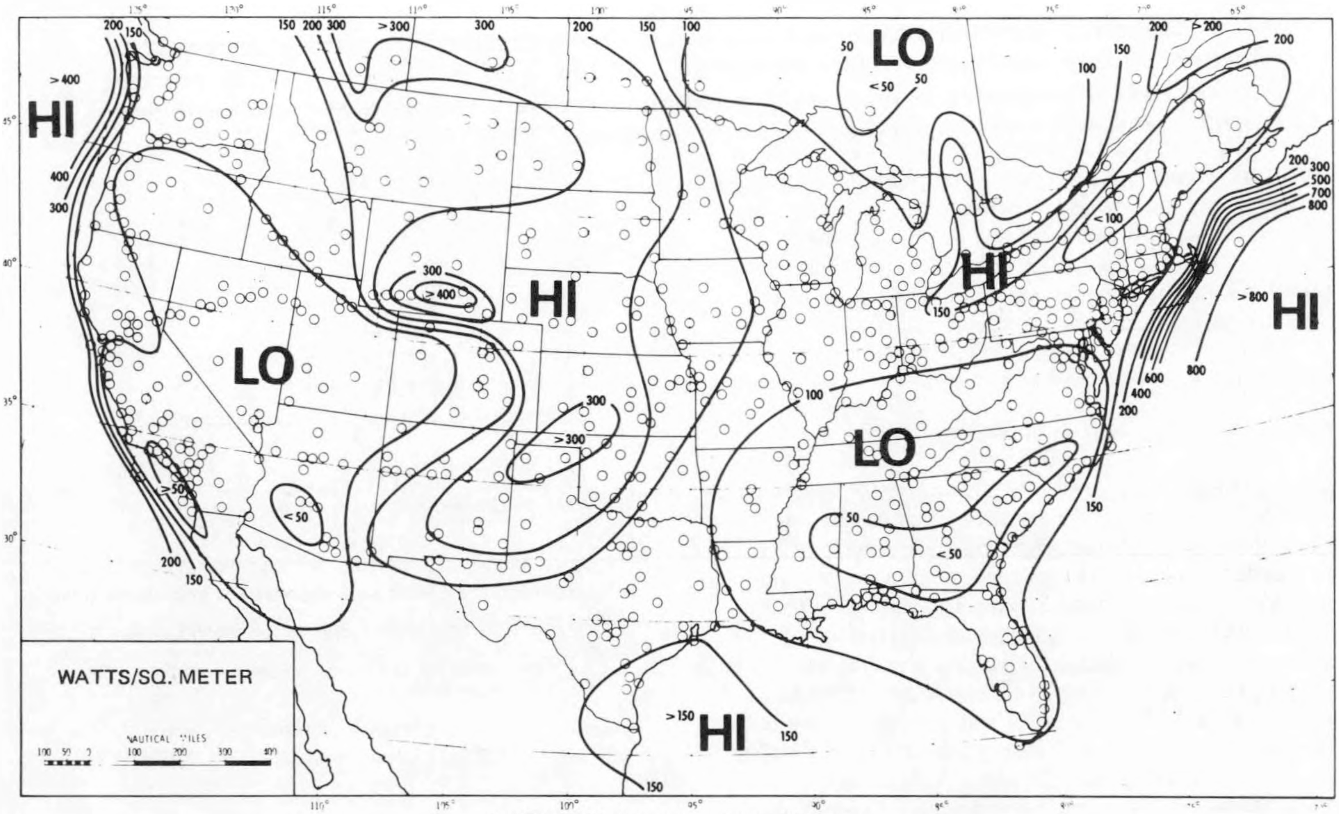


Figure 3. Global diffusion model

Item 4. *Wind-Power Survey*

Data on wind power available throughout the United States are being analyzed for application to various aspects of the problem of generating power by means of wind turbines. Wind variations of turbulence scale, diurnal (24-hour) periodicity, synoptic (weather map) scale and seasonal scale, are all important to either wind-turbine structural design, energy storage requirement estimates, power network planning, or cost-effectiveness calculations. A national wind-power map, based on a preliminary study, appears in Figure 4.



Available Wind Power — Annual Average

Figure 4.

Item 5. *Water-Entry Studies*

An exploratory development program was conducted to assess the feasibility of an antisubmarine weapon capable of high-speed water entry and fast sink rate. A series of full-scale water-entry tests was run using a family of ogive-nosed projectiles having a specified range of length-to-diameter ratios and ballistic coefficients. Dynamic loads and cavity-pressure measurements were obtained from surface impact to depths of 300 meters, for entry velocities of 60 to 300 meters per second. A later series of scale-model water-entry tests was carried out to extend the parametric study and to augment loading information with photographic recordings of physical events occurring during water entry. One frame of a high-speed film made during a typical test is shown in Figure 5.

Development of a miniaturized on-board telemetry system for direct data transmission through water facilitated acquisition of information having high-frequency content and precluded interference (by negating the effects of external instrumentation) with physical water-entry events.

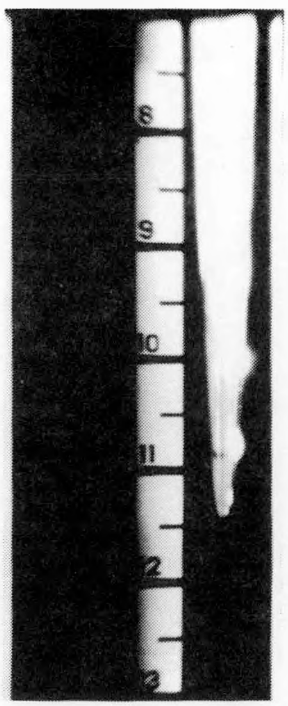


Figure 5. Water entry of scaled model

AEROMECHANICAL DESIGN

Hardware is developed to support research in aerodynamics. This activity comprises hardware design, structural analysis, fabrication, and testing. The hardware includes research rockets, aircraft-delivered vehicles, earth penetrators, recovery devices, aero-facility components, and wind-tunnel models, together with associated rigs and balances.

Hardware Design

Flight vehicles and aero-facility hardware are designed to meet specific requirements of research and development programs in progress or under consideration. Materials are chosen to survive extreme environments. (Items 1-3)*

Current Activities

Aircraft-delivered vehicles
Rocket-test configurations
Wind-tunnel models and instrumentation
Wind-tunnel facilities and components
Darrieus wind turbines

Structural Analysis

Analytical and numerical methods are developed to investigate structural response under extreme environments.

Current Activities

Analysis of stress and strain
Study of aeroelastic effects
Thermal and mechanical shock effects

Fabrication and Testing

From designs suggested by theoretical studies and computer modeling, wind-tunnel models and flight vehicles are fabricated and assembled. Full-scale vehicles are flight-tested at Tonopah, Kauai, and other test ranges.

Current Activities

Research rockets
Aircraft-carried vehicles
Earth penetrators
Wind-tunnel models and facilities

*See Highlights below.

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Earth Penetrators*

A collection of typical earth-penetrating vehicles is shown in Figure 1. It includes vehicles containing electronic packages that seismically and acoustically detect the presence of intruders and transmit the information to a central processing center. Some of these vehicles are delivered by aircraft; others are launched by mortars. The vehicles are designed with pop-out fins for flight stability, and with impact-deployed soil brakes to control penetration depth.

Item 2. *TATER Research Rocket*

The three-stage Talos-Terrier-Recruit (TATER) test vehicle (Figure 2), when launched at an elevation angle of 28 degrees, reaches a maximum velocity of 3200 meters per second about 11 seconds after launch, at an altitude of 4500 meters and a dynamic pressure of 4,310,000 pascals. The payload, separated beyond apogee at velocities of 300 to 600 meters per second, free-falls to about 1800 meters, where a parachute recovery system is deployed. The recovery system for use over water includes a flotation

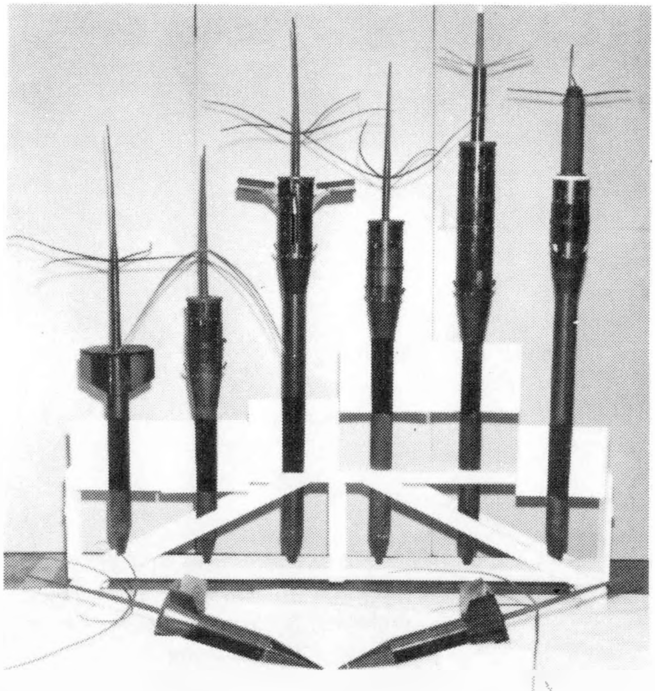


Figure 1. Typical earth penetrators

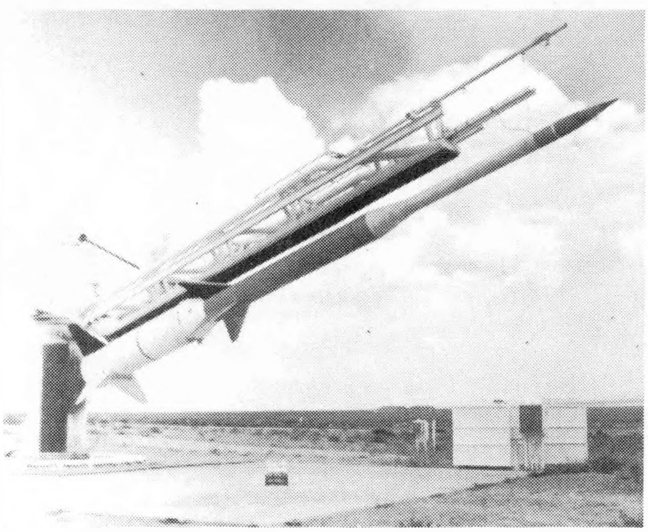


Figure 2. TATER research rocket

bag and radio beacon. The vehicle provides a hypervelocity test capability for studies of reentry vehicle nosetip shape change and boundary-layer transition in either clear air or aggravated-erosion environments.

Item 3. *Wind-Tunnel and Ballistic Range Models*

Examples of bomb, rocket, and reentry-vehicle models designed for wind-tunnel testing are shown in the background in Figure 3. The model in the foreground was designed for gun launch at transonic speeds through an instrumented ballistics range. Also shown is a precision strain-gage balance used to measure aerodynamic forces and moments on wind-tunnel models.

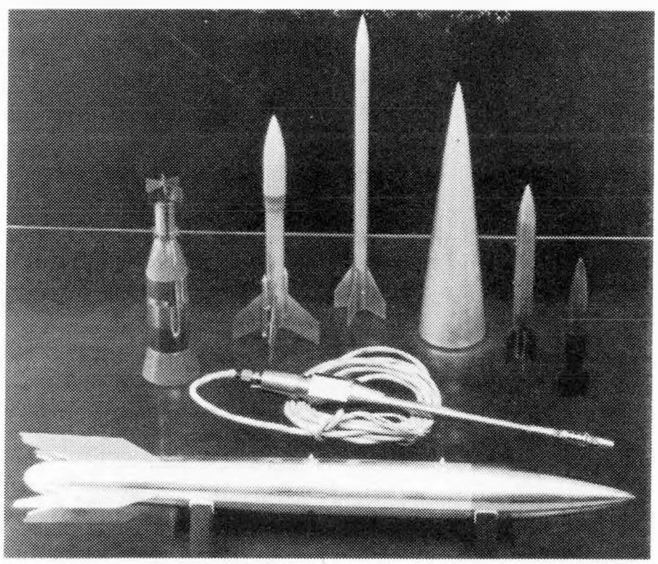


Figure 3. Test-model hardware

SAND74-0079
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APPLIED MATHEMATICS

Sandia Laboratories Technical Capabilities

Applied Mathematics

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115
and Livermore, California 94550 for the United States Energy Research
and Development Administration under Contract AT(29–1)-789

SAND74-0079
Unlimited Release

SANDIA LABORATORIES TECHNICAL CAPABILITIES

APPLIED MATHEMATICS

ABSTRACT

This report characterizes the applied mathematics capabilities at Sandia Laboratories. Selected applications of these capabilities are presented to illustrate the extent to which they can be applied in research and development programs.

APPLIED MATHEMATICS*

Research in applied mathematics is directed toward providing mathematical support for the Laboratories' technical programs. Research in numerical mathematics provides support for scientific computing and typically leads to the development of new or improved computer programs. Many problems associated with the command and control of nuclear weapons and with the reliability and security of communication networks require mathematical research in the related disciplines of graph theory, combinatorics, and coding theory. Research in mathematical physics is resulting in a better understanding of material properties and wave propagation. Research on the theoretical foundations of a number of mathematical tools used by scientists and engineers is delineating more clearly the range and usefulness of these tools. Statistical research is carried out in support of reliability studies, systems analysis, the design of experiments, and data analysis.

Applied Mathematics Technical Staff

	Professional Staff
Development of Computer Codes	30
Discrete Mathematics – Coding Theory, Combinatorics, and Graph Theory	6
Mathematical Physics	14
Theoretical Foundations of Mathematical Techniques	8
Statistical Analysis	15

*Compiled December 1974.

DEVELOPMENT OF COMPUTER CODES

Computer-code development, as distinct from program-writing, is aimed at providing high-quality, widely applicable codes to support scientific computation. Since such codes are at or near the state-of-the-art, their development usually requires some associated mathematical research. Mathematical codes are developed for general use – for the numerical solution of differential equations, for example. Other code development is often oriented toward specific types of physical problems.

Mathematical Subprograms

Effective scientific computing often depends on the availability of high-quality basic mathematical subprograms. State-of-the-art codes are developed, tested extensively and made available to the technical staff. (Items 1 - 4*)

Current Activities

- Adams methods for ordinary differential equations
- Runge-Kutta methods for ordinary differential equations
- Curve-fitting
  - Polynomial
  - Piecewise polynomial
- Galerkin techniques for stiff ordinary differential equations
- Special functions of mathematical physics
- Statistical codes
- Nonlinear optimization
- Quadrature

Special-Purpose Computer Codes

Codes are often developed for the study of particular physical processes. Those parts of a process that have been shown to be significant – by experiment, by mathematical analysis, or by computing experience – are incorporated in a mathematical model. Some numerical analysis is usually required before the mathematical model can be translated into a suitable computer code. (Items 5 - 8)

Current Activities

- Wave and hydrodynamics codes
  - 1-, 2-, and 3-dimensional codes
  - Propagation in composite materials
  - Coupled hydrodynamics and radiation
  - Impact and spall
- Finite-element codes
  - Static stress analysis
  - Fluid flow
  - Transient dynamics
  - Structural response
- Transport codes
  - Electron
  - Proton
  - Neutron
- Semiconductor device analysis codes
- Confinement of explosions
- Separating instrument response from experimental data
- Nozzle flow
- Boundary-layer flow problems in reacting fluids
- Dynamic simulation of the interception of maneuvering vehicles
- Satellite vulnerability

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*See Highlights, below.

DEVELOPMENT OF COMPUTER CODES

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Item 1. *Computer Codes for Ordinary Differential Equations*

Codes for the initial-value problem for ordinary differential equations have been written based on the Adams and Runge-Kutta methods. They are portable and well documented. Besides being efficient, the codes set a new standard for ease of use and robustness. These codes have a number of novel features, based on research, dealing with error estimates, step-size control, and automatic detection of stiffness.

Item 2. *Spline Curve Fitting with Computer Graphics*

The introduction of B-splines as a basis set for linear least-squares approximation has added considerable flexibility to the curve fitting of data. Algorithms based on B-splines have been developed and implemented on an interactive graphics system. The user at a graphics terminal interacts with the computer to change the curve-fitting parameters and sees the results of his changes displayed very quickly. In just a few seconds, piecewise polynomials with various degrees of continuity in the derivatives can be fitted to data points and displayed. Error plots, first and second derivatives, changes in the number and position of spline knots, changes in spline degree, and changes in equality or inequality constraints, are all available virtually at a stroke of the light pen.

Item 3. *Computer Programs for Bessel Functions Functions*

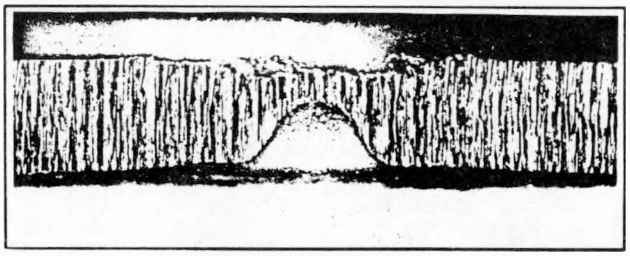
Efficient and robust codes have been written for evaluating the Bessel functions $I_\nu(x)$ and $J_\nu(x)$ for non-negative ν and x. The codes are based on recent work on uniform asymptotic expansions of Bessel functions in the order ν for $\nu \rightarrow \infty$. For $\nu \geq 32$, accuracies of the order of 10^{-15} are uniformly obtainable using these asymptotic expansions. Backward recursion on the standard three-term recursion relations is used to evaluate the functions for $\nu < 32$. Asymptotic expansions also provide the means for evaluating $K_\nu(x)$ and $Y_\nu(x)$ very accurately, but only for large orders, since backward recursion is not stable for these functions.

Item 4. *Applied Statistics Code Package*

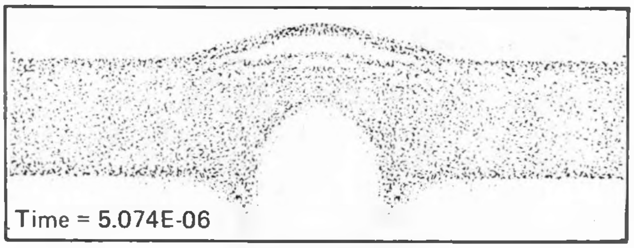
A user-oriented conversational package of statistical codes has been developed. It contains a variety of options including descriptive statistics, analysis of data according to the normal, exponential, Weibull, extreme-value, and log-normal distributions, regression analysis, Fisher's exact test, and random-number generations.

Item 5. *Two-Dimensional Stress-Wave Codes*

Two-dimensional stress-wave-propagation computer programs have been developed for the solution of a wide class of problems including those arising from rapid energy deposition. At energy levels considered for the initiation of nuclear fusion by an intense electron beam, the CSQ Eulerian code is used to simulate energy deposition and to calculate the resulting motion of materials. Vaporization, liquefaction, and spallation of solids are common in these studies. Calculated and experimental damage to an aluminum plate for an electron-beam diagnostic study are shown in Figure 1. The craters are similar, and excellent agreement between experiment and the calculation is obtained near the rear surface of the target where multiple spall layers are formed.



Experimental Damage



Calculated Damage

Electron-Beam Parameters:

Total energy — 4 kJ
Radius — 1 mm
Deposition time — 50 ns
Electron energy — 0.5 MeV
Electron density — 54 Gamp/m^2

Figure 1. Comparison of calculated and experimental damage to an aluminum plate

DEVELOPMENT OF COMPUTER CODES

Item 6. *Finite-Element Computations Employing Singular Functions*

Finite-element-method computations were developed for calculating the strength of singularities in linear elastic bodies. A generalized quadrilateral finite element that includes a singular point at a corner node forms the basis of the calculations. The displacement formulation is used and inter-element compatibility is maintained by blending functions in the neighboring elements. Plane stress, plane strain, and axisymmetric conditions are treated. Typical of the calculations that can be accomplished is the edge cracked panel shown in Figure 2. The comparison between calculated mode I stress intensity factors K_1 and analytic results is shown in Figure 3.

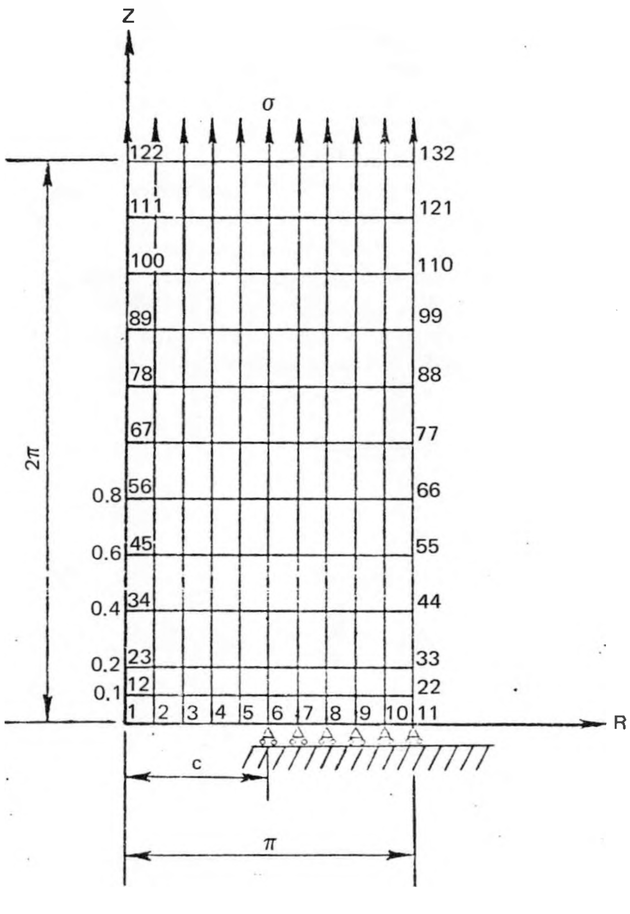


Figure 2. Finite-element definition of side-cracked panel

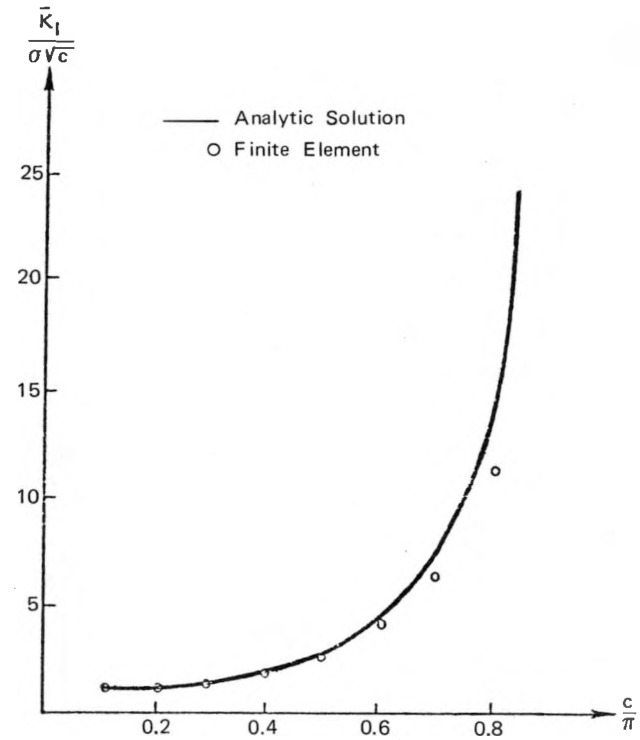


Figure 3. Stress intensity factor as a function of crack length

Item 7. *Finite-Element Computations for Large-Deformation Dynamic Response of Axisymmetric Solids*

Finite-element computations were developed for problems in solid dynamics for which a plane strain or axisymmetric representation is appropriate. The problem is treated as an initial-value problem and the response is obtained by integrating in time. An arbitrary quadrilateral mesh is used. The motion is assumed to vary bilinearly over the element using isoparametric coordinates. The strain and stress are taken as constant over the element, based on their values at the center of the element. The Galerkin form of the finite-element method is used to generate the spatial discretization. The resulting simultaneous equations in time are integrated using central difference expressions for velocity and acceleration.

Because a diagonal or lumped-mass matrix is used, the scheme is explicit. Because the integration procedure is only conditionally stable with respect to time step size, the step size is continuously monitored during analysis.

Figure 4 shows the result of a two-dimensional calculation. This is a particularly difficult calculation since there is a discontinuity in the impulse. It is a finite-strain-dominated problem involving membrane stretching. It entails biaxial stress states and rapid changes in stress resulting from the passage of membrane and bending waves. In view of past experiences with this problem, the results of the computations are quite good.

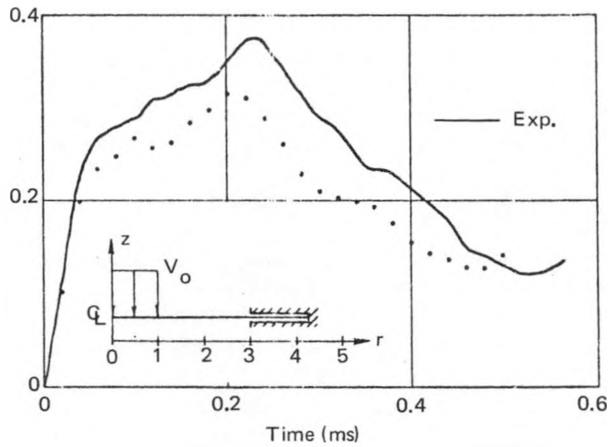


Figure 4. The central deflection of a clamped circular plate impulse loaded in the center with an initial velocity of 4410 in./sec. The plate material is 6061-T6 aluminum with a modulus E of 1.04×10^7 psi, a Poisson's ratio ν of 0.3, a hardening modulus E_t of 5.44×10^4 psi, a yield stress t_0 of 4.24×10^4 psi and a density ρ of 9.63×10^{-2} lb/in.^{3}. The radial displacement is fixed at r = 4.25 inches and the vertical displacement is fixed from r = 3.0 inches to the outer edge. Plate thickness is 0.125 inch. A uniform mesh of 4 elements through the thickness by 85 elements radially was used.

Item 8. *Separating Instrument Response from Experimental Data*

In the process of extracting the maximum possible information from experimental measurements, it is often necessary to separate instrument response from experimental data. Mathematically this problem requires the solution of a Fredholm integral equation of the first kind. A very versatile code has been developed for solving this notoriously difficult type of numerical problem. The code is successful because it offers the user great flexibility in specifying constraints on the problem. For example, if the user knows on physical grounds that the solution he wants should be positive and concave downward, he can feed this information into the computer, and the code will generate a solution with these properties.

DISCRETE MATHEMATICS

Support for programs dealing with the command and control of nuclear weapons often requires the capability to treat mathematical problems that are essentially discrete rather than continuous. Such problems also arise in data handling, communications, and reliability studies, for example. Coding theory and graph theory are the mathematical disciplines most commonly applied to such problems, and the tools of combinatorial mathematics and abstract algebra are often used. Research has been done in all of these areas.

Coding Theory

Coding theory was developed to deal with the problem of increasing the rate at which information is transmitted in noisy communication channels. It has also been found applicable to a number of other types of problems. For example, the problem of authenticating data transmitted from unattended seismic observatories currently under development, and problems associated with the command and control of nuclear weapons, were dealt with using coding theory. Research associated with these problems has led to very practical and significant theoretical advances. (Item 1*)

Current Activities

Message authentication
Coding theory applied to optimizing the signal-to-noise ratio of certain optical detectors
Software for the command and control of nuclear weapons

*See Highlights, below.

Graph Theory

Graph theory is used to model problems where the structure of interconnections among various objects is significant. Such networks or "graphs" that arise in applications are often too complex for brute-force analysis, and more sophisticated techniques must be employed. Often a judicious blend of computing and theory has been required for such problems. (Items 2,3)

Current Activities

Analysis of the reliability of communication networks
Fault-tree analysis
Failure-tolerant distribution nets

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Item 1. *Authentication*

Authentication theory is concerned with the "fingerprinting" of messages transmitted through a communication channel that is under the control of an opponent so as to maximize the probability that any alteration in a message will be detected by the authorized receiver. Authentication theory is a generalization of coding theory in that the statistically defined communication channel is replaced by a two-person zero-sum game in which the opponent's optimal strategy maximizes his expectation of having an altered message accepted as authentic and the transmitter-receiver's optimal strategy minimizes this expectation. The foundations of authentication theory have been established as a basis for the development of authenticating communication systems.

Item 2. *Vulnerability of Communication Networks*

Consider a set of stations with lines of communication possible among them. A graph, which is a set of nodes with a set of edges connecting them, is a good mathematical model of such a network, nodes being stations, and an edge being directed from node i to node j if station i can transmit directly to j. Since communication is not 100% reliable, the edges are assumed to have probabilities associated with them, and it is frequently of interest to know the probability that one specified station can send a message through the network to another specified station.

Algorithms have been developed that extend the set of graphs for which such calculations are possible. If a graph is too large for exact calculation, then useful upper and lower bounds for network reliability can be computed instead.

Item 3. *Failure-Tolerant Distribution Networks*

A frequently recurring problem in the design of communication systems, distribution networks, command and control systems, etc., is the construction of minimal networks (i.e., with the smallest number of links) that will still operate at a preassigned level of performance after a specific number of arbitrarily selected links have failed. The case in which all stations can originate messages was treated earlier, but the common case in which only a single designated station can originate a message was not. If n is the total number of receiving/relay stations, the problem is to design a network having the smallest number, $L(k,\ell;n)$, of two-way links so that k link failures will result in at most ℓ of the stations failing to receive a message. A useful lower bound for $L(k,\ell;n)$ (and the best possible in many cases) has been derived. For the case where "everyone must get the word," i.e., $\ell = 0$, a simple constructive characterization of the minimal networks has been established.

MATHEMATICAL PHYSICS

Physical problems are formulated in mathematical terms, and frequently the resulting mathematical problems cannot be solved by the routine application of known techniques. Research done in connection with such problems often represents a genuine blending of mathematics and physics. Research in mechanics is a particularly fertile source of mathematics problems that are intimately connected to physics.

Wave Propagation

Research is conducted in two broad areas: electromagnetic waves and mechanical waves in various kinds of materials. Studies of wave propagation in composites, in inhomogeneous materials, and in the presence of chemical reactions are especially fruitful sources of mathematical research problems. (Items 1 - 4*)

Current Activities

- Diffraction of scalar waves by edges
- Theoretical foundations of wave propagation in materials, including the effects of viscoelasticity, diffusion, chemical reactions, phase changes, and fracture
- Sound rays and acoustic intensity in a moving medium
- Spectral analysis and digital filtering

Applied Mechanics

Mathematical research supports theoretical and experimental studies dealing with the mechanical behavior of various materials. These studies typically are concerned with exotic materials or with materials in unusual or extreme environments. (Items 5,6)

Current Activities

- Thermal instability of explosive materials
- Singular solutions for fracture mechanics
- The development of turbulence in hypersonic boundary layers
- The interface between subsonic and supersonic gas-liquid flows

Reactor Mathematics

Design of the laboratory research reactors has required considerable mathematical support. Additional support is provided to help assess reactor performance. Analyses of reactor safety and accident simulation also involve a substantial amount of mathematical physics. (Item 7)

Current Activities

- Complete nuclear fuel-cycle neutronics
- Reactor design and performance assessment
- Safety analysis of reactor experiments and reactor designs
- Accident analysis of Light Water Reactor Systems
- Liquid Metal Fast Breeder Reactor experimental interpretation

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*See Highlights, below.

MATHEMATICAL PHYSICS

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Item 1. *Diffraction of Scalar Waves by Edges*

The problem of diffraction of scalar waves by an edge is of considerable interest mathematically as well as physically. Following the discovery that the half-plane problem has a simple analytical solution, it has been found possible to construct in closed form the solution for the problem of diffraction by a plane containing a slit. The method is being extended to deal with the problem of a plane screen containing an arbitrary hole.

Item 2. *Wave Propagation in Chemically Reacting Materials*

Various analytical techniques, including singular surface analyses and steady-wave analyses, are being used to examine the behavior of shock waves, acceleration waves, and acoustic waves in nonlinear materials with chemical reactions. These studies are aimed at determining the influence of the reactions on the growth and decay of a wave and on the wave profile. On the basis of the results, new procedures for determining material properties are being devised; and specific constitutive models involving multiple reactions are being developed for use in finite-difference wave-propagation codes. Many of the concepts employed in these studies have been found applicable to other materials exhibiting rate-dependent behavior such as viscoelasticity, phase transformations, and dynamic fracture.

Item 3. *Ray Acoustics in a Moving Medium*

The three-dimensional equations for rays and sound intensity in a moving medium have been derived. The ray paths and intensity can be computed by numerically solving a system of ordinary differential equations. For some reasonable models of the atmosphere the equations can be solved exactly. These developments also provide a practical way to study the influence of temperature and wind variations on sound propagating from a moving source.

Item 4. *Spectral Analysis and Filtering of Digitized Signals in Seismology*

Modern methods of spectral estimation and digital filtering are being used in the analysis of seismic data from underground explosions as well as earthquakes. Typical objectives are identification of wave components, signal-to-noise enhancement, detection, discrimination, measurement of energy, etc. General-use computer software includes the Fast Fourier Transform, power spectrum estimation, and many types of filtering. Digital filters and computer interfaces have been designed for seismic observatories.

Item 5. *Thermal Instability of Explosives*

The problem of calculating the critical surface temperature at which a piece of explosive material will explode spontaneously was reduced to solving a steady-state heat equation and a related eigenvalue problem. As a check on the underlying theoretical argument, the calculated critical temperatures of small pieces of ten different materials were compared with those obtained experimentally at Los Alamos Scientific Laboratories. The results are shown below:

Comparison Between Experimental and Calculated Critical Temperatures

Explosive Material	Critical Temperature (0°) Calculated	Experimental
HMX	254	253-255
RDX	218	215-217
TNT	292	287-289
PETN	197	200-203
TATB	335	331-332
BTF	276	248-251
NQ	206	200-204
PATO	290	280-282
HNS	318	320-321
DATB	324	320-323

Item 6. *Tensile Strip with Edge Cracks*

The problem deals with an infinite tensile strip (Figure 1) having a single notch of depth c perpendicular to the edge of the strip. Of interest is the stress intensity factor K, the nondimensional crack energy W^*, and the crack opening displacement u_y. Essential to the solution technique was the approximate extension of the integral transform solution for a notched half-plane, which is related to quarter-plane problems in the theory of elasticity. An extension to the method of Sneddon and Dos gives a solution for a general pressure distribution on the crack face. The method of solution required a numerical evaluation of a Fredholm integral equation of the second kind. The direct approximation used a 16-point Gauss-Legendre quadrature to reduce the Fredholm integral to a system of equations. The results are shown in Table I, where μ is the shear modulus and ν is Poisson's ratio.

MATHEMATICAL PHYSICS

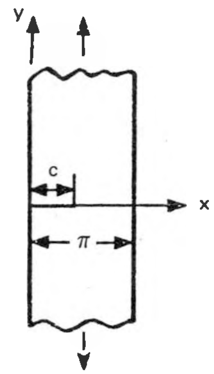

Figure 1. Edge-cracked panel under tensile load

TABLE I

Numerical Results for Problem

c/π	$K/\sqrt{c}$	W^*	$\frac{\mu u_y(0,0)}{p(1-\nu)}$
0·05	1·140	1·004	0·233
0·10	1·189	1·051	0·488
0·15	1·265	1·125	0·786
0·20	1·367	1·229	1·152
0·30	1·660	1·548	2·218
0·40	2·112	2·092	4·115
0·50	2·826	3·054	7·795
0·60	4·039	4·915	15·717
0·65	4·997	6·548	23·209
0·80	12·218	21·85	102·11
0·85	24·252	44·57	225·54

Item 7. *Assessment of Reactors for Safety Studies*

An assessment was conducted to determine the capabilities of Sandia Pulse Reactor III and the Annular Core Pulse Reactor for use in a program of research in reactor-safety technology. The neutronic transport and deposition results demonstrate a substantial capability for use in the area of overpower transient simulation, post-accident heat removal, and high-temperature equation-of-state and thermophysical properties.

THEORETICAL FOUNDATIONS OF MATHEMATICAL TECHNIQUES

Research is conducted primarily in the areas of numerical mathematics and classical applied mathematics. Theoretical work is aimed at obtaining a clearer understanding of when specific mathematical techniques should be used, how well they can be expected to work, or how they relate to other techniques. Experience and heuristic reasoning often help to clarify such issues, but basic research is required to obtain difinitive answers.

Analysis of Numerical Methods

Most research in this area is concerned with the numerical solution of differential equations. New methods are devised, error bounds are derived, and convergence theorems are proved. Theoretical results also illustrate differences between competing methods for solving problems, and provide guidance on which methods should be used for specific types of problems. (Items 1 - 4*)

Current Activities

Analysis of step size, order, and local error control for solvers of ordinary differential equations
Convergence of difference approximations for functional differential equations
Effects of stiffness on codes for solving nonstiff differential equations
Numerical solution of boundary-value problems for ordinary differential equations
Convergence of approximations to the motion of an ideal gas
Piecewise polynomial methods for initial-value problems

*See Highlights, below.

Applied Mathematics

Research is conducted in several areas of classical applied mathematics. The work is aimed at sharpening the mathematical tools used in these areas and extending the range of problems to which they can be successfully applied. (Item 5)

Current Activities

Singular perturbation theory
Bounds for ratios of Bessel functions
Two-point boundary-value problems

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Item 1. *Analysis of Numerical Methods for Ordinary Differential Equations*

The procedure of estimating local error and the control of error by step size and order changes in codes for solving ordinary differential equations have been analyzed. This has led to simpler, more efficient algorithms. In addition, ways of estimating global errors have been made practical. An understanding of the behavior of codes for nonstiff equations when confronted with a stiff equation has led to a way of coping with moderate stiffness and a test for severe stiffness. A cheap test has been developed for detecting requests for unattainable accuracies.

Item 2. *Numerical Solution of Boundary-Value Problems*

Several techniques have been investigated for the numerical solution of boundary-value problems for ordinary differential equations. These include invariant imbedding, orthonormalization, and deferred corrections for finite differences. The method of invariant imbedding converts the boundary-value problem into an initial-value problem via generalized Riccati transformations. Frequently the initial-value problem is numerically stable and provides a fast and accurate method for solving the boundary-value problem. The orthonormalization procedure combines the method of superposition with the

THEORETICAL FOUNDATIONS OF MATHEMATICAL TECHNIQUES

modified Gram Schmidt orthogonalization to maintain independence of the homogeneous equations. The deferred-corrections technique is an extrapolation procedure combined with a finite-difference method. These techniques are all designed for linear problems and are combined with a linearization procedure for nonlinear problems. Computer codes are under development using these techniques.

Item 3. *Convergence of Approximate Solutions for Functional Differential Equations*

The mathematical modeling of physical processes often leads to initial-value problems for ordinary differential equations. Sometimes a more accurate model of the physical situation is obtained when a term depending on the history of the solution is added to the differential equation. The numerical solution of these so-called functional differential equations has been studied. By appropriately modifying numerical schemes for approximating solutions of differential equations, one can obtain numerical methods for a functional differential equation. It has been proved, under reasonable hypotheses, that the resulting approximations converge to the solution of the functional differential equation.

Item 4. *Piecewise Polynomial Methods for Initial-Value Problems*

New discrete Galerkin techniques for approximately solving systems of first-order ordinary differential equations have been obtained by finding local Galerkin approximations on each step of the integration. Different classes of methods correspond to different quadrature rules used to evaluate the inner products involved. The approximate solution is a vector of N-th degree piecewise polynomials. It has been shown that the discrete Galerkin methods are equivalent to one-step collocation at the quadrature abscissas and also to interpolatory quadrature methods. If the N-point quadrature rule is of order $\nu + 1$, $\nu \geq N$, then these methods are of order ν at the mesh points. The schemes based on Gauss-Legendre and Radau (right end-point) quadrature are particularly suitable for stiff equations since these methods have orders 2N and 2N-1, and are A-stable and strongly A-stable, respectively.

Item 5. *Ratios of Bessel Functions*

Sharp new bounds have been derived for ratios of the Bessel functions I_ν and J_ν. These ratios arise in logarithmic differentiation, computation by continued fractions, tests for convergence of Bessel series, error estimates for truncated Bessel series, and other cases. The new bounds for the ratios also provide the basis for a new procedure for computing I_ν and J_ν. Bounds on the functions are obtained from the bounds on the ratios. It appears likely that the new procedure should rival the continued-fraction method for efficiency.

STATISTICS

Activity in this area is concerned with research in, and application of, statistical techniques. Statistics is frequently used in reliability studies, quality control, nuclear safety, and data analysis. Statistics is also used in some kinds of physical research problems. Computer support is an integral part of statistical activity.

Mathematical Statistics

Frequently, projects in the physical and engineering sciences call for a statistical technique that has not been developed. Statistical theory is then called upon to generate the necessary technique. Probability theory, distribution theory, and inferential theory are all used in developing the required procedures. (Items 1 - 5*)

Current Activities

- Goodness-of-fit tests
- Distribution-free accelerated-life tests
- Parametric and nonparametric prediction limits
- Design of sensitivity tests
- Tolerance limits based on censored data
- Cumulative sums in quality control
- Developing confidence limits for system reliability on the basis of component results
- Distribution theory
- Sampling theory
- Probability modeling

*See Highlights, below.

Applied Statistics

The application of statistical methods to problems in science and engineering is common. The design of experiments, analysis of data, interpretation and presentation of results, and input to modeling are all important applications of statistics. (Item 6)

Current Activities

- Design, analysis, and interpretation of independent experiments
- Linear and nonlinear regression analysis
- Design and analysis of sensitivity experiments
- Design of acceptance sampling plans
- Design of calibration studies
- Design and analysis of life-test experiments
- Assessing the reliability of engineering components
- Design of quality index
- Design of data storage and retrieval systems
- Monte Carlo modeling

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Item 1. *Goodness-of-Fit*

Most statistical methods (estimation and assessments of significance) are based on an assumption of some probability model or family of models. Before these methods are applied to data, it is desirable to have some assurance that the model is adequate. The data themselves can supply some such assurance by means of goodness-of-fit tests. Usually this is done by first making a goodness-of-fit test and then, if the result is satisfactory, using statistical methods based on the selected model family. However, investigation has shown that in some instances this procedure has undesirable properties. A technique has therefore been derived and used in which goodness-of-fit and model selection are considered jointly.

STATISTICS

Item 2. *Distribution-Free Accelerated-Life Tests*

For components with long lifetimes it is impractical or impossible to gather sufficient life statistics in tests conducted under normal conditions. An alternative is to run tests in an extreme environment that significantly shortens lifetimes. In such accelerated-life tests one gathers statistics from the distribution, say G, of life under accelerated conditions, but one wishes to estimate F, the distribution of life under normal conditions. The distributional assumptions underlying the concept of accelerated-life testing as it is often used imply that F and G have proportional hazard functions. This in turn implies that F and G are related in a special way; namely, $F(x) = 1 - [1 - G(x)]^{\theta}$ for some $\theta \leq 1$. Thus it makes sense to skip the distributional assumptions and start with only the assumption of proportional hazards. F can then be estimated if one takes a sequence of accelerated conditions and finds the regression of θ on the accelerating variable. From this estimate of θ and an estimate of G one can estimate F.

Item 3. *Prediction Intervals*

Prediction intervals can be used when one wishes to make a probability statement about observations in a second sample from a distribution F that is based on information in a first sample from F. A practical situation where prediction intervals would be useful is when a fixed relatively small number of units, say N, are to be produced and a variables measurement can be made on each unit. If one takes a sample of n units from the N units he can, using prediction intervals, make a probability statement about the location of the measurements of the remaining N-n units. If the form of F is assumed known (e.g., normal), one is dealing with parametric prediction intervals: if it is unknown one is dealing with nonparametric intervals. Nonparametric prediction intervals have been developed as well as parametric intervals for several different distributions, and these have been applied to quality-assurance problems.

Item 4. *Tolerance Limits Based on Censored Samples*

Applied statisticians are often called upon to construct tolerance limits based on a random sample for a distribution. The procedures for many distributions are well known if the random sample is complete. However, if the sample is not complete (often called a censored sample) for some reason, the problem of constructing such limits becomes more difficult. A procedure for constructing tolerance limits based on censored samples has been derived for the normal, extreme-value, and logistic distributions.

Item 5. *Confidence Limits on System Reliability*

In assessing the reliability of a system it is desirable, but often impossible or prohibitively costly, to have system reliability data. Instead, what may be available are a model, which expresses system reliability as a function of the reliabilities of the components that make up the system, and reliability (success/failure) test data on the components. A question that has been the subject of several investigations is how to use this information to make interval estimates of system reliability. A method has been developed that expresses component data as equivalent to pseudo-system results of $\hat{n}$ tests with $\hat{x}$ failures. This permits the usual binomial distribution results to be used and also provides a way to compare and combine component data with system data, if the latter are also available.

Item 6. *Design and Analysis of Sensitivity Experiments*

Reliability requirements are sometimes of the following form: At a stress level of x_o the probability of failure should not exceed p_o. Examples of stress variables are temperature, voltage, and components of a nuclear environment. One way to obtain data that can be used to help answer the question of whether the requirement is satisfied is to select n items, subject them to a stress of x_o, and count the number of failures. Another way is to divide the items among several stress levels; this experimental design is generally referred to as a sensitivity test or experiment. If the resulting failure proportions can then be modeled as a function of stress, then it may be possible to use these data to estimate the failure probability at x_o with more precision than if one had tested only at x_o. Thus, sensitivity testing can be more efficient than single-stress-level testing and this efficiency can be used in designing experiments; fewer test items will be required to obtain a specified precision. Numerical calculations and some applications indicate that efficiency factors of 10 to 1000 can be attained; that is, one can attain the same precision with a tenth to a thousandth as many test items as would be attained by a single-stress-level test.

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Sandia Laboratories Technical Capabilities

Biosciences

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115
and Livermore, California 94550 for the United States Energy Research
and Development Administration under Contract AT(29–1)-789

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SANDIA LABORATORIES TECHNICAL CAPABILITIES

BIOSCIENCES

ABSTRACT

This report characterizes the biosciences capabilities at Sandia Laboratories. Selected applications of these capabilities are presented to illustrate the extent to which they can be applied in research and development programs.

BIOSCIENCES*

Biological programs are directed toward an understanding of the effects of environmental conditions upon living systems. Emphasis is on incorporating physical, chemical, and engineering principles, theories, and techniques into the resolution of biological problems. While activities are described under the general headings of Environmental Biology, Applied Biology, and Analytical Biology, Biosciences is an interdisciplinary effort involving physicists, engineers, chemists, and mathematicians, as well as life scientists. Results from this effort include models of the lethal effects of heat and ionizing radiation (separately and in combination) on microbiological systems, new microbiological sampling devices and techniques, new sterilization processes, computerized systems representing man's interaction with a plutonium-contaminated environment, new information about the effect of heat upon radiation-induced mutation, the behavior of bacteria on surfaces, and the usefulness of heat/radiation combinations in vaccine development. Biosciences has application in such areas as the design and siting of nuclear reactors, management of radioactive materials, assessment of relative risk between nuclear and nonnuclear power generation, sterilization of space hardware and medical devices, and treatment of sewage sludge.

Technical Staff
and Investment in Equipment

	Professional Staff	Investment in Equipment (in $1000)
Environmental Biology	7	
Applied Biology	8	600
Analytical Biology	5	

*Compiled March 1975.

ENVIRONMENTAL BIOLOGY

This activity is primarily centered in experimental microbiology. Studies include examination of lethal and mutagenic effects on cellular systems. These effects are produced by heat, ionizing radiation, and selected environmental chemicals, as well as by pressure and humidity. Emphasis has been placed both on studying the response of cellular systems to combined environments whose effects are synergistic, and on elucidating subcellular events responsible for the synergistic reaction to these combined environments. Other activities include the study of airborne particles (radioactive, inert, and biological), their transport, behavior, and effects on surfaces, and means for controlling them.

Effects of Single Environments

Activities include study of the kinetics of the responses of bacteria, viruses, parasites, and mammalian cells to ionizing radiation, heat, and chemicals, and the study of subcellular systems that dominate such responses. Both lethal and mutagenic effects are investigated, and in selected cases, the effects of environmental modification of chemical systems are also studied. Changes in biological response as a function of other environmental parameters are also investigated; e.g., the rate at which dry heat induces auxotrophic mutations in bacteria is highly dependent upon relative humidity, and heat also influences bacterial "swimming" behavior. (Item 1)*

Current Activities

- Lethal and mutagenic effects of
  - Dry heat
  - Moist heat
  - Ionizing radiation (primarily γ and β)
  - Selected chemicals
- Influence of
  - Relative humidity
  - Oxygen
  - Pressure
  - Chemicals (salts, nutrients, radioprotectors/sensitizers)
- Molecular and subcellular system involvement
- Effects of temperature on behavior

Synergistic Environments

The effects of an environmental pollutant on a living system can be greatly modified by the presence of other pollutants. For example, heat can have a profound effect on the radiosensitivity or chemosensitivity of enzymes, viruses, bacteria, and mammalian cells. Not only are combined environments frequently more realistic but they also offer an opportunity for better understanding of single effects because these can be selectively manipulated. Activities are devoted to identifying combined environments that synergistically affect living cellular and chemical systems, and to gaining better understanding of the nature of combined effects. (Item 2)

Current Activities

- Combined heat and radiation environments
- Dose-rate effects and their modification
- Combined chemical environments
- Thermal enhancement of chemical effects
- Chemical protection against heat/radiation combinations
- Molecular studies
  - Electron spin resonance
  - Biochemical

Fine-Particle Physics

Activities are aimed at determining the transfer and retention of small pollutant particles in the environment. The particles of interest may be biological, inert, chemically active, or radioactive. The objective is to devise improved ways of controlling, removing, or predicting the behavior of particles that undesirably modify sensitive mechanical, electrical, chemical, or biological systems. Transfer media include air, water, and soil. These studies relate to quality assurance and control, contamination and disease control, nuclear systems reliability and safety, and environmental pollution. They include the characterization of particles and their transfer mechanisms, the monitoring and control of particles, and engineering design and planning for such control. Laminar-flow clean rooms provide an outstanding example of such design. (Items 3,4)

*See Highlights below.

Current Activities

- Particle characterization
  - Composition
  - Size
  - Shape
  - Wettability
- Particle-transfer mechanisms
  - Wind
  - Contact
  - Fluid
  - Biological vector
  - Gravitational
- Particle monitoring
  - Bacteriological sampling
  - Light scattering
  - Electrostatic sampling
  - Critical orifice techniques
- Particle control
  - Laminar-flow concepts
  - Chemical and physical removal techniques
- Engineering design and planning of devices and facilities
  - Experimental
  - Pilot
  - Full-scale

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Heat Effects on Bacterial Motion*

Two related laser light-scattering techniques have been used to study the motion of motile organisms in solution. The first, number fluctuation spectroscopy, gives information on the transitional motion of bacteria over distances of the order of the size of a focused laser beam. The second, intensity fluctuation spectroscopy, yields information about the rotational motion of bacteria from the rapid fluctuations in laser light reflected from a bacterial suspension. Combining these two techniques permits the separate study of transitional and rotational bacterial motion.

Figure 1 shows data on the temperature dependence of the transitional and rotational components of the swimming motion of *E. coli* bacteria. These data not only display a very steep temperature dependence of the swimming speed but also show that the helical path of the organism is temperature independent.

The mean distance between direction changes also can be measured. This type of measurement is useful in the study of such phenomena as chemotaxis, the attraction of microorganisms by certain chemicals.

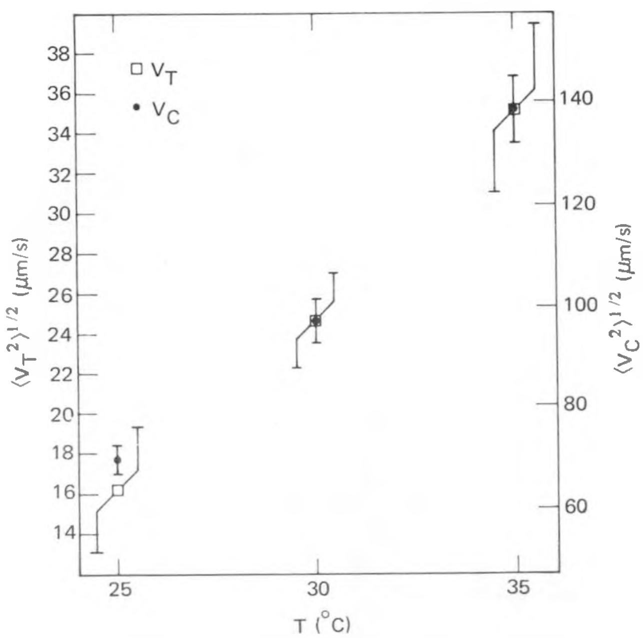

Figure 1. Temperature dependence of the transitional (V_T) and rotational (V_C) components of the swimming motion of *E. coli* bacteria

ENVIRONMENTAL BIOLOGY

Item 2. *Thermoradiation Sterilization*

During studies of the influence of temperature on radiobiological effects, it was found that all organisms investigated were inactivated synergistically by a simultaneous treatment of heat and ionizing radiation (thermoradiation). This synergism is evident only in certain temperature and dose-rate ranges which depend on the type of organism involved and other environmental factors. This is illustrated in Figure 2 for dry *Bacillus subtilis* var. *niger* spores. Similar results have been obtained with other bacterial spores, vegetative cells, bacteriophages, human viruses, and parasites.

Under proper circumstances, thermoradiation as a sterilization process offers many advantages over either heat sterilization or radiation sterilization separately. It has proved, for example, less time-consuming, more effective against many organisms, less sensitive to moisture and oxygen concentration, and less damaging to many materials.

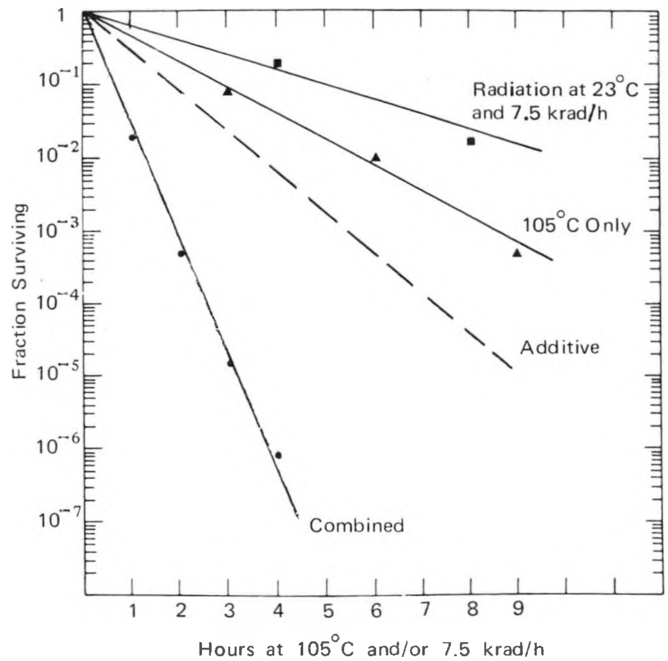

Figure 2. Example of synergism for dry *Bacillus subtilis* var. *niger* spores

Item 3. *Effects of Relative Humidity on Surface Particle Adhesion*

Programs to determine particle transport and retention characteristics have included a study of relative-humidity effects on small-particle adhesion to smooth surfaces (Figure 3). Particle transport on surfaces is of special interest as a primary means of carrying damaging particles into sensitive areas; this includes pathogenic organisms.

It was found that almost all particles are affected in some manner by water vapor in the surrounding air, particularly as the water content of the air increases. Of special interest are hygroscopic particles, which pick up moisture from the air, are partially or totally dissolved, and form a very strong bond with the surface on which they are located. At elevated humidities this occurs within a few minutes. Such particles are then firmly attached and are likely to be carried with the surface for some time and distance.

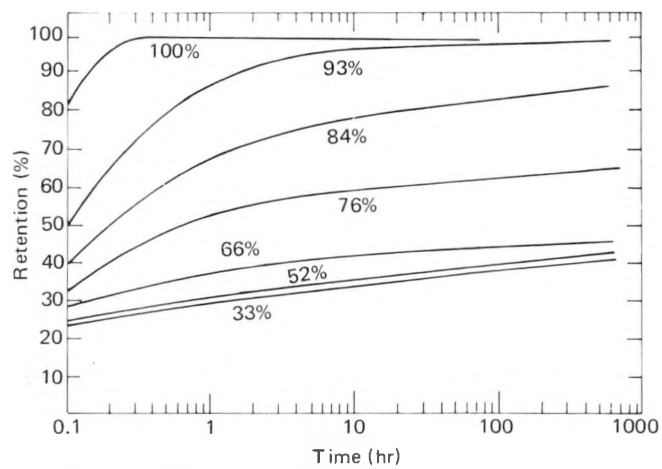

Figure 3. Effects of relative humidity on surface particle retention

Item 4. *Particle Control*

During a program to devise ways of eliminating small airborne particles, the "laminar-flow" clean room was invented. The development of the principle of laminar flow has led to a family of devices (clean room, clean bench, vented hood, etc.) now in wide use in industry, pharmaceutical plants, and over 200 hospitals (for surgical environments). Consultation services are provided on these devices to governmental, industrial, and medical facilities.

In addition, Federal Standard 209, "Clean Room and Work Station Requirements, Controlled Environment," was developed and coordinated in 1964. It and its revisions (209a and 209b) still are the U. S. Government-designated standard universally used by industry in the United States and in many countries abroad.

APPLIED BIOLOGY

The objective is to apply biological developments and inert-particle environmental controls to a variety of programs. Current emphasis is on the use of heat/radiation combinations as effective lethal agents in environmental, medical, municipal, and engineering programs, as well as in sterilization of spacecraft for planetary exploration. The development of effective hardware for experimental biological programs and as prototypes for actual application is included.

Applications to Medical and Public Health Problems

Activities include the use of heat/radiation combinations as sterilants in the treatment of blood; radiotherapy; development of vaccines; medical device sterilization, and the treatment of sewage sludge. (Items 1-3)*

Current Activities

- Sewage sludge treatment using radiation and heat
- Malaria sterilization/vaccine studies
- Heat/radiation effects on hepatitis antigens
- Heat/radiation effects on blood fractions
- Studies of heat as an adjunct to radiotherapy
- Induction of defective interfering particles in viral populations using heat and radiation

*See Highlights below.

Bioengineering

Bioengineering activities are directed toward the application of bioscience concepts and the development of tools and facilities required for further bioscientific studies. Typical instruments designed or developed include biological surface samplers, flash pasteurization systems involving heat and radiation exposures, and experimental devices to eliminate the clumping of bacteria on surfaces. Work may range from engineering design to prototype fabrication, testing, and actual use of hardware; a principal example is laminar air-flow clean-room technology. (Items 4,5)

Current Activities

- Environmental control and monitoring units for specialized experimentation
- Flash heating/irradiating units: design, fabrication, and testing.
- Laminar air-flow clean-room design
- Surface and air sampling devices
- Ultrasonic devices for tissue heating
- Laser light scattering for measuring bacterial swimming rates

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Waste Utilization Program*

This program represents a major effort to determine the utility of the reactor waste product cesium 137 in treating sewage sludge so that the sludge may be used on crop-producing land or in livestock refeeding programs. The objective is to rid sewage sludge of pathogenic organisms using a combined heat and cesium-137 radiation process that operates on a real-time, flow-through basis as an add-on to existing treatment processes. The optimal treatment combination is being sought through inactivation studies of polio virus, adenovirus, coliforms, fecal streptococci, and *Ascaris* ova. Figure 1 shows typical coliform inactivation data. The modification of physical characteristics of sludge (including settling rates, odor, chemical and biological oxygen demands) by heat and radiation is being studied. In addition, the activity includes experimental system design and fabrication, pilot-plant design and determination of cost factors, the study of sludge uses and accruing benefits, and safety analyses.

APPLIED BIOLOGY

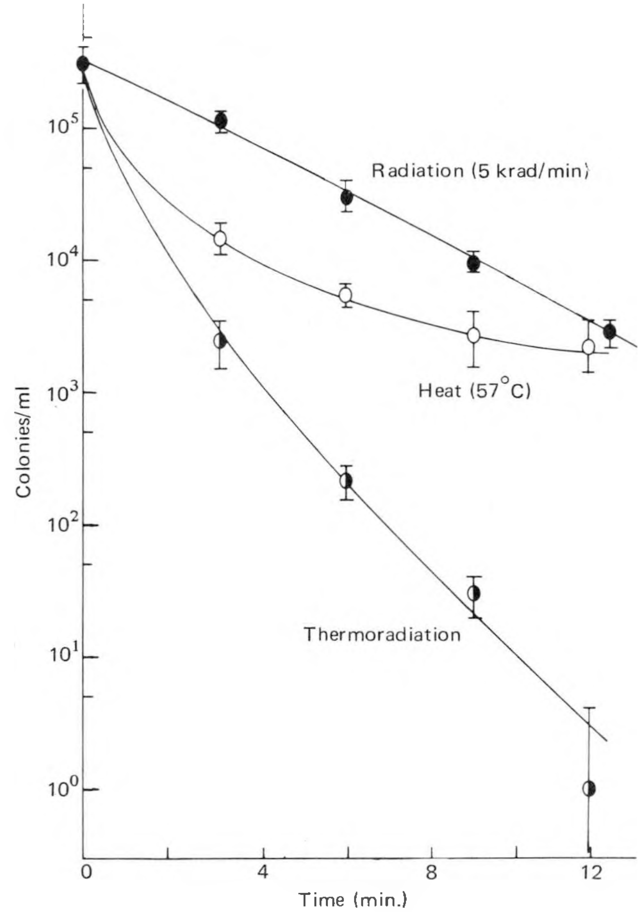

Figure 1. Inactivation curves for heat, radiation, and thermoradiation treatment of coliforms in sludge

Item 2. *Blood Sterilization*

Human blood can be contaminated by viral, bacterial and protozoan agents, most notably by hepatitis in the viral category. Data have suggested that the synergistic component of thermoradiation inactivates nucleated cells at temperatures and dose rates lower than those which appreciably damage many proteins. Thermoradiation thus may be useful in sterilizing whole blood or some blood fractions. Studies have been conducted to determine the heat and radiation limits to which whole blood and blood serum may be subjected without appreciably degrading them. Based on studies with a mouse malarial causative parasite, *Plasmodium berghei*, in an animal system, blood sterilization for malaria parasites appears feasible. In the course of these investigations, it was possible to immunize mice against large inoculations of virulent *P. berghei*.

Item 3. *Radiation Inactivation of Hepatitis B Surface Antigens*

In a joint study with the U. S. Public Health Service, the effects of heat and ionizing radiation on hepatitis B virus are being studied. Figure 2 depicts the degradation of surface antigens by radiation using standard radioimmunoassay techniques. The dose per log reduction in count is about 177 krads.

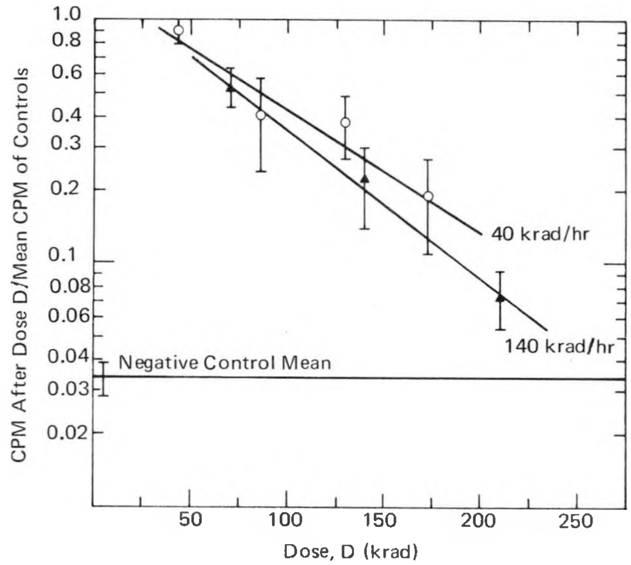

Figure 2. Inactivation of HB_SAg at low dose rates

Item 4. *Monitoring for Viable Particles on Surfaces*

A new method of monitoring for bacteria was developed during a program aimed at finding ways of evaluating surfaces for the presence of contaminating organisms. Other methods were only marginally efficient or in some undesirable manner modified the surfaces being monitored. The new method was made possible by development of the "vacuum probe" (Figure 3). The probe bears a sharp tip. When the tip is placed on a smooth surface and a vacuum is applied through the probe, the air flow attains a velocity that will remove contaminants from the surface. A membrane holder filter is attached to the tip to collect bacteria for later assay. The probe has a removal efficiency of over 90% for most environmentally deposited particles. It has been used to monitor spacecraft surfaces, hospital areas, and camera film. A commercial version is being marketed.

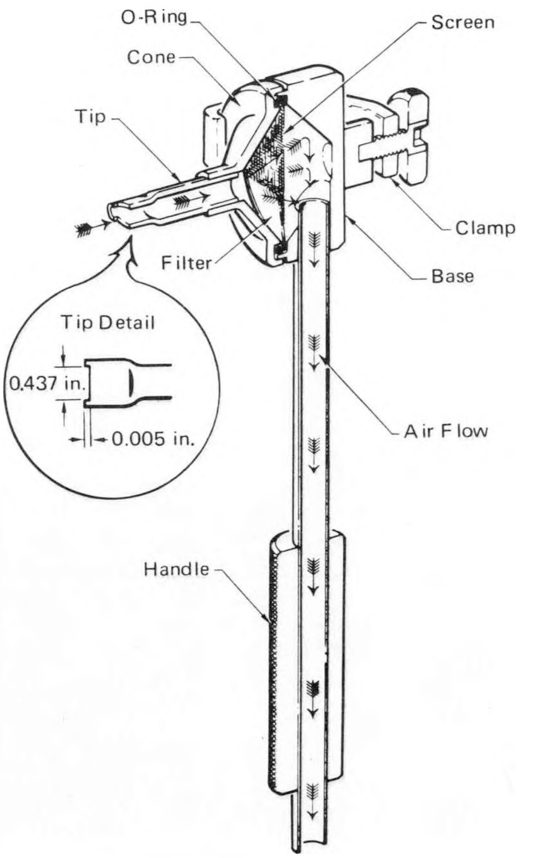

Figure 3. Cross section of vacuum probe showing air flow and a detail view of the Teflon tip

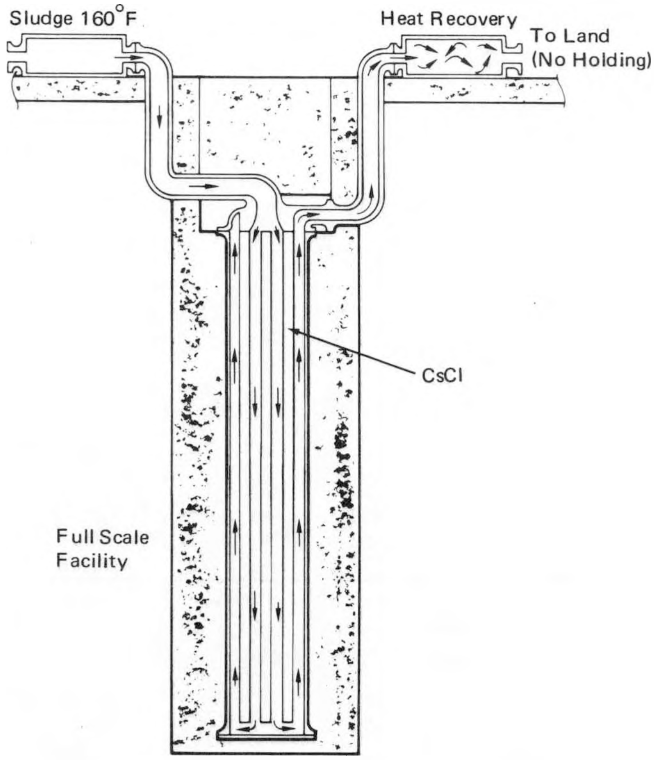

Figure 4. Full-scale cesium irradiation facility

Item 5. *Full-Scale Sludge Treatment Plant Design*

A preliminary design concept for the use of heat and radiation in the treatment of sewage sludge (see Item 1, above) is shown in Figure 4. This design permits real-time flow-through treatment that should, judging by current biological data, effectively rid sewage sludge of pathogens.

ANALYTICAL BIOLOGY

Mathematical models are developed of the interaction of biological systems with their environments, of the physical and chemical characteristics of biosystems and their cellular components, of selected specific subcellular processes, and of appropriate physical systems. Biosystems of concern range from viruses to man, while the environments of interest range from controlled laboratory environments to actual "polluted" environments in Southwestern cities. The objective is to provide a realistic framework in which environmental effects may be quantified for assessment and comparison purposes.

Environmental Models

System analysis is applied to biological complexes to quantitatively describe environments in terms of their probable pollution levels as a function of time and pollution source characteristics. One of the major outputs of these studies is the identification of "critical pathways (or factors)" from pollution source to the biological or physical system being investigated. (Item 1)*

Current Activities

- Potential oceanographic pollution from reactor wastes
- Environmental impact of the liquid-metal fast breeder reactor fuel cycle
- Transport of particles and gases from smokestacks
- Bioburdens on surfaces as a function of environmental control
- Critical-path analysis
- Computerization of models

Biological Response Models

Responses of biological systems to environmental stress are mathematically described. Lethal, mutational, and behavioral responses of bacteria, viruses, and mammalian cells are modeled as a function of total exposure, exposure rate, and other environmental conditions including water availability and pressure. Models are based on acceptable physical and chemical principles (absolute reaction rate theory, for example) so that extrapolations beyond measurable biological ranges may be made. (Items 2,3)

*See Highlights below.

Current Activities

- Lethal effects models of heat and radiation
- Behavioral effects of temperature on swimming bacteria
- Mutational effects models of heat and radiation
- Kinetic descriptions of formaldehyde inactivation of spores
- Effects of water availability on mutation and inactivation rates by dry heat
- Effects of oxygen availability on radiation damage

Physical/Chemical Models

Models are developed of the effects of environmental parameters on physical or chemical entities. In many instances, these effects are to be related to cellular response, while in others the interest is in the physical or chemical entity itself, such as sewage sludge or the antigenicity of hepatitis B virus. Efforts are made to model effects as a function of other environmental variables including pH, water activity, oxygenation, and pressure. (Item 4)

Current Activities

- Sludge settling rates as a function of dose, dose rate, and temperature
- Ultrasonic propagation in tissue and bone
- Radiation effects on sulfhydral groups of hepatitis B antigen
- Hydroxyl radical/DNA interaction related to virus and bacterial survival

ANALYTICAL BIOLOGY

* * *   * * * *HIGHLIGHTS* * * *   * * *

Item 1. *A Model of Surface Bioburdens*

Data strongly suggest that bacteria are deposited and removed from surfaces in clumps (particles). Such a process may be viewed as a particle birth-and-death process in which the bioburden depends upon this process and the distribution of organisms per particle. Under these circumstances, the distribution governing the surface bioburden, $P_j(t)$, takes the form of

$$P_j(t) = \sum_{k=o}^{\infty} \frac{[M(t)/\gamma]^k e^{-M(t)/\gamma}}{k!} Q(j,k)$$

where M(t) is the mean number of organisms on the surface at time t, γ is the expected number of organisms per particle, Q(j,k) is the probability that k particles contain exactly j organisms, $\lambda(t)$ is the particle deposition rate, $\mu(t)$ is the particle removal rate and $M'(t) = \nu\lambda(t) - \mu(t)M(t)$.

Because of the form of this expression, it is possible to precisely define sampling requirements for desired confidence intervals about mean estimates. This bioburden model which is unique in this attribute, was used to define sampling requirements on the surfaces of all Apollo lunar vehicles. Figure 1 depicts the model's ability to predict future burdens based on past examples.

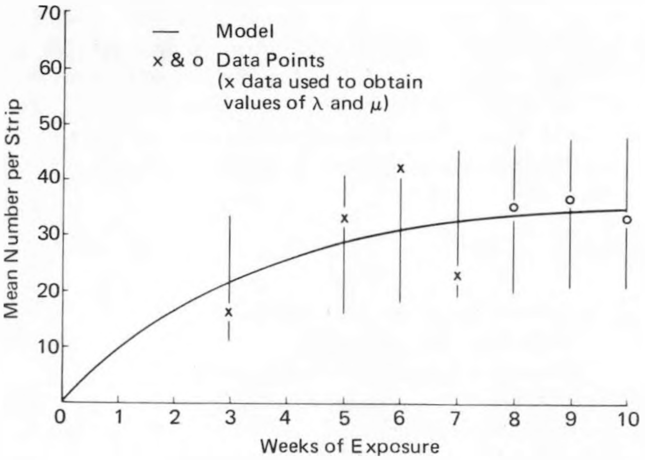

Figure 1. Prediction in "uniform" environment

Item 2. *Kinetics of Dry-Heat Sterilization*

A model of the death of bacterial populations in dry thermal environments has been derived by postulating that any or all of the three reaction types

$A \rightleftarrows B \rightarrow X$	(First Order)
$A \rightarrow Y$	(First Order)
$2C \rightarrow Z$	(Second Order)

may take place in individual cells and lead to sterility. Each arrow has an associated rate constant that was assumed to take the usual form (Eyring)

$$k_T = \frac{kT}{h} \exp(-\Delta F^{\neq}/RT)$$

with

$$\Delta F^{\neq} = \Delta H^{\neq} - T\Delta S^{\neq} + p\Delta V^{\neq} .$$

In this model, pressure effects are incorporated through the pressure parameter, p. Relative-humidity effects are seen in the activation entropy, $\Delta S^{\neq}$. The activation volume, $\Delta V^{\neq}$, is typically quite large, suggesting that "A" is a large molecule and lending more insight into inactivation mechanisms.

Item 3. *Quantitation of Combined Heat and Radiation Effects*

Models describing the effects of combined dry heat and radiation on bacterial spores have been developed. The survival of dry bacterial spores at temperature T and dose rate r_d, when logarithmic, can be described by

$$n(t) = n(o)\, e^{-(k_T + k_R + k_{TR})\, t}$$

where k_T is described in Item 2, above; k_R is the classical target theory term

$$k_R = C_1 r_d ,$$

ANALYTICAL BIOLOGY

and

$$k_{TR} = C_2(r_d)^{\alpha/T} e^{-\beta/RT},$$

where C_1, C_2, α and β are constants and n(t) is the population at time t. The agreement of this model with data is shown in Figure 2. The k_{TR} term is clearly not linearly dependent upon dose rate (r_d) so that "synergistic effects" are not strictly dose-dependent, suggesting an interpretation of dose-rate dependent phenomena, which are often viewed only as interesting anomalies. A physico/chemical interpretation consistent with the form of k_{TR} is a reaction of some unknown substance A with free radicals R° to form an inactive complex X:

$$A + nR^{\circ} \longrightarrow X$$

in which n is inversely dependent upon temperature.

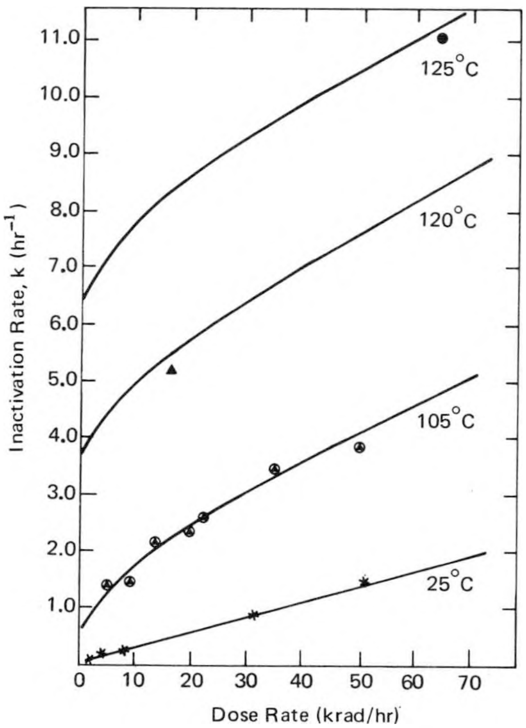

Figure 2. Comparison of model prediction (solid lines) with inactivation rates obtained from survivor data for *B. subtilis* var. *niger* spores in a dry state

Item 4. *Radiosensitivity vs DNA Content*

In a study of the radiosensitivity of a variety of cellular systems, it was observed that an approximate empirical relationship of the form

$$k = C\sqrt{\omega_{NA}}\, r_d$$

exists between the rate of cellular inactivation, k, the molecular weight of the dominant nucleic acid in the cells, ω_{NA}, and dose rate r_d. This appears to be a reasonable first-order approximation over ranges of ω_{NA} from 10^6 to 10^{13} Daltons, as shown in Figure 3.

Traditionally, the factor

$$V = C\sqrt{\omega_{NA}}$$

has been interpreted as "apparent target volume," and the target molecule(s) has been thought to be the dominant nucleic acid. The appearance of the square root of the molecular weight suggests possible electron interactions, and this is being investigated.

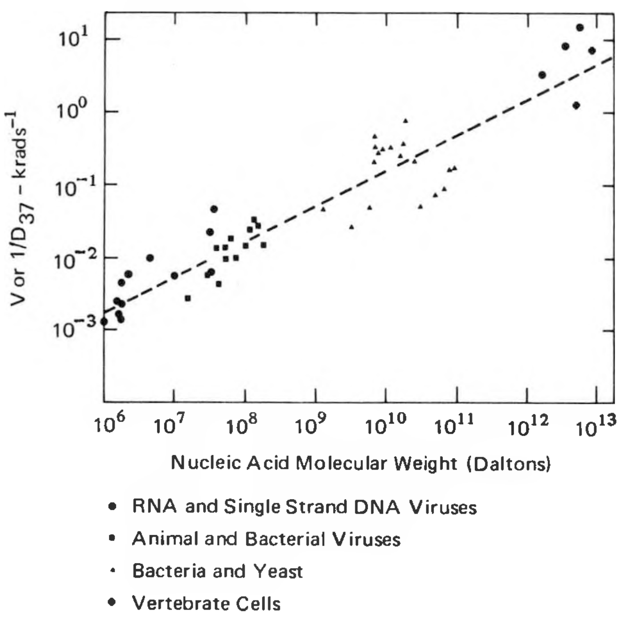

Figure 3.

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COMPUTATION SYSTEMS

Sandia Laboratories Technical Capabilities

Computation Systems

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115
and Livermore, California 94550 for the United States Energy Research
and Development Administration under Contract AT(29–1)-789

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SANDIA LABORATORIES TECHNICAL CAPABILITIES

COMPUTATION SYSTEMS

ABSTRACT

This report characterizes the computation systems capabilities at Sandia Laboratories. Selected applications of these capabilities are presented to illustrate the extent to which they can be applied in research and development programs.

COMPUTATION SYSTEMS*

The computing centers and their associated technical support organizations at Sandia Albuquerque and Sandia Livermore have the responsibility of planning, adapting, and operating large-scale digital computer facilities in general support of the scientific and engineering community of the Laboratories. Such modern, large-scale computers have become essential to the solution of such problems as the modeling of complex systems, component design and development, and the detailed simulation of physical phenomena. Also, a growing number of smaller digital computers are integrated into specialized facilities dedicated to the support of specific areas of research and development. These include such activities as experiment control, data acquisition, and test monitoring. There are also a few main-line computers devoted to management information and business data processing, but as these are nontechnical functions, they are not covered in detail here.

The central computing facilities are presently based on Control Data Corporation scientific computer systems. The Albuquerque facility consists of three CDC-6600's sharing a common mass-storage subsystem as well as extended core storage. The Livermore facility contains a single CDC-6600, also with an extended core capability. Remote job entry and interactive computation are increasingly emphasized. Time-sharing is accommodated at both centers but is represented more extensively at Albuquerque where a PDP-10 computer system is devoted exclusively to that function.

Computation Systems Professional Staff
and Investment in Equipment

	Professional Staff	Investment in Equipment (in $1000)
System Planning, Development and Support		
Central Computing	120	22,300
Time-Sharing System		1,700
Interactive Graphics Facilities		1,300
Computer-Based Special-Purpose Systems and Support	45	6,600

*Compiled November 1974

SYSTEM PLANNING, DEVELOPMENT, AND SUPPORT

These services are provided (1) to perform the long-range planning required for future computing systems, (2) to assemble and adapt computer facilities for the needs of the Laboratories, and (3) to determine and promulgate ways to use existing facilities most effectively. These activities encompass the evaluation of computer technology and its projection in the context of the evolving needs of the Laboratories, the adaptation and development of software for operating systems, the construction of software for specific applications, computer hardware specification and selection, mathematical services, communications, and consultation.

Computer System Support

Activities are directed toward the development and adaptation of computer facilities to meet evolving computing needs in the scientific and engineering areas. Recent emphasis has been in interactive computation, multicomputer networking, and remote entry. Specific developments have included the design and implementation of a software system permitting concurrent, multimachine access to a common, on-line mass-storage facility. Development of the existing Sandia Interactive Graphics System (SIGS) is another example. (Items 1-2*)

Current Activities

- Multicomputer network design and development
- Computer configuration structuring and selection
- System development for special-application computers
- Computer interface hardware design
- Front-end processor for interactive communications
- File management software development
- Operating systems and compiler support
- Simulation of computer systems

Mathematical Computing Support Services

Activities include mathematical modeling, numerical analysis and code construction relative to specific research and development problems or problem classes, as well as the development of generalized mathematical subroutines for broad use in numerous application codes. These subroutines collectively constitute the Sandia Mathematical Program Library. (Items 3-5)

Current Activities

- Applied mathematics and numerical analysis support services
- Mathematical program subroutine library development and updating
- Numerical analysis research
- Aerodynamic/ablation codes
- Fluid mechanics and heat-transfer analysis
- Generalized mesh generation for structural analysis computations
- Statistical signal-processing studies
- Field-test analysis support
- Computer benchmarking studies (test codes for evaluating new equipment)
- Neutron activation code development
- Remote-vehicle tracking analysis
- Crack-propagation studies

Consultation Support

These efforts include the collection and distribution of information bearing on effective use of computing facilities. In addition, a continuing program of technical training and consultation is conducted for the user community.

Current Activities

- Computing course development
- User consultation services
- Programming manual preparation
- Video taping of computer courses and symposia
- Computing newsletters
- Computer-operator training
- Corporate contact for inter-laboratory code distribution
- Maintenance of general-use program abstracts and computing library
- Code-improvement assistance

*See Highlights, below.

SYSTEM PLANNING, DEVELOPMENT, AND SUPPORT

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Triple CDC-6600 Computer Complex*

Operating-system software has been developed which allows the three CDC-6600's to share a common mass-storage facility. This sharing permits more effective use of existing, limited computer resources and provides better service. Its benefits include eliminating redundant copies of programs and data files; significantly reducing the use of magnetic tapes; facilitating program interchange among members of the technical staff, and providing fast access to files, which results in shorter job turnaround.

A detailed schematic of the triple CDC-6600 scientific computing complex at the Albuquerque laboratory is depicted in Figure 1. Note particularly the direct accessibility of the Model 844 disk subsystem to the three Model 6613 central processors.

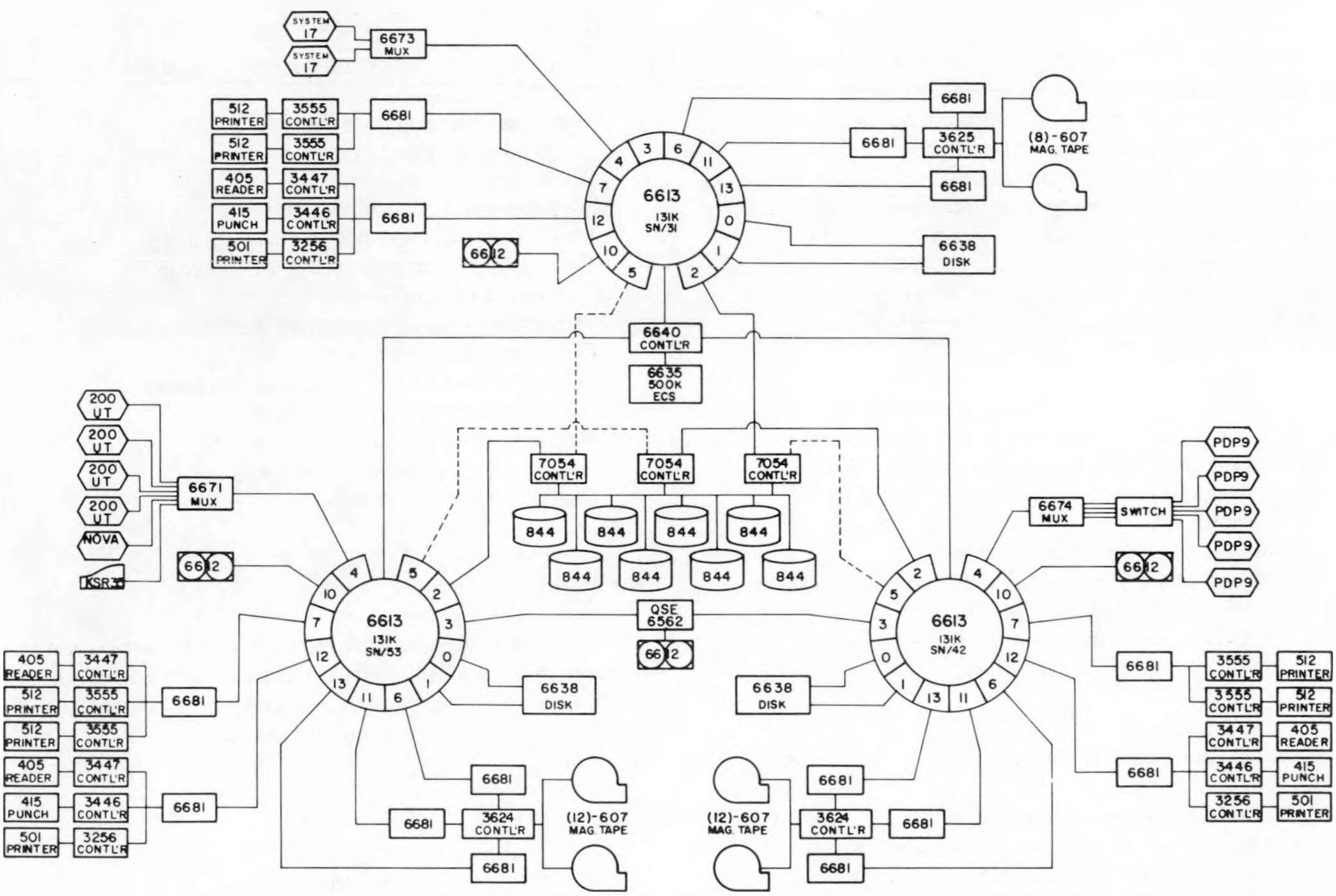

Figure 1. The triple CDC-6600 scientific computing center at Sandia's Albuquerque laboratory

SYSTEM PLANNING, DEVELOPMENT, AND SUPPORT

Item 2. *Further Expansion of the Scientific Computer Complexes*

An integrated computer network is being developed in Albuquerque that will help satisfy our growing demands for computer power. The network will be composed of five Control Data Corporation computers, as shown in Figure 2. The computers include the three existing CDC-6600's (central processor Model 6613), a CYBER-76, and a CYBER-172. The latter will function as the primary entry point for remote batch jobs submitted to the system. A major goal of the network is to provide enhanced remote access to the computer utility. A variety of terminals will be distributed throughout the Laboratories to allow convenient network access. These terminals will include:

6 Sandia Interactive Graphics System terminals;
3 high-speed (CDC System-17) remote-batch terminals;
5 medium-speed (CDC 200 UT) remote-batch terminals; and
up to 128 teletype-compatible time-sharing terminals.

The Livermore computing center will also undergo expansion with the installation of a second CDC-6600 before the end of FY 75. This computer will provide additional capacity to support remote-access terminals and to handle the increasing scientific computing workload. An expanded interactive graphics capability will be made available to scientific users. Various alphanumeric and graphics terminals will be installed in users' work areas. Management information systems (MIS) applications will also be transferred to the 6600, and remote-access capabilities will be offered to both scientific and MIS applications.

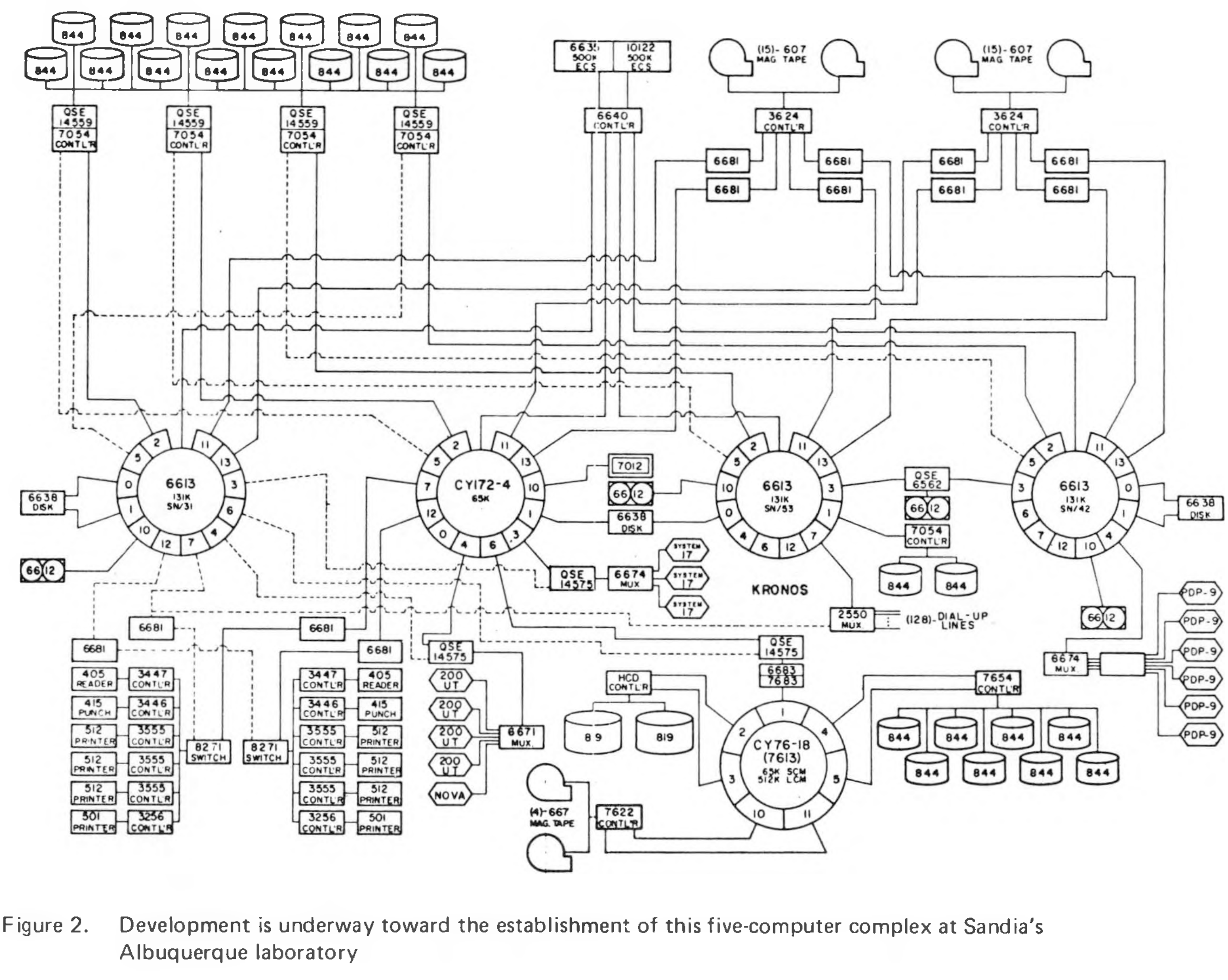

Figure 2. Development is underway toward the establishment of this five-computer complex at Sandia's Albuquerque laboratory

Item 3. *Research in Numerical Analysis*

A major emphasis in numerical-analysis research has been in the area of ordinary differential equations. As part of this effort, a state-of-the-art Runge-Kutta-Fehlberg code was developed for the solution of the initial-value problem, and another was developed for estimating the global error in the solution. The latter is the first code known to do this and was utilized in a scheme to solve boundary-value problems via an orthonormalization technique. This latter code has been used in the solution of a problem involving the Orr-Sommerfeld equation that arose in a study of the stability of boundary-layer flows. A suite of codes has also been developed to solve boundary-value problems via "shooting" (trial and error) techniques.

Item 4. *Applied Mathematics and Numerical Analysis Support*

Consultation and analysis are provided in numerous areas of applied mathematics and numerical analysis as they relate to a wide spectrum of physics and engineering problems. In support of other efforts within the Laboratories, the mathematical computing staff has recently (1) developed a code (QMESH) to produce two-dimensional meshes of quadrilateral elements for use with finite-element codes, which features ease-of-use, automatic smoothing and restructuring, and bandwidth minimization; (2) performed error-analysis studies for a proposed system that would track objects by measuring velocity using the doppler frequency of a signal from the object; (3) developed codes to process digitized motion-picture data of nose-cone ablation tests, calculate the ablation rate at various positions on the nose cone, and evaluate a mathematical model of the ablation, which is inherently very difficult to handle numerically; (4) developed a means of computing convective motion in a crucible of liquid metal subjected to a heat pulse, for use in analyzing a scheme to calculate thermal diffusivities of refractory liquids encountered in process metallurgy and reactor safety studies; and (5) assisted in the evaluation of the OMEGA long-range navigation system for use in the remote tracking of land vehicles.

The capabilities of QMESH are illustrated in Figures 3 and 4.

SYSTEM PLANNING, DEVELOPMENT, AND SUPPORT

Item 5. *Computer Simulation of the Motion of Maneuvering Vehicles*

Typical of a number of large codes written for research and development efforts is the program SANDMAN. This program is a six-degree-of-freedom trajectory program that makes possible the simulation of a variable number of masses moving freely on or within a rigid vehicle. The code permits the modeling of virtually any control system, along with its interaction with the dynamics of the vehicle. This includes control systems involving aerodynamically active components such as flaps or fins. For maneuvering-vehicle design studies, the use of this code can result in significant development cost savings, since the analysis of a new vehicle configuration or control-system design only requires the reworking of a special control routine within the code.

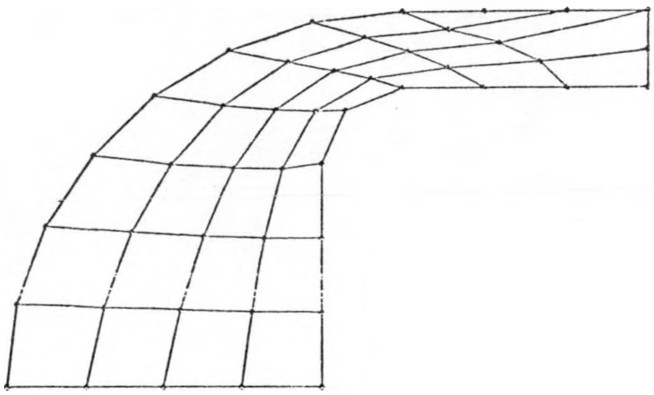

Figure 3. Mesh before modification by QMESH

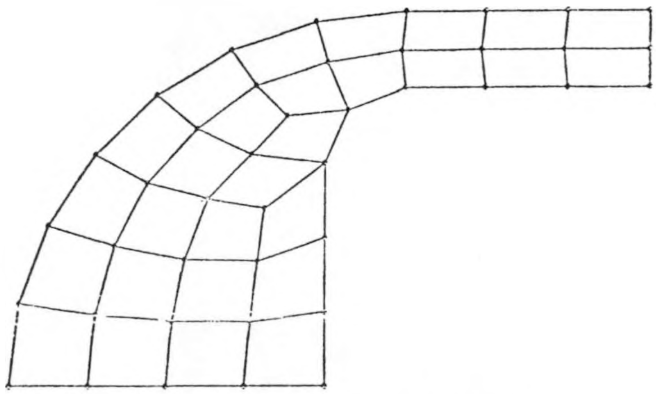

Figure 4. Mesh after modification by QMESH

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CENTRAL COMPUTING

The central computing facilities at both the Albuquerque and Livermore locations of Sandia Laboratories are designed to accommodate the concurrent processing of a number of individual programs. Economies of scale are thus achieved by the effective sharing of high-performance central processors and centralized mass-storage file subsystems. Both batch and interactive modes of computation are supported. The bulk of the general-purpose computing load is handled by these main-line systems. This includes applications in the system studies area, as well as fundamental research, weapon design, reactor studies and nuclear safety, component development, effects modeling, and test-data reduction. The main-line systems at the centers are approved for the simultaneous processing of both unclassified and classified information, through Secret.

Equipment

The Sandia Laboratories scientific computer systems are built around CDC-6600 computers, which are designed for high-speed extended precision calculations. The Albuquerque center contains three CDC-6600's sharing a common mass-storage subsystem that is accessible to all three computers concurrently. In addition, an extended core storage device (bulk core) is partitioned for use among the three computers. Interactive graphics applications are serviced by a network of five Digital Equipment Corporation PDP-9 computers remotely linked to one of the CDC-6600's. Another of the CDC-6600's supports the remote batch-entry load via several CDC-200 user terminals.

The Livermore center contains a CDC-6600 with extended core storage. A CDC-250 station, which is connected on-line to this machine, provides a high-speed interactive graphics and a microfilm plotting capability. In addition, a less expensive, low-speed interactive graphics capability is provided by two Tektronix 4002-A direct view storage tube (DVST) terminals.

Servicing the total scientific computing complex is an off-line computer output microfilm subsystem in the Albuquerque center consisting of a Datagraphix Model 4460 and a Model 4020. These devices can portray graphical information on 16 mm/35 mm film and microfiche. Computer-generated motion pictures, in color or black-and-white, can be produced to represent time-dependent physical processes.

Current Major Equipment (Albuquerque)

Computer Model or Feature	Number or Capacity
CDC-6600	3
Main memory size (each computer)	131,000 words*
Peripheral processors (each computer)	10
Extended core storage (shared)	500,000 words*
Available mass storage (shared)	83 million words*
Graphics computer stations (total)	5
Batch terminals (total)	5

*Word size is 60 bits.

Current Major Equipment (Livermore)

Computer Model or Feature	Number or Capacity
CDC-6600	1
Main memory size	131,000 words*
Peripheral processors	10
Extended core storage	500,000 words*
Available mass storage	47 million words*
Graphics computer station	1
Interactive terminals	4

*Word size is 60 bits.

Programming Languages and Special Processors

The central scientific computing facilities were acquired for the solution of problems in the research, design, development, and testing areas. Therefore, the programming languages, as well as the general-application software packages provided, are oriented toward this objective. FORTRAN is the primary language, although symbol manipulation, graphical plotting, simulation languages, and specialized higher-level software processors are also furnished. In contrast to the Laboratories' business data processing systems (a dual processor UNIVAC-1108 and a CDC-3600 computer), the emphasis has not been toward special languages for data-base management applications or other nonscientific activities.

Currently Supported Languages and Nationally Known Software Processors

- Assemblers and compilers
  - COMPASS
  - FORTRAN extended
  - FORTRAN (FUN)
  - SNOBOL
  - PASCAL
  - ALGOL-60
- Graphical plotting
  - SCORS
  - IGS/4460
  - SLPLOT
- Mathematical libraries
  - Sandia mathematical program
  - IMSL
- Continuous system simulation languages
  - CSSL
  - MIMIC
- Electronic circuit analysis
  - ITRAC
  - ECAP
  - SCEPTRE
  - NET
  - SPICE
- Heat transfer
  - CINDA
- Structural analysis
  - NASTRAN
- Spectral analysis
  - MACRAN

Mathematical Program Library

The Sandia Mathematical Program Library consists of a number of FORTRAN-callable, high-quality, general-purpose mathematical subroutines. These, in turn, are incorporated in numerous individual computer programs that require the particular mathematical computations provided. Extensive validation testing, a standardized software approach, user-oriented documentation, and backup consultative support typify this capability. Numerical analysis research is carried out in conjunction with this effort. As numerical techniques evolve, state-of-the-art improvements and/or replacements are made in the collection. This Library, although first implemented on the CDC-6600's, has been developed with the objective of achieving a high degree of code portability. A subcollection of the Library is in use on the PDP-10 time-sharing computer.

Current Routine Subcategories

- Linear algebraic equations
- Numerical quadrature
- Ordinary differential equations
- Data fitting and smoothing
- Eigenvalues and Eigenvectors of matrices
- Fourier transforms
- Zeros of functions and optimization
- Zeros of polynomials
- Special functions

Applications

Applications encompass a variety of technical areas where computer simulations have proved indispensable. The areas include system studies, fundamental research, weapon design, reactor studies and nuclear safety, component development, effects modeling, and test-data reduction. Specific codes, either developed or acquired, are being employed in studying wave-propagation phenomena and material response, weapon effects, heat transfer, structural analyses, atomic and molecular physics, plasma studies, aerodynamic simulations, and electronic circuit analyses. Characteristically, many of these problems for which the CDC-6600's were acquired tend to require extensive computation by the central processors. Also, the solution process often necessitates the use of a considerable amount of main memory. In addition, certain of these applications require for their practical solution the availability of extended core storage and/or mass storage. The existing computing facilities are tailored to handle this type of application load.

TIME-SHARING SYSTEM

The Digital Equipment Corporation Model PDP-10 computer at the Albuquerque computing center supports the time-sharing requirements of both Livermore and Albuquerque. Time sharing is the nearly simultaneous servicing of a multitude of users interacting with the computer via teletype-like terminals. This mode of computation plays an important role in program design, information retrieval and, in general, problem-solving activities requiring rapid turnaround and direct interactive control. The PDP-10 is used exclusively to service this time-sharing load; i.e., batch activities are precluded. Access to the system is via hardwired and dial-up lines. Because the latter tie into the commercial telephone network, the PDP-10 is limited to the processing of unclassified jobs, and access is controlled through special user passwords and terminal identifiers. Over 50 terminal users can be concurrently serviced by the system.

Equipment

The PDP-10 time-sharing facility is configured to provide optimal support for its highly interactive load. Interactive use of the system involves such things as the issuing of commands, the editing of information, and the initiating of computational activity. In this type of problem solving the user expects prompt response from the computer. To provide adequate concurrent service, the hardware configuration as well as the operating system ;oftware must exhibit certain characteristics. Of particular mportance is the structuring and management of computer nemory resources. The storage hierarchy in the PDP-10 ystem consists of a main memory, two levels of "swapping" torage (drum and fixed-disk) and random-access magnetic-isk storage for data and program files. The other istinguishing factor is the communication element. Two iniprocessors interface the PDP-10 with the approxi-ately 40 hardwired and 40 dial-up lines serviced by iis time-sharing system. Both 10 and 30 character-per-cond asynchronous transmissions are accommodated. ll terminals are compatible with teletype.

'urrent Equipment

Computer Model or Feature	Number or Capacity
PDP-10	1
Main memory	131,000 words*
Swapping storage	1.1 million words*
Available mass storage	20 million words*
Remote terminal lines	80

*Word size is 36 bits.

Programming Languages and Special Processors

The languages, special processors, and utilities supported on the PDP-10 reflect the breadth of applications amenable to interactive computation. Only a small subset of the software tools available is noted here. Typically, time-sharing systems are rich in supporting software. This is necessary because of the high degree of man-machine interaction involved. Thus, emphasis is placed on testing aids, editors, file manipulation and retrieval capabilities, etc.

Currently Supported Languages and Nationally Known Software Processors

- Assemblers and compilers
  - MACRO
  - BASIC
  - FORTRAN IV
  - COBOL
  - APL
  - AID
  - FOCAL
  - Miscellaneous cross assemblers, compilers, and simulators for minicomputers.
- Testing tools and editors
  - DDT
  - TECO
  - LINED
  - COED
  - TIDY
- Mathematical libraries
  - Scientific subroutine package (SSP)
  - Sandia mathematical program library (Subset)
  - Dartmouth BASIC library

Electronic circuit analysis
- ITRAC
- ECAP

Symbol (equation) manipulation
- REDUCE

Continuous system simulation language
- ANALOG

Document preparation
- RUNOFF
- TYPOUT

Optical analysis
- OPTAN

Applications

The time-sharing system services a large number of users, including those only occasionally or minimally involved in computation per se. The spectrum of applications is quite broad, ranging from theoretical modeling to engineering applications to test operation scheduling and quality control. Excluded are large-scale computation-bound codes. This restriction ensures adequate system response for jobs that are appropriate for a time-sharing environment. In any case, the primary use of the PDP-10 facility is for scientific and engineering applications requiring rapid turnaround and direct interactive control. Some of these applications are of a one-time nature. The PDP-10 in such instances represents an extension of the engineer's standard calculating tools. Other applications require the continued use of codes and the maintenance of data bases over extended periods of time.

A brief summary of application areas is as follows.

- Engineering and scientific calculations
- Cross compiling of code for various dedicated minicomputers
- Simulation of continuous systems
- Closed-form equation solution; i.e., symbol manipulation
- Technical document preparation and updating
- File maintenance and inquiry applications; i.e., test operation center scheduling, measurement standards files, etc.

INTERACTIVE GRAPHICS FACILITIES

Interactive graphics is a computational capability provided for applications requiring on-line decision-making based on a dynamic, visual depiction of the processes under consideration. Typical applications include network design, circuit layout, trajectory analysis, system simulations, and data fitting. The Laboratories' primary emphasis in the interactive graphics area is directed toward high-performance systems that provide a variety of graphical input and display devices, and afford maximum flexibility in interactive control. Satellite computer/controllers manage these interactive, refresh-scope-based facilities and provide the necessary interface to the larger centralized systems (CDC-6600's). Primary computation is done in the latter systems, and the results (display files, data arrays) are transmitted to the graphics satellites. Complementing the high-performance systems are a limited number of storage-tube graphics terminals directly linked to the Albuquerque PDP-10 computer and the Livermore CDC-6600.

Graphics Satellite Stations

The high-performance station at Livermore is a CDC-250, which has a direct channel link to the host CDC-6600. The CDC-250 provides a refresh-type scope display and interactive control that functions under a standard CDC operating system. There are also two Tektronix 4002-A direct-view storage tube (DVST) terminals connected to the CDC-6600.

The high-performance graphics complex in Albuquerque is collectively known as the SIGS (Sandia Interactive Graphics System). SIGS consists of six satellite computers (five PDP-9's and one PDP-15), each with a Vector General interactive display. The satellite computers, in turn, are connected to a single CDC-6600 computer via a high-speed synchronous communication link. Each satellite is capable of stand-alone operation with its full complement of local peripherals (disk storage, printer, card reader, tapes, etc.). Most computations, however, are accomplished in the host CDC-6600 system. A typical application would require programming at both the CDC-6600 and satellite ends. This Sandia-developed interactive graphics system is unique, both in the hardware and software sense. Therefore, it is not really compatible with comparable subsystems developed by Control Data. However, a modified version of CDC's IGS graphics software is employed in the CDC-6600 computer, and a standard communication protocol is used. (Item 1)*

*See Highlights, below.

Standard Equipment on Each of the Six Satellite Graphics Computers (Albuquerque)

Component or Feature	Number or Capacity
Main memory size	24,000 words*
Disk storage	524,000 words*
DEC tape transports	2
Electrostatic printer/plotter	1
Card reader	1
Teletype console	1
Direct view storage tube	1
Vector General display console	1
Graphics input devices:	
Keyboard	1
Light pen	1
Data tablet	1
Control dials	10
Features:	
21-inch refresh scope	
Hardware rotation	
Three-dimensional Vector representation	
Depth cueing	
Hardware scissoring	
Display subroutining	

*Word size is 18 bits.

Applications

Applications in which the existing interactive graphics facilities are used vary considerably and represent a growing spectrum of activities. The common thread, however, is the need to incorporate the human decision-making element into the computation process in an iterative manner. The best applications are those in which graphical portrayal of the problem plays an essential role in its solution.

Current Applications

Printed circuit board layout
Circuit design and analysis
Integrated circuit mask generation
Aircraft/store-separation analysis
Source/sink aerodynamic model calculations
Stability analysis of linear systems
Post-processing graphical analysis of hydrocode calculations
Generalized curve fitting
Data reduction
Mesh generation for large Lagrangian codes
Digital logic simulation
Material-strength modeling

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Interactive Graphics Codes*

Of the various interactive graphics codes developed, two deserve special mention for their extent of application and their relative impact. DAVINCI is an interactive program that allows the layout and updating of printed circuit boards. Basic DAVINCI options selected by a lightpen allow the user to display various combinations of circuit layers. The pictures can be enlarged by a software window option to permit examination of areas in closer detail. Clearance for electrical standoff is an important design parameter. The system provides visual and analytical checking methods. Manipulation capabilities allow parts to be added, deleted, revised, or duplicated. The final results are outputted in a manner suitable for generating artwork masters on automatic drafting machines, or alternatively for driving numerical-control machines.

The second code, GAIN, provides an interactive capability for defining network topologies in schematic form. The circuit descriptions, in turn, are transferred to an interactive version of SCEPTRE which computes and displays the response characteristics of the circuits so defined. This combination provides the designer with an iterative, human-oriented computational capability that expedites the design process.

Both GAIN/SCEPTRE and DAVINCI were developed for use on the SIGS graphics system. Figure 1 demonstrates the use of the latter code.

Figure 1. The DAVINCI code being used on the Sandia Interactive Graphics System

COMPUTER-BASED SPECIAL-PURPOSE SYSTEMS AND SUPPORT

Computers are being used increasingly to control laboratory equipment, to assist in on-line experimentation, and to acquire data. Following are examples of some of our major computer-based special-purpose systems. In each case a computer is integrated into a larger system and provides the critical control and processing required. Such computers, although usually general-purpose in nature, are thus essentially dedicated to the specific applications for which the system as a whole is designed.

Instrumentation and Data Systems

Four major computer systems are included in this category. Most final reduction of data from the various test sites is done on the CDC-6400 computer in Albuquerque. Telemetry, optical, radar, and various instrumentation data are processed by that facility. Playback is by an off-line CDC-3100 computer. Other facilities include an automatic data-processing system based on an XDS Sigma-5 computer, which is located in the environmental test area in Albuquerque. This system is used for on-line control of vibration testing and for post-test digitizing and analysis of data. Following preliminary analysis and validity testing, the results are often transmitted to the aforementioned CDC-6400 for final processing.

The same relationship with respect to the CDC-6400 holds for the DITAC system at the Tonopah Test Range. DITAC is an advanced real-time digital acquisition and plotting system engineered around a pair of Honeywell DDP-124 computers. In addition to its data-gathering function, DITAC controls the automatic positioning of cinetheodolites, tracking telescopes, and radar instrumentation. DITAC also handles the automatic focusing of optical instrumentation, and provides real-time target trajectory data to digital plotting boards and visual displays.

A data playback and digitizing system, built around an XDS-930 computer, also exists at Livermore. (Item 1*)

Current Activities

- Development of user-oriented data-reduction system
- Development of time-sharing technique for managing telemetry data base

Flight-Simulation Facilities

Analog and hybrid computer equipment is used to perform real-time flight simulations. In some instances, actual guidance-and-control hardware is incorporated into the data loop for more realistic simulation. These facilities play an important role in reentry-vehicle and rocket studies and other aerodynamic research and development work. The four facilities dedicated to flight-simulation work include two AD/FIVE's interfaced to a PDP-11/45; an EAI-7800 interfaced to an EAI-PACER; an EAI-580 and TR-48 interfaced to a NOVA-800; and an EAI-680. Each of the first two facilities includes a Carco three-axis angular-motion simulator interfaced to the hybrid computer equipment. Hardware may be mounted on the Carco device and subjected to the angular velocities and accelerations actually experienced in full-scale flight. (Item 2)

Current Activities

- Guidance and control-system development
- Six-degree-of-freedom flight simulations
  - Modified Euler approach
  - Method of quaternions
- Tricyclic angular motion studies
- Point-mass trajectory calculations
  - Rocket staging
  - Wind effects
- Aerodynamic heating investigations

Microelectronics Laboratory System

A dedicated computer system is used to control laboratory experiments involving semiconductor devices, and to perform high-speed data-acquisition and reduction on a real-time basis. The central computer is presently an EMR-6130 with 32,000 words (16 bits each) of core memory, 3 million words of disk storage, and various peripheral devices. Linked remotely to this computer are a number of Hewlett Packard minicomputers which, in turn, control semiconductor device testers. Data from the testers are processed, and summary information is plotted on graphics display stations in remote laboratories. The automated station provides the design engineer and the laboratory experimenter with processed experimental information on a real-time basis. (Item 3)

*See Highlights, below.

Current Activities

- Testing of device characteristics
  - Current versus applied voltage
  - Capacitance-voltage characteristics
  - Time-dependent effects
  - Microwave transistor S-parameters
- Measuring wafer characteristics
  - Sheet resistivity
  - Impurity concentrations
  - Lifetime values
- Evaluation of fabrication processes

Numerical Control Facility

A PDP-15 computer generates machine-tool programming instructions used to control machinery in the fabrication shops. Direct data transfer from computer to machine reduces lead time and practically eliminates wait time for program changes and program optimization. A link from the PDP-15 to the UNIVAC-1108 at the central computing facility permits the processing of computing jobs that exceed the capacity of the PDP-15.

Current Activities

- Real-time system programming
- Numerical-control part programming
- Tool application programming
- Computer interface design

COMPUTER-BASED SPECIAL-PURPOSE SYSTEMS AND SUPPORT

Laser Laboratory System

An on-line computer system is being used to acquire data for laser diagnostics on the Four-Beam Laser Facility. The computer is a Modular Computer Systems MODCOMP II-25 with a 32-thousand (16-bit) word capacity and a 1.2-million-word moving-head disk. Data on laser energy are acquired by waveform digitizers and digital nanovoltmeters. Waveform digitizer data are stored in local memories for later transmission to the computer and subsequent processing. A digital multiplexer continuously transmits nanovoltmeter data to the computer for processing on a real-time basis. The processed signals are displayed graphically. A data base is maintained on the disk to allow the computer to compare current laser performance parameters with optimum ones. This allows deteriorating components to be immediately identified for replacement.

Current Activities

- Monitoring of spontaneous emission for laser leads
- Monitoring of power photodiodes
- Monitoring of calorimeter outputs during calibration, and calculation of beam balances and energy per rod.

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *User-Oriented Data-Reduction Facility*

A major new data-playback/data-reduction system has been funded and is under development. The facility will consist of a state-of-the-art automated telemetry "front-end" coupled to the CDC-6400 mentioned earlier. With the addition of a major on-line graphics capability, the system will permit users to "interact" with their data and control the reduction process via CRT consoles. Turnaround time for field-test data reduction is expected to be substantially improved. Figure 1 is a schematic of the playback/data-reduction facility.

Item 2. *Rocket Stability Analysis*

The AD/FIVE-PDP 11/45 hybrid computer shown in Figure 2 was used in the flight-stability analysis of the Nike-Malemute sounding-rocket system. Causes of excessive angular motion observed in the flight of the second-stage Malemute were traced to certain high-order aerodynamic forces and moments acting normal to the plane of incidence. The analysis indicated the type of configurational changes required to obtain satisfactory flight characteristics.

COMPUTER-BASED SPECIAL-PURPOSE SYSTEMS AND SUPPORT

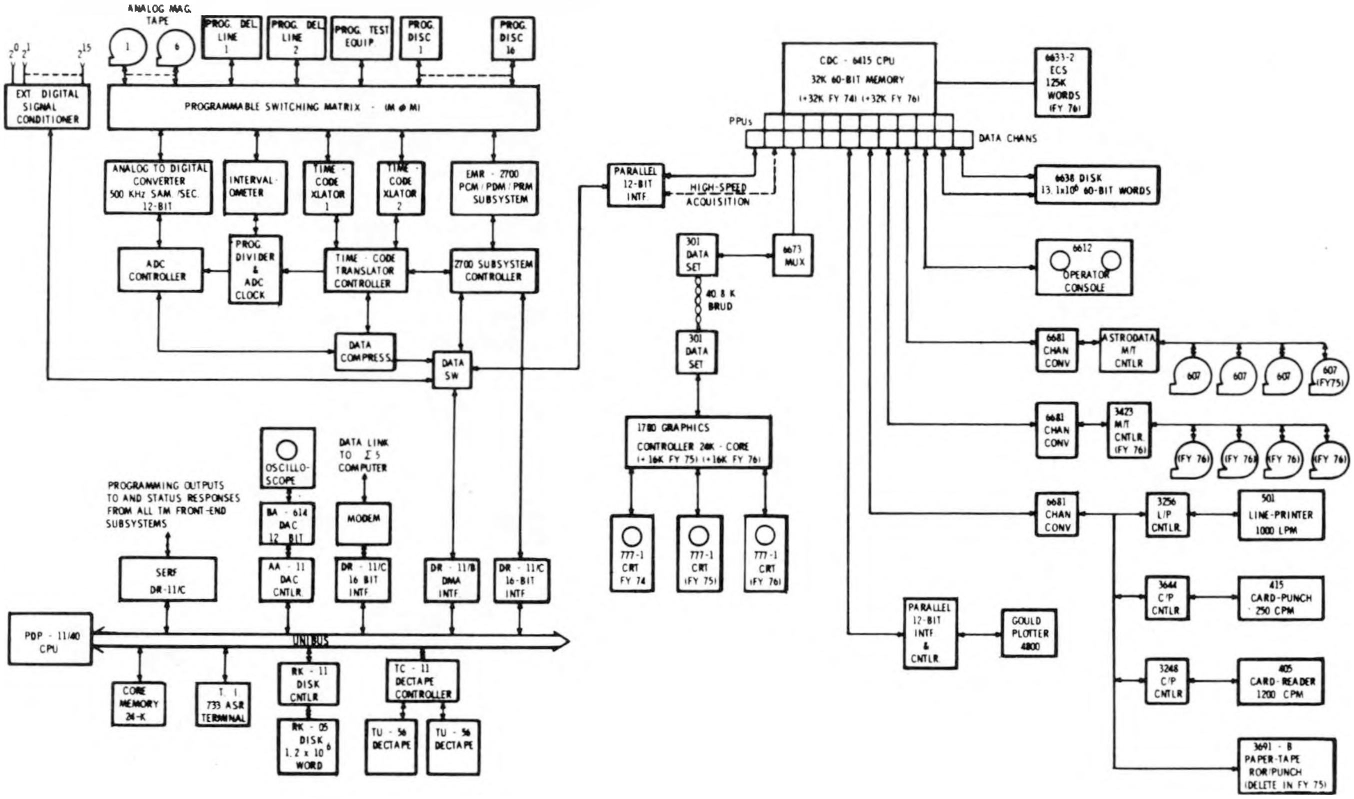

Figure 1. The CDC-6400 user-oriented data-reduction system

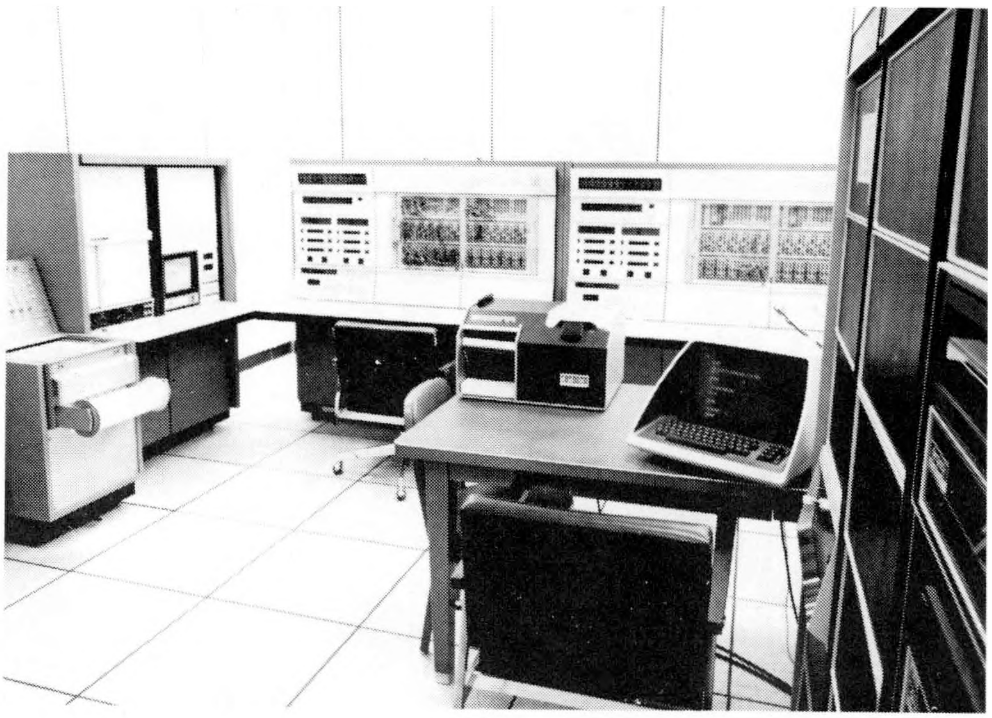

Figure 2. The AD/FIVE-PDP 11/45 hybrid computer

Item 3. *Microelectronics Laboratory Computer Development*

An expanded microelectronics laboratory is being constructed that will be capable of producing silicon semiconductor devices ranging from discrete devices to medium and large-scale integrated circuits containing thousands of transistors. To support this effort, a program has been implemented for the computer-aided design of circuit masks. In addition, computer codes are being used for circuit analysis and simulation studies bearing on the design of complex integrated circuits.

A sixth SIGS graphics station will be installed to support the growing computational load in this area. Moreover, the previously described microelectronics computer facility will be replaced by a more powerful system that will provide additional services such as monitoring and control of diffusion furnaces, ion implantation and wafer probing equipment, and radiation-effects testing. This data-acquisition and laboratory control computer is depicted schematically in Figure 3.

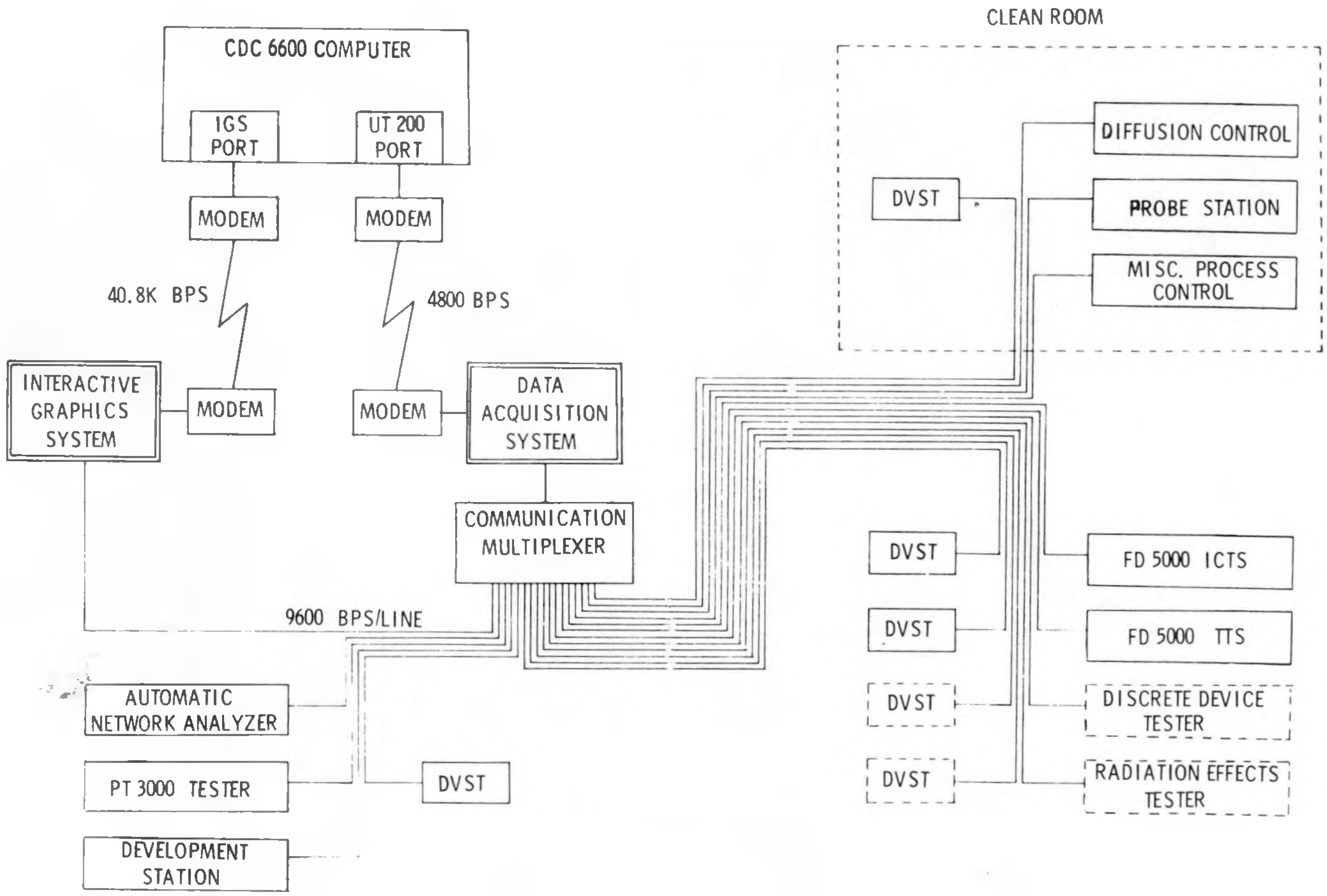

Figure 3. Microelectronics data acquisition system

SAND74-0084
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DESIGN DEFINITION AND FABRICATION

Sandia Laboratories Technical Capabilities

Design Definition and Fabrication

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115
and Livermore, California 94550 for the United States Energy Research
and Development Administration under Contract AT (29-1)-789

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SANDIA LABORATORIES TECHNICAL CAPABILITIES

DESIGN DEFINITION AND FABRICATION

ABSTRACT

This report characterizes the design definition and fabrication capabilities at Sandia Laboratories. Selected applications of these capabilities are presented to illustrate the extent to which they can be applied in research and development programs.

DESIGN DEFINITION AND FABRICATION*

Research and development programs are supported by developing and applying computerized design and record-keeping systems; maintaining records of and coordinating designs, specifications, and changes among contractors who produce parts of systems; and maintaining drawings of designed systems.

Processes are developed and hardware fabricated to provide experimental vehicles and models required by engineering and scientific organizations. Complementing the fabrication and development facilities are inspection, equipment repair, and process engineering services, as well as calibration services which interact with Sandia's Primary Standards Laboratory.

Design Definition and Fabrication
Technical Staff and Investment in Equipment

	Professional Staff	Skilled Staff	Investment in Equipment (in $1000)
Design	85	225	3000
Metal Processing	5	133	5050
Glass and Ceramic Processing	5	8	840
Composites and Plastics Processing	12	18	1300
Electrical Component Processing and Fabrication	8	27	1990
Heat Treating and Finishing Processes	4	7	510

*Compiled May 1975.

DESIGN DEFINITION

Detailed graphic† and written design-definition support is provided. Status information and some design configurations are maintained in computer files. Computer-aided design methodology is developed and made available to research and development groups. Internal and subcontractor engineering documentation and control systems are developed and coordinated.

Design Support

Design concepts provided by the engineering and research staff are translated into finished graphic and written form. Special test and acceptance equipment is designed, and material, fabrication, and test specifications are generated. (Item 1)*

Current Activities

Design coordination
Calculations
Drafting
Maintenance of Design Information Library

Design Techniques

Procedures and codes are developed to improve the efficiency of producing designs and assuring their accuracy through computer-aided design, process definition, and manufacturing techniques. (Item 2)

Current Activities

Interactive digitizing
Interactive network investigation
Interactive graphics
Direct numerical control
Computer-aided design and definition

Engineering Control Systems

Systems, procedures, and standards are developed for the control of drawing practices, change implementation, product identification, and record management. Interactive computer systems are developed to provide faster and more accurate data handling. (Item 3)

Current Activities

Drawing standards
Engineering application and control procedures
Computerized design information systems
Computerized communcation systems

Maintenance of Design Records

Current records of all drawings and design changes are maintained, and products manufactured in accordance with design specifications are marked so that products can be identified as required. Any modification of a design can be related to corresponding parts.

Current Activities

Management of engineering releases
Product control
Design information processing
Drawing reproduction and distribution

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†See Computation Systems, SAND74-0080, p. 9.
*See Highlights below.

DESIGN DEFINITION

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Determination of Inertial Properties of a Design*

Interactive digitizing equipment (Figure 1) is available for the analyst wishing to obtain weight, center of gravity, and moment of inertia of a design rapidly and accurately. The designer can digitize his drawing and determine the properties in minutes. The geometric data and material properties form a base that is processed through two computer programs for calculation of inertial properties.

Program DIGITIZ computes the properties of interest for solids of revolution and objects with constant cross sections. The geometry can be bounded by straight lines and circular, elliptic, or parabolic arcs. The program can determine the resultant properties of any collection of items, up to a maximum of 98 items. DIGITIZ has a maximum capacity of 400 points.

The CLAMP program computes the weight, center of gravity, and moments of inertia for solids of revolution and has a summing capability that can include point-mass items. It can store the properties of 30 items and 1000 points at any given time. The geometry can consist of straight lines and circles.

Item 2. *CADDAMS*

The Computer Aided Design, Definition, and Manufacturing System (Figure 2) is an evolving integrated system that permits the input of creative thought at the design stage, after which the encoded information is computer-processed via a unified data-base system to provide for the needs of design, analysis, definition, and manufacture. The activity consists of three basic subsystems and their interrelationships:

1. Design input systems.
2. Major computer (common data bases).
3. Processing systems (graphic definition, manufacture, and engineering release).

All subsystems are computer-augmented and are in communication with each other via major computers.

Item 3. *Interagency Communication and Control*

A close operating relationship is maintained with contractors responsible for production. Engineering information, changes, and production status are rapidly exchanged through a secure, computer-controlled network that operates both from and to Sandia, which has design responsibility, and the production agencies. Material lists related to specific drawings are maintained in a computer file, updated daily, and transmitted overnight to production agencies, whose computer files are automatically updated. Appropriately revised official drawings are printed out the next day. As information is transmitted, related computer files at Sandia are automatically updated.

Figure 1. Using interactive digitizing equipment, a design draftsman obtains coordinate information of a part geometry which will be used for computing properties of interest for solids of revolution.

DESIGN DEFINITION

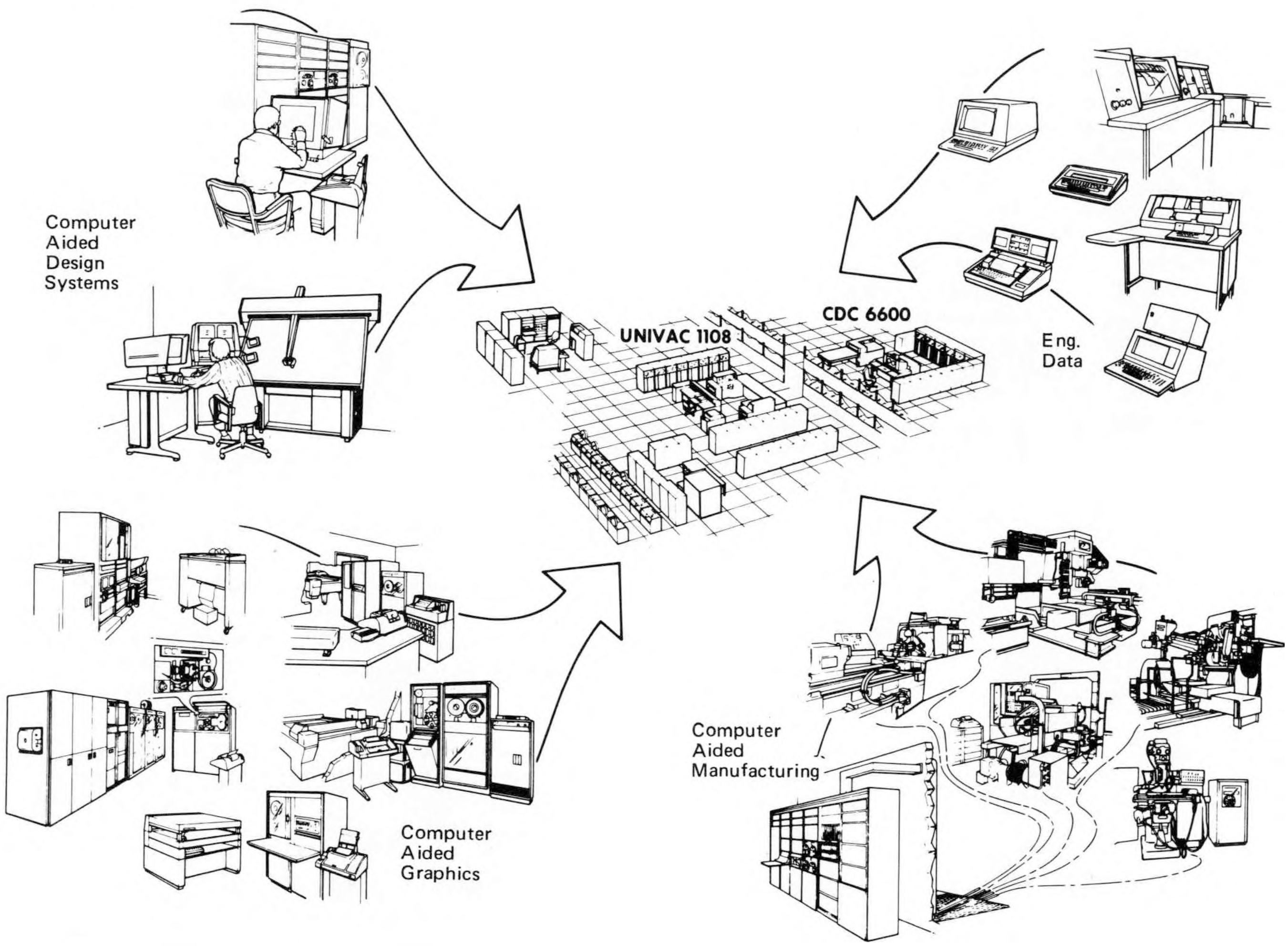

Figure 2. CADDAMS (Computer Aided Design, Definition and Manufacturing System)

METAL PROCESSING

Metal fabrication facilities are used to fabricate, modify, and assemble research and development items, and to develop new metal-processing techniques. Facilities include numerically controlled as well as conventional machines for machining, grinding, precision metal forming, patternmaking and metal casting, welding, and joining.

Machining

The machine shop provides facilities for the fabrication of piece-parts, subassemblies, and assemblies. Both conventional machining equipment and numerically controlled machines are used. Facilities are available for fabricating and assembling miniaturized components. (Items 1,2)*

Current Capabilities

- Conventional, numerical-control, and miniature machining
  - Turning
  - Milling
  - Drilling
- Electrical discharge machining
- Ultrasonic machining
- Grinding
  - Surface
  - Cylindrical
  - Internal
  - Jig
- Chemical milling
- Carbon and ceramic machining
- Hazardous-material machining
  - Explosives
  - Toxic materials

Precision Metal Forming

Precision prototypes are fabricated. Forming dies are used to provide complex shapes built to close tolerances.

Current Capabilities

- Shearing
  - Punching
  - Trimming
  - Notching
  - Ring and circle cutting
- Forming
  - Rolling
  - Bending
- Joining
  - Spot welding
  - Seam welding
  - Riveting
  - Electrodeposition

Foundry and Patternmaking Facility

A wide variety of patterns, wood models, and wood tooling is fabricated in the patternmaking facility. A non-ferrous foundry complements the wood-pattern facility, and is capable of producing a variety of quality sand castings. Furnace capacity varies with the alloy being poured, but, for example, aluminum shapes weighing up to 2000 pounds can be cast. (Item 3)

Welding and Joining

An extensive welding and joining laboratory is maintained for prototype fabrication. The structural welding facility includes complete welding and cutting equipment. (Item 4)

Current Capabilities

- Structural welding
  - Brazing
  - Gas welding
  - Shielded metal-arc welding
  - Gas tungsten-arc welding
  - Electron-beam welding
  - Hot press brazing and bonding
- Microwelding
  - Resistance spot welding
    - Opposed electrode
    - Parallel gap
  - Resistance butt welding
  - Percussive arc welding
  - Thermal compression bonding
  - Ultrasonic bonding
  - Microsoldering and brazing
  - Furnace brazing
  - Vacuum brazing
  - Laser-beam welding

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*See Highlights below.

METAL PROCESSING

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Five-Axis Numerically Controlled Milling Machine*

A five-axis milling machine is used for complex configurations. The term "five axis" describes the orientation of the machine head relative to the part being machined. The orientations are the three orthogonal rectilinear axes, rotation of the part, and rotation of the machine head by 90 degrees to the vertical position. The machine control unit takes digitized data from punched tape, performs certain arithmetic operations, and converts the information into analog signals to provide continuous control of the five axes. Figure 1 shows a part in an intermediate stage of the machining operation.

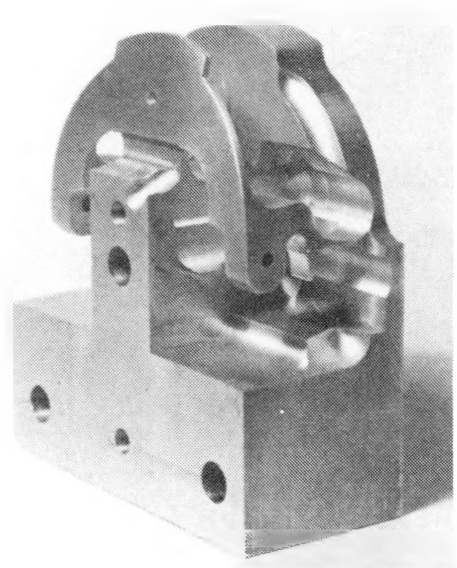


Figure 1. Part in an intermediate stage of machining

Item 2. *Miniature Machining and Assembly*

A switch was designed to sustain extreme abnormal environments without having its open contacts close or vice versa. The assembly contains 243 parts in a volume of 56 cubic centimeters (Figure 2). Units used in the development of the switch were fabricated in the miniaturization shop.

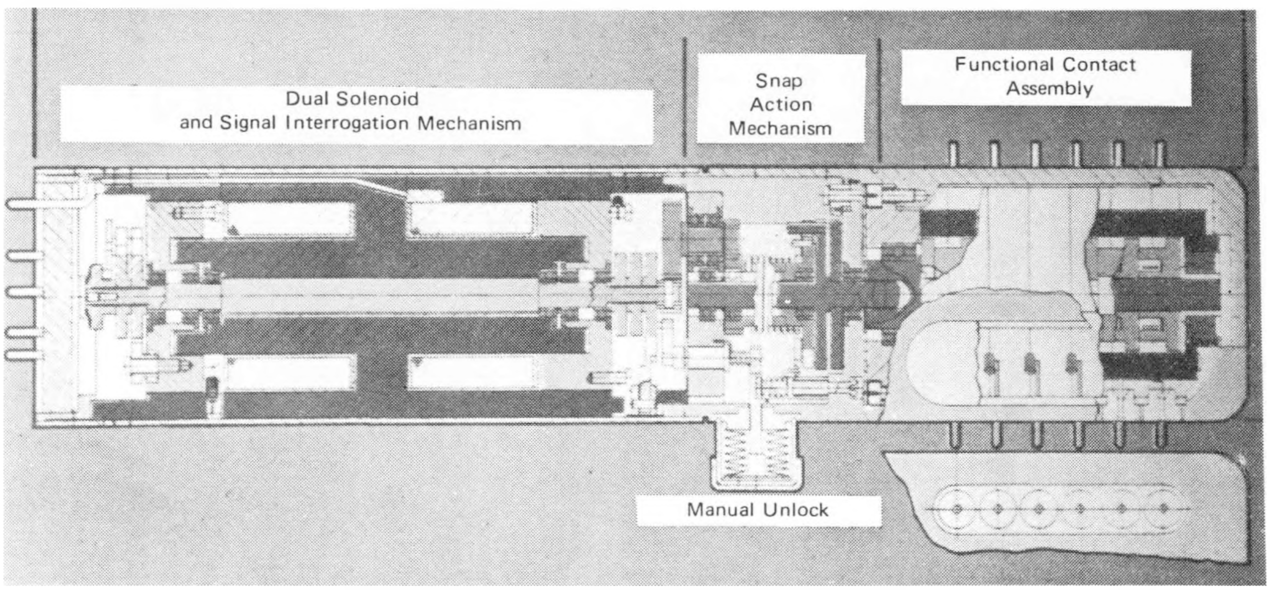


Figure 2. Miniaturized switch containing 243 parts within a cylinder about 11.4 cm long and 2.5 cm in diameter.

Item 3. *Quality Castings*

High-quality castings produced in the foundry are being used on a missile where forged or rolled components would normally be required (Figure 3). This has resulted in a considerable saving of time and money.

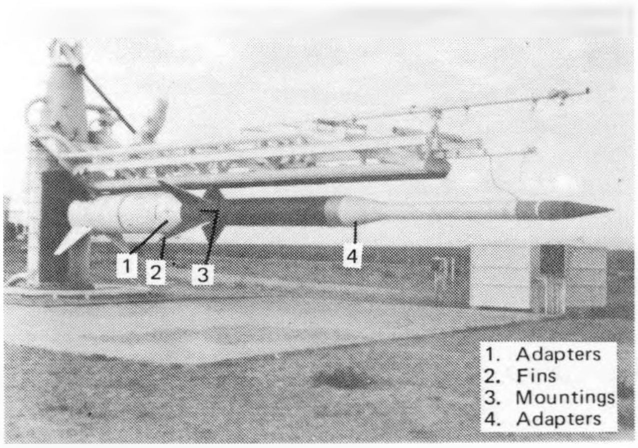


Figure 3. Missile components indicated by arrows are aluminum castings.

Item 4. *Laser Fusion Vacuum-Chamber Weld Assembly*

A sphere 3 feet in diameter to be used in the study of laser-beam fusion was fabricated using gas-tungsten-arc and electron-beam welding techniques (Figure 4). Fabrication of the sphere called for precise alignment and position tolerances and vacuum tight welds.

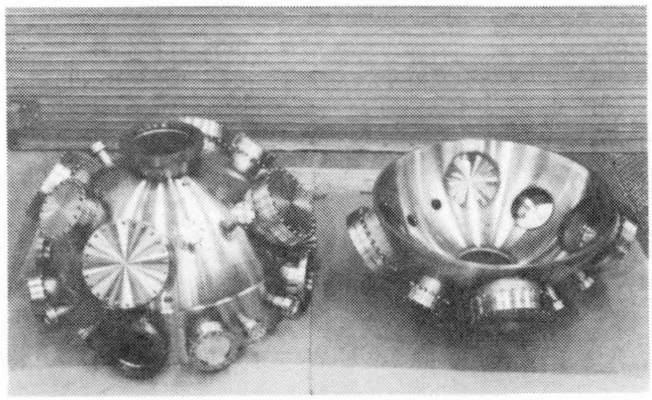


Figure 4. Vacuum chamber for electron-beam fusion facility.

GLASS AND CERAMIC PROCESSING

The glass fabrication and melt laboratory was established for the development of processes and for the fabrication of a wide variety of products requiring special glass applications.

The ceramics laboratory and the abrasives, composites, and toxic machining facilities are used to fabricate experimental, developmental, and prototype ceramic components using existing ceramics and machining technology and, as required, for developing or assisting in the development of new ceramic fabrication and materials-processing technology.

Glass Seals, Coatings, and Fabrication

The glass laboratory has wide capabilities, ranging from traditional glass-blowing of laboratory apparatus to new methods for bonding and sealing glasses into complex structures. (Items 1,2)*

Current Capabilities

- Glass blowing
- Forming
- Reflecting coatings
  - Silver
  - Aluminum
- Conductive coatings
  - Gold
  - Platinum
  - Silver
  - Tin oxide
- Vacuum baking, processing, and final sealing
- Glass-to-metal seals
  - Fusion sealing
    - Tubular
    - Edge
    - Butt
    - Window
    - Single and multiple seals
  - Header design and development for:
    - High-voltage isolation
    - High current
    - High or low operating temperature
    - Thermal shock resistance
    - Mechanical shock resistance
    - Static or dynamic loads
    - Corrosive environments
  - Electrical field assisted glass sealing (sealing well below the softening point of glass)
- Glass coatings and bonds
  - Screen printing
  - Spraying
  - Electrophoretic deposition
  - Transfer tape
  - Vacuum hot pressing (for precision, pore-free bonds)
- Special glass formulation by melting and drawing
  - Fabricating new and unusual glasses
  - Altering or tailoring properties (mechanical, physical, chemical, optical, electrical)
  - Glass tube drawing
- Glass characterization
  - Differential thermal analysis
  - Thermomechanical analysis
  - Differential scanning calorimetry
  - Thermogravimetric analysis
  - Thermal evolution analysis
  - Hot-stage microscopy

Ceramic Fabrication

In the ceramics laboratory are facilities for fabricating ferroelectric transducers, thermoelectric materials, and alumina and electrooptic ceramics. The facilities include equipment for batch formulations, calcining, milling, cold and hot pressing, sintering, machining, slicing, grinding, lapping, polishing, and glazing.

Current Activities

- Ferroelectrics (lead-zirconate titanate)
  - Batching
  - Pressing
  - Sintering
  - Slicing
  - Electroding
  - Polarizing
  - Transducer assembly

*See Highlights below.

Thermoelectric (silicon germanium)
- Vacuum hot pressing
- Precision slicing

Alumina ceramics
- Isopressing and bisquing of billets
- Precision forming
- Controlled high firing
- Surface finishing of fired ceramics

Ceramic Process Development

The ceramics laboratory performs process development for ceramic capacitors, electrooptic ceramics, lanthanum-modified lead-zirconate titanate (PLZT), thermistor materials, chemical-vapor deposition of silica, ceramic transducers (PZT), and alumina ceramics.

Facilities available for process development include a clean room, freeze-drying equipment, vacuum and atmospheric hot presses, plasma and induction chemical vapor deposition equipment, and thin-sheet casting equipment. (Item 3)

Current Activities

Material Processing
- Preparation of high-purity PLZT powders
- Characterization of ceramic powders
- Development of thermistor materials

Fabrication techniques
- Isopressing and hydraulic dry pressing
- Thin-sheet casting (doctor blade)
- Vacuum and atmospheric hot pressing
- Chemical vapor deposition
- Slip casting
- Refractory casting
- Machine forming

Firing processes
- Drying and curing
- Bisquing
- High-firing

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Gas Discharge Tube*

The tube in Figure 1 was designed and fabricated to reduce the thermal gradient over its entire length during operation. To achieve this, the discharge chamber is suspended by its electrical leads and gas inlet tube in liquid nitrogen. The liquid nitrogen is maintained in a vacuum jacket which surrounds the entire tube and incorporates a glass bellows to minimize undue stresses in the glass because of differential thermal expansion and contraction. There is a double-vacuum-jacketed optical view port in the discharge chamber for light output and observation.

The problems of fabricating such a device are illustrated by the glass-blower's skill in forming a multitude of ring seals in very tight quarters, including double-ring seals, glass-to-metal seals (electrical leads), and by the precise temperature control needed to allow the sealing of optically flat windows onto a tube without window distortion.

Item 2. *Glass Headers*

Glass-to-metal seals are used in headers to hermetically seal together terminals and end-plates with a strong bond having high electrical resistance (Figure 2). One problem during fabrication was that during the seal cycle the glass at the terminal interface flowed upward instead of forming the desired gentle radius. The type of glass being used had an affinity for iron oxide and continued to wet the surface as long as iron oxide was present. The problem was solved by fixturing the terminals so that during the preoxidation cycle, oxide was formed only in the seal area of the terminal.

Item 3. *Electrooptic Ceramics*

Lead-zirconate titanate is a transparent ceramic with optical qualities that can be changed electrically. It can hold a photographic image, "remember" signals as does a computer memory, and switch from transparent to opaque in 50 microseconds. A lead-zirconate titanate slug 5-1/4 inches in diameter and a window 3 x 4 x 0.25 inch thick, sliced from such a slug, are shown in Figure 3.

The electrooptic material is prepared from liquids by precipitation. It is then vacuum-hot-pressed to about the density of steel, and sliced in the ceramics development laboratory. Polished slices of electrooptic material like that illustrated are used to fabricate a mosaic window for military aircraft.

GLASS AND CERAMIC PROCESSING

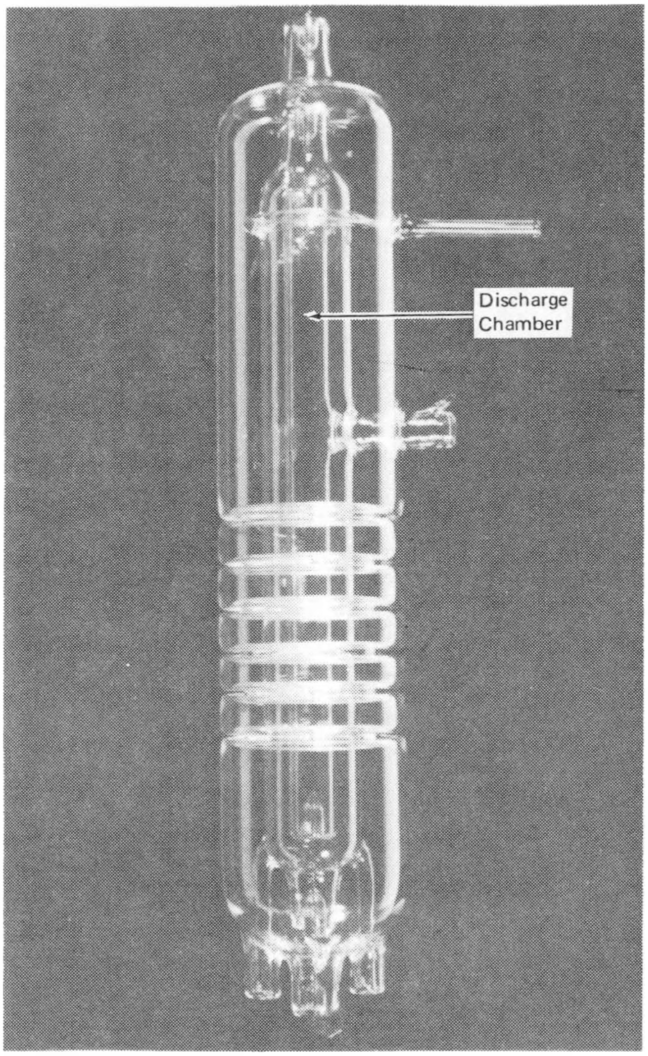


Figure 1. Special glass apparatus made by glass blower

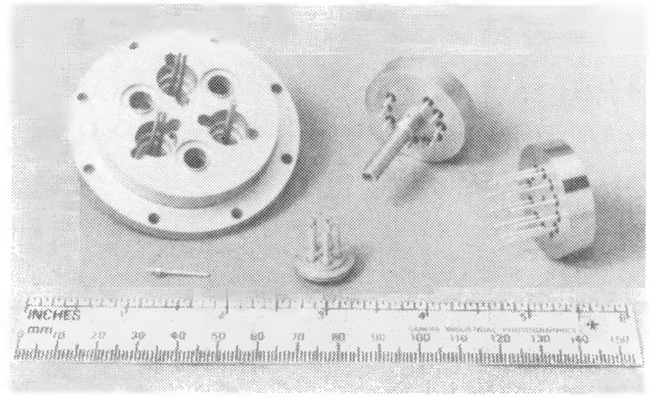


Figure 2. Hot pressed 5-1/4-inch-diameter PLZT slug and 3- x 4-inch electrooptic window sliced from a similar slug

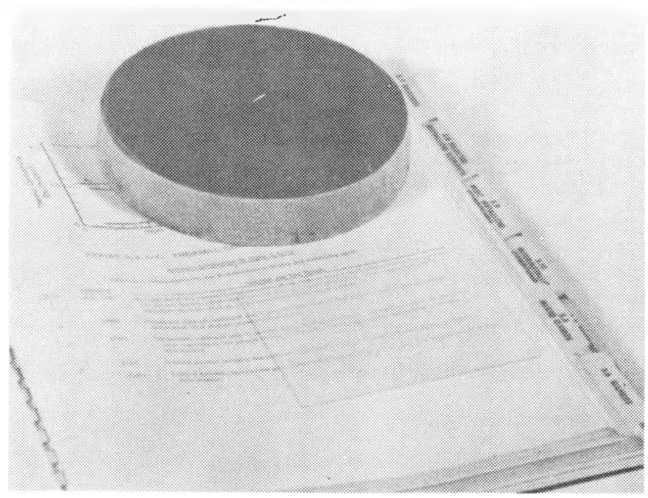


Figure 3. Glass headers

COMPOSITES AND PLASTIC PROCESSING

Composite materials and components are developed, processed, and fabricated. Processes include filament winding, resin impregnation, carbonization and graphitization, chemical vapor deposition, and plasma spraying.

Polymeric materials are processed and are fabricated for various applications. Processes are developed for the formulation of new plastics.

Carbon-Carbon Composites

Carbon-carbon composites are developed for various applications in which the unique high-temperature and erosion-resistant qualities of carbon are required. Helical-wound, continuous carbon filaments and continuously felted substrates are fabricated. Parts are provided for evaluation of chemical vapor deposition (infiltration) and pyrolized organic (impregnation) matrices. Reinforcement materials include carbon, graphite, glass, and metal. Matrix materials include plastics, carbon, and metals; (e.g., boron/epoxy, boron/aluminum, boron/copper, or stainless steel/aluminum). (Items 1,2)*

Current Capabilities

- Matrix development
  - Chemical vapor deposition (infiltration)
  - Pyrolyzed organics (impregnation)
- Fabrication
  - Filament winding
  - Carbonization
  - Infiltration
  - Graphitization
- Insulation
  - Carbon foams
  - Carbon composites with tailorable compressive and thermal properties for applications to 3000°C
- Chemical vapor deposition of carbon
  - Chemical kinetics and equilibrium thermomechanical calculations
  - Reaction modeling and experimental confirmation
  - Instrumentation methods
  - Deposit characterization

Plastics

In response to the needs of research and development groups, basic materials are modified by incorporation of plasticizers and fillers to improve characteristics such as mechanical and chemical properties and resistance to extremes of temperature and moisture. Capabilities have been developed in a number of phases of plastics technology including thermoplastic, thermosetting, and elastomeric materials.

Representative Materials

Polyolefins	Polyesters
Vinyl chloride polymers	Polysulfides
Fluorine-containing polymers	Epoxide resins
Acrylic plastics	Polyurethanes
Polyamides	Silicones
Polycarbonates	Miscellaneous plastic materials
Phenolics	

A processing facility is used to develop procedures for handling new materials. Included is a clean room for casting and encapsulating contaminant-free components. (Item 3)

Representative Processes

Molding	Formulating
Compression	Thermoforming
Transfer	Laminating
Injection	Coating
Compounding	Bonding
Milling	Sealing
Blending	Foaming

*See Highlights below.

COMPOSITES AND PLASTIC PROCESSING

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Rocket-Sled Heat Shield*

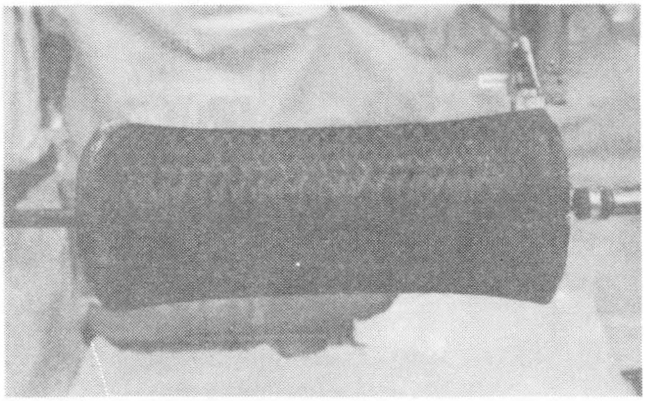
Figure 1 shows a filament-wound leading edge for a rocket sled. View A shows the part wound on a collapsible round mandrel. The part is then shaped into a wedge on a graphite mandrel before densification, which permits optimum use of the continuous filaments by preserving the filament-winding pattern. View B shows a segment of the final shape. Figure 2 shows an induction heating coil which can apply 1200°C ± 25°C from end to end to a conical part 6 feet high.

Item 2. *Carbon Foams*

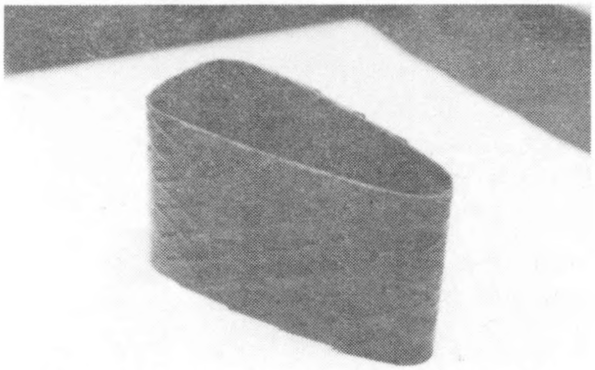
A facility was set up to investigate the characteristics of carbon foams. Use of the facility ranges from exploratory research to the fabrication of full-scale prototypes. Specific operations include organic synthesis, formulation, curing, carbonization, graphitization, evaluation, and testing. Carbon foam is a cellular material that combines high structural strength, high temperature resistance, and low density. The carbon structure is obtained from carbon precursors of cellular organic polymers by controlled pyrolysis in an inert atmosphere. The foam can be made in a wide range of densities.

Item 3. *Foam Encapsulation*

The encapsulation of fuzing and arming subassemblies required the use of a void-free foam having a density of 22 lb/ft^2. Mockup units were used for developing encapsulation process techniques. After encapsulation each mockup unit was checked for foam density and external and internal defects such as voids and cracks. Process techniques were thus developed, including location of mold pour points and vents. Using these techniques, production subassemblies were fabricated and tested successfully.



A. Filament-wound leading edge



B. Final wedge-shaped segment of heat shield

Figure 1. Rocket sled heat shield

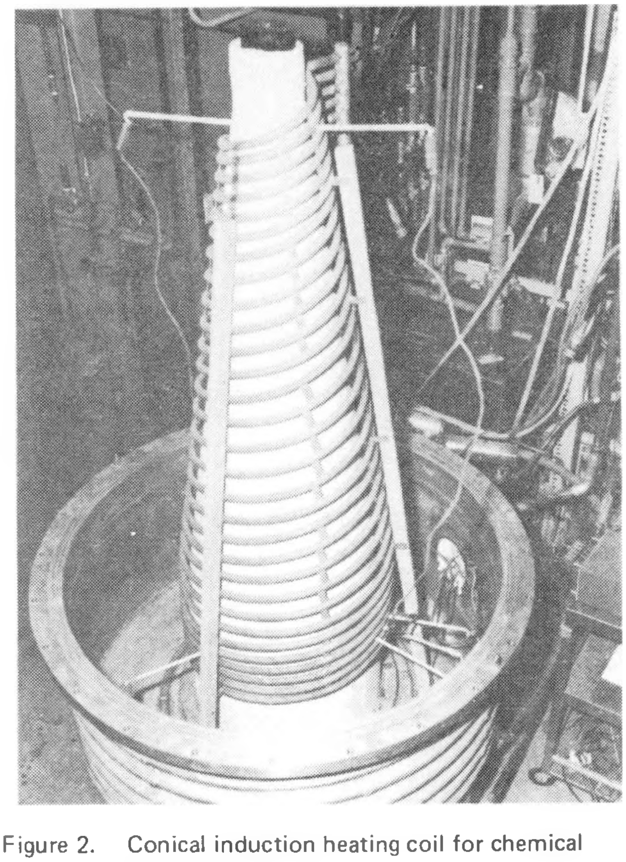


Figure 2. Conical induction heating coil for chemical vapor deposition

ELECTRICAL COMPONENT PROCESSING AND FABRICATION

Capabilities include process development and the fabrication of special electrical and electronic devices. Operational electronic equipment, such as testers and monitoring devices, are fabricated for testing and inspection purposes. Conventional hard-wiring is used, as well as state-of-the-art microcircuitry. Discrete components such as resistors, inductors, transformers, and capacitors for unusual applications or special demands are also developed and fabricated.

Thin-Film Deposition and Vacuum Devices

In the vacuum processes laboratory the emphasis is on vacuum deposition of thin films, while in the tube laboratory a variety of vacuum tubes and devices is designed, developed, and processed. (Item 1)*

Current Activities

- Thin-film vacuum deposition methods
  - Resistance evaporation
  - Electron-beam evaporation
  - Ion plating
  - Sputtering
    - Direct current
    - Radio frequency
- Film deposition
  - Elemental
  - Refractory
  - Alloy
  - Dielectric
  - Compound
  - Organic
- Characteristics produced using thin films
  - Optical
    - Antireflecting
    - Degrees of reflectivity or transmission
    - Variable-density filters
  - Mechanical
    - Modification of coefficient of expansion
    - Dispersion of stress waves
    - Diffusion processes
    - Energy absorption
    - Protective films
  - Electrical
    - Conductor size
    - Capacitor element values
    - Resistive element values
- Design, development, and processing of vacuum devices
  - Neutron tubes
  - Switching tubes
  - Spark gaps
  - Thermionic converters
  - Electron-beam guns
  - Ion tubes
  - Triode tubes
- Vacuum-device production processes
  - Wet and dry hydrogen and vacuum brazing
  - Chemical treatment of ceramics and metals
  - Ceramic metallizing and nickelizing
  - Ceramic-to-metal joining
  - Pumpout, bake, and gas backfill devices
  - Welding: tungsten inert gas and electron-beam resistance
  - Phosphor deposition, settling, and vacuum

*See Highlights below.

Hybrid Microcircuits

Processes are developed for prototype fabrication of hybrid microcircuits and new technology studies. The facilities include a Class 100 downflow clean room containing fine-line photolithographic and cleaning equipment. (Items 2-4)

Current Activities

- Thin-film deposition
  - Tantalum nitride
  - Chrome
  - Gold
- Photolithographic chemical processes
- Cleaning processes
  - Ultrasonic
  - Chemical
  - Cascade deionized water
  - High-temperature firing

ELECTRICAL COMPONENT PROCESSING AND FABRICATION

Bonding
- Hydrogen flame soldering
- Hot wire and infrared
- Thermal compression on beam lead devices
- Fine wire
- Parallel-gap ribbon

Substrate sizing
- Laser
- Diamond wheel
- Wire saw

Tantalum resistor trimming
- Laser
- Anodizing

Testing
- Bond and adhesion strengths
- Life cycling
- Temperature coefficient of resistance on thin-film resistors
- Functional testing of complete units

Electronic Fabrication

In this facility is equipment for fabricating, modifying, and packaging electronic components and highly specialized electronic equipment and instrumentation. Such units are used in simulation testing of components, telemetry packages, and weapon systems, and may be incorporated with minicomputers for test automation. (Items 5,6)

Coil Winding

This laboratory, as the name implies, is used in building normal and special electrical coils, most of which are prototypes for testing and evaluation.

Current Capabilities

Machine winding
- Layer
- Toroid

Wire size range: 0.25 to 460 mil

Form size range: 0.010 inch ID toroids to rectangles 4 x 5 feet

Component Testing

Electrical components are tested for their performance under anticipated operating conditions, including parametric testing in controlled environments.

Current Capabilities

Burn-in, aging, and life testing
- Voltage supplied to 10,000 V
- Current supplied to 200 A
  - Steady state
  - Ramp
  - Pulse

Thermal
- Temperature chamber 55 to 300°C
  - Steady state
  - Cycle
  - Shock

Time measurements
- Silicon-controlled rectifier
- Digital integrated circuits

Lead fatigue tests

Radiation tests on solid-state devices and tubes in the reactor facility

Automatic testers
- Build
- Modify

Environmental testing and evaluating

ELECTRICAL COMPONENT PROCESSING AND FABRICATION

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Electrical Switching Tube*

A tube used for electrical switching (Figure 1) typifies the components and processes developed by the vacuum processes and electronic tube laboratories.

Item 2. *Hybrid Microcircuits in Artillery-Fired Projectiles*

A microwave telemetry transmitter was constructed for use in an artillery shell. By the use of hybrid microcircuits, the telemetry package was reduced to a volume of 13 cubic centimeters. A signal is transmitted continuously from ignition, when axial acceleration is 12,000 x gravity, throughout the flight of the projectile.

Item 3. *Photochemical Processing and Microminiature Assembly*

Photographic techniques and electron beams are used to reduce photographs of printed circuit layouts. Photographic processes are used to define and mask areas to be etched so that chemical attack occurs only where material is to be removed. Reductions of 1000 to 1 are achieved. Printed circuits and integrated-chip masks are typical products of this process.

Associated with this activity is precision assembly. By the use of skills typical of watchmaking, miniature components are mounted, positioned, welded, and calibrated to form working systems of unusual operating limits and reliability.

Other applications of photoreduction include a variety of precision glass and metal parts for acceleration sensors, particle collectors, microminiature vacuum deposition masks, electrooptic ceramic lens grids, and other items of extremely small size or close tolerances.

Item 4. *Hybrid and Integrated-Circuit Masks*

Order-of-magnitude reductions are routinely made on such related items as hybrid-circuit and integrated-circuit masks. These masks permit the deposition of metals in precise patterns on substrates. A complete set of seven or more registering masks may be required to build an

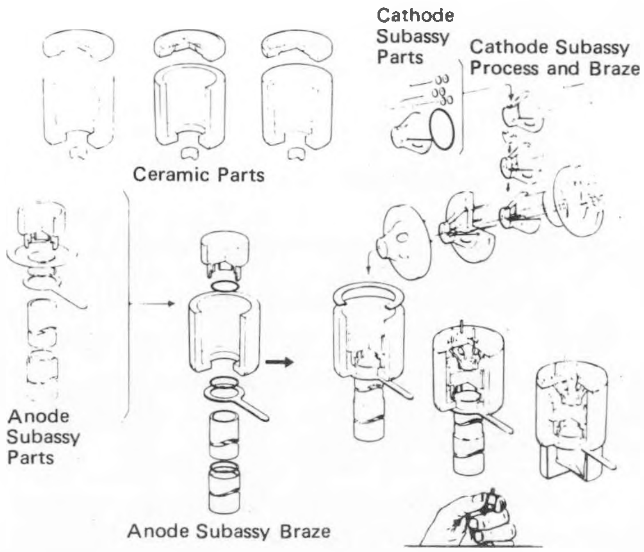


Figure 1. Electrical switching tube and assembly methods

integrated-circuit chip whose final dimensions may be only 0.323 square centimeter.

Item 5. *Wire-Wrapping Machines*

These are numerically controlled indexing machines operated by computer-generated punched tape. Pin-type printed circuit boards with integrated circuit plug-ins are wired using connections made by wrapping the connecting wires around the terminals. This method of circuitry packaging is effective when a high density of parts is required. Circuit boards up to 50 x 75 centimeters can be wired.

Item 6. *Force Balance Accelerometer*

A commercial force balance accelerometer (FBA) is being extensively redesigned to meet anticipated requirements of future inertial guidance systems and/or arming and fuzing systems in missiles. The instrument (Figure 2) must be packaged in a volume of 1 cubic inch and must be capable of measuring accelerations from fractions of a

ELECTRICAL COMPONENT PROCESSING AND FABRICATION

gravity to 200 x gravity in either direction along its sensitive axis, with an overall error of less than 25 percent across a range of stringent operating environments.

FBA operation is based on the principle of a sensing mass being supported against gravity forces by the electromagnetic force on a current-carrying coil in a permanent magnetic field. The working element starts with a glass wafer ground and polished to a flatness that is measured in wavelengths of light. Delicate flexures are chemically etched, conductor paths are applied by vapor deposition, coils are mounted, leads microwelded, and a component produced whose shock resistance is measured in hundreds of gravities but whose sensing accuracies are in hundredths of a gravity.

Models of the current design have performed well in laboratory testing, but development is still under way to improve bias stability and tolerance to environmental conditions.

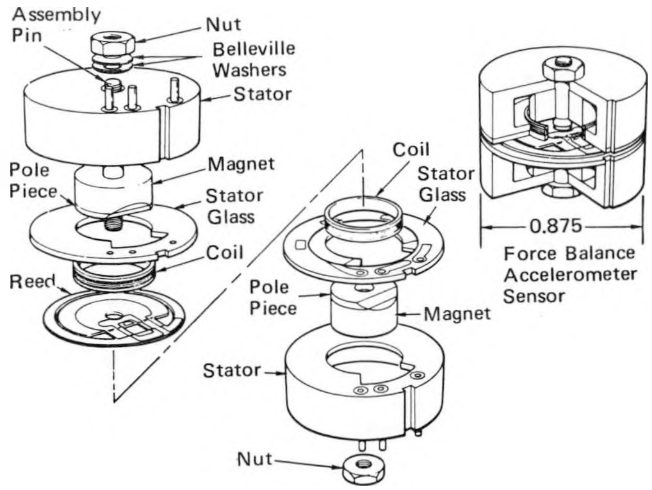


Figure 2. Sandia-modified force balance accelerometer packaged in a volume of 1 cubic inch

HEAT TREATING AND FINISHING PROCESSES

The heat-treat facility is equipped to perform a wide range of processes required in the heat treatment of ferrous and nonferrous alloys. Finishing services are provided by using flame and plasma spray as well as the plating and coating facilities. Finishes are applied for numerous reasons: wear resistance, corrosion or oxidation resistance, insulation or conductivity for electrical applications, and eye appeal.

Heat Treating

Strict process control is maintained and recorded for research and development programs requiring the heat treatment of unusual alloys to rigid specifications.

Current Capabilities

- Hardening
- Tempering
- Annealing
- Normalizing
- Carburizing
- Stress relieving
- Stabilizing

Flame and Plasma Spraying

A metal and ceramic spray facility is maintained for applying coatings that are insulative and resistant to corrosion, erosion, and high temperature.

Current Capabilities

- Oxyacetylene flame spray
  - Metal wire
  - Ceramic rod
  - Ceramic powder
- Plasma spray
  - Metal powder
  - Ceramic powder

Electroplating and Coating Laboratory

The plating laboratory provides metallic and oxide finishes on ferrous and nonferrous metals for many purposes including corrosion protection, wear resistance, low electrical resistivity, high dielectric properties, diffusion and thermal-compression bonding, and solar-energy absorption. Special capabilities range from color anodizing of prototype models to electroforming of miniature all-gold pressure vessels (targets for the electron-beam fusion energy study).

A full range of organic coatings can be applied in the coating laboratory, including systems for ordnance materials, ablation and heat-resistant coatings for rockets, satellite coatings, dry-film lubricants, and chemical and corrosion-resistant systems. Recent applications have included spraying of silver and copper onto the back surfaces of parabolic glass mirrors for the solar energy program.

Current Capabilities

- Specimen preparation
- Contaminant analysis
  - Atomic absorption spectrophotometer
- Nondestructive plating and coating thickness control instruments
- Organic coating application techniques
  - Spray
  - Fluidized bed
  - Electrostatic
  - Airless
  - Hot spray
  - Electrophoretic
- Coating laboratory testing
  - Total solids (evaporation of solvent residue)
  - Vehicle solids (centrifuge separation of pigment)
  - Percent pigment
  - Abrasion resistance
  - Salt-spray resistance
  - Scratch and mar
  - Impact
  - Accelerated high humidity
  - Outdoor exposure

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Sandia Laboratories Technical Capabilities

Earth Sciences

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115
and Livermore, California 94550 for the United States Energy Research
and Development Administration under Contract AT (29-1)-789

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SANDIA LABORATORIES TECHNICAL CAPABILITIES

EARTH SCIENCES

ABSTRACT

This report characterizes the earth sciences capabilities at Sandia Laboratories. Selected applications of these capabilities are presented to illustrate the extent to which they can be applied in research and development programs.

EARTH SCIENCES*

The earth sciences are directed principally toward an understanding of the response of the upper layers of the earth (soil and rock) to dynamic loading. The disciplines of geology, soil mechanics, fluid dynamics, and engineering mechanics have been combined to solve specific earth-response problems that fall outside the scope of any one technical area. Penetration, drilling, and measuring the response of the earth to explosions and earthquakes are of prime importance. In problem areas encountered at these laboratories, earth-material motions and strain rates are appreciably greater than are found in more classical studies of soil motion. Specific technical areas on which continuing emphasis is placed include dynamic stress analysis (as related to earth materials), terradynamics (phenomena attendant upon earth penetration by high-velocity projectiles), underground physics (the study of earth-material motions resulting from underground detonations), drilling technology, magma research, and the development of diagnostic instrumentation. The key element in each of these areas is the effort to understand the dynamic behavior of earth materials so that they can be characterized well enough to make specific problems solvable. Soil and rock are complex materials in terms of engineering properties, particularly during high loading rates and at high temperatures, and consequently there is a strong reliance upon empirical results.

Earth Sciences Technical Staff
and Investment in Equipment

	Professional Staff	Investment in Equipment (in $1,000)
Numerical Modeling	12	250
Terradynamics	26	1600
Underground Physics	23	5500
Drilling, Magma, and Diagnostic Technologies	46	1500

*Compiled February 1975.

NUMERICAL MODELING

Numerical modeling of various types of earth motion, from very low rates of deformation representing quasi-static behavior to high rates characterized by shock-wave propagation, has important applications ranging from mining and drilling to earth-penetrating weapons. Sophisticated numerical techniques, which have been developed and verified for calculating static and dynamic deformation phenomena in homogeneous laboratory material such as metals and plastics, have evolved to a point where they are being applied effectively to geologic materials. Any specific investigation involves both theoretical and experimental efforts. Theoretical work is associated with continuing improvements in numerical techniques as well as the development of better models for representing the physics of the various processes involved. Experimental efforts include laboratory determination of relevant material properties, as well as full-scale experiments with which computations are correlated. Numerical techniques for modeling motions in soils and rocks are important because, once verified, they provide technical answers more quickly and cheaply than experiments, and insight gained from this theoretical work often accelerates technical advancement.

Numerical Methods

A number of numerical techniques are employed to study geomaterial motions. Finite-difference methods find applications in material-response studies, while finite-element methods are more suitable for structural-response problems. Lagrangian techniques are appropriate for problems involving relatively low distortion, while Eulerian methods are generally used for high-distortion situations.

Current Capabilities

- Lagrangian finite-difference methods
  - One-dimensional dynamic
  - Two-dimensional dynamic
  - Three-dimensional dynamic
- Eulerian finite-difference methods
  - Two-dimensional dynamic
  - Three-dimensional dynamic
- Finite-element methods
  - Two-dimensional static and dynamic continuum
  - Three-dimensional static continuum
  - Two-dimensional static and dynamic shells
  - Three-dimensional static and dynamic shells
  - Creep

Physical Modeling of Earth-Material Behavior

The success and accuracy with which numerical methods reproduce experimental results depends largely on the adequacy with which physical models represent the behavior of various geomaterials. A continuing effort to improve existing models and develop new ones is an integral part of this program. (Item 1)*

Current Activities

- Three-phase equations of state
- Porous soils
- Viscoelastic and rate-dependent constitutive relations
- Variable-yield models
- Soil and rock "cap" models**
- Failure and fracture models
- Polymorphic phase changes

Measurement of Earth-Material Properties

Laboratory measurement of rock and soil properties serves the dual purpose of providing data required by physical material models and of providing a ready way of characterizing and ranking the various geomaterials. (Item 2)

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*See Highlights below.

**Constitutive models with pressure- and history-dependent yield surfaces.

Current Activities

- Static properties
  - Uniaxial tests
  - Triaxial tests
  - Multiaxial tests
- Creep properties
  - Consolidation of soils
  - High-temperature creep of rocks
- Dynamic properties
  - High-strain-rate testing
  - Triaxial Hopkinson bar
  - Gas-gun plate-impact tests
  - Electron-beam excitation

Applications

Important applications for geomaterial-motion calculations include such fields as earth-penetrating weapons and energy research. The ultimate aim of each project mentioned below is to optimize the design of both components and total systems so that they can most efficiently perform their desired function. (Items 3-6)

NUMERICAL MODELING

Current Activities

- Terradynamics
  - Remote material identification
  - Penetrability assessment
  - Prediction of penetrator loads and response
- Drilling
  - Rock-breakage processes
  - Cutter loads and design
  - Spark-drill performance
  - Water-jet performance
- Mining and excavation
  - Rock breakage
  - Tool performance
  - Water-jet performance
  - Explosive performance
  - Roof support and subsidence
- In-situ processing
  - Bed preparation
  - Roof support and subsidence
- Gas/oil stimulation
  - Underground explosions
  - Stemming
  - Ground shock
  - Hydrofrac
  - Roof support and subsidence
  - Rock fracture

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Water Jets Impacting Solids*

A two-dimensional, Eulerian, finite-difference code calculation was performed to examine the influence of a deforming target surface on the flow-field of an impacting water jet and to compare with existing solutions for a water jet impacting a rigid surface. The surface in this case had elastic-plastic properties similar to those of rock. In the computer simulation, a compressible, inviscid, cylindrical column of water 2 mm in diameter is made to strike the target at a velocity of Mach 2 (3 km/s). Computer code results such as those shown in Figures 1 and 2 reveal that solutions obtained for pressure and velocity distributions from water jets impacting rigid surfaces are poor approximations to realistic situations in which the target surface is deforming during jet impingement.

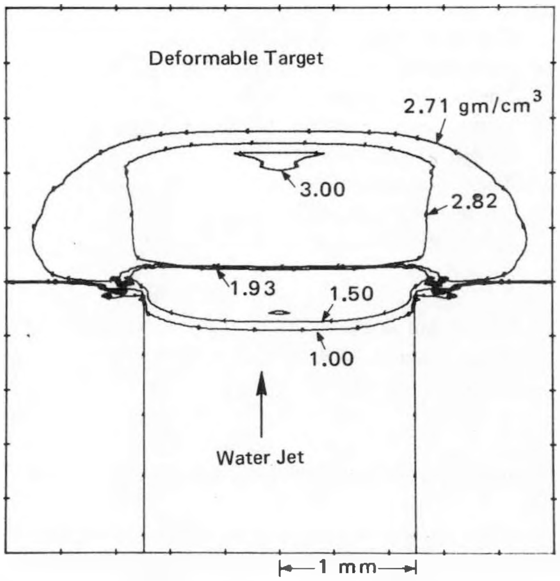

Figure 1. Density contours in jet and target 0.16 μsec after impact

NUMERICAL MODELING

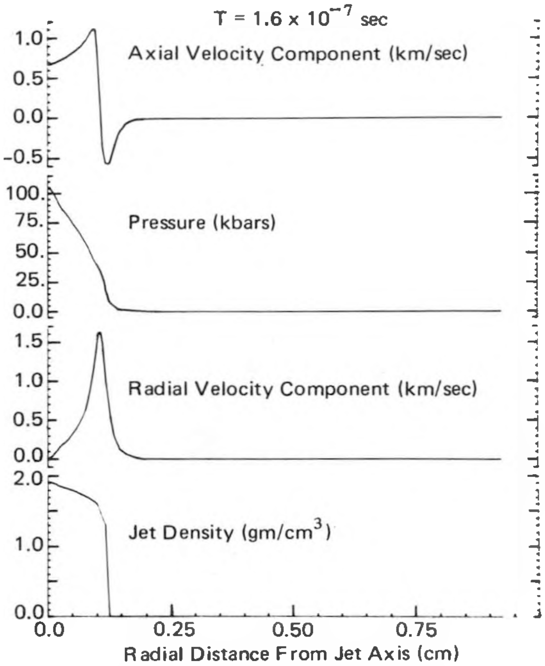

Figure 2. Radial distribution of jet velocity components, pressure and density at initial impact position.

Item 2. *Static Triaxial Stress Studies of Oil Shale*

A triaxial test machine is used to study the yield and fracture behavior of anisotropic oil shales as a function of kerogen content under various pressures. A computer is used to control the stress level as a function of confining pressure. These studies are providing data needed to construct constitutive models to be incorporated into numerical codes. A typical result (Figure 3) illustrates an increase of volumetric strain with compressive stress that is characteristic of soils and rocks. The soil and rock models are being used for engineering calculations in oil shale retort rubblization.

Item 3. *Spark-Drill Analysis*

A technique that may improve geologic drilling involves the use of high-energy electrical spark discharges to perform the mechanical work conventionally done by rotary drilling bits. The two-dimensional Eulerian computer code CSQ is used to clarify the relative importance of the initial shock produced by the spark and subsequent loading caused by bubble generation and collapse. (A bubble is formed by vaporization of fluids surrounding the spark-drilling mechanism.) The computations take into account the shape of the electrode, the proximity of the hole bottom, and the ambient pressure (depth) of the drilling medium. Figure 4 shows the bubble at 1 ms after a typical spark discharge. In this case, the electrode is 50 mm in diameter and spaced 50 mm from the hole bottom. The discharge of electrical energy produces an instantaneous specific internal energy of about 8.5 MJ/kg in the region directly below the center of the electrode.

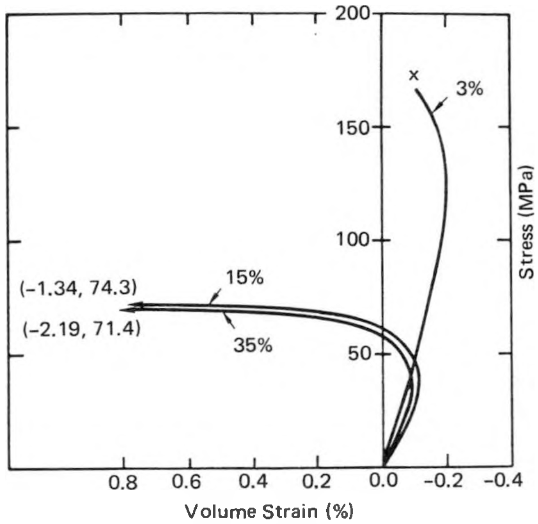

Figure 3. Axial stress-volume strain behavior of oil shale as a function of kerogen content (volume percent). Failure or fracture is denoted by X for the 3-percent shale and by the strain and stress values noted for the 15 and 35 percent shales.

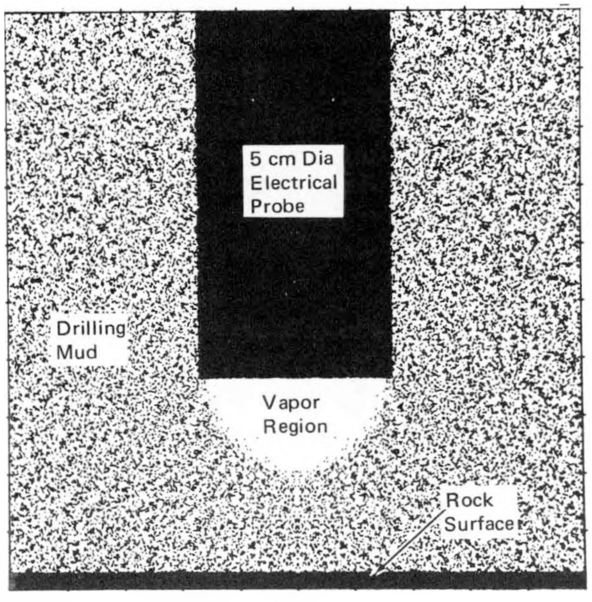

Figure 4. Computer simulation of the bubble formed when a 112-joule electrical spark is discharged in 5 μs in water.

Item 4. *Dynamic Loads on Earth-Penetrating Projectiles*

In conjunction with terradynamic experiments, two-dimensional stress-wave propagation codes are employed to predict penetration depths, deceleration histories, and dynamic loads imposed on projectiles. Constitutive relations for earth materials, determined by shock-wave and static triaxial stress experiments, have been incorporated into the TOODY two-dimensional code. Given appropriate geomaterial property data, calculations of projectile penetration can be performed for single or layered media. Material response is observed, including compaction behavior, and its relation to projectile velocity, nose configuration, and loads of the projectile is assessed to optimize projectile designs (Figure 5).

Item 5. *Triaxial Stress Facility*

The computer-controlled triaxial facility, shown in Figure 6 with the smallest test cell in place but without the computer, is especially adapted for the study of the yield and fracture surfaces of materials with complicated anisotropic constitutive response such as rocks and soils. Dilatancy effects, which are common in these materials, are being studied using this facility. The machine obtains very rapid response through a combination of computer-activated servo controls and extreme machine stiffness which permits it to follow the rapid decrease in flow stress that succeeds initial yielding in rocks. The machine has a 1.78 MN (400 kip) rating with 1 GPa (10 kbar) hydrostatic pressure. Machine stiffness is rated at 7.0 x 10^9 N/m (40 x 10^6 lb/in.) and loading rates of 2.9 cm/sec (1.16 in./sec) can be achieved.

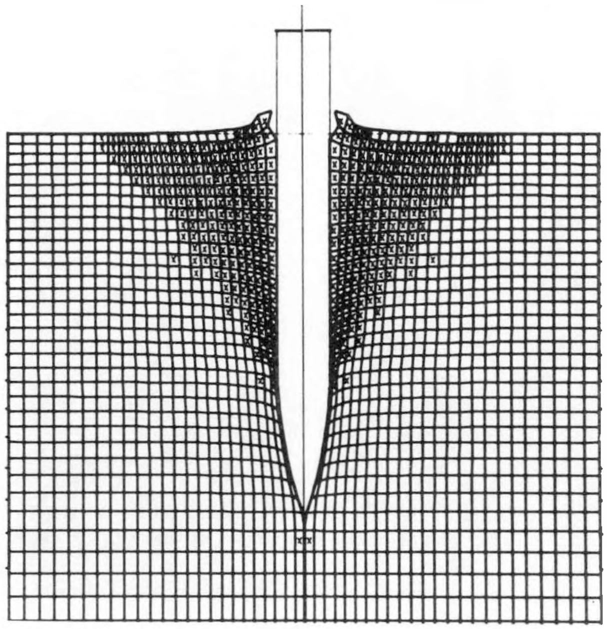

Figure 5. Regions of failure (8 msec after impact) produced in a soil medium by a 0.165-m-diameter projectile impacting at 152 m/s.

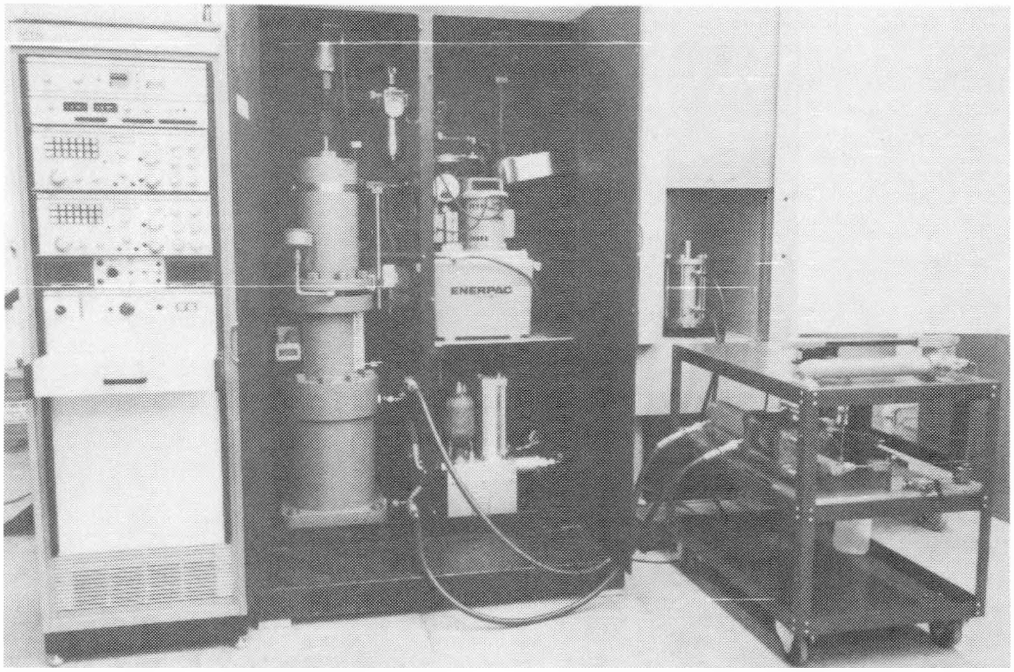

Figure 6. Computer-controlled triaxial stress facility

NUMERICAL MODELING

Item 6. *Failure Envelope for Geologic Materials*

The triaxial test facility is used to determine how static mechanical properties such as Young's modulus, yield stress, and fracture stress of geologic materials vary with confining pressure. Knowledge of these properties permits determination of failure surfaces, needed for the formulation of constitutive models. A typical result (Figure 7) illustrates the failure envelopes for three grades of oil shale. Data such as these are being used in constitutive models, particularly cap models, that are incorporated in existing numerical codes used for engineering calculations of oil-shale retort fragmentation, spark-drilling feasibility and design of cratering and earth-penetrating projectiles.

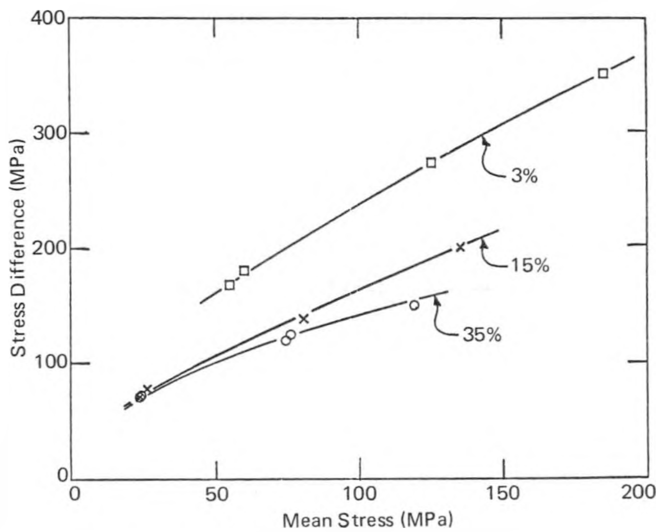

Figure 7. Failure envelopes for three grades of oil shale from the Anvil Points Mine. Stress axis was perpendicular to bedding planes. Oil-shale grade is labeled as volume percent of kerogen.

TERRADYNAMICS

Terradynamics is the study of earth penetration with high- and low-velocity vehicles. This program entails the study of the dynamic response of soil and other geomaterials to the intrusion and passage of high-velocity penetrators, as well as vehicle configurational studies to define more effective and stable penetrators. Activities include a test program to experimentally obtain earth-penetration data, the development of empirical equations to predict penetration depth and deceleration, remote target sensing and evaluation, and the development of earth-penetrating systems for specific applications. A penetrator instrumented to measure its own response during penetration of a known earth material is also used as a tool for remote measurement of the penetrability of unknown earth materials. Full-scale tests into natural earth targets provide supportive data for this primarily empirical program, and also provide phenomenological data for theoretical studies.

Experimental Penetration Studies

Data necessary for a better understanding of earth-penetration phenomena are obtained through full-scale tests into natural (in-situ) soil and rock targets. The penetrators are instrumented to measure instantaneous deceleration along both the lateral and longitudinal axes of the vehicle. The deceleration-versus-time records, twice integrated, provide a basis for calculating structural loads on the penetrator and its instrumentation, and a motion/time history during penetration. Since penetrator deceleration is the result of resistance offered by the target medium, an indirect measurement is made of the physical properties of the target as related to penetrability. (Items 1-6)*

Current Activities

- Parametric study of penetrator configuration
- Underground trajectory studies
  - Target materials, including nonhomogeneous targets
  - Impact angle
  - Angle of attack
  - Impact velocity
  - Configuration to enhance stability
- Complex penetrator configurations
  - Multiple body diameter
  - Terrabrakes (drag devices)
  - Detachable afterbodies
- Target media
  - Rock
    - Layered
    - Suspended boulders
  - Soil
    - Layered
- Data acquisition
  - Penetration path
  - Rigid-body deceleration
  - Effect of penetration on target material
  - Structural effect on penetrator
  - Penetration distance
  - Failure mechanism in massive rock
  - Effect of physical properties on penetrability

*See Highlights below.

Test Techniques

Since the efficacy of scaling penetrators and earth materials is not adequately understood in terradynamics, most tests are conducted in undisturbed earth targets. This requirement dictates that while the design and operation of field-test facilities are considered supportive activities, there must be an active technical interchange between the designer of the experiment and the designer of the facility or test capability. The test technique is selected on the basis of the desired impact conditions (angle, velocity), target requirements (accessibility, size), and penetrator configuration.

Current Activities

- Penetrators dropped from aircraft
  - Tests in remote or inaccessible areas
  - Low impact velocity (less than 500 m/s)
- Mobile air gun
  - Small penetrators (less than 7 cm in diameter)
  - Low impact velocity (less than 150 m/s)
- 8-Inch recoilless gun
  - Soil and rock penetrations at intermediate velocities
- Recoilless rifle (Davis gun)
  - High velocity (up to 1000 m/s)

TERRADYNAMICS

Empirical Prediction Techniques

In the absence of adequate theoretical solutions, empirical equations are developed to predict the penetration depth and deceleration profile of a projectile. Basic equations have been formulated for simple penetration into homogeneous natural-earth materials and layered earth materials, and complex penetrator shapes in homogeneous earth materials. Parameters considered were penetrator mass, diameter, nose shape, length, weight-to-area ratio, terrabrakes, detachable afterbodies, impact velocity, and target penetrability. (Item 7)

Current Activities

Definition of soil penetrability in terms of standard soil properties
Continued review of limits and degree of applicability of equations

Remote Target Penetrability Assessment

The objective of this activity is to maintain the capability to estimate the penetrability of target locations any place on earth. The estimates are based on the study and evaluation of subsurface geotechnical data by geotechnicians knowledgeable about the kinds of materials in the subsurface. On the basis of their information, experienced terradynamicists make penetrability estimates. The data needed for these assessments are derived from geologic maps and reports, soil maps, stereo air photos, other remote sensing data, well logs, and foundation borings. The validity of the assessments is governed largely by the amount and quality of these data available to the geotechnician.

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *High-Velocity Soil Penetration*

The terradynamics program is concerned with impact velocities from 30 to 1000 m/s, with particular emphasis on velocities above 450 m/s. Problems of a stable underground trajectory and penetrator structural strength are of primary concern.

A 295-kg earth penetrator impacted dry-lake playa at Tonopah Test Range, Nevada, at a velocity of 843 m/s and penetrated 64 m into moist-to-dry silty clay (Figures 1 and 2). The length-to-diameter ratio of 10 for the penetrator is considered near minimum in providing a stable subsurface trajectory. The penetrator, 22.9 cm in diameter, was made of D6AC steel to give it the strength to survive penetration. An inverse plug-type nose joint was used, and posttest evaluation of the recovered penetrator showed that shear boosters used in the joint had yielded, indicating that failure of the joint was imminent. From this and 12 other penetration tests at 460 to 900 m/s, it has been determined that a suitable soil penetrator should have a general configuration as shown in Figure 2, be made of D6AC steel or better, and if possible not have a nose joint.

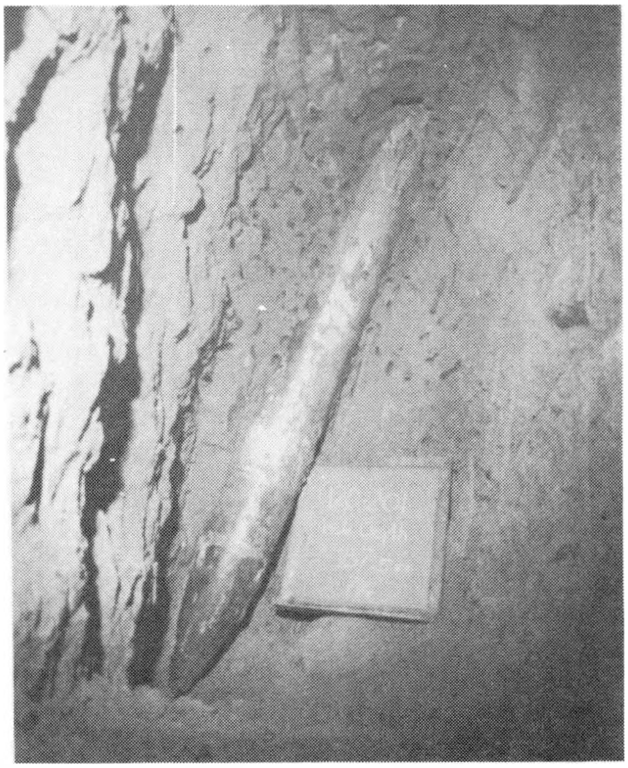

Figure 1. High-velocity penetrator imbedded in soil.

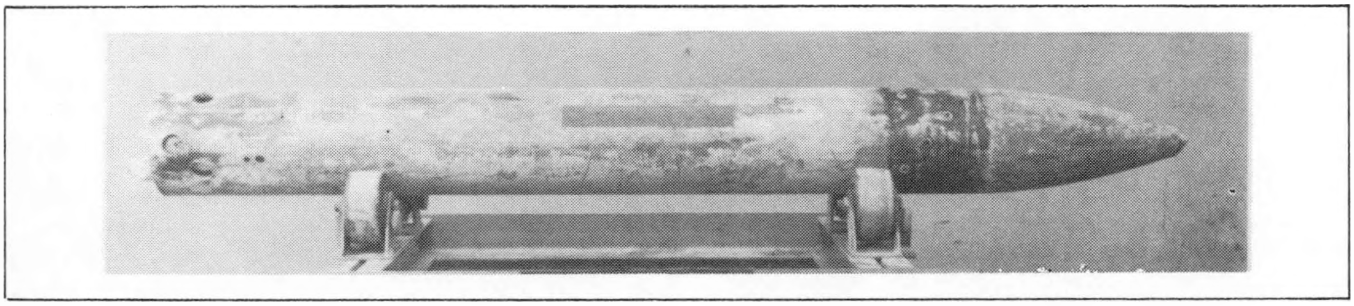

Figure 2. Recovered penetrator

Item 2. *Rock Penetration*

This program is focused upon specific problems attendant upon penetrating very hard earth materials. Terradynamic vehicles have survived penetration of 4.9 m of a massive formation of Tres Hermanos sandstone (unconfined compressive strength of 560 to 700 kg/cm^2). The vehicle configuration was the same as used in the high-velocity soil penetration tests (Figure 2). The impact velocity was 300 m/s, penetrator weight was 364 kg, and the diameter was 22.8 cm. As with the high-velocity penetrator, the weakest part of the vehicle was the nose joint, which is being avoided when possible on current designs. Instrumented rock penetrators typically record rigid-body peak decelerations of 4000 g. Other rock formations that have been successfully penetrated include:

Material	Compressive Strength (kg/cm^2)
Madera limestone	850 to 1000
Zuni granite	400 to 550
Thirsty Canyon welded tuff	290 to 600
Welded agglomerate	200 to 400

Item 3. *Mars Penetrator*

A penetrator is being designed to emplace scientific experiments below the surface of the planet Mars. The vehicle will make possible subsurface experiments in seismology, geochemistry, water detection, vertical-profile geology, and possibly heat flow. System design calls for the projectile to enter the Martian atmosphere in a high-drag configuration and to be programmed so that it will penetrate the surface in an attitude and at a velocity that will result in subsurface emplacement of the instrument package (Figure 3). As the vehicle impacts, a separable afterbody containing an antenna, a transmitter, and a command receiver is left at the surface. The afterbody remains connected to the penetrator by a multiconnector umbilical paid out from the forward section of the vehicle during penetration. A sequence of scientific experiments is then conducted, and the data are stored in an on-board memory until they can be transmitted to the orbiter for relay to earth.

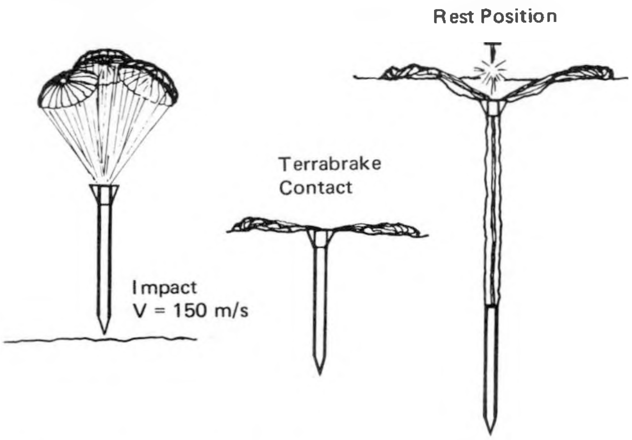

Figure 3. Implant sequence

Item 4. *Ice Penetrometer*

A penetrometer was developed for the U. S. Coast Guard to remotely measure the thickness of sea ice. The implant characteristics are shown in Figure 4. An accelerometer in the penetrator senses deceleration as it passes through the ice, and the data are transmitted in real time to a receiver in the drop aircraft. Two integrations of the deceleration-versus-time curve give velocity and depth profiles. By noting penetration depth at the time the deceleration level approaches zero, indicating that the penetrator is entering the water below the ice, one can determine ice thickness within ±7 cm. Ice thicknesses of up to 3 meters can be measured.

TERRADYNAMICS

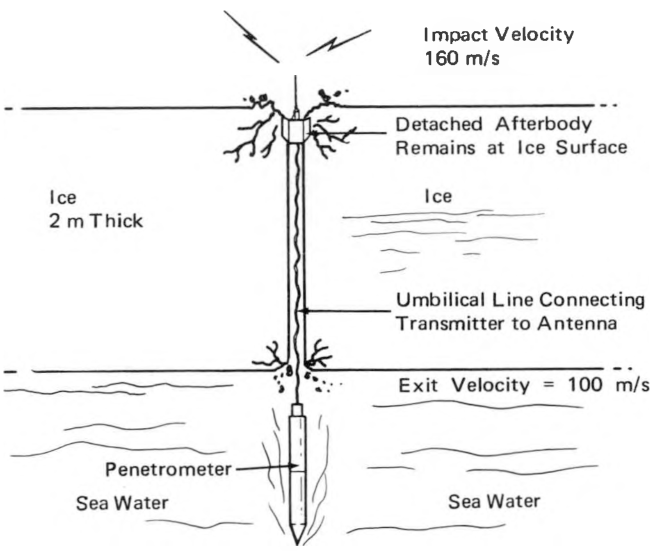

Figure 4. Ice penetration event

Item 5. *Earth Implant Systems*

For use during the Southeast Asia conflict, nine different air-delivered earth penetrators were developed that allowed implantation of seismic, acoustic, or other sensors (Figure 5) behind enemy lines to detect the passage of troops and vehicles. The system was designed to penetrate hard soil, leaving only the antenna above the soil surface. In soft soil, terrabrakes on the aft end of the penetrator engage the soil, allowing less than 38 cm of additional penetration so that the ground planes and vertical radiator of the antenna remain above the surface.

Item 6. *Aircraft Crash Investigation*

At the request of the U. S. Air Force Academy, an investigation was made of a T33 crash to determine whether terradynamic technology could be used to calculate the aircraft's velocity at impact. Soil penetrability was measured in the vicinity of the crash, and an analysis was made of the penetration performance of lead ballast weights which were in the nose of the aircraft. It was determined that the aircraft was traveling at 316 ± 25 knots at impact. This information helped the crash investigation committee to reconstruct the probable cause of the accident.

Item 7. *Earth-Penetration Depth-Prediction Equations*

The following equations were developed to predict the penetration depth of a simple penetrator in a homogeneous earth material:

$$D = 2\,SN\sqrt{W/A}\,\ln(1 + 2V^2\,10^{-4}), \quad V < 61\ \text{m/s}$$

$$D = 0.0117\,SN\sqrt{W/A}\,(V - 30.5), \quad V \geq 61\ \text{m/s}$$

where

D = Penetration depth along the path, meters
S = Index of soil penetrability, a constant that must be estimated on the basis of available soil data, dimensionless
N = Nose-shape coefficient, dimensionless
W = Penetrator weight, Kg
A = Area of penetrator, cm^2
V = Impact velocity, m/s

These equations are generally considered accurate within ±20%, with the greatest inaccuracy occurring in estimation of the value of S.

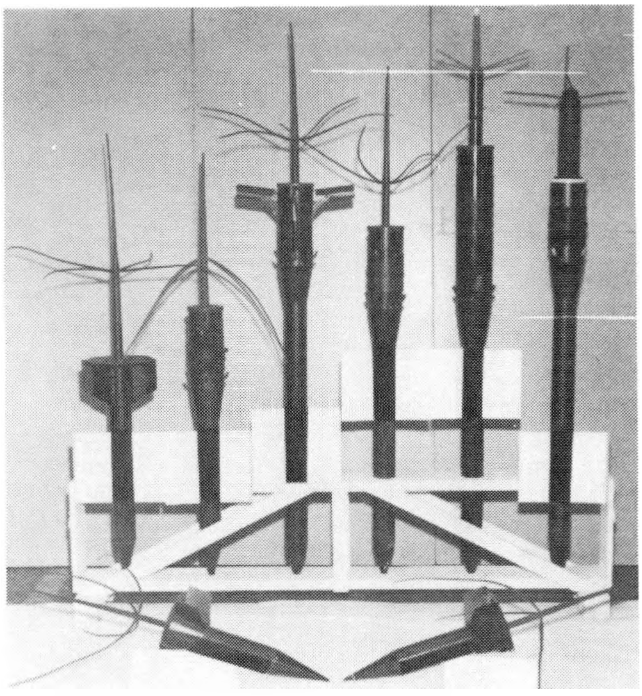

Figure 5. Earth penetrators

UNDERGROUND PHYSICS

Research in earth physics is directed toward understanding of the response of the earth and man-made structures to loads resulting from underground nuclear detonations, earthquakes, earth-penetrating missiles, detonations for industrial purposes, and acoustic generators. Investigations have encompassed stress and motion regimes ranging from megabars near nuclear detonations to minute seismic and acoustic vibrations of the earth. Seismic data have been used to study earth structure, locate subsurface features, and compare characteristics of earthquakes and explosions. High explosives have been used to examine many facets of underground explosions, particularly cratering effects. Interactions of earth motions with surface and underground structures are examined to assure safety and facility protection near underground detonations. Containment of radioactivity from nuclear detonations is an important aspect of underground physics studies, requiring an understanding of such behavior as fracture development and propagation, and fluid flow in cracked and porous media. This capability has found application in such fields as in-situ utilization of coal, oil shale, and recovery of heavy oils. All these areas of investigation are pursued experimentally, analytically, and with a wide range of numerical machine codes.

Phenomenological Studies

Investigations in this area involve prediction and experimental confirmation of physical phenomena that occur in geologic media after an explosive detonation. Predictive techniques may use empirical correlations with past experience, but mostly rely on numerical calculations performed on large computers using one- and two-dimensional codes. High-energy explosive detonations in alluvium, volcanic tuff, granite, salt, and several other rock types provide shock environments in which experimental measurements of shock parameters such as stress, acceleration, and particle velocity confirm and provide data to normalize the material equations of state. Postshot mining reentry into tunnels that have collapsed from detonation-induced ground shock has provided insight into problems of underground cavity stability, relative motions of structures in tunnels, stemming (plugging of emplacement holes), cavity and chimney formation, and many other phenomena amenable to visual inspection. Sandia Laboratories operates six seismic stations, five in Nevada and one in Albuquerque. All contain wide-band and short-period seismometers, and the Albuquerque station includes a laser strain seismometer 1600 meters long. (Items 1-4)*

*See Highlights below.

Current Activities

- Laser strain seismometer
- Operation of six seismic observatories
- Near-detonation surface-motion experiments
- Tunnel containment diagnostic measurements
  - Active acceleration
  - Passive stress
  - Stress
  - Time of arrival
  - Displacement
  - Temperature
- Free-field earth motion/stress measurements
- In-situ earth stress investigation
- Hydraulic fracturing experiments
- Tunnel stemming and chimney permeability
- Postshot tunnel reentry observations
- Instrumentation for in-situ coal and oil shale conversion
- Airblast phenomena from detonations
- Pore pressure variations due to seismic loading

Analytical and Material Studies

To explain the phenomena that accompany underground detonations, various analytical tools have been developed and applied. Numerical codes are used to address extreme temperature and pressure environments close to the detonation and in the strong-motion regime where motions are grossly inelastic and not amenable to analytic solution. Elastic-wave propagation in layered

UNDERGROUND PHYSICS

media is also treated numerically when the model is too complex for analytic solution. Both analytical and numerical techniques are applied to ascertain response of structures and openings imbedded in propagating stress fields. Methods of calculating compressible and incompressible fluid flow in permeable media are being developed. Theoretical studies of natural-earth stress and its influence on crack propagation and hydraulic fracture are being conducted.

Material properties necessary to the above studies are determined in-situ whenever possible but must be determined in laboratory experiments in many cases. Evaluation of geophysical bore-hole logs, seismic surveys, and surface electrical logs are used in the field, while high-pressure static and dynamic rock performances are determined in the rock mechanics laboratory. (Items 5-7)

Current Activities

- Influence of near-source layering on seismic signals
- Seismic efficiency of detonations in various geologic environments
- Stability of underground openings subjected to dynamic load
- Effectiveness of shock isolation grouts and cements
- Behavior of dry sand under confining stress
- Physical properties of tuff, granite, and oil shale
- Determination of in-situ stress by overcoring and hydraulic fracturing
- Source parameters from seismic wave inversion
- Correlation of airblast with degree of stemming (plugging of emplacement hole)
- Mapping in-situ coal burn with direct and indirect techniques
- Investigation of explosive fracture of oil shale
- Location of hydraulic fractures using geophysical methods
- Variations of in-situ stress with imposed ground-shock loading
- Influence of temperature and pressure on oil shale fractures and openings
- Behavior of structures loaded beyond their yield strength

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Item 1. *In-Situ Stress and Fracture Mapping of Hydraulic Fracturing of Tuff*

Hydraulic fracturing experiments were performed in the tuff formation of Rainier Mesa at the Nevada Test Site. The fracturing was performed in both vertical and horizontal boreholes with approximately 442 m of overburden, and in the vicinity of an existing tunnel complex. The principal stresses of the formation were derived from pressures used in the hydraulic fracture process and were of the order of 13 MPa maximum and 6.2 MPa minimum. Fracture patterns created in the horizontal holes were labeled with dyed water. The fracture pattern in the vertical borehole was tagged by a dyed cement grout. Hydraulic fracturing was performed in more than one zone in all boreholes. The fractures produced were mapped by mining from the tunnel complex and by physically examining the fractured formation. The fractures were found to have an approximate bearing of N45°E, which is also the direction of maximum principal stress. The hydraulic fracture result compared favorably with results from overcore testing.

Item 2. *Airblast and Ground-Motion Documentation*

Sandia and other agencies are involved in a continuing effort to calculate effects of underground explosions. To verify these calculations a recent series of four 10-ton high-explosive cratering detonations was conducted by the Defense Nuclear Agency. Sandia fielded instrumentation totaling 340 channels of ground-motion, stress, time-of-arrival, and air-pressure data. In addition, surface-motion photography was obtained. The experiment also yielded information on the effects of various emplacement hole diameters and the presence or absence of hole stemming. Extensive data analysis shows that geological differences between the four shot sites obscured differences in ground motion or stress that may have resulted from emplacement hole variations. Comparative parameter studies need to be conducted in as homogeneous a medium as possible. It was concluded, however, that gas escaping from the small-diameter (18 cm ID), 12-meter-deep hole contributed less than 20 percent of the total gas-venting impulse. It would appear that the small open hole was pinched off by hydrodynamic shock before substantial venting occurred. Comparison of data with calculations reveals that adequate modeling, especially at low stress levels, should incorporate the material layers and a good equation of state for each layer. Measurement of airblast parameters appears promising as a diagnostic aid in estimating variations of radioactivity injected into the air by nuclear cratering events of different emplacement geometries.

Item 3. *Surface-Motion Measurements From Underground Nuclear Detonations*

For selected nuclear detonations at the Nevada Test Site, three orthogonal components of ground-surface motion are measured with accelerometers and/or particle-velocity gages. Data are obtained from the point on the surface directly above the detonation out to distances several times the burial depth of the explosion. Information from transducers is telemetered to a central recording facility located up to 35 km from the explosion. Ground-motion data are used to analyze unusual containment behavior, to document differential motion across known or suspected faults, and to verify and improve predictions of strong motion to allow adequate shock isolation for the protection of trailers and buildings in the vicinity of the detonation. The influence of geologic media, especially shot environment on coupling, and acoustic layering on wave propagation, is being studied. Data are compared with code calculations to ascertain approximations of the model and to provide confidence in predictive calculations. Acoustic interfaces at depth have been observed to affect surface motions, but except for extreme cases not significantly. Energy coupling, on the other hand, may be significantly affected by the acoustic velocity and strength of the shot medium and can change surface motions by as much as an order of magnitude.

Item 4. *Free-Field Ground Motion From Underground Detonations*

Free-field ground motion induced by more than 60 contained underground nuclear explosions detonated at the Nevada Test Site and elsewhere has been measured. Data have been collated and analyzed for effects of the geologic environment on attenuation of peak amplitudes. The information spans the hydrodynamic and nonlinear regions out to the linear-response regime. More than 1100 peak stress and motion parameters were involved. Geologic media represented are dry alluvium, "dry" and "wet" tuff, and such hard rocks as granite, dolomite, salt, and sandstone. Regression analysis of the data, scaled by cube root of the yield and segregated into the various environments, indicates little difference in particle velocities for the different media through the strongly hydrodynamic region. Peak stress in this regime is attenuated as the inverse 2.96 power of distance, and particle velocity as the inverse 1.87 power. Outside the hydrodynamic region, scaled acceleration and particle velocity are of similar magnitude in saturated tuff and hard rock but are lower in dry tuff and lower still in alluvium. Scaled displacements are of roughly similar amplitude except in dry alluvium where they may be as much as one-half to one order of magnitude lower. Analysis of all particle velocities from the hydrodynamic regions and from wet tuff and hard rock in the nonlinear region shows a single and continuous trend over an amplitude range of about five orders of magnitude. The regression equation for this group of data is

$$u = 1.85 \times 10^4 (R/W^{1/3})^{-1.76 \pm 0.02}$$

where u is particle velocity in meters per second, R is range in meters and W is detonation yield in kilotons.

Item 5. *Seismic Studies*

Sandia has recorded the seismic data from all U. S. underground nuclear tests since 1961. Five stations are located around the Nevada Test Site at distances ranging from 144 to 379 km. A seismic observatory in Albuquerque has recently been supplemented by construction of laser strain seismometers 1600 and 250 meters long. One project of recent interest was correlation of amplitude data from this net with a consistent set of teleseismic magnitudes. This correlation was then used to investigate the relation between magnitude and geographic detonation-site parameters. Significant variations were found to exist for different media and, to a lesser extent, for similar source media separated by a few kilometers. The strain seismometer, by virtue of its broad dynamic and spectral range, records seismic signals without prefiltering. Digital filtering can then be used to suppress portions of the spectrum at will. Noise studies throughout the seismic spectrum will be one of the first efforts completed with this system.

DRILLING, MAGMA, AND DIAGNOSTIC TECHNOLOGIES

The activity in drilling, magma, and diagnostic instrumentation studies is directed toward the improvement of drilling penetration rates, the investigation of the properties of magma for possible energy extraction, and the development of diagnostic instrumentation for the definition of geological formations and for the measurement of in-situ energy extraction processes.

Improved Rotary Drilling Systems

New drill bits with either long life potential, higher penetration rates, or both, are being designed and tested. All proposed drilling systems are directly compatible with existing rotary drilling platforms. Of primary interest are hard-rock (geothermal) bits and slim-hole bits. (Items 1-3)*

Current Activities

- Terradynamic bit
  - Small-projectile rock penetration and fracture
  - Down-hole magazine and launcher design
  - In-situ drilling-rate tests
  - Composite projectile design
- Down-hole changeable bit
  - Mechanical design
  - Model fabrication
  - Prototype design and fabrication
  - Bearing-life testing
  - Laboratory drilling-rate testing
- Continuous-chain drill
  - Mechanical design
  - Model fabrication
  - Prototype design

Spark-Gap Drilling Research

Research in this area is currently directed toward understanding the complex phenomena associated with a high-energy spark discharge in a liquid and the resultant cavitation and cavity collapse. A broad series of experiments is being conducted to provide physical data for an analytical modeling program. Spark bits are being designed as part of the search for bit materials and for configurations capable of surviving the spark-induced environment for long periods of time. Various earth materials are being characterized, exposed to the spark bit, and analyzed to determine rock failure mechanisms. (Item 4)

Current Activities

- Laboratory drilling tests
- Spark-induced bubble dynamics studies
- Near-field shock-wave measurements in a liquid
- Spark energy distribution studies
- Optimum bit configuration studies
- Long-life bit design studies
- Down-hole electrical system preliminary design
- Mechanical-property measurements of rocks of interest
- Multidimensional computer modeling of the spark-induced event

Magma Research

Activity in magma research is directed toward the determination of the physical properties of magma, its compatibility with materials, the location and definition of deeply buried circulating deposits of magma, and the technology for extracting energy. (Item 5)

Current Activities

- Materials compatibility
- Corrosive effects of volcanic lavas
- Physical properties of lavas
- Heat transfer
  - Phenomena
  - Coefficients
- Remote Sensing Techniques

Diagnostic Instrumentation

Diagnostic technology is directed at the development of sensors, monitoring techniques, and data analysis systems by which the response of geologic media to a variety of forcing functions can be measured. Remote sensing techniques are being developed as are instrumentation systems which can successfully perform within the harsh in situ

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*See Highlights below.

environments. The application of this diagnostic technology in experimental field efforts coupled with numerical modeling allows a significant understanding of the behavior of geologic media. (Items 6-8)

Current Activities

- Field applications
  - Active seismic/acoustic
  - Passive seismic/acoustic
  - Resistivity
  - Thermal methods
    - Branched thermocouples
    - Gradient thermometry
  - Long-line gas sampling
  - Overburden tilt
  - Overburden displacement
  - Geophysical logging
- Laboratory support
  - Material properties
    - Coal
    - Oil shale
    - Associated formations
  - Material response
    - Acoustic properties
    - Acoustic emission
    - Resistivity
  - Simulated in situ environment
    - Material compatibility
    - Process parameter determination
- Analytical modeling
  - Instrumentation analysis
  - Data reduction techniques
    - Cross-correlation
    - Autocorrelation
    - Fast Fourier transformation
    - Spectral analysis
  - Heat transfer and flow analysis
  - Application of ablation codes
  - Process control development

Remote Sensing Techniques

Seismic and electromagnetic methods are the primary remote sensing techniques under investigation. Seismic sensors are being used to locate by triangulation sources of discrete signals created by stimulation or reaction within geologic media. Dynamic measurements of explosive stimuli are also included. At the surface, potential and electrical resistivity methods are used to measure underground features and changes to considerable depths. The detection of changes and the need for high resolution characterize the application of these techniques.

Current Activities

- Field applications
  - Mapping of massive hydrofracs
  - In situ coal gasification
  - In situ oil shale processing
- Techniques
  - Surface potential
  - Surface resistivity
  - Seismic triangulation
  - Free field earth motion/stress measurements
  - Explosive fracturing diagnostics

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Terradynamic Drill Bit*

The cost of hard-rock drilling is high because bit penetration rates are low and bit life is short. This has led to the development of the Terra-Bit (Figure 1) which would use small-diameter, high-velocity projectiles to fracture hard formations in front of a conventional rock bit. The concept is based on the hypothesis that it will be appreciably easier to drill a rock face that is already highly fractured, and that bit life will consequently be longer and penetration rates higher than with an unbroken rock face. A series of in-situ field tests has been conducted to test the theory, with the results shown in Figure 2. Bit penetration rates into Madera limestone (compressive strength 850 to 1000 kg/cm^2) were improved by almost a factor of 2, which is sufficient to warrant continued development of the concept. Future efforts will include development of the down-hole magazine, launcher, and projectiles made of lead, copper, or other materials leading to a demonstration prototype.

DRILLING, MAGMA, AND DIAGNOSTIC TECHNOLOGIES

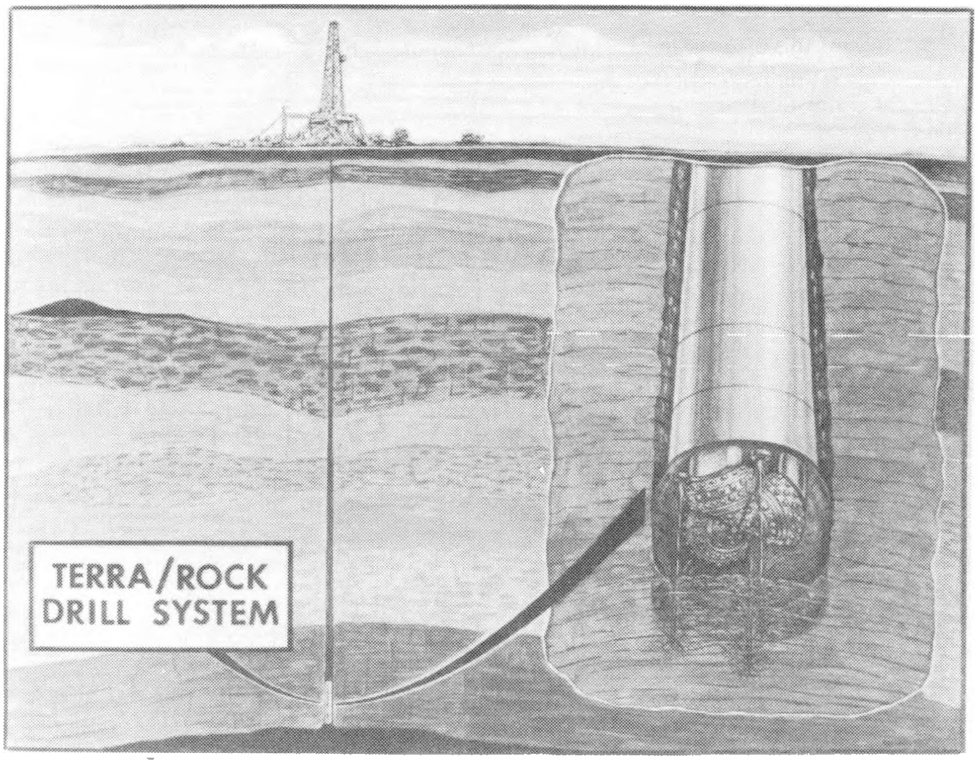

Figure 1.

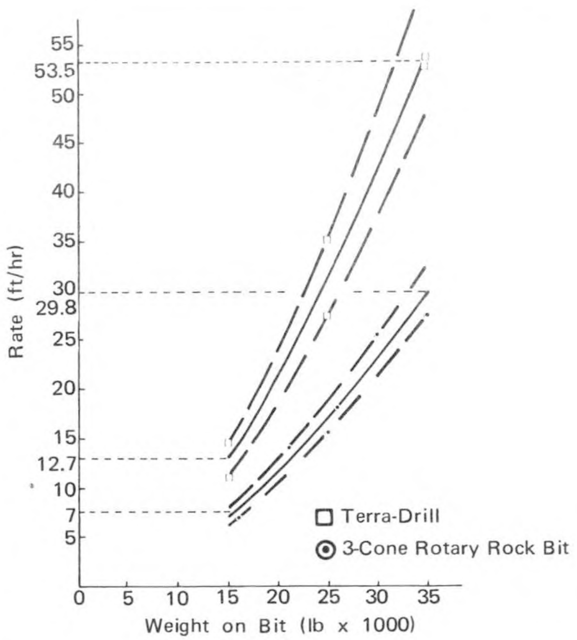

Figure 2. Terra-Drill vs rotary rock bit (7-7/8 in. diameter bit – 60 rpm – Madera limestone)

Item 2. *Down-Hole Changeable Bit*

A novel technique is being developed to change the cutting surface of a roller-cone bit while it is down-hole (Figure 3). The bit would contain a number of new cutting heads in a down-hole magazine. A cutting head is made up of an outer set of gage cutters, which cut the hole to "gage" diameter, and an inner cutter. When a cutting head wears, as determined by drilling-rate measurements made on the drilling platform, the old head can be moved into the magazine and a new one cycled into drilling position. The gage cutters are mounted on a folding structure so they can be rotated in and out of position. Many new cutter heads can be stored in the bit, joined by lengths of chain to cam followers attached to the heads. Appropriately placed bars could be attached to the chain for indexing the cutter heads. The changeable bit would allow cutter-head changes without the drill string being drawn from the borehole. If bit life comparable to that of current roller bits can be achieved, this system could save considerable time and money in deep drilling operations.

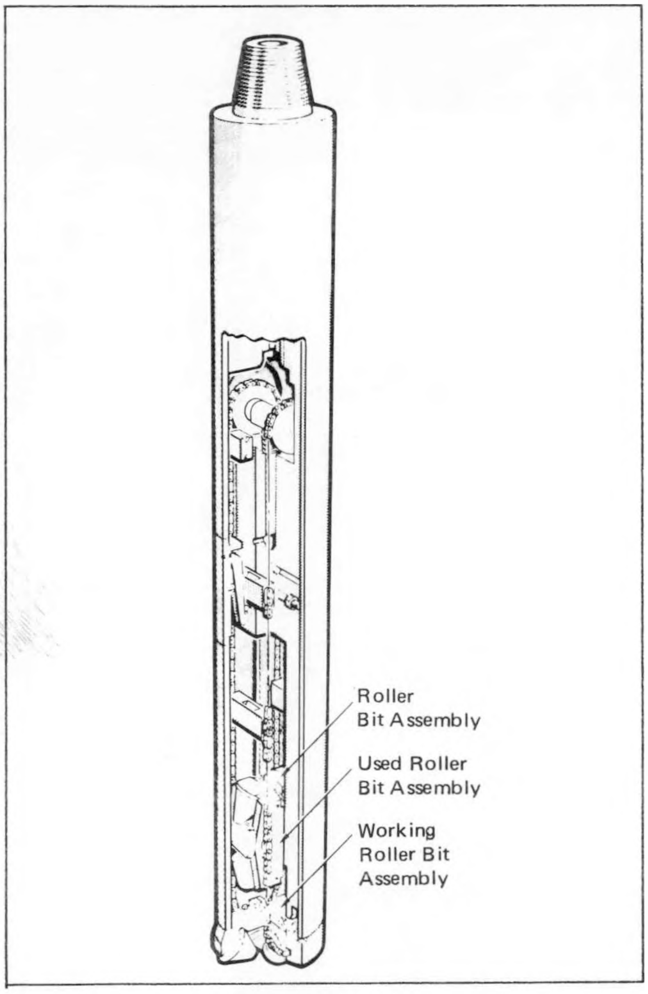

Figure 3. Down-hole changeable bit

Item 3. *Continuous-Chain Drill*

A long-life continuous-chain drill bit is under development in answer to a long-standing need of the drilling industry. If the life of bits can be prolonged, holes will be made less expensive because fewer round trips of the drill-string for bit replacement will be necessary. In the proposed drill, the bits will be in the form of a long chain surfaced with tungsten carbide or diamond chips (Figure 4). The chain is rotated by a spring-piston-pawl assembly, loaded by mud pressure. The cutting surface at any given moment will consist of six chain segments. When this surface wears out, a new surface can be rotated into place by simply decreasing mud pressure and backing the drill slightly off the bottom. The drill can then immediately be lowered and drilling resumed.

This type of drill is particularly suitable for the drilling of slim holes for exploratory work, which cost less in casing, bits, and rig time than standard holes.

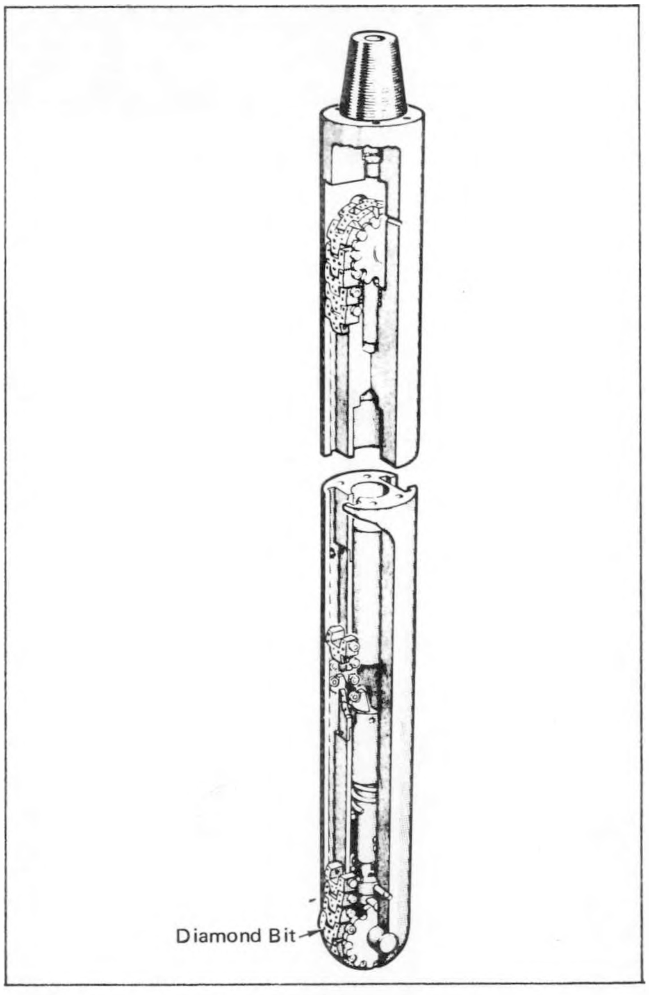

Figure 4. Continuous-chain drill

DRILLING, MAGMA, AND DIAGNOSTIC TECHNOLOGIES

Item 4. *Spark Drilling*

A new drilling technique is being researched and developed: drilling with shocks generated by electrical detonations and consequent cavitation in a drilling liquid. The technique may offer increased drill-bit life, as well as improved rock-removal efficiency with hole depth. The bit would consist of a down-hole electrical pulse generating system that discharges high-energy, precisely timed, short pulses between arrays of electrodes at the rock face (Figure 5).

The rock failure mechanism consists of several interrelated phenomena. The initial portion of the spark discharge generates a high-pressure shock wave (2 to 10 kbars), which is sufficient to cause many earth materials to fail. As a result of particle motion away from the discharge, a low-density void or bubble is created in the liquid. Because pressure is removed from the rock face by this low-density area, spall failures can occur. A bubble in the presence of a free surface will collapse nonuniformly and can create a very high-pressure jet into the free surface (the water-hammer effect), resulting in additional rock failure. This phenomenon has been well documented at atmospheric pressures in cavitation physics work. All of these effects can combine to yield a very efficient drilling system (Figure 6).

Techniques have been developed to measure near-field pressures generated by spark discharges in liquid, and multidimensional computer codes have been modified to simulate the action of a spark-generated bubble. A laboratory spark drilling system has been developed for tests at atmospheric pressure. With a spark system delivering 1950 watts (2.6 hp) to the rock face, laboratory penetration rates of 200 cm/hr in concrete and 39 cm/hr in marble and granite have been attained.

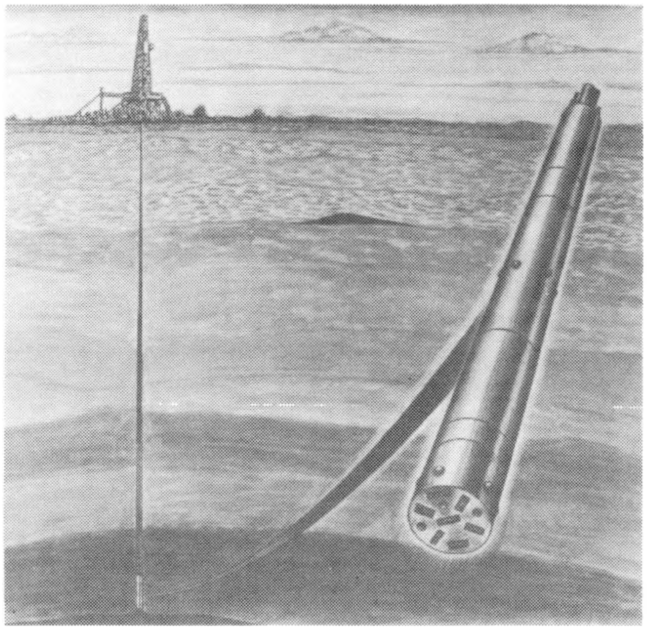

Figure 5. Spark drill system

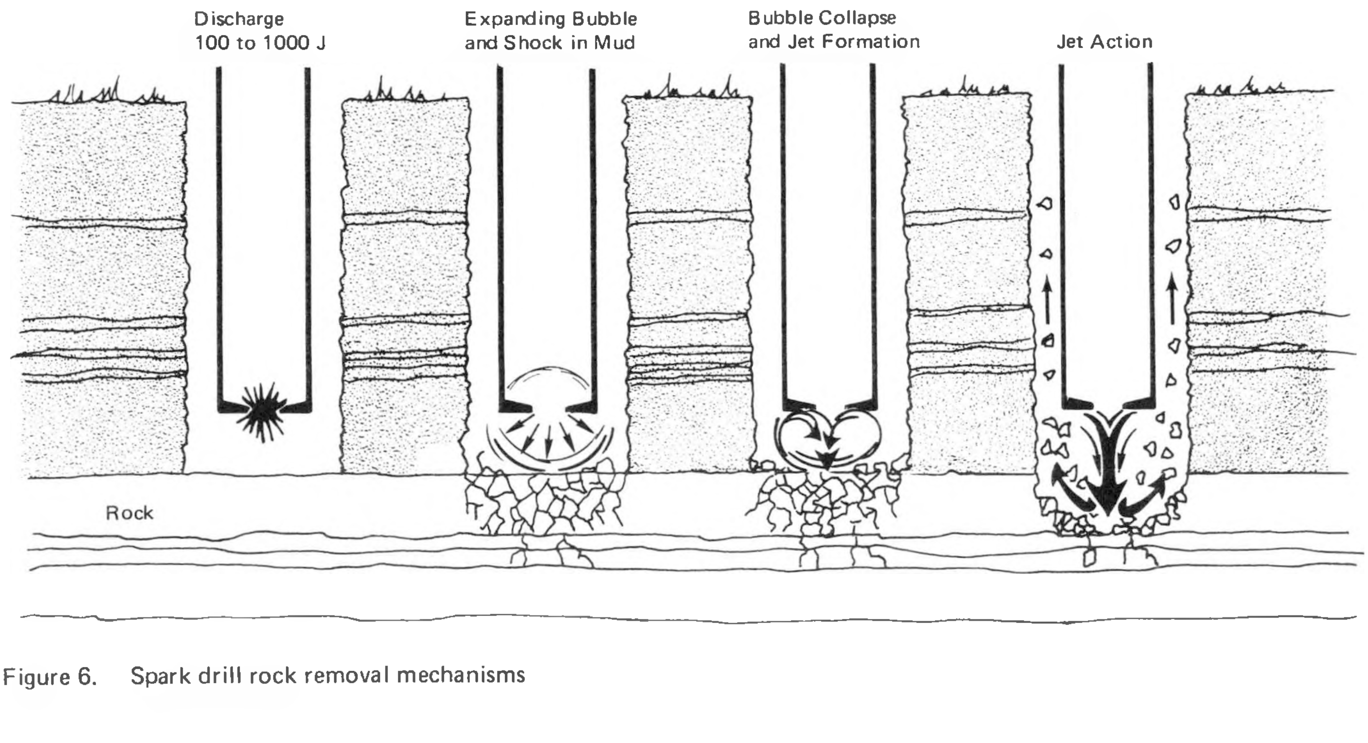

Figure 6. Spark drill rock removal mechanisms

Item 5. *Magma Energy Research*

Studies are under way to investigate the feasibility of extracting energy directly from deeply buried circulating magma sources. One method for direct extraction involves a closed heat exchanger which when inserted directly into the magma source transmits heat energy to the surface via a contained fluid. The heat energy is then converted into a desired form employing reasonably conventional techniques (Figure 7).

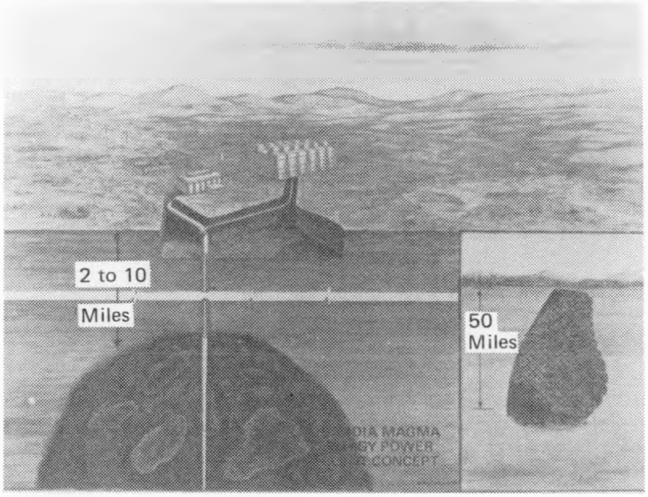

Figure 7. Conceptual drawing of an electrical generative station obtaining energy from a buried molten rock (magma) source using a closed, long tube boiler heat exchanger.

A laboratory experiment demonstrated that useful amounts of thermal energy could be extracted from a molten lava heat source: a single tube boiler was immersed in Hawaiian tholeiitic lava melted in an induction furnace (Figure 8). When part of the chilled lava was chipped away, the surface of the stainless steel probe was found undamaged (Figure 9).

Item 6. *Rock Springs In-Situ Oil-Shale Fracture Experiment*

Sandia Laboratories provided the geophysical survey and active instrumentation for an explosive in-situ oil-shale rubblization experiment conducted by the U. S. Bureau of Mines. The explosive was detonated in a propped hydraulic fracture system at a depth of 50 m (Figure 10). A geophysical survey of the formation provided in-situ property measurements and quantification of the explosive effects.

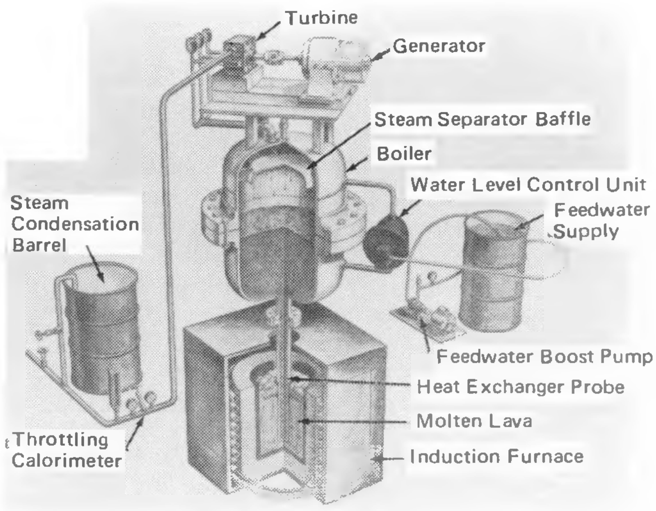

Figure 8. Sandia molten lava/single tube boiler experiment.

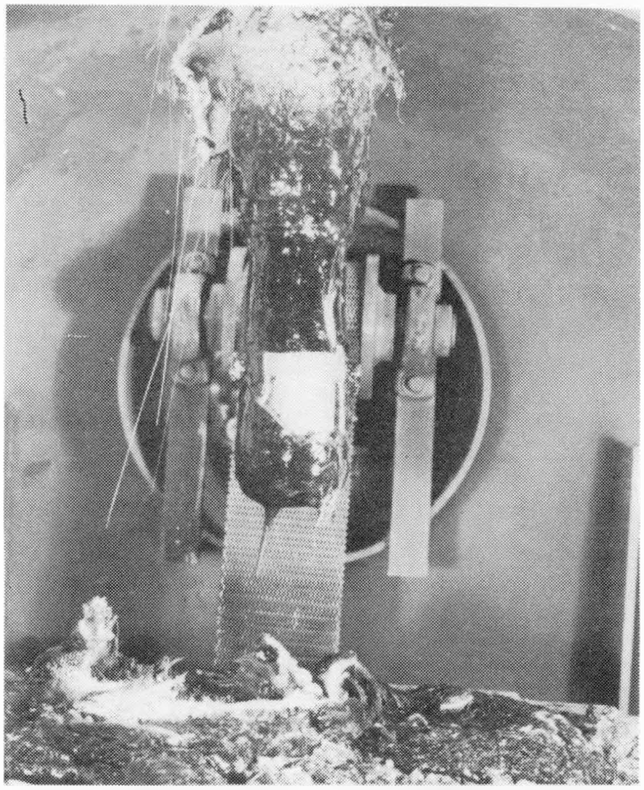

Figure 9. Single tube boiler after extraction from 24-hour experiment in molten lava.

DRILLING, MAGMA, AND DIAGNOSTIC TECHNOLOGIES

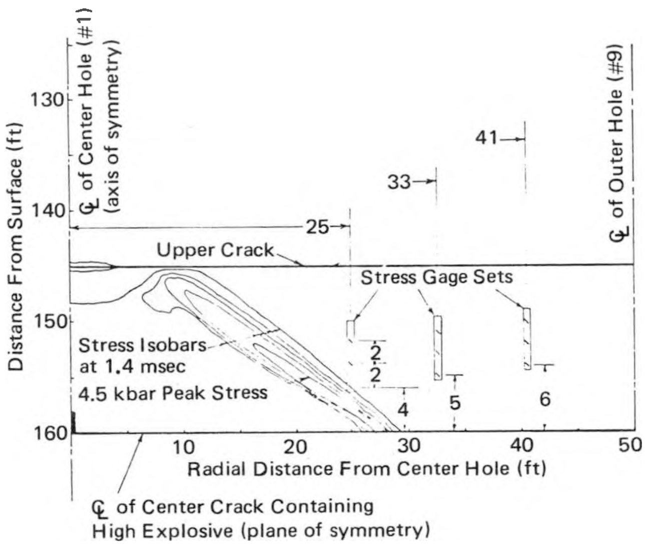

Figure 10. Two-dimensional stress wave calculations for the Rock Springs' explosive fracture test.

Additional material properties were measured from oil-shale cores and an equation of state was developed. The pretest design was modeled using a two-dimensional stress-wave computer code. Results of the calculations were used to aid design of the active instrumentation. Two types of instrumentation were used. To study shock-wave behavior in oil shale, 12 stress gages were placed in the formation at different locations relative to the explosive. Also, surface motion was measured using velocity gages and accelerometers. Surface-motion measurements were made to study the motion generated by a diffused source. Test results indicated that the experiment did not go as designed. The active measurements and geophysical survey were used to develop a model of the experiment. Results of the model as obtained using the computer code compared well with the field data.

Item 7. *In-Situ Coal Gasification Instrumentation and Process Control*

A long-range effort is under way to develop an integrated process-control system for in-situ combustion energy recovery technologies. An in-situ coal gasification experiment being conducted by the Bureau of Mines at Hanna, Wyoming, is being used to evaluate instrumentation sensor technology and initiate analyses leading to development of process-control models. Preliminary experiments at Hanna have shown that acoustic and thermal methods merit further study as techniques for determining the location and extent of combustion zones. Resistivity methods are also being examined for use as a remote means of establishing extent of the burn zone (Figures 11 and 12). Gas chromatography of samples obtained at locations ahead of, within, and behind the burn front permits a better understanding of the combustion products as a function of temperature and other process variables. To evaluate subsidence problems that may arise if large-scale in-situ conversion is employed, tilt and displacement measurements, as well as survey methods, are being obtained and used in analysis. This field instrumentation effort is supplemented by mathematical modeling of the thermochemical gas-combustion process and the space-time-temperature behavior.

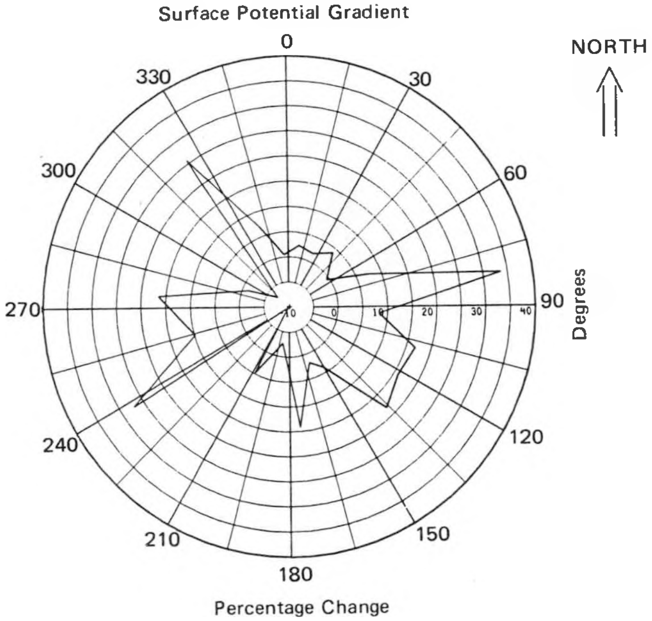

Figure 11. Hydrofrac resistivity mapping for Pinedale No. 7.

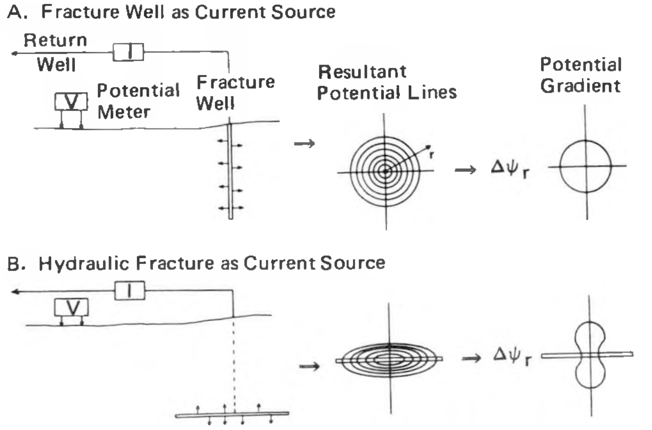

Figure 12. Surface potential fields and gradients which occur during implementation of the surface potential variation mapping technique. Refracture field is as illustrated in A and past fracture field is superposition of A and B.

As indicated in Figure 13, downhole instrumentation provides diagnostic information on the chemical and physical mechanisms associated with the underground process and allows determination of its extent and configuration. Correlations with near surface instrumentation allow these techniques, which are favored for process control, to be evaluated. Laboratory studies are under way to characterize important properties of the coal and associated formations. As appropriate, new sensors and instrumentation techniques are evaluated through laboratory tests to assure compatibility with the anticipated severe environments. This overall effort has application to any in-situ combustion process.

Item 8. *Hydrofrac Mapping*

Sandia Laboratories working in conjunction with El Paso Natural Gas has developed a program to determine the orientation and extent of the fracture induced by hydraulic pressures. In tight gas formations, where economic recovery depends on a large volume of the formation being in communication with the well bore, fracturing is an alternate to nuclear stimulation. Seismic signals associated with the fracture phenomenon are recorded at several locations for analysis, and by triangulation the source of energy can be located and the extent of fracture determined. An electric field, induced by current flowing through the fracture fluid, is measured on the surface during the operation; its charge reflects the orientation of the conductive fluid.

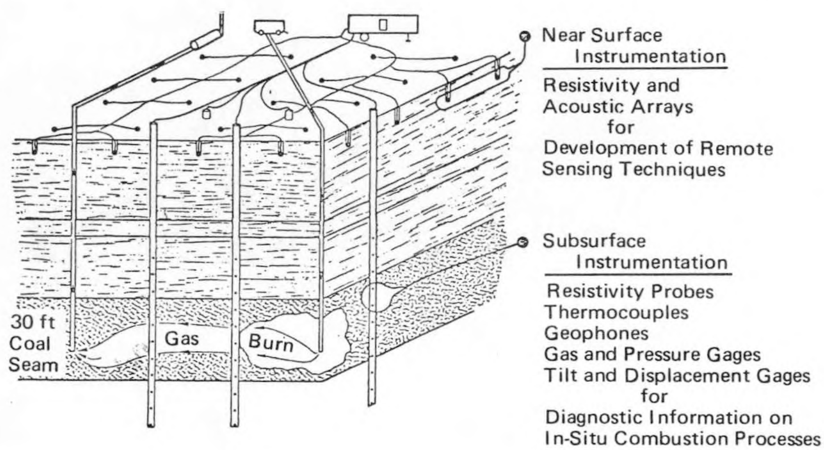

Figure 13. Instrumentation and process control development for in-situ coal gasification.

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ELECTRONICS

Sandia Laboratories Technical Capabilities

Electronics

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115
and Livermore, California 94550 for the United States Energy Research
and Development Administration under Contract AT(29–1)-789

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SANDIA LABORATORIES TECHNICAL CAPABILITIES

ELECTRONICS

ABSTRACT

This report characterizes the electronics capabilities at Sandia Laboratories. Selected applications of these capabilities are presented to illustrate the extent to which they can be applied in research and development programs.

ELECTRONICS*

The aim of the electronics activities is to acquire an understanding of the physical properties of elements used in electronic circuits and the effects of fabrication and processing on these properties. Reliability is a basic requirement, and predictable response is necessary under extreme environments such as mechanical shock, intense radiation, and large temperature excursions. Studies of the properties of silicon as influenced by processing variables provide reliable and innovative active elements. Work on various methods of discrete component attachment aids in the miniaturization of hybrid circuits. Substrate and thin-film studies are leading to new electronic materials and providing improved assembly methods.

Vacuum tubes are being designed that allow the rapid transfer of electrical energy and the generation of high-energy neutrons. Pulses of high-current high-voltage electrical discharges are generated by the controlled depolarization of ferromagnetic and ferroelectric materials.

Facilities exist for building hybrid microcircuits for evaluating prototype designs. There are large modern clean-room facilities for the fabrication of active semiconductor elements and large-scale integrated circuits. A laboratory is available for fabricating neutron generator tubes and high-energy switching tubes.

Electronics Technical Staff
and Investment in Equipment

	Professional Staff	Investment in Equipment (in $1000)
Active Semiconductors	32	2,500
Hybrid Microcircuits	26	870
Vacuum-Tube Technology	30	4,000
Pulsed High-Energy Technology	65	3,500

*Compiled October 1975

ACTIVE SEMICONDUCTORS

To assure a reasonable supply of semiconductor components that can meet the size, cost, and environmental constraints of new electronic systems, design techniques, process controls, and procurement methods are developed. Miniaturization is emphasized so that a high level of integration can be accomplished. This in turn leads to reductions in system costs and the significant improvement in reliability attained through redundancy.

Processing

The basic material used in essentially all electronic components of interest is single-crystal silicon. Electrical properties of the crystals are studied as a function of fabrication processes to establish technologies adaptable to optimization of the design of a transistor, diode, or monolithic semiconductor integrated circuit. (Items 1, 2)*

Current Activities

Stability of high-purity oxide passivation
- Electrical
- Temperature
- Ionizing radiation

Impurity doping of silicon crystals
- Thermal diffusion
- Ion implantation
- Process modeling

Mechanical packaging
- Metalization
- Wire bonds
- Beam bonds
- Die attachments

*See Highlights, below.

Design

The relation of electrical characteristics to stresses produced by environments and processing is studied both analytically and experimentally. Analysis is done with computer studies, modeling diffusion profiles, and other parameters before device processing. The development permits considerable customizing of circuits using standard technologies and building blocks. (Item 3)

Current Activities

Analytical capability
- One-dimensional device-analysis
- Logic simulation
- Computer graphic design
- Computer analysis of circuits
- Computer fault analysis

Special devices
- Large custom integrated logic systems
- Micropower transistors
- Radiation-tolerant bipolar devices
- Standard parts for custom integrated circuits
- Radiation-tolerant metal-oxide-silicon (MOS) devices

Quality assurance
- Interactive computer testing
- Special procurement procedures
- Environmental stress testing

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Radiation-Tolerant CMOS Development*

More than 150 variations on metal-gate CMOS (complementary-metal-oxide-silicon) processing have been performed to determine the effects of processing variables on CMOS radiation tolerance. Results have allowed development of an optimized radiation-tolerant process by which circuits are made capable of surviving over 10^6 rads Si. The process is compatible with existing commercial CMOS processing and quality controls. Models have been developed which incorporate observed radiation effects in CMOS. The models provide basic physical insight and suggest further improvements in radiation tolerance.

Item 2. *Solar-Cell Development*

A goal of solar-cell development is to optimize the design of single-crystal silicon solar cells for use in multisun, high-temperature environments. The cells are to be incorporated in a design that uses solar energy to provide the heating, air conditioning, and other practical needs of a community.

A one-dimensional device-analysis computer code was modified to simulate silicon cells. Beginning with the conventional solar cell, various designs have been successfully analyzed. The physical insight attained has led to modifications in the basic cell, resulting in superior properties at extreme conditions.

Silicon solar cells fabricated in the solid-state device laboratory have verified theoretical studies. Modified designs with optimum top-surface metal, as implied theoretically, have been fabricated and shown to be superior to the conventional cell at both multiple-sun illumination and high temperature.

Item 3. *Large Scale Integrated Circuit Capability*

A CMOS LSI (large-scale-integration) capability has been developed. Of principal interest is optimization of electronic elements to withstand radiation. The process sequences, including diffusions, oxidation, and anneals, that influence both n- and p-channel MOS radiation hardness and threshold voltages have been considered. The work was initially performed on MOS capacitors and subsequently confirmed by the fabrication and testing of CMOS inverter devices. A photolithographic operation was optimized to permit a pattern generation with 5-μm features and less than 4 defects/cm^2. Fabrication also required that wafers maintain a quality level of less than 5 particles (≥ 1 μm)/cm^2. The LSI CMOS capability has been demonstrated by the successful fabrication of functional 210 X 230-mil chips containing 1129 transistors.

HYBRID MICROCIRCUITS

The aim of the study of thin films and hybrid-circuit packaging technologies is to establish a scientific foundation for the materials used and for fabrication technology. The study includes identifying and implementing reliable methods of attaching and interconnecting discrete components.

Lithography

Chemical and physical processes are established for structuring and defining thin-film materials. Studies assure precision fine-line definition capabilities for film conductors, resistors, and dielectric materials. (Items 1, 2)*

Current Activities

- Computer-aided layout
- Electron-beam lithography
- Ion-beam etching
- Chemical etching
- Lithographic resist systems

Bonding and Interconnection

Techniques are developed for establishing predictable and reliable interconnection systems for hybrid microelectronic circuits. Materials and processing techniques have been developed that provide bonding capability for the diverse electronic component needs of hybrids. (Items 3, 4)

Current Bonding Methods

- Thermocompression
- Ultrasonic
- Thermosonic
- Wobble
- Compliant
- Solder

Substrate Studies

Thin films require a dielectric or insulating support to provide a stable carrier for films and components. The aim of substrate studies is to develop, chemically and physically, substrates that are compatible with processing needs and also have the properties of adhesion and heat conduction. (Item 5)

Current Substrate Materials

- Alumina
- Sapphire
- Beryllia
- Magnetic garnet films

Film Deposition

Studies of thick and thin-film materials and their interactions are conducted to provide hybrid microcircuit elements that will remain electrically and structurally stable throughout their anticipated life. Environments of interest include shock, vibration, temperature extremes, and electrical noise. (Items 6,7)

Current Activities

Thin Films	Thick Films
Conductors	Conductors
TiPdAu	Line definition limitations
CrAu	Bondability
Al	Resistor
Dielectrics	Stability
SiO_2	TCR, VCR, noise
Ta_2O_5	Static voltage sensitivity
Resistive Films	
Ta_2N	

Deposition Methods

- Sputtering
- Evaporation
- Chemical vapor

*See Highlights, below.

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Photolithography*

The procedure of optically transferring a pattern to a work piece and the performance of operations upon the work piece controlled by the pattern is called photolithography. By using this technique, and with the aid of photography and chemistry, a pattern can be generated on metal or nonmetal surfaces that serves as a mask to expose or protect the surface from subsequent operations such as chemical and plasma etching, plating, diffusion, epitaxy growth, and abrasion. A wide variety of thin films of either common, precious or rare-earth metals on solid substrates such as glass, ceramic, sapphire, garnet, and metal/metal compounds, as well as on flexible substrates, allows for this type of pattern generation. Patterns may also be defined in nonmetallic materials such as dielectrics. Successive patterns with as many as six levels of thin films have been achieved. Photolithographic processes developed at Sandia provide the only techniques available that will delineate the complex microminiature circuitry demanded by weapon systems, hybrid microcircuits, and special development programs.

Item 2. *Electron Beam Lithography*

Electron beam lithography makes possible improvements in information storage capacity, as well as higher frequency, lower noise, and higher power in magnetic bubble-memory arrays, acoustic surface wave devices, microwave transmitters, charge-coupled devices, and large-capacity metal-oxide-silicon devices. Line widths down to 0.1-1.0 μm can be produced. This method involves use of a short-wavelength ($\lambda \cong 1.7 \times 10^{-5}$ μm) high-energy electron beam (5-30 keV) with a spot size of < 0.05 μm to selectively expose the desired pattern by computer control. A resist-coated substrate is then developed with a solvent solution that selectively dissolves or retains the electron-exposed areas (depending on whether the resist is positive or negative-acting). This provides either channels to the substrate for subsequent metalization, or a mask to protect the underlying metalization from attack during etching.

Item 3. *Bonding*

Thermocompression lead-frame bonding involves applying controlled temperatures and pressures for a predetermined time to normally ductile materials aligned on substrate bonding areas. The basic technology for achieving strong, reliable bonds has been developed. Studies have included the effects of lead thickness and width, electroplating, bonding parameters, tool configuration, and substrate support. The introduction of an intermediary to promote deformationless bonding and thus increase flexure strength while maintaining peel strength has been shown to be a viable approach.

Capability exists to perform such interconnection techniques as thermocompression and thermosonic wire and ribbon bonding; ultrasonic wire bonding, and beam lead wobble bonding.

Compliant beam lead bonding has been recently developed and evaluated. This is a method of thermocompression bonding that is relatively insensitive to variations in device beam hardness and thickness. It also permits the beams to be bonded with minimum deformation and stress on the chip-beam connection.

A capability has been developed to evaluate interconnection reliability by using the scanning electron microscope, Auger electron spectroscopy, and several methods of nondestructive and destructive pull testing.

A study has been completed to determine the effects of organic contaminants on solid phase bonding. As seen in Table I, the angstrom thickness of photoresist residue directly relates to the quality of lead frame thermocompression bonding. This information can be used to predict possible bonding problems in production or as a criterion for the amount of cleaning necessary before subsequent bonding should be attempted.

TABLE I

Effect of Ozone Exposure on Photoresist Residue and Thermocompression Bond Strengths

Condition	Carbonaceous Layer (Å)	Lead Peel Strength[1] Mean	Max.	Min.	Lead Failure Mode
As-deposited	2 Å	2.61	3.05	2.45	100% heel
Spin contaminated with 100 parts acetone to 1 part photoresist	30 Å	0.76	1.4	0.0	100% delamination
Contaminated and exposed to 2% O_3, 27°C, 20 hrs	6 Å	1.39	1.90	1.10	100% delamination
Contaminated and exposed to 2% O_3, 27°C, 69 hrs	3 Å	2.35	2.7	1.9	100% heel

[1] Units are pounds

HYBRID MICROCIRCUITS

Item 4. *Soldering Components to Hybrid Microcircuits*

A method has been developed, using 50 percent by weight lead-indium solder, to attach applique components to thin-film gold hybrid microcircuits. Equipment available for solder flow is an infrared soldering system, Browne hydrogen flame resistance loop systems, and various types of hot plates.

Two intermettalic reaction layers have been observed when their interface is aged at elevated temperatures (70-170°C). The layers are shown in Figure 1. The compound nearest Au was established as Au_7In_3 by electron microprobe analysis, while that nearest the solder is a two-phase layer of $AuIn_2$ and Pb. The growth kinetics follows the linear law

$$d = d_o + \beta t$$

where d is total reaction-layer thickness, d_o is the original thickness (after soldering), β is a temperature-dependent parameter, and t is aging time. This time dependence has been measured at ten temperatures ranging from 70 to 170°C, which has established growth activation energy as 14000 calories per mole. This was done using the data on β, shown in Figure 2. These reaction layers are not brittle and do not lead to significant loss of solder joint strength after extended (1000-hour) aging tests.

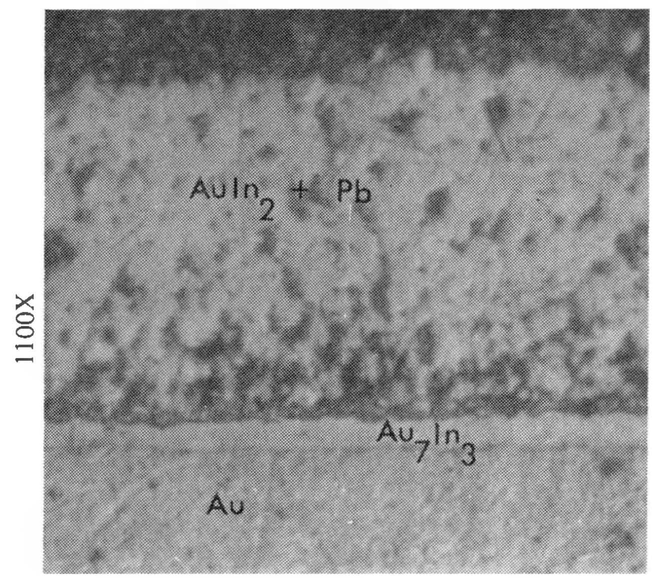

Figure 1. Solder-gold reaction showing gold indium intermetallic formation

Item 5. *Substrates*

Substrates are developed to provide a suitable base for depositing thin metallic films used in hybrid microcircuits (HMC). Standard thin-film HMC technology is tailored to be compatible with tape-drawn, as-fired, 99.5 percent alumina ceramic as the substrate material. While this very dense alumina exhibits extremely good electrical and mechanical properties, it does require the use of special cutting and drilling techniques. A tape-controlled ytterbium-aluminum-garnet laser is used to cut the alumina to size and holes are made by ultrasonic diamond drilling.

Recent studies have demonstrated that thin-film technology is also compatible with a new generation of ultrafine-grained alumina as well as single-crystal sapphire substrates. Both materials have improved surface finishes, permitting additional circuit miniaturization by allowing the reduction of conductor and resistor geometries.

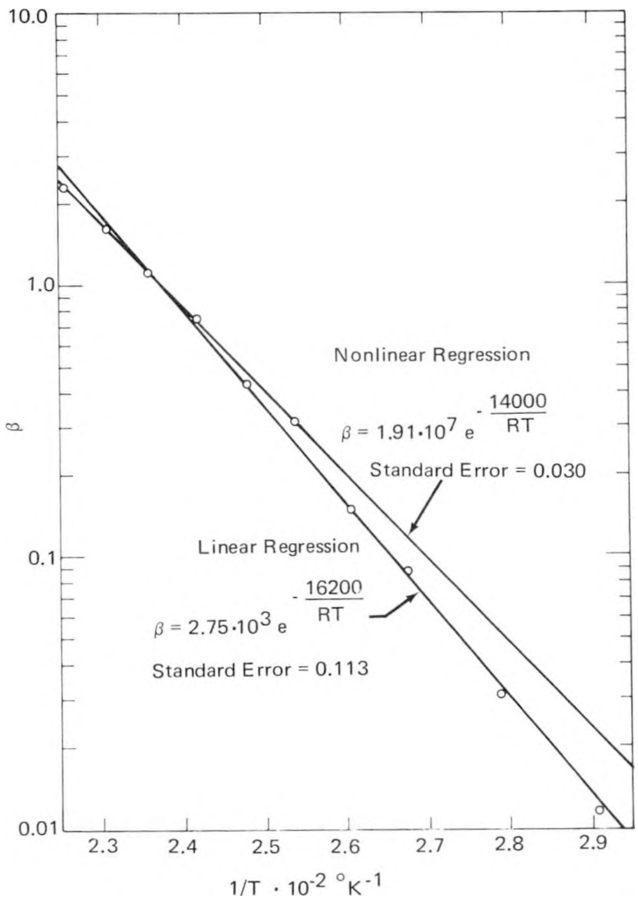

Figure 2. Arrhenius plot showing temperature dependence of β

Item 6. *Sputtering*

One significant application of sputter deposition is the fabrication of thin-film tantalum nitride resistor films for hybrid microcircuits. The objective is to incorporate the resistors as integral elements of the total thin-film network. The films are formed by depositing tantalum in a nitrogen argon atmosphere. Resultant films have a resistivity 30 times greater than that of bulk tantalum, as well as a negative temperature coefficient of resistance. There is also a capability for sputtering tungsten; the technique was used to interconnect thermocouples in a semiconductor thermopile used in development of a small isotopically powered thermoelectric generator.

In another application, where a requirement existed to lay down propagation patterns for magnetic bubble domain memory devices, permalloy films were sputtered.

Item 7. *Thick-Films*

While thin films are more generally used, it appeared in some development programs that thick films might offer significant advantages in terms of turnaround and cost. Thick-film technology is a technique for depositing materials on ceramic substrates by precision printing with viscous inks and subsequently firing these materials at very high temperatures to achieve stable electrical and mechanical properties and substrate adhesion. Depending on their composition, these materials may be conductors, resistors, or dielectrics. While these techniques can be used to produce hybrid microcircuits, they have recently been used to produce components such as those illustrated in Figure 3.

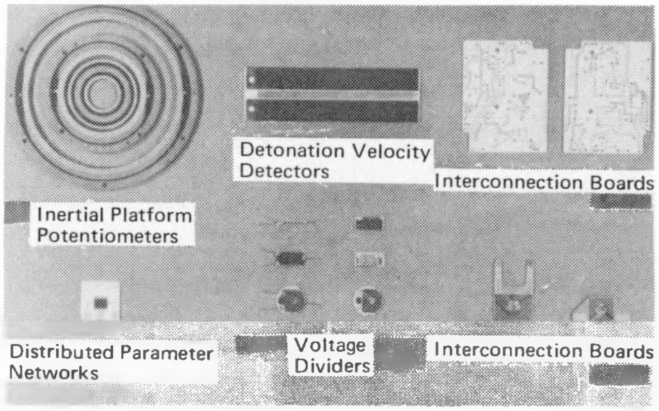

Figure 3. Thick-film applications

VACUUM TUBES

Programs are directed toward developing rugged, reliable neutron and vacuum tubes that will switch electrical energy when triggered under severe radiation environments. Physical processes and materials are studied to optimize choices for construction and production. Tubes are constructed of Al_2O_3 ceramic or glass-ceramic insulating materials and kovar or molybdenum metal parts, requiring ceramic-to-metal joining techniques.

Neutron Tubes

Neutron tubes are designed to provide 14-MeV neutrons. These tubes initiate nuclear weapon systems, must operate reliably after long periods of passive storage, and must withstand adverse environments such as high temperatures, shock, and radiation.

Current Activities

- Ion beam optics
- Ion beam-target interaction
- High-voltage breakdown
- Metal-ceramic bonding techniques
- Ion source design
- Hydrogen and helium permeation
- Laminated metals
- Thin-film evaporation
- Electrostatic field calculations
- High-sensitivity leak detection
- Power supplies
  - Electronic
  - Ferroelectric

Vacuum Tubes for Triggered Electrical Switching

Switching tubes are developed for use in applications where current discharges are to be delivered, on command, to external electrical loads. These devices use a small trigger arc to initiate full-vacuum anode-cathode discharge, resulting in a few tens of volts for initiating a 2-10 kV discharge.

Current Activities

- Anode and cathode design
- Arc erosion
- Field emission
- Gold diffusion bonding
- Ceramic-gold brazing
- Gas effect in discharge characteristics
- Al_2O_3 ceramic parts fabrication
- Gettering surfaces

Vacuum Arc Physics

Neutron tubes and vacuum switching tubes are designed to control vacuum arcs and be capable of reliably holding off high electric fields without random breakdown. The ion source for neutron tubes and the trigger for switching tubes use an arc discharge to produce charged species for actuation (ions or electrons, respectively).

Current Activities

- Anode phenomena
  - Anode temperature
  - Plasma temperature
  - Electron density
  - Ion energy
  - Plasma constituents
- Cathode phenomena
  - Plasma constituents
  - Spot formation
  - Spot theory
  - Erosion
- Plasma boundary measurements
- Gas effects
- Ion-beam mass analysis

Hydrogen and Helium in Metal Films

Hydrogen isotopes, specifically deuterium and tritium, are used in the manufacture of neutron generator tubes. Tritium is a radioactive isotope that decays into helium-3 with a half-life of 12.26 years. The helium-3 remains within the metal lattice although its dimensions are larger than those of tritium, causing concern about lattice strain and subsequent helium release. Thus, it is often necessary to analyze and understand metal hydrides and tritides. Of specific interest is the behavior of significant amounts of helium-3 in the lattice. These films and their contents are analyzed using charged-particle backscattering, gas analysis, ion microprobe, and a wide range of other analytic techniques.

VACUUM TUBES

Current Activities

- Thin-film deposition
- Hydriding kinetics
- Stress levels in thin films
- Proton backscattering
- Helium backscattering (Rutherford)
- Surface transport and kinetics
- Oxide surface films

PULSED HIGH ENERGY TECHNOLOGY

This technology is concerned with the generation and use of electrical energy. High-energy electrical pulses are produced by two principal techniques; explosive-to-electric transducers and capacitor discharges. The transducers use various phenomena to produce the electrical pulse, including compressed magnetic fields, ferroelectrics, and ferromagnetics.

Compressed Magnetic Fields

In a compressed-magnetic-field (CMF) generator, explosive energy is converted into electric energy by explosively driving a conducting armature into a magnetic field. Work done in overcoming magnetic forces results in an increase of magnetic energy in the system, which is coupled into electrical loads by solenoidal coils. Magnetic fields in the range of millions of Oersteads and electric currents in excess of 1 million amperes have been generated by this technique. (Item 1)*

Current Activities

- Development
  - Solenoidal coils
  - Explosive armatures
  - Explosive lenses
  - Coupled compressed-magnetic-field systems
  - Power supplies
  - Automated digital instrumentation
- Research
  - Magnetohydrodynamic modeling
  - Pure fusion weapon research
  - Armature metallurgy
  - Magnetic-field diffusion
  - Nonlinear circuit modeling

Ferroelectric Transducers

Another method of achieving high-level pulsed high-energy sources is through the use of ferroelectric (FE) materials. Two classes of these materials have been developed for transducer applications: conventional and slim-loop ferroelectrics. Their principal difference is in the shape of their polarization or electrical hysteresis loops. The FE material, an electric analog of a permanent magnet, exhibits permanent polarization or electric displacement when its electric field is zero. Slim-loop FE material, for all practical purposes, has no permanent polarization. Thus, its electric displacement is near zero when the electric field is zero.

In transducer applications FE material is depolarized by an explosively generated shock wave. Depoling during shock-wave transit results in release of the bound polarization charge, causing large transient currents. Slim-loop materials respond similarly except that their polarization charge is not bound but must be supplied by an external source. (Item 2)

Current Activities

- Development
  - Central power supply
  - Neutron-tube power supply
  - Contact fuze
  - CMF injector
  - Explosive lens
  - Automated digital looper
- Research
  - FE material characterization
  - Nonlinear circuit modeling
  - Electric field breakdown physics
  - Phase transition and transition kinetics

Ferromagnetic Transducers

The ferromagnetic transducer is another method used to obtain pulsed high-energy discharges. It derives its output from the shock-wave demagnetization of a magnetic core. It consists of an iron or nickel-iron magnetic core, an excitation winding, an output winding, and an explosive charge. The excitation winding is used to saturate the magnetic field in the core before the explosive is detonated. When the explosive is detonated, the shock wave it generates passes through the core, reducing its magnetization to that of air. The resultant collapse of magnetic flux density generates voltage in the output winding and current flows if an external load is present. The output current capability of a ferromagnetic transducer operating into a low impedance is a few kiloamperes. (Item 3)

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*See Highlights, below.

PULSED HIGH ENERGY TECHNOLOGY

Current Activities

- Magnetic materials
- New explosives
- Equivalent circuit modeling
- Hydrodynamic modeling
- CMF injector
- Exploding-bridgewire detonator firing set

Capacitor Discharge Technology

A form investigated for high-energy pulsed discharges is that of capacitor-discharge technology wherein a low voltage is converted to a high voltage (e.g., 28 Vdc to 6 kVdc) in times ranging between 0.1 and 1 second. The high dc voltage charges an energy storage capacitor that is command-switched into an electrical load by a vacuum-tube switch or an explosively driven solid dielectric switch. This technology has been developed for firing a variety of detonator configurations as well as powering spark bits in deep drilling research. The former application emphasizes high reliability and compact designs, and uses radiation-hardened dc-to-dc converters with capacitor charging capability up to 5 watts/in^3 and energy storage capacitors capable of achieving electric-field energy densities of 1.2 joules/in^3. Spark drilling applications emphasize very high energy storage and multiple firings by operating at 60 kV to provide 3-kilojoule sparks at a rate of 120 sparks/second.

Current Activities

- Energy storage capacitors
- Solid dielectric switches
- Vacuum switch tubes
- Integrated circuit operational amplifier regulators
- High-voltage solid-state switches
- Hybrid microcircuits dc-to-dc converters
- Modular circuit construction
- Power amplifiers
- High-reliability electronics packaging
- Optically coupled dc-to-dc converters
- Firing subsystems
- Spark drilling
- Transient pulse instrumentation
- Shock, temperature, and radiation-resistant circuits
- Missile stage separators
- Bolt cutters

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Compressed Magnetic Field Transducer*

A number of small, efficient compressed-magnetic-field generators have been developed (Figure 4). The generator consists of a solenoid coil with an explosively expanding armature located coaxially. After the explosive is detonated from one end, the armature expands, inductance is forcibly decreased, and coil current increased so as to conserve flux linkages. The objective is to achieve a compact pulsed high-energy source.

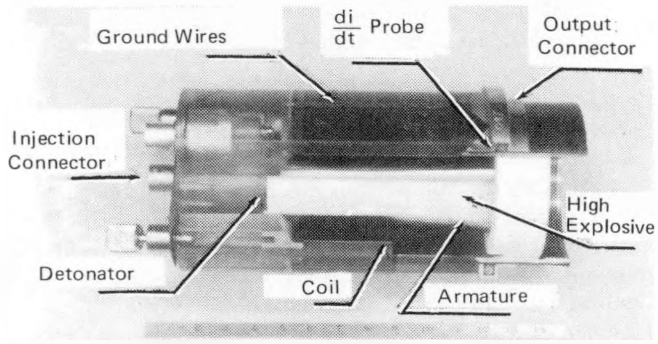

Figure 4. Compressed magnetic field generator

Item 2. *Central Power Supply*

The central power supply shown in Figure 5 incorporates both ferroelectric and compressed-magnetic-field technology to obtain a firing source for detonators connected to a power source.

PULSED ENERGY TECHNOLOGY

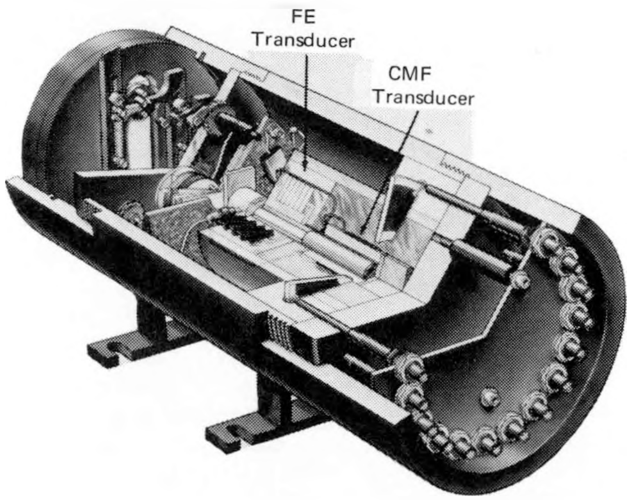

Figure 5. Central power supply

The stress wave from the rupturing glass releases the charge from the FE disks to fire a detonator, which in turn ignites an explosive stick that burns down the axis of the assembly. The radially expanding shock wave from the explosive stick first depolarizes six other FE washers connected in electrical parallel. The current from these washers flows through the coil of a small compressed-magnetic-field transducer, creating an initial magnetic field in the space between the coil and a conducting cylindrical armature inside the coil and concentric with it. The armature is filled with explosive which is part of the axial explosive train. As the explosive burns through the armature, it throws the armature out toward the coil, compressing the magnetic flux, and generating a large current in the coil. The coil is connected to 20 parallel output connectors.

Item 3. *Ferromagnetic Transducer*

A fundamental configuration of ferromagnetic transducers is shown in Figure 6. The magnetic core is nickel-iron and is laminated or tape-wound to prevent parasitic eddy currents. The core is wound with an excitation coil and an output coil. The latter can be matched to various load impedances by varying the number of turns. The explosive train consists of an initiating detonator, a lens, and a driver charge of explosives to actuate the ferromagnetic transducer when the detonator is fired. This detonates the lens, initiating the driving charge in a planar wave. The driving charge sends a pressure wave through one leg of the magnetic core, causing the relative permeability of the magnetic material to be reduced to one. The resultant field collapse generates voltage in the output coil. Transducers of this configuration produce about 1000 amperes.

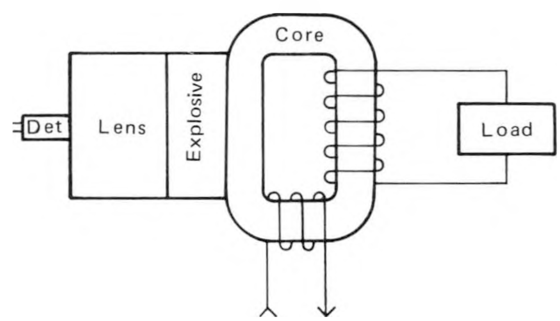

Figure 6. Ferromagnetic transducer configuration

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Sandia Laboratories Technical Capabilities

Engineering Analysis

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115
and Livermore, California 94550 for the United States Energy Research
and Development Administration under Contract AT (29-1)-789

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SANDIA LABORATORIES TECHNICAL CAPABILITIES

ENGINEERING ANALYSIS

ABSTRACT

This report characterizes the engineering analysis capabilities at Sandia Laboratories. Selected applications of these capabilities are presented to illustrate the extent to which they can be applied in research and development programs.

ENGINEERING ANALYSIS*

This function is concerned with calculating the responses of designs to their environments. Structural mechanics is used to aid in determining a design configuration and choosing materials suitable for the loads to be encountered in practice, particularly in severe dynamic environments. Stress-wave analysis centers on the propagation of stress waves arising from impact, explosions, transient radiation, and other extreme environments. Chemical analysis is used to determine the initiation and detonation characteristics of explosives, leading to useful applications of the sudden release of energy. Heat-transfer studies confirm the performance of heat-exchange systems, thermal protection materials, and rotating machinery based on various thermal cycles and phase changes. Aerodynamic calculations predict the behavior of vehicles in free and propelled flight. Environmental analysis is used to define the conditions a product might encounter during its lifetime. The analysis of control systems comes into play when environment-sensing devices, control mechanisms, and decision-making and guidance functions are combined. The design of electronic packages relies on circuit analysis. Nuclear engineering analysis activities are directed toward pulse reactor development, design, and operation. Reactor safety analysis relates to the occurrence of hypothetical disruptions of nuclear reactor operations. As a necessary adjunct to successful engineering computations, both mechanical and thermal material properties are determined.

The major facilities used in engineering analysis are the large digital computers, the static test lab, wind tunnel facilities, vibration testing facilities, and analog computers. Numerous pieces of equipment are used for material property testing.

Engineering Analysis
Level I Table

	Professional Staff	Investment
Structural Mechanics	50	–
Stress Wave Analysis	27	20
Explosives Analysis	5	–
Heat Transfer	46	100
Aerospace Enginnering	50	1000
Environmental Analysis	14	400
Controls Engineering	30	540
Electrical Analysis	77	250
Nuclear Engineering	18	5300
Reactor Safety Analysis	42	–
Material Properties	13	1250

*Compiled July 1975.

STRUCTURAL MECHANICS

Structural mechanics is used to predict the mechanical performance of a wide variety of parts and assemblies. Included are the load-carrying members in an assembly as well as subassemblies such as electronic components in which stresses are induced by extreme environments or by fabrication. Safety studies in conjunction with testing are used to predict and confirm the outcome of accident sequences in systems with engineered safeguards. In structural mechanics a range of static and dynamic analysis techniques is used – classical procedures in elastic solids and shells; statics, transient dynamics, vibrations, and rigid-body mechanics. Because of the severe loads that are customarily considered, elastoplastic, viscoelastic, composite, cumulative damage, creep, ductile and brittle fracture, and crushable-foam constitutive modeling of the materials is frequently used. Loadings considered include pressure, temperature changes, constant acceleration, blast, impulse, and impact. One of the major resources underlying the work in structural mechanics is an extensive library of finite-element and finite-difference computer programs. Computational procedures for static and dynamic problems, and constitutive formulations for cyclic plasticity and combined high-temperature creep and plasticity are also developed. Structural analysis is carried out in conjunction with extensive testing of individual parts and entire assemblies.

Static Stress Analysis

This form of analysis covers problems produced by external forces, temperatures, and constant accelerations. Work encompasses high-temperature creep, plastic collapse, ductile and brittle fracture, and thermoviscoelasticity as well as linear elastic solutions. Frequently, interfaces which close or open under load are treated. The majority of problems are solved using finite-element techniques both in two- and three-dimensional analysis are employed. Fracture mechanics can be addressed with the calculation of stress-intensity factors for planar and axisymmetric cracks. Detailed analyses of residual stresses in composite materials resulting from fabrication are made using equivalent anisotropic elastic modeling. (Item 1-5)*

Current Activities

Thermal stress analysis
High-temperature creep
Plastic collapse
Thermoviscoelasticity
Composites
Pressure-vessel analysis

*See Highlights below.

Transient Dynamic Response

The most common dynamic analyses involve impact, blast, and impulse. A variety of constitutive models (elastoplastic, viscoelastic, crushable and elastic foam) is used in the analysis. Numerous axisymmetric shells and solids loaded symmetrically are analyzed. In addition, many problems are characterized as comparatively weak structures surrounded by protective materials all of which are subjected to severe impact or blast. Calculations are made that involve large deformations and finite strains. (Item 6)

Current Activities

Membrane inflation
Buoy dynamics
Dynamics of members in tension only
Earth penetrator structural response

Shock and Vibration Analysis

The responses of systems and electromechanical components to severe shock and vibration environments are analyzed. A structural dynamic model is used to predict possible failures and to provide excitation levels for subsystem designers. Extensive analysis, testing, and subsequent data interpretation are used to define the model. (Items 7,8)

Current Activities

Mode shape and frequency determination
Shock spectra
Lumped-parameter models
Nonparametric models

Seismic Studies

The aim of these studies is to determine the response of structures to loading produced by earthquakes. Seismic inputs are characterized as low-acceleration amplitude, long-duration ground motions that excite the fundamental modes in structures. Starting with bedrock excitations, the soil/structure interaction is broken into three parts. Near-field transmission calculations take the seismic inputs from bedrock to the immediate vicinity of the structure. Media-structure interactions describe foundation interactions and resultant response to seismic input. From the foundation response, the response of the primary structure is generated. (Items 9,10)

Current Activities

Near-field transmission
Media-structure interaction
Primary structure response

Acoustic Analysis

Generation, propagation, dispersion, and reflection of acoustic waves, and their interaction with structures, are studied both analytically and experimentally for a variety of applications. (Items 11,12)

Current Activities

Acoustic waves in nonhomogeneous media
Underwater acoustics
Fluid/structure interaction
Wave transmission and reflection

Response of Structures At and Beyond Failure

Weak-link/strong-link concepts (where one part remains functional after another part is guaranteed to have failed, thus assuring predictable behavior) in accident analyses require extensive calculations to establish the relative performance of the weak and strong links. (Item 13)

Current Activities

Brittle fracture
Ductile fracture
Crush

Technique Development

Techniques used in analysis are advanced by the improvement of established procedures and the development of new ones. The study of temporal integration schemes quantifies their frequency shift, damping, and stability. The development of elastoplastic constitutive theories focuses on the accurate description of reverse and cyclic loadings. Models of high-temperature creep which approach elastoplastic behavior at high strain rates are under development. Cumulative damage models have been developed to provide a continuous description of material failure. Algorithms for nonlinear static solutions using an approximate tangent stiffness are under active development. (Items 14-17)

Current Activities

Time integration procedures
- Stability
- Frequency shifts
- Damping

Constitutive modeling
- Finite strain plasticity
- Cyclic plasticity
- Combined creep and plasticity
- Cumulative damage

Nonlinear static deflection algorithm
- Tangent modulus
- Initial modulus
- Approximate tangent modulus

Mesh generation
- 3-D interactive graphics
- 2-D self-organizing

Finite strain transient response

STRUCTURAL MECHANICS

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Thermal Stress Analysis*

An analytical capability has been developed to combine aerodynamic heating, thermal, ablation, and stress analysis techniques. The analysis is applicable to axisymmetric (or two-dimensional) structures subjected to axisymmetric loading; axisymmetric structures with asymmetric loading can also be analyzed when the asymmetries are representable by circumferential harmonics. Complicated material behavior (temperature-dependent, orthotropic, nonlinear) can be included. As an example of this capability, Figure 1 shows a finite-element idealization of a "typical" reentry vehicle nosetip. Figure 2 shows a temperature distribution at a particular point in time, and Figure 3 shows the thermal stresses developed at that point by the temperature field.

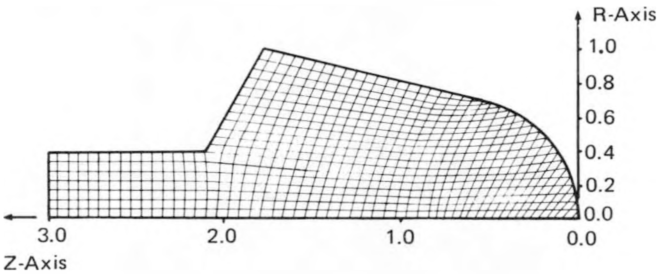

Figure 1. A finite-element mesh idealization of a graphite reentry-vehicle nosetip.

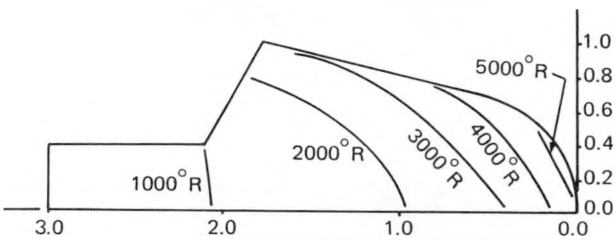

Figure 2. Thermal contours at a point in reentry.

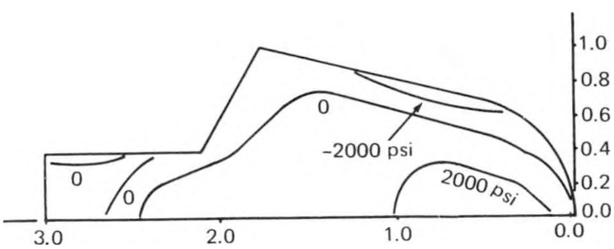

Figure 3. Thermal stresses that result from the temperatures of Figure 2.

Item 2. *Two-Dimensional Static Stress Analysis*

Analytical capabilities have been developed to perform two-dimensional (plane stress, plane strain, and axisymmetric) static stress analyses of both shell and solid structures subjected to mechanical or thermal loadings or their combination. Infinitesimal or finite-strain assumptions are incorporated together with a wide variety of material-behavior assumptions. The most commonly used material behavior is the temperature-independent, time-independent, isotropic, linear elastic model; however, it is often necessary to include increasing complexity in material behavior such as plasticity and creep. As an example of this capability, Figure 4 is a finite-element idealization of a ceramic-to-metal seal of a ceramic vacuum tube. Figure 5 shows the calculated residual maximum principal stress contours developed in the tube by the brazing operation in fabrication.

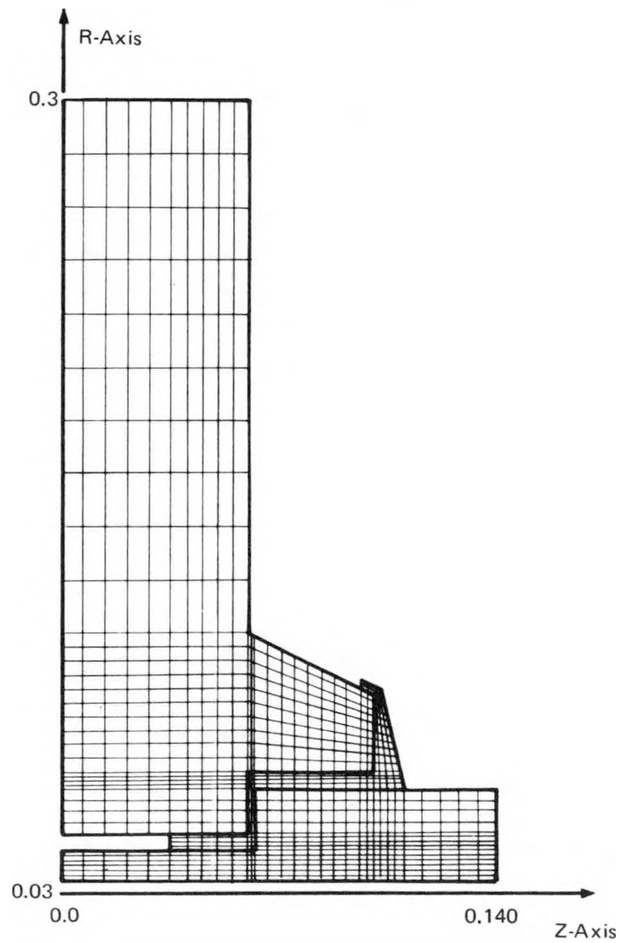

Figure 4. A finite-element mesh idealization of a ceramic-to-metal seal in a ceramic vacuum tube.

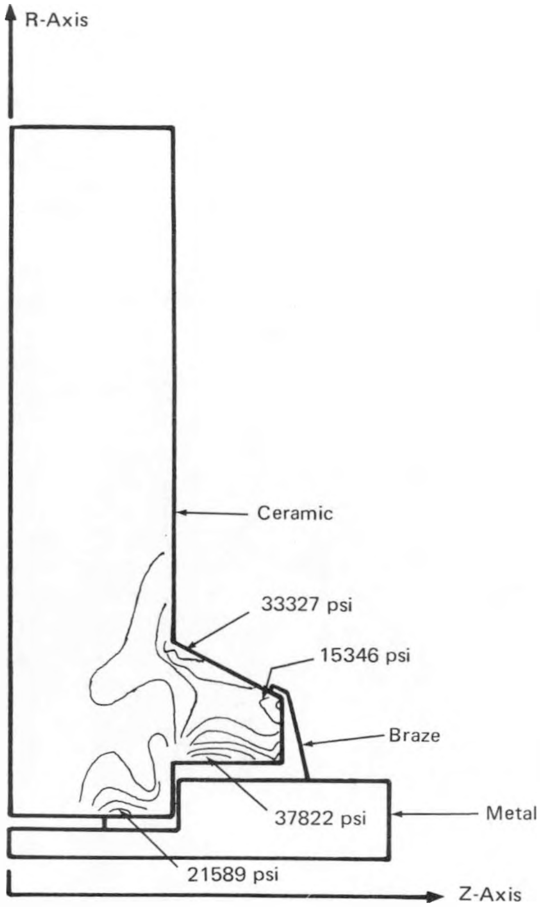

Figure 5. Maximum principal stress contours in the ceramic arising from the brazing operation used to seal the ceramic to the central metal tube.

Item 3. *Three-Dimensional Static Stress Analysis*

Analytical capability has been developed to perform three-dimensional static stress analyses of shell and solid structures subjected to mechanical and thermal loading. The analysis treats the assumptions of infinitesimal strain and linear elastic material behavior. A limited capability exists to perform elastic-plastic three-dimensional calculations. Implied in this capability is use of input and output data processors, which are essential in three-dimensional analyses. This type of analysis finds application to structural, electrical, and electromechanical components. As an example of this technology, Figure 6 shows the three-dimensional finite-element idealization of an encapsulated electrical component. When subjected to a combination of mechanical loads, the top surface deforms as shown in Figure 7. Calculated stress contours on a particular plane can also be plotted as shown in Figure 8.

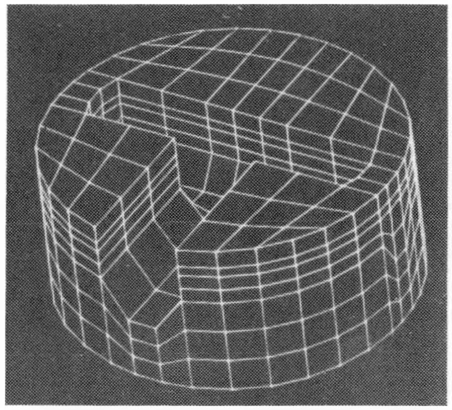

Figure 6. A three-dimensional finite-element mesh idealization of an encapsulated electrical component.

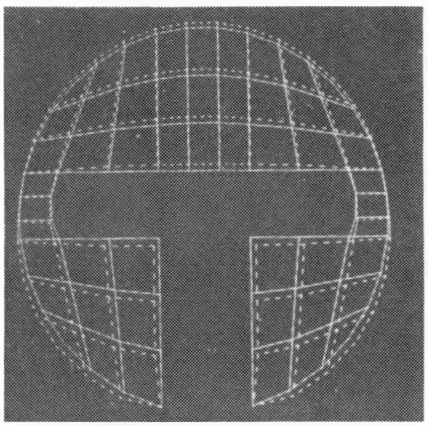

Figure 7. Deformed shape of the mesh on a plane through the structure.

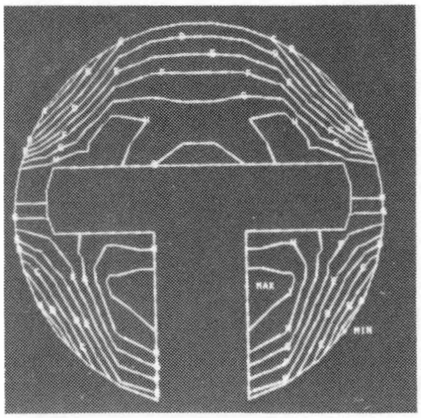

Figure 8. Maximum principal stress contours on a plane through the structure.

STRUCTURAL MECHANICS

Item 4. *Mechanics of Anisotropic Materials*

Elastostatic and thermoelastic analytical tools have been developed for the study of anisotropic and composite materials subjected to thermal and mechanical loads. The technology is applicable to the analysis of major and minor components of the structural, electrical, and electromechanical type that are subjected to residual stresses by fabrication. As an example of component fabrication stress analysis, Figure 9 shows the circumferential component of stress as a function of the radial coordinate in a capacitor immediately after it is wound. The two curves illustrate the importance of including anisotropic material characterization when it is present. The curve labeled "isotropic" shows the result of ignoring anisotropic effects.

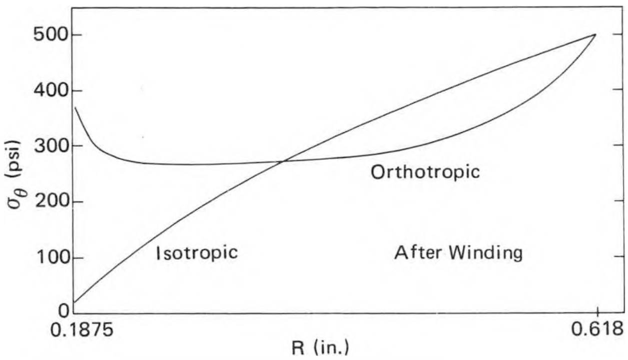

Figure 9. Circumferential stresses in the dielectric material of a wound capacitor with and without orthotropic effects, as a function of capacitor radius.

Item 5. *Two-Dimensional Load-Limit Analysis*

Load-limit analysis is used to find the maximum load a structure will carry without collapsing. As an example of this capability, Figure 10 shows a finite-element idealization of a small axisymmetric pressure vessel. Figure 11 shows the finite-element idealization of the area of interest in the vessel. Figure 12 shows the deformed shape (exaggerated) and Figure 13 the stress contours resulting from internal pressure.

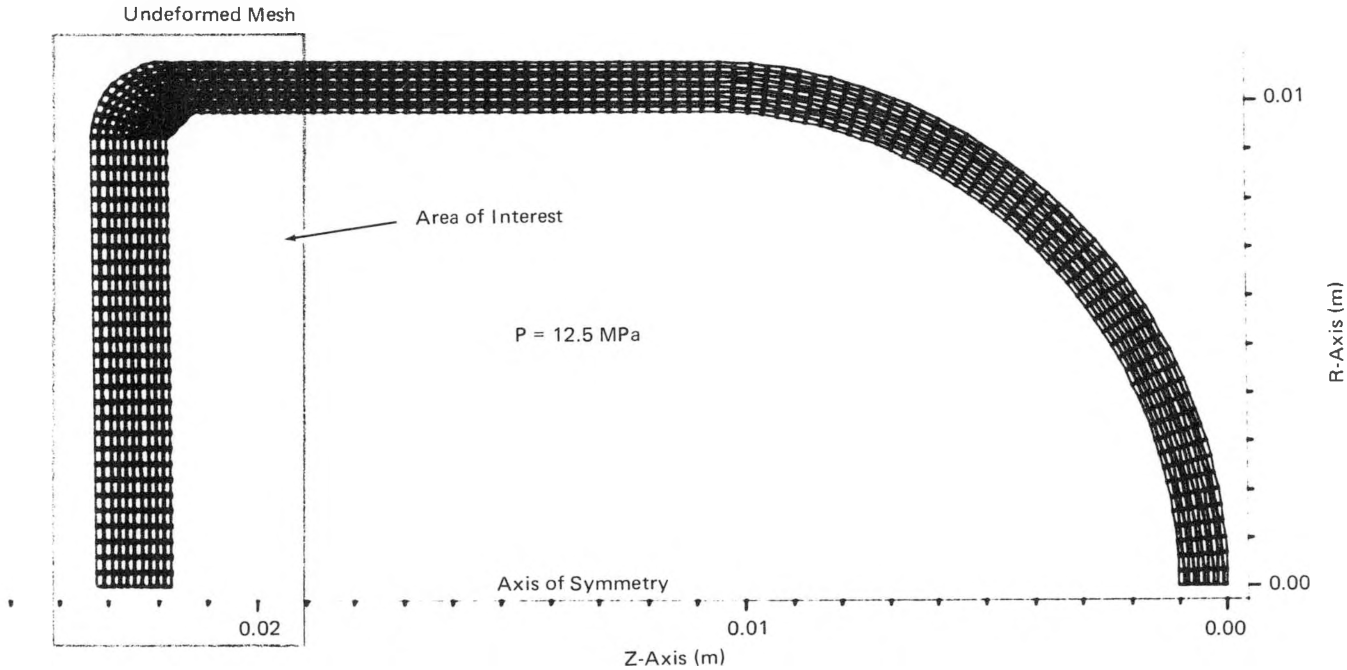

Figure 10. A finite-element mesh idealization of an axisymmetric pressure vessel.

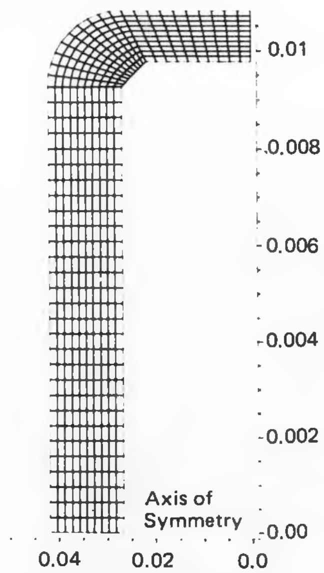

Figure 11. Finite-element mesh idealization of the area of interest in the pressure vessel of Figure 1.

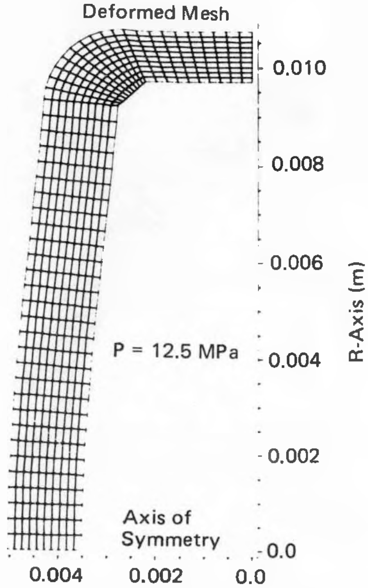

Figure 12. The deformed shape (exaggerated) of the area of interest caused by internal pressure.

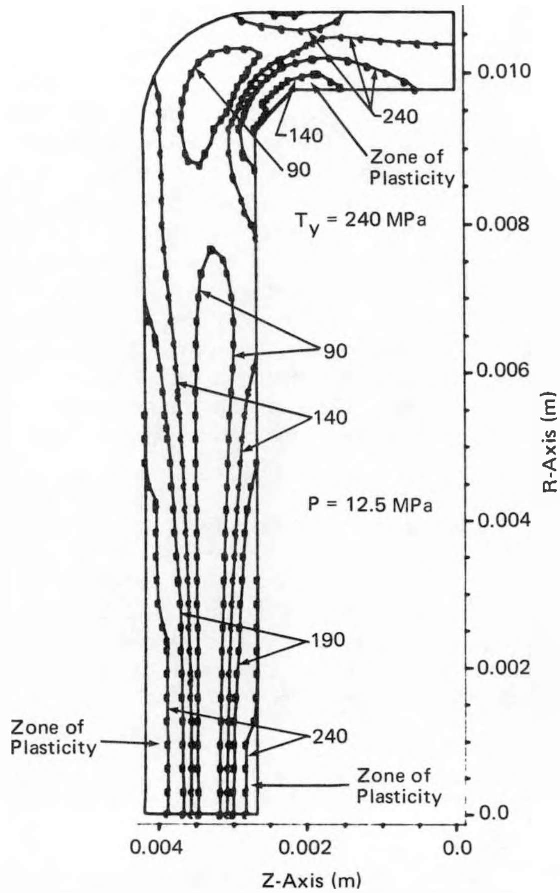

Figure 13. Stress contours developed in the area of interest by internal pressure.

Item 6. *Fuel-Cask Severe-Impact Study*

A truck-transported shipping cask for spent reactor fuel was investigated using static and dynamic structural analysis methods to determine whether an accident involving it and a railroad train would result in the release of spent reactor fuel (Figure 14). It was assumed that the train was traveling 80 miles an hour at the time it impacted the trailer carrying the fuel cask. The computer investigation used both a large-deflection, nonlinear finite-element code to predict cask response, and a lumped-mass model of the locomotive. Nonlinear couplings between masses were used to simulate the crushing and large-scale deformation of the locomotive superstructure and failure of welded and bolted connections. The analysis showed that the cask would be accelerated by the impact with the superstructure to a velocity of 63 mph before it was struck by the locomotive's alternator (Figure 15). The impact was judged insufficiently severe to cause leakage of spent reactor fuel.

STRUCTURAL MECHANICS

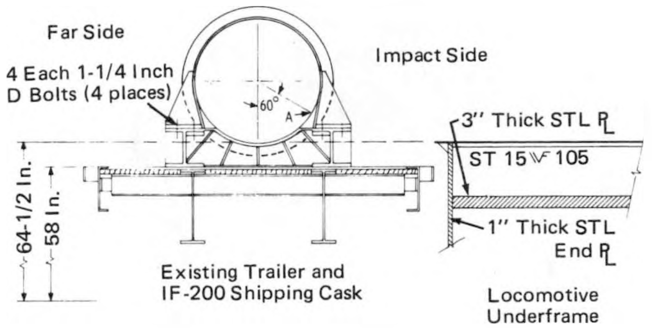

Figure 14. Position of cask and locomotive underframe at impact.

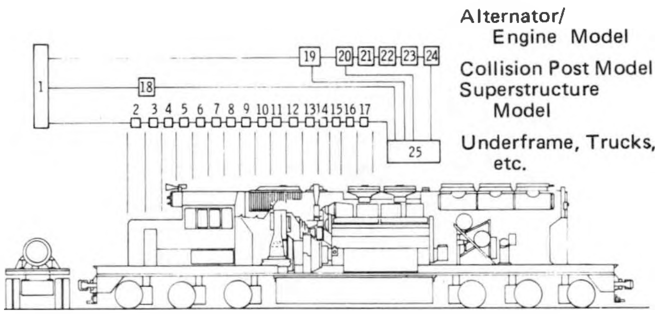

Figure 15. Spring-mass model of six-axle freight locomotive.

Item 7. *Lumped-Parameter Models*

A lumped-parameter structural dynamic model is typically made before a prototype of the system exists. Once the system prototype is tested, the test data become an important source of information for improving the model. A technique has been developed to obtain a physical model directly from test data. The process involves three distinct steps. First, transfer functions from the input to the response points are obtained from data gathered during a random vibration qualification test. These functions are then used to obtain modal parameters of the model. Finally, the modal parameters are used to obtain physically meaningful lumped parameters associated with the model.

Item 8. *Nonparametric Modeling*

The development of the fast Fourier-transform has made practical some well-known linear system analysis techniques. Frequency response functions (transfer functions) are obtained from analytical models or from actual test data. These frequency response functions are then used, with or in place of the traditional structural model, to predict response to shock and vibration excitations.

Item 9. *Near-Field Transmission*

A computer investigation of the effects of local geologic irregularities on the transmission of seismic waves was made. The finite-element method was used to model a geologically diverse region (Rio Grande valley at Albuquerque) in two dimensions (Figure 16). Responses were compared with those of horizontally uniform models for a variety of inputs. It was demonstrated that the distortion of short-period body waves was highly influenced by local geologic irregularities, whereas surface waves and long-period body waves were relatively unchanged. Large areas of block faulting (typical of rift valleys) were shown to have a paramount influence on seismic signals.

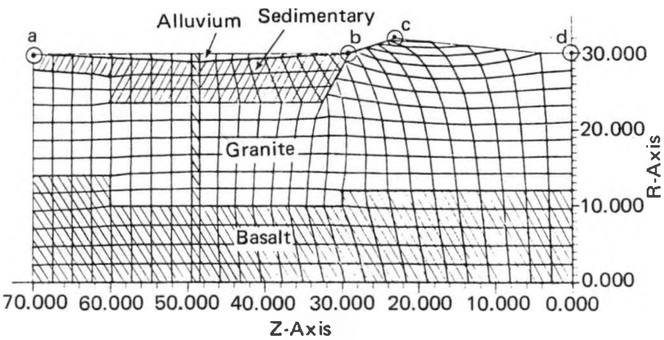

Figure 16. Central mesh area.

Item 10. *Primary Structure Response*

The Sandia annular core pulse reactor beam tube and experiment chamber were analyzed to determine their responses to a seismic input. The shock spectrum of an earthquake that was more severe than any experienced in the Albuquerque area was computed and used to predict maximum deflection in a critical part of the beam tube. The analysis showed that during an earthquake of such severity, the experiment chamber would not contact the reactor core.

Item 11. *Underwater Structural Sound Source*

A low-frequency structural underwater sound source was developed and tested. The associated fluid/structure interaction problem was analyzed. Theoretical and experimental correlation was achieved as illustrated in Figure 17.

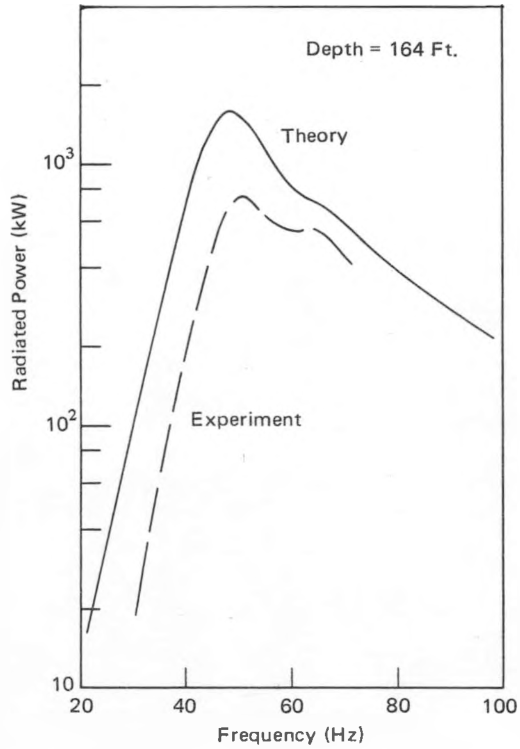

Figure 17. Radiated power versus frequency for a sound source submerged in 164 feet of fresh water.

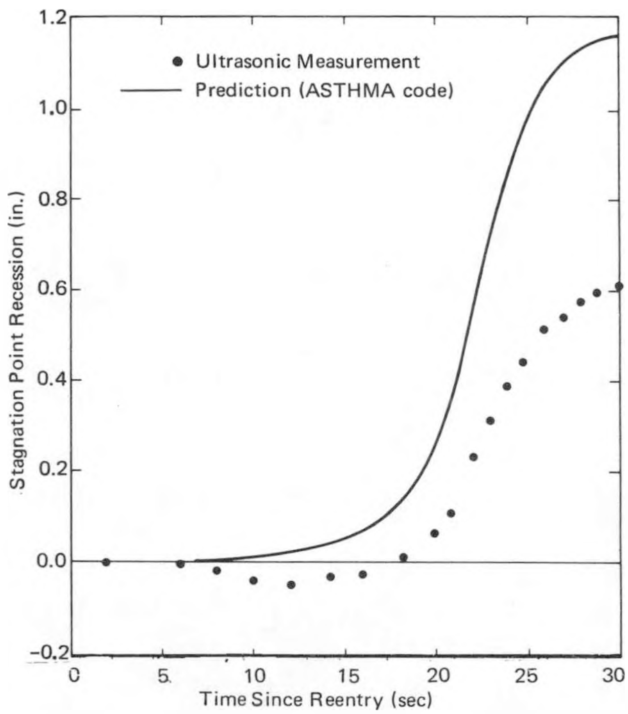

Figure 18. Ultrasonically measured and predicted (ASTHMA code) stagnation point recession histories.

Item 12. *Wave Transmission and Reflection*

The capability of measuring in-flight reentry vehicle nosetip recession using ultrasonic shear-wave transmission and reflection has been developed and flight tested. Since accurate nosetip-recession predictions are difficult, measurements are needed to assess their validity (Figure 18). The results of another recent test showed good agreement between the 0.57-inch value of stagnation-point recession determined from the recovered nosetip and the 0.58-inch value measured in flight after erosion had stopped.

Item 13. *Accident Analysis*

The capability exists to perform analyses at or beyond the failure limit of materials and components. The technology is directed toward structures subjected to accident environments and to the strong-link/weak-link concept of accident analysis. In this approach, a component contains items with greatly differing mechanical strengths and thermal resistances. The strong link has an incipient failure level in excess of the guaranteed failure level of the weak link. The strong link precludes component function until the weak link fails, at which point the assembly can no longer inadvertently function. Structures subjected to thermal environments have been analyzed as well as structures subjected to mechanical "crush" environments. As an example of this technology, Figure 19 shows an idealized component containing defined strong and weak links. When subjected to dynamic crush, the responses of the weak and strong links can be determined (Figure 20).

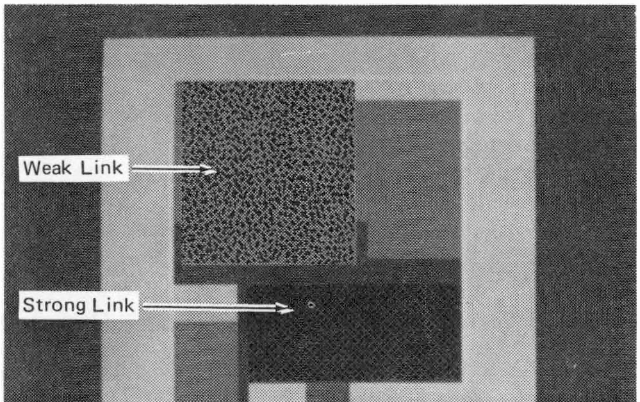

Figure 19. A two-dimensional cross section of an electronics package showing the relative positions of various pieces.

STRUCTURAL MECHANICS

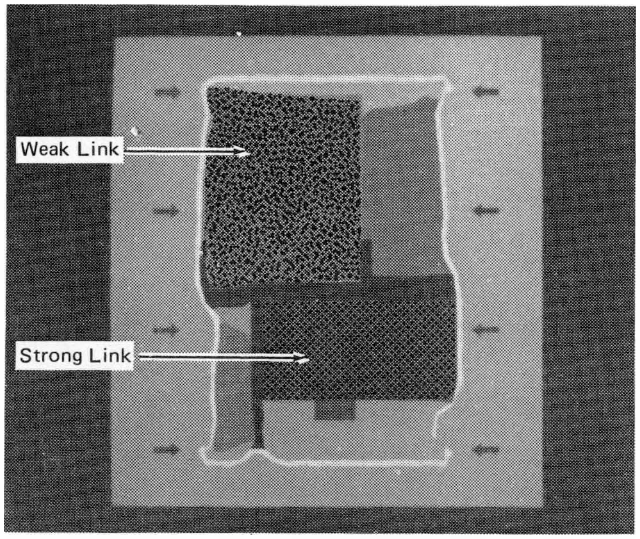

Figure 20. The result of applying a dynamic crushing load. Note the greater crush of the weak link in relation to the strong link.

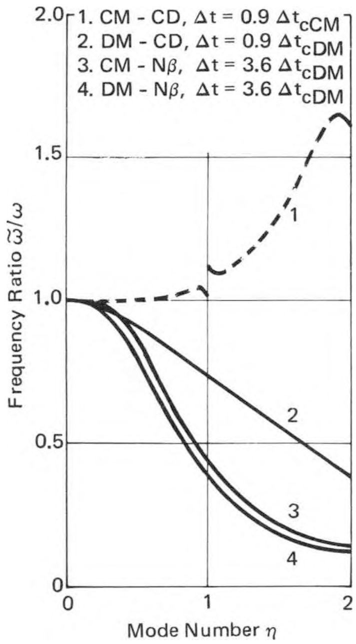

Figure 21. The ratio of computed frequency to exact frequency versus nondimensional mode number for central difference (CD) and Newmark β (Nβ), $\beta = 1/4$, time integrations combined with consistent mass (CM) and diagonal mass (DM) finite-element discretizations of the beam equation using cubic displacement assumptions.

Item 14. *Numerical Time Integraton in Structural Codes*

Numerical time-integration methods in structural codes are topics of continuing study. Frequency and amplitude distortions are introduced by all discrete temporal integration methods. The errors can be minimized by choosing discretization methods in time and space which introduce compensating distortions. Figure 21 shows the frequency distortion associated with four combinations of discretization. The solid curves are all equal work curves. The dashed curve, which is for the central difference/consistent mass combination, is handicapped by both a lower critical time step and a nondiagonal mass matrix, which necessitates the solution of a set of algebraic equations at each time step. Central difference, Newmark beta, Houbolt, and Wilson-Farhoomand as well as modal decomposition and integration are used in various structural codes.

Item 15. *Two-Surface Plasticity Theory*

A plasticity theory has been developed to describe the moderate rate loading of metals. The theory uses two nested surfaces in deviatoric stress space rather than a single loading surface. Each surface moves and enlarges independently. The stiffness of the system is a function of the distance between the stress state and the outer surface. Uniaxial stress/strain curves from this theory are characterized by a gentle transition from elastic to plastic behavior as shown in Figure 22. Theoretical work in numerical analyses is correlated with experimental results to improve code accuracy in predicting biaxial behavior of the model.

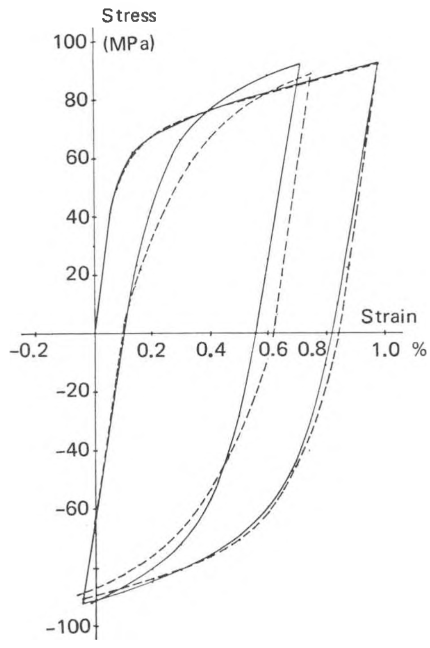

Figure 22. Uniaxial stress-strain curve for 6061-0 aluminum (solid line) compared with theory (dashed line).

Item 16. *Combined Creep and Plasticity*

A mathematical theory of time-dependent plasticity has been developed to describe the multiaxial behavior of metals at high temperature and slow loading rates. Damage generation and damage healing mechanisms are modeled in this theory rather than creep strains and plastic strains. This physical identification allows the theory to describe primary creep, Bauschinger effect for creep, and creep recovery. It approaches a conventional plasticity theory in the limit, as seen in Figure 23, without the use of loading-unloading criteria and inequalities. Secondary creep is characterized as a state where damage generation and healing processes are in dynamic equilibrium. Incorporation of the theory into structural codes and experimental-theoretical correlation work are parts of this continuing effort.

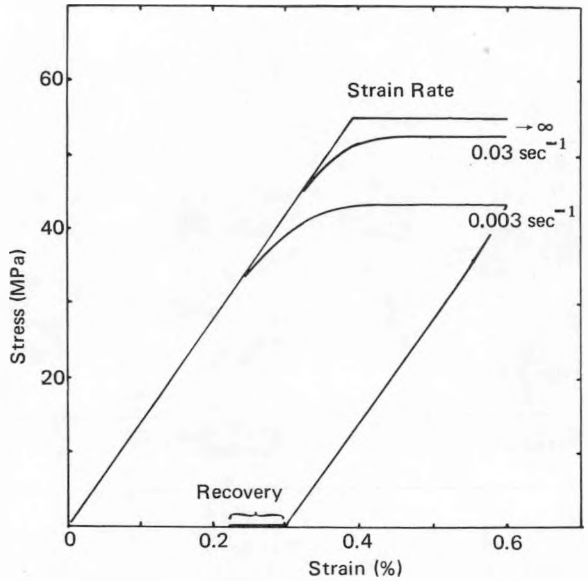

Figure 23. Stress-versus-strain behavior at various strain rates for a time-dependent plasticity model which also incorporates recovery or annealing.

Item 17. *ACCESS: A Structural Mechanics Computer Program Library*

To implement efficient use of available structural mechanics software, a central reference system called ACCESS (a Computer Code Entry Search System) has been developed. The system primarily provides quick identification of available programs, furnishes all information needed for their use, and establishes standards for the documentation and maintenance of programs.

A catalog of available programs is maintained which contains an index of programs by class of structure and by the phenomenology treated in the program. The catalog also contains a description of each code in text form and pertinent facts about the program. Each code is in a category indicating the status of the program: for example, whether it is being written, being implemented, or is a production program. Production programs that have the greatest use are placed in permanent files in the computer in both card image and compiled form, for easy access. For planning purposes, an accounting system allows determination of actual use history.

Of 155 programs in ACCESS, 31 are maintained on the permanent files.

STRESS-WAVE ANALYSIS

Stress-wave analysis is directed toward an understanding of stress-wave propagation in materials. The results are applied to the design of components and systems that will be subjected to impact, explosions, transient radiation, and other extreme environments. Emphasis is on the development of methods for analyzing engineering designs. The necessary techniques result in computer codes for stress-wave propagation in one, two, or three dimensions, requiring modeling of the dynamic response of structural metals, composites, polymers, porous materials, explosives, and geologic materials. Rate-dependent elastic-plastic, viscoelastic, porous, and dispersion response, including brittle and ductile dynamic failure, shock-induced chemical reactions, and phase changes, are representative areas of effort. Major areas include stress-wave codes and phenomena, constitutive relations, physics of explosives, and measurement techniques for material response.

Material Constitutive Relations

Joint theoretical and experimental analysis efforts have as their goal the characterization of the dynamic response of broad classes of materials and the determination of constitutive equations especially for incorporation into numerical computer codes. Programs are aimed at characterizing the response of materials to severe environments generally involving a combination of high stresses, high strain, high heating rates, and high temperature. Models of material response are used to correlate material behavior over diverse stress-loading conditions, ranging from quasi-static to the upper limit of strain-rates associated with shock-wave loading. Closely associated with the constitutive models is development of the necessary dynamic fracture models. These models, together with specific material-property data and numerical codes, find use in the solution of design, engineering and safety problems. (Items 1-4)*

*See Highlights below.

Current Activities

- Constitutive models
  - Soils/rocks
    - Variable-yield
  - Composites
    - Dispersive linear and nonlinear
  - Polymers
    - Nonlinear viscoelastic
  - Explosives
    - Kinetic
  - Porous media
    - Rate-dependent pore collapse
  - Mixtures
    - Mechanical kinetics
    - Transformation kinetics
  - Metals
    - Elastic/plastic
    - Work-hardening
    - Rate-dependent
  - Ceramics
- Fracture models
  - Fracture initiation and growth
  - Cumulative damage
  - Spallation
  - Geologic material failure
- Test Conditions
  - Stresses
    - 0 to 500 GPa
  - Strain rates
    - 10^{-3} to 10^{6}/s
  - Impact velocities
    - 0.01 to 10 KM/s
  - Heating rates
    - 0 to 10^{11} K/s

Computer Program Development

Wave-propagation computer programs are developed and applied to yield a more detailed understanding of stress-wave mechanics. Versatile codes are applied to obtain solutions to problems required in the analysis and design of systems and components, and to reduce the number of expensive experiments and design time. (Items 5-7)

Current Activities

- Specific codes
  - Lagrangian one-dimensional
    - CHART-D
    - WONDY
    - CONCHAS
    - SWAP
  - Lagrangian two-dimensional
    - TOODY
    - TOOREZ
  - Eulerian two-dimensional
    - CSQ
    - DORF
  - Two-dimensional generalized coordinates
    - ADAM
  - Three-dimensional
    - TAOSS
    - THREEDY
    - TRIOIL
- Numerical methods
  - Alternating direction
    - Time step splitting
  - Characteristics
  - Finite difference
    - Artificial viscosity
  - Shock fitting
- Constitutive relations
  - Thermodynamically complete multiphase hydrodynamic description
  - Elastic-plastic-strain hardening
  - Rate-dependent yielding
  - Cumulative damage failure criteria
  - Porous materials
  - Composites
  - High explosives
  - Phase-change kinetics
  - Nonlinear viscoelastic
- Features
  - Energy transport
    - Radiation diffusion
  - Automatic one-dimensional rezoning
  - Two-dimensional Lagrangian rezoning
  - Sliding interfaces
    - Contact boundaries
  - Interactive graphics
  - Plotting packages
  - Coupled wave propagation
    - Structural response
- Initial and boundary conditions
  - Time-dependent energy sources
  - Time-dependent boundary conditions
  - Applied boundary stresses or position
  - Initial velocity conditions
  - General initial zoning
- Applications
  - Ballistic penetration
  - Ground-shock propagation
  - Hypervelocity impact
  - Cratering by explosives
  - Shaped charges
  - High-explosive containment
  - Rain and dust erosion
  - Laser and electron-beam-generated stresses
  - Metal forming and cutting by explosives
  - Rock-material disintegration
  - Failure thresholds for safety requirements
  - Radiation-induced impulse

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Armor-Plate Spall Strength*

Projectile penetration characteristics of armor plate has been analyzed. An accomplishment of the program was the close correlation of an experimental hypervelocity penetration test with numerical wave-propagation code predictions. Success of the calculations was due to material-property input based on experimental determination of the spall strength of armor plate (information not previously available). Figure 1 shows spall separation initiated in armor plate by conventional gas-gun impact experiments. The thin plate is a flyer plate, which was impacted at a velocity of 0.335 mm/μs against the target. A spall strength of 3.8 GPa was determined.

STRESS-WAVE ANALYSIS

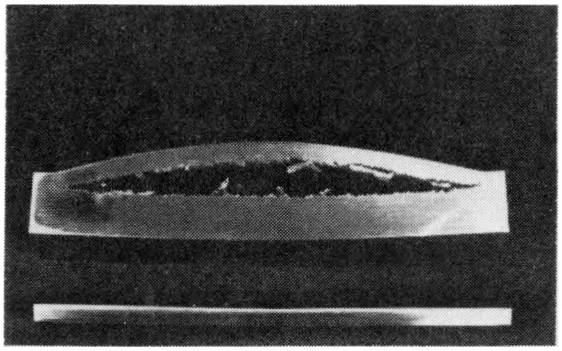

Figure 1. Spall of armor-plate steel produced in experiment to determine dynamic tensile strength.

Item 2. *Constitutive Equation Modeling in Composites*

Studies of wave propagation in composites has resulted in several constitutive models. Extension of a rigorous mathematical description of a linear elastic model with microstructure to higher orders, specifying interlamellar stress and strain constraints, has led to a greater understanding of internal stress and strain fields. Still further understanding has resulted from a realistic statement of external boundary conditions and a knowledge of the role of interlaminar load failure in governing wave propagation.

While elastic theories aid in understanding wave propagation, a series of "homogeneous" material models have proven the most useful. These models allow nonlinear stress-strain description. One, for example, treats composites as rate-dependent solids of the Maxwell type. Excellent agreement has been obtained between calculated stress-wave profiles and laboratory experiments on a cloth-laminate quartz-phenolic composite. Stresses were calculated to within 5 percent, as were wave speeds. Further extensions of the model incorporate thermodynamics and porosity. In this form, the model is useful in engineering design calculations which replace expensive and prolonged field testing.

Item 3. *Shock Initiation of Detonation in PBX-9404*

High-resolution measurements of the structure of plane waves propagated through PBX-9404 explosive have yielded information about the growth rate of weak shocks toward detonation. Comparison of the detailed structure of observed wavefronts with theoretical results permits the determination of rates of release of chemical energy behind the shock and study of the interplay between this energy release and viscoelastic dissipation of energy in controlling wave growth. Information on the properties of explosives is used in developing ordnance and in safety assessments of potential accident situations involving explosives.

Item 4. *Static Triaxial Stress Studies of Oil Shale*

A computer-controlled triaxial test machine is used to study the yield and fracture behavior of anisotropic oil shales as a function of kerogen content under various loadings. A typical result (Figure 2) illustrates the increase of volumetric strain with compressive stress unique to rocks and soils (dilatancy). This effect is dominant in geologic materials, and triaxial studies are providing data needed to construct constitutive models. Such models, incorporated into numerical codes, are used for engineering calculations in developing earth-penetrating projectiles, cratering, rock drilling and blasting, and oil-shale retort rubblization.

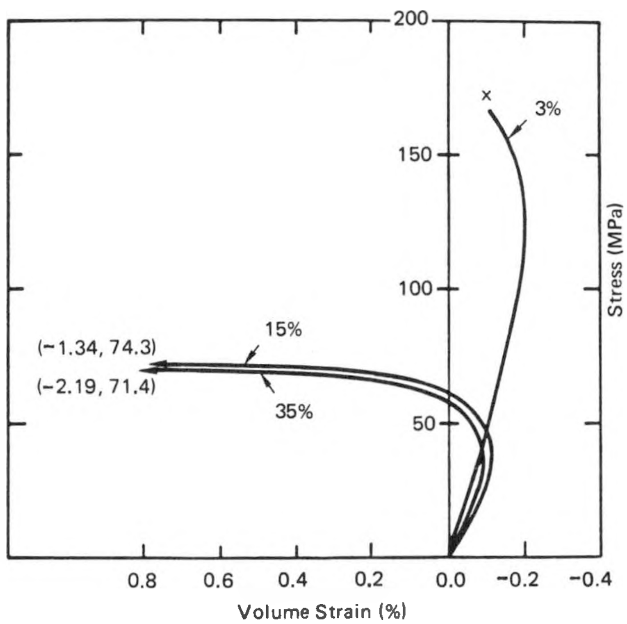

Figure 2. Axial stress-volume strain behavior of oil shale as a function of kerogen content (volume percent). Failure or fracture is denoted by X for the 3-percent shale and by the strain and stress values noted for the 15 and 35 percent shales.

Item 5. *Safety Analysis for Radioactive Material Containers*

The response during impact loading of a heat-source capsule (Figure 3) for a radioisotopically powered thermoelectric generator was analyzed to determine structural integrity. The capsule consists of a fuel pellet made of a radioactive isotope, surrounded by a foam material, which is in turn surrounded by layers of special alloys.

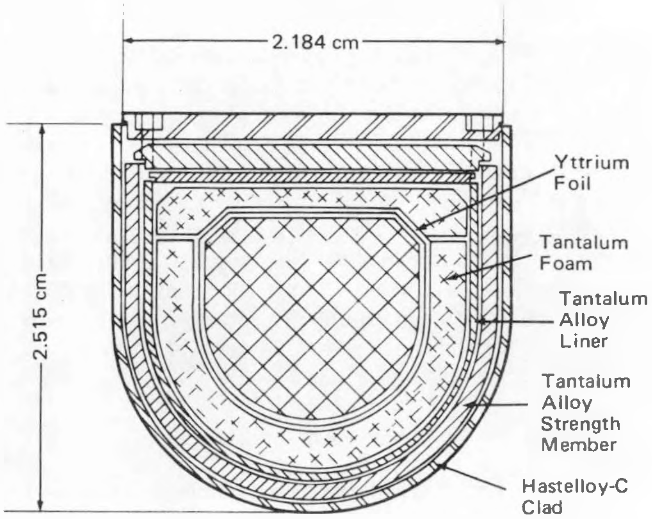

Figure 3. Heat source for radioisotopically powered thermoelectric generator

To predict whether the outer case of the capsule would rupture under impact, calculations were performed with a two-dimensional wave-propagation code (TOODY) capable of providing the deformation history for each part of the capsule. In one calculation the impact surface was at the spherical end; in another, at an angle with the corner of the capsule's flat end. Reduction in strength of the outer layer of material because of welding was modeled. Results showed that the outer structure of the capsule should remain intact, and that the toxic radioisotope would not be released.

Item 6. *Dynamic Loads on Earth-Penetrating Projectiles*

In conjunction with terradynamics experiments, two-dimensional stress-wave propagation codes are employed to predict penetration depths, deceleration histories, and dynamic loads imposed on projectiles during impact and penetration. Constitutive equations for earth materials, determined by shock wave and static triaxial stress experiments, have been incorporated into the TOODY two-dimensional code. Given appropriate geomaterial property data, calculations of projectile penetration are accurate for single or layered media (Figure 4). Material response, including compaction behavior and failure, is observed and its relation to projectile velocity, nose configuration, and projectile loads, is assessed to optimize projectile designs.

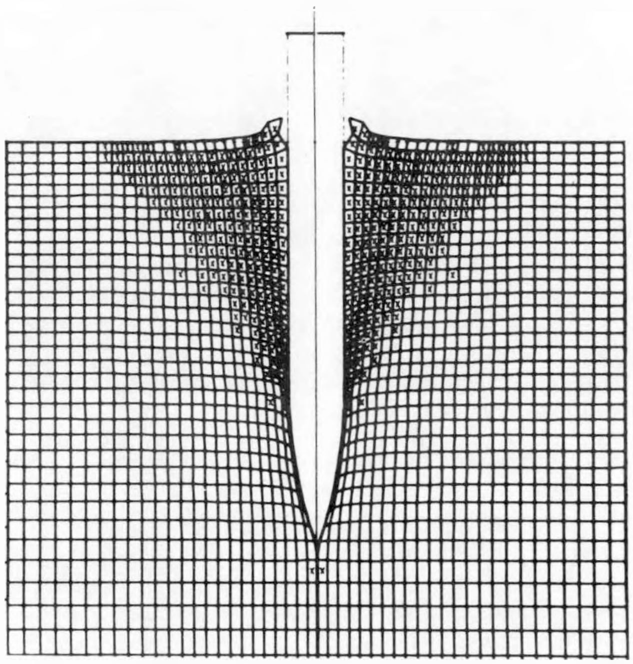

Figure 4. Regions of failure (8 msec after impact) produced in a soil medium by a 0.165-m-diameter projectile impacting at 152 m/s.

Item 7. *Exploding-Foil-Driven Flyer Plates*

In certain problems regarding impact testing of materials and explosive initiation it is necessary to accelerate thin plates to velocities of the order of 5 km/s. A technique has been developed in which the accelerating force is provided by thermodynamic pressure generated when aluminum foils are vaporized by the passage of large electric currents. The performance of such systems has been analyzed through application of the one-dimensional

STRESS-WAVE ANALYSIS

hydrodynamic code CHART-D and the two-dimensional code CSQ. These codes contain equations of state for aluminum and air that are valid over the range of pressure, temperature, and density encountered. With these equations of state, and simpler ones for less critical components, system performance has been analyzed over a wide range of mechanical dimensions, materials (including air-filled gaps), and for various times of energy deposition. The critical link between the electric current and energy-deposition in the foil is a subroutine of the computer program, which includes a tabulation of experimental data on electrical heating of metals.

These calculations have proven accurate for the range of parameter variations checked, as indicated by the comparison in Table I.

TABLE I

Comparison of Experimental and Computed Results for Exploding Foil-Shots

Foil Size* (in.)	Flyer Velocity** After 5 mm Displacement (km/sec)		Time of Flight (μs)	
	Experimental	Computed	Experimental	Computed
0.375 x 0.375 x 0.004	6.25	6.45	1.0	0.75
0.5 x 0.5 x 0.003	5.25	5.35	1.3	1.01
1.0 x 1.0 x 0.002	5.40	5.45	–	1.16

*Aluminum foil.
**Mylar flyer, thickness 0.01 inch.

EXPLOSIVES ANALYSIS

This activity is directed toward developing ways of predicting both explosive behavior and the effect of detonation on material in contact with the explosive. This predictive capability is supported by theoretical and experimental research and verification testing. Applications have ranged from design of explosion containers and blast-resistant structures to the design of explosive initiators and analysis of rock-blasting problems. Capabilities in such related areas as formulation and manufacture of explosive materials and devices, quality assurance, and reliability analysis are important adjuncts.

Initiation Phenomena

Stimuli usually initiate detonation in explosives by producing a weak reaction that grows to detonation. Analysis of explosive behavior in this subdetonation regime is necessary for the design of sophisticated explosive devices, for safety assessment, and for the design of initiation systems themselves.

To support design studies, methods have been developed for predicting initiation of explosives by high-velocity impacts, sparks, exploding wires, and contact with detonating explosives of other types. Safety studies usually involve initiation by low-velocity impact, crushing, or heating.

Analysis of explosive response to low-level mechanical stimuli is possible, but is currently based on rather special criteria derived from experiment. Thermal-ignition phenomena can be treated analytically by solving a heat-conduction problem in which the chemical reaction is included as an energy source. (Items 1-5)*

Current Activities

- Thermal ignition
  - Heat conduction and thermochemical instability in reactive materials
  - Shock heating and thermal ignition of homogeneous explosives
- Wave growth and decay studies in heterogeneous explosives
  - Acceleration waves
  - Shock waves
- Exploitation of experimentally derived initiation criteria
  - Pressure history criteria
  - Detonator burst-current criteria
  - Detonation buildup tests
  - Detonability limits for fuel/air explosives
  - Safety tests
- Initiator design
  - Electrical detonators
  - Flyer-plate initiators
- Related test activity
- Theoretical and experimental research

Explosive Performance

Studies are directed toward an understanding of loads imposed on nonreactive materials in contact with detonating explosive. Analyses range in detail and accuracy from the application of Gurney formulae to use of computer codes that solve the partial differential equations representing the physical and chemical theories of detonation. These latter codes, in their most highly developed form, are also capable of determining charge criticality and solving problems of initiation and transfer of detonation. (Items 6-9)

Current Activities

- One- and two-dimensional Chapman-Jouget calculations
  - WONDY
  - TOODY
  - CHART-D
  - CSQ
- One-dimensional reactive calculations
  - WONDY
- Chemical equilibrium code calculations
  - TIGER
  - CEC-74
- Gurney theory
- Response of nonreactive materials to detonations

*See Highlights below.

EXPLOSIVES ANALYSIS

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Thermal Explosion Theory*

Analytical studies are used to define and calculate critical parameters governing the thermal ignition of solid explosives. With the reaction kinetics of explosives modeled as a function of temperature only, analysis of both the steady and transient forms of the governing heat equation has shown the existence of a critical temperature that depends on the geometry of the material. If the temperature in the explosive exceeds the critical value, the temperature increases rapidly and thermal ignition results. These calculations are in agreement with experimental observations. In Table I, calculated critical temperatures of small cylinders of ten explosive materials are compared with experimental results obtained at the Los Alamos Scientific Laboratory. Current investigations aim at further calculations for engineering applications and determination of the influence of reactant consumption on predicted behavior.

TABLE I

Comparison Between Experimental and Calculated Critical Temperatures

Explosive Material	Critical Temperature (°C) Calculated	Experimental
HMX	254	253-255
RDX	218	215-217
TNT	292	287-289
PETN	197	200-203
TATB	335	331-332
BTF	276	248-251
NQ	206	200-204
PATO	290	280-282
HNS	318	320-321
DATB	324	320-323

Item 2. *Equation of State of Nitromethane*

To facilitate shock-initiation calculations for nitromethane, an internally consistent thermodynamic equation of state for the liquid has been determined experimentally. Thirty-eight thermodynamic parameters have been tabulated over a range that includes pressures to 20 GPa, temperatures to 2000 K, and compressions to one-half the normal volume. A computer file of these data has been constructed and is available as a subroutine for wave-propagation codes. An example of the information available is given in Figure 1, which shows the temperatures achieved for varying degrees of shock compression of nitromethane at three values of initial temperature.

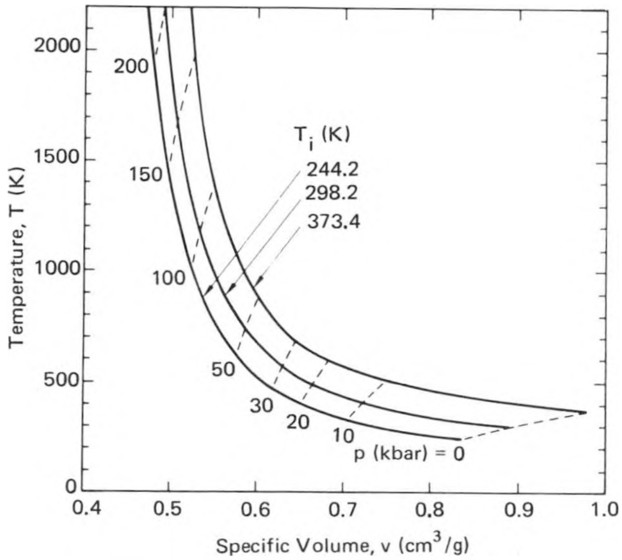

Figure 1. Temperature-specific volume states achievable behind shock waves of various strengths for three values of the initial temperature.

Item 3. *Shock Initiation of Detonation in Nitromethane*

Shock initiation of detonation in nitromethane, a representative homogeneous explosive, has been studied both experimentally and theoretically. In the experiments, room-temperature samples of the material were compressed by plane shocks to pressures from 7.5 to 9.5 GPa. Diagnostic information in the form of the ignition time interval, τ, and the particle velocity history of the shock-compressed liquid were obtained from simultaneous streak camera and velocity interferometer records. These data have been favorably compared with predictions obtained from the application of thermal ignition theory using an equation of state for nitromethane, along with chemical kinetic data on exothermic decomposition of the shock-heated liquid. A linear variation of log τ with the calculated temperature behind the inert shock wave is predicted theoretically and observed experimentally for ignition times of the order of 1 microsecond. These results are of specific importance in the behavior of nitromethane and are of general interest because they contribute to our understanding of the physics of initiation and detonation of homogeneous explosives.

Item 4. *Wave Propagation in Heterogeneous Explosives*

Analytical and numerical solutions of impact problems involving explosives require a realistic theory of their dynamic mechanical, thermal, and chemical behavior. To this end, experimental and analytical techniques are used to study the propagation of shock waves, acceleration waves, and acoustic waves in heterogeneous explosive materials. The study, aimed at determining the dynamic response of such materials over a wide range of stresses and temperatures, will determine the thermomechanical and thermochemical properties necessary to predict such behavior as shock initiation and transition to detonation. The experimental information is used to formulate models for use in codes that permit the numerical solution of engineering problems. A theoretical model of the behavior of shocks of various strengths is compared with experimental observations in Figure 2.

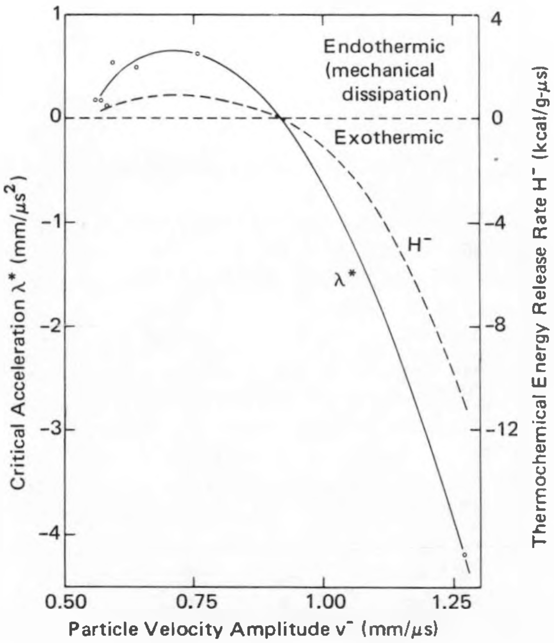

Figure 2. Acceleration behind shocks of varying strengths that separates the region in which the shock grows in strength from that in which it decays. Also shown is the energy release rate at the critical condition corresponding to steady wave propagation.

Item 5. *Wave Propagation Calculations for Chemically Reacting Media*

A subroutine has been developed for use with the finite-difference Lagrangian code WONDY-IV to calculate one-dimensional wave propagation in rate-dependent materials whose response can be characterized by a finite number of internal-state variables. This code is applied to the study of chemically reacting solids with internal-state variables representing the extent of the individual reactions involved. The study is aimed at determining the influence of the reactions on the evolution of shock-wave profiles and at determining the role of boundary conditions on the shock initiation and transition-to-detonation behavior of explosive materials. From these studies, it will be possible to refine the experimental procedures used to evaluate dynamic material properties.

Item 6. *Gurney Theory of Explosive Performance*

Gurney formulae provide a way of estimating the velocity of explosively accelerated material to within about 10 percent in typical configurations. These formulae represent global momentum and energy balances calculated on the assumption that velocity distribution in detonation products is linear. For a given geometrical configuration the Gurney formula expresses the velocity of driven material to that of the explosive. In each case the velocity is proportional to the square root of a "Gurney energy" characteristic of the particular explosive used and its density.

Hydrodynamic solutions for a matrix of test problems have been obtained to determine the range of applicability of the formulae. These calculations also lead to an improved understanding of the relationship between the Gurney energy that scales the formula to experimental observations and the thermochemical energy liberated in calorimetric experiments. Figure 3 shows a comparison of an analytical solution for the velocity of an explosively driven plate with the velocity predicted by the Gurney model. Calculations using the chemical equilibrium code TIGER have been used to derive correlations between Gurney energy and the more readily determined quantities of explosive density and detonation velocity.

Item 7. *Design of Flyer Plate Initiators*

Detonation is often transmitted between elements in an explosive train by driving a solid plate or fragments across a gap to impact an explosive charge. To facilitate the design of these transfer devices, an analytical model

EXPLOSIVES ANALYSIS

has been developed that combines the Gurney formula for flyer-plate acceleration with the pressure-history initiation criterion, $P^2\tau$ (P denotes shock pressure applied to the explosive and τ the duration of its application). Using this model, it has been possible to optimize the configuration of transfer devices within various sets of constraints. For example, one can maximize the initiation product for a device of fixed length, or one can minimize the length of a device delivering a given initiation product.

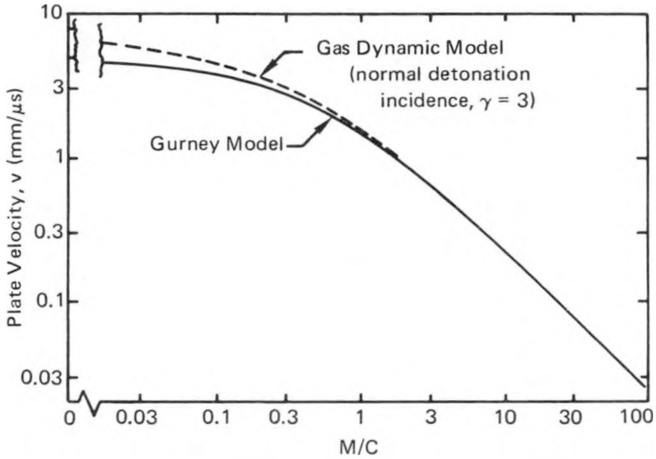

Figure 3. Gas dynamic and Gurney predictions of the velocity of explosively driven plates for various ratios of plate mass, M, to charge the mass, C, of composition B explosive.

Item 8. *Explosion Containment*

A variety of analytical and numerical studies has been conducted to facilitate the design of explosion-containment vessels. In these vessels kinetic energy produced by the explosion is converted to heat by irreversible shock compaction of metal foams, and motion imparted to the inner parts of the vessel is arrested by a ductile structure driven far into its plastic range of deformation. These systems have been analyzed in detail using the wave codes CHART-D, WONDY, and TOODY (Figure 4). The various materials are represented, respectively, by the JWL equation of state for detonation products, the P-α model of foam compaction, and the theory of elastic-plastic flow with strain hardening. Special fracture models are used to account for fragmentation of inner portions of the vessel.

Item 9. *Computer Simulation of an Oil-Shale Fragmentation Test*

Computer simulation of events involving the detonation of explosives permits evaluation of the sensitive

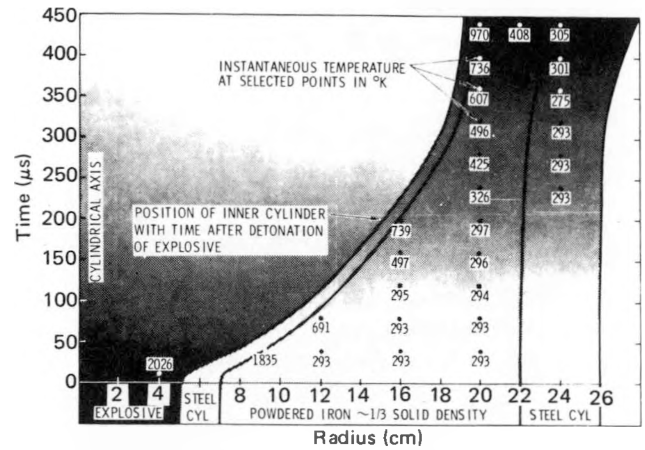

Figure 4. The position of the various parts of a containment vessel subsequent to the detonation of the enclosed explosive and selected temperatures are shown.

parameters of the models. Several such simulations were conducted with the aid of the TOODY stress-wave propagation programs, and were used to evaluate the fragmentation of oil shale by detonation of a liquid explosive emplaced by hydraulic fracturing techniques. In these two-dimensional simulations, a thin horizontal layer of explosive was sandwiched between two much thicker sheets of oil shale. Detonation of the explosive resulted in shock and release-wave interactions near the upper and lower free surfaces of the shale layers, causing tensile stresses that exceeded the strength of the shale, and fragmentation occurred (Figure 5). The principal parameter studied was the degree of fragmentation as a function of the relative thicknesses of the explosive and the oil-shale layers.

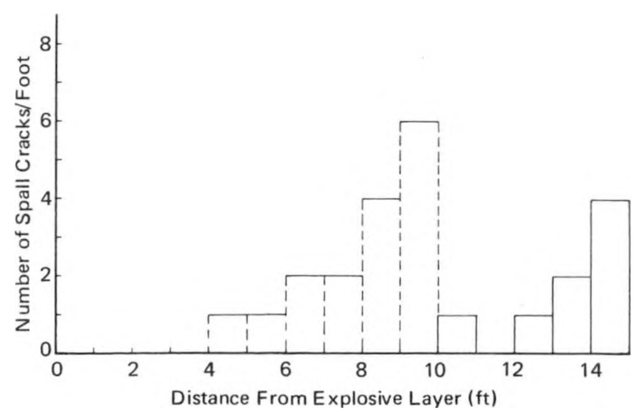

Figure 5. Spall-induced fracturization as a function of the thickness of the oil shale layer.

HEAT TRANSFER

Heat-transfer analyses are concerned with the performance of thermal devices or the response of objects to thermal environments. Problems involving thermal conduction are frequently handled by developing a lumped-parameter representation of the physical problems. The lumped-parameter network is then solved using a numerical finite-difference heat-transfer computer program such as CINDA. In some cases analytical or approximate analytical methods, such as the integral conduction method, are used to solve conduction problems. Problems involving fluid heat-transfer effects such as convection, boiling, and melting are analyzed using numerical or analytical methods such as boundary layer or perturbation techniques. Small-scale laboratory-model experiments are frequently used to check assumptions in the analytical or numerical models and to generate data to compare with analytical or numerical calculations.

Conduction Heat Transfer

This work is concerned with predicting the temperature response of various objects where the primary mode of heat transfer is thermal conduction. Both analytical methods and numerical conduction codes are used in the analysis. (Item 1)*

Current Activities

- Three-dimensional transient finite-difference conduction calculations
  - Variable thermal properties
  - Phase change
  - Moving boundaries
  - Nonlinear boundary conditions
  - Internal heat generation
- Finite-element conduction calculations
- Integral conduction method
- Approximate temperature profile method
- Analytical solutions
  - Classical methods
    - Linear problems
  - Asymptotic expansions and singular perturbations
    - Nonlinear problems
  - Effective thermal properties for composite solids

*See Highlights below.

Convection and Melting

Current activity is devoted to analyzing problems involving natural convection in cavities, frequently with the inclusion of phase change and moving boundaries. Numerical, analytical, and experimental techniques are used in solving these problems. (Item 2)

Current Activities

- Finite-difference convection calculations
  - Two-dimensional (plane or cylindrical)
  - Transient
  - Constant properties
  - Laminar
  - Turbulent (eddy model)
  - Internal heating
- Finite-element convection calculations
  - Two-dimensional (plane or axisymmetric with arbitrary boundaries)
  - Steady-state
  - Constant properties
  - Laminar
  - Internal heating
- Boundary-layer solutions
  - Laminar
  - Turbulent
  - Internal heat generation
- Experimental modeling
  - Dye tracer techniques
  - Laser holographic interferometry
  - Classical (Mach-Zehnder) interferometry
  - Internal heat generation
  - Electrically heated electrolytes
  - Resistance heaters
  - Transient heat-sink simulation

HEAT TRANSFER

Spectroscopic measurements
Flame (combustion zone) radiative properties
Absorptive
Emissive properties of gases, liquids, and solids

Energy Systems

Heat-transfer analyses are made of devices such as solar collectors, heat exchangers, and steam generators. Studies are also made of the thermal performance of overall energy systems such as solar collector plants, oil-shale extraction schemes, and magma-tap systems. These studies involve thermodynamic analyses, energy balances, and transient performance predictions. (Item 3)

Current Activities

Transient heat-transfer analyses
Energy balance calculations
Classical thermodynamics
Analytical boiling calculations
Experimental boiling studies
Heat-exchanger design
Convective heat extraction
Forced convection
Natural convection in enclosures
Turbine design
Boiler design
Collector field optimization
Transient thermodynamic/hydrodynamic system analyses
Heat transfer in porous media with combustion
Liquid and gas fluidized media
Ionic transport in porous media with convection

Fire Analysis

Predictions are made of thermal input from fires ranging from long-term fueled fires to brief but high-intensity thermal inputs resulting from fireballs caused by the explosion of gaseous or dispersed liquid-fuel clouds. Part of this problem deals with the design and instrumentation of fire tests; another is concerned with predicting the response of various objects and devices to a fire environment. (Item 4)

Current Activities

Momentum modeling of expanding clouds from pressurized liquids
Combustion modeling of large fuel/air clouds
Fireball instrumentation design
Computer simulation of fires
Convection and radiation modeling
Internal conduction response to fires
Experimental fire tests
Fire response of bodies by integral conduction method
Analytical modeling of flame-emission properties
Plume studies

Radiation Heat Transfer

This work is concerned with predicting the temperature response of various objects where the primary mode of heat transfer is by thermal radiation. (Item 5)

Current Activities

Radiative surface properties
Radiative exchange between diffuse or specular surfaces (gray and nongray)
View-factor calculations
Satellite temperature control
Radiation in absorbing
Emitting media
Radiation interaction with other heat-transfer modes
Infrared detector responsivity to various inputs
Solar radiation spectral and total modeling
Combustion-zone radiation
Collection of solar radiation calculations
Plasma radiation
Continuum and line
Radiative gas dynamics and hydrodynamics
Modeling of gas absorption
Emission properties

HEAT TRANSFER

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Conduction*

For possible disposal of radioactive wastes in deep underground rock cavities, it was necessary to predict the position of the cavity boundary separating the molten rock from solid surrounding rock as a function of time. A boundary-layer subroutine was added to the CINDA conduction code so that the combined effects of conduction, convection, melting, and the moving boundary of the solid/liquid interface could be treated. Figure 1 shows the predicted position of the melt front at successive times. Not only does the cavity grow with time but there is a tendency for it to melt its way upward.

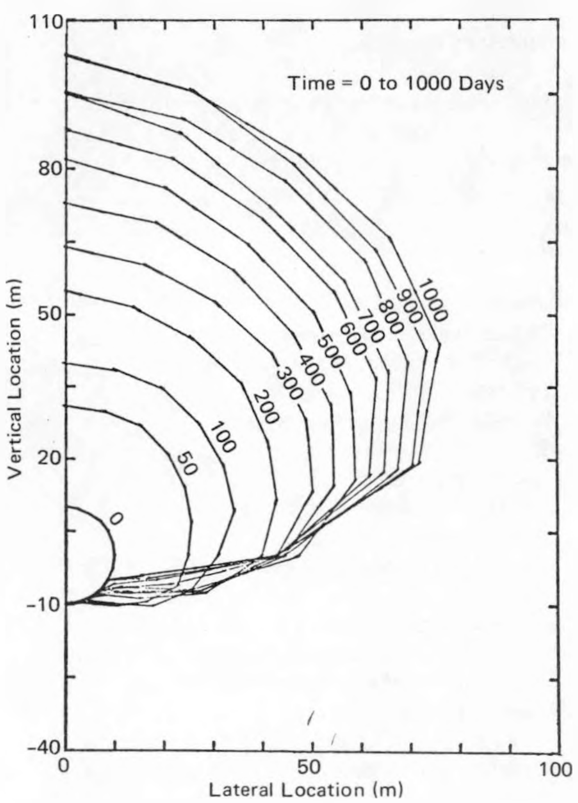

Figure 1. The growth of the solid/liquid interface is shown for the simulated disposal of radioactive waste in deeply buried rock.

An experiment was run to check conduction calculations for the deep-rock disposal of radioactive wastes. A cylindrical electric heater was placed in a large granite block buried in the ground in an attempt to simulate radioactive heat in a rock cavity. The CINDA conduction code was used to predict temperatures in and outside the rock. Figure 2 shows the close agreement between CINDA predictions and actual thermocouple measurements taken during the test.

Item 2. *Convection and Melting*

The technique of laser holographic interferometry is being used to determine the temperature field in a cavity filled with a fluid containing a uniformly distributed heat source. Heat generation was made uniform by passing an electric current through an electrolytic solution of NaCl in H_2O. The interference fringes shown in Figure 3 can be used to plot isotherms in the fluid. The large number of fringes near the wall indicates that the thermal gradient (heat flux) is quite large there.

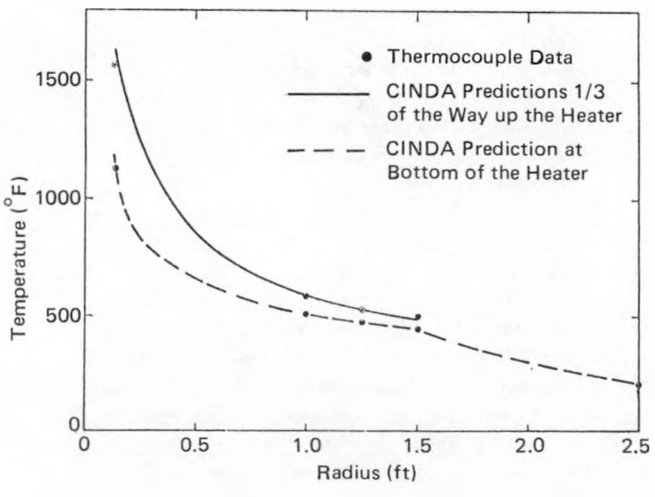

Figure 2. Predicted and measured temperatures, 25 days into the test.

HEAT TRANSFER

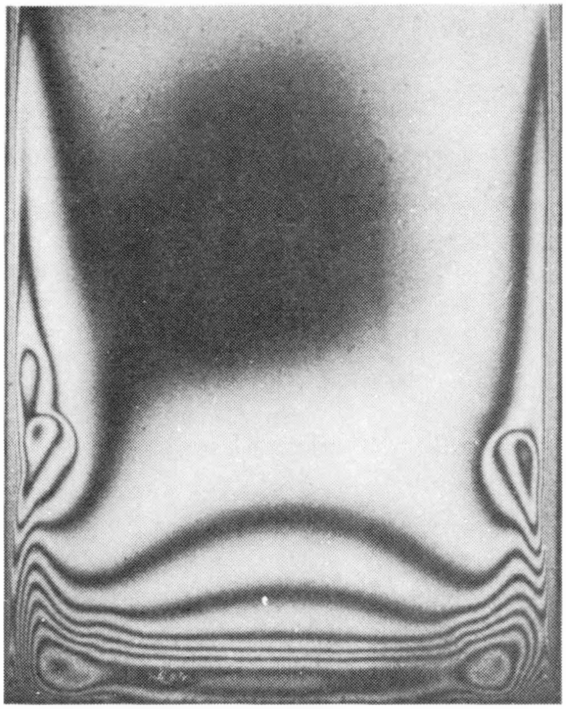

Figure 3. Isothermal interference fringe pattern produced by laser holographic interferometry in a heat-generating fluid.

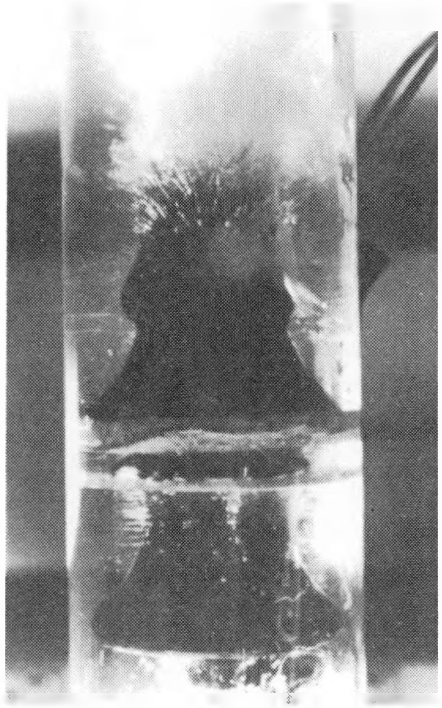

Figure 4. Convection dominated melting produced in a tube of ice containing a cylindrical heat source.

The combined effects of convection, internal heat generation, and melting occur in a number of important problems such as radioactive waste-disposal methods and in the analysis of hypothetical core meltdown in nuclear reactors. Model experiments have been run with electrical heaters, simulating radioactive heat sources, in mediums such as ice and solidified glycerin. Figure 4 shows a complex melted region, produced by convective effects, in a tube of ice. Convection causes additional melting to be more pronounced in the sideward direction near the top of each liquid cell. Figure 5 shows a melted pocket produced in a tube of solid glycerin. Figure 6 shows the same experiment after the molten region has migrated upward through the solid glycerin.

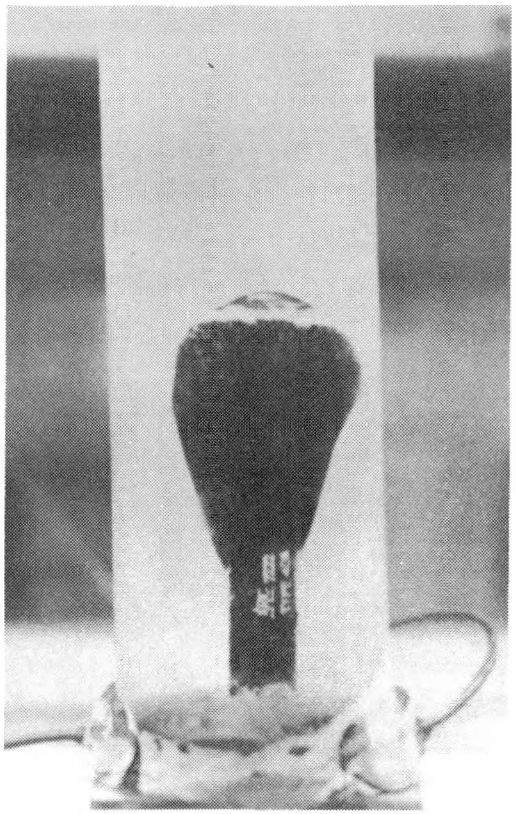

Figure 5. Melted region caused by a cylindrical heat source in a tube of solidified glycerin.

Item 3. *Energy Systems*

A geothermal energy scheme known as Magma Tap deals with the extraction of thermal energy directly from deep pockets of molten magma in the earth. Analyses are being performed for a preliminary experiment in which electricity will be generated by heat extracted from a large crucible of molten rock. A special boiler (Figure 7) and turbine (Figure 8) are being designed for this experiment. Figure 9 shows the turbine/generator in the test bed where the performance of the turbo-generator on a steam cycle is being measured prior to the molten-rock heat-extraction experiment.

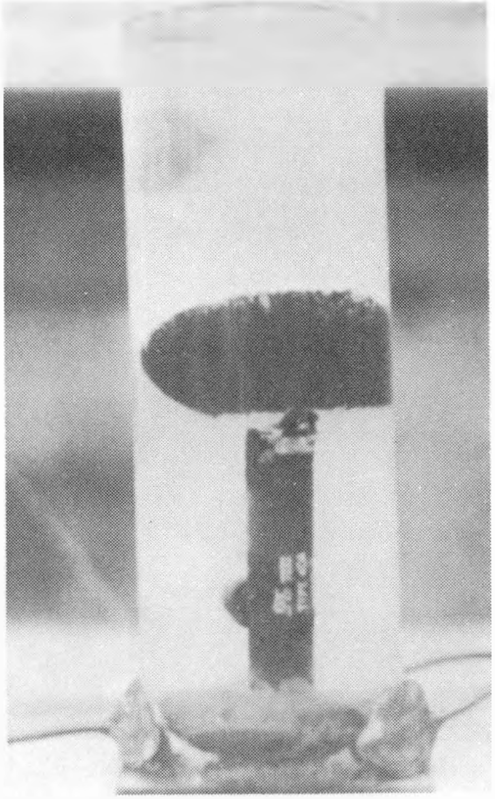

Figure 6. Migration of a molten region caused by convective effects in a tube of solidified glycerin.

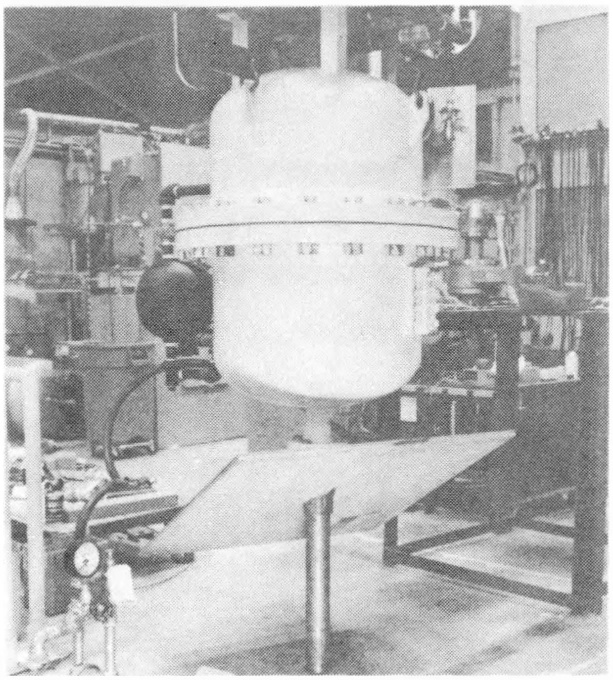

Figure 7. Single-tube boiler used in the molten lava/heat extraction experiment.

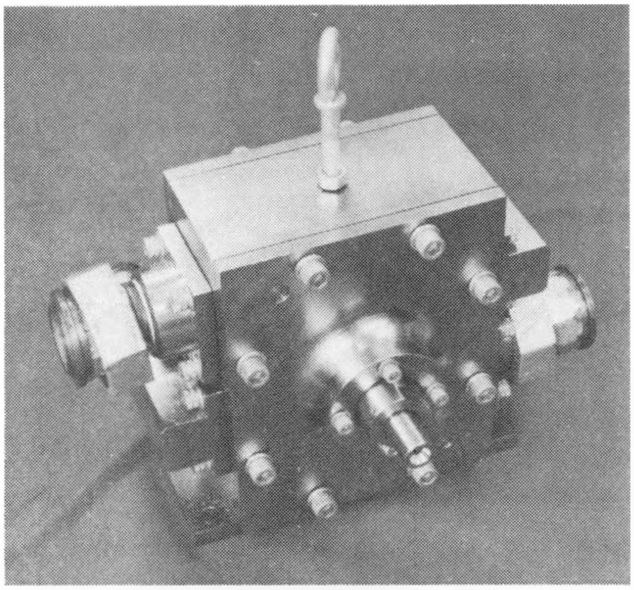

Figure 8. Vane turbine for molten lava/heat extraction experiment.

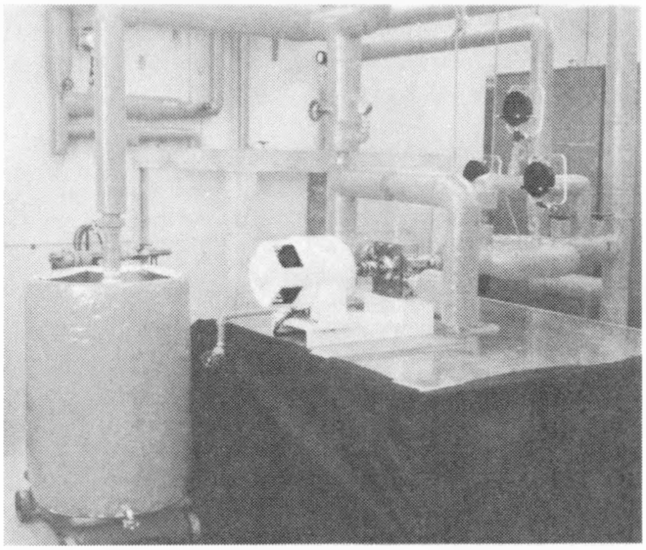

Figure 9. Vane turbine in steam cycle test bed.

Item 4. *Fire Analysis*

Numerical finite-difference codes are used to analyze problems involving fires where the combined effects of conduction, convection, and thermal radiation are important. A typical problem is predicting the effect of a fire on cable trays in a nuclear reactor. Figure 10 shows how isotherms (constant-temperature lines) and streamlines (fluid-flow lines) develop with time for a fire on the floor of a cable-tray room.

HEAT TRANSFER

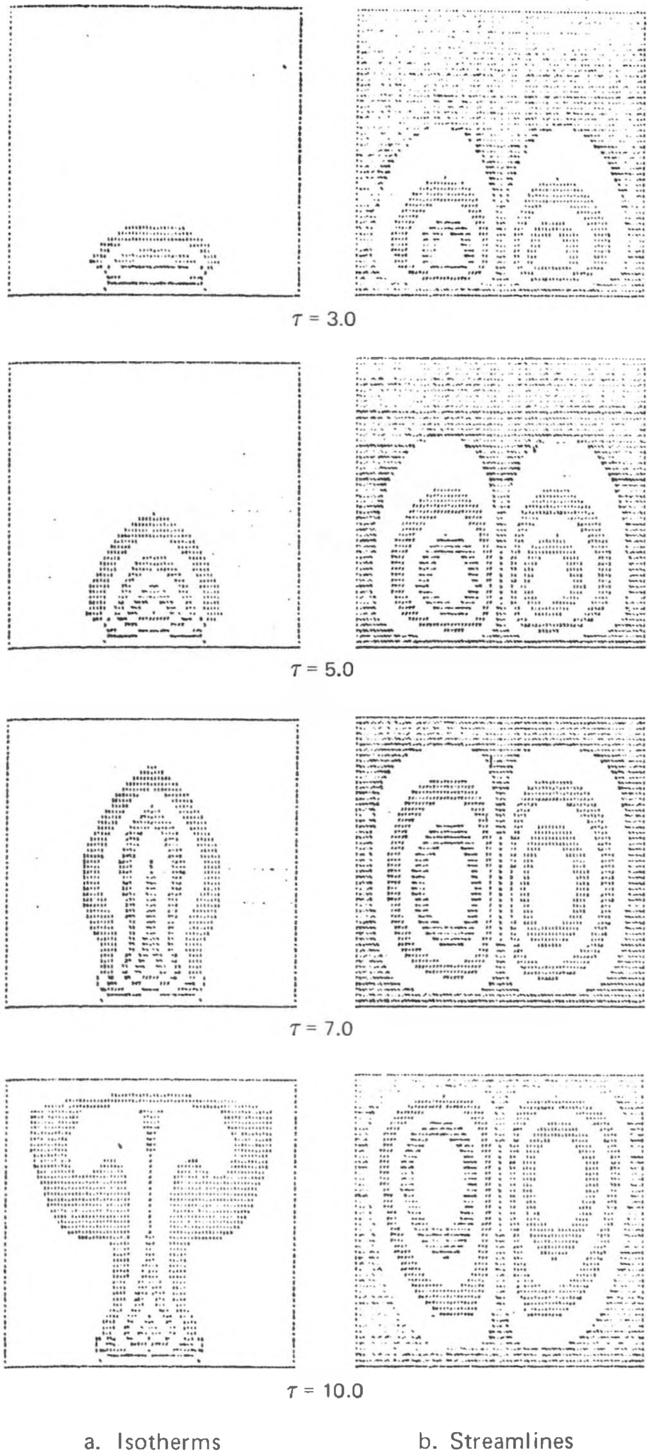

Figure 10. Computer-generated isotherm and streamline profiles for a simulated cable-tray fire in a nuclear reactor.

When tanks of pressurized liquids such as propane are ruptured, expansion energy creates a rapidly growing cloud. Such clouds may present a thermal hazard if the liquids are flammable (e.g., propane) or a health hazard if toxic (ammonia). Analytical models have been developed which predict cloud growth rate. Figure 11 shows a comparison of predictions and experimental growth measurements for a cloud resulting from a sudden release of 930 pounds of propane into air. This type of information can be used to predict the extent, in both time and size, of possible thermal hazards.

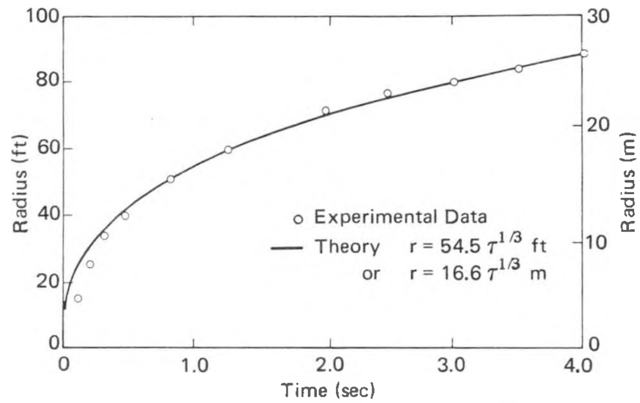

Figure 11. Cloud growth for sudden release of 930 pounds of propane.

Item 5. *Radiation Heat Transfer*

Radiation heat transfer can be divided into two categories: physical and geometric. The area of geometric radiation is where a portion of radiant energy reaches a surface from an emitting source. This problem can be solved with ray-tracing techniques. An example is a solar collector field where one collector may shadow another by varying amounts during a day. A computer code that solves for such shadowing has been developed using the techniques of radiative ray tracing. Figure 12a shows the shadow pattern produced on a collector by adjacent collectors arranged as shown in Figure 12b.

A study considered the feasibility of rapidly cooling an infrared thermal-radiation detector from room temperature to about liquid argon temperature (87 K). Figure 13 shows the experimental setup used to cool and monitor the detector temperature. The radiative energy source was a blackbody of the proper temperature to simulate the desired infrared signature.

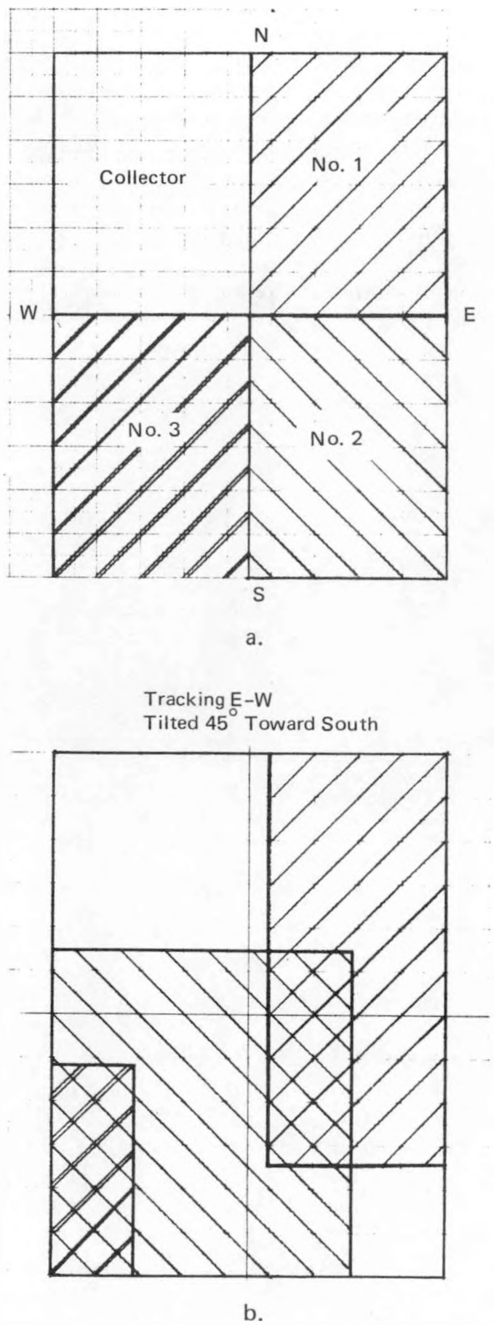

Figure 12. Computer-generated shadow pattern on a solar collector produced by shadowing from adjacent collectors.

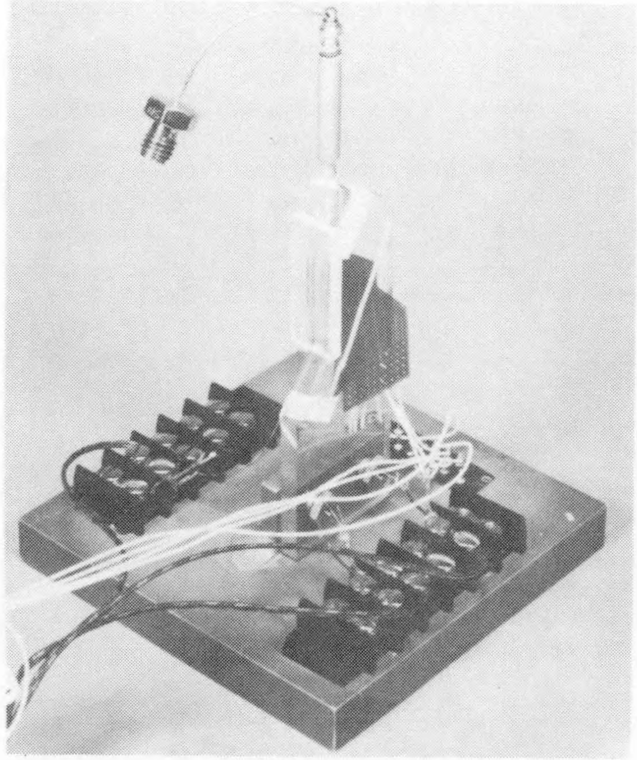

Figure 13. Rapid-cooldown test of an infrared thermal-radiation detector.

AEROSPACE ENGINEERING

Aerospace engineering analyses relate to such areas as fluid dynamics, aerothermodynamics, and flight mechanics. Specific problems are formulated mathematically and solved analytically or on appropriate computational equipment. Digital computer codes are developed for the calculation of aerodynamic coefficients, flow fields, heat transfer, material ablation, and vehicle motion. Analog and hybrid (analog/digital) computer programs are developed for vehicle stability and control studies and flight-test data analyses.

Flight Mechanics

The fundamental equations of motion are modified by appropriate assumptions to obtain analytical solutions of specific types of flight mechanics problems and to identify important parameters. Cases not tractable in closed form are solved by computational methods. Various 6-degree-of-freedom digital, analog, and hybrid computer programs are used in the study of complex phenomena. (Item 1)*

Current Activities

Geometric and mass asymmetries
Unsymmetrical stability derivatives
Nonlinear aerodynamics
Unguided flight characteristics
Guidance and control studies
Trajectory analyses

Aerothermodynamics

An analytic capability using computer codes has been developed for the design of high-performance reentry vehicles and rockets. This capability includes definition of the flow-field-generated thermal environment, and the prediction of heat-shield ablation and thermal-stress responses of the structure to this environment. (Item 2)

*See Highlights below.

Current Activities

Pressure-distribution prediction
Interaction phenomena
Base flows and wakes
Boundary-layer transition
Thermal modeling
Heat transfer and ablation
Material structure, properties, and performance

Aerodynamic Loading

Mathematical models of the nonuniform flow field around stores during external carriage on an aircraft are used in computer simulations to calculate detailed aerodynamic load distributions for use in structural analyses of store configurations. Similarly, computer simulations of the complex flow field around the aircraft itself are used to predict the motion of stores during separation from the aircraft. These motion studies are made during store development to determine effects of configurational changes. Movies illustrating the separation process are computer-generated to aid in the analysis. These computer-generated aerodynamic data are particularly useful in early development when the design is insufficiently defined to justify costly wind-tunnel and full-scale flight tests. (Items 3,4)

Current Activities

Development of mathematical aircraft models
Extension of calculational capabilities from subsonic to supersonic speeds
Supersonic aircraft deliveries
Rocket-boosted store separations
Correlation of predictions with test results

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Mass Asymmetry-Induced Roll*

Trim angles caused by aerodynamic asymmetries, center-of-gravity offset, and principal-axis tilt can produce large roll-rate excursions in conical reentry-type vehicles. Theoretical studies resulted in analytical expressions which separate the individual effects of aerodynamic, mass, and inertia asymmetries. As shown in Figure 1, roll-rate behavior predicted by the analysis compares well with that derived from a 6-degree-of-freedom computer code.

Item 2. *Nosetip Ablation Prediction*

Successful performance of high-speed rockets and reentry vehicles depends in part on accurate design and analysis of the thermal protection system. Analytic techniques have been developed that use digital computer codes to predict the imposed thermal environment, vehicle surface energy and mass balances, the resultant transient ablation, and temperature and thermal-stress responses. An example of the analysis capability is shown in Figure 2 where predicted and actual ablated contours for a recovered high-speed rocket graphitic nosetip are compared.

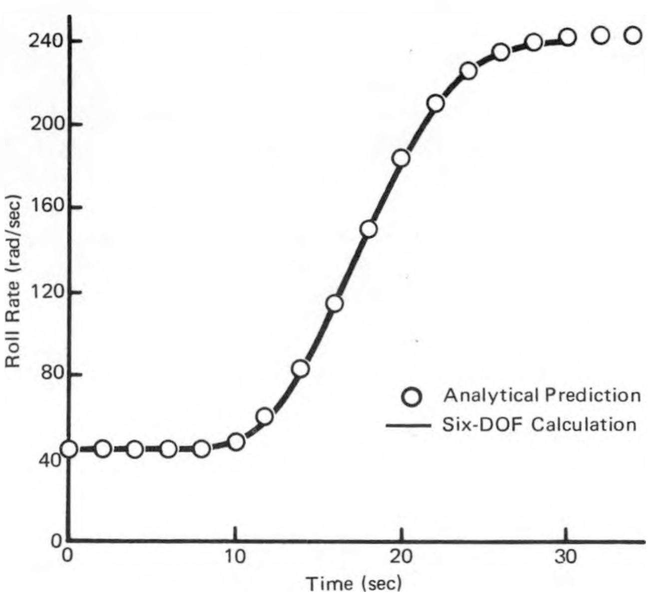

Figure 1. Example of mass asymmetry effect on reentry-vehicle roll rate.

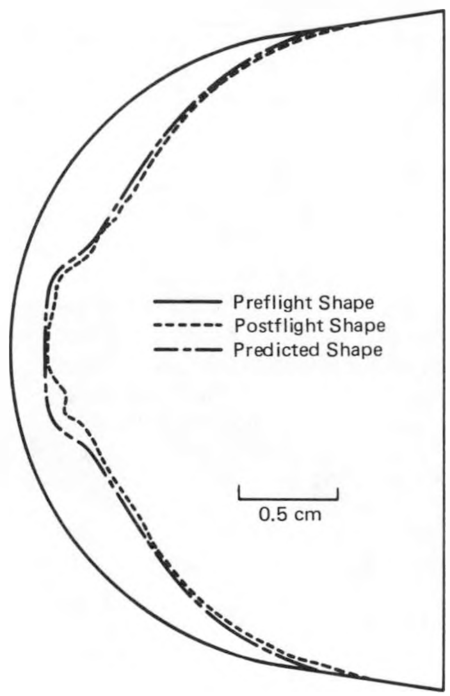

Figure 2. Comparison of predicted and actual nosetip recession.

Item 3. *Aircraft/Store Separation Trajectories*

Computer simulations of the motion of stores released from aircraft are made to demonstrate safe separation and to obtain initial pitch data for use in dispersion calculations. Figure 3 portrays the safe separation of a canard-controlled missile from an F-4 aircraft; the trajectory predicted by computer simulation compares favorably.

Item 4. *Aerodynamic Load Distributions*

Detailed aerodynamic load distributions on weapons during aircraft carriage are required for structural analysis of the weapon's case, case joints, and fins. Computer simulation of the complex flow field around the aircraft is used to calculate these load distributions. Shown in Figure 4 is the calculated aerodynamic load distribution (in a vertical plane) along the body of a canard-controlled missile during carriage on an F-4 aircraft.

AEROSPACE ENGINEERING

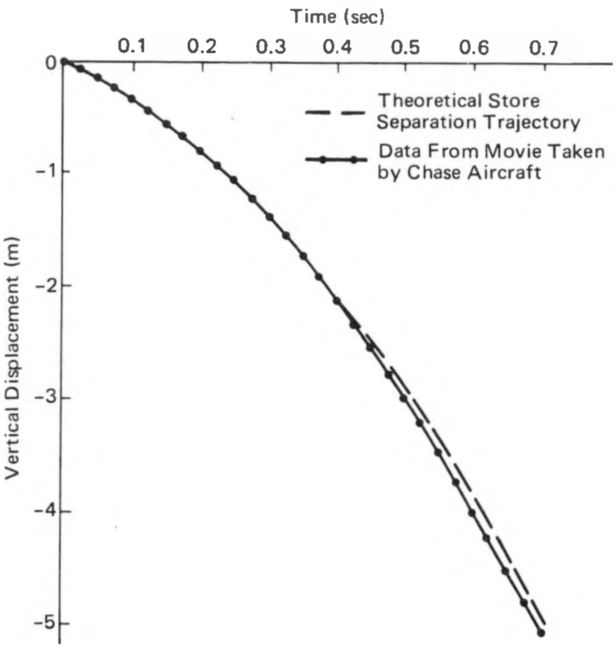

Figure 3. Comparison of theoretical and observed trajectories for a canard-controlled missile ejected from an F-4 aircraft (Mach number = 0.7 at 4600 metres altitude).

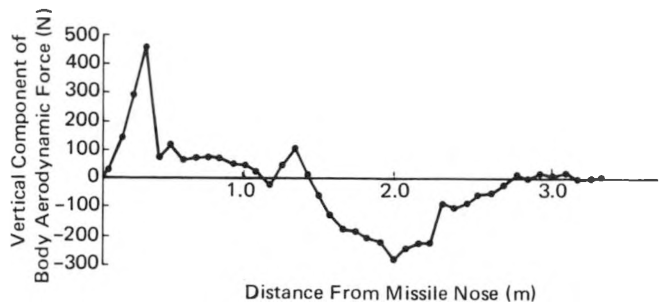

Figure 4. Calculated vertical component of aerodynamic load distribution along the body of a canard-controlled missile on an F-4 aircraft (Mach number = 0.95, 4 g symmetric pullup at 2100 metres altitude).

ENVIRONMENTAL ANALYSIS

The use of analytical techniques to describe the types and magnitudes of forces, temperatures, accelerations, and similar parameters that a product might experience during its lifetime is referred to as environmental analysis. Expected or normal environments, such as handling, transportation, and storage, are of sufficient general interest that they have been documented in a data bank. Other environments, because of infrequent occurrence or uniqueness, require extensive individual analysis for their definition. Examples of the latter are descriptions of transportation accident severities, of pressures, accelerations, and forces in gun tubes, and of forces resulting from exposure in high-intensity radiation fields.

Normal Environments

Descriptions of normal environments, which are documented in an environmental data bank, have evolved through three stages of analytical endeavor: data search, evaluation, and cataloging. These descriptions of use, storage, transportation, and handling environments include information on acceleration/time signatures, acoustic noise, atmospheric content, biota, humidity, precipitation, pressure, radiation, shock, temperature, trajectory, vibration, and wind. (Item 1)*

Current Activities

- Shock and vibration analysis
  - Digitized accelerometer measurements
    - Peak distribution percentiles versus frequency
    - Shock spectra
    - Fourier spectra
  - Three-dimensional probabilistic reconstruction
    - VAIL, SHAIL programs
  - Environmental envelopes
    - Mean
    - Sigma
    - 10 to 2000 Hz
- Reentry-vehicle vibration
  - On-board recorders
    - g versus time
    - Power spectral density versus time
  - Recovered packages
- Temperature
  - Thermographs
    - Storage temperatures
      - Highs, lows, deviations
    - Fitted models

*See Highlights below.

Abnormal or Unusual Environments

Capabilities are oriented toward the description of environments for which insufficient information is available to permit efficient product design. Analytical efforts have resulted in descriptions of such diverse subjects as severities of transportation accidents, forces acting on components fired in artillery projectiles, and forces experienced by structures in intense radiation fields. (Items 2-4)

Current Activities

- Transportation accident description
  - Accident rates, frequency, and velocities
  - Time-temperature models for hydrocarbon fires
    - Fuel distribution
    - Radiation transport
    - Emissivities
    - Durations
  - Impact analysis
    - Angular dependence
    - Hertzian theory
    - Probabilistic description
  - Mechanical response of trains and trucks
    - Spring-mass modeling
    - Tiedown capabilities
    - Container behavior
  - Response of high explosives
    - Detonation thresholds in impact
    - Deflagration-to-detonation transfer in fires
  - Contaminant spread
    - Type of HE response
    - Contaminant diffusion
    - Meteorological perturbations
- Interior ballistics
  - Balloting forces
    - Transverse loading
    - Lagrangian formulation
    - 3 degrees of angular freedom
    - Unbalanced projectiles

ENVIRONMENTAL ANALYSIS

- Engraving and frictional forces
  - Band-pressure-force model
  - Quasi-static and dynamic experimental verification
  - Breech-pressure dependence
- Structural loads on projectiles
  - Strain gages for band pressures
  - On-board accelerometers
  - Unloading stresses
  - Acceleration loads
- Interior ballistic predictions
  - Alpha-law burning
  - Lagrangian approximations
  - Nobel-Abel equation of state
  - Retardation forces
- Radiation heating of structures
  - Energy deposition
    - Gruneisen coefficients
    - Material response
  - Impulse and momentum
  - Experimental
    - Laser interferometry
    - Impulse gages
    - Stress-wave properties
  - Mechanical response
    - Finite-element and closed form
    - Nonuniform loading
    - Transient
  - Theoretical/experimental correlation

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Normal Vibration Environments*

Analysis of the vibrating environments experienced by cargo during its transportation has been of long-standing interest. These environments have been extensively measured for all common shipment methods. Figure 1 shows a composite of these measured frequency-resolved accelerations for ships, planes, trucks, trailers, and trains.

Item 2. *Transportation Accidents*

Analysis of transportation accidents is oriented to the generation of predictive models of impact, puncture, fire, crush, and immersion environments. These models are hybrids, consisting of a combination of statistical and analytical techniques.

Figure 2 shows one such model, generated by an analysis that took into consideration accident statistics concerning aircraft impact velocity and angle, type of soil impacted, and energy transmitted into the soil. This information was then used to deduce the energy available to damage cargo in the aircraft. The parameter E_d/W is available energy normalized by container weight and is, to first order, relatable to drop height onto an unyielding target. This model can implement a cost-effectiveness argument to select test criteria for packaging to be carried in air transport.

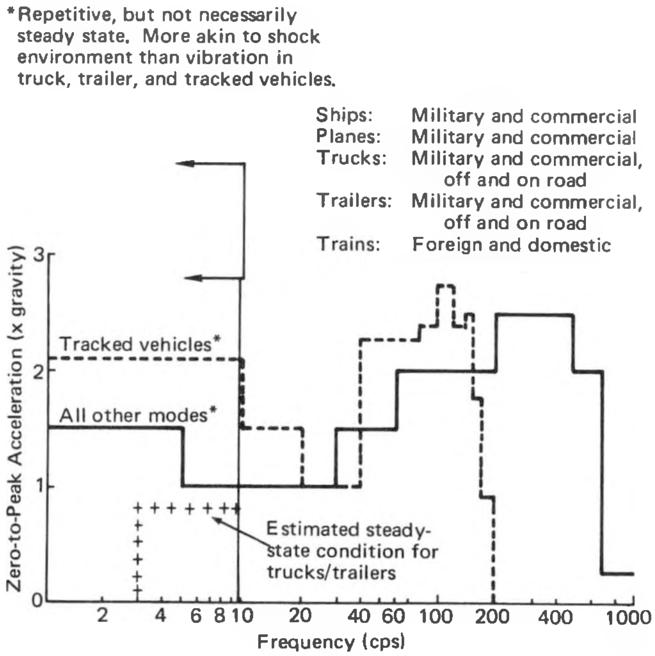

Figure 1. Envelope of 90-percent probable extreme vibration environment experienced by cargo in all modes of transport.

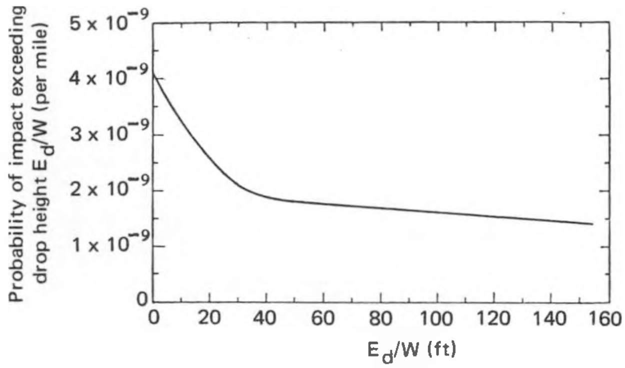

Figure 2. Probability of an aircraft accident producing an impact exceeding a given drop height, E_d/W, per aircraft mile.

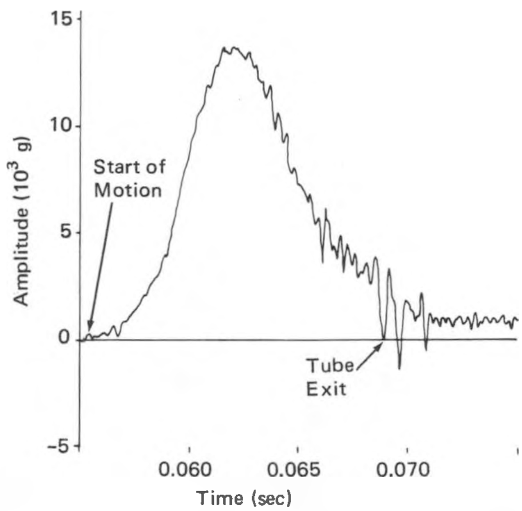

Figure 3. Axial acceleration of a projectile in 155-mm gun tube.

Item 3. *Internal Ballistics*

The behavior of projectiles in gun tubes and the forces acting on them is important not only for projectile design but also when ballistic methods are used for simulation of other large linear or radial acceleration loading conditions. A joint experimental and analytical program defined many forces acting on a projectile that had not been adequately described. Figure 3 shows one of the first acceleration-time signatures ever recorded of a shell during its translation down an artillery tube.

Item 4. *Radiation-Induced Stresses*

Short-duration mechanical loading of structural members is one of several manifestations of high-intensity radiation pulses. Analysis of the ability of structures to perform in such radiation environments requires description of these loads. Techniques have been developed that make it possible to describe the generation of stress pulses which can result in either material or structural damage under a wide variety of electron beam, x-ray, laser, and neutron exposures.

CONTROLS ENGINEERING

This activity is primarily oriented toward analysis of the design and performance of navigation, guidance, and control systems for flight vehicles. Computer programs are developed and used to provide simulation models of sensors that measure the system state, and mechanisms that change that state in accordance with open or closed-loop control strategies.

Component Modeling

Models are developed for gyroscopes, accelerometers, analog-to-digital converters, stable platforms, and aerodynamic control-surface actuators. Component models are combined to produce, for example, navigation systems. The combined models are subjected to error studies based on individual component accuracies. (Item 1)*

Current Activities

- Time-constant determination
- Frequency range determination
- Statistical accuracy parameters
- Environmental sensitivities
  - Thermal transients
  - Radiation effects
  - Mechanical vibration
- Stability evaluation
- System error analysis
  - Propagated covariance matrix methods

*See Highlights below.

Systems Analysis

Classical frequency domain methods as well as modern optimal control methods are applied in the design of both analog and digital flight control autopilots for maneuvering flight vehicles and other feedback loops. Full 6-degree-of-freedom flight dynamic codes are developed and used to evaluate candidate designs. A hybrid computer coupled to a motion table is used to simulate control loops. Simulation techniques are continually improved on the basis of comparisons of flight data with preflight simulations. (Items 2,3)

Current Activities

- Frequency domain root locus
- Optimal control methods
- Six-degree-of-freedom analysis
  - Acceleration and angular rate sensors
  - Aerodynamic forcing functions
  - Thruster forcing functions
  - Mass redistribution
  - Feedback and decoupling strategies

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Item 1.

A platform was developed to stabilize a set of optical instruments which are mounted on a ship (Figure 1). The platform provides the means for pointing the optical instruments while providing three-axis isolation from angular ship motion. Three low-cost, single axis, rate-integrating gyros and a two-axis bubble level provide inputs to servo electronics which drive DC motors on each gimbal to stabilize the platform.

Operational features of the platform include continuous alignment to a level orientation. The azimuth pointing direction relative to ship's heading is adjustable by a switch and meter at the control console. Gimbal freedom is ±15 degrees in pitch and roll and ±120 degrees in azimuth. Under dynamic shipboard conditions, alignment to level is accurate to within ±0.25 degree. Azimuth pointing accuracy is ±5 degrees with a ±5 degrees/hour drift rate. Optical instrument field of view is 40 degrees in the horizontal plane and 5.5 degrees in the vertical.

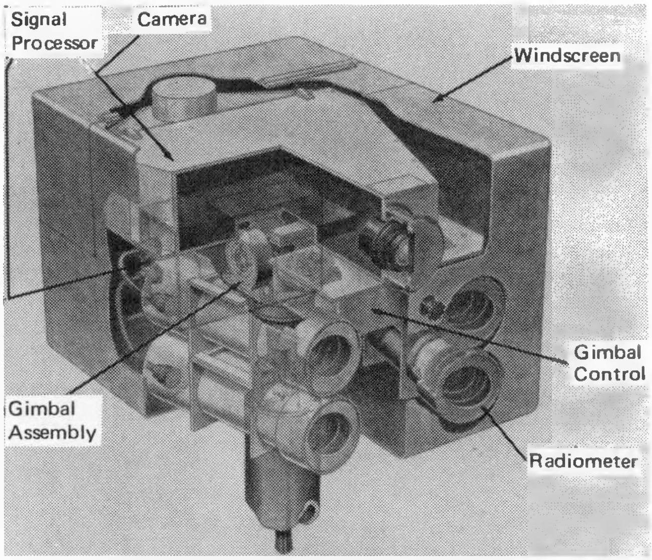


Figure 1. A low-cost, lightweight camera stabilization platform developed for shipboard application.

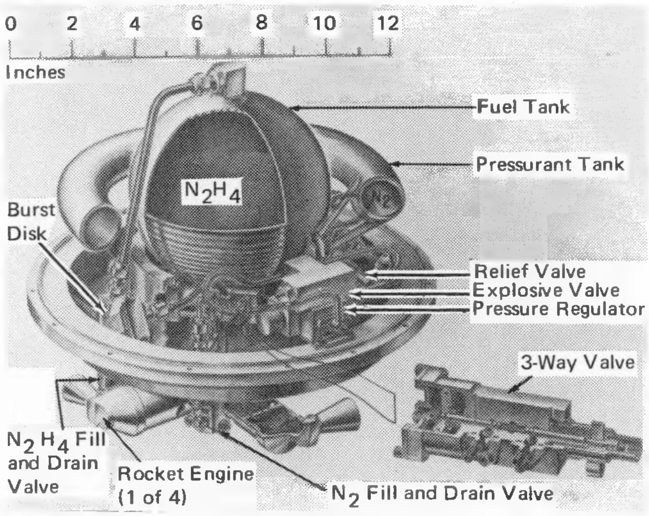


Figure 2. Rocket engine module.

Item 2.

Figure 2 shows a rocket-engine module used in conjunction with an all-fluidic sensing and logic system to control the roll rate of a flight test vehicle. The test was designed to simulate a reentry-vehicle flight condition where, without control, center-of-gravity offset and body-trim mechanisms would have resulted in the vehicle locking into roll resonance.

ELECTRICAL ENGINEERING

The aim of electrical engineering analysis is to develop, test, and evaluate methods for designing reliable electronic circuits able to withstand severe environments. Emphasis is placed on developing a basic understanding of device and circuit operation, including possible failure modes in extreme environments, particularly radiation. Computer codes are used extensively to optimize component and circuit design and to minimize engineering time and cost.

Circuit Analysis and Modeling

Circuit-analysis techniques are used to predict the performance of electrical networks ranging from simple linear circuit configurations to complex nonlinear circuits. Analysis includes detailed comparison of theoretical and experimental results to obtain an understanding of circuit operating characteristics and to determine techniques for optimizing circuit design.

Device models for use in a variety of circuit-analysis computer codes are developed for the study of electronic devices as determined by electrical behavior at their terminals. Models are developed for semiconductor devices, ferroelectric components, exploding wires, spark gaps, coils, transformers, and capacitors. (Items 1-6)*

Current Activities

- Circuit operation
  - Semiconductor memories
  - Integrated circuits
  - Electrical networks
  - Microwave circuits
  - Guidance and control systems
  - Compressed magnetic field generators
- Design analysis
  - Optimization
  - Sensitivity
- Modeling
  - Semiconductor devices
  - Linear devices
  - Nonlinear components

*See Highlights below.

Nuclear Radiation Effects

The exposure of microelectronic materials and components to high-energy particle or photon radiation can cause significant changes in material and device properties. Improper circuit operation and failure of electronic systems can result if these possible changes are not considered during system design. Studies are in progress to characterize microelectric materials which are subjected to to radiation. (Items 7-9)

Current Activities

- Fast neutron effects
  - Basic damage mechanisms
  - Transient annealing
- Ionization effects
  - Photocurrents
  - Trapped charge
- Component effects
  - Semiconductor devices
  - Insulating materials
  - Other components

Device Analysis

The purpose of this form of analysis is to predict the operation of semiconductor devices as a function of device structure, impurity profile, trap density, and bias conditions. The nonlinear hole and electron continuity equations and Poisson's equation have been solved for a one-dimensional semiconductor device structure by the use of numerical techniques. The solutions provide the hole, electron, and electric field distributions throughout the device for a specified impurity doping profile and terminal bias conditions. Device design is optimized and equivalent circuit models are developed for particular applications. (Items 10,11)

Current Activities

- Physics
  - Carrier trapping
    - Energy level
    - Capture and emission rates
    - Density
  - Carrier mobility
  - Doping profile effects
  - Radiation effects
- Design and analysis
  - p-n junctions
    - Diodes
    - Solar cells
    - Pin detectors
    - MOS diodes
  - Microwave devices
    - Transistors
    - TRAPATT diodes
    - IMPATT diodes
  - Transistors
- Circuit modeling
  - dc characteristics
  - Transient effects
  - Frequency response

Integrated Circuit Design

Computer programs are developed to aid the engineer in the semiautomatic design of digital large-scale integrated circuits. These codes are used to assist in basic logic circuit design, logic simulation, fault analysis, generation and verification of test sequences, analysis of circuit operation, layout of the integrated circuit chip, and generation of the mask artwork. The designs are based on a standard-cell approach. The layout codes place standard logic cells on the chip in an optimum configuration and route all interconnections between the cells and the input and output pads. (Items 12,13)

Current Activities

- Logic design
  - Minimization
  - Partitioning
  - Simulation
- Analysis
  - Fault analysis
  - Waveform analysis
  - Timing
- Layout
  - Cell placement
  - Routing
  - Plotting
  - Checking
- Interactive graphics
  - Cell design
  - Chip modification
  - Plotting

Electromagnetic Radiation Effects

The purpose of this study is to determine the effects of radiation upon electrical circuits, with particular attention given to the production of extraneous signals in systems that must operate exoatmospherically. Incident photon radiation can interact with system boundaries (e.g., satellite skin and walls of component boxes) to produce an electron current density in the system. This current produces electromagnetic pulse fields that can couple energy into electrical circuits and other sensitive components, causing permanent damage to components or electrical transients that can produce system malfunction. (Item 14)

Current Activities

- EMP
  - Signal coupling
- IEMP
  - Photon-electron transport
  - Compton currents
- Effects on components
  - Cables
  - Semiconductors
  - Explosives

Electromagnetic Field Studies

The ability to predict the properties of the electromagnetic pulse (EMP) generated by a nuclear explosion is a problem of continuing interest. Studies are under way to develop computer programs which solve Maxwell's equations to find the EMP for charge and current distributions that are produced by the explosion. Other effort is directed toward a quantitative understanding of the fields produced inside systems (internal EMP) by penetrating gamma radiation. (Items 15,16)

Current Activities

- High-altitude EMP
- Effect on exposed missiles
- Nonlinear air conductivity effects
- Internal EMP

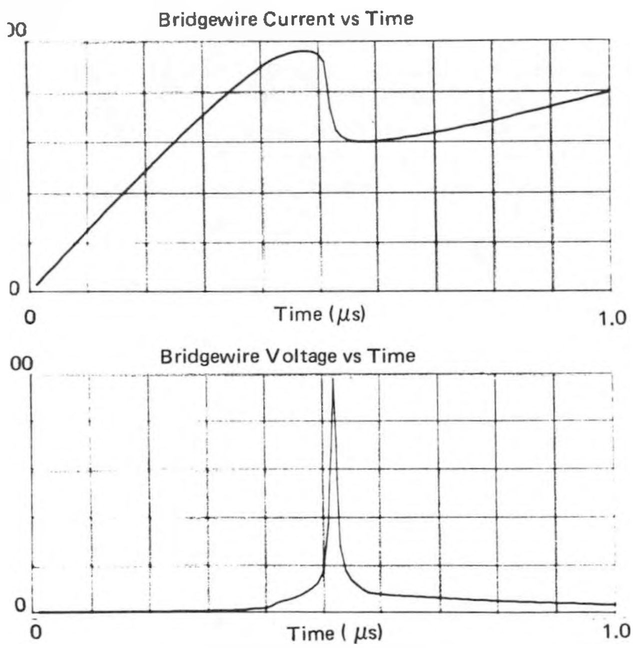
LECTRICAL ENGINEERING

* * * * * * *HIGHLIGHTS* * * * * * *

tem 1. *Analysis of Electrical Circuits Containing Exploding Wires*

A computer code has been developed to predict the ehavior of lumped-parameter electrical circuits in which ıe resistance value of one or more elements is strongly ;fected by Joule heating. The code performs a numerical ıtegration of the system of ordinary differential equations ıat describes circuit behavior. At each time-step of this tegration the resistance values are updated using experientally determined dependencies of resistivity on action $= \int i^2 dt$. These resistivity functions have been measured r 23 metals, and are entered in the computer memory tabular form.

The code has been applied to the design of firing stems for exploding-bridgewire detonators, to the prection of circuit overload behavior resulting from fuse ilure, and to other situations where Joule heating is of ıportance. Both tabular and graphic outputs are provided; ı example of the latter appears in Figure 1, for the probm of discharge of a 4-μF capacitor bank charged to 250 V ırough a gold wire 0.0015 inch in diameter.



gure 1. Computer program graphical output results for the analysis of a 1 μF, 1 μH, 0.1 ohm, 1000-volt capacitor discharge system exploding a 0.038 mm diameter by 1 mm long gold wire.

Item 2. *Ferroelectric Model Applications*

Nonlinear, time-dependent equivalent circuit models of ferroelectric materials under normal and axial-mode transient stress conditions are used to predict the electric current developed in time-dependent, nonlinear electrical circuits by impact and by explosive-driven ferroelectric power supplies.

Item 3. *Feedback Regulator Analysis*

A dc-to-dc converter comprises a class of nonlinear feedback regulators. A generalized form of the describing function technique of Kochenberger, Dutilh, and others has been developed which facilitates an accurate description of the subsystem in closed form, allowing analysis of circuit behavior and prediction of the effects of parameter changes.

Item 4. *Spark Drilling System Design*

Several engineering-analysis techniques are being used in the design of a pulsed power system for spark drilling in deep rock formations. A two-dimensional code which solves Laplace's equation is used to predict the electric scalar potential and electric field distributions within high-voltage regions of the spark bit and pulse generator. Circuit-analysis codes are used to describe the spark drilling system's response to the nonlinear, time-dependent electrical behavior of the liquid medium in which the spark bit is immersed.

Item 5. *Modeling of Shock-Wave Compressed Ferroelectrics*

Short-duration electrical pulses of a few hundred kilowatts can be obtained by shock-wave-induced depolarization of ferroelectric ceramics. To incorporate these devices into useful circuits requires an understanding of depolarization phenomena as well as the dielectric properties of shocked and unshocked ceramic material. An experimental and theoretical program is under way to investigate these parameters. The results of a recent investigation, in which the ceramic was shunted by a resistive load, permitted an evaluation of the dielectric properties of the ceramic under conditions of high stress and electric field (Figure 2). This information allows a prediction of the response of the ceramic when shunted by more general reactive loads.

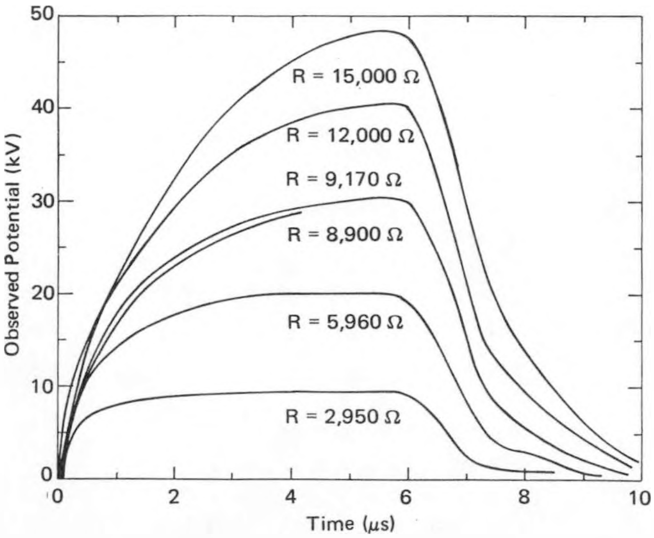


Figure 2. Electrical response of a shock-wave compressed ferroelectric ceramic.

Item 6. *Analysis of Compressed Magnetic Field Generators*

Millions of amperes of electric current can be generated by explosively expanding a conducting armature against a magnetic field contained within a solenoid coil. This operation compresses the magnetic flux into a smaller region and thus causes an increase in the magnetic field and an increase in the current flowing in the solenoid. This sequence of events results in a decrease in inductance of the solenoid as the armature is expanded outward. A computer model of compressed magnetic field (CMF) generators based upon representing the coil and armature as series connected, one turn loops has been completed. The program solves the equivalent CMF circuit to predict the time-dependent coil current by relating the time-dependent inductance and resistance of the system to the expansion of the armature.

Theoretical studies of CMF generators are complicated by the multidimensional nature of the generator operation, by nonlinear resistive diffusion and by the phase variation and compressibility of the conductors. A two-dimensional magnetohydrodynamic computer program has been written specifically for the CMF generator application. A two-dimensional Eulerian material response code has been used as the basic structure. A Eulerian computer program is most convenient for computing problems with self-consistent magnetic flux compression, and the program incorporates a variety of material response models including elastic-plastic flow, mixed phase equations of state and fracture models. An efficient solver of the two-dimensional magnetic diffusion equation has been mated to the basic Eulerian hydrocode. The magnetic diffusion solver provides for the use of a temperature-dependent resistivity, and computes electromagnetic fields and current densities in the conductors as a function of time to determine joule heating and magnetic forces on the conductors. Numerous test cases have been run to check the computer solutions with analytic results. Total system energy is conserved to about 5 percent after 300 to 400 time-steps, even for cases with strong resistive diffusion and two-dimensional armature motion.

Item 7. *Radiation Effects on Switching Circuits*

Prompt-radiation effects on medium-power switching circuits are simulated using the time-domain SCEPTRE circuit-analysis computer program. Typical simulations include the effects of photocurrents and induced electromagnetic pulses (IEMP) on circuits containing semiconductor devices (transistors, diodes, and Zener diodes), passive components, and vacuum switching devices. Simulated effects on overall circuit behavior correlate well with experimental data, and the technique is now used to predict the effects of design changes.

Item 8. *The Relationship of Device Geometry to its Neutron Radiation Tolerance*

Calculations have been performed to determine the relative importance of device regions in establishing neutron tolerance. For conventionally diffused profiles in bipolar transistors with fixed device parameters, calculations indicate that there may be an optimum transistor base width that will yield maximum neutron hardness. The analysis indicates that hardness can be increased substantially by using a fabrication process that provides a device profile with a shallow, abrupt emitter and a narrow base region. Devices in which these criteria are used are extremely tolerant to neutron irradiation and show a current gain greater than 10 after a neutron fluence of 10^{16} n/cm^2 (E > 10 keV).

Item 9. *Evaluation of Resistor Response to Ionizing Radiation*

A theoretical examination of the effects of ionizing radiation on diffused resistors was performed to ascertain the feasibility of using them in hardened dielectrically isolated integrated circuits. Two basic effects – conductivity modulation and photocurrent generation – essentially determine diffused resistor hardness. Theoretical and experimental results indicate that moderately radiation-hard diffused resistors in dielectrically isolated integrated circuits can be achieved using the following guidelines:

1. Use a high-conductivity buried layer.

ELECTRICAL ENGINEERING

2. Minimize the volume of the isolation region (meandering is not necessary).

3. Although not critical, connect the high-potential end of the resistor to the isolation region.

4. Use as high a conductivity layer as practical to minimize the effects of conductivity modulation in the diffused p layer.

Item 10. *Analysis of Neutron-Irradiated pn Junctions*

Numerical calculations have been used to study small signal-trapping effects in neutron-irradiated pn junctions as a function of frequency. Good agreement has been obtained between calculations and experimental data in n-type silicon using two acceptor centers to model the trapping centers produced by neutron irradiation. A single-level donor center has been used for p-type material. These calculations indicate that complex changes in carrier distributions within the device can be responsible for a rather simple change in terminal capacitance and conductance (Figure 3).

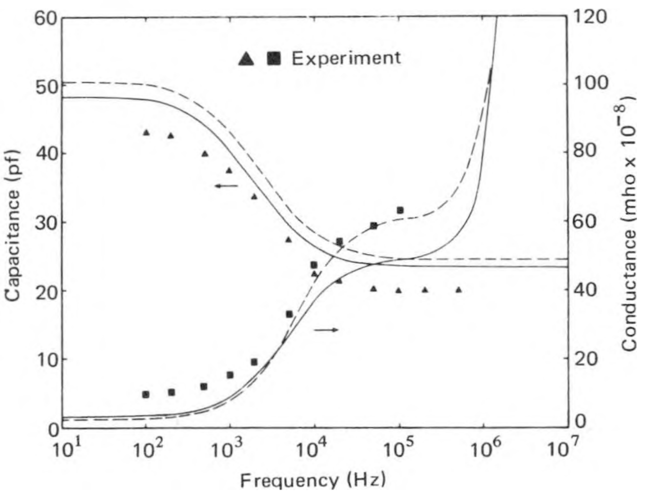


Figure 3. Calculated capacitance and conductance as a function of frequency for a gold doped diode at zero bias ($N_t = 9.0 \times 10^{14}$ cm^{-3}).

Item 11. *Effects of Doping on Solar Cells*

Numerical techniques have been used to study the theoretical efficiency of solar cells having various impurity doping profiles and surface and bulk lifetime values. These studies confirm the power-conversion efficiency of 11.8 percent for commercial silicon solar cells. The calculations indicate that efficiencies greater than 20 percent can be achieved by increasing the lifetime in the substrate and the diffusion region and by decreasing the surface recombination velocity.

Item 12. *Metal Nitride Oxide Silicon Memories (MNOS)*

Circuit-analysis codes are used extensively in several MNOS/large-scale integration chip designs. Typically, portions of the chip consisting of 100 transistors or less are simulated to determine the static and dynamic operation of a proposed design and layout. The simulations are used to check for logic errors and to identify timing and noise problems. Often, a modification in the layout or a redesign to reduce power consumption is indicated.

Item 13. *Use of Graphics in Circuit Design*

Computer aids have been used to design several integrated circuits using a bulk complementary metal oxide semiconductor technology. The development of in-house design capability has permitted the complete logic design, simulation, and preparation of the mask artwork to be completed for a specified chip in 4 to 8 weeks. Summary statistics for five chip designs are shown in Table I. A photograph of the timer chip is shown in Figure 4.

TABLE I

Integrated Circuit Chip Designs

Chip Description	Number of Cells, Pads and Devices	Area (cm^2)	Percent Cell-Pad to Chip Area
Timer	132 44 1027	0.322	50.3
Sequencer	110 38 827 + Memory	0.384	55.3
Control Logic	138 38 1085	0.315	49
Universal Counter Shift-Register	101 42 746	0.291	46

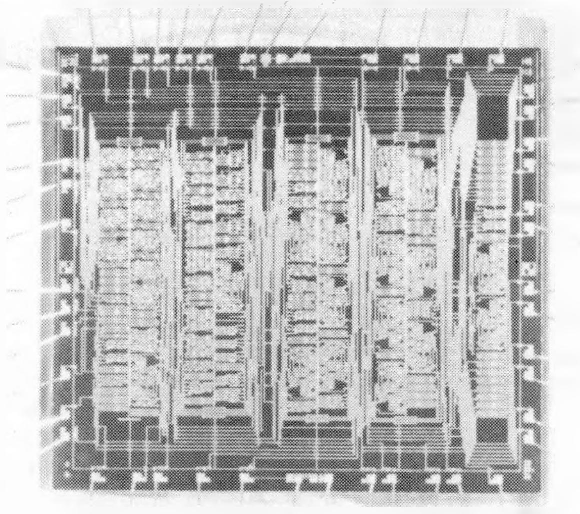


Figure 4. Photograph of timer integrated circuit (chip is 0.55 x 0.59 cm).

Item 14. *Radiation Response of Electrical Systems*

Analysis of the transient response of an electrical system to a pulsed radiation source requires a variety of engineering analytical methods. A photon-electron transport analysis is used to predict electron motion or current density within the medium containing the electrical system. The current density acts as a source function in Maxwell's equations; therefore, solutions of Maxwell's equations are used to predict the spatial and time behavior of the electromagnetic fields. Coupling techniques are then used to relate the electromagnetic fields to electrical energy sources within the circuits. Circuit-analysis codes are applied to determine circuit response.

Item 15. *Electromagnetic Pulse from Nuclear Explosions*

Several computer codes have been developed for modeling various aspects of the electromagnetic pulse (EMP) produced by nuclear explosions. The SHARP (Sandia High-Altitude Radioflash Prediction) code calculates the first ~0.5 μs of the EMP produced by a high-altitude burst. This signal is predominately radiation from Compton electrons gyrating about the earth's geomagnetic field. In order to evaluate missile vulnerability to electromagnetic effects, the electric fields and air conductivities calculated in SHARP have been used as input to other codes which estimate the electrical current induced on conducting missile skins.

Item 16. *Satellite Vulnerability to Nuclear Explosions*

A computer program has been developed which is useful in satellite vulnerability studies. For a given satellite orbit and nuclear explosion position, the program calculates the probabilities that various environments produced by the explosion will exist at the satellite. The relation between the position of the satellite in its orbit and the time of burst can be taken to be random. Typical code input includes satellite-orbit parameters, burst position and weapon parameters, vulnerability and kill criteria, circuit models, and the list of effects to be included. Possible effects include those produced by neutrons, x-rays, gamma rays, EMP, internal EMP, delayed gamma rays, electrons, and solar-flare protons. The output indicates the probability of survival of system and its components, the magnitude of various effects as a function of distance, or the cumulative probability of an effect as a function of the size of the effect.

NUCLEAR ENGINEERING

Activities are directed toward development, design, and experimental applications of pulse reactors. Analysis techniques developed by Sandia are used for pulse reactor applications in addition to standard techniques used for steady-state reactors. Analysis for in-pile experiments is required to predict experiment performance and to properly interpret measured data. Experiments involve simulating neutron and gamma-radiation environments. Reactor safety experiments which simulate power reactor accident conditions are also analyzed.

7

Pulse Reactor Physics

Analytical techniques are used to describe the transient and steady-state performance of a reactor. Critical configurations of a reactor core or of fuel elements in a storage container are analyzed. Transient analysis includes the coupling of various feedback mechanisms with neutron kinetics to properly describe the power-time behavior of a reactor. (Items 1-4)*

Current Activities

- Neutron transport
  - Discrete ordinate methods
  - Monte Carlo techniques
- Transient analysis
- Criticality
- Reactor heat transfer

Pulse Reactor Stress Analysis

A dynamic thermal-stress analysis that allows for the mass inertia of fuel elements is used to calculate the behavior of pulse reactors which produce power pulses tens of microseconds in width. Large temperature gradients are present in fuel elements after a pulse, and temperatures as great as 2000°C are possible. Quasi-static thermal-stress analyses coupled with transient heat-transfer calculations are necessary, with temperature-dependent material properties included. The rapid motion of control mechanisms and loads imparted to the nonfuel structures of the reactor are analyzed. (Item 5)

Current Activities

- Dynamic stress analysis
  - Inertia effects
  - Temperature dependent properties
- Quasi-static stress analysis
  - Coupled heat transfer
  - Temperature dependent properties
- Stress analysis of structural components
- Experimental methods
  - Transducer measurements
    - Strain and displacement
  - Photoelastic techniques

Reactor Safety Studies

The use of pulse reactors in power-reactor safety studies provides experimental data necessary for the analysis of many potential accident conditions. Experiments are planned and performed to simulate the effects of fuel melting, fuel-coolant interactions, and post-accident heating conditions.

Current Activities

- Liquid-metal fast breeder reactor safety experiments
  - Post-accident heat removal
  - Molten fuel-clad interactions
  - Molten fuel-coolant interactions
  - Overpower transients
  - Molten fuel motion detector

*See Highlights below.

NUCLEAR ENGINEERING

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Item 1. *Annular Core Pulse Reactor (ACPR)*

The ACPR, a TRIGA type pulse reactor (Figure 1) is used for reactor safety research experiments, transient irradiation of electronic components, activation analysis, pulse reactor fuel studies, neutron radiography, and radiation-effects experiments. The minimum pulse width is 4.7 ms, corresponding to a maximum energy release of 100 MW-sec. Neutron fluence levels in excess of 3×10^{15} nvt are available in the dry 9-inch-diameter 12-inch-high central cavity. A design study is under way to upgrade reactor performance characteristics by a factor of 3.

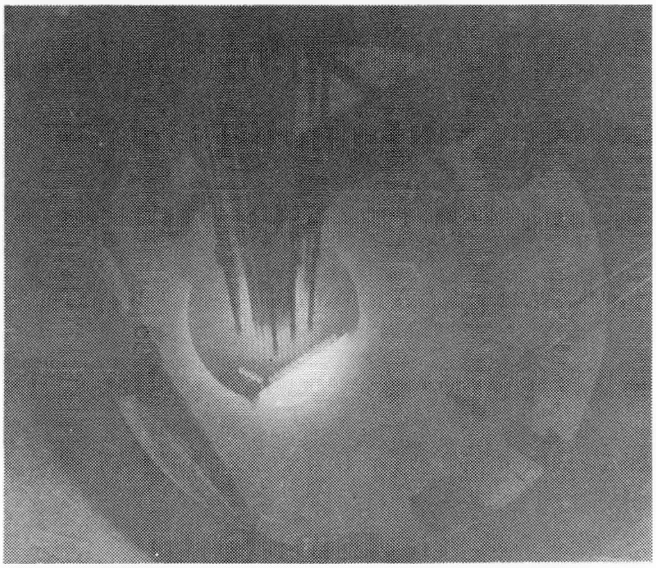

Figure 1. Annular core pulse reactor.

Item 2. *Sandia Pulse Reactor II (SPR II)*

SPR II is a fast-burst reactor used for radiation-effects experiments, neutron-excited laser experiments, reactor-safety research studies, reactor physics experiments, and fuel-material evaluations. The reactor (Figure 2) produces neutron fluences of 8×10^{14} nvt during a pulse width of 50 μs. The exposure volume at the center of the reactor is 1.5 inches in diameter and 8 inches high. Consisting of six plates of fully enriched uranium alloyed with 10 wt% molybdenum, the core has a total mass of 104 kg.

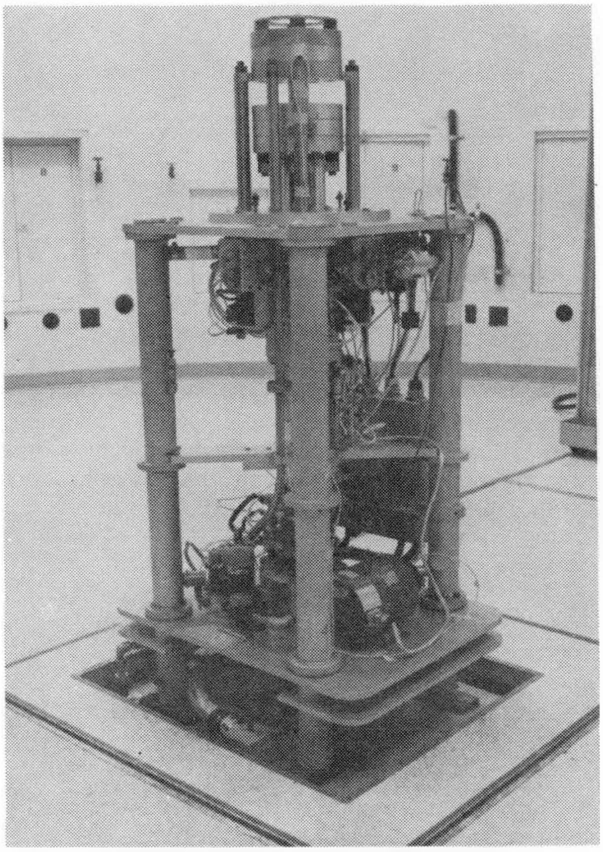

Figure 2. Sandia pulsed reactor II.

Item 3. *Sandia Pulse Reactor III (SPR III)*

SPR III (Figure 3) is the second fast-burst reactor designed and built by Sandia. Scheduled to begin operation in 1975, it will deliver a fluence of 6×10^{14} nvt with a pulse width of 50 μs in a central irradiation volume 7 inches in diameter and 12 inches in length. SPR III is unique in that it uses external reflectors for control and pulse initiation. A single control system will operate both SPR II and SPR III on an interchangeable basis.

Item 4. *Reflector Experiments*

The use of an external reflector for pulse production in a fast pulse reactor was demonstrated with SPR II. A pneumatic device was attached to SPR II so that an aluminum reflector could be rapidly raised vertically adjacent to

NUCLEAR ENGINEERING

the core. The same pulse characteristics were observed irrespective of whether the reactivity addition was by reflector or pulse rod (Figure 4).

Item 5. *Pulse Reactor Calculation*

A coupled kinetic-elasticity model for pulse reactor calculations was developed to predict performance characteristics. The agreement between this model and SPR II data is shown in Figure 5. The model was developed with SPR II and used in the design of SPR III.

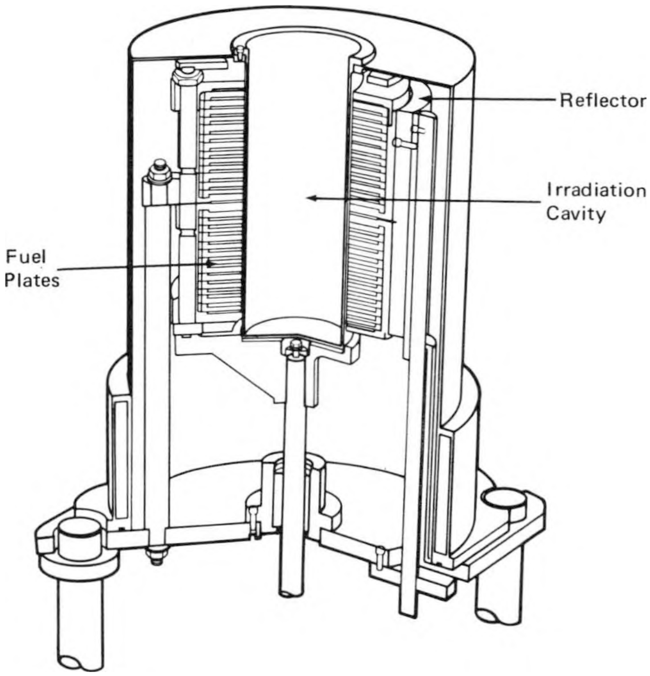

Figure 3. Sandia pulsed reactor III.

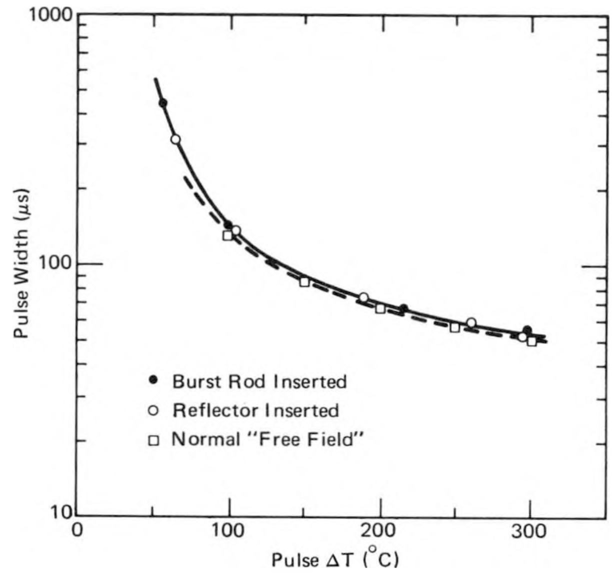

Figure 4. Results of pulsed reflector experiment.

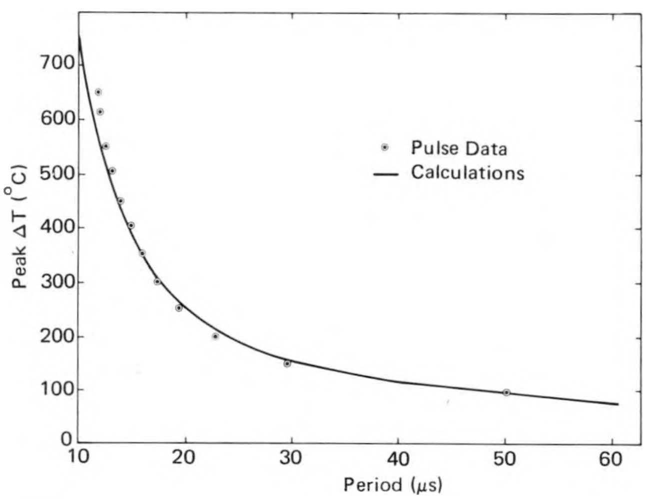

Figure 5. Yield vs period.

REACTOR SAFETY ANALYSIS

This activity includes two general categories: analysis of the safety of new laboratory experimental facilities, and independent assessment of the safety of commercial nuclear power plants.

Reactor Safety Codes

Computer codes are used to predict the dynamic response of reactor systems under severe transient or accident conditions. These codes solve complex coupled problems of neutronics; material and structural response; fission-product release, transport, and deposition; and environment effects. Fault-tree codes are employed in assessment of risks arising from reactor accidents.

Current Activities

- Neutronics codes
  - Discrete ordinate
    - DTF-IV
    - TWOTRAN
  - Monte Carlo
    - SORS
    - JUGADOR
    - KENO II
  - Diffusion
    - EXTERMINATOR
    - AIM-6
  - Kinetics
    - KOKIEL
    - POWER-Z
    - RAMP
- Wave-propagation codes
  - One-dimensional
    - WONDY
    - CHART-D
  - Two-dimensional
    - TOODY
    - CSQ
  - Structural response codes
    - SLADE
    - SLADE-D
    - HONDO
    - UNIVALUE-II
    - CHILES
    - TACOS
    - SOR
    - GNATS
    - SHELL-SHOCK
- Fission-product transport
  - FISSP
  - CLOUD
  - DIFOUT
- Dose calculation
  - RADS
  - Ligh-water reactors
  - Loss-of-coolant accident code
    - RELAP
    - WHAM
- Fault-tree codes
  - SETS
  - SEP

Reactor Safety Studies

Studies are under way to evaluate the safety of commercial nuclear power plants. These studies combine system-analysis capability with use of applicable computer codes, laboratory experiments, and system tests. (Items 1-3)*

Current Activities

- Safety and security of nuclear power plants against acts of sabotage
- Experimental fast-reactor safety research
- Core meltdown experimental review and research
- Effects of natural disasters, tornados
- Gas-cooled reactor safety research
- Fast-reactor accident modeling
- Analytical support to test facilities
- Fracture control and monitoring
- Post loss-of-coolant hydrogen gettering
- Vulnerability of nuclear fuel cycle to conventional wartime attack

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*See Highlights below.

REACTOR SAFETY ANALYSIS

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Dynamic Response of Power Burst Facility In-Pile Tube*

Calculations have been performed to determine the dynamic response of components of the in-pile tube (Figure 1) of the Power Burst Facility (PBF) and the dispersion of a pressure pulse in the coolant. The facility is operated for ERDA by Aerojet Nuclear Company at the Idaho National Engineering Laboratory. The Sandia calculations were done at their request. Reactor fuel elements will be tested under conditions of transient energy deposition by suspending them in the in-pile tube, which is mechanically isolated from the PBF. The catch basket, in the lower end of the in-pile tube, is designed to catch and contain any fuel debris after the transient. The response of the catch basket to a design base pressure pulse was analyzed in detail by using three finite-difference computer programs: CHART-D (one-dimensional) and TOODY and HONDO (two-dimensional). Both the one- and two-dimensional analyses indicated that certain design features of the catch basket were marginal. Propagation of the tensile wave in the breech-locking mechanism of the in-pile tube was calculated using HONDO. Stress components at points where the breach threads contact the support structure were calculated as a function of time. The calculated stress values were compared with allowable stress for the materials used in the breech mechanism to ascertain design adequacy. Finally, coolant flow in the inlet-outlet nozzles was calculated for a simplified geometry with CSQ.

Results of the calculations were made available for use in any redesign of the PBF or similar structures.

Item 2. *Light-Water-Reactor Core Meltdown Experimental Review*

An extensive survey has been made of information bearing on a hypothetical core-meltdown accident in light-water reactors. The first objective was to obtain a compendium of applicable experimental evidence. Literature from the nuclear power field and from other scientific disciplines and industrial sources was reviewed. Investigators and other knowledgeable persons were interviewed. A second objective was to determine what data are required, and to determine the adequacy of existing data. In previous core-meltdown studies, only land-based plants had been examined. Therefore, a third task was to examine offshore plants to determine the applicability of on-shore plant analysis to particular areas therein and to determine what information peculiar to offshore plants was needed. The study is being used to plan future light-water-reactor core-meltdown research.

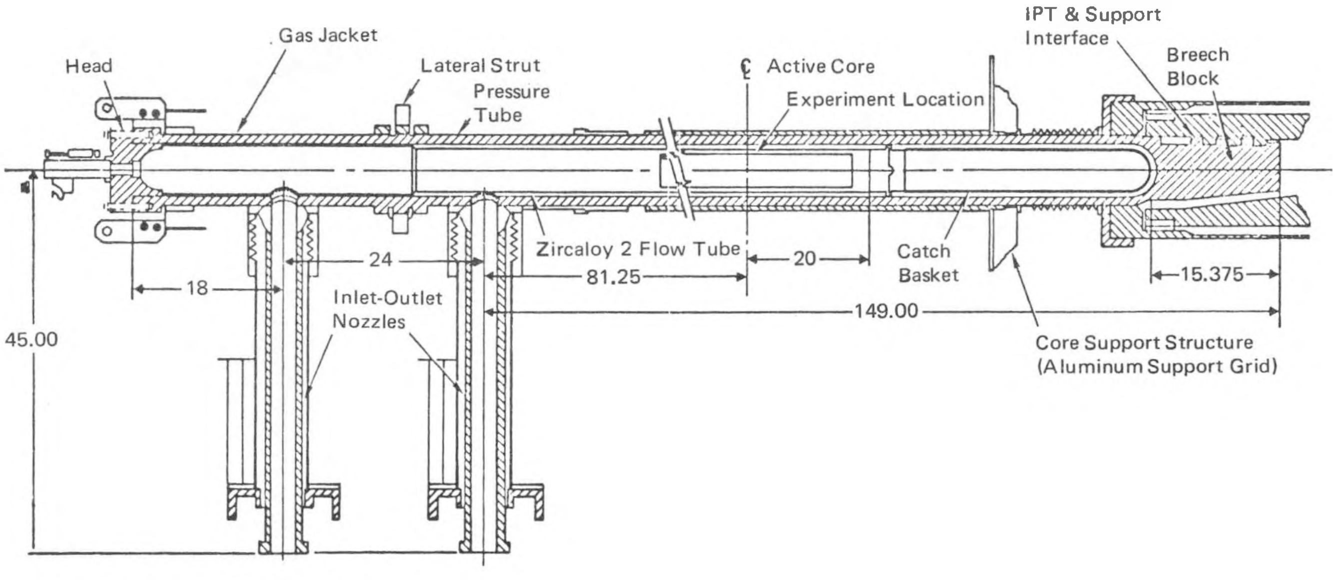

Figure 1. Axial cross-section of in-pile tube.

Item 3. *Vulnerability of Tornado-Resistant Structures*

This program is designed to evaluate the vulnerability of structures to missiles generated by tornadoes. Planks, a pipe, and a car at 200, 100, and 50 mph, respectively, are being tested into reinforced concrete walls representative of nuclear production facilities. Present structural design criteria use ballistic penetration and perforation equations derived for nondeformable missiles.

Program scope for the future calls for model testing with subsequent full-scale verification of impact phenomena for various wall thicknesses and missiles. Plans will be based on test results and on other work to be conducted in this field.

MATERIAL PROPERTIES

Studies are aimed at understanding the mechanics and physics of material behavior so that descriptive models can be developed for incorporation into analysis techniques. The studies rely on a coupling of material science, mechanics of materials, and analysis techniques to assure that descriptive models being developed are physically realistic as well as compatible with the analyses. Emphasis is on understanding mechanisms that control mechanical and thermal phenomena. New methods are being developed to study these phenomena under the severe environments associated with nuclear weapons, reactor safety, and nuclear-waste disposal. Study results, in the form of models or physical parameters, are then incorporated into computer solutions of engineering problems.

Mechanical Behavior

Goals of studies on mechanical behavior are the characterization of essentially all classes of materials: metal, ceramics, composites, polymers, and geologic and porous materials. The studies provide specific mechanical-property models describing deformation, fracture or other failure modes for a variety of environments. (Item 1)*

Current Activities

- Fracture, brittle and J-integral studies
- Uniaxial, biaxial and triaxial stress states
  - Wave propagation
    - Uniaxial strain
    - Hypervelocity impact cratering
- Phase transformations
  - Diffusion controlled
  - Shock-induced polymorphic
  - Shock-induced melting, vaporization
- Thermomechanical behavior (temperature history effects)
- Temperatures to 3000°C

*See Highlights below.

Thermal Properties

Techniques have been developed for obtaining data on various thermal properties required for system analysis and design. The capacity to make rapid measurements of materials in extremely high temperatures is available. Studies of thermal properties are used for weapon design and for solar energy and reactor safety studies. Materials include conventional solids as well as refractory liquid compounds. (Items 2-3)

Current Activities

- Thermal conductivity
- Thermal diffusivity
  - Positive and negative
  - Long and repetitive
  - Pulse techniques
  - Multiple-sample handling,
  - Extremely high-temperature
  - Refractory liquids
- Thermal expansion
  - Refractory liquid metal density
- Enthalpy and heat capacity
  - Electromagnetic levitation and (inert)
  - liquid-gas calorimetry
- Radiative and absorptive properties

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *High-Temperature Mechanical Properties*

The very high-temperature mechanical properties of graphitic materials are being determined after short times (seconds) at temperature and at strain rates up to approximately 10/second. The technique involves self-resistance heating of tensile or compressive specimens by passing a high electrical current through them in a preprogrammed, feedback-controlled heating cycle and then mechanically loading the specimen monotonically or cyclically through a predetermined stress or deformation history. Load and strain are monitored electronically and optically so that constitutive relations and fundamental deformation mechanisms for arbitrary thermal and mechanical histories can be determined.

To obtain temperature uniformity along the specimen length, the graphite grips are heated separately by RF induction (Figure 1). This increases the temperature of the ends of the specimen and reduces thermal conduction away from its center.

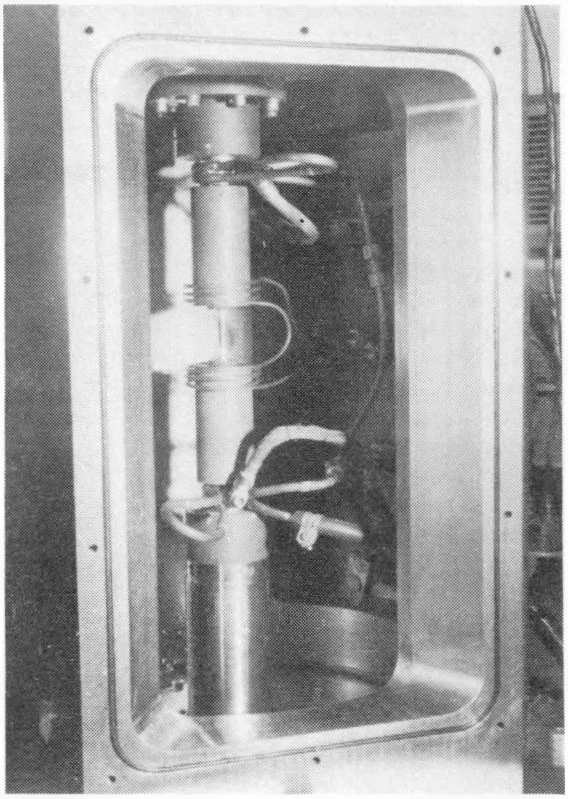

Figure 1. View of inside of test chamber showing load strain arrangement and RF coils used to obtain temperature uniformity along the specimen gage length.

The strain is determined by optically tracking small ceramic cement nodules which are illuminated with a laser. The optical trackers view through narrow-band interference filters to block out specimen incandescence. The technique has general applicability for studying the thermomechanical behavior of any conducting material subjected to particular thermal and/or deformation histories, including cyclic loading, thermal ratcheting, and creep. Graphite sublimation temperatures can be reached in a few seconds under controlled conditions.

Item 2. *Liquid Metal Levitation*

A sample of liquid uranium is levitated and heated in an electromagnetic field before being dropped into a liquid-argon calorimeter for heat-capacity measurements (Figure 2). Electromagnetic levitation heating is a valuable tool for high-temperature measurements because it eliminates reactions with containers. The calorimeter provides a totally inert environment for precise measurements of thermodynamic quantities for use in heat-transfer analyses.

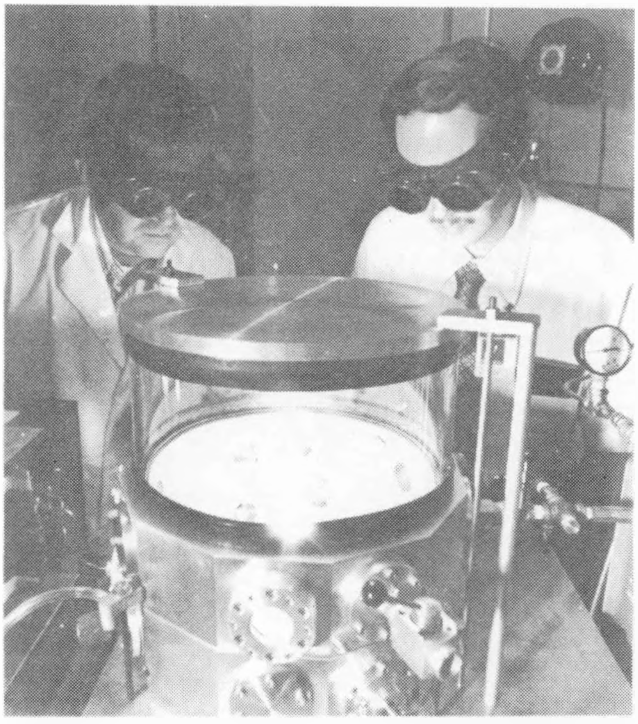

Figure 2. High-temperature property measurements.

MATERIAL PROPERTIES

Item 3. *Thermal Diffusivity*

The apparatus used to make thermal-diffusivity measurements employs a pulsed ruby laser to induce a thermal transient in materials. It is arranged to accommodate up to 20 samples at one time and to acquire and process the data automatically; it is one of the largest capacity systems in the world for thermal-property measurements (Figure 3).

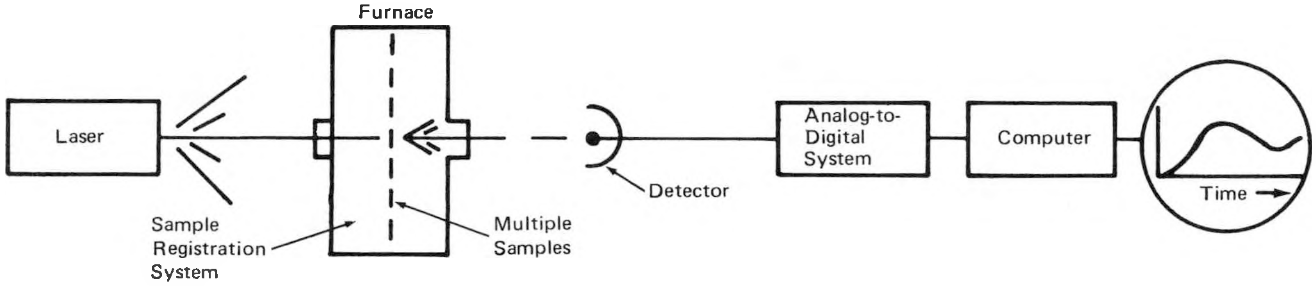

Figure 3. Pulsed thermal diffusivity measurements.

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Sandia Laboratories Technical Capabilities

Explosives Technology, Electrochemistry and Electromechanisms

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115 and Livermore, California 94550 for the United States Energy Research and Development Administration under Contract AT(29–1)-789.

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SANDIA LABORATORIES TECHNICAL CAPABILITIES

EXPLOSIVES TECHNOLOGY, ELECTROCHEMISTRY AND ELECTROMECHANISMS

ABSTRACT

This report characterizes the explosives technology, electrochemistry, and electromechanisms capabilities at Sandia Laboratories. Selected applications of these capabilities are presented to illustrate the extent to which they can be applied in research and development programs.

EXPLOSIVES TECHNOLOGY, ELECTROCHEMISTRY, AND ELECTROMECHANISMS*

Activities in explosives, electrochemistry, and electromechanisms are primarily directed toward the design and development of components. A demand for components made to high standards of reliability, safety, and longevity for use in nuclear weaponry has required research and development to make possible an understanding of the mechanisms that control component operation, and to use these mechanisms for practical purposes.

Most of the components designed either generate or are actuated by electrical signals. Operational constraints have necessitated miniaturization, long-term material compatibility, and an ability to withstand severe environments.

Studies in explosives, particularly detonation physics and the chemistry of explosives, have led to reliable ways to use the sudden release of chemical energy. Chemical and thermal-conversion processes are used to release the energy stored in batteries. Studies in electromechanisms have resulted in miniaturized components for environment sensing, electrical switching, and timing.

The major facilities for conducting research and advanced development of explosives, electrochemical and electromechanical components are fabrication facilities, chemical laboratories, gas guns, firing sites and environmental test facilities.

Explosives Technology, Electrochemistry, and Electromechanisms
Technical Staff and Investment in Equipment

	Professional Staff	Investment in Equipment (in $1000)
Explosives Technology	35	2800
Detonation Physics		
Chemistry of Explosives		
Facilities and Instrumentation		
Electrochemical Power Sources	16	1100
Electrochemistry		
Physical Chemistry		
Thermal Analysis		
Facilities		
Electromechanisms	148	2117
Environment Sensing		
Guidance and Control		
Switching Technology		
Timing Technology		
Analysis		
Test Equipment		

*Compiled November 1975.

EXPLOSIVES TECHNOLOGY

Explosives research and development encompasses the disciplines required to design, develop, manufacture, and test specialized, reliable explosive components and subsystems that are compatible with extreme environments.

Research is conducted in detonation physics and explosives chemistry, including the synthesis, formulation, processing, stability, compatibility, initiation, deflagration, detonation, and detonation-transfer characteristics of explosives and pyrotechnic formulations. The efforts have led to a better understanding of chemical stability, of the critical energy necessary for initiation, and of the most efficient ways to use chemical energy in explosive components and subsystems. Components are designed and prototypes fabricated for subsequent manufacture at various integrated contractors and commercial suppliers. This combination of research and engineering has resulted in the development of miniaturized, reliable, extended-life, radiation-resistant components as well as sophisticated explosive subsystems and precision test methods to measure explosive and material response to shock loading.

The major facilities for explosives research and development include chemical laboratories, mechanical and explosives fabrication facilities, gas guns, quartz-gage and velocity-interferometer measurement systems, and environmental testing and firing sites. The latter possess a broad range of modern test equipment and firing capabilities.

Detonation Physics

Theoretical and experimental work is centered on the detonation physics of gaseous, liquid slurry, and solid explosives. Applied studies of the sensitivity of explosives to electrical, thermal, impact, and shock stimuli are motivated by needs for both safety and design information. Techniques have been developed for measuring explosive output and for describing the detonation of explosives in wave-propagation computations.

Initiation Phenomena

The mechanism of initiation is a process in which a low-energy input produces a weak chemical reaction that grows to detonation. Analysis of explosive initiation is necessary for the design of detonators and explosive devices, and for safety studies. Methods are developed for predicting initiation of explosives by various stimuli. Emphasis is placed on understanding the initiation mechanism by studying electrical, shock, and thermal stimuli. (Items 1-3)*

Current Activities

- Electrical initiation of detonation
  - Exploding-bridgewire physics
  - Criteria for initiation
  - Detonator and firing-system performance
- Shock initiation of detonation
  - Equation-of-state studies of explosive materials
  - Experimental investigation of shock initiation
  - Input pressure-history criteria
  - Critical energy input
  - Theoretical studies of initiation mechanism
  - Fuel/air explosives
  - Safety testing
- Thermal ignition
  - Heating and thermochemical instability
  - Influence of confinement on explosive burning

*See Highlights, below.

EXPLOSIVES TECHNOLOGY, ELECTROCHEMISTRY AND ELECTROMECHANISMS

EXPLOSIVES TECHNOLOGY

Detonation Phenomena

Studies in detonation phenomena are directed at efficiently transferring the latent chemical energy of explosives into controlled kinetic energy and to determine the chemical composition or the critical dimensions of a charge that will only marginally sustain detonation Gurney formulae or numerical techniques, which solve the partial differential equations representing the physical and chemical theories of detonation, are used to optimize conversion processes. Laser velocity interferometery has been developed to measure reaction-zone length in mild detonating fuse and heterogeneous explosives. (Items 4-6)

Current Activities

- Gurney output theory
- Gurney energy measurements
- Explosive containment
- Reaction-zone thickness measurement
- Fuel/air explosives
- Composite explosives
- Slurry explosives
- Propagation in mild detonating fuze

Stress-Wave Analysis

Constitutive equations of state of explosives are developed through an iterative process between formulation of the equation of state and the development of stress-wave propagation programs.

The programs are applied to solving problems in the analysis of explosive initiation and detonation physics experiments and in the design of components and systems. Application of wave-propagation programs reduces the number of development tests, allows for more complete data interpretation, and gives a fundamental understanding of device performance. (Items 7-10)

Current Activities

- Stress-wave codes
  - Lagrangian one-dimensional
  - Lagrangian two-dimensional
  - Eulerian two-dimensional
- Chemical codes
  - Chemical equilibrium
  - Equation of state of detonation products
  - Gurney energy
  - Detonation velocity and pressure
- Constitutive relations
  - High explosives
  - Nonlinear viscoelastic
  - Thermodynamically complete multiphase hydrodynamic description
  - Elastic-plastic strain hardening
  - Rate-dependent yielding
  - Cumulative-damage failure criteria
  - Porous materials
- Applications
  - High-explosive containment
  - Shaped-charge design and penetration
  - Explosive metal forming and cutting
  - Explosive cratering
  - Ballistic penetration
  - Ground-shock propagation
  - Explosive initiation
  - Component design

Component Design

Detonation physics and explosive chemistry capabilities are combined with component engineering to design safe and reliable explosive components and systems. (Items 11-16)

Representative Developments

- Mild detonating fuze
  - Timers, precision detonation velocity
  - Stage separation
- Confined mild detonating fuze
- Flexible linear-shaped charge
  - Cutting and destruct
- Detonators
  - Exploding-bridgewire
  - Spark gap
  - Hotwire
- Various explosive components
  - Valve actuators
  - Igniters
  - Piston motors
  - Explosive switches
  - Explosive bolts
  - Photoflash cartridges
  - Gas generators
  - Spin rocket motors
  - Plane-wave lenses
  - Line-wave generators
  - Smoke puffs and rockets
  - Solid dielectric switches

EXPLOSIVES TECHNOLOGY

Explosive systems
- Explosive containers
- Pulsed power sources
- Sample recovery containers
- Fuel/air explosives
- Parachute deployment
- Flight termination

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Shock Initiation of Detonation in Nitromethane*

The process of shock initiation in a representative homogeneous liquid explosive (nitromethane) has been studied experimentally and theoretically. In the experiments, liquid explosives initially at room temperature were compressed by plane shocks to pressures from 7.5 to 9.5 GPa. Diagnostic information in the form of the ignition time interval, τ, and the particle velocity history of the shock-compressed liquid were obtained from simultaneous streak-camera and velocity-interferometer records. These data have been favorably compared to predictions obtained from thermal ignition theory using a complete equation of state for nitromethane along with chemical kinetic data on the exothermic decomposition of the shock-heated liquid. A linear variation of log τ with calculated temperature behind the inert shock wave is predicted theoretically and observed experimentally for ignition times of the order of one microsecond. These results are of specific importance regarding the behavior of nitromethane and are of general interest as they contribute to an understanding of the physics of the initiation and detonation of homogeneous explosives.

Item 2. *Criteria for Electrical Initiation of Detonation in the Explosive PETN*

Information on the initiation characteristics of PETN is needed for the design of safe and reliable exploding-bridgewire detonators. A threshold burst current criterion has been developed which takes into account the composition and dimensions of the bridgewire and the surface area and temperature of the explosive.

Measurements have been made of the sensitivity of granular PETN to initiation by a discharge of static electricity. It was found that initiation required only a small amount of energy (~10 mJ) but that it had to be delivered in a very short time interval (~30 ns): for example, electrical discharge from the human body, though furnishing sufficient energy, is not deposited with sufficient rapidity to initiate PETN, which is why PETN can be handled with relative safety. Low-energy initiation of PETN at high power levels can be met by discharging a capacitor. Spark-gap detonators employing this principle have been designed and tested.

Item 3. *Wave Propagation Studies in a Solid Explosive*

The behavior of shock, acceleration, and acoustic waves in the plastic bonded explosive PBX-9404 were studied to determine physical and chemical properties relating to the performance of this explosive.

Shock experiments at 3.3 GPa revealed a strong deflagration reaction that was the principal contributor to shock growth. The instantaneous heat release rate at the shock front was determined from the growth rate of shock amplitude and acceleration of the explosive material immediately behind the shock front. Figure 1, obtained from particle-velocity histories measured by laser interferometry, depicts growth in both amplitude and material acceleration.

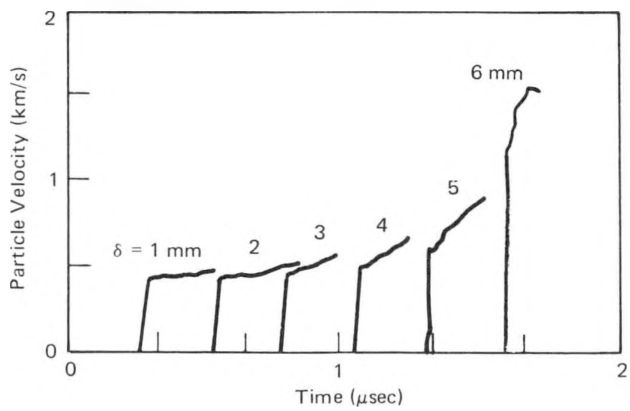

Figure 1. The developing shock waveform was observed at various explosive thicknesses, δ. For the shock input used here, growth to detonation required 7.2 mm of shock travel.

Acceleration waves were found to decay for two reasons: reverse curvature in the PBX-9404 Hugoniot at low stress levels (i.e., $\partial^2 \sigma/\partial \epsilon^2 < 0$), and viscoelastic losses in the material. The decay approached a single curve, independent of initial acceleration amplitude, after 7 mm of wave propagation, implying that shock waves develop only when deflagration pressures exceed about 1.0 GPa.

Acoustic waves were dispersed by two mechanisms: viscoelastic losses and geometric dispersion owing to the composite nature of the explosive mixture. The acoustic velocity intercept at zero frequency (2.89 km/s) was slightly lower than acceleration-wave velocity (3.17 km/s), as expected.

Item 4. *Detonation Limits for Fuel/Air Explosives*

Tests have been conducted to determine the concentration limits within which detonation can occur in large unconfined volumes of various mixtures of hydrocarbons and air. The mixtures were metered into large envelopes of thin polyethylene film and initiated by detonation of explosive boosters. Detonability limits of unconfined fuel/air mixtures are narrower than when confinement is provided, but increase with increasing booster mass. Detonation limits are observed to broaden and sensitivity to increase as one progresses from fuels in which carbon atoms are singly bonded to each other to those in which double and then triple carbon-carbon bonds are present (Figures 2 and 3).

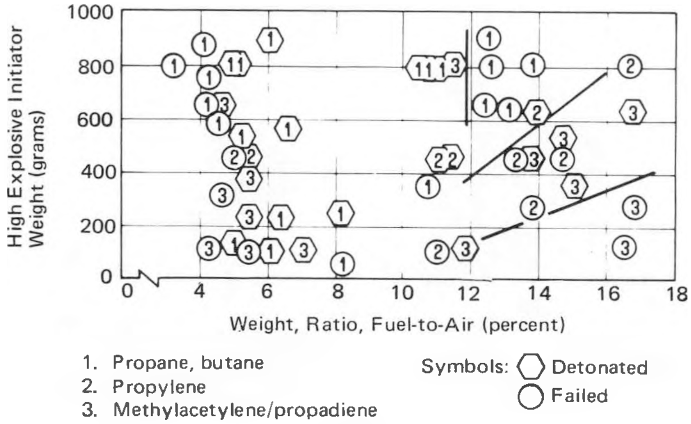

Figure 2. Experimental data points for detonation of four fuels.

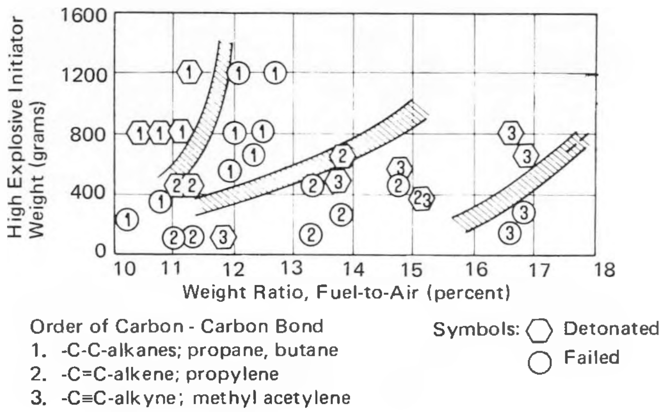

Figure 3. Experimental data points for detonation of four fuels with rich mixtures.

Item 5. *Method for Analyzing Explosive Performance*

Gurney formulae provide a general way to estimate the velocity of explosively accelerated material to within 10 percent in typical configurations. These formulae represented global momentum and energy balances calculated on the assumption that velocity distribution in detonation products is linear. For a given geometrical configuration, a Gurney formula expresses the velocity of driven material as a function of the ratio of the mass of driven material to that of the explosive. In each case the velocity is proportional to the square root of a "Gurney energy" characteristic of the explosive used, and its density.

Hydrodynamic solutions for a matrix of test problems have been obtained to determine the range of applicability of the formulae. These calculations also lead to an improved understanding of the relationship between the "Gurney energy" that scales the formula to experimental observations and the thermochemical energy liberated in calorimetric experiments. Figure 4 shows a comparison of an analytical solution for the velocity of an explosively driven plate with the velocity predicted by the Gurney model. Calculations using a chemical equilibrium code TIGER have been used to derive correlations between Gurney energy and the more readily determined quantities of explosive density and detonation velocity.

EXPLOSIVES TECHNOLOGY

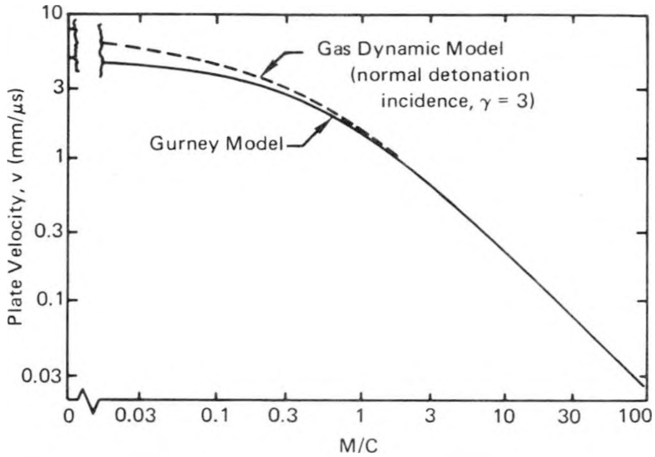

Figure 4. Gas dynamic and Gurney predictions of the velocity of explosively driven plates for various ratios of plate mass, M, to the mass, C, of Composition B explosive.

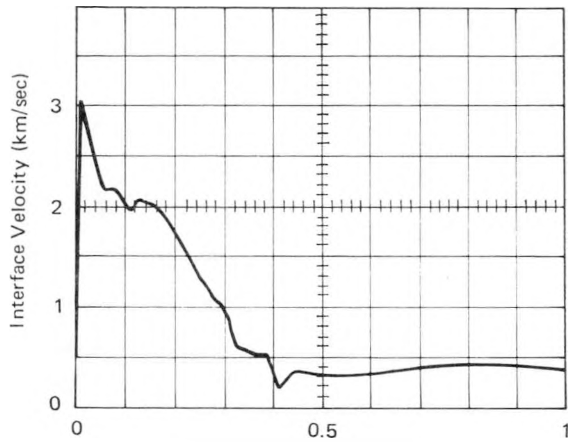

Figure 5. VISAR-measured velocity history of a fused-silica/detonation-product interface. (Time t_1 is interpreted as the chemical reaction time for MDF when detonation was incident against the fused silica plate.)

Item 6. *Interferometry in Explosive Studies*

Special laser interferometers developed at Sandia have been used to advantage in shock-wave studies of inert materials. Recently, a VISAR-type velocity interferometer system has been applied in explosive research and development work. VISAR instrumentation is designed for nanosecond time resolution and permits clear determination of discontinuities in velocity. Studies of the growth or decay of shock and acceleration waves in solid explosives have yielded fundamental information on the mechanical and chemical behavior of these materials. This information is being used to model the growth of shock waves toward detonation and will be applied in the study of the transition from deflagration to detonation. VISAR measurements of the velocity history of explosively driven solids can be used to determine the performance of explosive components or the structure of detonation waves. For example, VISAR was used to observe the detonation waveform in mild detonating fuze with a 1-mm-diameter explosive column. Detonation reaction time (Figure 5) was found to vary substantially as a result of different explosive conditions, which can affect the reliability of detonation propagation.

Item 7. *Thermochemical Estimation of Explosive Energetics*

A thermochemical method has been developed for estimating the useful energy output of an explosive for metal-acceleration applications. Thermochemical computer calculations were made of detonation states and internal energy states along the detonation-product gas expansion isentropes for a number of C-H-N-O explosives of various densities. The difference between the internal energy of the expanded products and that of the unreacted explosive represents conversion to kinetic energy; this difference is a function of the expansion ratio and is a measure of energy output. The energy output at three-fold expansion of the products correlates well with the experimentally determined Gurney energy, which is the effective value of the total kinetic energy generated per unit mass of explosive. Energy output is also correlated with a factor involving the quantity and mean molecular weight of product gases and an estimate of energy release calculated by assuming the products to be N_2, H_2O, CO_2, and C. Given the empirical chemical formula of a real or hypothetical C-H-N-O explosive, this correlation permits estimation of the Gurney energy within ~5 percent as a function of density. This represents a significant advance in a priori analysis of explosive energetics.

Item 8. *Analysis of Detonator/Firing System Performance*

The design of firing systems for exploding-bridgewire detonators is greatly facilitated by the use of a computer code to analyze circuit behavior. The critical part of the analyses involves accounting for the effect of the resistance change in the bridgewire as it melts and is subsequently vaporized by the current passing through it. This problem has been solved through experimental determination of the resistivity of 23 metals as a function of the action $g = \int i^2\,dt$, and entering this data compendium into the computer memory in tabular form. The data are used to update bridgewire resistance at each timestep of the numerical integration of the circuit differential equations. In this way circuit behavior can be predicted in detail, and to high accuracy. Once the current pulse through the wire is known, it can be compared with existing criteria for explosive initiation to predict detonator function.

In addition to firing system design, numerical calculations are made to predict circuit overload behavior when fuses "blow," and is used in other applications where joule heating is of importance. There is good correlation with experimental observations, as is illustrated in Figure 6.

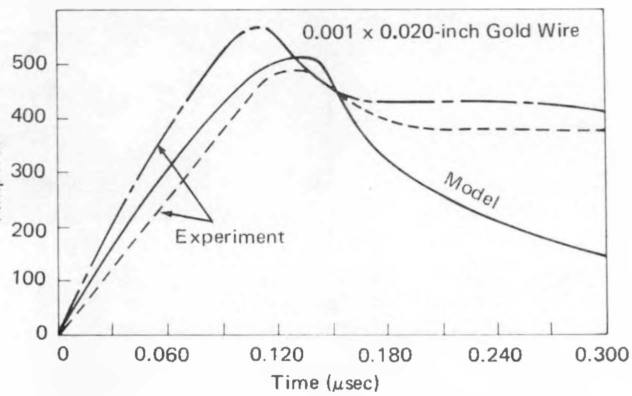

Figure 6. Behavior of a gold bridge-wire in an overload condition.

Item 9. *Equation of State of Nitromethane*

To facilitate shock-initiation calculations for nitromethane, an internally consistent thermodynamic equation of state of the liquid has been determined experimentally. Thirty-eight thermodynamic parameters have been tabulated over a range that includes pressure to 20 GPa, temperatures to 2000 K, and compressions to one-half normal volume. A computer file of these data has been constructed and is available as a subroutine for wave-propagation codes. An example of the information available is given in Figure 7, which shows the temperatures achieved for varying degrees of shock compression of nitromethane at three values of the initial temperature.

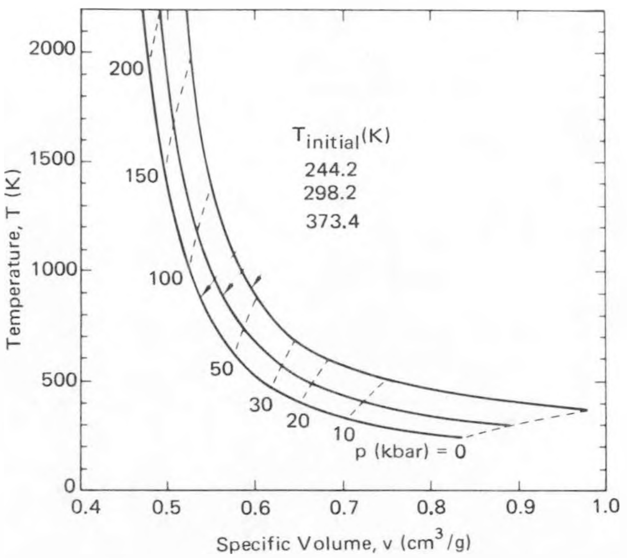

Figure 7. Temperature-specific volume states achievable behind shock waves of various strengths for three values of the initial temperature.

Item 10. *Computer Simulation of Oil-Shale Fragmentation*

Computer simulations of events involving explosive detonation are used to complement field tests. Several such simulations, conducted with the TOODY wave code, were used to evaluate fragmentation of an oil-shale formation by detonation of a liquid explosive. In these two-dimensional computer simulations, a thin horizontal layer of explosive was sandwiched between two thicker sheets of oil shale. The simulated explosive detonation resulted in shock and release-wave interactions near the upper and lower free surfaces of the shale, causing fragmentation. The principal parameter studied was the degree of fragmentation as a function of the relative thicknesses of the explosive and the shale (Figure 8).

Item 11. *Low-Voltage Exploding-Bridgewire Detonators*

Exploding-bridgewire detonators have typically required a firing source charged at 1500 to 3000 volts. A low-voltage detonator has been developed that requires less than a 500-volt source. This is achieved by coupling the detonator close enough to the source that total circuit inductance is maintained at about 100 nanohenries. Sufficiently high currents are obtained at relatively low charge voltage because of minimized inductance and resistance. Fairly large capacitors

(4-5 μfd) are used to assure sufficient energy. They are small physically, however, because of low voltage ratings. The detonator uses a gold bridgewire matched to the firing source. Satisfactory storage characteristics are achieved through the use of a thermally aged PETN explosive.

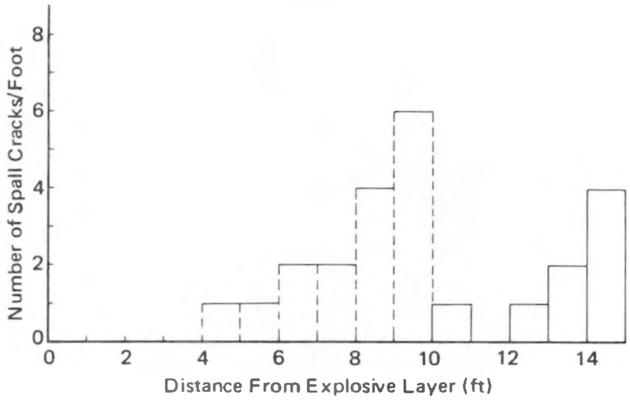

Figure 8. Shock-induced fracturization as a function of the thickness of the oil shale layer.

Item 12. *Sample Recovery Container*

The recovery of test specimens exposed to the radiation of underground nuclear explosions is made possible by explosively closing the pipe containing the specimens. Timing of the closure is critical, as the interval between irradiation and debris arrival is of the order of a few hundreds of microseconds. For example, a 10-cm-diameter pipe is sealed in less than 200 microseconds using 860 grams of explosive wrapped around the pipe, initiated by two line-wave generators (Figures 9 and 10).

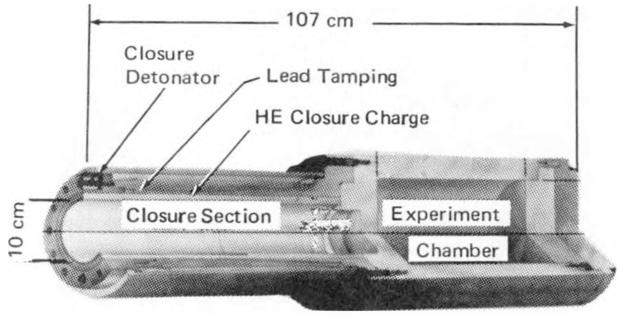

Figure 9. Cutaway of closure section and experiment chamber in pipe leading from underground detonation.

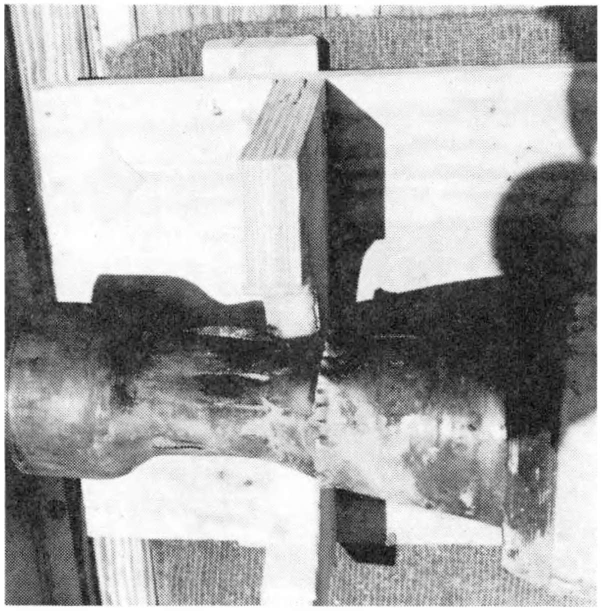

Figure 10. Cross section of sample recovery canister after detonation

Item 13. *Detonation Transfer by Flyer Plate Impact*

Detonation is often transmitted between elements in an explosive train by explosively driving a solid plate across a gap to impact a second, or acceptor, explosive. An analysis was developed to model detonation transfer. The analysis allows optimization of engineering design parameters with a reduced experimental test program. The criterion taken for initiation of the acceptor explosive was imposition of some critical value of initiation sensitivity (p^2t) on the boundary of the acceptor. Here, p and t denote initial impact pressure and the duration of its application, respectively. The design criterion was to maximize p^2t within a set of system design constraints by optimal selection of the flyer material and thickness, as illustrated in Figure 11.

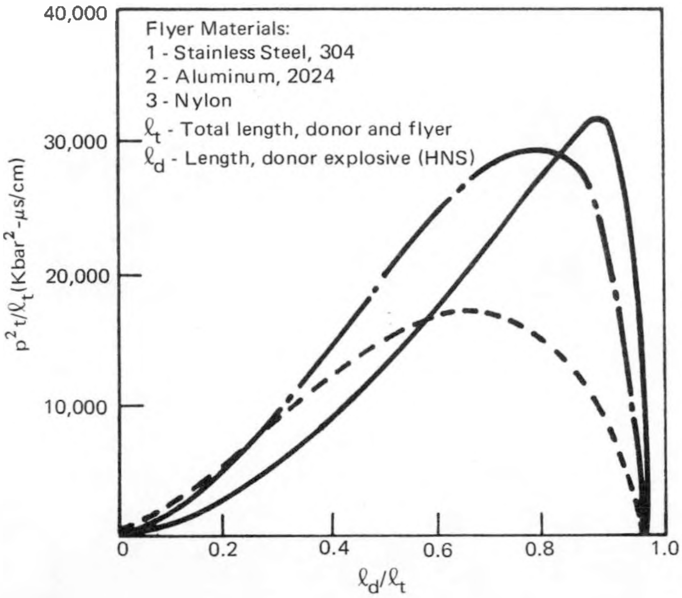

Figure 11. Initiation product versus ℓ_d/ℓ_t.

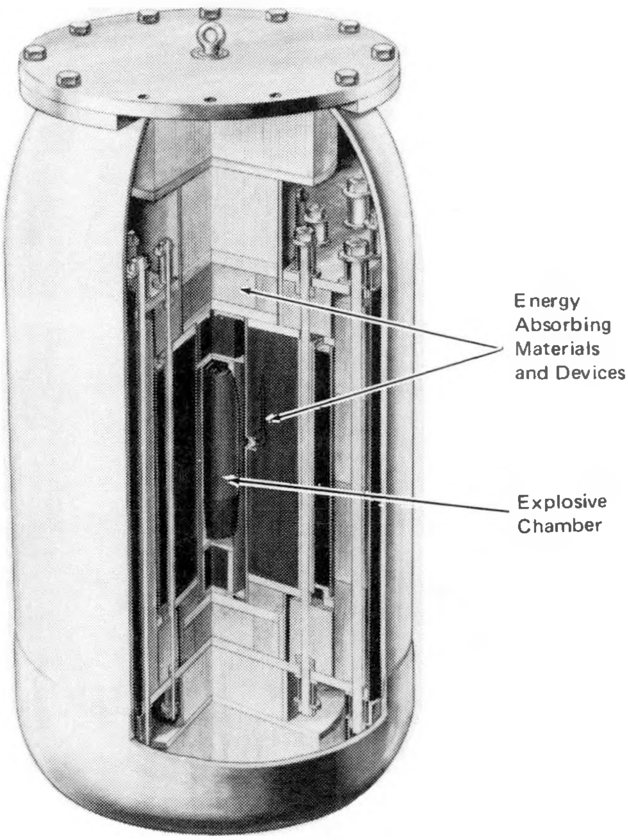

Figure 12. Prototype explosion container.

Item 14. *Explosion Containment*

Interest in the containment of explosions has led to the development of devices to contain hot gaseous detonation products, high-velocity metal fragments, and other debris that may be produced when high explosives are detonated. In these devices, energy is removed from the detonation products by allowing them to do work within irreversibly compacting porous metal. The outward motion of the explosion debris and the compacted metal is then arrested by the application of forces in a momentum trap that consists of strong reinforcing layers, either alone or in combination with shock-absorbing material. Finally, the cooled quiescent gases are contained in a pressure vessel surrounding the energy and momentum trap. In the largest-scale test to date, the detonation of 13.5 kg of explosive in a 2.1-m^3 vessel resulted in its being subjected to a pressure of only 0.48 MPa. Calculations suggest that container weight need be only some 100 times that of the explosive to be contained (Figures 12 and 13).

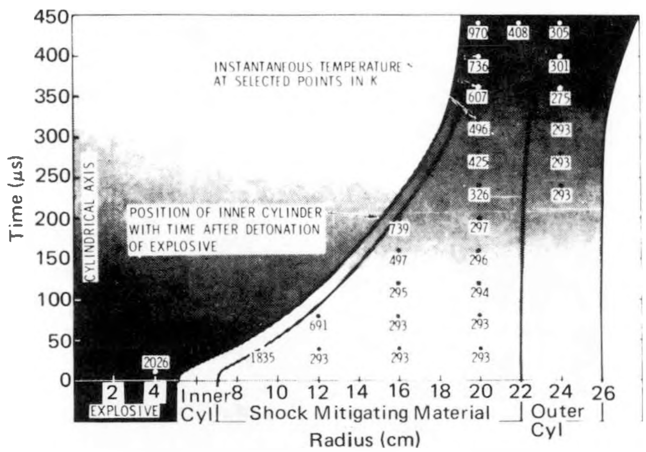

Figure 13. Positions and selected temperatures of the various parts of a containment vessel after detonation of the enclosed explosive.

EXPLOSIVES TECHNOLOGY

Item 15. *Mild Detonating Fuze*

Mild detonating fuzes (MDF) have been used in ordnance for cutting, detonation transfer, and time-delay applications. Typically, detonation velocity has standard deviations of 50 to 100 metres/second. This uncertainty has been reduced to 5 metres/second by the development of an aluminum sheath containing two grains of explosive per foot.

The manufacturing process includes rigid controls on explosive purity, particulate contaminants, aluminum purity, tube loading procedures, and processing controls. After fabrication the MDF is hydrostatically compacted at 60,000 psi for 2 minutes. The resulting MDF has increased timing precision, greater design margins at interfaces as a result of higher detonation pressures, and a demonstrated high reliability.

Item 16. *Confined Detonating Fuze Design*

Detonation must frequently be transmitted from point to point without damage to surrounding components. This may be accomplished by using a small-diameter (~0.5 mm) detonating column within a metal sheath that is sufficiently thick to confine all detonation-product gases. Analysis of the operation of confined detonating fuze permits determination of the sheath thickness required for confinement as a function of the dynamic strength and ductility of the sheath material for a specified explosive load. Conservation of energy requires that the Gurney energy of the explosive be absorbed in plastic work during deformation of the sheath. As input to the calculation, the yield behavior of the metal must be described in terms of a stress-strain law and ultimate strain. The solution is of closed form for rigid perfectly plastic or for linear work-hardening models of material strength. The former model is adequate for aluminum and for stainless steel, while mild steel is better described by a rate-dependent hardening model. This approach could also be applied to the design charges for the explosive forming of metals.

EXPLOSIVES TECHNOLOGY, ELECTROCHEMISTRY AND ELECTROMECHANISMS

Chemistry of Explosives

The aim of explosives chemistry is to understand the chemical and physical characteristics of explosives and pyrotechnics. Emphasis is placed on knowledge of material characteristics, and on preparation procedures for individual materials. Accelerated aging, compatibility, and stability tests are used to demonstrate that the component will meet the required storage life. These tests provide an understanding of the temperature dependence of aging and the mechanisms of explosive degradation processes.

Synthesis of Explosives

This study is aimed at preparing new explosives with improved thermal stability, initiation sensitivity, safety, and reproducible physical properties. Laboratory studies examine all aspects of composition from initial preparation through pilot-plant production. (Items 1,2)*

Capabilities

Laboratory synthesis - up to 50 grams of explosive
Intermediate scale remote facility - up to 500 grams.

Current Activities

- Synthesis of explosives
  - HNS
  - HNAB
  - Inorganic coordination compounds
  - Pyrotechnic formulations
    - $TiH_2/KClO_4$
    - $Ti/KClO_4$
    - Pyroplastics
- Explosive processing
  - Control particle size and distribution
  - Control surface area
  - Prepare desired polymorph
  - Minimize manufacturing contamination
  - Maintain purity achieved in laboratory
  - Maintain control over production
- Explosives under study
  - PETN
  - RDX, HMX
  - HNS
  - HNAB
  - PYX
  - NONA
  - TACOT
  - BTF
  - Extrudable explosives
- Pyrotechnics being evaluated
  - $Ti/KClO_4$
  - $TiH_2/KClO_4$
  - $B/CaCrO_4$
  - B/KNO_3
  - Ti/B
  - $B/CaSi_2/Pb_3O_4/KClO_4$/Plastic
  - Pb/Al

Thermochemistry

Thermal analysis is used to measure chemical reaction rates of explosives at various temperatures. Reaction rates at low temperatures are predicted on the basis of the temperature dependence of reaction rates at higher temperature and the understanding of the mechanisms of change. This information is used to predict component life when long-term aging information is unavailable. (Items 4,5)

Current Activities

- Thermal analysis
  - Differential thermal analysis
  - Differential scanning calorimeter
  - Thermogravimetry
  - Thermomechanical analyzer
- Calorimetry
  - Enthalpy of reaction
  - Bomb calorimeter
  - Component output
- Ignition sensitivity
  - Laser
  - Time to explosion

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*See Highlights, below.

EXPLOSIVES TECHNOLOGY

Compatibility Testing

Compatibility of explosives or pyrotechnics with adhesives, plastics, and other structural materials is studied. Reaction rates are measured for use in selecting materials that will not be subject to degradation within a specific time when subjected to various environments. (Items 6,7)

Current Activities

- Chemical reactivity tests
  - Gas analysis
  - Gas chromatograph
  - Mass spectrometer
  - Microscopic examination
    - Hardness testing
    - Optical microscope
    - Scanning electron microscope
  - Pressure increase (vacuum stability)
- Accelerated tests
  - Differential thermal analysis
  - Differential scanning calorimeter
  - Thermogravimetry
  - Time to explosion
  - Corrosion potential
  - Cyclic voltammetry
  - Polarization curves

Chemical Analysis

Classical and advanced analytical techniques are used to synthesize and characterize explosives and pyrotechnics. In addition to chemical-analysis instruments such as scanning electron microscopes, electron microprobes and Auger spectrometers are used to identify and study surface reactions such as corrosion and incompatibility. (Item 8)

Current Activities

- Chemical methods
  - Gravimetric
  - Volumetric
    - Automatic
    - Complexometric
    - Calorimetric
  - Gas chromatography/mass spectroscopy
    - Gases, vapors, solids
  - Liquid chromatography
    - High pressure
  - Combustion techniques
    - Gases in solids
    - Elemental composition of organics
- Electrochemical
  - Polarography
  - Coulometry
  - Specific ion electrodes
- Spectroscopy
  - Auger
  - Emission
  - Atomic absorption
  - IR, UV, visible
  - Ion scattering
  - Electron
  - Appearance potential
  - Proton-induced x-ray fluorescence
- Activation analysis
  - Thermal neutrons
  - Fast neutrons
  - Pulsed
  - Radiochemistry
- Optical microscopy
  - Hot stage
  - Polarizing light
- Particle size analysis
  - Gas adsorption
  - Zeiss particle analysis
  - Quantomet (optical aided analysis)
- Electron methods
  - Transmission microscopy
    - Defect structures
    - Electron diffraction
  - Scanning electron microscopy
    - Nondispersive elemental analysis
    - Fractography
    - Topography
    - Particle size distribution
  - Electron microprobe
    - Nondispersive elemental analysis
    - Computer-controlled data acquisition
    - Quantitative analysis
    - Spatial distribution of elements
    - Computer imaging of data
- X-ray methods
  - Diffraction
    - Powder patterns
    - Computer identification of crystalline phases
    - Lattice parameter
  - Fluorescence
    - Energy dispersive elemental analysis
    - Wavelength dispersive analysis

EXPLOSIVES TECHNOLOGY, ELECTROCHEMISTRY AND ELECTROMECHANISMS

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Synthesis and Production of HNAB*

The preparation of hexanitroazobenzene (HNAB) was studied in the laboratory in quantities from 50 to 500 grams, and procedures were developed for pilot-scale production. The preparation requires the following steps:

Picric Acid
↓ $POCl_3$ in DMF
Picryl Chloride
↓ hydrazine
Hexanitrohydrazobenzene
↓ nitric acid
Crude HNAB
↓ filter, recrystallize
HNAB
↓ heat 160°C
HNAB-polymorph III

The production of HNAB has been shown to be dependent upon the accurate measurement of reagents, particularly in the reaction of picryl chloride and hydrazine. The removal of manufacturing contaminants is essential because no materials of high atomic number inclusions over 0.25 mm are allowed in the final product.

Item 2. *Synthesis of Trichlorotrinitrobenzene*

1,3,5-trichloro-2,4,6-trinitrobenzene (TCTNB) is an intermediate product in the manufacture of the insensitive explosive 1,3,5-triamine 2,4,6-trinitrobenzene (TATB). New nitration procedures to prepare TCTNB have been developed which decrease the concentration of by-products (1,3,5 trichloro-2,4 dinitrobenzene and 1,3 dinitro-2,4,5,6 tetrachlorobenzene) which interfere with the subsequent manufacture of high-quality TATB. The new procedure uses a nitration mixture of nitric acid and oleum which can be recycled. Previous methods using oleum and sodium nitrate required disposal of large quantities of waste acid.

Item 3. *Application of Hexanitrostilbene (HNS) in Explosive Components*

High-temperature applications in advanced systems have established the need for an explosive capable of functioning after exposure to temperature environments up to 530 K. Low vapor pressure, resistance to radiation, relative insensitivity to shock, and ease of manufacture are additional desired characteristics.

Hexanitrostilbene (HNS) has been found qualified to meet these requirements. Basic engineering design data have been acquired on HNS in aluminum-sheathed mild detonating fuze and linear shaped charges. As an example, the thermal stability of HNS is compared in Figure 1 with that of three other contemporary explosives. Combinations of time and temperature that cause a 1 percent decrease in detonation velocity are shown.

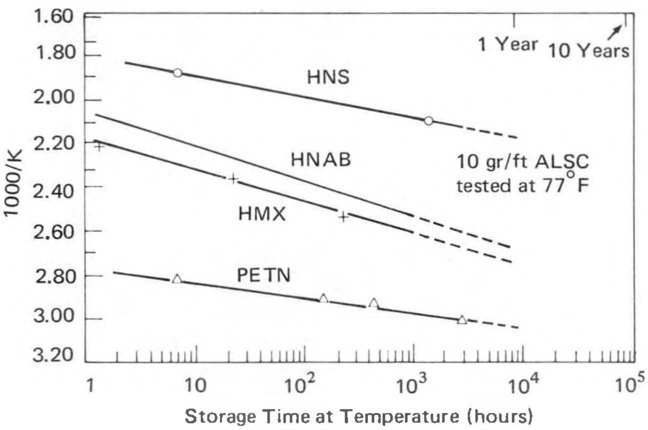

Figure 1. Effect of thermal aging on decrease in detonation velocity. Data shown represent an average decrease of 1 percent.

Item 4. *Response of Confined High Explosives to Thermal Studies*

The exposure of a moderate quantity of confined high explosive to a thermal stimulus yields information that is useful in safety analysis. Specific areas that have been addressed are the conditions of heating rate and confinement under which the high explosive (HE) will respond by detonation, and the comparison of thermal sensitivity between various HE formulations and densities.

EXPLOSIVES TECHNOLOGY

Extensive testing has been conducted in which a simulated system containing up to 6 pounds of HE is exposed to thermal environments ranging from ramp heating at 50°C/hr to immersion in a hydrocarbon fuel fire.

Major observations to date are (1) HE formulations with HMX respond similarly to similar thermal stimuli; (2) HMX-containing formulations can be caused to detonate, even at very low confinement (~8,000 psi static yield) provided that the thermal input is low level; (3) hydrocarbon fire immersion generally results in rapid weakening of the confinement and moderately rapid heating of the HE surface so that at the time of surface ignition the bulk of the HE has not been sufficiently thermally sensitized to support a detonation, and (4) in no circumstances of heating and confinement or density variation has a formulation of TATB been caused to detonate.

Item 5. *Hexanitroazobenzene (HNAB) Polymorph Characterization*

Successful use of hexanitrozobenzene (HNAB) in components has required characterization of the various polymorphs. HNAB has three polymorphs that are stable at standard conditions and two others that exist near the melting point of the explosive (221°C). The chemical properties of the polymorphs, which are stable at ambient conditions, are similar, but physical properties differ significantly:

Polymorph	Melting Point	Density g/cc
I	~180°C	1.79
II	~205°C	1.75
III	~195°C	1.72

Hot-stage microscopy was used to determine the various polymorphic transition temperatures and melting points. Form I changes to II at 65°C and to III at 120°C. The II and III transition seems to be inhibited and is difficult to observe.

In addition to the above properties, the crystal structures of HNAB I and II have been determined by direct methods and refined by analysis of Mo Kα intensity data. The crystalline properties are:

Space Group	$P2_1/C$	$P2_1/a$
a (A°)	10.149 (4)*	10.632 (4)
b	8.263 (3)	21.869 (7)
c	10.055 (4)	7.585 (3)
B (°)	97.29 (4)	102.56 (4)
Cell contents	$2[C_{12}H_4N_8O_{12}]$	$4[C_{12}H_4N_8O_{12}]$
D g/cc (calc)	1.795	1.744
D g/cc (obs)	1.799	1.750

Item 6. *Pyrotechnic Compatibility*

Compatibility between pyrotechnics and component materials such as bridgewires and electrodes cannot be evaluated by gas evolution techniques due to sample size and chemical reactions which may not evolve gases. Cyclic voltammetry has been used to examine the interaction between Tophet C and potassium hexacyanocobaltate in aqueous solution. Immersion tests indicate no significant corrosive attack; however potentiokinetic sweeps indicate pitting and etching and a narrow passive region. Testing in components revealed a similar chemical attack at 50 percent humidity in less than one year (Figure 2). Hexacyanocobaltate is not being used in explosive components because of incompatibility with electrodes and bridgewires.

Figure 2. Corrosion on Tophet C after exposure to potassium hexacyanocobaltate for 260 days at 50 percent humidity. Scanning electron micrograph at 3000X.

Item 7. *Compatibility Testing*

Compatibility tests allow measurements of the quantity of gas evolved when explosives, propellants, and pyrotechnics react with structural materials and adhesives. The quantity of gas produced by an intimate mixture of two materials is compared with that evolved by the individual materials, and material compatibility is then assessed. Total quantity of gas evolved is measured and quantitatively analyzed by gas chromatography. This provides an indication of reaction rates as well as the reaction mechanisn. The data in Table I show the volume of gas produced by the reaction of hexanitroazobenzene with cured EN-7 at 100°C for 48 hours, indicating a potentially incompatible combination.

TABLE I

	N_2	N_2O	NO	CO	CO_2	H_2O	Total Volume (μ liters)
HNAB	1.2	0	1.0	0	1.2	27.8	31.4
EN-7 (Cured)	2.2	1.0	0	1.0	49.5	224	278
HNAB + EN-7 (Cured)	52.7	2.4	52.7	2.1	100	82	790

EXPLOSIVES TECHNOLOGY

Facilities and Instrumentation

Explosive firing facilities and instrumentation are used to conduct system and component tests. Impulse testing methods using flyer plates and photoinitiated or mesh-initiated explosives are used to simulate the rapid loading of surfaces. Ground and target impacts are evaluated by the use of rocket sleds and a specialized firing facility in which a rocket/cable combination is used to impact a test vehicle on an instrumented target.

Facilities

Test facilities are used to characterize and evaluate explosives, to use the explosive release of energy, to evaluate other materials and designs, and to test systems and components that contain explosives.

Aerial Cable Test Facility

Capability

Explosive limit - 15,000 pounds
Test vehicle weight - up to 20,000 pounds
Maximum velocity - 1000 feet/second

Instrumentation

High-speed cameras
Impact sensors
Pressure transducers
Velocity measurement
Aerial camera
Telemetry on board test vehicle

Use

Simulation of air drop
High-speed impact tests

Propagating Explosive Facility

Capability

Explosive limit - 50 pounds

Instrumentation

Flash x-ray system
High-speed streak and framing cameras
Fastax cameras
Tape recorders
Oscilloscopes
Piezo-resistive and piezo-electric transducers

Use

Simulation of radiation-induced impulse
- Sheet explosive
- Rod explosive

Containment tests
Flyer-plate acceleration
Blast effects

Light-Initiated Explosives Facility

Capability

Explosive limit - 5 pounds
- Remote explosive synthesis silver-acetylide/silver-nitrate
- 140-kilojoule, 50-kilovolt capacitor bank
- Explosive waste disposal

Instrumentation

Tape recorders
Disk recorders
Oscilloscopes
Radio frequency-shielded instrumentation trailer
Pressure transducers

Use

Impulse simulation
Flyer-plate acceleration

Mesh-Initiated Explosives Facility

Capability

5-pound explosive limit
Remote spray application of PETN on irregular surfaces
Initiation at 200 points/in.^{2}
Area of explosive -- typically 20 by 50 inches

Instrumentation

Tape recorders
Oscilloscopes
Transducers
Instrumentation trailer

Use

Impulse simulation
Containment tests
Flyer-plate acceleration

Coyote Canyon Test Site

Capability

Explosive limit - 10,000 pounds
Fragment range - 10,000-foot radius

Instrumentation

High-speed streak and framing cameras
Tape recorders
Pressure transducers

Facilities

Two underground trailer bunkers
Photographic bunker
Underground cables

Use

Large-scale explosive tests

Tonopah Test Range (Nevada)

The Tonopah Test Range is a large, remote facility for testing large explosive charges and both new and operational weapon prototypes. Major test capabilities and facilities include hard and soft targets, rocket launchers, electronic and optical tracking systems, photographic recording systems, telemetry receiving stations, and meteorological measuring equipment. A complete description of the capabilities and facilities is available.*

*Testing (SAND-74-0088), or
The Tonopah Test Range (SLA-74-0231)

Capability

Explosive detonation (large scale)
Rocket-motor test stand (300,000-lb thrust)
Rocket launchers
Gun site
  155-mm
  8-inch

Use

Explosive component testing
  155-mm and 8-inch guns
Earth penetration
Explosive cratering
Rocket testing
System flight tests

Explosive Environmental Testing

Sophisticated environmental test equipment has been developed to test explosive components and systems under acceleration, shock, vibration, and climatic conditions. The purpose of these tests is to establish system or component integrity in the use environment. Specific information on these capabilities is available.* (Items 1-6)**

Instrumentation and Facilities

A variety of modern explosive test facilities is available to support basic and applied research on the characteristics and use of explosives and pyrotechnics. New instrumentation techniques and automatic data-reduction systems have been developed and used to study stress-wave propagation in explosives and non-reactive materials. (Items 7,8)

*Testing (SAND-74-0088), or
Environmental Test Facilities (unnumbered), June 1972
**See Highlights below.

EXPLOSIVES TECHNOLOGY

Explosive Test Sites

Capability

Inside test bays - 3-gram limit
Outside test bays - 500-gram limit
Underground chamber - 900-gram limit
Topside firing site - 22.5-kg limit
Fragmentation pit - 4.5-kg limit
Environmental test chamber
Framing cameras - 5 x 10^6 frames/second
Streak cameras - 20 mm/μsec
Flash x-ray - 3 exposures
Time interval meters - 1-nsec resolution

Use

Experimental investigation of initiation
Detonator performance
Explosive power supply testing
Explosive containment
Explosive output testing
Shaped-charge development
Component development and testing
Accelerated aging

Component Fabrication Facilities

Capability

Automatic explosive loaders
Remote loading presses
Bridgewire and end closure laser welder
Mild detonating fuse draw facility
Remote post-mortem facility

Use

Explosive component development
Pyrotechnic component development

Two-Stage Light Gas/Powder Gun Facility

Capability

20-mm launch tube 0.05 kg at 10 km/s
28-mm launch tube 0.1 kg at 8 km/s
63-mm launch tube 0.5 kg at 5 km/s
89-mm powder gun 2 kg at 2.3 km/s

Use

Hypervelocity single-particle impact physics
Ballistic penetrations
Rain and dust erosion
Internal ballistics
Constitutive equation studies
Phase transformations
Compaction of porous materials
Explosive initiation and detonation

Compressed-Gas Gun Facility

Capability

63-mm diameter, 0.23 kg at 1.7 km/s
101-mm diameter, 0.36 kg at 1.0 km/s
101-mm diameter, 0.37 kg at 0.6 km/s

Use

Constitutive equation studies
Spall and fracture studies
Instrumentation development
Component development

Nondestructive Testing

A complete range of neutron, x-ray, and gamma-ray sources is available for support of explosive and non-explosive radiography requirements. Specialized radiographic equipment such as flash x-ray, DXT, micro-radiography, and 20-40 vidicon cineradiography is available as well as film-reading and density-measuring equipment. Techniques such as ultrasonics, acoustic emission, and laser holography are also available.*

Capability

Neutron radiography
  Annular Core Pulse Reactor (ACPR)
    2 x 10^7 neutron/cm^2 sec
    Collimator ratio 65/1 to 500/1
    Film exposure area 17 x 17 inches
    Explosive limit 250 grams
  Californium-252 source
X-radiography
  5 keV to 10 MeV
  Explosive rated - 23 kg
  Radiation gaging (DXT)
  Portable-source on-site radiography

*A summary of nondestructive capabilities is given in a companion report, Testing, SAND74-0088.

EXPLOSIVES TECHNOLOGY, ELECTROCHEMISTRY AND ELECTROMECHANISMS

EXPLOSIVES TECHNOLOGY

Use

Verify presence of explosive
Density measurement
Inspection of explosive interfaces
Component acceptance
Migration of adhesive

Capability

Ultrasonics
Eddy current
Infrared thermography
Dye penetrants
Flash radiography
Image analysis and enhancement
Laser interferometry

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Aerial Cable Test Facility*

A steel cable suspended across a canyon provides a versatile support 200 metres high for aerial experiments or impact tests. The facility has been used extensively for "pull-down" impact tests in which a rocket sled on the ground is used to increase the acceleration of large items dropped from the cable, and to ensure their impact at a target location (Figure 1). Effective use can then be made of photographic or other instrumentation because it can be accurately located and aimed relative to the impact point. The facility can handle heavy test items (up to 10 tons), can generate impact velocities up to 350 m/s, or allows detonation of explosive charges of less than 15,000 pounds.

The facility was used recently to experimentally determine the impact vulnerability of various explosives in simulated nuclear weapons. A change in explosive formulation from PBX-9404 to TATB, for example, significantly increased the impact velocity required to cause detonation of the explosive charge.

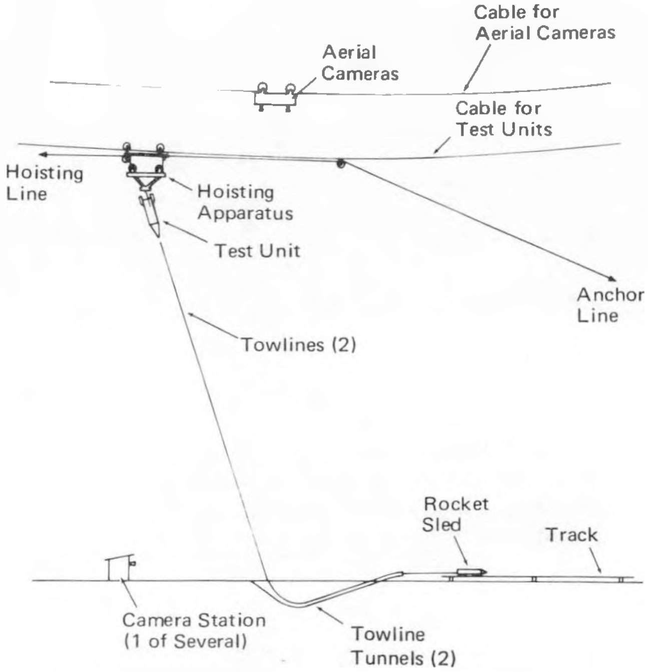

Figure 1. Cable Site

Item 2. *Aerial Cable Site*

The electroexplosive facility (Figure 2) provides a laboratory in which explosive-driven electric generators are tested and evaluated. The two-story structure features an underground vault containing a 600-kilojoule capacitor bank to provide explosive generators with their original current. Experiments are conducted on the outdoor firing pad or in a room where the experiment is protected from the explosion. The explosive generators convert 5 to 8 percent of the explosive chemical energy to electromagnetic energy, allowing pulses of 20 to 30 megajoules.

Instrumentation accessible from both the outdoor firing pad and the experiment room includes high-speed framing, streaking, and time-resolved spectrographic cameras, a three-channel 300-kV pulse x-ray system, 50 data channels and appropriate timing. This equipment may be used with explosive generator experiments involving a maximum of 90 kg of explosive. Experiments not employing explosive generators are also conducted, and may involve up to 200 kg of explosive.

EXPLOSIVES TECHNOLOGY

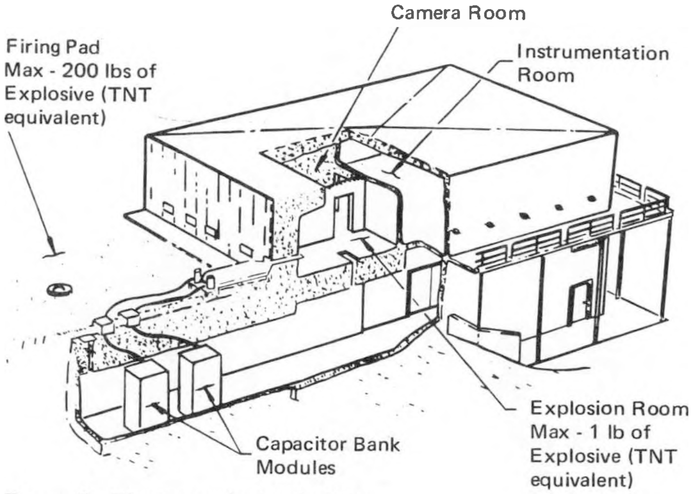

Figure 2. Electroexplosive facility

Item 3. *Rotating Flyer Plates*

Explosives are used to accelerate massive slowly rotating plates to high velocities (Figure 3). The device to be impacted is positioned at a distance along the flight path sufficient to allow rotation of the flyer plate before impact. Any angle between the plate's surfaces and its velocity vector may be obtained. Either metal or plastic plates are used to study impact response against either hard or soft materials. In a recent experiment, 200 kg of explosive was employed to propel an 11-kg plate to 3700 m/s during evaluation of full-scale fuzing hardware. Equipment is available to study impact by use of pulse x-ray or high-speed photographs.

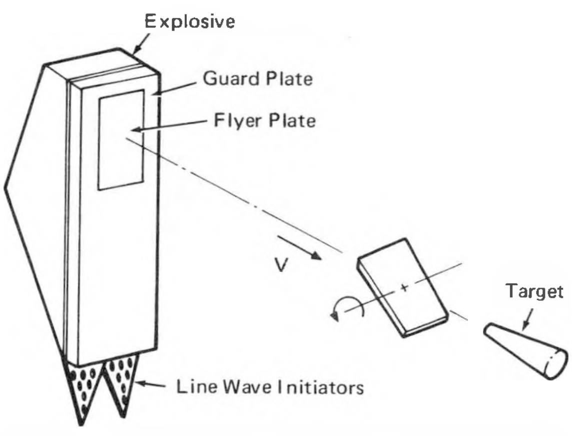

Figure 3. Method for accelerating massive flyer plates.

Item 4. *Light-Initiated Explosives Facility*

A technique for impulse loading has been developed wherein a structure is sprayed with a coating of silver-acetylide/silver-nitrate, a light-sensitive explosive (Figure 4). This explosive has great initiation sensitivity and can be detonated in thin layers. When detonated by an intense light flash, the explosive delivers a pressure load that simulates x-ray impulse effects on a test structure. The technique is particularly useful for experiments involving structures with irregular surfaces or irregular impulse contours.

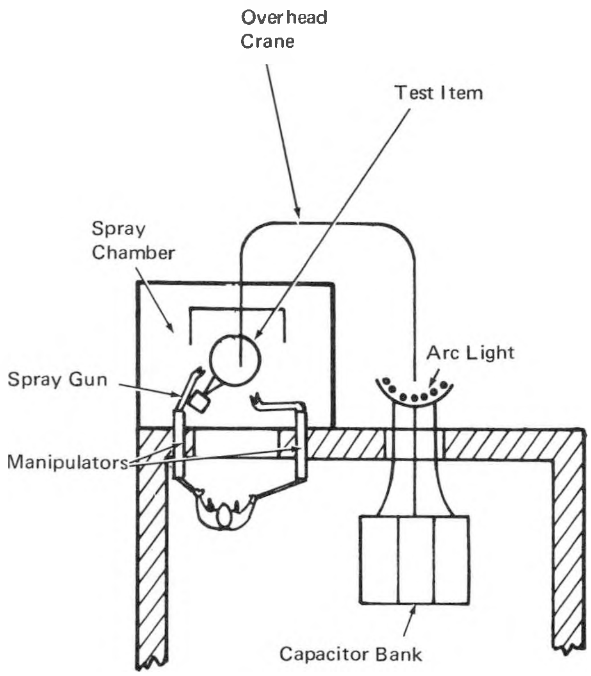

Figure 4. Plan view of the light-initiated explosives facility.

The manufacture, handling, and firing of 2 kg of the explosive are accomplished by remote control. A 1.0-m^2 area may be initiated with a simultaneity of 1 μsec by a 100-kj, 40-kHz capacitor-discharge light source. Impulse levels above 10 Pa·s are achievable, with surface pressures exceeding 100 MPa (Figure 5). Three channels of pulse x-ray and 40 channels of analog signal recording are also available.

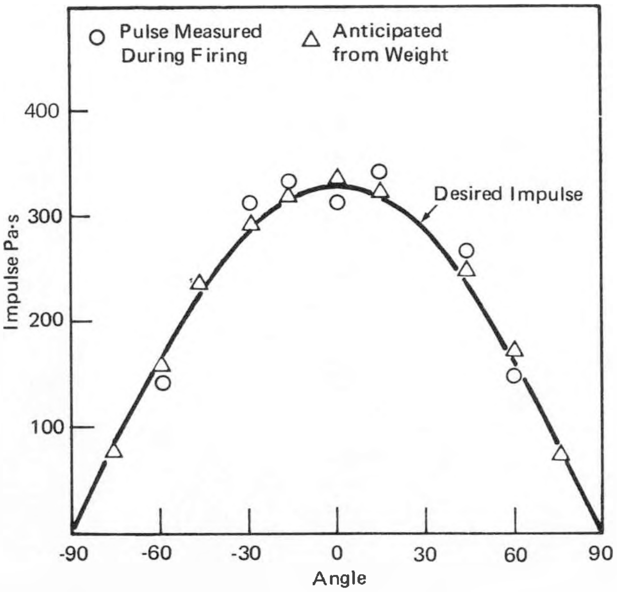

Figure 5. Comparison of impulse measurements to desired impulse for a structural loading experiment

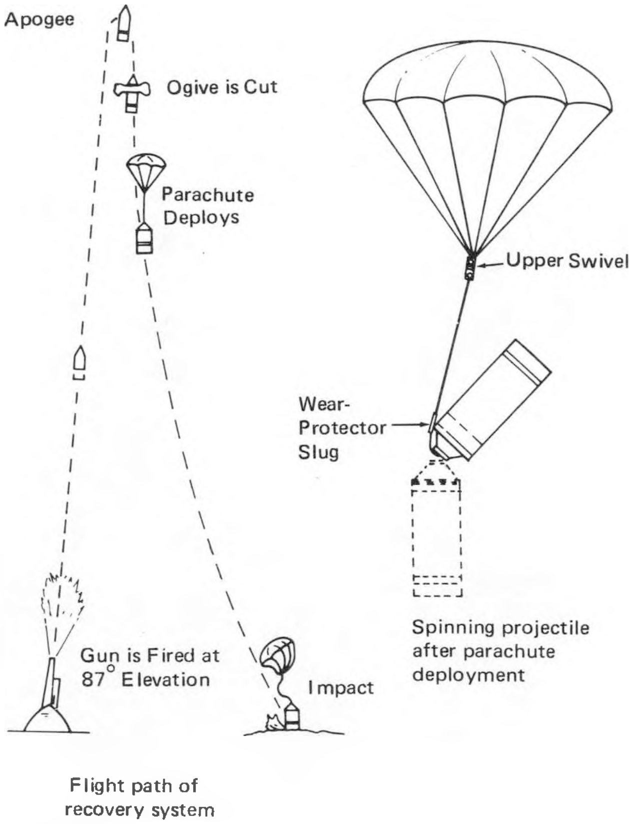

Figure 6. Use of a parachute to recover test projectiles.

Item 5. *Projectile Recovery System*

A new way to recover projectiles fired from 155-mm and 8-inch rifles has been developed (Figure 6). The method consists of attaching a parachute to the forward section of the test projectile and firing the projectile into a nearby vertical trajectory (85- to 87-degree elevation). Three to five seconds after apogee, a mechanical timer initiates an explosive linear-shaped charge that severs the wind screen and deploys the parachute. Swivels decouple the projectile from the parachute, allowing the spinning projectile to be lowered to earth in a base-first attitude for a soft recovery.

Advantages of this method include: (1) easy recovery of the projectile body for analysis; (2) all parachute and landing accelerations are in the same direction as the setback acceleration, but of much smaller magnitude; and (3) the system is compatible with the recovery of RF telemetry data, both while the projectile is in the gun barrel and during flight.

Item 6. *Two-Stage Light Gas/Powder Gun Facility*

This facility, shown in Figure 7 being prepared for a hypervelocity single-particle impact test, can achieve velocities of 10 km/s. The facility includes a 15-m flight range and features precise control of the flight and impact of the projectile. When used for constitutive equation work, impact planarity of flat-nosed projectiles is maintained to better than 1.0 milliradian. Instrumentation includes velocity interferometry, in-flight stereo and holography, flash x-ray, and numerous electronic devices.

4

EXPLOSIVES TECHNOLOGY

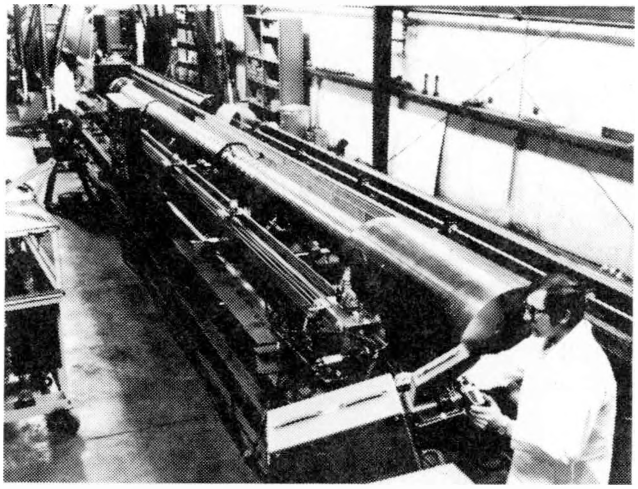

Figure 7. Two-stage light gas/powder gun facility.

Item 7. *Velocity Interferometer Instrumentation*

A velocity interferometer system (VISAR) that can be used with any reflector has been designed and constructed. It will measure surface velocity histories as low as 0.1 mm/μs with an accuracy of 1 percent and a temporal resolution of a few nanoseconds. The system has two separate delay legs of different lengths to eliminate uncertainty in the fringe number at any instant of time. Interference fringe information is recorded on waveform digitizers and data are reduced automatically using a PDP-11, which decreases data-reduction time from 10 hours to two minutes per experiment without loss of accuracy or precision. Figure 8 shows the result of shocking an iron specimen and making use of the 13-GPa phase transition wave. A plane wave lens introduced a 15 GPa pressure wave into a 2.5 mm sample. The elastic precursor (E wave) and phase transformation wave (P1-wave) were separated from the initial loading wave and were recorded at the rear surface. The E and P1 waves agree with previously measured waves, verifying the accuracy and precision of the system.

Item 8. *Calculator-Controlled Data System*

An electronic data-acquisition and reduction system has been assembled for use with tests of developmental components in the explosive dynamics laboratory. The central controller is a programmable calculator. Output devices consist of a page-width printer, a plotter, and a magnetic-tape cassette recorder. A number of data input options is available. Nonrecurring signals in the millisecond, microsecond, and nanosecond range can be inputted to transient recorders and transferred to calculator memory. Two-way communication is possible with a digital multimeter and an electronic counter. Analogs recorded on oscillographs can be entered with an X-Y digitizer. Tabulated data can be entered from magnetic tape or from punched cards. Current applications include analyses of capacitor-discharge firing-set parameters, electrostatic discharge energy, electrothermal response of bridgewire systems, dynamic resistance of bridgewire circuits during activation, and force output of explosive actuators (Figure 9).

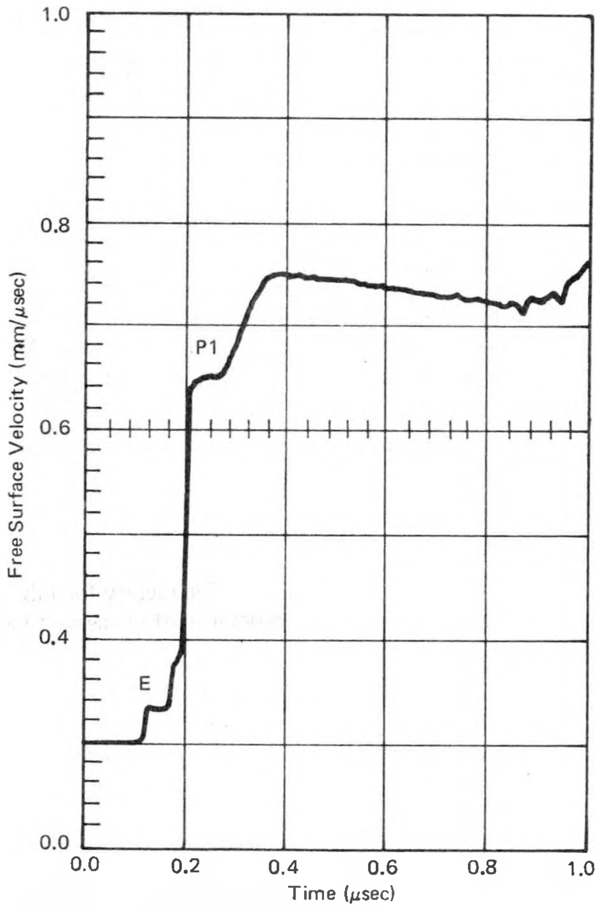

Figure 8. Free-surface velocity.

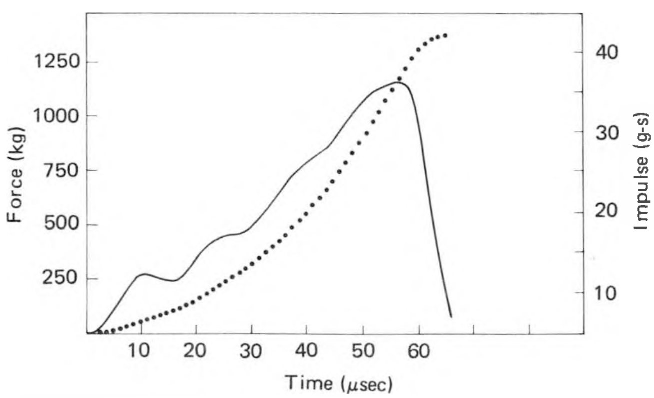

Figure 9. Computer plot of the loading of a test vehicle.

EXPLOSIVES TECHNOLOGY, ELECTROCHEMISTRY AND ELECTROMECHANISMS

ELECTROCHEMICAL POWER SOURCES

Electrochemical, chemical, and thermal studies are directed at obtaining a basic understanding of electrochemical systems and applying this knowledge to new systems, improved power source designs, and more accurate process specifications. Most of these studies are related to thermally activated batteries, which are characterized by the use of a fused-salt electrolyte.

Prototype thermally activated batteries are designed, developed, and tested in a laboratory facility. The results are specifications for a tested, manufacturable thermal battery meeting a specific set of requirements, including high reliability, ruggedness, and durability. Other types of power sources, developed by commercial suppliers, are tested in the laboratory facility. Test results are used to determine the operating characteristics of these power sources and their ability to satisfy requirements for specific applications.

Electrochemistry

Standard electrochemical techniques are used to study electrode polarization and redox reactions. For studies of fused-salt systems, these techniques are modified for use at high temperatures (300 to 1200°C) and for the study of chemical compatibility of materials with fused-salt systems that are extremely reactive at these temperatures.

Current Activities

- Fused salts
- Aqueous electrolytes
- Organic electrolytes
- Solid electrolytes

Studies

- Polarization
- Optical microscopy
- Electrochemical mechanisms
- Electrochemical kinetics
- Single-cell testing
- Ionic and electronic conductivity
- Chemical reactions and kinetics

Physical Chemistry

Characteristic of electrochemical systems, particularly fused-salt systems, are side chemical reactions involving both the original chemical constituents of the system and chemical species generated as products of electrochemical reactions. An understanding of these reactions is necessary not only for calculating such characteristics as battery efficiencies, energy densities, internal heat generation, electrolyte conductivity, and polarization effects, but also for improving battery performance. For the study of fused-salt systems, special experimental techniques are usually required. (Item 1)*

Current Activities

- Chemical mechanisms
- Reaction kinetics
- Phase diagrams
- Surface-tension measurements
- Surface chemistry
- Viscosity measurements
- Thermal analysis

Thermal Analysis

The internal temperature of thermal batteries can range from -54°C in the unactivated state to greater than 600°C when activated. Consequently, designing and understanding these batteries requires thermal characterization of the materials used. This information is then used to calculate internal battery temperatures as a function of time, to compute design parameters, and to select appropriate materials for specific applications. Modified thermocouple techniques are used to measure internal battery temperatures for experimental verfication of theoretical models and as an aid in battery design.

*See Highlights, below.

ELECTROCHEMICAL POWER SOURCES

Current Activities

- Heats of reaction
- Specific heats
- Phase diagrams
- Melting points
- Heats of transition
- Eutectic compositions
- Thermal stability
- Decomposition mechanisms
- Computerized thermal models
- Thermocouple measurements

Facilities

Experimental equipment and a facility for fabricating prototypes are used for the design, development, and testing of thermal batteries and for the testing of other battery systems. Most of the experimental equipment is adapted for the investigation of fused-salt systems.

The facility for fabricating prototypes provides the capability of processing basic chemicals, fabricating and assembling battery components, and finishing with hermetically sealed thermal batteries which are then tested against specific requirements. The facility includes a dry room, which is necessary for handling the hygroscopic materials used in thermal batteries; e.g., calcium and lithium chloride. The dry room is capable of maintaining less than 150 parts per million water content (0.5% relative humidity) at 72°F. (Item 2-7)

Current Facilities

- Experimental
  - Thermogravimetry
  - Differential scanning calorimetry
  - Drop calorimetry
  - Glove boxes (1 ppm O_2, N_2, H_2O)
  - Differential thermal analysis
  - Single-cell testing
  - Hot-stage microscopy
  - Cyclic voltammetry
  - Potentiometry
  - Chronopotentiometry
  - Rotating disc voltammetry
- Analytical
  - Wet chemical analysis
  - Particle-size analysis
  - Electron probe analysis
  - X-ray diffraction
  - Spectroscopy
    - Auger
    - Atomic absorption
    - Optical emission
  - Scanning electron microscopy
- Laboratory Facility
  - Dry room (3000 ft^2, 150 ppm moisture, 72°F)
  - Processing and fabrication equipment
    - Powder blenders
    - Granulator
    - Grinding mills
    - Ball mills
    - Slugger
    - Fusing furnaces
    - 20 to 100-ton manual presses
    - 100-ton automatic press
    - Air curtain hoods
    - Tungsten inert gas welding facility
  - Machine shop
  - Environmental test chambers
  - Automated battery testers
  - Computer-controlled testers

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Basic Studies*

Experimental measurements of fundamental properties are needed for the understanding of battery performance. In one study the 800°C isotherm of surface tension as a function of the composition of the lithium chloride-potassium chloride binary system was determined (Figure 1). The solid curve, representing experimental measurements, is compared with the dashed curve calculated from the Guggenheim-Prigogine theory for this system. Agreement between data and theory is good: the average difference is less than 0.5%. These data demonstrate that this theory is valid for calculating surface tensions for this system and can be used in explaining the mechanism by which this fused-salt electrolyte wet the adjacent anode surfaces.

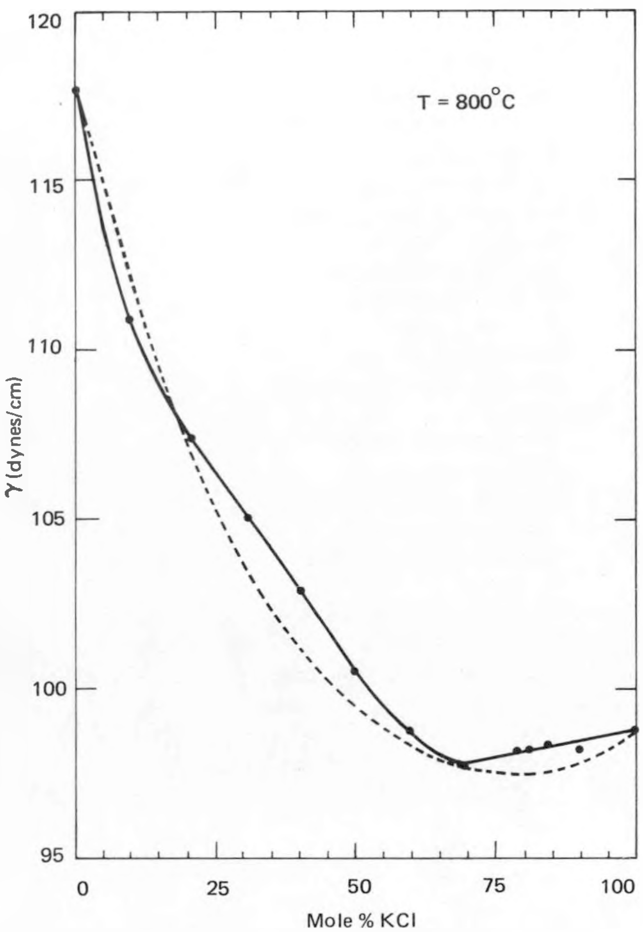

Figure 1. Experimental and calculated surface tension of the LiCl-KCl binary system

Item 2. *Thermal Battery Characteristics*

Fused-salt thermal batteries have proved to be the best source of electrical power for periods up to one hour. They have high reliability, long shelf-life, excellent electrical performance, and a wide range of design capability.

In Table I the characteristics of thermal batteries are compared with those of other commonly used reserve type battery systems. The comparisons clearly illustrate the superiority of thermal batteries for applications requiring up to one hour of operation.

Item 3. *Testing of Other Battery Systems*

When more than an hour of electrical power is required, electrochemical systems other than thermal batteries are considered. These include silver-zinc, nickel-cadmium, lead-acid, lithium (organic electrolyte), mercury-cadmium, solid electrolyte, and magnesium.

The performance of such batteries is tested as a function of storage time, storage temperature, operating temperature, and rate of discharge. These test data are then used to establish battery designs for specific applications.

Item 4. *Types of Thermal Batteries*

The thermal battery lends itself to a wide variety of designs and applications. Characteristics of various thermal battery designs are given in Table II, and examples of the corresponding batteries are shown in Figure 2.

TABLE I

Comparison of Reserve Type Battery Characteristics

	Thermal	Silver-Zinc	Pb-HBF_4	Nickel-Cadmium
Current density (mA/cm^2)	150	150	40	20
Pulse capability (mA/cm^2)	10,000	2500	300	300
Voltage per cell	2.5	1.4	1.5	1.2
Spin capability (rps)	350	NA	400	NA
Activated life	1 hr	days	minutes	days
Reliability	> 0.996	< 0.990	< 0.990	< 0.990
Shelf life (years, loss)	15, 0%	5, 30%	10, 10%	NA
Maximum ruggedness (x gravity)	20,000	2000	20,000	2000
Temperature range yielding 75% of peak capacity (°C)	100	50	110	60
Minimum and maximum ambient operating temperatures (°C)	-200/200	0/60	-40/60	-10/50
Relative cost	X	3X	X	2X

ELECTROCHEMICAL POWER SOURCES

TABLE II

Typical Thermal Batteries

Type of Thermal Battery	Time to Full Power (ms)	Current (A)	Voltage (V)	Life (s)
Pulse	75	50	7	1
Fast rise	100	20	28	5
Power	300	10	28	300
Multivoltage (Note 1)	300	10	-	300
Long life power	750	10	28	3600
High voltage	2000	0.01	500	60
Spin (350 rps) (Note 2)	400	5	28	120
Multipurpose (Note 3)	-	-	-	-

NOTES:
1. Example: 28, 17, 12, 9, 0, -12, -17, and -28 volts ± 10% regulation.
2. Capable of withstanding high angular velocities.
3. Two or more capabilities in one battery. Example: a pulse section to provide power quickly until a power section can reach operating voltage.

General Characteristics: Demonstrated reliability greater than 0.996.
Demonstrated shelf life of 20 years.
Shock capability up to 20,000 x gravity.

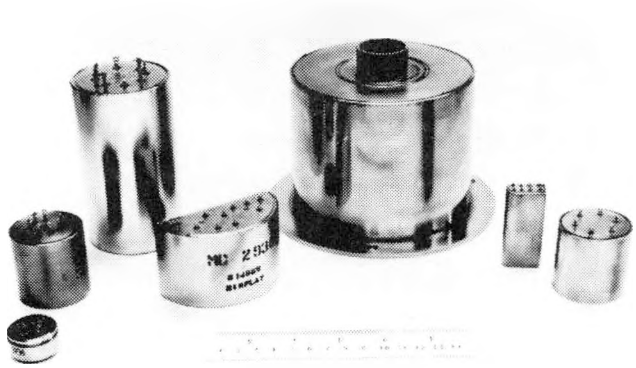

Figure 2. Types of thermal batteries. Clockwise: pulse, fast rise, power, multivoltage, long life power, high voltage, and spin.

Item 5. *Pellet Technology*

Pellets used in thermal batteries are developed in the laboratory facility. Shown on the left in Figure 3 is a pressed DEB pellet, in the center a measured amount of heat powder in a die cavity just before pressing, and on the right a pressed heat pellet. A DEB pellet and a heat pellet, combined with a calcium anode, constitute a complete thermal cell.

The DEB pellet is named for its three constituents: the calcium chromate depolarizer, the lithium chloride-potassium chloride electrolyte, and the finely divided silica binder that immobilizes the electrolyte when molten. The heat pellet consists of a special iron powder as a fuel and potassium perchlorate as an oxidizer. These pellets produce 220 calories per gram and are used to activate a thermal battery by raising its internal temperature to the operating range of 500 to 600°C.

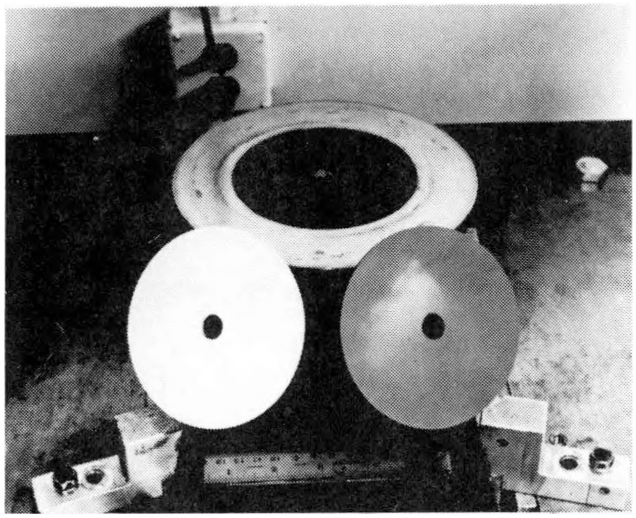

Figure 3. Left to right: A DEB pellet, heat powder ready for pressing, and a pressed heat pellet.

Item 6. *Thermal Battery Stack Assembly and Cutaway Model*

Shown in Figure 4 are a thermal battery stack assembly and a cutaway model revealing how the assembly is encased in insulation and welded into a battery case. The stack assembly on the left is being used to develop a 50-minute power battery. The wires protruding from the stack are leads from thermocouples used to measure internal cell temperatures during battery operation in an experiment. In the model on the right, the dark band running down the center of the cell stack assembly is a pyrotechnic fuse strip, which is ignited by an electrical match in the top of the battery and burns down the side of the stack assembly, igniting the heat pellets to activate the battery.

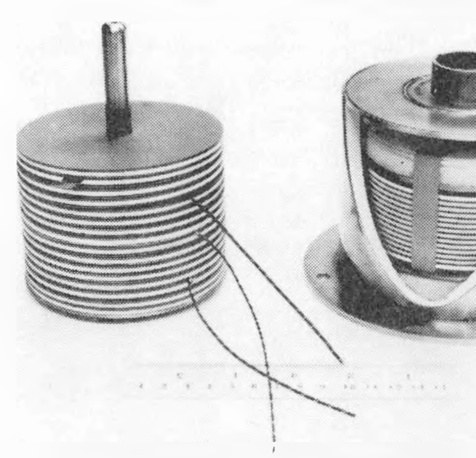

Figure 4. A thermal battery stack assembly and a cutaway model of a completed battery.

Item 7. *Computer-Controlled Battery Testing*

Shown in Figure 5 are the principal results of a computer-controlled test of the 50-minute power battery discussed in Item 6. The battery is connected to a programmed tester that simulates the required load profile, records a high-speed oscillographic voltage trace, and prints out the desired test data which, in this example, are time, voltage, and temperature of the top, middle, and bottom cells of the battery. The tester also converts these data into digital form, which is then fed to a calculator-plotter. The calculator computes several functions, such as operating time to specified cutoff voltages, energy densities, maximum cell temperatures, and coulombic output.

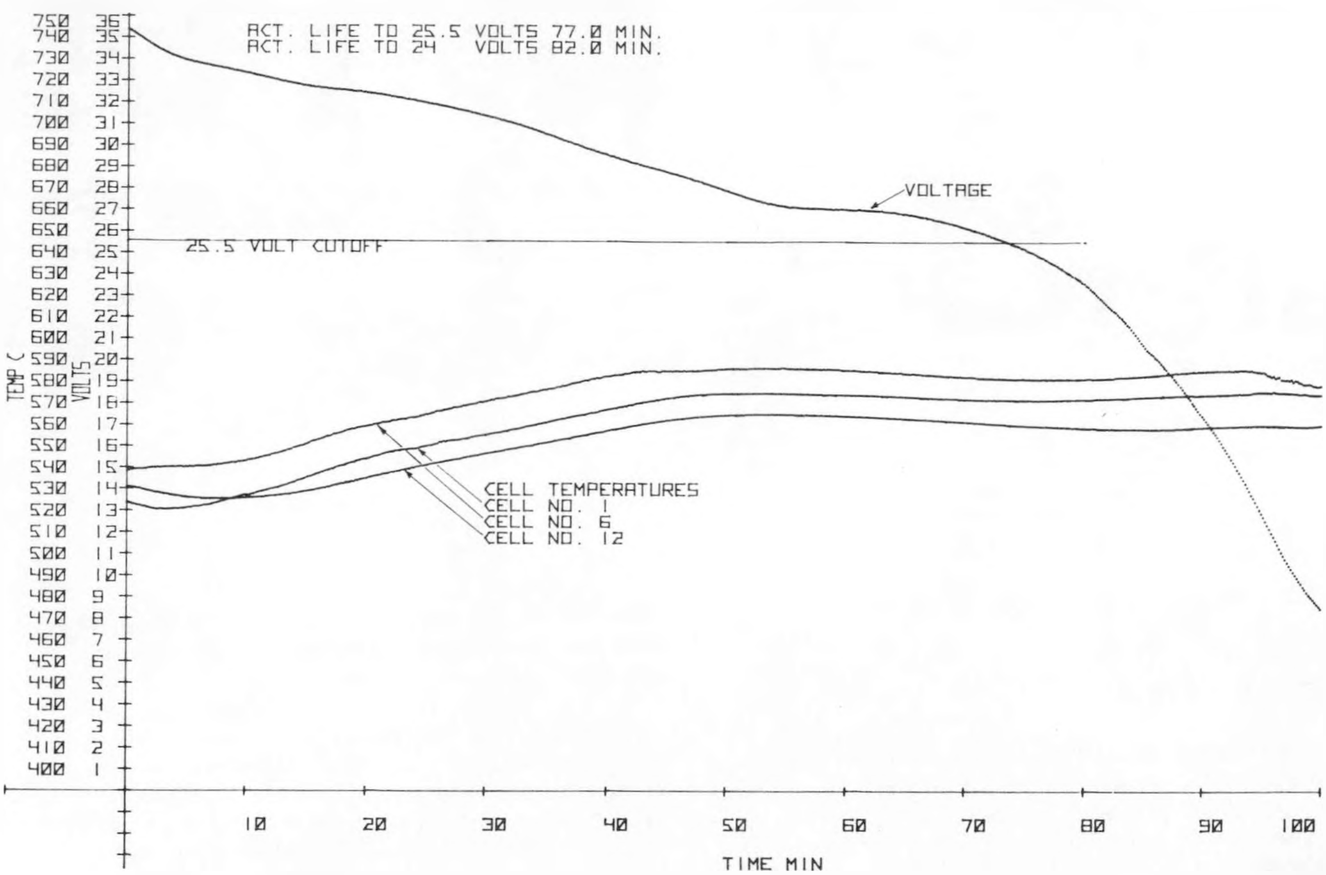

Figure 5. Computer-controlled test data for a 50-minute power battery

ELECTROMECHANISMS

This activity is concerned with the design, analysis, and evaluation of miniaturized, reliable, and durable electromechanical devices used to measure the characteristics of environments, to provide guidance information or control, and to create and respond to simple or complex electrical signals. Mechanisms are analyzed and test equipment is designed. Fabrication and miniaturization laboratory facilities support the activity.

Electromechanisms are devised for a variety of systems that must function in environmental extremes and that have stringent requirements on reliability, safety, and security. Disciplines involved include fluid mechanics, kinetics, dynamics, and electronics. Material and processing studies assure compatibility of materials over long periods and under severe thermal, mechanical, and radiation environments. Prototypes are fabricated in the model shops and are tested in simulated environments or in operational systems.

Environment Sensing

Sensing devices are used to measure the characteristics of such environments as acceleration, pressure, time, and temperature for the purpose of defining physical conditions or controlling the response of a system to its environment. The devices are based on the flow and metering of fluids, the elastic response of materials, and magnetic and electrical effects.

Pressure sensors have been designed and developed to measure absolute and differential pressures. Some designs cause switch closures and others analog outputs. Bourdon tubes, diaphragms, and bellows are the most common prime movers. Temperature sensors have also been developed. (Items 1-3)*

Current Activities

Acceleration
- Fluidics
- Mechanics
- Pressure
- Temperature

Guidance and Control Technology

Guidance and control mechanisms sense environments, and on the basis of that information, generate signals for a prescribed response. The technology is used in both weapons and testing: there are weapon systems whose effectiveness is increased by the addition of guidance mechanisms, and many tests of materials and systems are best conducted in a controlled flight environment where guidance and control are needed. Two major areas of guidance and control are the stable platform and the navigational computer. (Items 4,5)

Current Activities

Inertial systems
Airborne computer systems

Switching Technology

Efficient and reliable electromechanical switches are designed to operate in a prescribed manner even when subjected to adverse environments, but to remain unresponsive to improperly applied stimuli. (Items 6,7)

Current Activities

Trajectory sensors

Timing Technology

Large numbers of timing devices have been developed or modified from commercial items. Escapement-regulated timers are especially versatile. The basic types are verge, cylindrical, or detached lever, powered by springs or solenoids, and with fixed or variable time settings. Their timing range is from 150 ms to 24 hours; they can be actuated manually, electrically, or by explosive squib, and are used to close switches or generate electrical signals.

Pulse counters have also been designed and built that use a rotary solenoid to count pulses from an electronic timer, thus providing large numbers of hard mechanical precisely timed switch closures. (Item 8)

*See Highlights, below.

Analysis of Electromechanical Devices

Analytical techniques are used to design electromechanical components, to determine their reliability, and to calculate their response to adverse environments. Mathematical modeling of electromechanical systems has led to innovative security and protection devices.

Current Activities

Geometry and force analysis
Tuned rotor gyroscopes
Inertial platforms
Security containers

Test-System Development

Test systems are designed and fabricated to evaluate the response of components, subassemblies, and entire designs to environments that include electromagnetic fields, temperature, pressure, acceleration, and vibration. Test systems often are computer controlled to generate environments of interest.

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Acceleration Sensor*

A spring/mass mechanism called Rolamite is used for sensing greatly differing magnitudes of acceleration. The versatility of this mechanism, which was designed and patented by Sandia, is attained through the use of metallic bands of controlled thicknesses, slots of various cross section cut out of the band, and by rollers with selected masses.

An application of this mechanism is to assure the safe operation of artillery projectiles. The safety device (Figure 1) senses the longitudinal and angular accelerations of the projectile. Only if these accelerations are consistent with a prescribed response will the shell be armed.

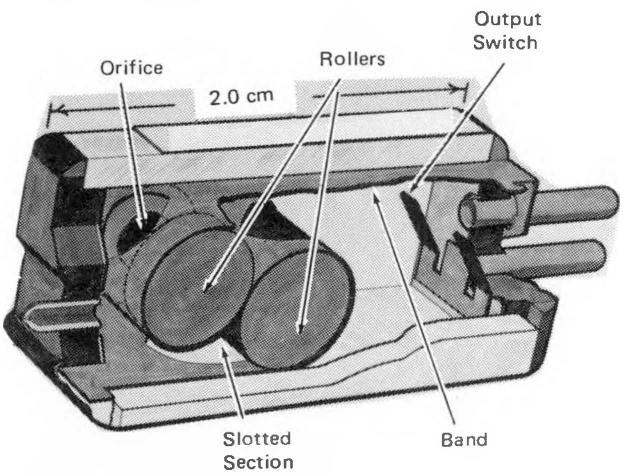

Figure 1. Rolamite inertial switch

Item 2. *Acceleration Transducer*

A force balance accelerometer developed to measure accelerations of ± 250 x gravity is shown in Figure 2. It consists of a precision glass reed (inertial mass) suspended betweeen two stators. The reed is plated on each side, as are the stators, to create an air dielectric capacitor on each side. As the reed is moved by acceleration forces, the capacity increases on one side and decreases on the other. This change in capacity is sensed by electronic circuitry and amplified into an electric current as a function of reed displacement. Also mounted on each side of the reed are coils through which the current is routed. These coils create an electromagnetic restoring force on the reed to move it back to the null position. This restoring force current is routed through a stable fixed resistance which results in a voltage output proportional to the applied acceleration.

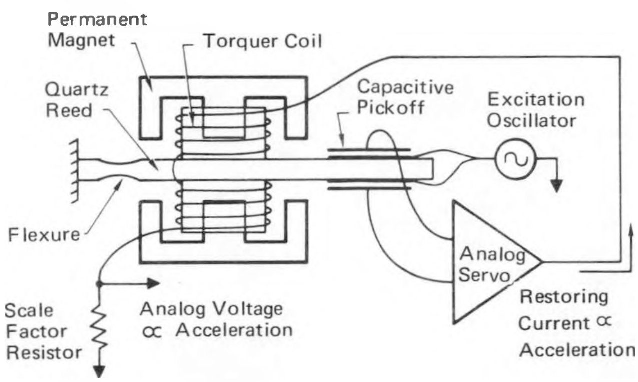

Figure 2. Force balance accelerometer

ELECTROMECHANISMS

The device is used for continuous monitoring of launch acceleration profiles, measurement and control of maneuvering systems, and, by integration, measurement of velocity and distance changes. The range of acceleration measured and the balance between size, complexity, and accuracy are functions of the application.

Item 3. *Pressure Sensor*

An example of a combined temperature and pressure sensor is a pressure switch with an operating point that varies with temperature. The operating point is varied by sealing a reference pressure in the case which acts on one side of an aneroid pressure-sensing element. The nominal operating point is 22 psia at 77°F. At other temperatures, operating pressure varies as predicted by

$$P = \frac{22(t + 460)}{537}$$

The device is used to remotely monitor pressure in a sealed pressurized weapon container. The sloping operating curve reflects a differential pressure that is relatively constant with respect to the weapon compartment pressure, which also varies with temperature. If the system leaks excessively, the pressure drops below the switch operating point, resulting in an open circuit.

Item 4. *Roll-Stabilized Inertial Measurement System (RIMS)*

The RIMS uses a single-axis platform to provide a roll-stabilized base for inertial instruments that measure the attitude and acceleration of a reentry vehicle. The instrument cluster contains three single-axis rate-integrating gyros and three force-balance accelerometers. The gyros control yaw, pitch, and roll of the platform. A potentiometer on the platform gimbal measures the position of the vehicle relative to the nonrotating instrument cluster. Outputs from the gyros and accelerometers are digitized by a converter, whose outputs in turn are processed by signal-conditioning circuitry and telemetered to ground receivers.

Choice of the single-axis platform for the RIMS was based on an analysis of attitude-error propagation during exoatmospheric coning flight. The analysis indicated that single-axis platform attitude error depends on gyro drift, (<1 degree/hour) and on the scale-factor stability of the pitch and yaw gyros (0.03 percent). The resulting attitude error using the single-axis platform was within acceptable limits and approached the performance of conventional multigimbaled platforms. The single-axis platform was selected because its weight was half that of a multigimbaled platform.

Item 5. *Airborne Computer*

A general-purpose digital computer is being developed to provide on-board computation for navigation, guidance, and control of inertially guided systems. It is microprogrammable, i.e., it allows a change in the problem to be solved through software without changing computer hardware. The 16-bit machine can perform arithmetic functions in either a fractional fixed-point or floating-point format in both single and double precision. The computer comprises a central processing unit, a data memory, and an input/output interface.

A microprogrammed control memory operates the overall computational and control circuits. It performs basic arithmetic and logic operations through a set of up to 256 separate instructions.

The data memory is a high-speed read/write random-access memory which stores input data to the computer and also temporarily stores data that is being manipulated by the arithmetic logic unit, or that may later be transmitted to an outside peripheral.

A combined analog/digital and digital/analog converter forms parallel binary words out of analog input to be used directly by the central processing unit or stored in the data memory. Internally generated digital data can also be converted to analog signals for output information.

Item 6. *Fluid-Metering Switch*

Time delays and integrating functions are achieved using fluid-metering devices. An oil-metering acceleration switch (Figure 3) is used to sense missile launch environments. A compression spring holds a piston in the reset position until missile acceleration produces enough inertial force for the piston to overcome the spring preload. As the piston moves, silicone oil is metered through a sharp-edged orifice in the piston and also between the piston and cylinder. Before total piston stroke is reached, normally-open contacts close, followed by operation of a detent mechanism that latches the piston in the actuated position.

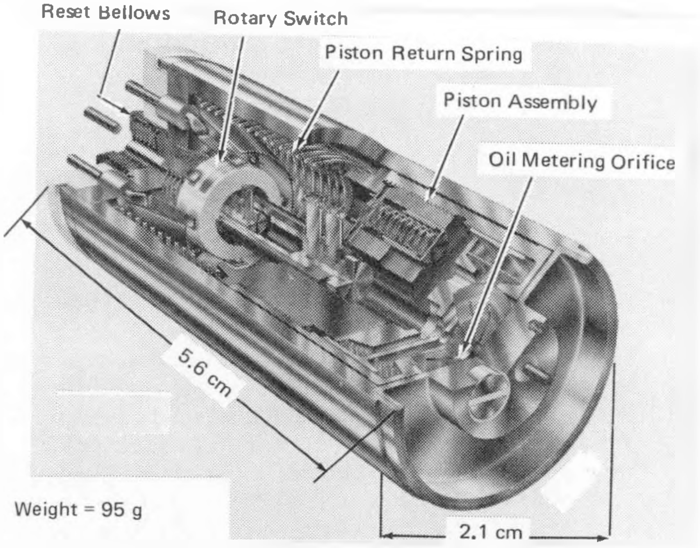

Figure 3. Fluid metering switch.

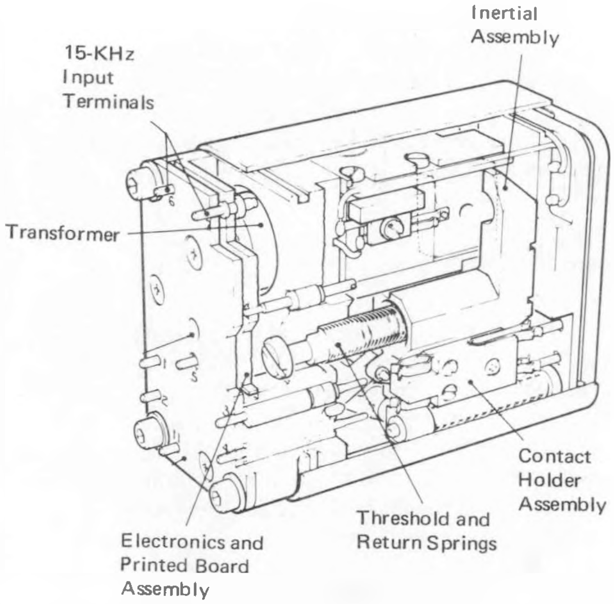

Figure 4. Inertial switch.

Item 7. *Escapement-Regulated Switch*

Verge escapement mechanisms are used to provide delayed action by integrating applied forces over time. These switches are easily actuated by an electrical signal and are relatively insensitive to temperature.

Figure 4 shows an escapement acceleration switch used to sense missile environments. A very rugged solenoid lock is incorporated to eliminate the possibility of the mechanism being operated by abnormal environments. In operation the solenoid lock and bias spring restrain the seismic mass until an electrical signal releases the lock and until acceleration becomes large enough to overcome the spring. Mass speed is then regulated by the verge escapement to which the mass is connected by means of a rack. Switching contacts are carried by the sensing mass and can only close after a minimum acceleration-time product has been achieved.

Item 8. *Timers*

A timer was developed that provides an arming signal at a prescribed altitude for a reentry vehicle without the need for prelaunch time settings. The timer, which works in conjunction with an oil-damped inertial switch, approximately identifies the system reentry trajectory by measuring the time between two prescribed acceleration levels. On the basis of this measurement, the timer operates a switch that arms the system. A schematic of the timer is shown in Figure 5 and an operational configuration in Figure 6.

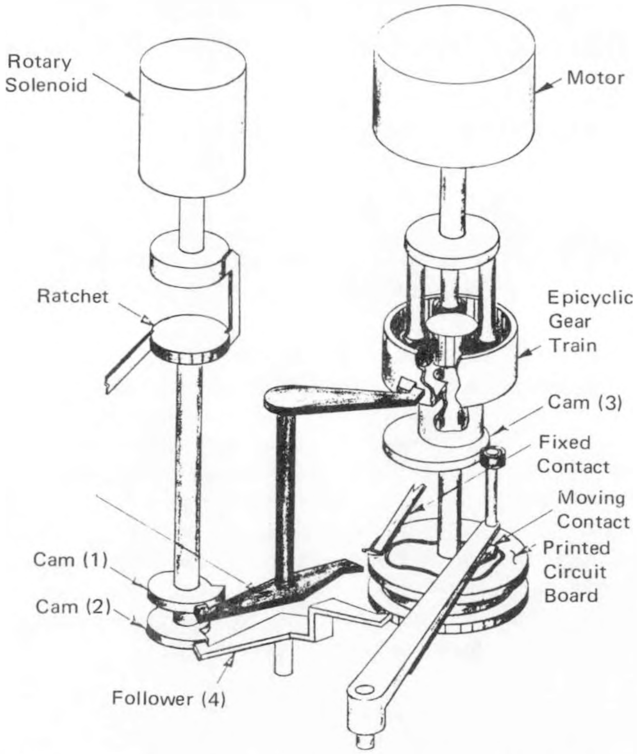

Figure 5. The timing of an arming signal is achieved by sensing prescribed accelerations by an inertial switch. Signals from the switch accuates the rotary solenoid. Depending upon the time between signals, the mechanism closes electrical contacts that arms the system.

ELECTROMECHANISMS

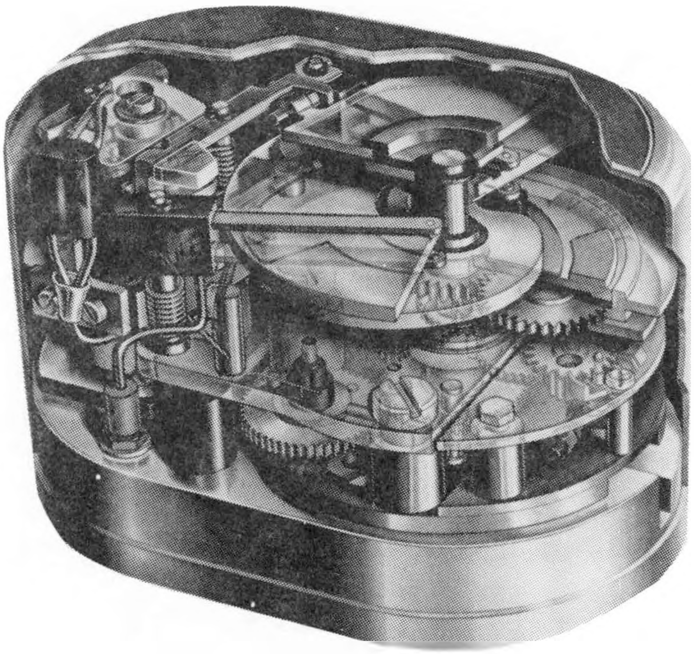

Figure 6. An operational trajectory sensing timer.

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Sandia Laboratories Technical Capabilities

Instrumentation and Data Systems

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115
and Livermore, California 94550 for the United States Energy Research
and Development Administration under Contract AT(29—1)-789

INSTRUMENTATION AND DATA SYSTEMS

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SANDIA LABORATORIES TECHNICAL CAPABILITIES

INSTRUMENTATION AND DATA SYSTEMS

ABSTRACT

This report characterizes the instrumentation and data systems capabilities at Sandia Laboratories. Selected applications of these capabilities are presented to illustrate the extent to which they can be applied in research and development programs.

INSTRUMENTATION AND DATA SYSTEMS*

An extensive instrumentation and data-reduction activity is maintained. Many advanced designs now in development must operate in extreme environments such as those encountered in space, in high radiation fields, or under severe mechanical, thermal, and electromagnetic loads. The instrumentation activity provides instruments that will measure characteristics of the environments, measure responses and performance of materials and systems operating in them, and locate accurately the position of the systems in the environment. To fulfill these tasks, new instrumentation systems are developed and existing techniques modified. Instrumentation is fielded in conjunction with design and testing activities.

Data-processing and data-reduction are integral activities that provide test information in various forms, including charts, graphs, photos, movies, or special forms, depending upon needs.

Instrumentation and Data Systems
Professional Staff and Investment in Equipment

	Professional Staff	Investment in Equipment (in $1000)
Data Acquisition Systems	506	77,054
Transducers		
Communications		
On-board data storage		
Optical recording		
Tracking instrumentation		
Mobile and transportable		
Special Instrumentation	47	2,876
Meteorological		
Photometric		
Quality Assurance		
Radiation Analysis		
Data Reduction Systems	105	9,315
Magnetic		
Optical		

*Compiled September 1975

DATA ACQUISITION SYSTEMS

Data are acquired by subsystems that transform a property of a test item into a recognizable signal, transmit the signal, and receive and record the information for further analysis. The property to be measured is transformed by different kinds of transducers, depending upon objectives and ambient operating conditions. Data transmission from the test vehicle can be immediate or delayed, and transmission media can vary from space to substrata of the earth. Data storage is constrained by availability of power and space in telemetry applications. Optical data recording is concentrated on high-speed, short-duration phenomena.

Besides data-acquisition systems made up of subsystem modules for specific applications, there are tracking systems that remotely measure the dynamic motions of test objects, and both mobile and transportable instrumentation carriers are used in remote regions.

Transducers

The purpose of a transducer is to detect a measurable property and to transform its signal into a measurable form. Transducers are used to measure the test environment or the response of a component or system to that environment, or to control or monitor the function of a system. Some transducers are selected for their ability to survive and operate in severe mechanical environments in which high-level short-duration forcing functions are produced. Others are selected because they operate properly in combined environments; e.g., severe thermal, radiation, and electromagnetic fields. The accuracy of a transducer is determined by the Primary Standards Laboratory.* (Items 1-7)**

Measured Parameters

- Force
- Heat flux
- Humidity
- Position and derivatives
  - Angular
  - Rectilinear
- Pressure
- Radiation levels and rates
  - Alpha
  - Beta
  - Gamma
  - Neutron
- Strain

*See "Measurement Standards," SAND74-0077.

**See Highlights below.

Transducer Types

- Force balance
- Light-sensitive diodes
- Magnetostrictive
- Piezoelectric
- Potentiometric
- Variable reluctance
- Variable resistance
  - Metallic
  - Semiconductor
- Thermocouples
- Linear variable differential transformers
- Linear velocity transformers

Capability for Primary Standard Calibration

- Acceleration
- Flow
- Humidity
- Length
- Mass
- Pressure
- Radiation sources
  - Alpha
  - Beta
  - Gamma
  - Neutron
- Temperature

Communications

Radio frequency (RF) communication systems transmit data or commands from or to remote instrumentation. RF systems are used for both atmospheric and underground communications. High reliability is emphasized in their design. These systems can be hardened against ionizing radiation of 10^{12} rad (Si)/sec and mechanical shock of 20,000 x gravity for 12.5 milliseconds (half sinewave). Most components are temperature-hardened to 150°C.

Hardwire communication systems provide capability for relatively nearby data measurements. Hardwire channels are simple and, over short distances, less costly than RF channels. They are usable in static as well as high-shock, high-velocity environments. Where distance permits, sensors on a rapidly accelerating test vehicle are connected directly to stationary data-recording systems by hardwire. Hardwire connections are extensively used where data must be collected before a damaging shock environment generated by the test reaches the cabling, as is characteristic of underground nuclear testing.

Combined hardwire and RF channels are useful in penetrometer research where an antenna remains on the surface as the penetrator executes its underground or underwater trajectory, connected by wire to the antenna. (Items 8,9)

Current Development Activities

Impact velocity
Radio transmission through earth
Relay transmitter with message storage
Space position of multiple objects

On-Board Data Storage

On-board storage makes it possible to retain data that cannot be transmitted in real time. On-board storage must function in and survive the same severe environments as other data-acquisition subsystems and also withstand the environments encountered by the carrier. Information packing density must accommodate the quantity of data to be stored in the space available. These storage units will collect data at a high rate and play it back at a lower rate. In other applications, readout awaits location or physical recovery of the on-board storage unit. Suitable nonvolatile or low-power volatile memories are sought, together with compatible logic and long-life power sources. Continual development is necessary to improve these parameters. Data capacity of typical units ranges from 14,000 to 500,000 bits. (Items 10–13)

Current Techniques

- In use
  - Volatile high-density memory
    - Integrated-circuit shift registers
  - Nonvolatile medium-density memory
    - Plated wire
    - Twister
- Under investigation
  - Nonvolatile high-density memory
    - Bubble
    - Ferroelectric

Optical Recording

High-performance optical recording is used to obtain scientific data. For recording purposes, special-purpose cameras, processes, and techniques are developed as needed when commercial items are not available. Capabilities include capturing one pictorial dimension as a function of time to deal with high-velocity particles (streak camera), capturing a high-resolution image of an object traveling at a very high velocity (image-motion camera), and capturing high-resolution images of short-duration events (image-dissection camera, framing camera, and stroboscopic-mode video systems). Where illumination can be controlled, high-intensity light sources are developed to meet requirements of specific rise times, durations, and quench times (spark sources, gas discharge, and flash systems). Where illumination is low, image-intensification techniques are used to aid both video and film optical recording; an application is in magnification up to 15 power. Capability exists for aerial and underwater optical recording, on film and in video. Optical data can be recorded in all but the most adverse environments.

Equipment is being developed to increase realizable frame rates above the present capability of 20×10^6 frames per second so that better resolution can be obtained of high-speed or short-duration events. Computer analysis is being used to advance the state of the art in cameras, lens elements, and other optical-system designs, and optical tracking situations are simulated to permit optimization of instrument application. (Items 14–15)

Current Techniques

- Holographic high-density data recording
- Framing camera
  - Rotating mirror (to 3×10^5 frames/sec)
  - Proximity focused (5×10^8 frames/sec)
- Image-dissection camera (to over 1×10^7 frames/sec)
- High-intensity light sources
- Rotating-mirror streak-framing camera (100 mm/ms)

Current Applications

- Computer analysis
  - Lens design program (IBM 7090)
  - Optical tracking simulation
- Solar aureole; apparent radiated energy

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Tracking Instrumentation Systems

Tracking a target to obtain trajectory and other engineering data is the purpose of several types of instruments, both mobile and fixed. Much of this instrumentation is at the Tonopah Test Range in Nevada; however, some is mobile for test support at various locations. Most of the capability is oriented to atmospheric trajectories obtained by radar, laser tracker, cinetheodolite, and Doppler systems. Computer analysis of test plans by optical-tracking simulation helps optimize the use of optical instrumentation. Other engineering information is obtained by telemetry ground stations or Newtonian telescopes which also track the target. Sandia develops or modifies tracking mounts and optical systems to meet the needs of the project. Underwater trajectories are traced by hydrophone networks. (Items 16-21).

Current Techniques

- Laser tracker
  - Control of remote tracker
  - Control of remote cameras
  - Control of target
  - Real-time position and velocity measurement
- Radar
  - Range measuring improvement

Mobile and Transportable Instrumentation Systems

Mobile instrumentation systems are essential to the investigation of interactions between systems and the atmosphere or the geomagnetic field. It has been necessary to measure in-situ parameters, inject tracer materials, and assess system performance over a wide range of altitudes and other test conditions. Tests are conducted where support facilities are minimal in such remote areas as the high seas, underwater to 1200 meters, multicanopied jungles, deserts, the Arctic ice cap, glaciers, islands, high altitude terrain, endoatmospheric regions above 15,000 meters, and subterranean regions. Instrumentation test beds include rocket payloads, artillery shells, earth penetrators, balloons, aircraft, trailers, and easily transportable systems that can be handled as baggage for shipment. (Items 22-27)

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Tunable Dye Laser for Isotopic Atomic Spectroscopy*

Isotopic atomic spectroscopy is used as a diagnostic tool in transient conditions to measure trace constituents in vacuum tubes. They can be measured at such low concentrations as 10^6 atoms sampled. Experimental measurements of trace constituents in the atmosphere by remote monitoring, and isotopic trace-level determinations of the effluent of nuclear fuel-processing plants are under way.

A variety of pumped-dye lasers has been developed for these applications. Techniques for producing ultra-narrowband tunable dye lasers have been established for different dyes, permitting operation over the visible spectrum (0.4 to 0.9 micron), which encompasses almost all atomic absorption lines. Techniques for precise wavelength measurement as well as stabilization of the laser oscillation frequency have been reduced to routine procedures.

Item 2. *Well-Logging*

A feasibility study has recently been undertaken to determine the possibility of using pulsed neutron sources for logging exploratory uranium bore-holes. This involves the measurement of epithermal neutron decay of the scintillator signal resulting from the detection of epithermal [energy $>(1/40)$ eV] neutrons as a function of increasing time.

Item 3. *Instrumentation for In-Situ Fossil Fuel Processing*

Instrumentation and process controls are being developed for in-situ processing of coal, oil shale, and other fossil fuels. Recovery of energy from fossil fuels by in-situ processes generally involves burning a portion of a carbonaceous deposit in its natural underground location to provide heat for converting coal to gas and liquids, oil shale to oil and gas, and heavy oils and tar sands to pumpable oils.

Instrumentation sensors and measurement techniques are being evaluated in an in-situ coal-gasification experiment (Figure 1) and will be extended to in-situ oil shale processing. An objective is to develop techniques to monitor the burn front including the development of sensors capable of detecting the front from a considerable distance.

Sensors are being used on the surface and at various depths in 18 instrumentation wells near Hanna, Wyoming. Instrumentation includes thermocouple arrays, surface and subsurface resistivity probes, geophones, in-seam gas-sampling systems, and gages to measure tilt and displacement of the overburden near the coal seam.

Ready detection of the burn front is an important element in the in-situ gasification scheme since it will permit injection of air and oxygen at the right place and time, thus helping to maximize gas recovery.

The ultimate objective is to develop an integrated process-control system. This involves developing detailed diagnostic information on the chemical and physical mechanisms involved in combustion, sensors for monitoring all relevant combustion factors, and a computerized data-acquisition and analysis system.

Item 4. *Ablation Detector*

To permit determination of the amount of material ablated from reentry vehicles under various conditions, a nose cone is seeded with very small Ta^{182} gamma sources precisely positioned within the material along a line where erosion is expected.

During flight, as these sources are removed by aerothermal ablation or rain erosion, the gamma level is reduced. A gamma detector, positioned near the gamma sources, senses the removal of each source. The detector output voltage level corresponds to the intensity of the gamma flux and diminishes abruptly as each gamma source is removed. The resulting analog signal is processed and transmitted to the ground station where it is recorded in real time. When the known source positions, their removal time, and the rocket flight information are correlated, a material-removal history is obtained (Figure 2). The system has also been used to measure sidewall ablation on a heat shield.

Item 5. *Electro-Optic Accelerometer*

For determination of the decelerations of objects hitting concrete barriers at high velocities, commercial accelerometers are adequate but must be calibrated. Optical interferometry with electronic delay differentiation is used. Test accelerometers are subjected to a half sine wave of acceleration in the range from 10,000 to 100,000 x gravity peak, with time to the pulse peak from 60 to 1500 microseconds. These transient accelerations result from electromagnetic repulsion between a pulsed current in a drive coil and induced currents in the metallic driven element on which the accelerometer is mounted. The primary electro-optic accelerometer output is the maximum acceleration ±3 percent, determined as the average acceleration over a window of approximately 1 microsecond. The system also outputs the analog representation of the upper half of the acceleration pulse shape. The accelerometer is useful, for example, in weapon ground-burst applications and in evaluation of structural loading by tornado-driven objects.

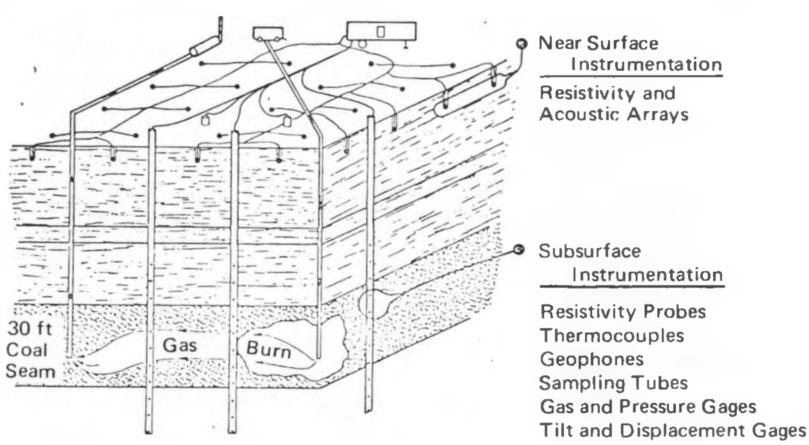

Figure 1. Instrumentation and process-control development for in-situ coal gasification

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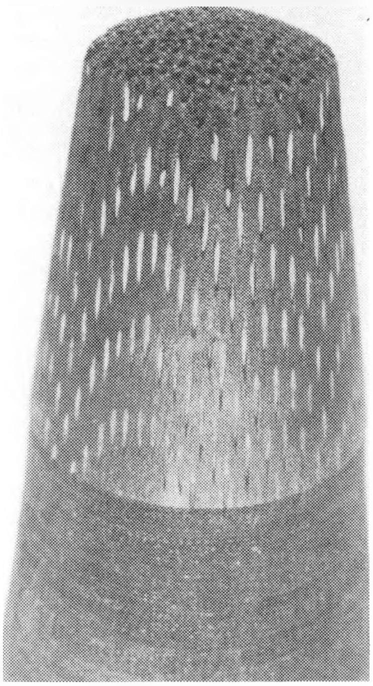

Figure 2. A nosetip after flying through rain clouds at 3200 meters/second

Item 6. *Pulsed Neutron Detector*

A device was required that would provide the health physicist a direct measurement (in REM —roentgen equivalent man) of single or multiple short bursts of neutrons. A detector was developed which provides a pulse counting system capable of being carried by one person. The equipment has been calibrated with pulses as short as 7 x 10^{-6} sec and has a sensitivity as low as 5 x 10^{-5} REM.

Item 7. *Radiation Dosimetry*

ERDA requires that employees likely to receive a radiation dose in any calendar quarter in excess of 10 percent of published standards must be radiation-monitored. A personnel radiation dosimetry program has been developed that provides this coverage for beta, x-ray, gamma, and neutron exposures over wide energy ranges and exposure levels.

The system used for routine (nonaccident) situations utilizes a thermoluminescent dosimeter that is automatically evaluated and identified. Its association with the user is done by computer as are data reducing, record keeping, and report generating functions.

Activation materials have been added to some dosimeters to extend the capability of the system when required. Doses may be measured from low environmental background levels of 10^{-2} REM to levels associated with severe accidents (10^4 to 10^6 REM).

Item 8. *High Shock Environment Telemetry Communication System*

Telemetry for artillery projectiles and earth penetrators (Figures 3 and 4) must function during and after exposure to high shock. Not only must the instrumentation operate during the severe environment, but the data must be recovered after the vehicle has penetrated as much as 50 meters of earth. Shock-hardened components have been developed out of which telemetry systems are fabricated to meet the requirements of a particular mission. Telemetry packages as small as 5 cm in diameter and 35 cm long are now possible. The number of time-multiplexed data channels ranges from 1 to 78. A typical system operates in environments of longitudinal shock of 16,000 x gravity peak with a duration of 12 milliseconds; angular acceleration of 325,000 radians/second^2 peak concurrent with angular velocity of 1700 radians/second; and temperatures from -40°C to +80°C.

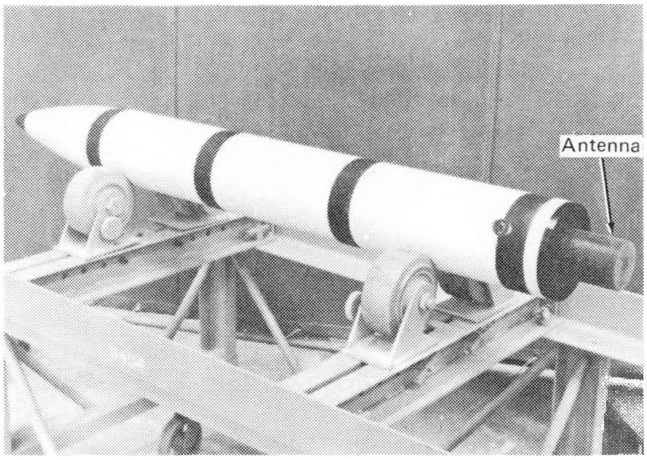

Figure 3. Penetrator with antenna

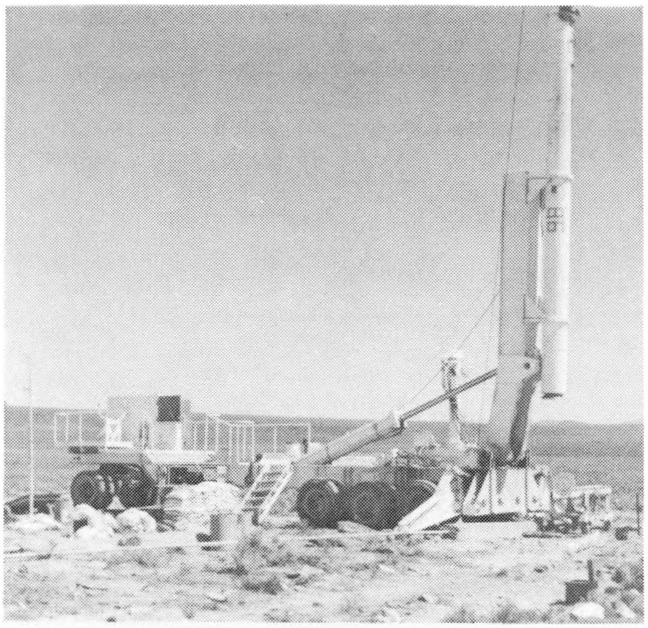

Figure 4. Gun used for earth penetrator testing

The capability has been developed to provide communication to the surface from a transmitter buried 50 meters in earth. Its application is prompt determination of stored data from penetrometer research vehicles without physical recovery (Figure 5). A companion downlink (surface-to-underground) is being developed that can both turn on a quiescent buried transmitter and turn it off again. The downlink will increase the amount of recoverable data or the number of times over an extended life that buried sensors can be interrogated. The chief downlink design constraint is 100 watts maximum transmitter power.

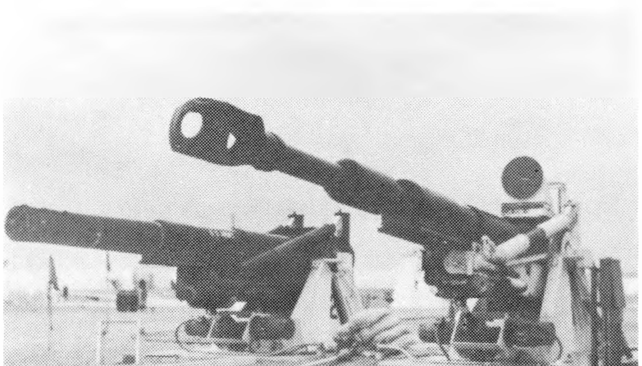

Figure 5. Artillery cannons for high-shock testing

For the uplink (underground-to-surface), a rate of 1000 bits per second with a rate of less than one error in 100,000 bits has been achieved from a depth of 52 meters using 10 watts in a pulse-code-modulated/frequency-modulation system operating at 10.5 kHz, a standard Inter-Range Instrumentation Group (IRIG) frequency. Transmission lasts from 30 to 40 minutes. The transmitter package is 10 cm in diameter. The design has been optimized for the range of soil conductivity found in the continental United States.

Item 9. *Remote Observation Post*

The U. S. Marines needed to obtain data about movement of enemy equipment and personnel at remote locations where it would be extremely dangerous to have listening equipment manned. Sandia developed a system to collect, time-tag, and store data from numerous remote seismic sensors and to retransmit the stored data on command from a remote interrogating station. The system can discriminate between troop movements and vehicular traffic. Storage capacity is one-half million bits or approximately 45 thousand messages. Unattended operation for over one month is possible. The system is designed for one-man portability and installation, and can be packaged or airdrop installation.

Item 10. *155-mm Artillery Shell Application*

Several encoding and memory systems have been developed for use in the 155-mm artillery shell, where they must withstand 20,000 x gravity when the shell is fired. An in-barrel pulse-code-modulation data encoder contains 36,000 bits of memory and collects data for approximately 200 milliseconds while the shell is in free flight. High densities of data storage are obtained using integrated-circuit shift registers as serial memories. 1024-bit registers are connected into chains which receive serial digital data. When the chain is filled, the output of the last register is connected to the input register and the data are recirculated. The system also collects in-flight data and transmits it in real time with the stored in-barrel data.

Item 11. *Bubble Memory Technology*

Bubble memory technology has been developed for use in penetrometers and other systems. In magnetic bubble memories, digital information is stored as cylindrical domains which exist in thin films of certain magnetic materials–for example one of the magnetic garnets. This technology takes advantage of the unique properties of nonvolatility and

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radiation resistance possessed by such devices. These properties, in combination with low operating energy requirements, ruggedness, and very high bit packing density (10^6 to 10^8 bits/cm^2) allow magnetic bubble memories to overcome many of the problems of earlier memory systems. A nonvolatile memory can retain information after power ceases to be supplied to the unit and is advantageous for penetrometer on-board data systems. In this case, a limited power source means short operating life so that the possibility of a quiescent operating mode for a penetrometer data system allows some combination of longer useful life, increased data capacity, or greater functional flexibility. Radiation-resistant memory is required for close-in placement of diagnostic data systems in underground nuclear testing.

Item 12. *Self-Contained Environment-Measuring Systems*

To serve as backups for obtaining data very near underground nuclear shots, self-contained environment-measuring systems have been developed. One of these is a plated-wire 196,608-bit random-access memory used in a digital recording system for a 55,000-kg steel canister. A memory-controlled pulse-code-modulation encoder converts input analog data channels into a serial bit stream that is broken into 24-bit words and loaded into the plated-wire memory. The encoder can retrieve information from the memory and retransmit it, or the data can be retrieved by laboratory test equipment.

Another self-contained system is the piggyback "twistor" memory which, in its present configuration, is organized as 1024 words with 14 bits/word. Piggyback twistor is a type of magnetic memory where information is written into it electronically and will remain in memory indefinitely without any holding current required. The twistor memory and its 6-channel data-encoding electronics are contained in a steel canister 23 cm in diameter and 91 cm long which is buried near underground nuclear shots.

Other nonvolatile memories are being investigated, such as ferroelectric arrays that are low-power, small, radiation-hardened, and compatible with the voltage levels of digital integrated circuits.

Item 13. *Sea-Ice Penetrometer Telemetry System*

A penetrometer was developed for the U. S. Coast Guard to remotely measure the thickness of sea ice. Implant characteristics are shown in Figure 6. An accelerometer in the penetrator senses deceleration as it passes through the ice, and the data are transmitted in real time to a receiver in the aircraft used to drop the penetrator. Two integrations of the deceleration-versus-time curve give velocity and depth profiles (Figure 7). By noting penetration depth when deceleration approaches zero, indicating that the penetrator is entering the water below the ice, ice thickness is determined within ±7 cm. Ice thicknesses of up to 3 meters can be measured.

Item 14. *Solar Aureole Radiation Measurements*

Solar photography systems have been developed, including processing chemistry for producing wide-latitude negatives, to directly photograph the sun and surrounding sky to quantitatively determine the apparent radiated energy of the solar aureole under various cloud conditions and sun positions (Figure 8). The data-reduction method uses sensitometry (a technique for measuring the density variations of photo-resistive materials caused by their response to incident energy) to read the wide-latitude negatives, which may have a density variation of up to six orders of magnitude.

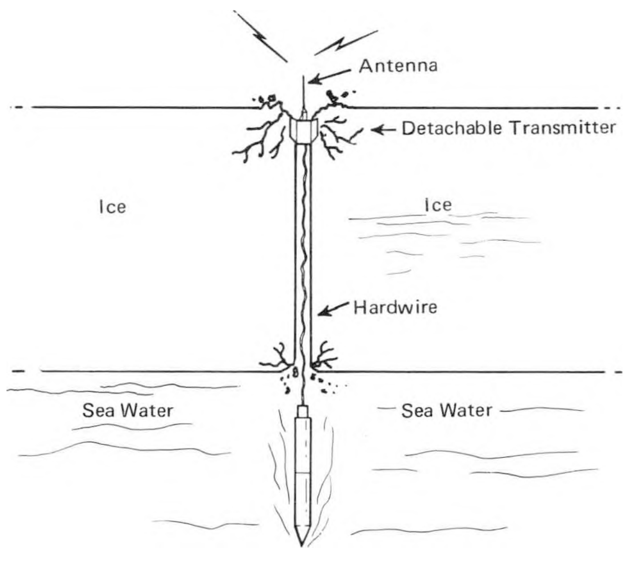

Figure 6. Sea ice penetrometer during penetration

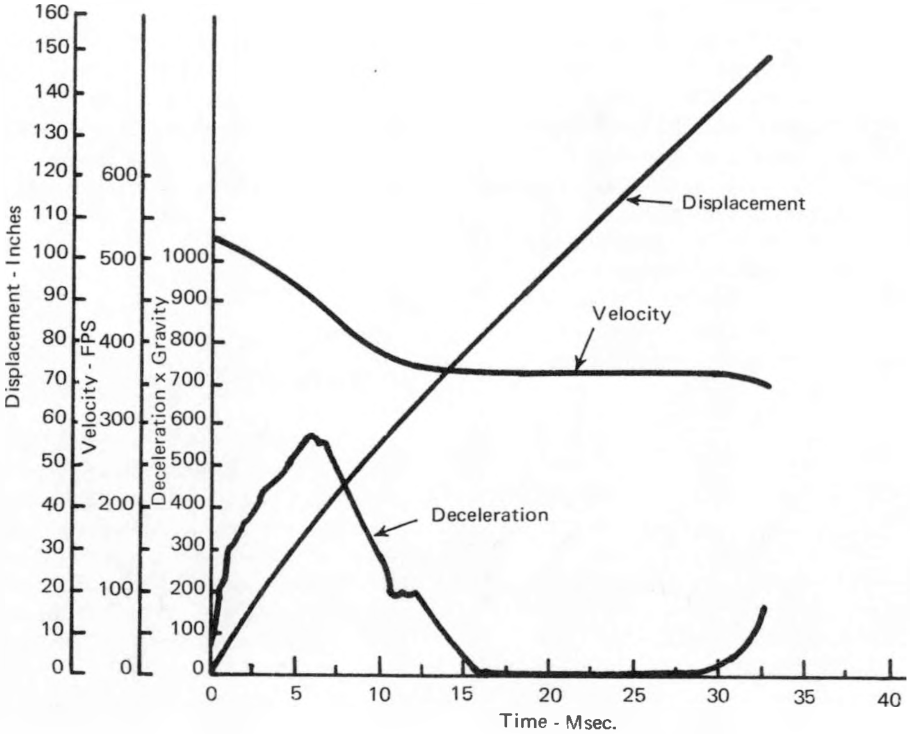

Figure 7. Typical plot for sea ice penetrometer

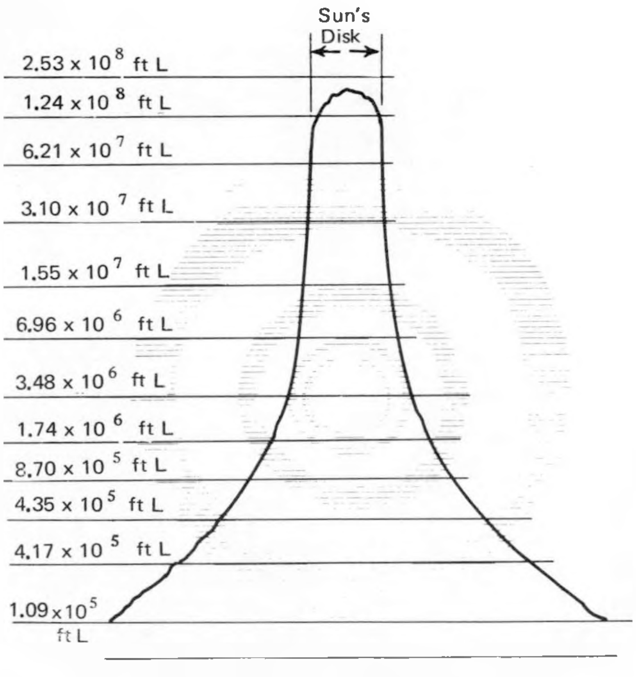

Figure 8. Analog plot and isodensity trace in foot-Lamberts (ft L) of a photograph of the sun taken on an overcast day

Item 15. *Holographic High-Density Data Recording on Reusable Media*

A method is being developed to achieve high-density data recording on an erasable, reusable medium. Holographic recording in the desired format at a repetition rate of up to 500 kHz using optical light guides has been demonstrated in the laboratory. Typical optical pulses are 10 to 50 nanoseconds in duration. Recording, erasing, and re-recording of holographic data on reusable thermoplastic materials has also been demonstrated in the laboratory. These techniques could be used where space is at a premium, as in a satellite.

Item 16. *Cinetheodolites*

A required characteristic of a class of shells or bombs is the consistency of the ballistic trajectory. To minimize the number of tests required to demonstrate this characteristic, an accurate trajectory-measuring system is necessary. Cinetheodolite tracking systems obtain such high-accuracy trajectory data. Tracking is manual after the target has been acquired by radar. Data, recorded on film, consist of the target image on which are superimposed cross hairs that locate the optical boresight axis and the numerical azimuth

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and elevation of the mechanical boresight axis. A network of nine Contraves Model C cinetheodolites obtains trajectory information on targets requiring accuracies exceeding radar capability. The cinetheodolites are located along the main flight path at Tonopah Test Range. Three units are movable to any of several prepared pads to provide as nearly ideal geometry as possible for any given test. These movable units are equipped with radio-frequency communication and timing systems; the fixed units are linked to a land-line system. Frame rates available are 5, 10, and 20 pictures per second with either black and white or color film (Figure 9).

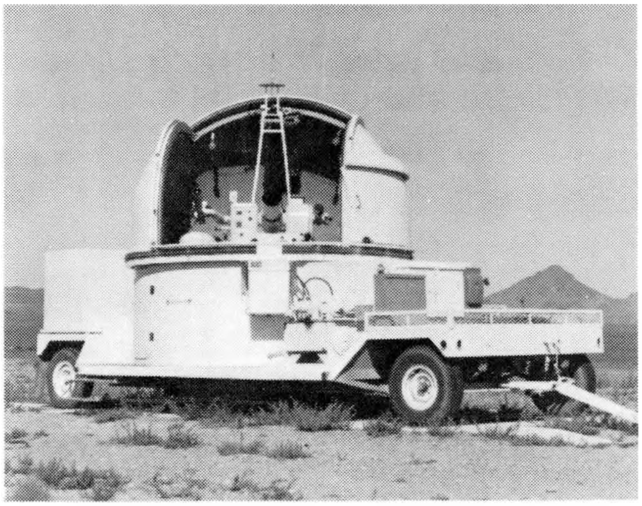

Figure 9. Mobile Contraves cinetheodolite

Item 17. *Laser Tracker*

The requirement for obtaining detailed pictures and accurate trajectory data on highly dynamic targets led to the development of a laser tracker (Figure 10). The laser illuminates the target, and the receiver optics projects the return spot on the optical receiver where it is centered. A shaft encoder on a gimballed mirror records azimuth and elevation angles. Range information is obtained by modulating the laser beam with a continuous-wave signal and measuring the phase shift.

The tracker is used to record trajectory data on rocket sleds and small free-flight missiles. Time-event photography of high-velocity flights occurs at rates as great as 400 frames per second on color film and 800 frames per second on black and white film. System resolution of trajectory information is 0.1 milliradian in both azimuth and elevation, and 0.75 meter in range. Tracking range extends to 6 kilometers for a "cooperative" target carrying 1000 square centimeters of Scotchlite, or to 12 kilometers if the target carries a glass corner-cube reflector. Slew rates and accelerations are 3.3 radians/sec and 2.0 radians/sec^2, respectively.

Item 18. *Radars at Tonopah Test Range*

Five radars at Tonopah Test Range provide target acquisition, trajectory data measurement, test-vehicle recofery data, and range safety (Figure 11). As target-acquisition systems, radars transfer their data to a system which calculates a parallax correction for all other tracking systems at the range having mounts that can be automatically driven. The mounts are driven with the corrected radar data until the target is acquired, after which a human operator takes over the tracking operation. Radar collects trajectory data for test analysis and evaluation only when target size and location preclude successful use of more accurate tracking systems (e.g., the cinetheodolites). When a test vehicle must be recovered, radar data are processed through a digital computer that provides an immediately available impact location.

Item 19. *Gun Projectile Doppler Radar Velocimeter*

To prove that gun-fired projectiles with nuclear warheads have the same ballistic properties as conventional projectiles, it is necessary to accurately measure the velocity of the shell as it emerges from the gun barrel. A Doppler radar was developed and has been successfully used to measure the average velocity of a gun-fired shell between the time it emerges from the gun barrel and the time muzzle blast arrives at the radar mounted at the rear of the gun (Figure 12). Measurement before blast arrival at the radar is a unique capability of the system.

The usual targets are shells having diameters from 155 to 203 millimeters. When the system is set to one of five apertures, each of which is approximately 150 m/sec wide, it will measure velocities from 150 to 1000 m/sec. Measurement uncertainty is 0.07 percent within 3-sigma limits. The Doppler radar velocimeter is more reliable than a dual streak-camera system, and precludes the time delays associated with film processing and reading. Another capability of the velocimeter is a diagnostic indication when coning of a shell occurs (obtained from fine structure in a trace of the return pulse).

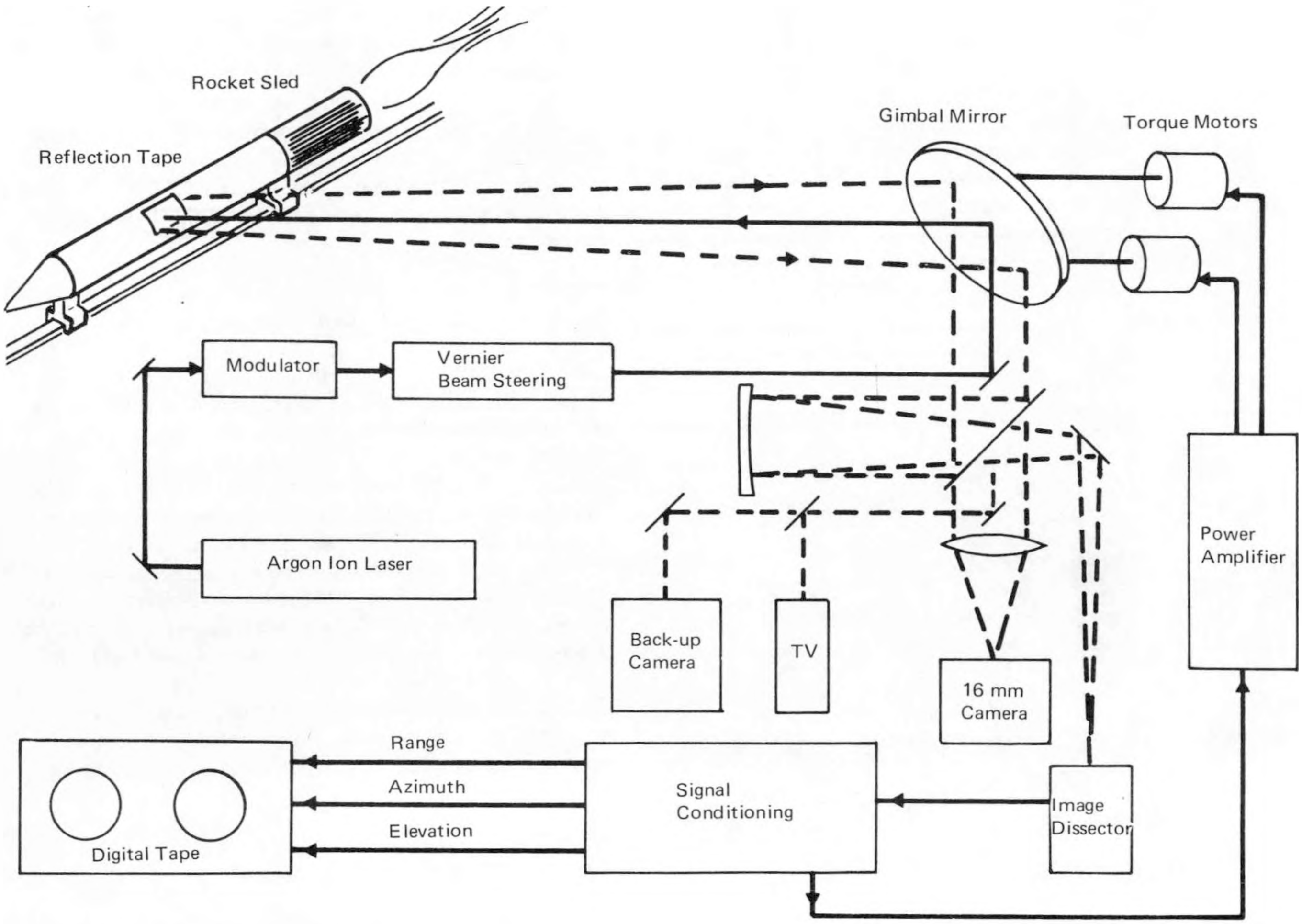

Figure 10. Laser tracker

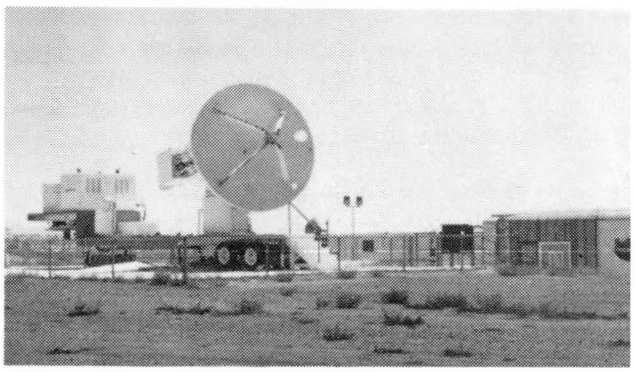

Figure 11. Instrumentation radar at Tonopah Test Range

Item 20. *Telemetry Ground Stations*

Telemetry ground stations receive and record data transmitted by telemetry systems aboard test vehicles. To obtain the best signal at the very-high and ultra-high frequencies transmitted, receiving antennas either are pointed in the general direction of the target or are placed on tracking mounts to follow its trajectory. Tonopah Test Range has three fixed and three trailer-mounted transportable telemetry ground stations to provide good coverage of all portions of the range. All stations have 1.5-MHz seven-track tape recorders, diversity combining S and L band receivers, and a common Inter-Range Instrumentation Group B time standard.

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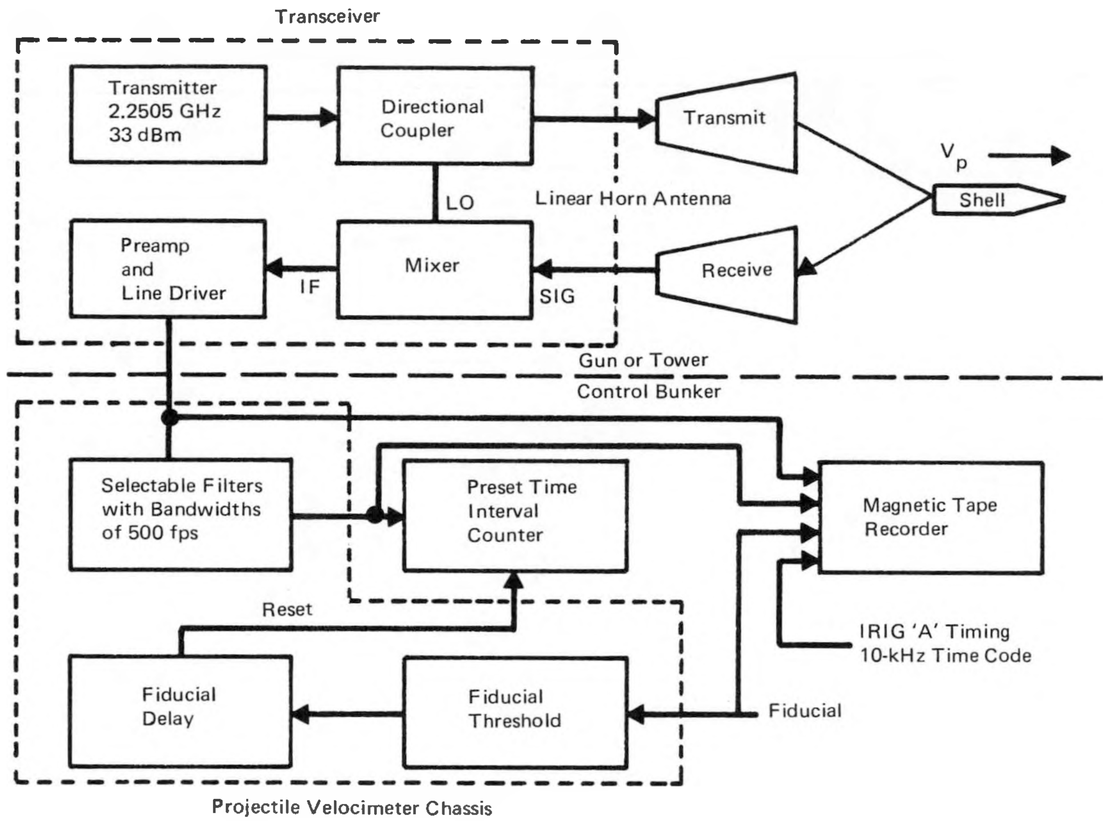

Figure 12. Block diagram of continuous-wave Doppler system

Item 21. *Optical Tracking*

Because on-board instrumentation cannot monitor everything that could malfunction during ballistic tests, Sandia has several tracking-telescope systems at the Tonopah Test Range and Barking Sands, Hawaii, to obtain event, attitude, and documentary photography. Eight of these systems have 40-cm-diameter primary mirrors with a focal length of 3 meters. One system has a 61-cm-diameter primary and a basic focal length of 3 meters that can be optically amplified to 6 meters. The tracking telescope includes an automatic focus correction system for a 1.5 to 90 km range to insure high-quality photography. The cameras use either 16, 35, or 70 mm film at rates to 360 pictures per second. The telescopes are on various fixed and mobile tracking mounts that have azimuth and elevation slew rates and accelerations up to a maximum of 1.5 rad/sec and 1.5 rad/sec^2, respectively.

Item 22. *Airborne Instrumentation Platforms*

Studies of the earth's magnetic field require accurately pointed optical instruments at precisely located airborne positions almost anywhere in the world. Extensive scientific data-gathering systems have been developed for use on two ERDA-assigned NC-135 aircraft equipped with inertial navigation systems.

Magnetic-field tracing experiments require sensitive optical equipment such as intensified television, film camera, and spectrographic systems to view both the injection of barium into the earth's magnetic field and its motion in the field. Continuous communications and experiment coordination are provided by high-frequency radio and very-high-frequency satellite channels. The extremely important instrument-platform position are provided by dual inertial navigational systems, and in addition data are used by an on-board minicomputer to generate precise pointing angles for the optical instruments.

Flight position, and pointing parameters are recorded and available in digital format for in-flight processing, near real-time data reduction, and quick-look determination of mission results.

Item 23. *Long-Duration Stratospheric Composition Studies*

A series of cooperative experiments provides scientific data on the chemical composition of the stratosphere. At balloon float altitudes of 25 to 50 km, payloads weighing up to 200 kg gather data for 24 or more hours. In addition to providing overall payload design, integration, and engineering support, Sandia fields such scientific instruments as mass, ultraviolet, and infrared spectrometers, and special wind-drift measuring devices (Figure 13).

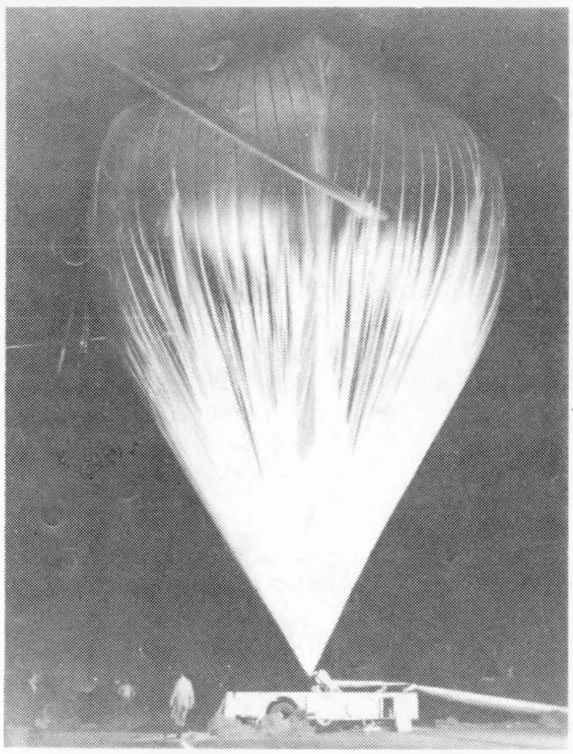

Figure 13. Instrumented balloon

Item 24. *Stellar X-Ray Experiment*

Low-energy x-radiation from two sources in the constellation Cassiopeia were studied in a stellar x-ray experiment. Sandia provided the rocket carrier system, telemetry, attitude control, and recovery system as well as range facilities and support.

Because x-rays are absorbed by the upper atmosphere, such studies must be done at altitudes above 100 km. A Terrier booster with a Sandhawk second stage carried the 33-cm-diameter, 330-cm-long, 193-kg payload to an apogee of 300 km.

The trajectory provided approximately 7 minutes above 100 km altitude, with 1-1/2 minutes allowed for maneuvering the payload to the proper pointing positions and 5-1/2 minutes for data taking.

Twenty-eight channels of frequency-modulated, multiplexed telemetry feeding two transmitters carried x-ray data, state-of-health information, and the position and rate information necessary for attitude control. The star camera provided the only on-board data storage. Star-field photographs taken at a rate of approximately one per second provided a means of resolving the pointing direction to within 0.0017 radian.

Item 25. *Rocket Capabilities*

Rockets are used as instrumentation platforms for high-altitude tests. In the following table are rocket systems that Sandia has modified or developed.

Name	Payload Diameter (cm)	Payload Weight (kg)	Payload Apogee (km)
Nike Cajun	15	35	130
Nike Apache	15	35	170
Nike Tomahawk	23	57	325
Terrier Tomahawk	23	80	390
Sandhawk Tomahawk	23	75	540
Nike Tomahawk	30	115	175
Sandhawk	33	120	155
Terrier Sandhawk	33	95	420
Terrier Malemute	41	160	500
Terrier Sandhawk	43	350	125
Strypi IIR	79	800	280
Strypi IVR	79	400	600

DATA ACQUISITION SYSTEMS

The following systems are used for ablation and erosion studies.

Name	Payload Diameter (cm)	Payload Weight (kg)	Payload Experiment Velocity (m/sec)
Terrier Recruit	23	32	2640
Talos Terrier Recruit	23	32	3170
Strypi VII, 3-Stage	52	50	6130*
Strypi VII, 3-Stage	52	60	5910**

*At -25° reentry angle.
**At -35° reentry angle.

In-flight functions can be controlled by on-board programmers or by radio command. Parachute deceleration and recovery systems are available for both land and water impact (Figure 14).

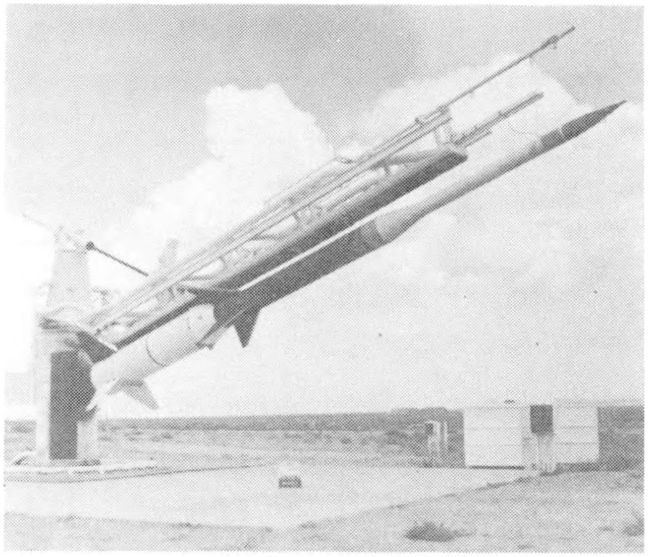

Figure 14. Talos-Terrier-Recruit rocket assembly used for rain erosion studies

Item 26. *Mobile Instrumentation*

Geological conditions, logistics, and economic considerations preclude having permanent instrumentation capabilities at all test locations. Instead, Sandia has more than 100 large mobile instrumentation trailers. Most of these are 3 meters wide by 12.2 meters long. Each trailer is a complete instrumentation system with its own Diesel power generators, air conditioning, control systems, and instrumentation. The instrumentation is mainly oscilloscope and magnetic tape recording. Tape channels are usually multiplexed and frequency-modulated to obtain maximum tape packing density, but each machine also has wide-band frequency modulation and direct-record options for higher-frequency response.

A capability also exists of fielding recording systems that are sufficiently compact and light to be transportable to any place in the world; a complete system was flown to Hawaii as excess baggage. Acquisition and transmitting systems consisting of both hardwire and radio-frequency standard IRIG voltage-controlled oscillators (about 150 channels) and 6-kHz carrier (about 100 channels) are available. The magnetic tape recording units can be packaged in a suitcase-size container.

Item 27. *Determination of Impact Velocity*

The velocity of test vehicles with respect to the earth is of primary importance for many tests. Such data are very difficult and expensive to obtain, especially at very remote locations, by conventional methods. The problem is solved inexpensively by recording in the drop aircraft, or another airborne platform, signal-strength variations from the vehicle's telemetry transmitter. Impact velocities are obtained very quickly by analyzing the frequency of the periodic reduction of radio-frequency signal strength ("nulls") which are caused by the effect of the multipaths of transmission and are detected by the telemetry receiver's automatic gain control circuitry (Figure 15). Experiments have proved that the vertical component of the impact velocity can be determined to within a 2-percent error.

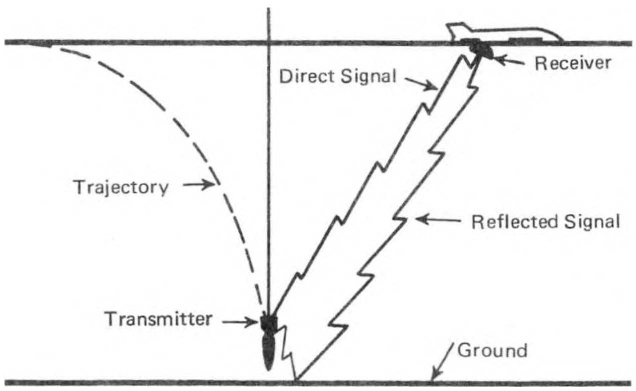

Figure 15. Signal multipath used to determine vertical velocity

SPECIAL INSTRUMENTATION FACILITIES

The development of data acquisition instrumentation for diverse activities such as meteorological, photometrics, quality assurance, and radiation analysis is provided by the special instrumentation activity.

Meteorological Instrumentation Facilities

Meteorological data are required for test safety, weather prediction, calculation of aeroballistic parameters, estimation of refraction effects on tracking instrumentation, and determination of rocket-launcher settings. Test safety involves calculation of potentially damage-causing shock-wave foci for explosive tests, and monitoring atmospheric electrostatic potential to warn of levels hazardous for explosives handling or for outdoor work in locations favorable for lightning strikes. Weather prediction makes it possible to avoid scheduling tests during adverse conditions for both test safety and suitability of atmospheric conditions for optical test instrumentation. Calculation of aeroballistic parameters requires knowledge of temperature, relative humidity, pressure, density, and winds as a function of altitude. This same information is used to estimate refraction corrections for optical and radio-frequency instruments and to adjust rocket-launcher settings. Meteorological instrumentation systems have been developed for each principal testing location, each system tailored to the testing needs that predominate at the particular site. (Items 1-3)*

Photometric Instrumentation Facilities

Photometrics is a way of measuring properties that can be sensed in the optical spectrum from infrared through visible and into the ultraviolet. In most cases the phenomena are recorded on film or other photosensitive media for future analysis. Facilities for this work cover the fields of sensitometry, spectrophotometry, spectral radiometry, and time-resolved spectroscopy.

Facilities are available both in the laboratory and for field use to measure the photometric properties of various sources including optical recording materials. Spectrophotometry and spectral radiometry are conducted for both laboratory and field sources. Spectroscopy is applied to time-resolved photographic spectral studies of sources of low intrinsic radiance. Both cine and streak modes of operation are available.

*See Highlights below.

Spectrophotometry

Wavelength:	0.185 to 3.0 microns
Modes:	Transmission Reflection Observance Percent concentration
Physical States:	Gas Liquid Solid
Readout:	Chart recording Digital display Computer interface

Spectral Radiometry

Wavelength:	0.2 to 1.1 microns
Response Time:	10 nanoseconds
Readout:	Oscilloscope
Calibration:	Black body source Irradiance standard Radiance standard

Spectroscopy

Wavelength:	Dependent upon photocathode response
Streak Rate:	1 to 100 nanoseconds per millimeter
Frame Rate:	5×10^5 to 2×10^7 frames per second

Quality Assurance System-Test Equipment

To support the Quality Assurance activity in component and system testing, test equipment is designed, fabricated, and maintained for specific programs. This includes automated test beds that provide the environmental inputs necessary for system or component operation, and record critical system outputs as well as a variety of diagnostic information. The equipment is designed to test complete systems in simulated-use sequences. Real-time data are collected by hardwire in both digital and analog modes. Many systems are designed to meet a specific test requirement, e.g., for testing during system development to prove design intent; critical limited-life component testing, and testing in critical assembly areas.

SPECIAL INSTRUMENTATION FACILITIES

Test systems include: investigation of the operation of environment-sensing devices, failure-mode duplication testing, opto-electronic simultaneity instrumentation development testing, and performance tests of systems subjected to accidental or unusual environments. (Items 4-5)

System Test Equipment Capabilities

- Environments and forcing functions
  - Acceleration
  - Adaption kit simulation
  - Aircraft drop
  - Altitude or depth
  - Combined environments
  - Linear or rotary force
  - Impact
  - Dynamic parachute deployment
  - Radar target simulation
  - Extreme temperature
- Measurements
  - Digitization, high-speed waveforms
  - Energy
  - Flow or mass rates of pressure systems
  - Frequency
  - Neutron flux
  - Radio-frequency power, average and peak
  - Simultaneity
- Special tests
  - Critical materials evaluations
  - Live detonators
  - Explosive activation and containment
  - Life testing
  - Spin rockets

Radiation Analysis Instrumentation Facilities

Data acquisition in the laboratory from samples collected in the field is a significant aspect of radiation analysis. Facilities include automated alpha spectrometry, a radiation counting laboratory for samples having picocurie activity, and a large variety of other apparatus. (Item 6)

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Albuquerque Lightning Early Warning and Meteorological System*

This system collects potential gradient and meteorological information from remote sites around the Sandia-Albuquerque area for the purpose of establishing safe operating conditions at sites where explosives are used, and displays the information for the operator at the control station. The information is also retransmitted to special displays at explosive-handling test sites for safety purposes. Data collection is over telephone lines and interrogated radio-frequency link. Retransmission is over telephone lines and radio-frequency output. The entire system is controlled by a central minicomputer. Operator output information is on a cathode-ray-tube display and long-term data storage is on cassette cartridges.

Item 2. *Tonopah Test Range Meteorological System*

At Tonopah Test Range the meteorological system uses a radar-directed L-band telemetry antenna to receive temperature and relative-humidity data from a radiosonde attached to a weather balloon. Meteorological and radar-tracking data are processed in real time for digital magnetic tape recording. The recorded data are then computer-processed to provide a listing of altitude, temperature, relative humidity, pressure, density, and wind information, or they can be input directly into programs requiring meteorological data.

Item 3. *Kauai Test Range Meteorological Instrumentation*

Fixed and mobile lower and upper atmospheric wind-measurement systems are used to allow accurate rocket launcher settings. Meteorological balloons are tracked by modified Nike/Ajax radars; the current wind profile through which the rocket will fly is determined by computers and is considered in launcher-setting computations.

Item 4. *Detonator Simultaneity Testing*

Detonators and their firing systems are evaluated by measuring the simultaneity of detonator function time to within ±2 nanoseconds. This measurement is made by using the light generated by the initial shock wave from each detonator (referred to as detonator breakout). The shock wave compresses the trapped air, causing it to emit light. This light pulse is sometimes enhanced by a thin coat of aluminum silicofluoride on the detonator surface. Bifurcated fiber optics transport the light pulse out of the explosive containment box to two separate photodiodes which convert the impulse into an electrical signal. The bifurcated fiber optics and two photodiodes provide measurement redundancy.

A multichannel measurement system is used to record the time interval from a common start signal (usually detonator current) to each detonator breakout signal.

Item 5. *Missile Environment Simulation*

Centrifuge simulation of a phase of flight profile of a current missile system proved to be a fixturing design challenge. Requirements of the profile were a 2-second period of +80 x gravity followed by a 2-second period of -40 x gravity, with a transition time of less than 200 milliseconds. Shock pulses during the transition were not to exceed 350 x gravity for more than 6 milliseconds or 100 x gravity for more than 10 milliseconds. Acceleration normal to the axis of the test unit was to be maintained at a constant 78 x gravity during the entire profile.

Fast transition is accomplished by pivoting the components about their axes at a predetermined point during the gravity profile. Radial forces acting on an adjustable counterweight set for a slight imbalance provide the energy for fixture rotation. The latching mechanism is released by a gas-driven cylinder and the shock at the end of rotation is mitigated by polymer material. Acceleration normal to the test unit is controlled by slowing the centrifuge during the critical time of rotation.

Test results proved that all design objectives were achieved. Time of transition is approximately 100 milliseconds and shock is reduced to less than 70 x gravity for 10 milliseconds.

Item 6. *Radiation Counting Laboratory*

A radiation-counting laboratory capable of counting radioactive samples in the picocurie range is maintained for health physics, environmental sampling, and tracer studies. The laboratory includes a selection of solid-state, proportional-chamber, Geiger-Mueller, and scintillator detectors in conjunction with a variety of instrumentation (pulse height and/or shape discriminators, single and multichannel analyzers, and multiscalers).

The samples are counted in the gross or spectrum mode, either individually or in automated counting systems, with immediate display or data storage, and with data reduction by computer if required.

A variety of low-background shields and coincidence networks is also available.

DATA REDUCTION SYSTEMS

Data reduction converts test data from the format and medium in which it was acquired to a format and medium usable by the test requester either directly or for subsequent analysis. Data coming into the reduction process are either recorded on magnetic tape or on a pictorial medium (film, photographic print, or chart paper) which requires optical processing. Output from data reduction can include oscillographic stripcharts or oscilloscope photos derived from data on magnetic tape, a digital magnetic tape in a standard format, and computer-generated plots of reduced data.

Magnetic Tape Processing

Magnetic tape processing begins with an oscillographic stripchart that allows a first assessment of test data as soon as possible after a test. Judgments are made on the basis of these "quick-look" data as to whether test objectives have been met. About half of all data channels require no processing beyond the quick-look stage. The other half, however, are usually converted to digital data for secondary processing by computers. This conversion involves editing and digitizing or pulse-modulation decommutation.

Three facilities are capable of processing analog or digital data recorded on either analog or digital magnetic tape. The total tape-processing workload among the three is approximately 50,000 data channels annually. A data channel is one data variable, usually from a single transducer. (Items 1-3)*

Optical Data Processing

Optical data processing transforms graphic into digital data to permit subsequent computer analysis. Capability exists to digitize a graphical trace recorded on a Polaroid print, stripchart, or frame of film; to track and digitize one point per frame for a sequence of frames photographed with a cinetheodolite; to obtain time tags for events pictorially recorded on film; and to scan an image, either transparent or opaque, to measure image density. (Items 4-5)

*See Highlights below.

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Oscilloscope Display Digitizer*

Two versions of an economical vidicon digitizer have been developed that use any commercial oscilloscope to digitize fast transient or repetitive waveforms at an effective sampling rate up to 25 gigahertz. One model is for laboratory operations and the other is portable for field operations.

Unique features include the ability to simultaneously photograph and digitize the trace, freeing the operator from having to precisely adjust the vertical trace position.

Light from a trace on the cathode ray tube of the oscilloscope is coupled to the target of the vidicon tube with a beam splitter and mirror. The vidicon tube converts the light image to an electrical signal which is sampled and converted to 500 nine-bit digital words. These are stored in a metal-oxide-semiconductor memory from which the data can be extracted and viewed on the display unit. The data can also be directed to a minicomputer or other peripheral device.

In addition to its portability, the field model has the advantage that the memory is compatible with either fast or slow peripheral devices. Calibration signals are digitized and analyzed by a computer, which then uses the calibration factors to properly scale the data in engineering units and to correct for vertical and horizontal nonlinearities. With prior calibration, the digitizer is accurate to ±0.4 percent of full scale.

Item 2. *User-Oriented Data Reduction System*

A new data-playback/data-reduction system has been developed that consists of a state-of-the-art automated telemetry "front-end" coupled to a Control Data 6400 computer. The system allows users to interact with their data via graphics CRT consoles and perform a wide variety of secondary processing. Users can receive high-quality electrostatic plots during any step of the process within minutes of the request. The user-oriented system allows much of today's analog processing to be converted to digital.

The automated telemetry front-end provides fast, error-free signal processing of raw data recorded on magnetic tape in the field, and will process pulse-modulation formats in addition to digitizing analog signals. Digital data are copied onto disk storage and are thus made available to a battery of some 60 interlinked program modules appropriate to the interpretation and analysis needs of the user.

In the batch mode, the user requests the predetermined set of sequenced programs necessary to complete his reduction process. Figure 1 is a schematic of the playback/data-reduction facility.

Requested library programs and the parameters needed by the programs are placed on punch cards and run on a demand-priority basis. Output typically consists of graphical plots.

In the interactive graphic mode, the user enters processing requests at the graphics terminal and may interrupt the processing at any point to request plots in hard copy or on the terminal screen. Human judgment may override, change or supplement the calculations of the computer program. On the terminal screen, an engineer using a light pen may alter the data; then if desired any program module may be reexecuted.

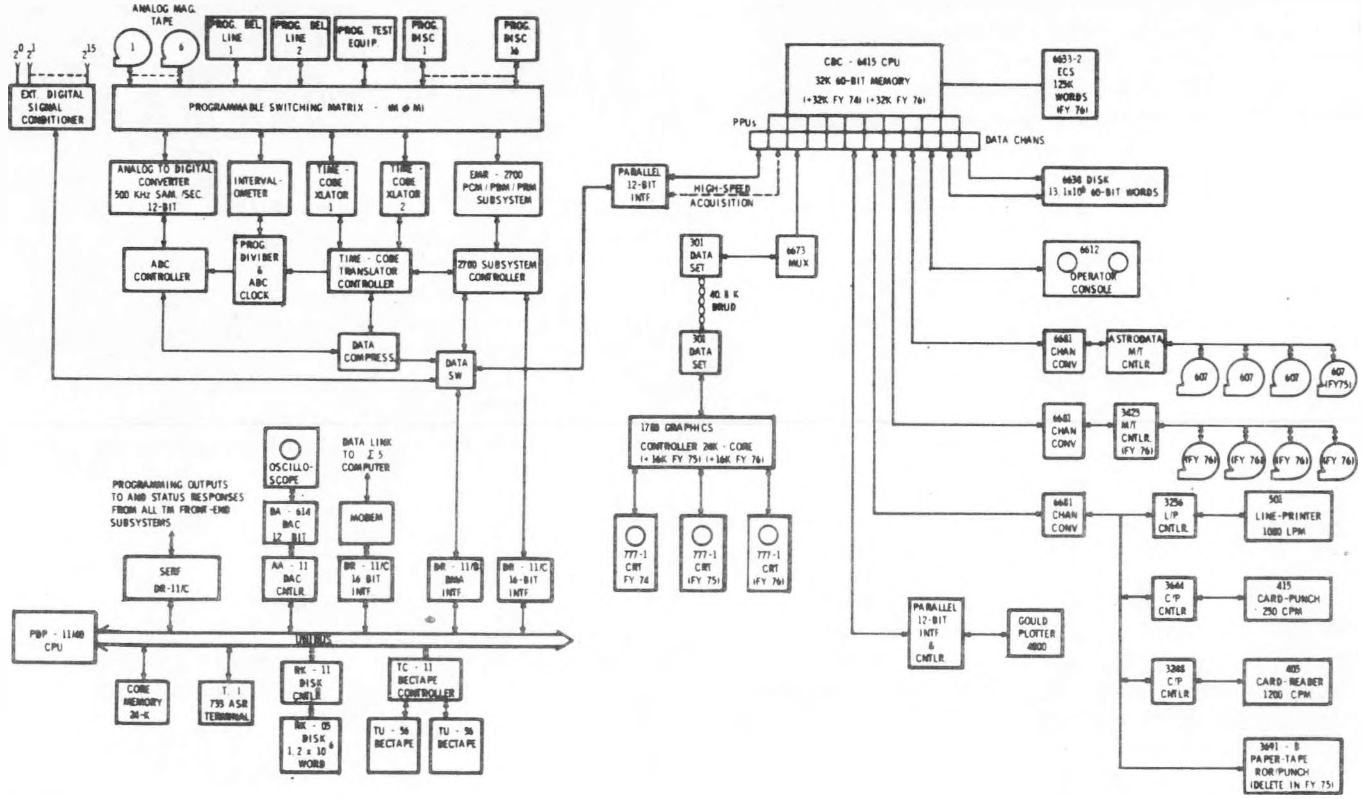

Figure 1. The CDC-6400 user-oriented data-reduction system

DATA REDUCTION SYSTEMS

Current Reduction Program Modules

Calibration correction of raw data
Conversion to engineering units
Correlation functions
Data entry, optical
Data entry, radar
Differentiation
Filtering, digital
Integration
Pulse modulation decoding
Reformatting of tape
Shock spectrum calculation
Statistical analyses

Item 3. *Data-Base Program for User-Oriented System*

A data-base gathering technique has been developed. A data base includes all information necessary to control the playback process, convert raw information to calibrated engineering units, and produce plots in the desired formats. Called Playback-Reduction User Network Editor (PRUNE), the technique uses Sandia's time-sharing computer system. The time-sharing terminal has two integral magnetic-tape cassettes that will record data-base information. The user inputs the required data-base parameters for a given test via the terminal in a fully conversational manner with the time-sharing computer. An editor identifies mistakes in data entry ranging from simple typographical errors to meaningless requests or formats. The partial or completed data base may be recorded on cassette at the user's terminal. At any future time, a partial or completed data base may be reentered into the time-sharing computer from the cassette for updating. The completed data base will be input to the user-oriented system through an identical terminal connected to a minicomputer in the telemetry front end.

Item 4. *Polaroid Print and Film Digitizing*

Data curves on a transparent or opaque medium may be digitized by three methods. First, on a Telereader, the image is projected onto a ground-glass screen on which the operator centers cross-hairs and presses a foot switch to produce a punched-card output. The second method uses an automatic print reader which is a computer-controlled scanner that tracks and digitizes a curve with operator assistance, producing a magnetic tape output. This is the faster and more generally used method. Film sizes of 16 and 35 mm as well as other data sizes to 28 cm x 28 cm can be accommodated.

A third method uses a sonic digitizer, a system where the operator holds a pen-like cursor and traces the curve to be digitized on a tablet with an X and Y array of microphones. The pen generates a spark that is acoustically coupled to the array, and X,Y coordinates are determined by acoustic propagation delay. Data output is on magnetic tape. Input data sizes to 50 cm x 50 cm can be accommodated.

Item 5. *Film Densitometry*

The automatic print reader may be used to measure film density of transparent images or brightness levels of opaque material that must be front-lighted. Better results are obtained with transparencies or 16 or 35-mm film because illumination of the film area is more nearly uniform. The system provides an output that is linear with respect to optical density. Addressable resolution of the system is 1/4000 with an optical resolution of 1/1000. Flexible operation is provided for selection of the area to be scanned and the spacing between the data points. Output is on 7-track, CDC-6400 compatible magnetic tape.

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MATERIALS AND PROCESSES

Sandia Laboratories Technical Capabilities

Materials and Processes

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115
and Livermore, California 94550 for the United States Energy Research
and Development Administration under Contract AT(29–1)-789

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SANDIA LABORATORIES TECHNICAL CAPABILITIES

MATERIALS AND PROCESSES

ABSTRACT

This report characterizes the materials and processes capabilities at Sandia Laboratories. Selected applications of these capabilities are presented to illustrate the extent to which they can be applied in research and development programs.

MATERIALS AND PROCESSES*

Materials and process activities have emphasized the balance between research and development necessary to provide materials compatible with the extreme environments and performance requirements associated with nuclear ordnance.

Specific technical areas which have continuing emphasis include metallurgy, composites, surface characterization and thin films, polymers, ceramics, and high-temperature characterization. Complete processing and fabrication facilities assure the capability for early evaluation and use of tailored materials. Efforts are focused on material applications involving structural and electronic materials, thermal and electrical insulation, radiation shields, and shock mitigation. Key elements in these efforts are functionability, reliability, and longevity.

This interdisciplinary approach to scientific materials engineering results from the recognition that many disciplines are required to understand, characterize, and apply materials and from the fact that material design is an essential element in meeting the objectives of quality, functionality, and life. In effect, the responsibility of a materials group extends beyond the development of a material into the understanding and description of its behavior in the extreme environments to which it will be subjected. The following table summarizes the allocation of the staff according to the activity.

Materials and Processes Technical Staff
and Investment in Equipment

	Professional Staff	Investment in Equipment (in $1,000)
Metallurgy	40	2757
Composites	11	1475
Surface Metallurgy and Film Deposition	16	1004
Polymers	26	1515
Ceramics	18	984
Glass and Glass Ceramics	8	726
High-Temperature Characterization of Materials	14	1383
Laboratory Analysis	19	2935

*Compiled October 1974.

METALLURGY

Metallurgical programs are directed at the application of conventional alloys in designs that must withstand abnormal conditions and of unconventional alloys in designs that must function in both normal and abnormal conditions. Special emphasis is placed on understanding the mechanisms of metal failure which are then used to design new materials or to allow use of conventional materials near their physical limit with high reliability. Methods to quantitatively measure failure behavior in terms of material properties, load, and environments are under continuous development. Long storage time and ultrahigh reliability requirements demand careful study of compatibility and aging behavior of alloys in contact with a variety of substances. Advanced melting technology is applied in the development of unconventional alloys. The reliable use of these alloys requires characterization of their joining and fabrication properties.

Areas under study include physical, mechanical and powder metallurgy; fracture control; joining; corrosion and compatibility; and stress corrosion cracking and hydrogen embrittlement.

Physical Metallurgy

Programs are aimed at improving materials properties and tailoring mechanical and physical properties for specific needs. Studies assure that materials will remain physically and structurally stable when utilized in specified environments which include very low and high temperatures, irradiation, static stress, hydrogen atmospheres, and cyclic loading (Items 1-3*).

Current Activities

- Metal structural determination
- Phase stability
  - Transformation kinetics
  - High temperature
  - Low temperature
  - Irradiation
  - Stresses
- Thermomechanical processing
  - Isotropic properties
  - Anisotropic properties
  - Strength
  - Stability
  - Uniformity
  - Stress corrosion cracking resistance
  - Fatigue resistance
  - Fracture resistance
- Solidification
  - Strength
  - Physical properties specifications
  - Phase stability
  - Uniformity

*See Highlights, below.

Mechanical Metallurgy

Mechanisms controlling mechanical behavior are studied to allow predictions of how metals will respond to environments which are difficult to simulate. These predictions provide a basis for processing materials to meet specific mechanical requirements and to assure designs with long-lasting mechanical integrity under adverse conditions and with specified mechanical response characteristics (Items 4,5).

Current Activities

- Stress relaxation - creep
  - Temperature effects
  - Casting and solidification effects
  - Prior thermomechanical working effects
- Dislocation dynamics
  - Constitutive relations
  - Prediction of behavior
- Stress-strain behavior
  - Temperature effects
  - Loading conditions
    - Strain rate
    - Combined stresses

Powder Metallurgy

Methods for fabricating parts from metal powders are being used to form intricate shapes and to control porosity (Item 6).

Current Activities

Powder characterization
- Size
- Shape
- Surface area
- Density
- Mercury porosimetry

Classification
- Screening
- Air (to 10 μm)

Attritioning
- Crushing
- Milling
- Shearing
- Impaction

Consolidation
- 40-ton semiautomatic cold compaction press
- 30-ton hot uniaxial vacuum press with temperature capabilities to 2500°C
- 25,000-psi - 1500°C hot isostatic press
- 30-ton cold isostatic press
- Sintering furnaces good to 2500°C, vacuum, hydrogen, argon, and nitrogen
- Plasma spraying facilities for toxic and nontoxic powders - 40-KVA system

Analytical instrumentation and special facilities
- Four-station argon glove box with furnace sintering dilatometer to 1800°C operation
- Permeability
- Density
- Surface area porosimetry

Fracture Control

Linear elastic fracture mechanics and more advanced methodologies for characterizing materials which exhibit plasticity provide a frame of reference for a fracture control program. Experimental and analytical programs have resulted in changes in structural design philosophy and have given guidance to materials development efforts. Quantitative design studies have been performed with emphasis on proof-testing, determination of structural weak links resulting from processing, and establishment of nondestructive testing criteria (Item 7).

Current Activities

Technological studies
- Elastic fracture
- Ductile fracture
- Large-scale plasticity
- Analytical techniques

Structural studies
- Pressure vessels
- Ballistic cases
- Reentry vehicle substructures
- Pulse reactor fuel plates
- Waste containment vessels
- Earth penetrating vehicles

Material studies
- Fatigue
- Stress corrosion
- Hydrogen embrittlement

Joining

Processes developed for the fabrication of structures and for the electrical and structural assembly of microminiature electromechanical and electronic components characterize the joining activities. Detailed analyses of welding processes allow specification of operating parameters for specific materials combination and geometries. High reliability is attained through rigid in-process control. Studies are performed on the influence of metallurgical variables and contamination on weld quality (Items 8-10).

Current Activities

Microwelding process
- Electrical resistance
- Inert gas tungsten arc
- Pulsed arc
- Percussive arc
- Ultrasonic
- Thermocompression
- Laser

Material studies
- Substrate microstructures and chemistry
- Bulk contamination
- Surface contamination
- Phase stability
- Bond strength

Structural applications
- Diffusion bonding for artillery-shell rotating bands
- Radioisotope thermoelectric generator assembly by diffusion bonding
- Stainless-steel vessels

METALLURGY

- Electrochemical joining
  - Materials deposited
    - Nickel
    - Nickel-cobalt alloy
    - Copper
  - Materials joined
    - Aluminum to stainless steel
    - Stainless steel to stainless steel
    - Uranium alloys to 4340 steel
    - Beryllium to beryllium

Corrosion and Compatibility

Material life times are predicted and increased through an understanding of metallic corrosion processes. Studies investigate the compatibility of metals with other materials, both metallic and organic.

Current Activities

- High-pressure studies
  - 30,000 psi
- Temperature effects studies
  - -50°C to 2000°C
- Prevention techniques
  - Films
    - Organic
    - Metallic
    - Chemical combination
  - Electromechanical
  - Alloy modification

Stress Corrosion Cracking and Hydrogen Embrittlement

Research techniques have been developed for precise studies of stress corrosion cracking and hydrogen embrittlement. Emphasis is placed on determining the mechanisms of these phenomena. The specification of benign environments and the development of methods of slowing or preventing environmental cracking are important goals of the program (Item 10).

Current Activities

- Alloy system studies
  - Ferrous
  - Titanium
  - Aluminum
  - Uranium
- Environment studies
  - Hydrogen
  - Chloride and other aqueous solutions
  - Oxygen
  - Water and water vapor
  - Molten salts
- Testing techniques
  - Initiation specimens
    - Wire
    - Tensile specimens, smooth and notched
  - Propagation specimens
    - Constant displacement
      - Double-cantilevered beam
      - Compact-tension
    - Environmental test rings
  - Constant load
    - Tapered-doubled cantilevered beam
    - Compact-tension
    - Single-edge notch
  - Prevention studies
    - Films
      - Organic
      - Metallic
      - Nonmetallic (oxides, nitrides, etc.)
    - Electromechanical
    - Alloy modification

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Alloy Studies*

To enable the development of alloys tailored to meet esoteric requirements, the following facilities have been acquired: (1) a melting laboratory capable of heats up to 500 pounds, (2) forming facilities for producing increases in strength through controlled thermal-mechanical deformation, (3) a welding laboratory in which a wide spectrum of controlled tests are performed and where heat-affected zones are duplicated, (4) a hydrogen compatibility laboratory in which typical mechanical properties over a wide spectrum of pressure at room temperature are measured and in which crack growth behavior is monitored, (5) a mechanical testing laboratory in which all of the applicable properties including the latest fracture toughness criteria utilizing J-integral concepts are measured, (6) an advanced microchemistry laboratory which allows the definition of microsegregation for a wide spectrum of elements, (7) the latest x-ray diffraction and transmission microscopy equipment which enhances analytical capabilities, and (8) modeling techniques which ensure transfer of developmental materials and processes to model design hardware.

Item 2. *Phase Stability*

Studies of the influence of melting and fabrication techniques, of quench rate and aging time-temperature combinations and of minor impurities and composition variations on stability have led to the establishment of specifications for the reliable use of uranium alloys. For example, a widely used uranium alloy, U-7.5%Nb-2.5%Zr, can become highly unstable if improperly processed. Thus specifications were provided for processing the alloy which ensured mechanical and physical stability over long storage times.

Item 3. *Solidification*

A vacuum consumable arc remelt facility (Figure 1) is being used to determine the effect of melting parameters on solidification structures. Detailed investigations in the areas of arc physics, heat transfer, magnetic fields, furnace atmospheres, and macrosegregation provide the major research directions in this program. Information obtained from this investigation is of economic and practical importance in the melting and fabrication of uranium alloys and more common metals.

Item 4. *Beryllium-Copper Stress Relaxation*

The excellent strength and electrical properties of Cu-1.8% Be alloy have led to its use in a variety of applications, such as spring contacts in electrical connectors which must function reliably after storage for long times. It was found that certain ranges of strains and temperatures commonly found in connector applications result in catastrophic failure of the alloy. The development of a dislocation dynamics model describing the stress relaxation behavior of the material allowed specification of the mechanical and temperature environments over which the alloy could be safely used. Long-time experiments have validated the predictions of this model.

Item 5. *Thermal Degradation of Aluminum Alloys*

Thermal histories of aluminum-alloy structures and components may range from slow heating and long times at slightly elevated temperatures to rapid in-depth heating at very high homologous temperatures. A capability was needed for predicting the strength of the alloys after arbitrary thermal histories. A study therefore was made of the effect of various thermal environments on the strength of the aluminum alloys 6061-T6 and 7075-T73.

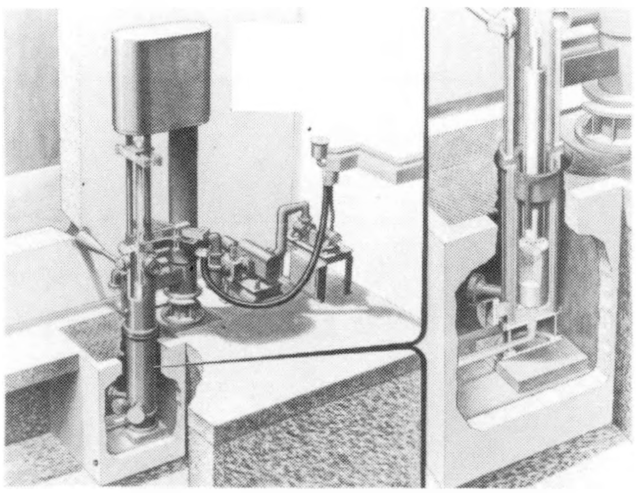


Figure 1. Vacuum consumable arc remelt facility

2

METALLURGY

Slow heating was produced in samples by closed-loop joule heating, and rapid in-depth heating by pulsed electron beams. Results showed that the thermal environments which increase the thermodynamic stability of the strengthening phases also tend to decrease the alloys' sensitivity to strength-degradation effects that occur with rapid heating. This behavior was explained in terms of the kinetics of coarsening of the metastable second-phase particles. A relationship was derived which permits predicting strength as a function of thermal history, and the activation energies for particle coarsening determined from this relation compare favorably with values from the literature.

Item 6. *Powder Metallurgy*

A device was required that would limit gas flow to 10^{-6} cm^3/s. One of the devices developed was a porous stainless steel with a controlled pore size. In recognizing that flow control devices of any design can be plugged from contaminants in the gas, extensive studies led to the conclusion that a porous device with multiple, tortuous flow paths of varying dimension was greatly superior to uniformly sized flow dimension devices with either single or multiple flow paths. The powder process proved to be highly reproducible and relatively insensitive to both gas and particulate contaminants. Development of an advanced porosity characterization technique allowed construction of flow geometry maps (Figure 2) through these devices (Figure 3).

Item 7. *Fracture Control*

Fracture mechanics technology of ductile materials has been directly applied to pressure vessel material selection and proof-test certification specifications. These studies, which were able to accurately predict the failure pressure of a vessel containing a flawed weld, precipitated a major material and design change. The changes provided a pressure vessel resistant to catastrophic failure resulting from manufacturing defects or stress corrosion cracking.

Fracture toughness studies have also provided the basis for specification of a unique heat treatment for a proprietary alloy steel, D6A-C. The alloy in this heat-treat condition is extremely resistant to fracture; earth penetrating vehicles manufactured from this material have been able to withstand repeated penetrations into the earth at initial velocities of 2400 ft/sec (Figure 4). Previously utilized high-strength alloys would fail at impact velocities greater than 1800 ft/sec.

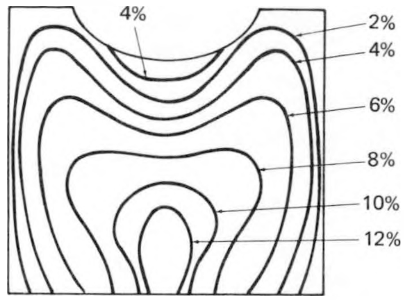


Figure 2. Porosity gradients observed in the 10^{-6} cm^3/s sintered flow control device

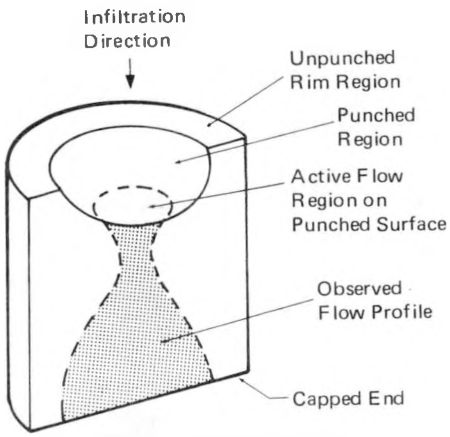


Figure 3. The hour-glass-shaped flow geometry for the 10^{-6} cm^3/s sintered flow control device

Figure 4. Earth penetration

Item 8. *Diffusion Bonding of Artillery Shell Rotating Bands*

Advanced diffusion bonding techniques have provided methods for joining materials that preclude conventional joining techniques. For example, a copper-10 percent zinc obturator band was joined to a Ti-6%Al-6%V-2%Sn artillery-shell base by diffusion bonding (Figure 5). The bonded obturator, which is near the base, survived the firing environment of 54,400-psi breach pressure and the high plastic deformations associated with the engraving of the rifling in the bore.

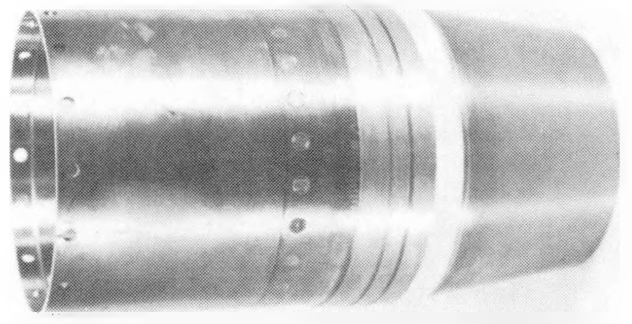


Figure 5. Obturator bonded to artillery shell

Item 9. *Microwelding*

In the production of a rotary solenoid-driven switch, a manufacturer encountered severe cracking problems in welds involving the iron-cobalt alloy, Hiperco-50. Because long range order in this alloy can raise the ductile-to-brittle transition to above room temperature, the manufacturer incorrectly attributed the weld cracking to the brittleness of Hiperco-50. Knowledge of the metallurgy of the welds, along with analysis based on metallography and scanning electron microscopy, allowed the problem to be identified as being that of hot cracking rather than brittleness of the alloy. Furthermore, hot ductility tests demonstrated that Hiperco-50 itself is not prone to hot cracking but is subject to liquid metal embrittlement when welded to alloys plated with gold. A metallographic section of a Hiperco-50 test sample exhibiting liquid metal embrittlement by gold is shown in Figure 6.

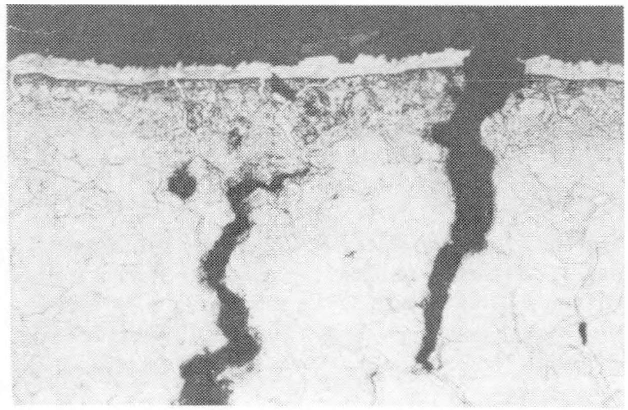


Figure 6. Liquid metal embrittlement

Item 10. *Electrochemical Joining*

The electrochemical process has been used for constructing a structural bond between aluminum and stainless steel in 40-inch-diameter rings. No other joining process could be found for these parts. Full-size parts are now being produced (Figure 7). Electrochemical joining has been shown to be feasible for the reliable joining of high-strength pressure vessels. In addition, joining of steel to uranium and beryllium to beryllium is now feasible.

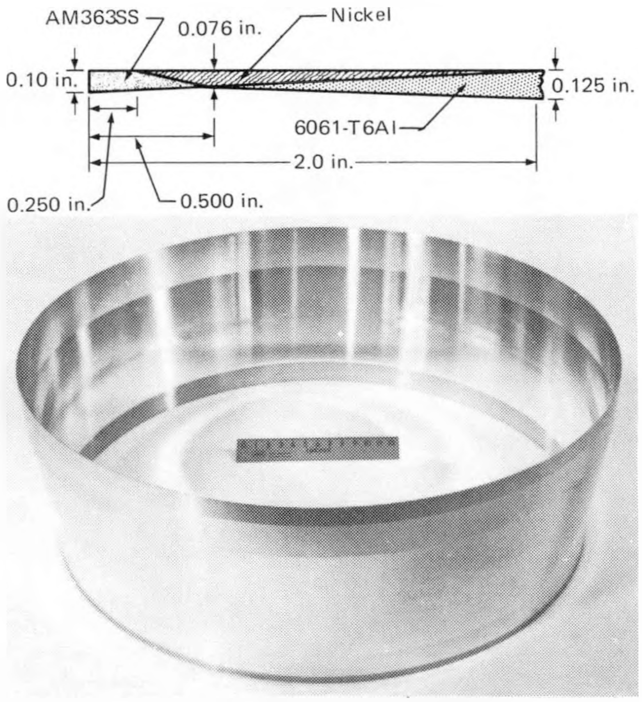


Figure 7. Cross section of electroplated joint and completed part

Item 11. *Stress Corrosion Cracking*

New specimen designs and application of fracture mechanics techniques have allowed quantitative determinations of the effects of environments and material history on stress corrosion cracking kinetics of uranium alloys. This new technology enabled specification of dry nitrogen as a gas which would prevent stress corrosion cracking of U-7.5%Nb-2.5%Zr alloy when used in a stressed condition. Furthermore, coatings which greatly reduce the stress corrosion susceptibility of the aluminum alloys and which have enabled continued use of susceptible alloys exposed to hostile environments have been formulated.

COMPOSITES

Techniques in the field of high-performance fiber-reinforced composites have progressed to the point where these materials are being utilized in weight-limited or otherwise severe applications. The commercial development of high-strength and -stiffness boron, graphite, and organic filaments allows the materials scientist to combine these filaments with suitable matrix materials for the solution of specific engineering problems. The mechanical behavior characteristics of a number of composite systems have been defined, and special attention has been given to creep and long-term failure, fracture toughness, and resistance to thermal stress. Composite materials have been designed and fabricated with either metal, resin, or carbon matrices to achieve high specific strengths and moduli and improved resistance to elevated temperature, corrosion, and radiation environments. The types of materials under investigation and the methods of analysis and characterization are outlined below.

Metal-Matrix Composites

Metal-matrix composites are being designed and fabricated for applications where resistance to elevated temperature deformation and high strength and stiffness to weight ratios are of importance. Materials systems and fabrication techniques are being utilized for a variety of applications (Items 1,2*).

Current Activities

- Matrices
  - Aluminum alloys
  - Magnesium alloys
  - Titanium alloys
  - Uranium alloys
- Filaments
  - Boron and borsic
  - Aluminum oxide
  - Stainless steel
  - Tungsten
- Infiltration
  - Plasma spraying
  - Liquid infiltration
  - Alkyl decomposition
- Densification
  - Platen hot pressing
  - Isostatic pressing
  - Miniature hot roll bonding
  - Pressureless sintering
  - Monolayer tape bonding
- Fabrication of complex shapes
  - Thick-walled cylinders
  - Spheres
  - Plates
  - Rings

*See Highlights, below.

Resin-Matrix Composites

Reinforced resins, the most highly developed class of composites, possess high specific strengths and moduli. Many of the processes used to form the composites have been well characterized (Items 3,4).

Current Activities

- Matrices
  - Epoxies
  - Polyesters
  - Phenolics
  - Polyimides
  - Silicones
  - Urethanes
  - Filaments
    - KEVLAR-49®
    - KEVLAR-29®
  - Graphite and carbon
  - Glass
  - Boron
  - Quartz
- Characterization
  - Mechanical properties
    - Fracture behavior
    - Failure criteria
    - Viscoelastic analyses
  - Thermal properties
    - Glass transition temperature
    - Thermal expansion
    - Thermal cycling

Mechanical Characterization of Composites

The mechanical test program generates data needed for the certification of structural composites as engineering materials.

Current Activities

- Mechanical testing
  - Simple tension testing
  - Individual filament testing
  - Biaxial loading of cylindrical specimens
  - Split-ring shear testing
  - Internal pressurization of cylindrical laminates
  - Burst testing of spherical parts
  - Notched and unnotched bend specimens
  - Thermal testing
    - Thermal expansion
    - Thermal conductivity
  - Composite parameters
    - Filament volume fraction
    - Filament diameter and strength
    - Interfacial properties
  - Statistics of the filament strength distribution
  - Filament orientation

Creep and Long-Term Behavior of Composites

Knowledge of the creep and time-dependent failures of filaments and composites is being applied to designs that frequently require the composites to sustain loads for extended time periods.

Current Activities

- Filament and composite creep
  - Relationships for predicting long-term response
  - Statistical aspects of fracture
  - Reliability
- Time-dependent failure
  - Accelerated testing
    - Data generation
    - Increased stress
  - Failure modes
    - Progressive fiber failure
    - Matrix failure
    - Interface failure
  - Statistics of the filament strength distribution

- Compound Testing
  - Fibers
    - Boron and borsic
    - KEVLAR-49®
    - KEVLAR-29®
    - Graphite
  - Matrix materials
    - Metals
    - Epoxy resins

Carbon-Carbon Composites

Carbon-carbon composites have been developed for various applications which require the unique high-temperature and erosion-resistant properties of carbon. Two major substrates were evaluated: helical-wound continuous carbon filaments and continuously felted substrates. Chemical vapor deposition (infiltration) and pyrolized organics (impregnation) were evaluated as matrices. A carbon insulating material also was developed with tailorable compressive and thermal properties for 3000°C use (Item 5).

Current Activities

- Composite properties and behavior
  - Ambient and high-temperature mechanical properties
  - Thermal conductivity
  - Thermal expansion
  - Ablation
  - Thermal stress resistance
  - Fracture mechanics and toughness
  - Nonlinear behavior in transient heating conditions
  - Composite characterization
- Chemical vapor deposition (CVD) of carbon
- Chemical kinetics and equilibrium
- Thermochemical calculations
- Reaction modeling and experimental confirmation
- Instrumentation methods
- Deposit characterization

COMPOSITES

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Boron-Aluminum Composites*

Figure 1 shows the die arrangement used to fabricate a cross-plied cone frustum.

Figure 2 shows the cross-plied cone frustum fabricated by this process for possible structural applications.

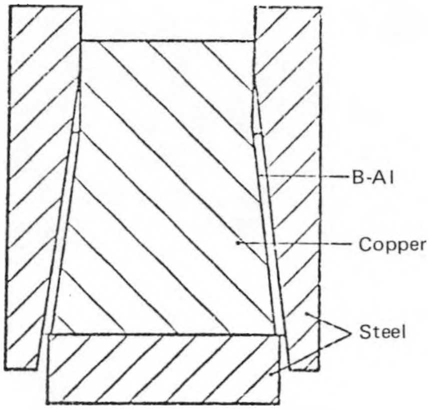


Figure 1. Die arrangement for hot-pressing boron-aluminum conical shapes

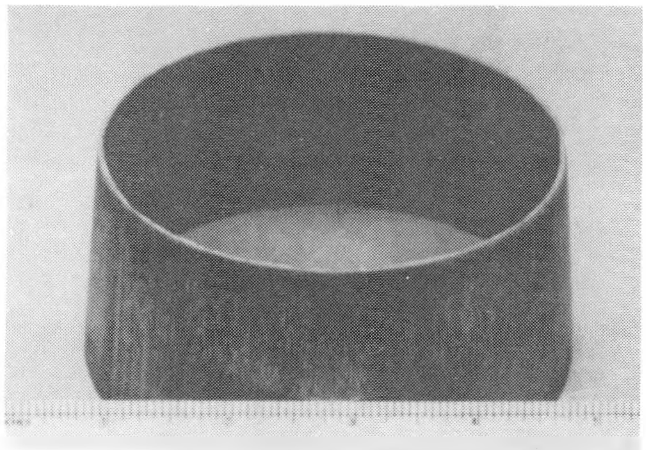
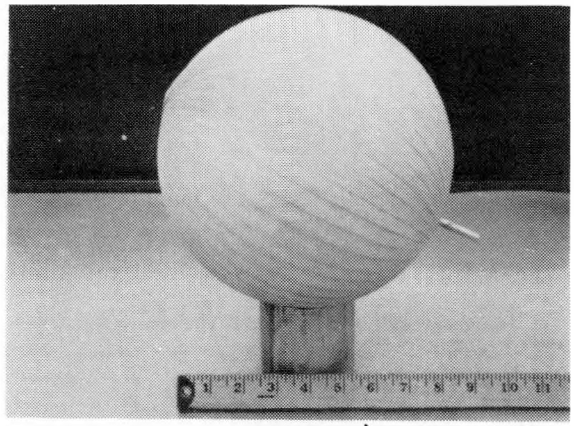


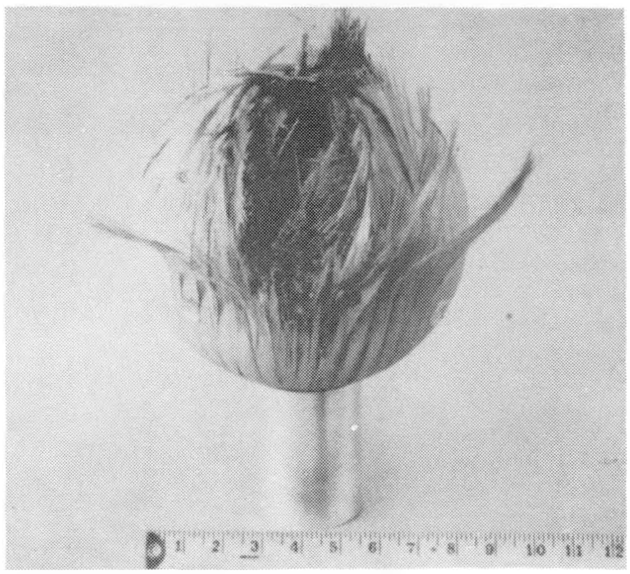
Figure 2. Cross-plied cone frustum

Item 2. *Metal-Matrix Composite Pressure Vessels*

Analysis, design, and fabrication development of both resin and metal-matrix composite pressure vessels have resulted in parts such as the boron-aluminum pressure vessel shown in Figure 3a; Figure 3b shows the pressure vessel after burst testing.



a. Boron-aluminum pressure vessel



b. After burst testing

Figure 3. Pressure vessels

Item 3. *Flywheel Energy Storage*

Studies are being conducted on high-performance composite flywheels that offer significant increases in energy density over conventional materials. Figure 4 shows a prototype flywheel, 8 inches in diameter, circumferentially wound from Kevlar 49/epoxy.

Item 4. *Package Stiffeners*

The graphite-epoxy stiffener shown in Figure 5 successfully reduces deformation and restrains cracking of the potting material during gun firing.

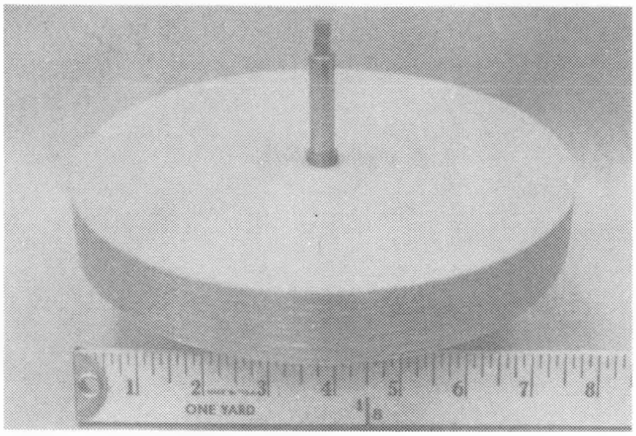


Figure 4. Developmental flywheel

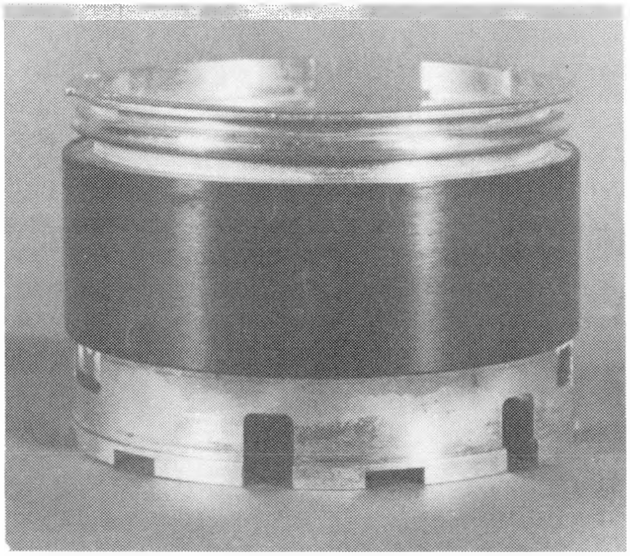


Figure 5. Circumferentially wound graphite-epoxy component package stiffener

Item 5. *Carbon-Carbon Composites*

Two classes of carbon-carbon composites have been developed for heat-shield applications. Figure 6 shows the filament-winding operation for a flight-sized heat shield.

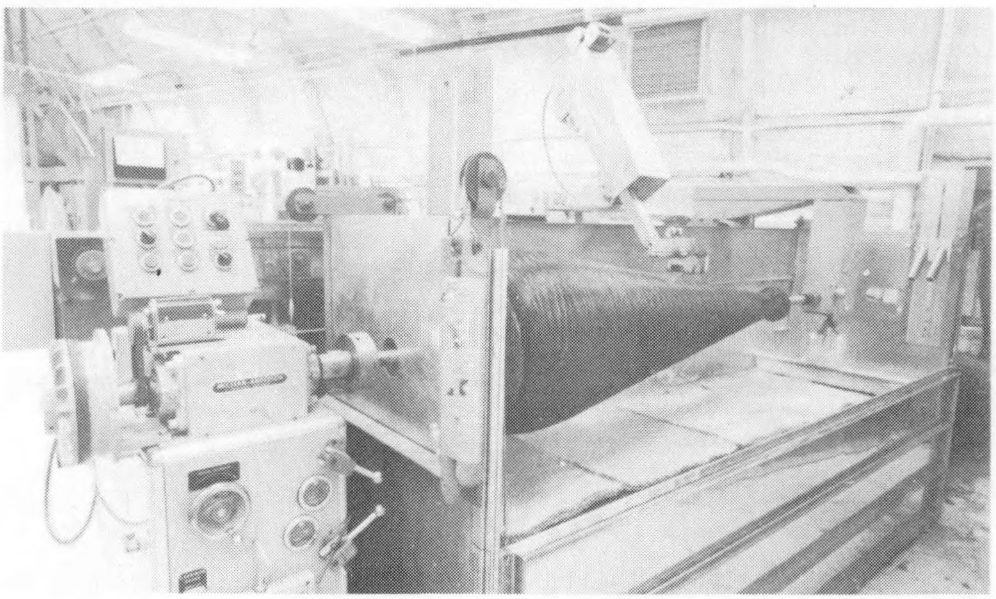
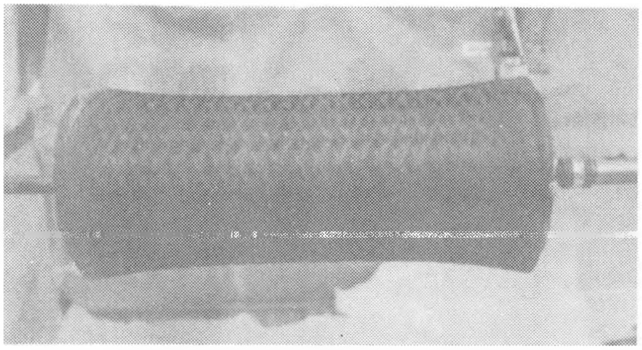


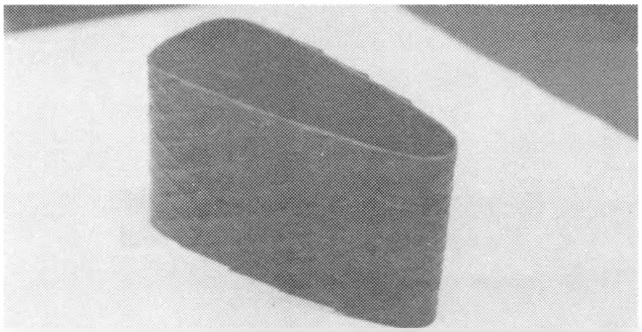
Figure 6. Filament-winding operation for a flight-sized heat shield

COMPOSITES

Figure 7 shows a filament-wound leading edge for a rocket sled. View a is of the part wound on a collapsible round mandrel. The part is then shaped into a wedge on a graphite mandrel before densification. This permits optimum use of the continuous filaments by preserving the filament-winding pattern. View b shows a segment of the final shape. Figure 8 shows a conical induction heating coil. This coil achieves a uniform temperature of 1200°C ± 25°C from end to end on a 6-foot-high conical part.



a. Part wound on a collapsible round mandrel



b. Segment of final shape

Figure 7. Filament-wound leading edge for a rocket sled

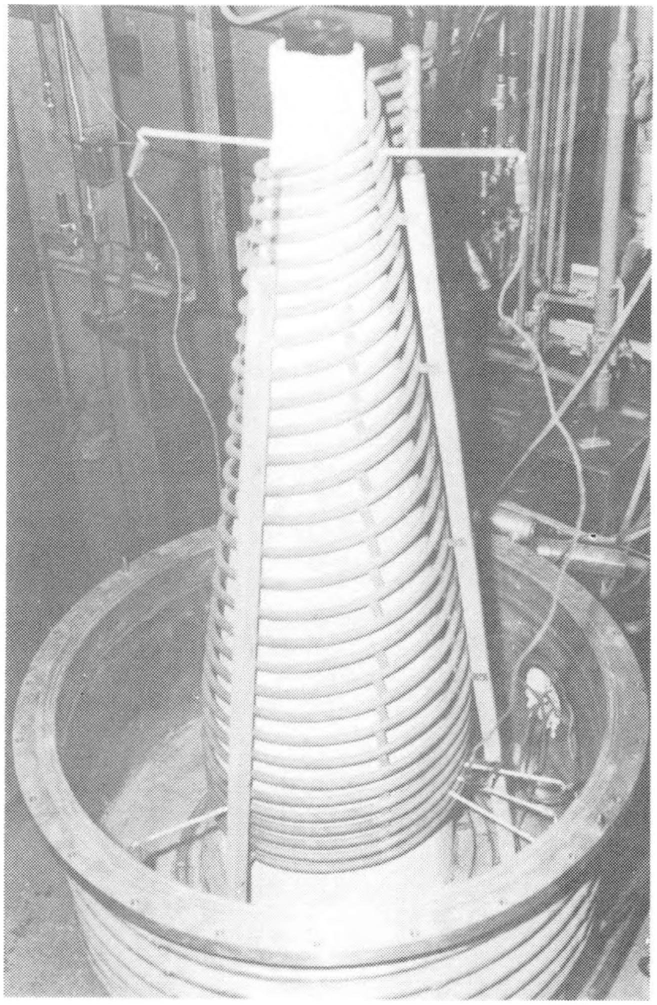


Figure 8. Conical induction heating coil for chemical vapor deposition

SURFACE METALLURGY AND FILM DEPOSITION

Emphasis on miniaturization and applications of solid-state materials to microelectronics has projected thin-film technology and surface effects into a major role in current designs. An ability to produce films by a full spectrum of deposition techniques, to study surface properties as they affect performance in specific applications, and to define the processes necessary for dependable, reproducible thin films leads to an integrated approach to designs involving surface technology and thin films.

Surface-Surface Contact Studies

Concern with high reliability has led to increasing emphasis on studies relating surface phenomena to reliability. Since many electrical functions are controlled by electrical contacts, the testing and operational characteristics of contacts are of particular interest. The importance of joining and bonding in microelectronics and other high-reliability areas has led to studies of cleaning, surface treatment, and bond testing. From these studies several fundamental findings have emerged and new technologies have been developed (Items 1 - 5*).

Current Activities

- Electric contact studies
  - Material deformation during contact
  - Effect of wipe on contact resistance
  - Low-voltage arcing of contacts
  - Contact materials evaluation

- Friction and wear
  - Surface hardness as related to friction
  - Effect of hydrogen atmosphere on surface deformation
  - Low-friction amalgam surfaces
- Microwelding
  - Joining process development
  - Testing of weld bonds
- Surface cleaning
  - Cleaning technique evaluation
  - Development of cleaning techniques
  - Sputter cleaning
  - Ultraviolet radiation cleaning
  - In-process cleaning specifications
  - Storage techniques for cleaned surfaces
- Surface treatment
  - Activated plasma treatment of organic surfaces
  - Chemical passivation of surfaces
- Adhesive bonding
  - Organic adhesives
- Development laboratories
  - Welding
  - Cleaning
  - Electrical contact

*See Highlights, below.

Deposition of Materials

The continuing need to provide coatings and films for development work has led to the establishment of facilities for the deposition of materials for research and development. From these efforts several technological advances have been made which allow new design capabilities, and materials with special properties have been fabricated (Items 6 - 10).

Current Activities

- Electrochemical
  - Electrodeposition
  - Anodization of metals
  - Electrophoretic coating
- Physical vapor deposition
  - Sputter deposition
  - Vacuum deposition
  - Ion plating
  - Gas evaporation
- Chemical vapor deposition
  - Fabrication of high-purity quartz
  - Epitaxial silicon deposition
  - Composite fabrication
- Plasma spraying
- Glow discharge polymerization
- Ion implantation
- Development laboratories
  - Electroplating
  - Physical electronics
  - Microelectronics
  - Neutron generator

SURFACE METALLURGY AND FILM DEPOSITION

Item 1. *Effect of Wipe on Contact Resistance*

Wipe is generally considered desirable for electrical contacts, to obtain low contact resistance. If the contacts are contaminated, however, this is not necessarily so, as can be seen in Figure 1. A small amount of wipe is desirable but excessive wipe causes contaminants to build up ("prow" formation) and give sporadically high contact resistance. Monitoring contact resistance during wipe can be used to determine contact contamination. By designing the contacts to have limited wipe, the likelihood of prow formation can be limited.

Item 2. *Low-Voltage (<10-Volt) Arcing*

It has been assumed in the past that contact arcing could not take place if the applied voltage is less than the ionization potential of the materials involved (10 to 15 volts). Recent studies have shown that arcing can take place down to the melting voltage of the material (<1 volt). Figure 2 shows the "pits" on the cathode and "splats" on the anode caused by multiple electrical discharges at only 0.45 volt. This quite typical damage indicates that, even in low-voltage testing of contacts, arcing causes deterioration that in turn can affect performance.

Item 3. *Surface-Surface Contacting Apparatus*

A major problem in surface-surface contact studies is in controlling the environmental parameters. Figure 3 shows an apparatus for making such studies. This device allows control of vibration, wipe, impact, normal load, transverse load, surface condition, environment and temperature. It measures contact load/area deformation, contact resistance, and surface topography coefficient of friction and coefficient of adhesion. The data shown in Figure 1 were obtained with this apparatus.

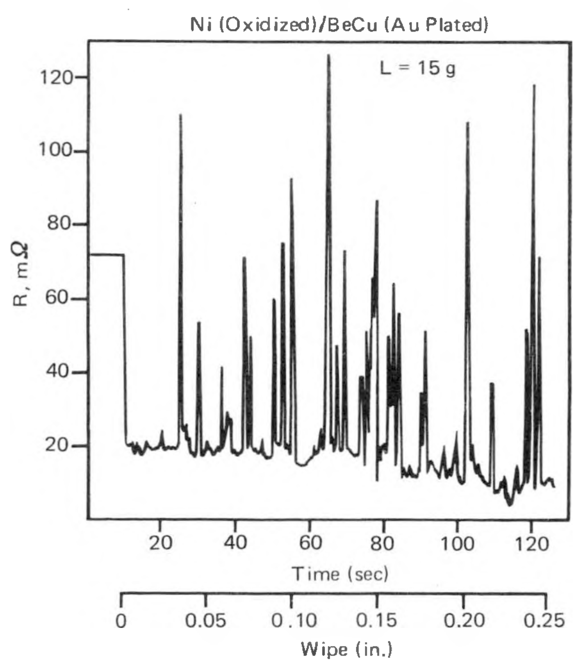


Figure 1. Contact resistance as a function of wipe for contaminated contacts

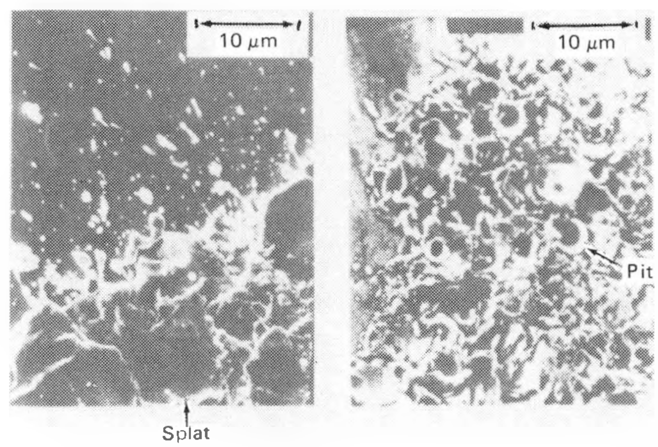


Figure 2. Pits and splats caused by arcing in 0.45-volt discharges

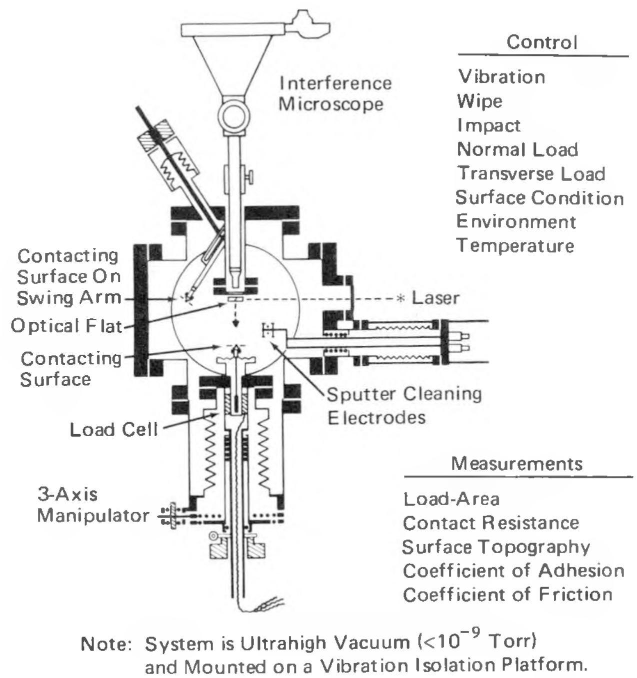


Figure 3. Bakeable ultrahigh-vacuum system for measuring the mechanical and electrical properties of contacting surfaces

Item 4. *Shear Tester for Ball Bonds*

The apparatus shown in Figure 4 was developed to allow reproducible testing of thermocompression ball bonds. It employs a carefully positioned knife edge to shear the bond. Force is measured with a load cell. The data shown in Figure 5 were obtained with this apparatus. Each data point consists of 20 individual tests.

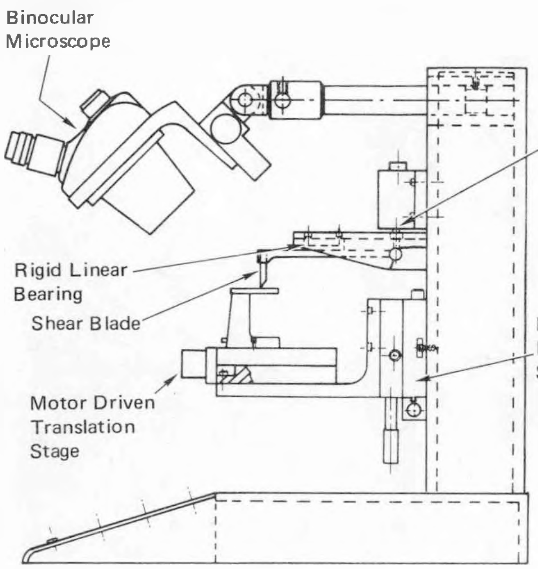


Figure 4. Apparatus for reproducible testing of thermocompression ball bonds

Item 5. *Cleaning by Ultraviolet Radiation*

A cleaning technique has been developed to clean hydrocarbon contamination from nonoxidizable surfaces. The surface is exposed to ultraviolet radiation from a mercury vapor lamp in the presence of oxygen. The radiation causes bond scission and creates ozone, a powerful oxidizing agent. Oxidation of the carbonaceous contaminant causes it to volatilize. This cleaning technique works well on ceramic and gold surfaces. Figure 5 shows the shear bond testing of gold-gold ball bonds formed after sputter cleaning and after ultraviolet cleaning. The ultraviolet radiation technique is an excellent way also of preparing clean surfaces for storage, to prevent recontamination.

Item 6. *Joining by Electrodeposition*

Joining by electrodeposition has been found to solve metal joining problems in several systems where conventional metal joining techniques fail. An example is the joining of aluminum and stainless-steel rings, using electrodeposited nickel as shown in Figure 6. Electrodeposition joining has been shown to be feasible for the reliable joining of high-strength pressure vessels. In addition, joining of steel to uranium and beryllium to beryllium is now feasible.

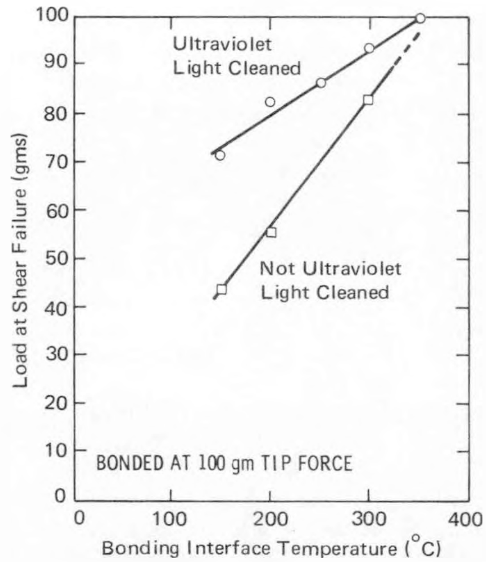
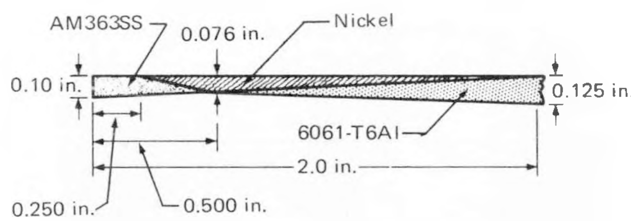


Figure 5. Effect of ultraviolet-light cleaning on thermocompression bonding of gold (gold wire, 0.001 inch in diameter, pulse T.C. ball bonded to dc-sputtered cleaned gold-chromium metallization)



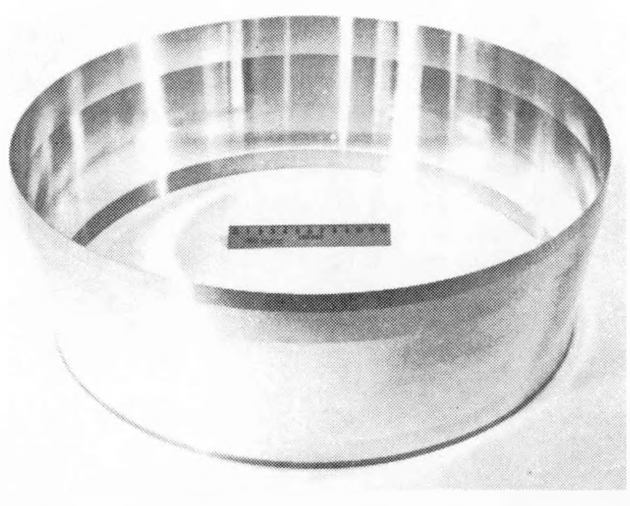


Figure 6. Cross section of electroplated joint and completed part

SURFACE METALLURGY AND FILM DEPOSITION

Item 7. *Ion Bombardment Modification of Film Morphology*

The unique morphologies often associated with deposited materials determine some of their properties. It has been found that thick deposits of many materials develop a columnar morphology, resulting in a weak, low-density material. Ion bombardment during deposition disrupts this growth mode, giving a high-density structure. Figure 7 shows two sputter-deposited tungsten films deposited at the same time. Film A had no ion bombardment during deposition while film B was subjected to ion bombardment during deposition. Note the drastic change in film morphology.

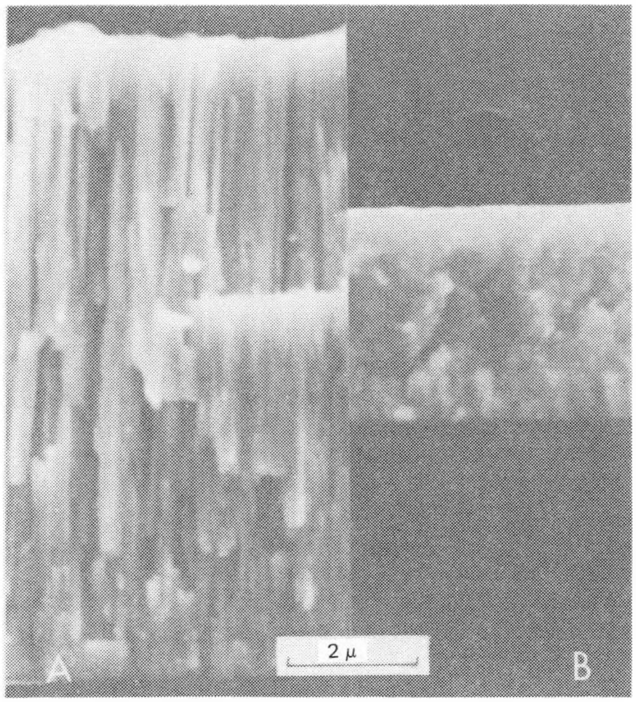


Figure 7. Simultaneously sputter-deposited tungsten films, showing effect of ion bombardment

Item 8. *Helium in Metals*

The behavior of inert gases in metals is of interest in nuclear reactor technology, plasma containment and the storage of $^3H_2$. One method of fabricating helium/metal alloys in order to study diffusion, bubble formation, and gas release is to co-deposit the materials in a gas discharge. With the use of this technique up to 40 atomic percent, helium may be incorporated into metals such as gold, tungsten, and palladium. Figure 8 shows the amount of helium incorporated into a gold film as a function of film bias during deposition. Helium/metal alloys have been formed and the initial stages of diffusion/bubble formation have been studied by transmission electron microscopy.

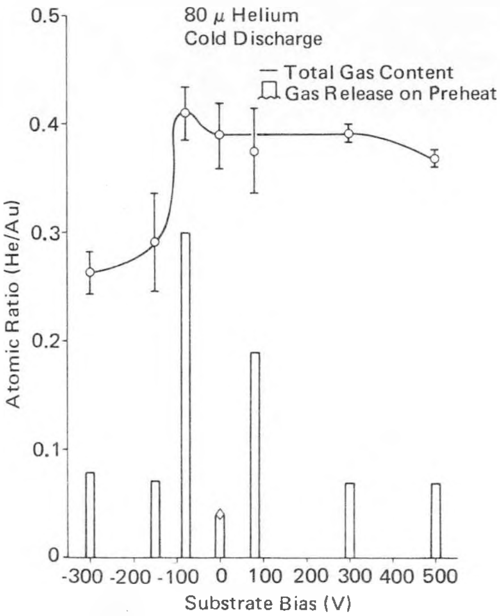


Figure 8. Helium incorporated into a gold film as a function of film bias

Item 9. *Security Systems*

As part of the effort to safeguard material from unauthorized intrusion, a large-area capacitor has been developed for use on aluminum structures. The dielectric layer is formed by barrier anodization of the aluminum, followed by the deposition of a glow discharge polymer film. The counter electrode is an evaporated film. Capacitors with areas of up to 2000 cm^2 have been formed. Penetration of the dielectric layer lowers the resistance, which is electronically detected. Figure 9 shows an aluminum shell with such a capacitor coating.

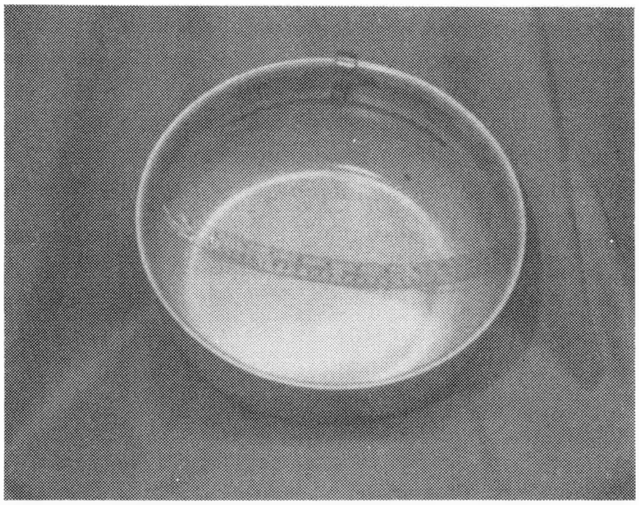


Figure 9. Aluminum shell with capacitor coating

Item 10. *Solar Absorbing Coatings*

In the utilization of solar energy for heating, it is desirable to have a "selective absorber": i.e., one that absorbs energy in the solar spectrum but does not radiate in the infrared. Such coatings have been prepared by electrodeposition techniques (black nickel), vacuum deposition (lead sulfide) and gas evaporation techniques (selenium and germanium). Gas evaporation is the thermal vaporization of material in a high residual gas pressure which causes vapor phase nucleation and affects the film morphology. Table I summarizes some of the solar absorptances and emittances obtained.

TABLE I

Solar Absorptance and Emittance Data

	α_s (m = 2) (smooth glass)	$\epsilon_{240°C}$ (1018 steel)
Polished 1018 steel	--	0.12
PbS* (0.2 μm)	0.90	0.14
PbS* (0.5 μm)	0.98	0.2
PbS* (1.5 μm)	0.99	0.42
Ge* (0.5 μm)	0.58	--
Ge* (1 μm)	0.61	0.54
Ge** (0.5 μm)	0.91	--
Ge**(1 μm)	0.98	0.48

*Vacuum evaporated ϵ = emittance
**Gas evaporated α = absorptance

POLYMERS

In the polymeric materials program, polymeric materials are being used to solve problems in new and unusual ways and to develop materials such as high-temperature foams, encapsulants, and stress-relief foams for special environments. Examples of recently developed materials include a passive dosimeter system, an organic hydrogen getter system, and a tough high-temperature foam for structural applications. In addition, research capabilities are being applied to the behavior of polymeric and insulator materials in environments such as high-energy radiation and high electric fields.

Polymer Research

The mechanical, electric, and optical behavior of a variety of polymeric compounds subjected to wide temperature variations, chemical attack by foreign chemical agents, static stress, cyclic loading, ionizing irradiation, and high electric stress has been determined for numerous applications. Emphasis is on the application of the physical and chemical processes underlying these properties (Item 1*).

Current Activities

- Mechanical properties
  - Creep and stress relaxation
  - Temperature effects
  - Grüneisen coefficient
- Chemical properties
  - Chemical degradation
  - Aging
  - Hydrogen getter
- Permeation by gases
- Plasticization by high-pressure gases
- Electronic properties
  - Electrical conductivity
  - Dielectric behavior
  - Energy transfer and excited-state lifetimes
  - High-voltage breakdown
  - Piezoelectric, ferroelectric, and electric properties

Polymer Development

New polymers have been developed and existing polymers have been modified for new applications. In addition to the tailoring of the properties of polymers to specific requirements, studies have assured that the materials will not change properties when placed in hostile environments such as high and low temperature, humidity, irradiation, static and dynamic stresses, and corrosive atmospheres (Item 2).

Current Activities

- Foam development
  - High temperature
  - Energy absorbing
  - Heat-activated
- Encapsulant development
  - Improved urethane rubbers
  - Rubber-modified epoxies
  - Encapsulation processes
  - Fiber-filled epoxies
  - Removable encapsulants
  - Self-destruct encapsulants
- Adhesives development
  - Surface treatments for bonding
  - Adhesive processes
  - Evaluation of new adhesives

Polymer Processing

A complete processing facility, including compression, transfer, and injection molding equipment, as well as clean-room casting and vacuum encapsulation, assures a capability for early utilization and evaluation of materials tailored to specific project needs. This facility is used for the development of procedures for handling new materials and for application of a wide variety of polymers to new designs and prototypes (Item 3).

Radiation Effects Studies

Electrical, optical, and mechanical properties of organic materials under a variety of radiation conditions are being studied for the solution of design problems. Environments include very high and low dose rate radiation and electron beams as well as temperature effects under the different radiations. New techniques for measuring radiation dose are being developed concurrently with the understanding of the microscopic interaction of the radiation with organic materials.

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*See Highlights, below.

Current Activities

- Radiation-induced conductivity in insulators
- Radiation effects in polymers and organic crystals
- Passive and active dosimetry
- Radiation effects in optical materials

High-Voltage Breakdown

Studies of the physics of surface flashover under a variety of conditions, including the rate of increase of field at the vacuum dielectric interface and the effect of insulator surface composition, are being applied to the design of pulsed electron accelerators and other high-voltage equipment. The physics of vacuum gap breakdown is also being pursued with a variety of voltage pulse shapes and cathode and anode materials. Insulator design concepts are tested for applicability to specific device high-voltage-breakdown problems (Item 4).

Current Activities

- Surface flashover
- Bulk breakdown
- Vacuum gap breakdown

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Hydrogen Getter*

In closed systems which must function over a long time, the buildup of molecular hydrogen from corrosion of metals presents two problems. If hydrogen exceeds about 4% in the gaseous mixture, a combustion hazard exists. Even lower concentrations, a few hundred parts per million, may suffice to spoil the vacuum in glass or ceramic vacuum tubes.

A hydrogen gettering system using an acetylenic hydrocarbon derivative coated onto a noble metal inert substrate carrier has been developed to reduce the molecular hydrogen levels in air to below 0.5 part per million. The hydrogen gettering reaction proceeds in two steps to form an inert saturated compound:

$$R - C \equiv C - R' + 2H_2 \xrightarrow{Cat} R - CH_2 - CH_2 - R'$$

Figure 1 illustrates the gettering action at an initial hydrogen pressure of 5.5 psia. The open circles are experimental points, and the solid line is the calculated pressure versus time curve (assuming a simple two-step inhomogeneous gas solid reaction).

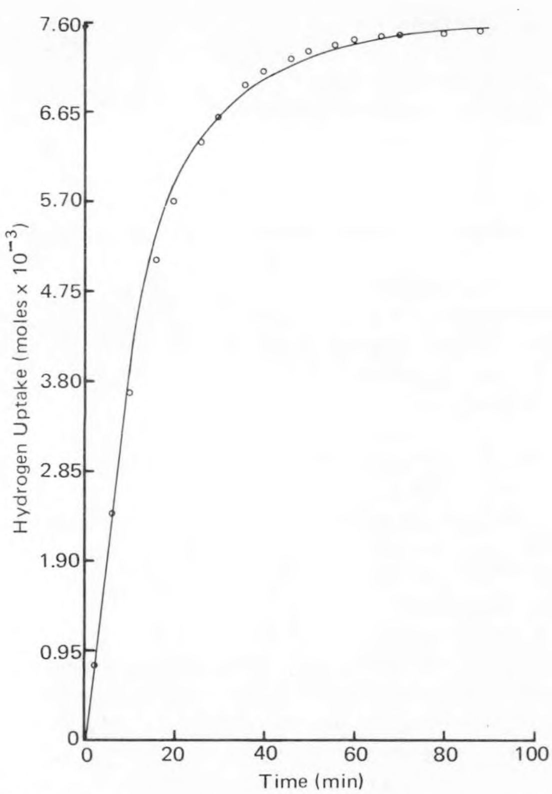

Figure 1. Hydrogenation of propargyl phenyl ether (PPE)

POLYMERS

Item 2. *Self-Destruct Encapsulant*

A self-destruct and conductive residue material has been developed for nuclear safety and security applications. This material will be used to incapacitate certain vital weapon components in the event of an accident involving a fire. Figure 2a shows a specimen of this temperature-sensitive material that consists of an epoxy-anhydride matrix filled with appropriate quantities of silver oxide and lead dioxide. This unique material exhibits all the dielectric properties of similar epoxy encapsulants; yet, upon heating to 165°C, it will ignite spontaneously (Figure 2b) in a self-sustaining destructive oxidation-reduction reaction and will deposit a conductive silver-lead sponge residue (Figure 2c).

Item 3. *Acoustic Membrane*

A recent example of combined material and process development is the design of a very low modulus elastomer for a pulsing acoustical membrane for underwater energy propagation. In this process, materials were matched to the specific physical requirements of the membrane, tooling was designed, and processes were developed so that scaled-up hardware could be tested on short time scales to simulated service conditions.

Item 4. *High-Voltage Breakdown*

When a dielectric surface in vacuum is pulsed with a high voltage with a risetime of a few nanoseconds, the surface breaks down to, at most, a few ohms impedance in less than 10 nanoseconds. A model developed to explain the fast flashover and the essential elements is depicted in Figure 3. Electrons are field emitted at the metal-dielectric-vacuum triple function; surface charging which results causes many of the leading-edge electrons to arc back into the surface. Electrons with energies in the kilovolt range will cause secondary emission which multiplies the number of electrons. Another effect of this current is to generate a conductive plasma from material on the surface. Experiments on the effects of magnetic fields and velocity of the leading-edge electrons confirm the model.

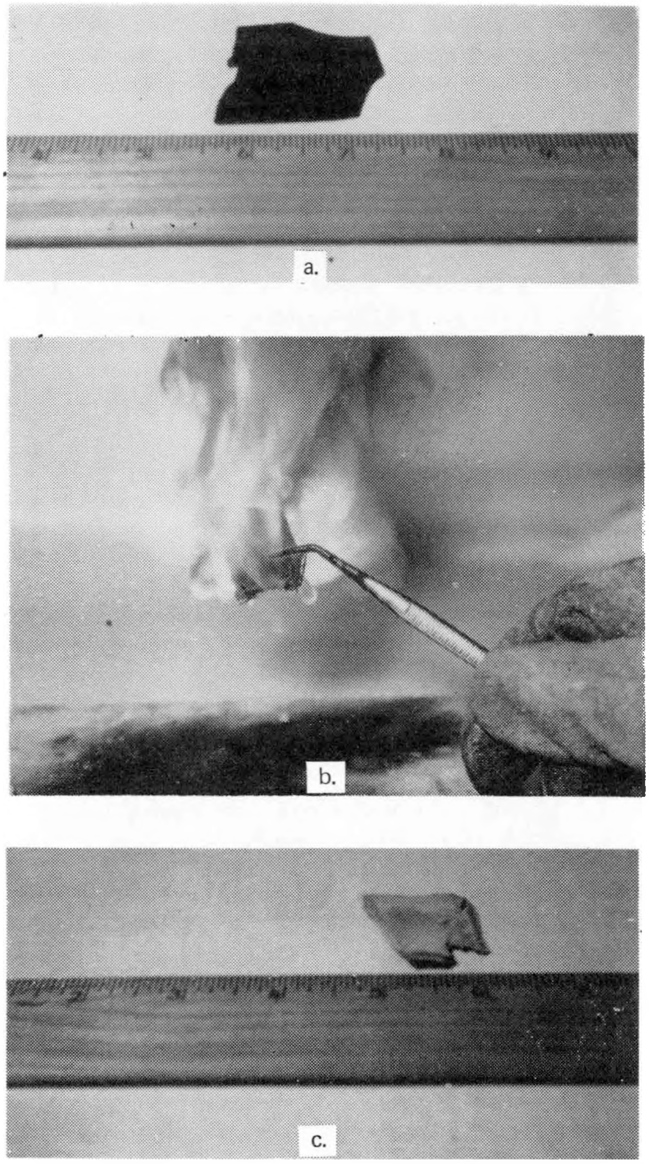

Figure 2. Self-destruct encapsulant before, during, and after ignition

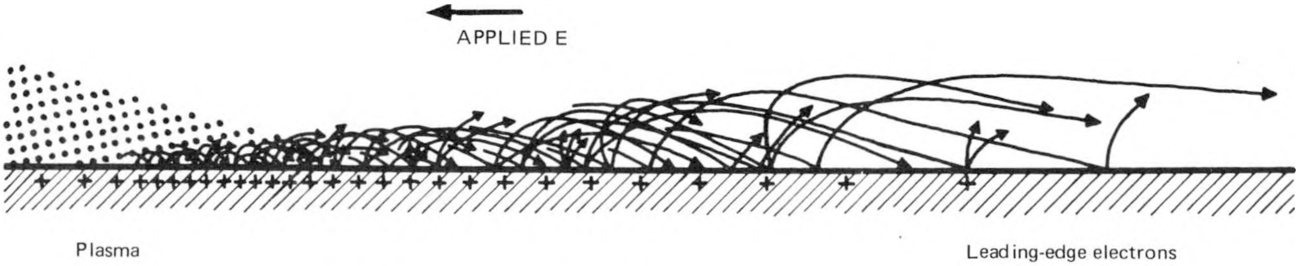

Figure 3. Regenerative electron multiplication and surface charging

CERAMICS

The study and development of ceramics with special properties provide a basis for designing and fabricating insulators, piezoelectric and ferroelectric generators, electrooptic devices, capacitors, envelopes, and other mechanical and electrical components.

Ferroelectric and Electrooptic Materials Development

The lead zirconate-titanate (PZT) ceramics are used in a variety of applications, including high-voltage and high-current generators. Specialized atmosphere sintering and hot-pressing procedures are being researched and developed to produce transparent ceramics for electrooptic applications (Items 1,2*).

Current Activities

- Explosively actuated power supplies
- Variable density filters and shutters
- Light gates (discrete, linear, and two-dimensional arrays)
- Small- and large-aperture fast shutters
- Polarization switches
- Spectral (color) filters
- Flash-blindness protection devices
- Ferroelectric-photoconductor (FE-PC) scattering-mode image and information storage devices
- FE-PC reflective-mode surface deformation image and information storage devices
- Optical voltage, current, power, and temperature sensors

Fabrication and Processing

Pilot plant facilities exist for fabricating experimental, developmental, and prototype ceramic components. Laboratory facilities support the development of new technology in the fabrication and processing of ferroelectric, thermoelectric, and alumina ceramic materials (Item 3).

Current Activities

- Ferroelectric transducers
- High-purity PLZT powders
- Ferrooptic devices
- Radioisotope-powered thermopiles
- Ceramic capacitors
- Thermistor materials
- Alumina insulators and substrates
- Refractories (kiln furniture)

*See Highlights, below.

General Fabrication Capabilities

- Powder processing (calcining, milling, sizing)
- Pressing (hydraulic and isostatic)
- Slip casting
- Firing (drying, sintering)
- Vacuum and atmospheric hot pressing
- Machining (grinding, drilling, slicing, lapping, polishing)

Special Facilities

- Clean tunnel for high-purity materials preparation
- Thin sheet casting
- Chemical vapor deposition (induction heating and plasma)
- Freeze drying
- Injection molding
- Ferroelectric electroding and polarizing
- Transducer assembly
- Punching and laminating press for capacitor fabrication
- Toxic materials machining

Properties Measurement

Ceramics are characterized in terms of structure, chemistry, electrical and mechanical properties, etc. In addition, some specialized measurements are made for specific project objectives.

Current Activities

- Electrical properties
  - Dielectric strength
  - Conductivity
  - Hysteresis loop parameters
  - Piezoelectric properties
- Optical properties
  - Electrooptic parameters
  - Transmission (optical density)
  - Refractive index
- Microstructure and powder characterization
  - Particle size
  - Density
  - Hot-stage microscopy
  - Optical and scanning electron microscopy
  - Surface area measurement
  - Differential thermal analysis

CERAMICS

- Fracture and mechanical properties
  - Fractographic analysis
  - Fracture velocity
  - Thermal expansion
  - High-temperature creep (viscosity)
  - Internal stress

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Pulse Power Generators*

Ferroelectric, antiferroelectric, and paraelectric ceramics, made principally from suitable modifications of the lead zirconate titanate compositions, are being used in the arming, fuzing, and firing of explosively actuated electrical power-supply components for high-voltage and high-current pulse power generation.

Item 2. *Electrooptic Ceramics*

Four ceramic elements from the first successful PLZT slug of a size near that required for the U. S. Air Force mosaic window are illustrated in Figure 1. The rectangular samples are 3 x 3-1/2 inches in size and 0.025 inch in thickness. A preliminary optical polish is used to evaluate material transparency. Wafers are arranged in mosaic form to simulate the aircraft window segment.

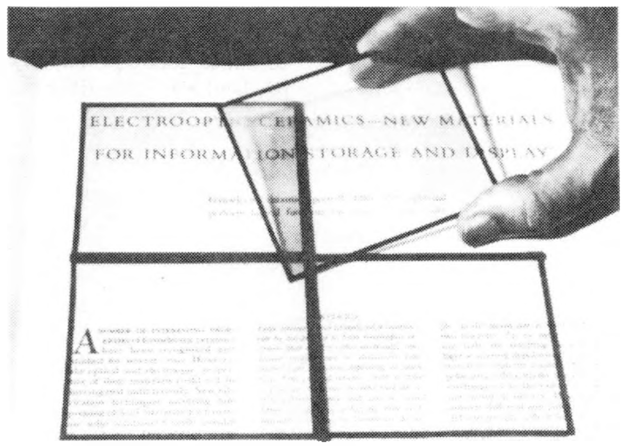

Figure 1. Mosaic window ceramic elements

Item 3. *High-Energy Density Ceramic Capacitors*

Ceramic capacitor compositions (Figure 2) based upon high-dielectric-constant, paraelectric phases in the lead-barium zirconate-titanate system are being developed primarily for high-energy density storage capacitor applications. Emphasis is on (1) development of compositions and processes for maximum energy density (2 to 10 joules per cubic inch), (2) studies of accelerated life testing (3) investigation of methods for attaining very high insulation resistance, and (4) hot-pressing for improved monolithic capacitors.

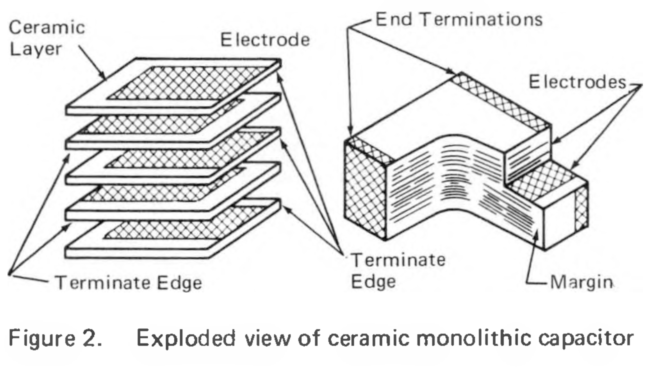

Figure 2. Exploded view of ceramic monolithic capacitor

GLASS AND GLASS CERAMICS

The utilization of glasses and glass-ceramics in component design proceeds through adaptation of "standard" materials by process development and through development of new materials with special properties. Implementation of the development programs requires capabilities ranging from production and evaluation of experimental melts to component prototype fabrication.

Glass

Various applications in nuclear technology and energy programs require the development of special glass materials and processes.

Current Activities

- Special glasses
  - Fuel waste disposal
  - Improved GSC-4 sealing glass
  - High-purity alkali borosilicates
- High-purity silica
  - Chemical vapor deposition
  - Plasma fusion of powder
- Solar energy
  - Antireflecting coatings
- Research
  - Role of water in mass and charge transport
  - Electrical conductivity

Special Capabilities

- Fabrication
  - Reactive plasma chemical vapor deposition
  - High-temperature tube drawing
- Characterization
  - High-temperature electrical conductivity

Glass-Ceramics

Glass-ceramics represents a new materials area featuring the ease of glass forming in fabrication of parts combined with the high-strength and high-temperature stability of ceramics. The wide range of compositions which can be crystallized and the variety of crystal morphologies that can be produced makes it possible to "tailor" a glass-ceramic for a specific application (Item 1*).

Current Activities

- Glass-ceramic-to-metal seals
  - Application of commercial glass-ceramics
  - Development of low-permeability glass-ceramics
  - Development of high-resistivity enamel
  - Pressure sealing and inert atmosphere sealing
- Frangibles (prestressed dicing materials)
  - Security systems
  - "Volatile" substrates
- Research
  - Nucleation and crystallization
  - Fracture velocity (atmospheric effects)
  - Gas permeation

Special Capabilities

- Fabrication
  - Glass melting and forming
- Characterization
  - Viscosity
  - Differential thermal analysis
  - Hot-stage microscopy

Fabrication and Melting

Support of the glass and glass-ceramic programs is provided in facilities which can synthesize and process melts from raw materials into shapes suitable for materials and component design evaluation. In addition, "standard" glasses can be processed by techniques ranging from traditional glassblowing to the bonding and sealing of glasses into complex structures (Items 2-4).

Current Capabilities

- Glass apparatus fabrication
  - Glassblowing (all types of glass, to a maximum of 18 inches in diameter by 36 inches long)
  - Forming
  - Reflective coatings (silver, aluminum)
  - Conductive coatings (gold, platinum, silver, tin oxide)
  - Vacuum baking, processing, and final sealing

*See Highlights, below.

GLASS AND GLASS CERAMICS

- Glass-to-metal seals
  - Fusion sealing (tubular, edge, butt, window, single and multiple pin seals)
  - Header design (for high voltage, high current, high or low operating temperature; resistance to thermal or mechanical shock, static or dynamic loads or corrosive environments)
  - Field-assisted glass sealing (sealing well below the softening point of glass)
- Glass coatings and bonds
  - Screen printing
  - Spraying
  - Electrophoretic deposition
  - Transfer tape
  - Vacuum hot pressing (for precision, pore-free bonds)
- Specialty glass melting and forming
  - High-temperature melting
  - Rod and tube drawing
  - Pressing
  - Heat treating (annealing, crystallizing)
  - Machining

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Glass-Ceramic Materials*

The high-temperature stability of glass-ceramics and the ability to tailor glass-ceramic properties to specific requirements are being utilized in various applications. Figure 1 shows a low-permeability glass-ceramic employed as an insulator in a prototype long-life tube.

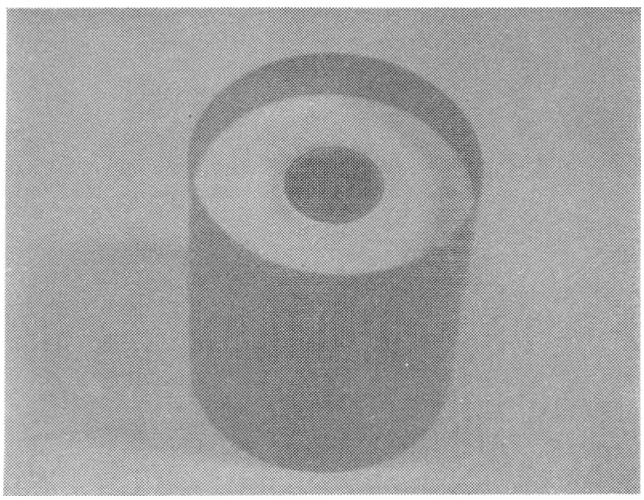

Figure 1. Low-permeability glass-ceramic as an insulator in a long-life tube

Item 2. *Glass Melt and Pour*

Figure 2 shows a technician pouring molten glass into a machined mold. The glass will be pressed into the mold with the carbon paddle held by the second operator to produce a complex finished glass part.

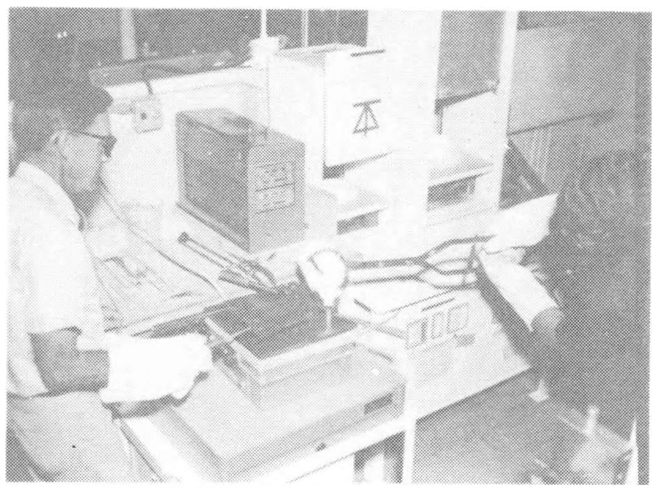

Figure 2. Glass molding operation

Item 3. *High-Vacuum Quartz Microbalance*

Figure 3 shows an example that portrays the glass technology necessary for the fabrication of this system, which is used to prepare thin-film samples for metallurgical and crystallographic studies. The following features allow highly precise gravimetric determinations to be made during deposition under controlled conditions:

Magnetic shutter
Vacuum dewar
Electron gun
Cryogenic pumping
Evaporation source
Glass-to-metal seals
Interior coating of transparent conductive film

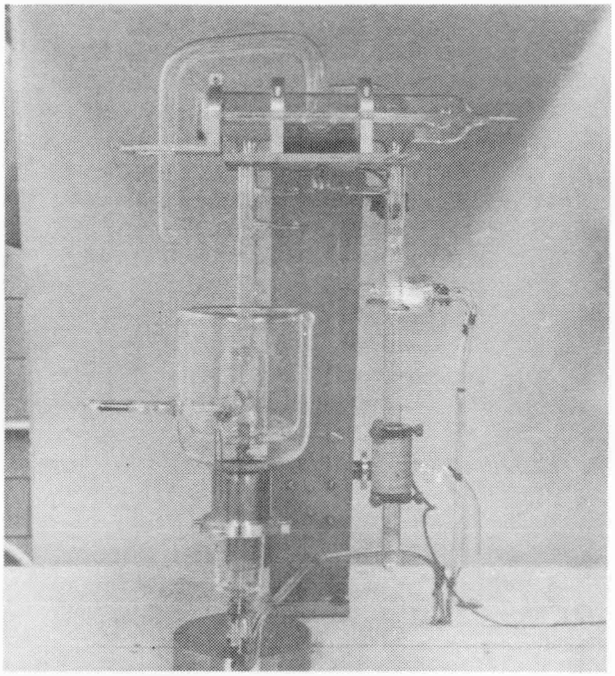

Figure 3. High-vacuum quartz microbalance

Item 4. *Glass-to-Metal Headers*

An array of hermetically sealed multiple-pin stainless-steel headers is shown in Figure 4. The extreme dimensional tolerances of the electrode positions required the design, fabrication and use of special fixtures with expansion characteristics that closely match those of the header, in addition to features that control the delicate formation of oxides necessary for strong glass-to-metal seals.

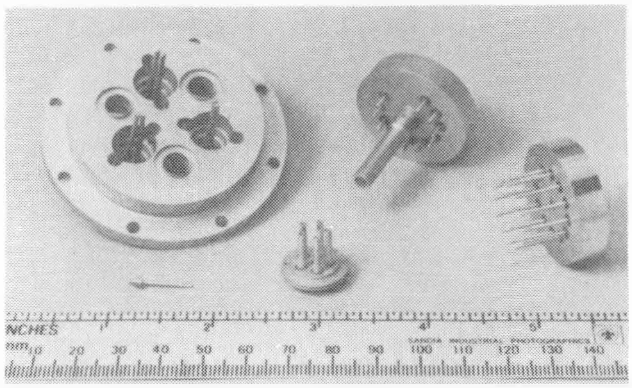

Figure 4. Typical headers

HIGH-TEMPERATURE CHARACTERIZATION OF MATERIALS

Advanced systems have required materials capable of withstanding exposure to extreme environments, particularly that of high temperature. As a result, extensive capabilities have been developed for measuring the behavior of materials in both pulse heating and continuous heating conditions. Examples of some of the special capabilities which have been developed are (1) techniques for measurement of extremely high temperatures, (2) techniques for acquisition of physical properties at these temperatures, (3) methods and analysis procedures for determining thermomechanical response of materials during high-energy pulse heating, and (4) material handling methods which enable studies of material chemical reactions occurring under extreme temperature conditions.

High-Temperature Properties of Materials

Studies of phase relationships, chemical properties, and physical properties of materials at extremely high temperatures provide a basis for the design and analysis of advanced systems for high-temperature applications (Items 1-5*).

Current Activities

- Investigation of the phase diagrams of carbon and other refractories
- Determination of the vaporization kinetics of carbons and metal carbides under pulse heating conditions
- Thermal diffusivity studies of carbons and metal carbides at temperatures above 3000°K
- Enthalpy and heat-capacity measurements of liquid uranium and its alloys
- Studies of the combustion of several refractory metals
- Development of a theory of vapor nucleation in refractory materials
- Extensive investigation of the melting behavior of refractory oxides
- Studies of high-temperature melting-point standards
- Theoretical investigation of critical phenomena in metals
- Metal-hydrogen phase studies at high temperatures and pressures
- Development of advanced pyrometric techniques
- Mechanical properties to 3000°C

Dynamic-Thermal Response of Materials

Extremely rapid pulse heating of materials results in stress waves which can produce considerable material damage. Activities here are directed toward developing methods for controlling the generation and propagation of these waves so that their effects are minimized. This involves developing experimental and analytical methods for measurements in many areas.

Current Activities

- Internal stress generation
  - Grüneisen parameters
  - Effects of porosity, inhomogeneities, and anisotropy
- Stress propagation
  - Effects of porosity, inhomogeneities, and anisotropy
- Damage and failure
  - Spallation
  - Compaction
  - Degradation of properties
- Phase changes and thermal effects at high temperature
  - Solid-solid transformations
  - Melting
  - Vaporization

The above measurements were accomplished by developing techniques using the following specialized equipment:

- Pulsed electron beam machines
- Pulsed lasers
- Velocity and displacement interferometers
- Holography and holographic interferometers
- Piezoelectric gaging
- Ballistic pendulum gaging

Thermal Properties

Techniques have been established for obtaining data on the various thermal properties required for system design and application. The facilities which have been developed can make rapid measurements on a wide variety of materials.

*See Highlights, below.

HIGH-TEMPERATURE CHARACTERIZATION OF MATERIALS

Studies in thermal properties are directed to an understanding of the response of materials to intense pulses of energy. In particular, they are used to understand blowoff-induced impulse (Item 6).

Current Activities

- Thermal conductivity
- Thermal diffusivity
  - Positive and negative pulse methods, multiple sample handling
- Thermal expansion
- Enthalpy and heat capacity
  - Electromagnetic levitation and liquid-gas (inert) calorimetry
- Radiative and absorptive properties

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Vaporization of Refractory Materials Under Pulse Heating Conditions*

In many instances, the vaporization behavior of refractory materials under pulse heating conditions must be known to evaluate system performance. An example occurs in safety analyses of nuclear reactor excursions. Techniques such as those shown in Figure 1 are required to obtain vaporization data for such hostile environments. Here a high-energy pulsed laser is used to provide intense momentary heating of fuel materials. The composition of the resulting vapor is then analyzed with a time-of-flight mass spectrometer.

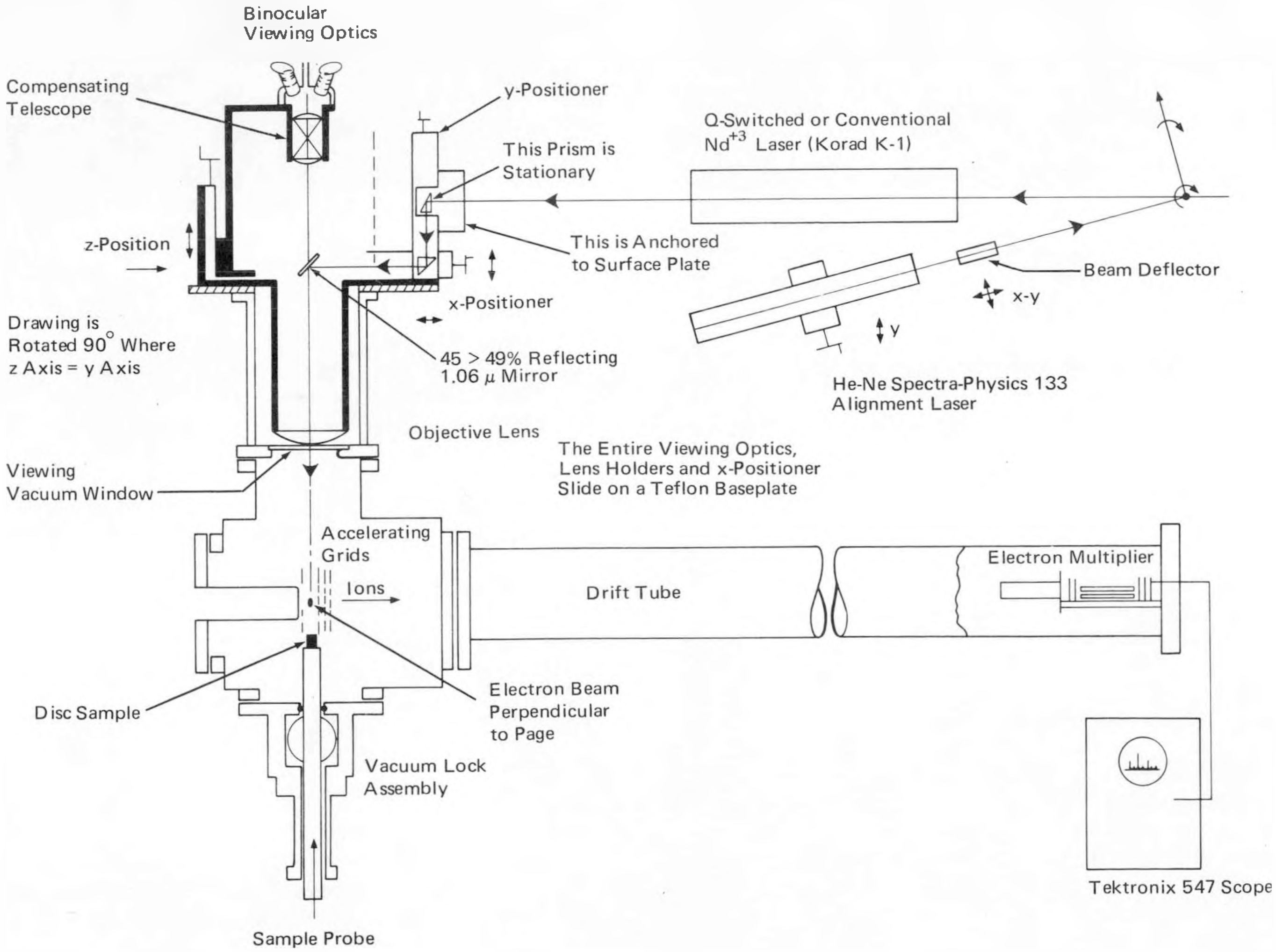

Figure 1. Laser-mass spectrometer system

HIGH-TEMPERATURE CHARACTERIZATION OF MATERIALS

Item 2. *Liquid Metal Levitation*

In Figure 2, a sample of liquid uranium is levitated and heated in an electromagnetic field in preparation for dropping into a liquid argon calorimeter for heat-capacity measurements. Electromagnetic levitation heating is a valuable tool for high-temperature measurements because it eliminates reactions with containers. The liquid argon calorimeter is also important because it too provides a totally inert environment.

Item 3. *Exploding Zirconium Droplet*

A small droplet of zirconium metal is heated to above its melting temperature and allowed to drop through an oxygen atmosphere. At a certain stage in the combustion process, the droplet explodes and produces many small droplets of incandescent material (Figure 3).

Item 4. *High-Pressure Isotherms of Uranium Hydride*

Studies of the pressure-temperature-composition relations of hydrides are conducted at up to 10,000 psi and 1000°C. Isotherms (Figure 4) for the uranium-hydrogen system show the pressure plateaus indicative of a two-phase region connecting the metal and uranium trihydride phases.

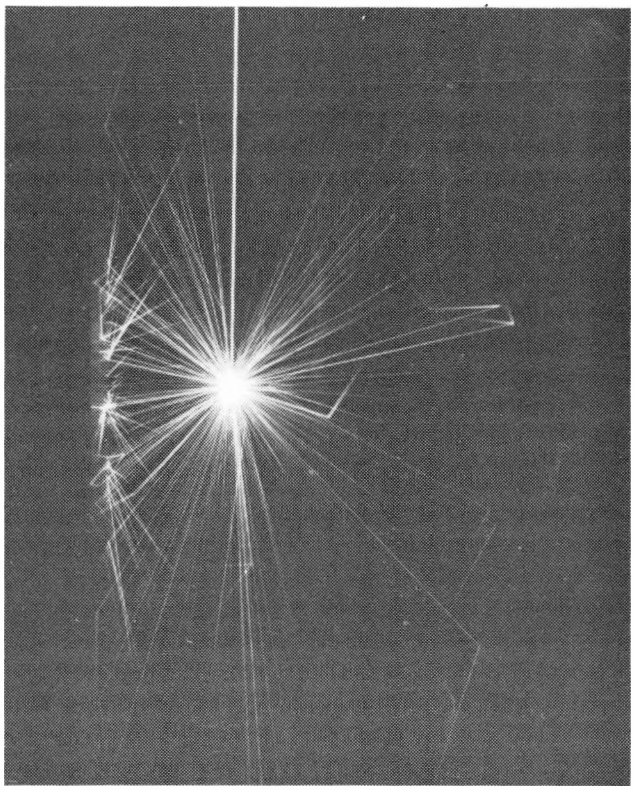

Figure 3. Metal combustion

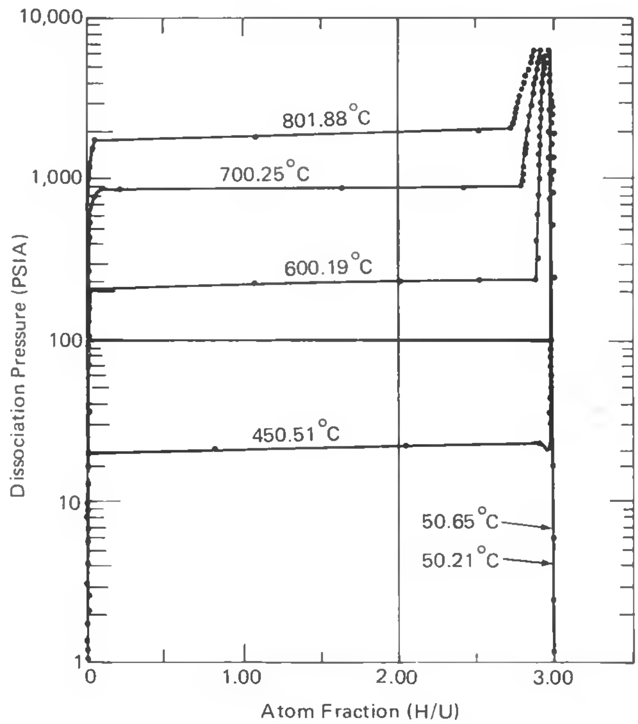

Figure 4. Uranium-hydrogen system isotherms

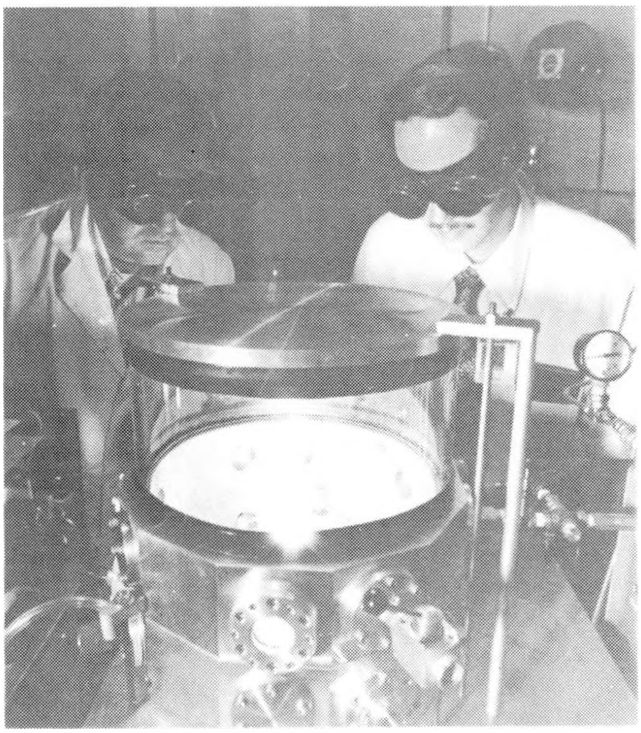

Figure 2. High-temperature property measurements

HIGH-TEMPERATURE CHARACTERIZATION OF MATERIALS

Item 5. *High-Temperature Mechanical Properties*

The very high-temperature mechanical properties of graphitic materials are being determined after short times (seconds) at temperature and at strain rates up to approximately 10 per second. The technique employs self-resistance heating of the tensile or compressive specimen by passing a high electrical current through the specimen in a preprogrammed, feedback-controlled heating cycle and then mechanically loading the specimen monotonically or cyclically through a predetermined stress or deformation history. Load and strain are monitored electronically and optically so that constitutive relations and fundamental deformation mechanisms for arbitrary thermal and mechanical histories can be determined.

In order to prevent thermal conduction along the specimen and in the end grips from producing large temperature gradients in the specimen, the graphite grips are heated separately by radio-frequency induction to create thermal barriers (Figure 5).

The strain is determined by optically tracking 3 to 5-μm-thick metal targets sputtered onto the specimens, which are illuminated by an argon laser. The optical trackers view through narrow-band interference filters to block out the specimen incandescence. The technique has general applicability for studying the thermomechanical behavior of any conducting material subjected to particular thermal and/or deformation histories, including cyclic loading, thermal ratcheting and creep. Graphite sublimation temperatures can be reached in a few seconds under controlled conditions.

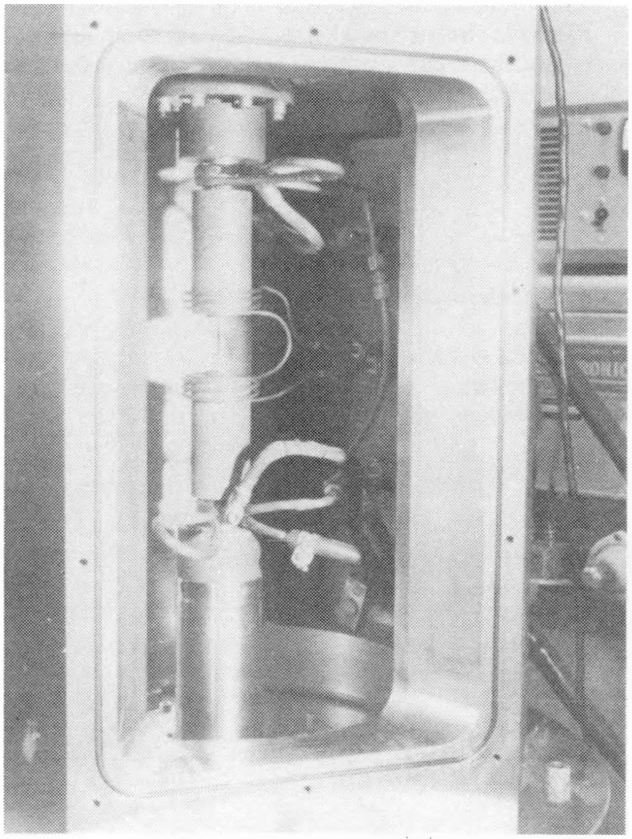

Figure 5. Graphite tensile specimen is shown in position in high-heating-rate, medium-strain-rate system. Photo shows induction coils for heating graphite grips, current leads for resistively heating specimens, and cooling coils to protect insulators and the load cell.

Item 6. *Thermal Diffusivity*

The apparatus used to make thermal diffusivity measurements employs a pulsed ruby laser to induce a thermal transient in materials. It is arranged to accommodate up to 20 samples at one time and to acquire and process the data automatically; this is one of the largest-capacity systems in the world for thermal property measurements (Figure 6).

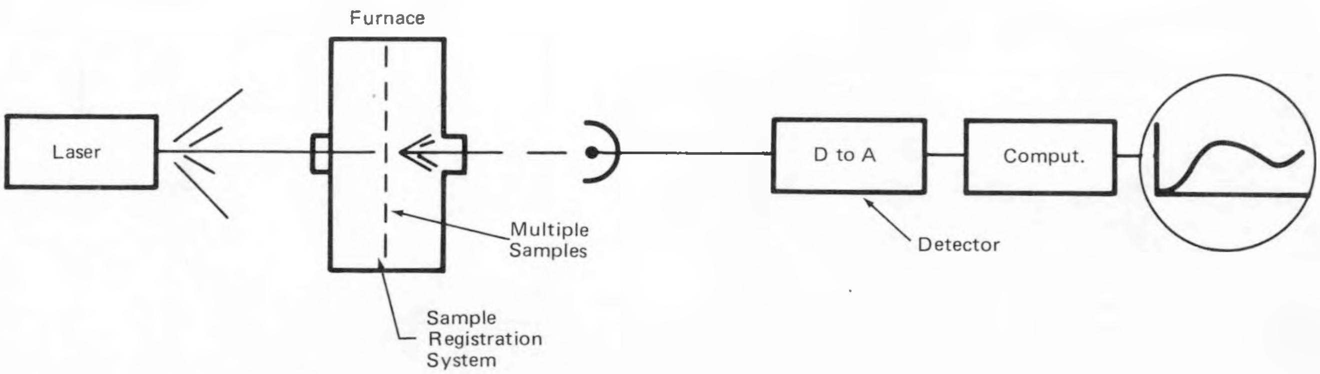

Figure 6. Pulsed thermal diffusivity measurements

LABORATORY ANALYSIS

The generation of accurate information on the composition, structure, and morphology of materials is the basis for a capability for predicting material responses in extreme environments and optimizing the selection of materials for design. A modern analytical capability promotes the use of complementary methods of materials characterization and allows analyses of commercial and experimental materials. Recent accomplishments include detailed analyses of solid-state materials, complete descriptions of filamentary "growths" on electrical contacts, and examinations of multiple phases resulting from high-temperature diffusion phenomena.

Analytical Techniques

Classical and advanced instrumentation techniques for the qualitative and quantitative characterization of materials are available (Items 1- 4*).

Current Activities

Solution Techniques
- Gravimetry
- Titrimetry
- Coulometry
- Ion-selective electrodes
- Polarography
- Absorption spectrophotometry
- Atomic absorption spectrometry

Direct analytical methods
- Organic microanalysis
- Gas chromatography
- Activation analysis
- Vacuum fusion
- X-ray fluorescence spectrometry
- Emission spectroscopy

Structure/spatial distribution methods
- Electron microprobe
- Photoelectron spectroscopy
- Ion scattering spectroscopy
- X-ray diffraction
- Scanning electron microscopy
- Transmission electron microscopy
- Appearance potential spectroscopy

*See Highlights, below.

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Gas Chromatography/Mass Spectrometry*

With the use of gas chromatography to effect separations and mass spectrometry to identify individual species, volatile samples can be quickly and accurately identified. Figure 1 is a chromatogram of the gases from a shale oil study and the mass spectrum of one of the compounds which was produced.

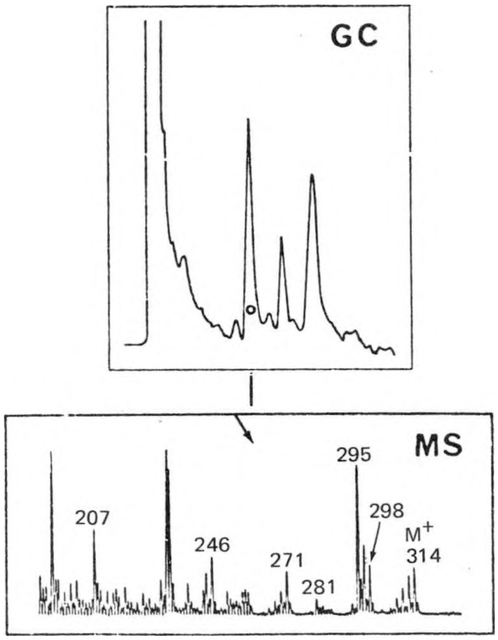

Figure 1. Gas chromatogram and mass spectrum of a compound produced

Item 2. *Electron Microprobe Technique*

The life expectancy of interconnections used in thermopiles constitutes a serious constraint on design. At normal operating temperatures, solid-state diffusion can result in the loss of circuit continuity in unacceptably short times. Platinum-rhodium alloy is currently being considered for use as an interconnection in a pile which makes use of silicon-germanium as the thermoelectric. The curves in Figure 2 show the variation in elemental composition across the interconnection-thermoelectric interface resulting from elevated temperatures. The data were acquired with the electron microprobe operating under computer control, and the plot was generated automatically by the instrument.

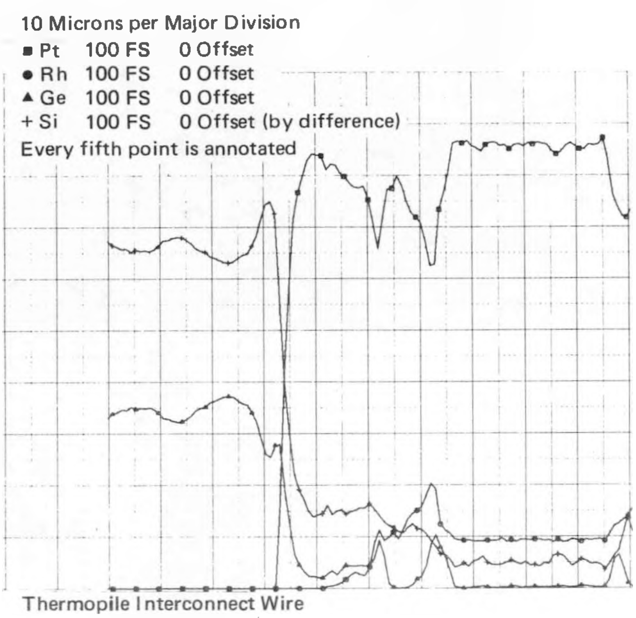

Figure 2. Data obtained by electron microprobe

Item 3. *Chemical Methods*

Porosity in a gold-chromium thin-film system was determined to be the primary cause of lead failures in a hybrid microcircuit system. A chemical spot test technique in which the reagent is dissolved in a gel was used to verify the existence of pores and show their spatial distribution. Figure 3 shows the surface after use of the spot test reagent.

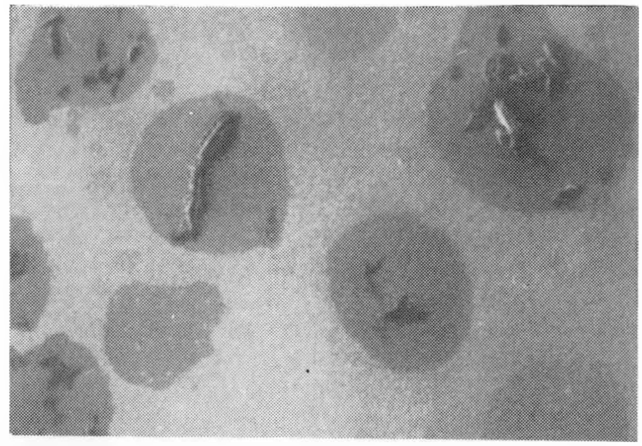

Figure 3. Chemical spot test technique

Item 4. *Scanning Electron Microscopy*

This technique is used to identify contamination and flaws resulting from poor bonding, hot spots, and melt regions. Figure 4 shows a deposit of corrosion products on a wire lead which is bonded to a microcircuit. The ability to describe such irregularities contributes significantly to quality and process control activities.

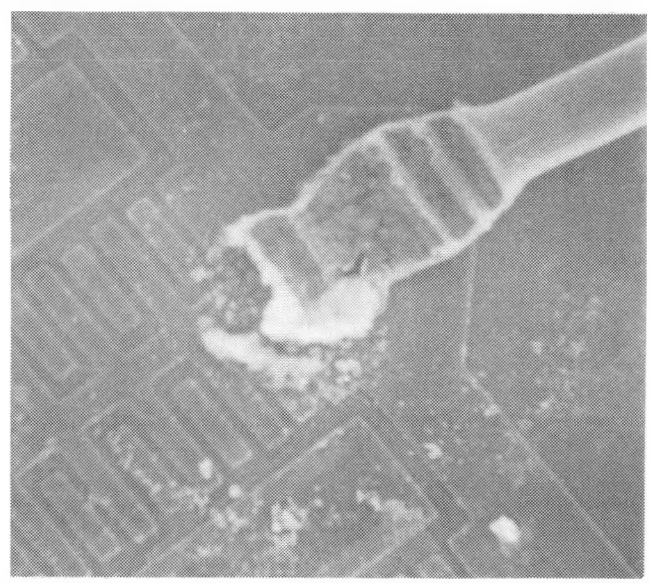

Figure 4. Identification of contamination

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Sandia Laboratories Technical Capabilities

Measurement Standards

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115
and Livermore, California 94550 for the United States Energy Research
and Development Administration under Contract AT(29–1)-789

MEASUREMENT STANDARDS

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SANDIA LABORATORIES TECHNICAL CAPABILITIES

MEASUREMENT STANDARDS

ABSTRACT

This report characterizes the measurement standards capabilities at Sandia Laboratories. Selected applications of these capabilities are presented to illustrate the extent to which they can be applied in research and development programs.

MEASUREMENT STANDARDS*

The measurement standards activity assures measurement agreement among participating research, development, design, production, acceptance, and quality assessment groups and agencies. To this end it promotes a common administrative and technical base of procedure and capability, embodied in physical references and practices of high accuracy and sophistication. When possible, values are referred to those defined by the National Bureau of Standards.

Activities of the ERDA Primary Standards Laboratory, which is managed by Sandia Laboratories, are aimed at the development and maintenance of primary reference standards, and their application to the calibration of other reference standards in the overall standards system. A research and development program in measurement technology is devoted to assuring that new standards and accuracy levels will be available when required. Program and measurement activities of participating groups and agencies are examined on a continuing basis, for the purpose of formulating recommendations to assure balance and compatibility in standards efforts. Consultation service is provided on measurement and standardization problems, and technical audits and surveys of contractor standards laboratories are conducted on a regular basis.

In addition to the Primary Standards activity, a hierarchy of standards laboratories and calibration stations carries the units of measurement to the working level. Standard quantities maintained and applied include parameters of direct and alternating-current electricity, microwave measurements, electrical pulse characterization, radiation (ionizing and optical), mechanical measurements (including length and mass), and environmental measurements.

Measurement standards capabilities may be divided into two areas: administrative, or program management, and technical, or measurement disciplines.

Measurement Standards Staff
and Investment in Equipment

	Staff	Investment in Equipment (in $1000)
Measurement Standards Program Management	8	–
Measurement Disciplines		
Direct Current	14	900
Alternating Current	11	450
Microwave	5	700
Electrical Pulse	4	250
Radiation	3	300
Mechanical	15	800
Environmental	12	800

*Compiled in January 1975.

MEASUREMENT STANDARDS PROGRAM MANAGEMENT

Program management efforts are concerned with the technical administration of the overall standards and calibration system. A system has been established to provide physical measurements when and where needed, and to assure that measurements made by many different agencies are accurate. This requires attention to practices used from research activities through manufacture and quality assessment. The magnitude of the commitment is illustrated by the schematic representation of the Energy Research and Development Agency and the Albuquerque Operations Office standards and calibration system shown in Figure 1, and by the fact that more than 270,000 items are calibrated by some 500 metrologists and technicians in this system each year.

Technical audits (measurement experiments) are conducted periodically to determine the degree of technical competence of participating laboratories and groups. Formal surveys of the operations of standards laboratories are aimed at confirming good technical and administrative practices. As needed, new standards and procedures are developed and disseminated throughout the system. Assistance, advice, and instruction are made available through numerous functions of the Primary Standards Laboratory including courses and seminars, studies of environmental factors such as shock measurement and control during shipment of instruments, recommendations relating to the specifics of facilities and equipment for standardization and measurement, and application of computers to technical (data reduction) and administrative (instrument recall and control) problems. Activities in support of national and international standards include the issuance of contracts to the National Bureau of Standards for development of advanced measurement methods, and participation on international standards committees.

Recently instituted measurement-assurance programs are aimed at the application of statistical methods to the continued assurance of good measurements throughout the system. In these programs, the accuracy capabilities of standards laboratories are determined by checking personnel, equipment, procedures, and techniques as well as reference standards.

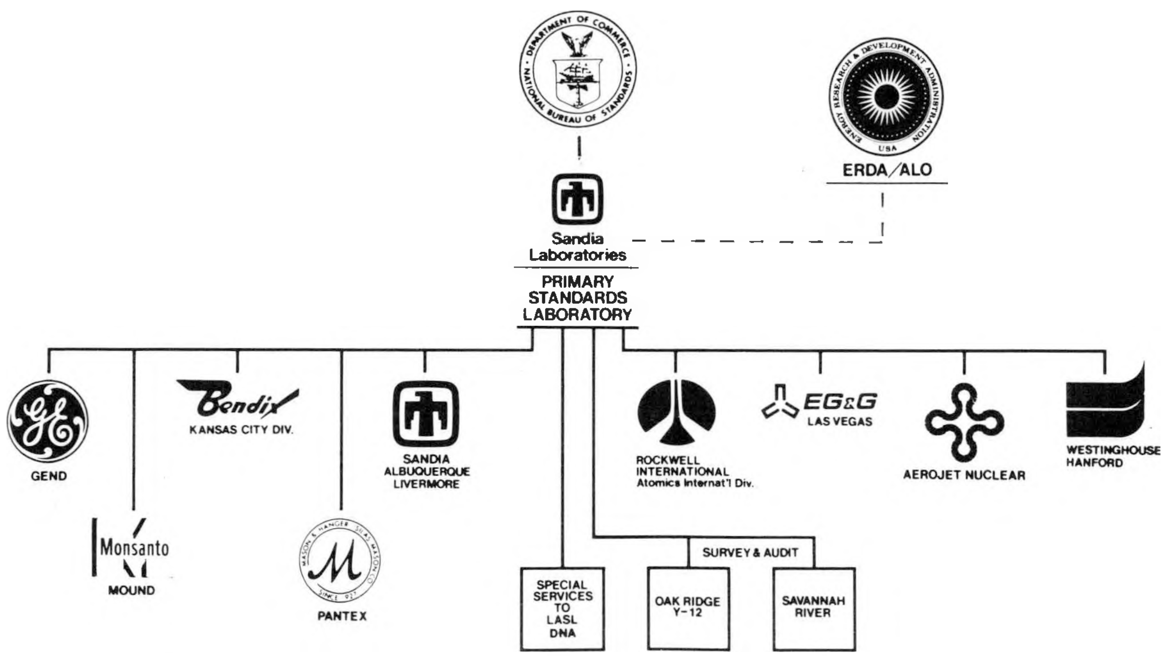

Figure 1. Standards program

MEASUREMENT DISCIPLINES

Technical activities are aimed at establishing, maintaining, and applying standards that are the physical representations of measurement units. A calibration capability is maintained for a broad range of reference and transfer standards as well as for a wide variety of measuring instruments. The measurement facility has the equipment and expertise for special measurements of unusual accuracy or difficulty, and provides consultation on measurement problems.

A significant part of the technical effort is directed toward the development of new standards, procedures, and automated calibration systems. (Item 1)*

Direct-Current Electrical Quantities

The value of the volt is maintained with groups of saturated standard cells, and is kept in agreement with the legal national reference by participation in the National Bureau of Standards Transvolt Program. Transportable standard cell banks are used to transfer the value to other laboratories. The standard of resistance is maintained with a group of Thomas 1-ohm resistors, some of which are carried to the NBS each year for certification. Saturated cells, standard resistors, and auxiliary precision instruments are used to measure current, to calibrate ratio devices that extend the range of voltage and resistance measurements, and to assign values to standards and instruments used by other laboratories. Research and development are conducted to achieve the higher accuracies required by such diverse activities as electron-beam applications and determination of the half-life of radioactive materials. (Items 2-4)

Current Activities

- Standardization
  - Maintain voltage standards
  - Maintain resistance standards
  - Determine ratios
  - High-voltage facility
  - High-current facility
- Development
  - AC Josephson volt standard
  - Transportable standard cell bank
  - Automatic standard-cell test facility
  - High-resistance bridges
  - Computerized data analysis
- Evaluation
  - Zener diode voltage standards
  - Unsaturated standard cells
  - Current comparator bridge methods
  - Drift in standard resistors

*See Highlights below.

Alternating-Current Electrical Quantities

Quantities standardized are alternating voltage and alternating current, lumped parameter impedance, voltage and current ratio, and time and frequency. Voltage and current measurements are made principally using thermal transfer methods, which compare reactance-free resistive heating effects of the alternating parameters with those of the corresponding direct parameter. Measurements are made over a frequency range of approximately 10 Hz to 1000 MHz.

Specialized services are supplied for research and development. One example is the dissemination of timecodes by telephone line, facilitating time measurements at widely scattered locations with 0.0001-second agreement. (Item 5)

Current Activities

- Standardization
  - Thermal transfer standards
    - Voltage
    - Current
  - Capacitance
  - Inductance
  - Ratio Transformers
- Development
  - Thermal transfer techniques
  - High-frequency, very low-reactance measurements
- Time and Frequency Dissemination
  - WWV time and frequency signals
  - Time codes
  - Standard frequencies
- Consultation
  - Unusual reactance measurements
  - Special time and frequency measurements

Microwave Quantities

Microwave measurements are made at wavelengths generally in the 2 to 200-cm range. Signals at these wavelengths are used in radar, telemetry, communications, and

MEASUREMENT DISCIPLINES

dielectric-loss heating systems. Standards and measurement capabilities find application in the electrical characterization of items such as signal sources, passive and active transmission-line components, signal detectors, antennas, and materials. Recent developments in the areas of automated data-taking, quantum devices, and transmission-line theory provide the basis for research and development efforts in this area. (Items 6, 7)

Current Activities

- Standardization and Measurement
  - Attenuation
  - Impedance
  - Phase shift
  - Pulse power
  - Continuous-wave power
  - Electrical length
  - Complex dielectric constant
  - Power efficiency
  - Reflection coefficient
  - Coupling, directivity factor
  - Distributed cable parameters
- Development
  - Network analyzer calibration
  - Sandwich slot-line matching
  - Power equations
  - Attenuation measurements via cryoelectronics

Electrical Pulse

Primary effort has been directed toward the understanding of pulsed current and voltage effects on components designed to function at much lower levels of (continuous) stress than those applied in the pulsed application. Fortunately many components will tolerate very high stresses for very short periods of time, if the time-averaged stress is low. However, the component may exhibit unexpected characteristics under operating conditions, involving both reversible and irreversible changes. Studies are made of high-voltage-gradient and power effects on the performance of components, and of initiation and propagation of breakdown. Test systems have been developed for measuring the performance of various pulse voltage and current generating and measuring equipment. Development work has advanced the state of the art in measurement at relatively low levels (Item 8) and advanced new concepts of voltage measurement at high levels. (Item 9)

Current Activities

- Development
  - Electrooptic systems
  - Voltage dividers
  - Calibration systems
    - Current-viewing resistors
    - Current pulse transformers
  - Current pulse generators
  - Voltage pulse generators
- Standardization
  - Capacitive voltage dividers
  - Resistive voltage dividers
  - Current transformers
  - Electrooptic systems
  - Peak-reading voltmeters
  - Current-viewing resistors

Radiation Standards

Standards of measurement are maintained for sources and detectors of optical, alpha-particle, and pulse neutron radiation. Laser power and energy are measured calorimetrically. Emission rates from alpha-particle sources are determined in a gas-filled proportional counter. Pulse neutron standards have been developed without the benefit of comparable standards at the national level, and are based on associated-particle counting at the target of the positive-ion accelerator where test pulses are generated.

The detailed implementation of pulse neutron standards has led to limited capabilities in continuous-emission natural-source (Pu Be) neutron standards, and strengths and quantum energies of gamma sources. (Items 10,11)

Current Activities

- Calibration
  - Laser power
  - Laser pulse energy (to 2 J)
  - Activation-type pulse neutron detectors
  - Check sources for neutron detectors
  - Alpha source emission rate
  - Special timers
  - Nuclear scalers (counters)
  - Specialized nuclear measurement equipment
    - Pulse generators
    - Spectrum splitters
    - Detector gain control loops
    - Programmed power supplies
- Design and development
  - Laser pulse calibration
  - Radiometry
  - Low-geometry alpha detector
  - Alpha emitter disintegration rate measurement
  - Spectrum peakfinder (analog)
  - Radionuclide half-life measurements
  - Delay/gate timers
  - Data interface hardware
  - New primary pulse neutron calibration facility

- Special measurements
  - Optical properties of materials
    - Refractive index
    - Birefringence
    - Electrooptic coefficient
  - Alpha source emission spectrum
  - Gamma source energy spectrum
  - Check source strength and purity
  - Pulse neutron detector quality

Mechanical Measurements

Measurements encompassed by this discipline are those characterized primarily by a physical property. Specific measurements include mass, length, pressure, flow, volume, specific gravity, and vacuum.

Whenever possible, measurements are referred to NBS calibrated standards. Two activities — mass and length — rely only upon NBS analysis programs for their operation and control. In areas where NBS does not provide calibrations (e.g., gas leaks), measurements are determined by combinations of the fundamental standards: mass, length, time, and temperature. Where feasible, check standards are incorporated into the measurement process for routine monitoring of measurement accuracy.

Measurement processes in this discipline are continually undergoing improvements in accuracy and/or extensions of range. (Items 12-15)

Current Activities

- Standardization and Measurement
  - Gas flow
    - Gas leaks
    - Flow nozzles
    - Flow venturis
    - Laminar flowmeters
    - Variable-area flowmeters
    - Thermal gas flowmeters
  - Geometry
    - Angle
      - Cylindrical squares
      - Autocollimators
    - Flatness
    - Roundness
    - Surface texture
    - Specific forms
  - Length
  - Mass
  - Pressure
    - Micromanometers
  - Vacuum
  - Volume
- Development
  - Gas flow modeling of flowmeters
  - Dynamic gas-flow standards
  - Leak equations
  - Absorbing film thickness measurement
  - Multiple film thickness measurement
  - Gage-block calibration by comparison methods
  - Mass-analysis program for special nuclear materials
  - Density determination
  - Dual piston gage development
  - Pressure safety analysis
  - Evaluation of vacuum gages
  - Evaluation of vacuum hardware
  - Vacuum standards development
  - Vacuum-gage transfer standards

Environmental Standards

Standards of measurement are maintained for humidity, acceleration, temperature, and some chemical constituents. Areas of application include environmental measurements, simulated-environment testing, advanced development, and safety. Continuing analysis of the accuracy of acceleration standards has led to specialized capability in single-degree-of-freedom accelerometer response characterization in both time and frequency domains. (Items 16-18)

Current Activities

- Calibration
  - Humidity sensors
  - Dew-point hygrometers
  - Psychrometers
  - Seismometers
  - Shock accelerometers
  - Vibration accelerometers
  - Platinum resistance thermometers
  - Thermocouples
  - Optical pyrometers
  - Ribbon-filament lamp standard
  - Liquid-in-glass thermometers
  - Refractory-metal thermocouples
  - Infrared pyrometers
  - Total-radiation pyrometers
  - Standard gas mixtures
- Design and development
  - Accelerometer pulse calibration
  - Instrument/computer interface hardware
  - Voltage zero-crossing detectors
  - Instrument-control logic circuits

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Special measurements
- Mass loading of piggy-back vibration standards
- Characteristic response of accelerometers
- Cross-axis sensitivity of accelerometers to 10,000 Hz
- Step response of humidity sensors
- Background vibration in measurement laboratories
- Moisture level within sealed assemblies
- Reentry vehicle acceleration instrumentation

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Typical Measurement Accuracies*

Typical accuracies for a number of different measurements are given below. The values quoted are well within the capability of the Primary Standards Laboratory. They do not, however, apply to every calibration, since certified accuracies depend upon the quality of the item submitted for calibration and the specified period for which the certification is valid. In most cases, measurement precision (repeatability) is much better than the accuracy quoted.

Quantity	Range	Accuracy
DC voltage	Microvolts to 150 kV	0.0001 to 0.1%
DC resistance	0.0001 to 10^{14} ohms	0.0003 to 5%
DC current	10^{-8} to 3000 A	0.0010 to 0.025%
DC ratio	1:1 to 1:100,000	0.0001 to 0.1%
Capacitance	10^{-8} to 1.1 F 10 Hz to 100 MHz	0.0005 to 4%
Inductance	10^{-9} to 1000 H 10 Hz to 100 MHz	0.02 to 4%
AC voltage	30 μV to 1000 V 10 Hz to 900 MHz	0.005 to 6%
AC current	5 mA to 200 A 10 Hz to 50 KHz	0.02 to 1%
Reflection coefficient	100 to 6000 MHz (swept) 20 to 18,000 MHz (fixed)	0.02 to 0.05% 0.003 to 0.01%
Power (continuous wave)	0.1 to 10,000 mW 30 and 100 to 12,400 MHz (fixed)	1.5 to 7%
Power (pulse)	0.1 to 5000 mW 800 to 8000 MHz (fixed)	3 to 10%
Attenuation - 0 to 80 dB 0 to 50 dB	30 to 16,000 MHz (fixed) 100 to 6000 MHz (swept)	0.007 to 0.5 dB 0.1 to 0.6 dB
Pulse current	To 1000 A	4%
Pulse voltage	To 600 KV	1 to 4%

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Quantity	Range	Accuracy
Laser power at 633 nm λ	1 to 60 mW	8%
Laser pulse energy at 633 nm λ	10 mJ to 2 J	15%
Alpha particle emission	10^2 to 10^6/min	3 to 6%
Neutron short pulse	10^3 to $10^8/cm^2$	9 to 25%
Gas flow	10^{-12} to 10^{-3} cm^3/s STP 10^{-3} to 10^4 cm^3/s STP	5 to 50% 1/2%
Length	To 200 nm 0.01 to 20 inches 4 to 20 inches	5 nm 2 to 4 μ inches 1 μ inch/inch
Mass	1 mg to 1 Kg 2.5 to 1000 lb	0.0001% 0.0003%
Pressure	0 to 500 psi 500 to 100,000 psi	0.02% 0.25%
Vacuum	10^{-8} to 10^{-3} torr 10^{-3} to 1 torr	10% 3%
Volume	To 500 cm^3 500 to 10,000 cm^3	0.1 cm^3 To 0.25%
Humidity – dew point	-60° to +65°C Equivalent dew point temperature	0.2 to 2°C
Vibration	10 to 10,000 Hz @ 10 x gravity peak	1.5 to 2.5%
Shock	500 to 10,000 x gravity	5%
Temperature	-183° to 6300°C	0.003° to 30°C

Item 2. *Josephson Volt Facility*

The Josephson junction is a superconducting solid-state quantum device in which electrical conduction takes place by means of coupled electron pairs. It has numerous remarkable characteristics, one being the direct conversion of frequency (of an applied electrical field) to electrical potential according to quantum-mechanical principles. Since extremely accurate frequency standards are now commonplace, this capability of the junction makes practical the establishment of very accurate voltage standards.

In July 1972, the U. S. Legal Volt became linked to the Josephson volt by the assigned value of 483.593420 THz/V_{NBS} for the constant 2 e/h, where e is the charge on the electron, h is Planck's constant, THz is terrahertz, and V is volts. A Josephson volt facility is being established at Sandia Laboratories. It will increase the accuracy of voltage standards in the Primary Standards Laboratory and reduce problems associated with maintaining standard-cell voltage reference banks. Disadvantages of the new facility include the requirement that the junction must be operated at temperatures approaching absolute zero, and the small potential developed: only 5 to 10 millivolts with an applied signal in the 5-to-10 gigahertz range (Figure 1).

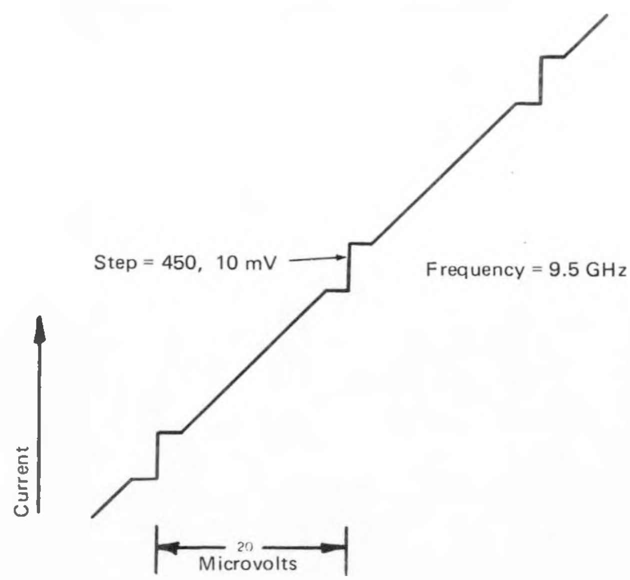

Figure 1. Josephson voltage steps

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The electrical impedance of the junction is quite small at microwave frequencies, so that the present use of waveguide to bathe the device in an alternating electrical field is very inefficient. A slot-line feed is being developed which gives an excellent match between the signal source and the junction, and which is small enough to be included in the liquid-helium dewar that cools the junctions. Under investigation are niobium junctions which, unlike lead Josephson junctions, can be handled repeatedly at room temperature without damage.

Item 3. *Transportable Standard-Cell (EMF Reference) Bath*

For many years chemical standard cells have been used as laboratory references of electromotive force (EMF), or electrical potential, and as a means of transferring the unit volt between laboratories. In these applications it is important that the cells be protected from temperature extremes and sudden temperature changes. To provide this temperature protection during use and shipment, a transportable standard-cell air bath has been developed. The primary temperature control is a thermostatically controlled electric heater in the inner compartment of the bath; a secondary control in the outer compartment uses the heat of fusion of two metallic alloys that melt at 20° and 25°C. Aided by insulation, the fusion energies provide bounds on temperatures experienced by the inner compartment. Because the outer control is passive, total power demand by the device is modest – 0.8 watt supplied by six D-size mercury cells. The complete bath with shipping container and battery pack has a mass of 14.5 kg, and measures 20.3 x 22.9 x 30.5 cm. One kilogram of the gallium fusion alloys is sufficient to permit an 8-hour exposure to the extremes of 0° or 40°C. The alloys are automatically restored to their original states upon exposure to a controlled laboratory environment. The baths have been used in the National Bureau of Standards Transvolt Program.

Item 4. *An Automatic Standard-Cell Test Facility*

An automatic calibration facility, designed and placed in service in 1962, has led to increased quantities and quality of data obtained and hence to more thorough analysis of tested standard voltaic cells. The automatic comparator has a load capacity of 40 cells, has a resolution of 0.1 microvolt, and makes one measurement each 10 minutes. Output is provided both in printed tabular form and on paper tape for computer analysis. At full loading the system can process over 690 cells per year.

Use of this facility has resulted in a significant improvement in cell characterization, including plots of cell behavior during test. Shown on the left side of Figure 2 is the voltage response of a typical unsaturated cell to a single temperature shock and, on the right, of the same cell exposed to a cyclic temperature variation. Results such as this led to a modification of test procedure when it was shown that peak deviation of cell potential from the temperature-stabilized value was a more reliable indicator of cell quality than the previously used criterion of recovery time. The extended, uninterrupted measurement sequences needed to establish such conclusions can be obtained only through automated measurements.

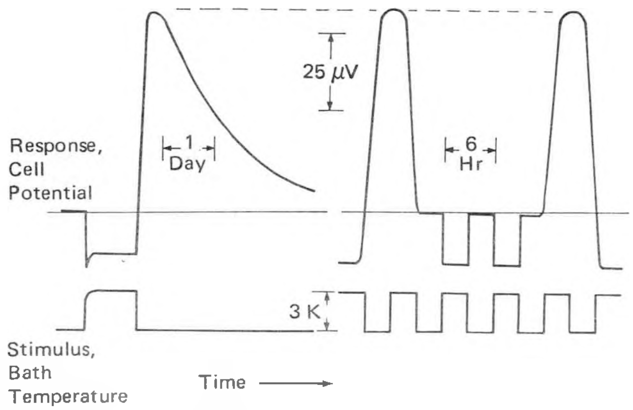


Figure 2. Unsaturated cell thermal shock response

Item 5. *Automated Calibration System*

A system has been designed that automatically calibrates digital voltmeters, especially the HP-3400 series. This series can be externally programmed, and provides a binary-coded decimal output that is fed back to a minicomputer. The advantages of such a system are:

1. Uniform and consistent test points and procedures.

2. Elimination of manual data recording and calculation.

3. Time-saving.

A digital voltmeter that is not externally programmable and does not provide binary-coded decimal output can also be calibrated with the automated calibration system, although more operator interaction is required. Calibration programs are stored on cassettes and are read into the minicomputer memory as required.

Typical accuracies of the system are:

DC Volts	1 to 1000 V dc	±0.003%
	10 to 100 mV dc	±0.015%
	100 to 1000 mV dc	±0.01%
AC Volts	0.1 to 1000 V ac	Within rated accuracy of H-P 745A/746, typically 0.02%
DC Current	20 to 100 mA	±0.015%
DC Resistance	100 ohms	±0.03%
	500 ohms	±0.03%
	1 kΩ to 1 MΩ	±0.025%
	10 MΩ	±0.05%

About 210 instruments are calibrated each year. On the average, an instrument can be calibrated in half an hour, compared to a typical 4 hours by conventional methods.

Item 6. *Automatic Network Analyzer*

A Hewlett-Packard Model 8542B Automatic Network Analyzer (ANA) is available to measure scattering (and other) parameters of one- and two-port devices over any set of frequencies in the 0.1 to 18 GHz range. The integral computer and interactive graphics features of this commercial instrument permit rapid acquisition, manipulation, and display of measured results in a variety of forms. Figure 3, for example, shows a plot (generated on the ANA) of the magnitude of the input reflection coefficient of a 4 to 5 GHz bandpass filter over the 2 to 10 GHz frequency range.

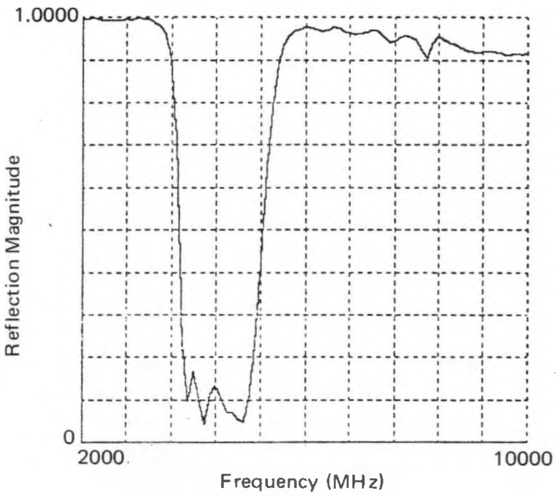


Figure 3. Bandpass filter test 2 to 10 GHz input reflection magnitude 4 to 5 GHz passband

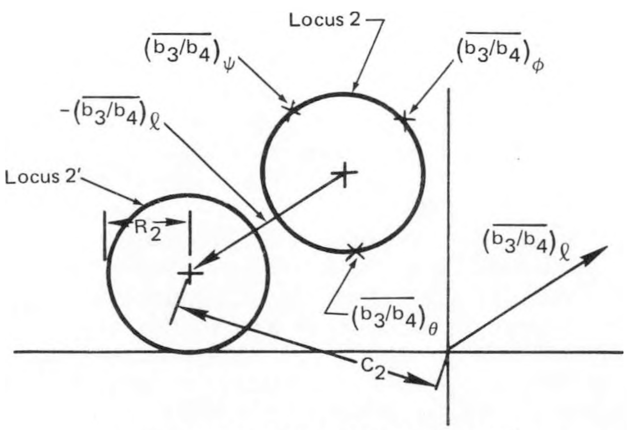
The economy of measurement, rapid turnaround, and elimination of human error that are characteristic of the ANA make it practical to perform measurements of greater sophistication and complexity than could be accomplished by manual means. For example, it is impossible to explore hour-to-hour stability of a component when the required measurement takes 2 days to complete manually; such measurements can be done by the ANA in a few minutes.

Development work is underway to improve measurement accuracy by improving precision of calculation, and to extend applications to include three- and four-port devices.

Item 7. *Power-Equation Techniques*

The Primary Standards Laboratory at Sandia Laboratories was a pioneer in the application of power-equation techniques conceived by G. F. Engen of the National Bureau of Standards. These techniques virtually eliminate from power measurements uncertainties resulting from electrical impedance mismatches. Furthermore, such measurements are independent of the impedance of the transmission line in which they are made, and so eliminate the need for precision connectors. Power-equation concepts, which are based on complex variable theory, have been most useful in determining the efficiency of thermistor mounts.

Figure 4 illustrates graphically a typical equation, this one used in a thermistor-mount calibration. The complex-plane plot shows the experimentally determined points ψ, ϕ, and θ, and vector ℓ. The three points determine the circle labeled Locus 2, which is then translated by $-\ell$. The resulting circle, in its new location, characterizes the mount under test.



Conjugate Mismatch Factor = $1 - (C_2/R_2)^2$

Figure 4. Graphical interpretation of the mismatch factor power equation

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Item 8. *Precision Low-Voltage Pulse System*

Single or multiple pulses of less than 500 volts peak amplitude are generated and measured with an amplitude accuracy of 0.25 percent. Pulse-generation methods used predetermine amplitude within this accuracy, as contrasted with methods that preset values approximately and must measure each pulse as it is produced. Measurements can be made on pulses of any duration from one nanosecond upward. Pulse waveshapes can be varied without affecting accuracies. Precise voltage-amplitude control is obtained by using a zener diode immersed in liquid nitrogen.

Item 9. *Electrooptic Pulse-Voltage Measuring System*

This measuring system was developed at Sandia as a more accurate way of measuring pulse voltage than is provided by voltage dividers. The system comprises a light source (helium neon laser), an electrooptic light modulator (nitrobenzene-filled Kerr cell or potassium dihydrogen phosphate Pockels cell), an analyzing polarizer, and a photodetector. It provides a wider frequency response than voltage dividers, and is free of many problems that affect voltage-divider measurements (e.g., sensitivity to ground-current loops, stray capacities, and extreme pulse loading). It can be calibrated to provide pulse-voltage measurements to an accuracy of ± 1 percent. Cells have been constructed to operate in the range of 10 to 100 kilovolts, and similar systems have been operated to 300 kilovolts. The National Bureau of Standards has developed the original Sandia concept into a national standard.

Item 10. *Pulse Neutron Standards*

Because no standards are available at the National Bureau of Standards for measuring 14-MeV neutron pulses, Sandia's standards have been derived on the basis of length measurements and absolute alpha-particle counting. A positive ion accelerator produces up to 10^9 neutrons per second in short bursts (10 to 100 milliseconds). Associated-particle counting establishes neutron yeilds with an accuracy of about 6 percent.

The basic standard is used to calibrate lead-activation and silver-activation neutron detectors, and these in turn are used as standards in calibrating other detectors. Final accuracy is about 9 percent. Data recording is automatic, and data reduction by computer insures consistent and impartial evaluation of calibration results. Commercial equipment is used wherever possible, but it has been necessary to develop many pieces of specialized interface and measurement equipment.

Item 11. *Quality Measurement of Lead-Activation Pulse-Neutron Detectors*

In general it is desirable to have reasonable assurance that a standard submitted for calibration is of acceptable quality before it is certified. In the case of the neutron detectors known as "lead probes," the method of making a quality determination was not obvious. Experience and analysis led to devising a quality coefficient based on the pulse-height spectrum of the probe output signal when the probe is excited by a barium-133 gamma check source. A typical output spectrum is plotted in Figure 5, along with the negative of its slope after smoothing. The empirical quality coefficient is defined as

$$Q = 1 - \frac{S_{min}}{S_{max}}$$

where the S's are as illustrated in the figure. In the case of an ideal compton step in the spectrum, Q equals one. This measurement is made on every probe before calibration, and has led to the discovery of specific defects such as faulty optical coupling, deteriorated optical reflecting surfaces, and noisy photomultiplier tubes.

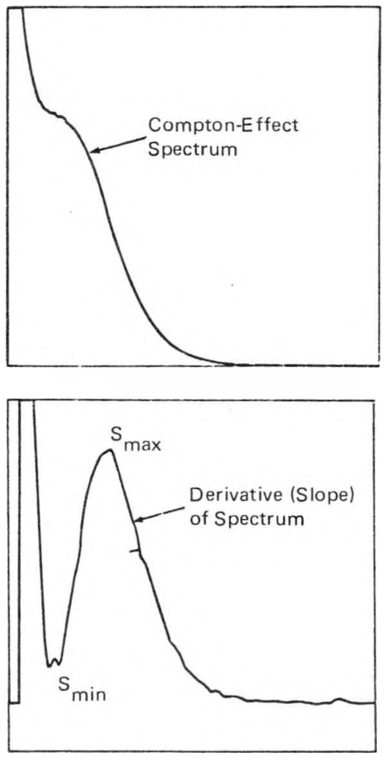


Figure 5. Pulse height spectrum from a lead probe, and the negative of its slope

Item 12. *Precision Surface Topography*

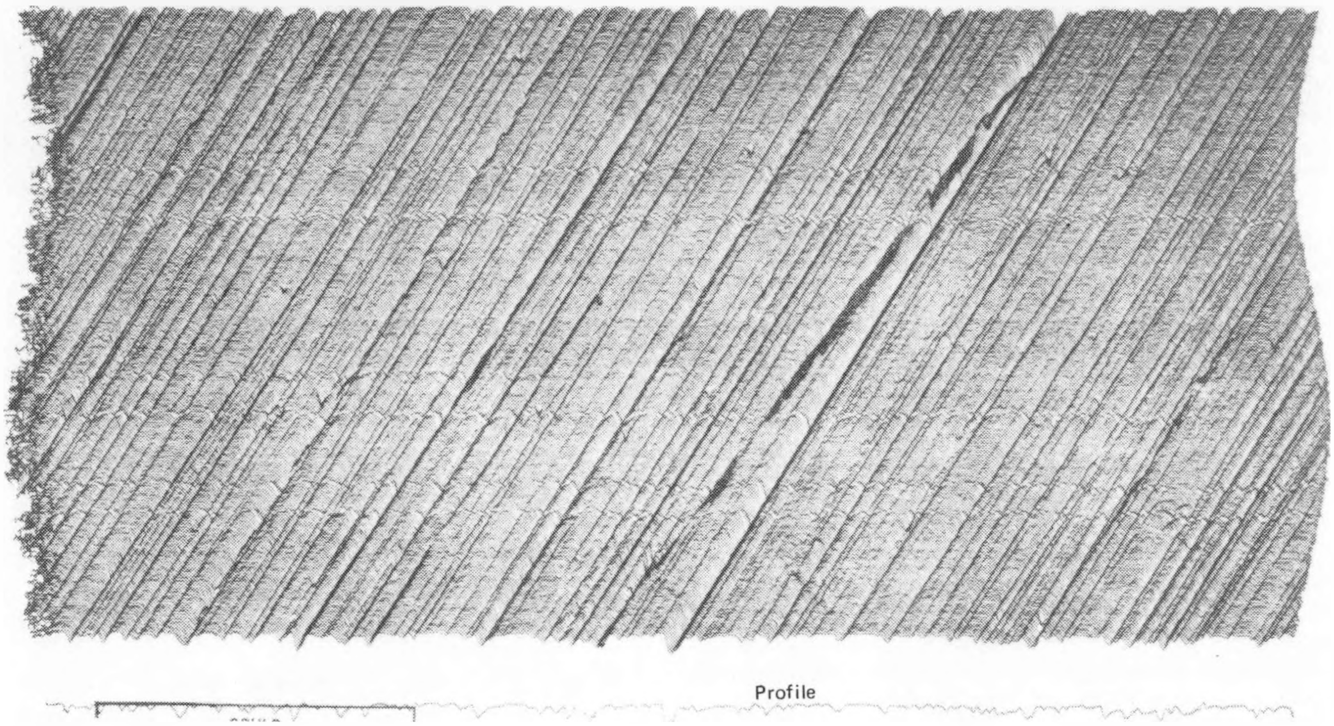
To answer numerous requests from research and development groups whose projects require spatial surface measurements rather than the customary single-trace surface profiles, a microtopographer has been acquired. This instrument senses and records surface topography to 1 microinch in elevation in a continuous scan of an area ranging in size from 0.005 inch to 2.0 inches x 2.0 inches. Surface geometry is reproduced with an overall system accuracy of 1 percent on a standard X-Y recorder chart (Figure 6).

Scanning speed, line separation, and magnification are selectable. X-Y plane magnifications range in six steps from 5X to 200X, and Z-scale sensitivity in 13 steps from 10X to 100,000X. At the highest Z-scale sensitivity, 1 microinch of stylus displacement on the work surface is reproduced as 0.1 inch of pen displacement on the chart.

Item 13. *Dual Piston Gage*

A dual piston gage (Figure 7) has been developed for calibrating sensitive micromanometers. With its two piston gages (one for generating a reference pressure, the other for test pressure), accurate differential pressures can be obtained. A unique feature of this instrument is the incorporation of both gages in the same vacuum bell jar, which reduces the effect of variation in back-pressure. Pressure differentials as low as 0.25 millitorr can be generated. The upper limit is 100 torr. Above this pressure, other instrumentation is used.

Calibration accuracy is limited primarily by the quality of the micromanometer under test. However, accuracies of 0.1 percent of full scale are routinely possible.



Magnification: x and y axes; 200X
Vertical axis; 2000X

Figure 6. Precision surface topography

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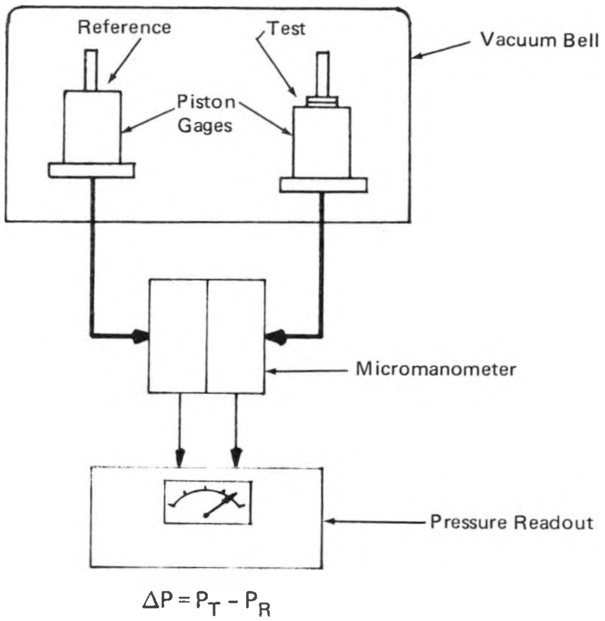

Figure 7. Dual piston gage

Item 14. *Gas Leaks*

Several methods and corresponding facilities exist for the calibration of gas leaks. Their use depends upon the leak rate and the required accuracy. In all cases these methods are tied to an absolute calibration system in which a mass spectrometer is used as a detector. The mass spectrometer's ability to distinguish various gases permits the calibration of leaks without interference from extraneous gas sources such as outgassing.

The effluent gas from the leak is confined until enough is obtained for analysis. An equivalent "standard" quantity obtained by precision pressure-volume-temperature methods is also analyzed. This standard output, the test output, and the accumulation time are used to calculate the leak rate. Corrections are made for such interfering factors as temperature variations, system background, and volume effects.

This method yields absolute accuracies of 5 percent in the range of 10^{-5} to 10^{-7} cm^3/s at standard temperature and pressure. Other ranges can be done to lesser accuracy. Any nontoxic, nonradioactive gas leak can be calibrated. A unique application of this method is the calibration of leaks containing more than one gas.

Item 15. *Gas-Flow Modeling of Variable-Area Flowmeters*

Calibration of small variable-area flowmeters for use with explosive, toxic, or costly gases is often required. To avoid the safety hazard of dangerous gases and the cost of expensive gases in the standards laboratory, a method for predicting the calibration factor of a flowmeter for one gas by calibrating it with another gas has been developed and evaluated. Typical test results on a 150-mm (scale-length) spherical float variable-area meter show a maximum prediction error of 2.5 percent. The modeling technique is also applicable to orifices, nozzles, and venturis where lower prediction errors would be expected.

Item 16. *High-Temperature Black-Body Furnace*

This furnace is used for calibration of radiation pyrometers and for special tests from 800 to 3000°C. The furnace shown in Figure 8 is operating at about 2000°C in an interferometry experiment.

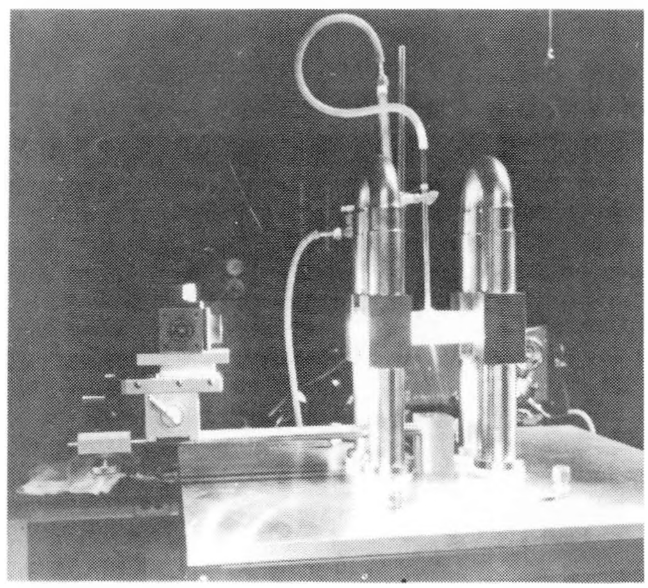

Figure 8. Furnace

Item 17. *30,000 x Gravity Shock Facility*

A derived reference is required to support shock testing as there are no national measurement standards for shock. The reference is derived from length, time, and electrical measurements traceable to national standards.

The facility used to establish the shock standard (Figure 9) consists of an air gun capable of generating a 1000 to 30,000 x gravity peak acceleration pulse in a shock accelerometer. Comparing the resultant velocity change of the accelerometer to its electrical output provides the required shock-sensitivity calibration.

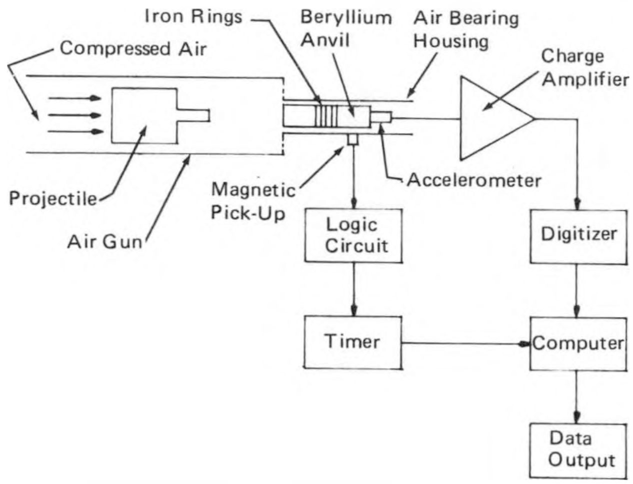

Figure 9. 30,000 x Gravity Shock Facility

Item 18. *Gas Analysis*

Four mass spectrometers are used for gas analysis, covering a mass/charge ratio from 2 to 1100 with a range of resolution from 10 to 1000. One instrument is a combination gas chromatograph-mass spectrometer specially equipped with a computerized data-handling system that is particularly suitable for hydrocarbon identification. The other instruments are used for analyses of internal gases of components.

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PHYSICAL SCIENCES

Sandia Laboratories Technical Capabilities

Physical Sciences

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115
and Livermore, California 94550 for the United States Energy Research
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SANDIA LABORATORIES TECHNICAL CAPABILITIES

PHYSICAL SCIENCES

ABSTRACT

This report characterizes the physical sciences capabilities at Sandia Laboratories. Selected applications of these capabilities are presented to illustrate the extent to which they can be applied in research and development programs.

PHYSICAL SCIENCES*

Research in the physical sciences is directed toward understanding basic phenomena, enhancing physical characteristics, and developing predictive capabilities for practical applications. Studies in the physics of solids, surfaces, and thin surface layers are leading to improvements in solid-state devices. Work on the dynamics of stress and shock waves is directed toward generating computer codes to augment and/or replace costly and time-consuming hardware testing. Investigations into the interaction of radiation with matter are resulting in techniques to ameliorate radiation-induced damage in solid-state components. Research in laser fusion and electron-beam fusion constitutes an essential part of the nation's program to harness thermonuclear fusion as a future energy source, and also provides nearer-term radiation sources for weapon-effects studies. Fission reactor activities are aimed at developing improved fuels and enhanced safety for commercial power reactors.

The major facilities for conducting research in the physical sciences include several high-energy Van de Graaff accelerators, heavy-ion and high-current accelerators, ultrahigh vacuum facilities, gas-gun installations, high-intensity lasers, intense pulsed electron accelerators, and pulse reactors, Other facilities are cited in the text of this report.

Physical Sciences Technical Staff
and Investment in Equipment

	Professional Staff	Investment in Equipment (in $1000)
Physics of Surfaces and Thin Surface Layers	14	1490
Physics of Solids	33	3350
Solid Dynamics	50	2820
Interaction of Radiation with Matter	22	2515
Laser Fusion	24	3600
Relativistic Electron-Beam Research	24	2150
Research Reactors	7	2800

*Compiled October 1974.

PHYSICS OF SURFACES AND THIN SURFACE LAYERS

Research in this area is concerned with the understanding, analysis, and control of surfaces and thin surface layers. The technologies involved include ion implantation, near-surface analysis, composition analysis, electronic structure analysis, and related problems in microelectronics, corrosion and diffusion, and catalysis at surfaces. The development of theoretical models is supported experimentally by a wide range of surface spectroscopies.

Ion Implantation

Ion implantation is used to control the properties of thin layers of solids by implanting ions of energies between 1 to 2000 keV. Examples of ion-solid interaction problems are the depth distribution of the ions, the final lattice location of the ion, the lattice damage, and the annealing kinetics of damage. Ion implantation easily controls, within tight tolerances, parameters related to impurity content, composition, and dimensions which are important in solid-state sciences such as metallurgy, semiconductor physics, and insulator research. (Items 1 - 4)*

Current Activities

- Metals
  - Corrosion barrier layers
  - Simulation of radiation damage and transmutation effects in reactor materials
  - Primary alloying
  - Superconductors
  - Stress corrosion studies
  - Bonding layers
- Semiconductors
  - Dimensional control on doping profiles
  - Doping concentration control
  - Low-temperature device processing
  - Compound semiconductor devices
  - Simulation of radiation damage effects
- Insulators
  - Simulation of radiation damage and transmutation effects in reactor materials
  - Ionization-induced conductivity
  - Crystallization nucleation in glass-ceramics
  - Stressed-layer production

Near-Surface Analysis

Ion beams have unique capabilities for the analysis of the near-surface properties of materials. Among these are direct lattice location measurements using the phenomenon of ion channeling in which a collimated ion beam is guided by rows or planes of atoms in a crystal. Such channeled ion beams are used to detect and determine the crystal-lattice location of impurity atoms or displaced host-lattice atoms. Ion surface analysis also provides a nondestructive technique for determining composition variation with depth in micron-thick layers. (Items 5,6)

Current Techniques

- Nuclear elastic scattering (Rutherford ion backscattering)
- Nuclear inelastic scattering (nuclear reaction microanalysis)
- Ion-induced X rays
- Secondary ion emission upon ion sputtering

Current Activities

- Hydrogen and helium location in metals
- Thin-film interdiffusion and intermediate phase formation
- Metal-silicide formation in semiconductor contacts
- Diffusion of hydrogen in solids
- Impurity contamination in SiO_2

Composition Analysis

The composition of an alloy surface may be quite different from that of the bulk. This affects material characteristics with respect to lubrication, catalysis, corrosion, etc. These properties are affected also by contaminants in quantities less than a single atomic layer. Elemental analysis of the surface depends on a determination of either the mass or charge of the atomic nucleus. Facilities are available for both determinations. (Items 7,8).

Current Techniques

- Nuclear charge methods
  - Auger electron spectroscopy
  - Soft X-ray appearance potential spectroscopy
  - Auger electron appearance potential spectroscopy

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*See Highlights, below.

Nuclear mass methods
- Binary scattering of noble gas ions
- Ion microprobe mass analysis
- Field desorption spectrometry

Structure Analysis

The characteristics of solid catalysts are determined by the outermost atomic layers. Thus it is necessary to study the atomic arrangement of the surface as well as the surface topography. The analysis of low-energy electron diffraction spectra of clean surfaces is being extended to include chemisorbed monolayers.

The reactivity of a surface is sensitive to the kind and concentration of its imperfections. The characterization of surface imperfections on an atomic scale, both theoretically and experimentally, deals with surface roughness (atomic steps) and with disorder produced by inert gas atoms imbedded in single-crystal surfaces. (Items 8,9).

Current Techniques

Microscopic
- Scanning electron microscopy
- Interference fringe microscopy

Atomic-scale
- Low-energy electron diffraction
- Field ion microscopy

Electronic Structure Analysis

A critical question in understanding the surface properties of alloys or compounds is the extent to which

the constituents retain their own electronic states or share their electrons in a common band. Although the inner shells of the atoms do not directly participate in chemical bonds, both the excitation and recombination transitions associated with the inner shells may involve states within a few eV of the Fermi energy. The line shapes corresponding to these transitions thus reflect the chemical environment of the atoms. The line shapes may convey information regarding either filled or empty states.

Current Techniques

Filled-state probes
- Auger electron spectroscopy

Empty-state probes
- Soft X-ray appearance potential spectroscopy
- Characteristic ionization loss spectroscopy

Facilities

The facilities available for surface analysis include
- Van de Graaff accelerators (2.5-MeV, 2.0-MeV and 400-keV),
- a 300-keV heavy-ion accelerator, and
- an 80-keV high-current accelerator; each with ultrahigh vacuum facilities and
- high- and low-temperature target stages.

Samples can be mounted on precision goniometers for ion channeling measurements. The 80-keV high-current heavy-ion accelerator is integrated with the 2.5-MeV Van de Graaff so that ion-implanted samples can be analyzed *in situ* without exposure to air. A high-voltage transmission microscope is being installed to allow *in situ* examination of implanted samples.

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Simulation of ^{3}He Buildup in Metal Tritides*

Long-term stability of metal tritides depends on the disposition of the ^{3}He product of tritium radioactive decay (12-year half-life). Ion implantation of He into metals and metal hydrides has been used to simulate He buildup on short laboratory time scales. The internal stress, volume expansion, He lattice location, and He release have been simulated for a number of metal tritides. The results allow engineering decisions to be made on time scales much shorter than would be possible if aging data were available only from naturally aged tritides.

Item 2. *Correlation of Theoretical and Experimental Results for Ion Range and Damage*

An understanding of ion implantation requires the existence of a viable theory for calculating the depth distribution both of the implanted ion and of the damage caused by the ion as it comes to rest. Results of a newly developed calculational procedure have been compared with a variety of experimental measurements on metals, semiconductors, and insulators. In all cases the agreement, being within experimental uncertainty, has confirmed the theoretical model.

PHYSICS OF SURFACES AND THIN SURFACE LAYERS

Item 3. *Defect Identification Using Isotopic Implantations*

A number of previously unidentified lattice defects in silicon have been identified unambiguously by isotopic enrichment through ion implantation. The introduction of silicon, oxygen, and carbon isotopes which possess a nuclear moment enhances certain hyperfine interactions with paramagnetic electrons located on defects. Electron paramagnetic resonance measurements of the defects then allows identification of the structure and impurity content of the defect. Annealing studies of these samples provide information on the thermally stimulated reordering and disassociation of the defects.

Item 4. *Primary Alloying with Ion Implantation*

The composition of a thin layer near the surface of a solid can be altered by high-fluence ion implantation. Compounds have been formed in this manner. The oxides, nitrides, and carbides of the semiconductors silicon and germanium have been formed for potential passivation and electrical isolation applications. The compositions of ternary compound semiconductors have been altered to adjust the band gap of the material. Oxides, nitrides, and carbides of metals have been formed for enhanced corrosion resistance and mechanical hardness.

Item 5. *Lattice Location of Deuterium in Tungsten*

The diffusional and precipitation properties of an impurity in a solid are often strongly influenced by the lattice site occupied by the impurity in the host lattice. In many applications hydrogen or helium are important impurities (e.g., fusion reactor materials damage). Ion channeling and nuclear reactor microanalysis using the $D(^3He,p)^4He$ reaction have been combined to measure the lattice location of D in a tungsten single crystal (W). Figure 1 shows the ^{3}He ion backscattering yield from W, as well as the nuclear reaction yield from implanted deuterium (D) as a function of the angle of the ^{3}He beam with respect to the tungsten ⟨100⟩ axis. The figure shows that the implanted deuterium is interstitially located.

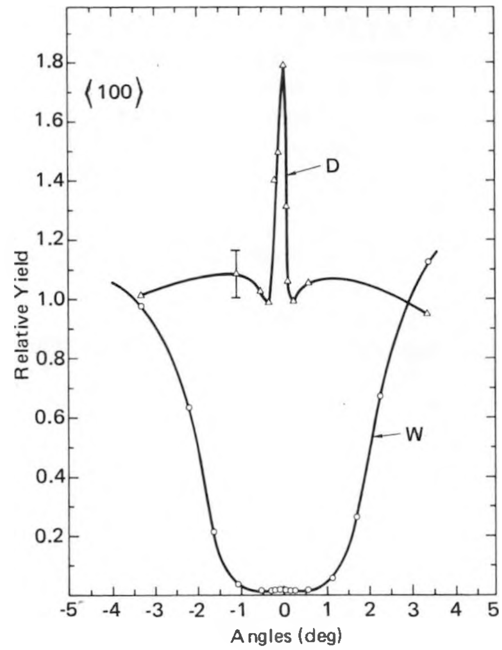

Figure 1. ^{3}He ion backscattering from W and nuclear reaction yield from implanted D

Item 6. *Contact Degradation on Radioisotopic Thermoelectric Generators (RTG)*

Solid-solid reactions between a semiconductor and a thin-film metal electrode at high temperature are very common. If the semiconductor is silicon or a silicon-germanium alloy, silicon tends to leave the semiconductor bulk and, in many cases, react with the metal films forming a metal silicide layer. This layer alters the mechanical and electrical properties of the contact and causes contact failure. The formation of WSi_2 was monitored in W-SiGe couples to simulate the high-temperature behavior of a radioisotopic thermoelectric generator. The ion backscattering spectrum shown in Figure 2, taken of a W-SiGe couple after aging for 20 hours at 675°C, shows WSi_2 layer formation and Si depletion in the SiGe near the W-SiGe interface. This depletion leads to void formation and eventually contact failure. Based on this information and electrical aging information, contact lifetime was predicted to be in excess of 1000 years at the operational temperature of 400°C.

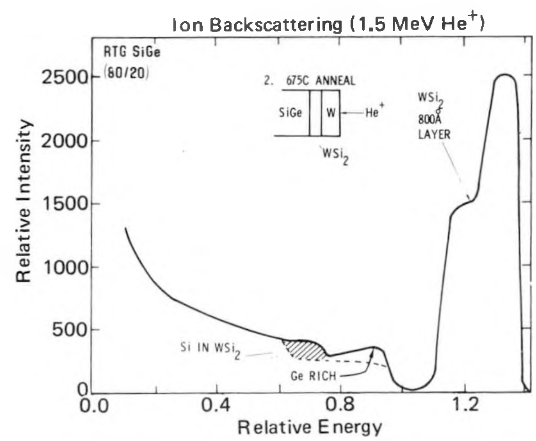

Figure 2. Ion backscattering spectrum of W-SiGe interface showing WSi_2 layer formation

Item 7. *Soft X-Ray Appearance Potential Spectrum of a Stainless-Steel Surface*

Soft x-ray appearance potential spectroscopy consists of determining the excitation thresholds of characteristic x-rays from the derivative of the total x-ray emission spectrum. With this technique the loss of corrosion resistance of stainless steel subjected to high temperature in vacuum has been shown to be the result of chromium depletion at the surface (Figure 3). Appearance potential spectroscopy has been applied also to problems in the electronic structure of metals and alloys, oxidation, microcircuit bonding, and impurity segregation.

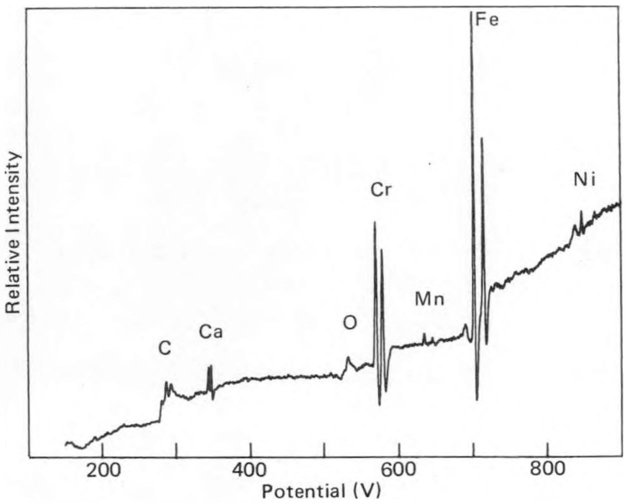

Figure 3. Appearance potential spectrum of a 304 stainless-steel surface

Item 8. *A Gated Field Desorption Micrograph of a Tungsten Surface*

The surface of W shown in Figure 4 was imaged in atomic resolution by the impact of individual W^{3+} ions on a channel plate image intensifier. The ions were produced by field evaporation when a narrow, high-voltage pulse was applied. The ions move in straight lines normal to the surface. By time gating the image intensifier, any mass-to-charge ratio can be selected for imaging. It is thus possible to image the distribution of selected impurities over the surface of the specimen. This instrument has been used to investigate hydrogen chemisorption, field ionization states, and the role of anode surface asperities in high-voltage breakdown.

Item 9. *Quantitative Surface Analysis by Proton-Induced X-Ray Fluorescence*

Analysis of proton-induced x-rays (PIX) provides quantitative compositional information on surface films.

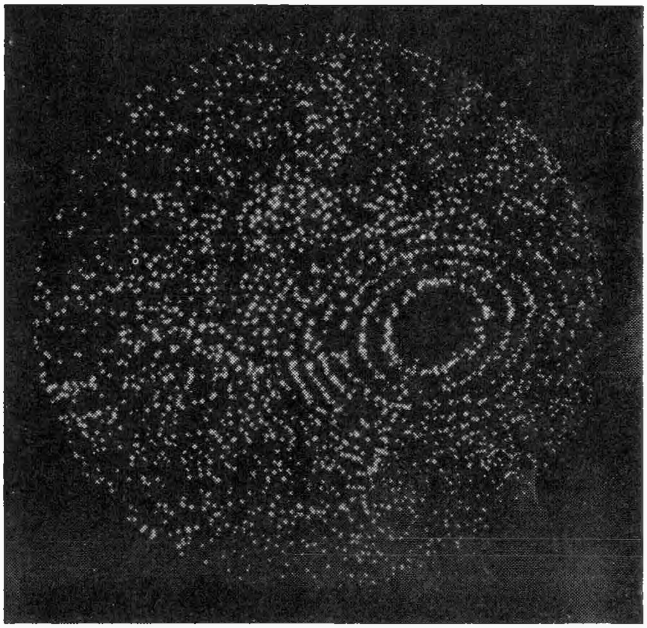

Figure 4. Field desorption micrograph of W surface

In particular, oxide thicknesses for various metals have been determined from the number of oxygen x rays generated during bombardment by 100- to 400-keV protons. The PIX spectrum, recorded with a Si(Li) detector, for proton bombardment of a 300 Å Al_2O_3 oxide layer on aluminum is displayed in Figure 5. The absence of an x-ray continuum for ion-induced x rays permits direct quantification of the characteristic x rays for small, elemental surface concentrations. This nondestructive technique has facilitated the measurement of film thicknesses for oxides 20 to 4000 Å thick.

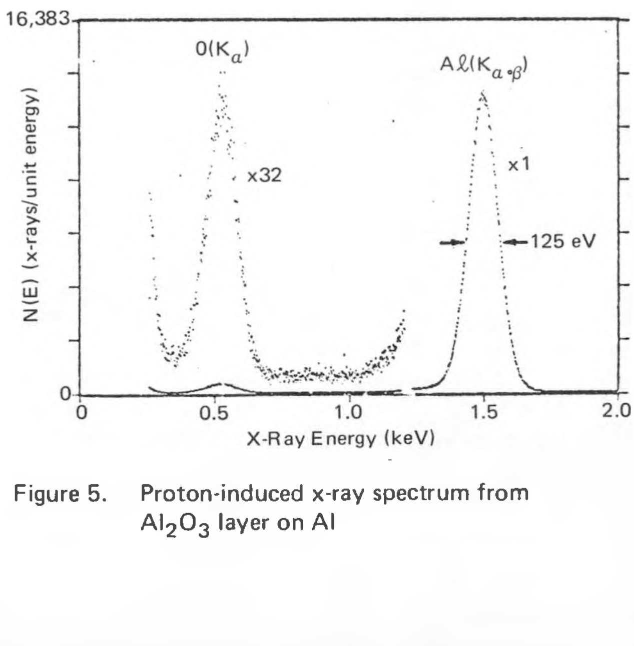

Figure 5. Proton-induced x-ray spectrum from Al_2O_3 layer on Al

PHYSICS OF SOLIDS

Solid-state physics research is concerned with the electronic and structural properties of solids, materials synthesis and characterization, diffusion in solids, and solid-state devices. It includes theoretical and experimental studies of the electrical, magnetic, acoustic, optical and structural properties of solids, as well as of the variation in these properties as a function of temperature, electric and magnetic fields, high pressure, rapid energy deposition, and other influences.

Fundamental Theoretical Studies

Theoretical studies are aimed at understanding phenomena occurring in solids or at solid surfaces. Activities range from developing phenomenological models for aiding in interpretation of experiment to large-scale calculations applying fundamental laws to elucidate the behavior of solids. (Items 1 - 3)*

Current Activities

- Magnetism
  - Phenomenological models
  - Fundamental models
  - Magnetostriction
- Phase transformation
  - Critical phenomena
  - Percolation theory
- Surface physics
  - Low-energy electron diffraction
  - Adsorbed atoms
  - Catalytic activity
  - Auger spectra
- Electronic band structures
  - Fermi surfaces
  - Optical spectra
  - Transition metal compounds
  - Semiconductors
  - Ionic crystals
- Atoms, defects, and carriers in solids
  - Stopping power studies
  - Diffusion of atoms
  - Diffusion of vacancies
  - Polaron theory

Electrical Transport Properties

Studies are aimed at determining the basic electrical (and ionic) transport mechanisms in both crystalline and noncrystalline solids. Emphasis is on understanding both electronic and ionic conduction mechanisms as they relate to physical phenomena of interest. Capabilities exist for measuring the properties of both bulk materials and thin films over a wide temperature range (1 to 1100 K) and in ultrahigh vacuum (to 10^{-11} torr). Experiments are correlated with theoretical studies of band structure and hopping conductivity in solids. (Items 4-9)

Current Activities

- Electrical properties of crystalline semiconductors
- Electrical transport in low-mobility solids
- Ionic transport in solid electrolytes and at interfaces
- Switching and memory phenomena in amorphous semiconductors
- Amorphous to crystalline transitions
- Metal-insulator transitions
- Superconducting transitions
- Electrical tunneling at metal-insulator-semiconductor interfaces
- Electrical contact phenomena
- High-electric field effects
- Dopant precipitation in semiconducting alloys
- Materials
  - Single-crystal semiconductors
  - Heavily doped semiconductors
  - Amorphous semiconductors
  - Insulators
  - Thermoelectrics
  - Superconductors
  - Solid electrolytes
- Electrical and Ionic Measurements Capabilities
  - Conductivity (ac and dc)
  - Hall mobility (10^{-3} to 10^{4} cm^2/V sec)
  - Drift mobility
  - Thermoelectric power
  - Differential conductance
  - Photoconductivity
  - High-temperature ultrahigh vacuum *in situ* transport measurements
  - Auger spectroscopy and sputter etching for determining ionic diffusion and transport in solids

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*See Highlights, below.

Dielectric and Magnetic Properties

Programs and capabilities are aimed at understanding physical phenomena and defining applications for ferroelectric, piezoelectric, dielectric, and magnetic materials. Of special interest is the relationship between crystal structure and physical properties, as well as the influence of high pressure (stress), temperature, and radiation on those properties (Items 10-13).

Current Experimental Capabilities

Hydrostatic pressure up to 3 GPa (1GPa = 10 kbar)
Quasihydrostatic and shock-wave pressure up to ~50 GPa
Temperatures from 1.5 to >1000 K, with above-pressure capabilities
Ultrasonic velocity and attenuation
Brillouin, Raman and infrared light scattering
Electron spin resonance
Static magnetization measurements
Dielectric constant, loss and breakdown measurements
Electrical conductivity measurements
Pulse high-current source (thousands of amps)

1. Ferroelectric Materials

Materials of interest include perovskites, hydrogen-bonded ferroelectrics, and lithium niobate and tantalate. (Items 10,13)

Current Activities

Phase transitions and transition kinetics
Critical phenomena
Lattice dynamics
Light scattering
Soft-phonon mode instabilities
Acoustic-optic mode interactions
Vanishing of ferroelectricity at high pressure
Dielectric breakdown
Electrooptic properties
Kinetics of domain rotation
Effects of compositional changes

Current Applications

Pulse power sources
Stress gages
Transducers
Radiation detectors and shutters
Image display and storage devices
Optical filters and shutters
Voltage regulators
High-capacity capacitors

2. Magnetic Materials

Magnetic metals, alloys, oxides and other compounds are studied and developed for specific applications. (Items 11,12)

Current Activities

Pressure- or shock-wave-induced demagnetization
Phase transitions
Magnetic interactions
Critical phenomena
Spin dynamics in low-dimensional systems
Domain wall dynamics
Itinerant-electron magnetism
Invar problem
Strain- (or stress-) induced magnetic anisotropy
Compositional (chemical) effects

Current Applications

Pulse current and voltage generators
Magnetic bubble devices
Switches

3. Piezoelectric and Dielectric Materials

Crystalline, polycrystalline and polymeric materials are of interest.

Current Activities

Piezoelectric coefficients
Dielectric constant
Dielectric loss
Phase transitions and critical phenomena
Phonon instabilities
Anharmonic lattice dynamics
Viscoelasticity

Current Applications

Time-resolved stress-wave gages (quartz, lithium niobate, sapphire)
Radiation detectors
Electromechanical transducers
Passive pressure gages
Radiation-tolerant dielectrics (controlled thermonuclear reactors, laser and radar windows)

Structural Properties

Under study is the relationship of atomic or crystal structure with physical properties, which necessitates

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detailed information on the location and relative thermal motion of atoms within crystals, as well as changes in the symmetry of the lattice due to environmental stresses (temperature, pressure, magnetic interactions, and electric fields). These investigations employ x-ray diffraction techniques utilizing automated data collecting systems; crystal-structure information may be obtained over a wide range of temperature and pressure. (Items 14,15)

Current Activities

- Phase transitions
  - Solid-solid
  - Pressure-induced
  - High-temperature
  - Exchange-striction
- Crystal structure
  - Low and high temperature
  - Coordination environments
  - Hydrogen bonding
  - Interatomic separations
  - Pressure effects
- Thermodynamic properties
  - Compressibilities
  - Thermal expansivities
  - Debye temperature
- Thin-film characteristics
  - Ion-implanted reactions
  - Lattice strain
  - Particle size

Mass Diffusion

Studies are being conducted on the properties of solids and of interfaces between solids as they are influenced by atomic and ionic diffusion. (Items 16-18)

Current Techniques

- Radioactive tracer analysis
- Auger spectroscopy in conjunction with sputter etching
- Ion backscattering in conjunction with ion implantation
- Electron microprobe analysis

Current Activities

- Impurity diffusion
- Interdiffusion of Pt in Si
- Diffusion of Ge in SiGe alloys
- Diffusion of Cu in single-crystal Be
- H and He permeation in metals, glasses and glass-ceramics
- Diffusion and intermetallic compound formation in Cu-Au system

Material Synthesis and Characterization

Various materials-preparation techniques are employed to produce materials for solid-state research. Single crystals, polycrystalline materials, ceramics, and glasses are studied. For studies of the intrinsic physical properties of materials, single crystals offer the advantages that properties influenced by crystallographic orientation are more easily defined. For studies of grain boundary effects, polycrystalline materials are utilized. (Items 19, 20)

Current Activities

- Crystal growth
  - Vapor transport
  - Czochralski
  - Bridgman
  - Liquid-phase epitaxial
  - Electrochemical
  - Nonaqueous solvent
  - Solution
  - Fused salt
- Glasses and ceramics
  - Crystallization kinetics
  - Tracer diffusion
  - Conductivities
  - Internal friction
  - Permeation
  - Hot-pressing techniques
  - Chill casting
- Characterization
  - Thermal properties
  - Mass spectrography
  - Nuclear magnetic resonance
  - Mossbauer
  - X-ray diffraction
  - Magnetic susceptibility
  - Spectroelectrochemical
  - Voltammetry

Solid-State Devices

Solid-state device programs are aimed at a basic understanding of the physics of semiconductor and ferroelectric ceramic devices. Semiconductor device work has emphasized the study of transient and permanent radiation damage effects in silicon devices. Semiconductor microwave devices have been studied both by device physics computer simulation of performance and by scattering parameter network characterization and modeling. Ferroelectric ceramic device work has concentrated on characterizing the electrooptic properties of transparent lead-lanthanum-zirconate-titanate ceramics and employing these effects in electrooptic devices. (Item 21)

Current Activities

- Electrooptic ceramic device applications
  - Large-area, high-speed shutters
  - Wavelength selective filters
  - Self-limiting variable density filters
  - Image storage and conversion
  - Holographic page composer

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Electronic Band Structure Studies*

In studies of the electronic and structural properties of amorphous semiconductors, calculations have been completed which compare arsenic in the black phosphorous structure with arsenic in the usual (rhombohedral) structure. Those studies show that the Bienenstock black phosphorus model for amorphous GeTe is consistent with photo-emission data. It is found that arsenic in the orthorhombic (black phosphorus) structure has a multipeaked valence band density of states much more like amorphous GeTe than like the known densities of states for rhombohedral As or Sb.

Item 2. *Stopping Power Studies*

Accurate calculations have been made of the depth distribution of ionization produced by 40- to 400-keV heavy ions implanted into silicon and germanium targets. Elastic scattering of the ions by the target atoms and the ionization produced by the target recoil cascades are included in these calculations. Such calculations are useful in the interpretation of various charge-state-dependent effects accompanying ion implantation, including, for example, the activation of radiophotoluminescent dosimeters, enhanced defect annealing rates, and enhanced diffusion.

Item 3. *Percolation Theory*

A concentration-dependent detrapping mechanism using percolation theory has been successfully applied to explain rapid helium diffusion in aged tritides. Similar ideas have been applied to conductivity mechanisms in amorphous materials and diffusion in silicon-germanium alloys. These studies will be relevant also to materials compatibility in controlled thermonuclear reactors.

Item 4. *Theory of Hopping Conduction in Disordered Solids*

The effects of short-range disorder on electrical transport in low-mobility solids have been studied by examining correlated small-polaron hopping motion. (A small polaron is a charge carrier and its associated short-range lattice distortion.) Of the various kinds of disorder the most significant type was found to be that associated with disorder of the local atomic vibrational frequencies. The molecular crystal model, the basis for most small-polaron studies, has been extended to include these effects. It has been shown that the essential features of the correlated-hopping theory may generally be applied to disordered materials.

Item 5. *AC Conductivity in Disordered Materials*

A new theoretical model, developed to account for ac conductivity in Sc_2O_3, may be applicable to a wide variety of disordered materials. Studies have shown that prior explanations of ac charge transport in amorphous solids have been defective and further suggest that only careful measurements of the conductivity as a function of frequency and temperature can yield information on the underlying transport mechanisms.

Item 6. *Memory Phenomenon in Amorphous Semiconductors*

The memory effect in amorphous (glassy) semiconductors results from a transformation from an amorphous to a crystalline state. In GeTe-based glasses, studies have shown that thermal annealing induces large increases in the conductivity. These conductivity changes result from a surface-nucleated, two-stage crystallization process.

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The first phase to segregate is crystalline Te. With extensive annealing a metallic-like conductivity behavior is observed and is associated with crystallized GeTe (second-stage crystallization product). These electrical and structural changes are the basis of the memory phenomenon and have application to both electrically and optically switched memory devices.

Item 7. *Electrical Switching and Acoustic Emission in Amorphous Semiconductors*

Acoustic emission produced during electrical switching of amorphous semiconductors has been studied. Results show that an acoustic signal is emitted 1 to 10 μs before switching from the high- to low-resistance states. This emission is associated with the initiation of the switching process and appears to result from very rapid heating in a small filamentary region (Figure 1). This heating produces a compressional acoustic wave. Other emissions observed during switching are of a somewhat different character and result from sample cracking. From these studies, information is obtained about both the physics of the switching process and the integrity of the glass after the switch.

Figure 1. Current filament formed on surface of AsTeI semiconducting glass during electrical switching

Item 8. *Dopant Precipitation in SiGe Alloys*

The precipitation of phosphorus in P-doped SiGe alloys varying in silicon content from 67 to 81 atomic percent has been investigated. Experimental results have been compared to the Lifshitz-Slyozov model for precipitation, using parameters determined from short-term anneals of less than 2000 h. From these results resistivity changes were predicted for thermoelectric elements which had been life tested to 40,000 h. These studies have provided a method for calculating long-term degradation of SiGe thermoelectric elements.

Item 9. *Electron Tunneling in SiGe-Metal Contacts*

Studies of W-SiGe electrical contacts for Radioisotopic Thermoelectric Generator applications have shown that thin oxide layers can be used as diffusion barriers to hinder the W-Si reaction without degrading the electrical properties. In these studies the electron-tunneling characteristics of contacts with thin oxide layers were determined from differential conductance (dI/dV) measurements at low temperatures. The tunneling electrons are sensitive to the thickness and shape of the oxide barrier, to defects within the oxide, and to the Fermi level position. Results show that the as-prepared contacts have an insulating oxide layer with defect states. With heat treatment (500°C or 16 h) the electrical characteristics change and stabilize. The stabilized conductance is attributed to a partial breakdown of the oxide layer, yielding a metal-semiconductor contact.

Item 10. *High-Pressure Ferroelectric Studies*

High pressure, as a variable for studying ferroelectric phenomena, provides for varying the balance between short-range and long-range forces. Recent optical and dielectric studies at high pressure have shed light on ferroelectricity in perovskite and in hydrogen-bonded ferroelectrics and have resolved questions concerning the nature of the fundamental excitations. A specific sample is the finding that the ferroelectric soft mode in KH_2PO_4-type crystals, which is heavily overdamped at all temperatures at zero pressure, becomes an underdamped oscillatory mode at high pressure. The ferroelectricity in these crystals vanishes at 0 K at high pressure (Figure 2). The details of how $T_c \rightarrow 0$ K at high pressure make it possible to decide between competing theoretical models.

Item 11. *Ferromagnetic Cores*

A magnetized ferromagnetic core can be thought of as an energy-storing device, the energy E being proportional to the square of the magnetization. If the core is made to lose all or part of its magnetization by, for example, rapid heating or a pressure pulse, the change in magnetic flux induces a voltage in the secondary coil, thereby delivering a power pulse to the load (Figure 3). This concept has been utilized to develop a family of pulse power sources with well defined characteristics. Ferroelectric elements can be utilized in an analogous fashion.

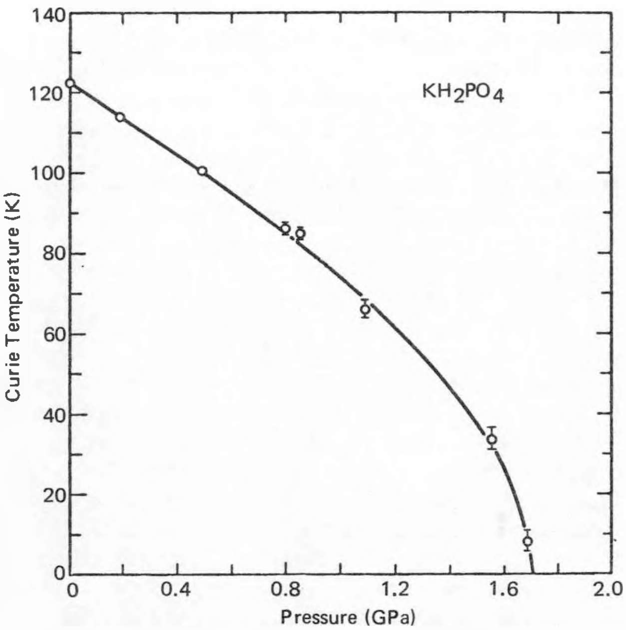


Figure 2. Vanishing of ferroelectricity in KH_2PO_4 with pressure

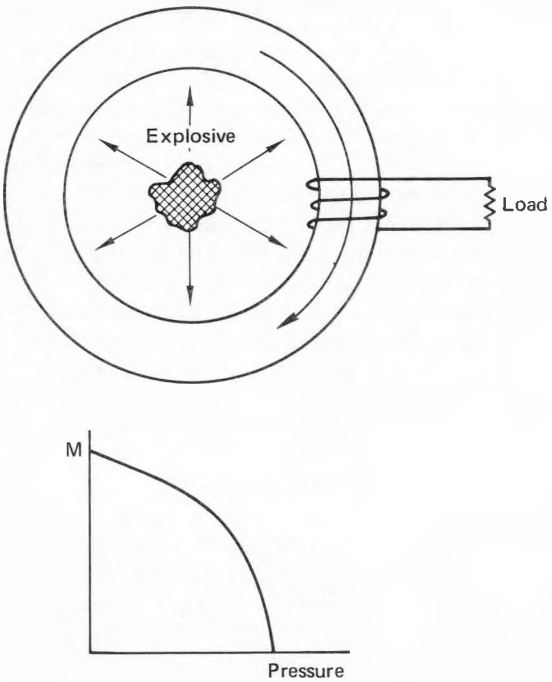


Figure 3. Ferromagnetic properties and applications. Pressure of shock wave destroys magnetization, resulting in flux change and induced voltage across load.

Item 12. *Pressure-Induced Magnetic Transitions*

Pressure effects are involved in the study of magnetic properties because the exchange forces responsible for magnetic ordering are strong functions of interatomic distance. Recent studies of the alloy chromium +2.8 atomic percent iron have shown that two antiferromagnetic-type transitions occur at pressures greater than 84 MPa, whereas only one transition occurs at atmospheric pressure (~0.1 MPa). Such studies help elucidate phase boundaries in alloy systems and identify new pressure-induced phenomena.

Item 13. *Pressure-Induced Soft Modes in Electrooptic Crystals*

Research has been conducted in the interpretation of structural phase transitions in terms of soft phonon modes. Figure 4 shows a pressure-induced soft mode in the electrooptic crystal TeO_2. This, the first known and well characterized pressure-induced soft mode, is characterized by a slow shear velocity along $\langle 110 \rangle$. The velocity of this mode decreases with pressure and ultimately vanishes. When it vanishes, the restoring force for the ionic displacements associated with this mode also vanishes, and the crystal transforms into a new phase.

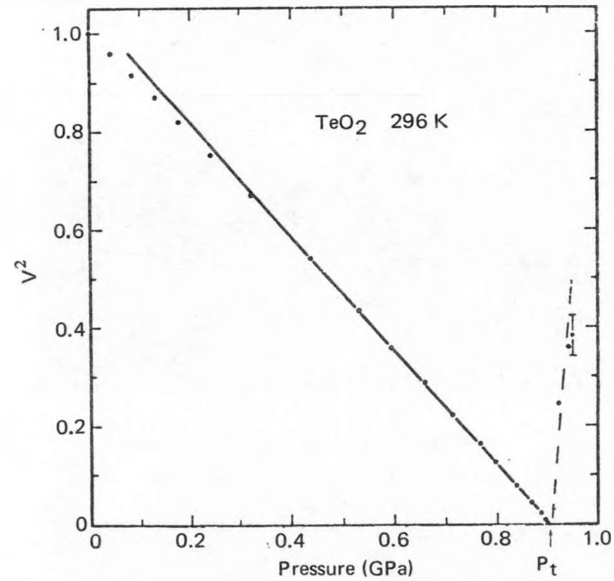


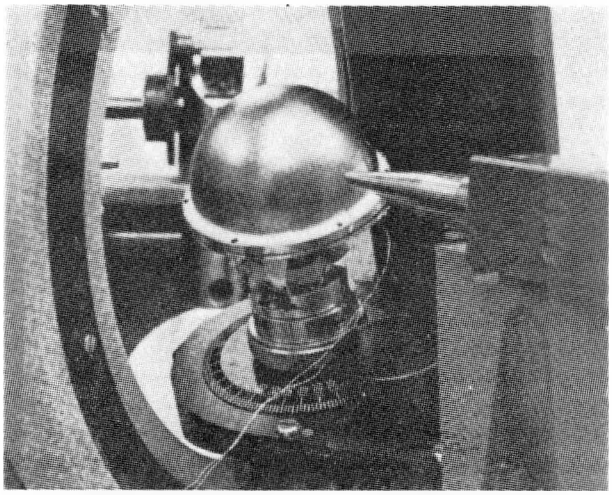
Figure 4. Vanishing of pressure-induced soft mode in TeO_2

Item 14. *Materials of Low Thermal Expansion*

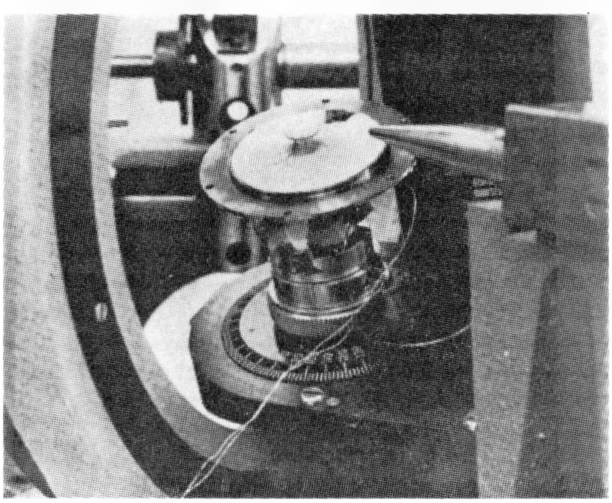
Several materials with low thermal expansion have been examined by single-crystal x-ray techniques to

PHYSICS OF SOLIDS

determine the relationship of structure on thermal properties (Figure 5). Such results on $A\ell_2TiO_5$ provided information on the behavior of ceramic bodies formed from such materials. Studies of $HfTiO_4$ and $ZrTiO_4$, as well as alloys of $Hf_{1+x}Ti_{1-x}O_4$, established the interconnection between thermal expansivities, compressibilities, polymorphic transformations and composition. The importance of impurities on thermal-expansion behavior was established in beryl and emerald, suggesting how such impurity-doped materials could be employed to tailor-make zero-expansion parts for laser interferometers.



a. Beryllium hemispherical cover prevents heat loss



b. Cover removed to illustrate heater assembly

Figure 5. High-temperature x-ray furnace developed to investigate thermal expansion and crystal structures

Item 15. *Pressure Effects on Structure*

The influence of the structural properties of a wide variety of crystalline materials has been determined through the use of a beryllium pressure cell (Figure 6). Some of the materials studied and the associated physical phenomena of interest include (a) superconductivity in NbS_2 and $NbSe_2$, (b) ferroelectricity in KDP-type crystals, and (c) Fermi surfaces in ReO_3, As, Bi, and Sb.

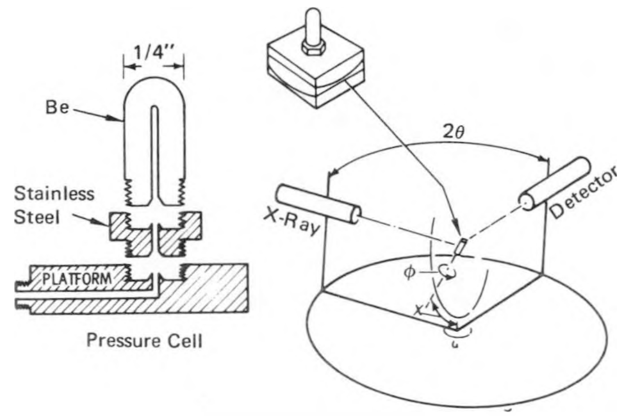


Figure 6. High-pressure x-ray cell for studying compressibilities and crystal-structure changes with pressure. Cell is made of beryllium, which easily transmits CuKα radiation, and is mounted on a platform to allow small angle corrections.

Item 16. *Ge Diffusion in SiGe Alloys*

A model based on percolation theory has been developed for describing the diffusion of germanium in SiGe alloys. This model satisfactorily explains the dependence of both the diffusivity preexponential and the activation energy as a function of alloy composition. A feature of this model is that it treats the host alloy as a microscopically heterogeneous mixture. This is in sharp contrast to standard treatments, which do not adequately describe the experimental results and which assume insensitivity to the local environment by treating the alloy as a homogeneous material.

Item 17. *Interdiffusion of Platinum and Silicon*

The interdiffusion of platinum and silicon has been investigated to develop a model for predicting electrical contact degradation. Planar bulk platinum-silicon diffusion couples were thermally annealed, and the concentration profiles were established, using an electron microprobe.

Six intermetallic compounds were observed to form in the interdiffusion region: PtSi, Pt_6Si_5, Pt_2Si, Pt_7Si_3, Pt_3Si, and Pt_4Si. The interdiffusion coefficient was determined within each intermetallic compound. Activation energies ranged from 0.93 eV for Pt_2Si to 2.14 eV for PtSi.

Item 18. *Gas Permeation in Metals and Glasses*

A long-term study is in progress on gas permeation in metals and glasses. For metals, the program has emphasized permeation of hydrogen isotopes in stainless steels and palladium alloys. In particular, the role of oxides of stainless steel in the permeation process has been investigated in some detail, using a variety of surface tools. In the palladium permeation program, the role of alloy constituents in the permeation process has been investigated at different temperatures. In the glass permeation program, hydrogen-isotope and inert-gas migration (helium) has been investigated. Parameters such as pressure and temperature, as well as the role of additions to the glasses and various glass structure types, have been included in the study.

Item 19. *Materials Preparation*

Materials prepared for solid-state research have included β-$LiA\ell SiO_4$, β-Alumina, La_2O_2S, KVO_3, As, SbSI, and Ge_xSi_{1-x}. High-quality thermoelectric alloys ($Si_{0.8}Ge_{0.2}$ doped with appropriate levels of phosphorus or boron) of essentially 100% theoretical density have been prepared by employing proper chill casting, planetary ball milling, and vacuum hot-pressing procedures. Various sodium silicate and lithium aluminum silicate glasses also have been prepared with tailor-made expansivities, conductivities, permeability, and mass diffusion characteristics.

Item 20. *Material Characterization*

Several experimental techniques have been used in characterizing materials. For example, the kinetics of structural changes in amorphous semiconductors, as well as the decomposition products produced during electrical switching, have been studied, using thermal gravimetric and differential thermal analyses coupled with mass spectrometry. The magnetic properties of Pt/Rh and Pd/Rh alloys have been determined by NMR techniques and by low-temperature magnetic susceptibility measurements. The properties of nonaqueous solvents have been investigated, using voltammetry and spectro electrochemical techniques, and the effects of density and porosity on noble-metal film electrode interfaces have been examined.

Item 21. *Scattering-Mode Ferroelectric-Photoconductor Image Storage Device*

In a recently developed image storage and display device, the image is stored by means of a longitudinal electrooptic scattering effect in transparent lead-lanthanum-zirconate-titanate (PLZT) ferroelectric ceramics. The basic device consists of a PLZT ceramic plate and a photoconductive film between two transparent electrodes. The image is stored by focusing it on the photoconductive film while a voltage is applied to the device electrodes. The image is erased by applying a voltage of reverse polarity. Photographic images with high resolution and a good gray scale (Figure 7) can be stored in the ceramic and projected onto large-area screens.

a. Print from original negative used to store the two images

b. Image stored between electrically poled and electrically depoled states

c. Image stored between thermally depoled and electrically depoled states

Figure 7. Cerampic image storage

SOLID DYNAMICS

Research in solid dynamics is concerned with the propagation of stress waves in materials, especially as related to the design of systems and components that must survive impacts, explosions, transient radiation, and other extreme environments. Methods are developed for assessing designs and predicting performance, which include computer codes for stress-wave propagation and theoretical models for the dynamic response of materials. Theories are formulated for rate-dependent elastic-plastic, viscoelastic, porous, and dispersive material response, for dynamic failure in brittle and ductile materials, and for shock-induced chemical reactions and phase changes. Theoretical work is supported experimentally with the use of gas guns, explosives, electrical discharges, and pulsed radiation sources, as well as with more conventional static and dynamic loading devices. Major areas of research are stress-wave codes, shock-wave phenomena, constitutive relations, physics of explosives, and measurement techniques for material response.

Stress-Wave Codes

Wave-propagation computer programs are developed for a more detailed understanding of stress-wave mechanics. Codes are applied to solve problems in the analysis and design of systems and components, and to reduce reliance on expensive experiments. (Items 1 - 4) *

Current Activities

- Specific codes
  - Lagrangian one-dimensional
    - CHART-D, WONDY, CONCHAS, SWAP
  - Lagrangian two-dimensional
    - TOODY, TOOREZ
  - Eulerian two-dimensional
    - CSQ, DORF
  - Two-dimensional generalized coordinates
    - ADAM
  - Three-dimensional
    - TAOSS, THREEDY, TRIOIL
- Numerical methods
  - Alternating direction—time step splitting
  - Characteristics
  - Finite difference—artificial viscosity
  - Shock fitting
- Constitutive relations
  - Thermodynamically complete multiphase hydrodynamic description
  - Elastic-plastic-strain hardening
  - Rate-dependent yielding
  - Cumulative damage failure criteria
  - Porous materials
  - Composites
  - High explosives
  - Phase change kinetics
  - Nonlinear viscoelastic
- Features
  - Energy transport—radiation diffusion
  - Automatic one-dimensional rezoning
  - Two-dimensional Lagrangian rezoning
  - Sliding interfaces—contact boundaries
  - Interactive graphics
  - Plotting packages
  - Coupled wave propagation—structural response
- Initial and boundary conditions
  - Time-dependent energy sources
  - Time-dependent boundary conditions
  - Applied boundary stress or position
  - Initial velocity conditions
  - General initial zoning
- Typical Applications
  - Ballistic penetration
  - Ground-shock propagation
  - Hypervelocity impact
  - Cratering by explosives
  - Shaped charges
  - High-explosive containment
  - Rain and dust erosion
  - Laser and electron-beam-generated stresses
  - Metal forming and cutting by explosives
  - Rock-material disintegration
  - Failure thresholds for safety requirements
  - Radiation induced impulse

*See Highlights, below.

Shock-Wave Phenomena

Shock-wave phenomena of interest are those dealing with physical effects produced by high pressures associated with shock waves. Electrical and magnetic properties of shocked materials are studied. Thermodynamic properties involving equations of state, melting, vaporization and polymorphic phase changes also are under investigation. Research activities are aimed at identifying and modeling physical phenomena through strongly coupled experimental and theoretical efforts. Interest in these phenomena is motivated by a variety of applications ranging from radiation-induced vaporization and melting to instrumentation techniques, fast electrical switches, and pulse power sources. (Items 5,6)

Current Activities

- High-pressure equation of state
  - Solids
  - Liquids
  - Porous materials
- Melting and polymorphic phase changes
  - Transformation kinetics
  - Finite yield strength effects
  - Changes in electrical and magnetic properties accompanying transformation
- Electron-beam- and laser-induced stress generation
  - Melting and vaporization
  - Grüneisen parameter determination
  - Temperature-dependent yield strengths
- Piezoelectric, ferroelectric, ferromagnetic, and piezoresistive effects
  - Quartz
  - Lithium niobate
  - Manganin
  - PZT, $BaTiO_3$
  - Magnetic materials
- Device concepts
  - Pulse power sources
  - Fast switches
  - Explosive initiators
  - Dynamic stress gauges

Dynamic Response and Constitutive Relations of Materials

Research is aimed at characterizing the dynamic response of materials and determining constitutive equations, especially for use in computer codes. Programs are aimed at characterizing response of materials to severe environments of stress, strain rates and temperature. Models have been used to correlate material behavior under conditions ranging from quasi-static loadings to ultrahigh strain rate loadings. Constitutive and fracture models, together with specific material property data and numerical codes, are used in solving design, engineering and safety problems. Measurements also are made to verify computer-code predictions and to provide guidance in material selection. Available instrumentation permits determination of response during both loading and unloading of stresses. (Items 7-10)

Current Activities

- Constitutive models
  - Soils/rocks—variable-yield models
  - Composites—dispersive linear and nonlinear
  - Polymers—nonlinear viscoelastic models
  - Porous media—rate-dependent pore collapse models
  - Mixtures—mechanical and transformation kinetics models
  - Metals—elastic/plastic, work hardening, rate-dependent models
  - Ceramics
- Fracture models
  - Fracture initiation and growth models
  - Cumulative damage models
  - Spallation models
  - Geologic material failure models
- Test conditions
  - Stresses—0 to 500 GPa
  - Strain rates—10^{-3} to 10^6/s
  - Impact velocities—0.01 to 10 km/s
  - Heating rates—0 to 10^{11} K/s

Physics of Explosives

This activity covers basic and applied research on the behavior and utilization of chemical explosives. Emphasis is on the initiation of detonation in explosives by high-velocity impact and by the electrical explosion of metallic wires. Facilities include firing sites instrumented with high-speed cameras and with electronic and electrooptical shock-wave instrumentation.

Exploding-wire studies are supported by a cable-discharge square-pulse generator capable of delivering current pulses of 6 microseconds duration and up to 8000 amperes amplitude. (Items 11-14)

Current Activities

- Shock initiation and detonation
  - Theoretical studies and code development
  - Experimental investigation of shock initiation
  - Equation-of-state studies of explosive materials
  - Studies of fuel/air explosives
- Electrical initiation of detonation
  - Exploding-wire physics
  - Criteria for initiation of detonation by exploding wires and sparks
  - Detonator and firing-system performance

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- Utilization of explosives
  - Theoretical and experimental studies of explosive output
  - Studies of mild detonating fuze
  - System design studies
    - Booster interfaces
    - Initiation systems
- Containment of explosions
  - Theoretical and experimental investigation of explosion containment vessels

Instrumentation and Facilities

As a consequence of the programs in constitutive modeling, shock-wave phenomena and physics of explosives, instrumentation techniques and facilities have been developed for studying and producing stress waves in materials. Major instrumentation developments are the submicrosecond-resolution quartz gauge, and displacement, velocity and diffuse reflecting surface velocity interferometer systems. To support programs in impact physics, in-flight stereo and holographic recording techniques are under development. (Items 15-17)

Current Activities and Facilities

- High-resolution techniques
  - Material motion: interferometry
    - Displacement
    - Velocity
    - Diffuse reflecting surface velocity
  - Shape: in-flight
    - Stereographic
    - Holographic
  - Stress
    - Manganin piezoresistive gauges
    - Lithium niobate piezoelectric gauges
    - Sapphire dielectric gauges
    - Quartz piezoelectric gauges
- Specialized major developed facilities
  - Two-stage light gas/powder gun facility
    - Capabilities
      - 20-mm launch tube, 0.05 kg at 10 km/s
      - 28-mm launch tube, 0.1 kg at 8 km/s
      - 63-mm launch tube, 0.5 kg at 5 km/s
      - 89-mm powder gun, 2 kg at 2.3 km/s
    - Use
      - Hypervelocity single-particle impact physics
      - Ballistic penetrations
      - Rain and dust erosion
      - Internal ballistics
      - Constitutive equation studies
        - Phase transformations
        - Compaction of porous materials
        - Explosive initiation and detonation
  - Compressed-gas gun facility
    - Capabilities
      - 63-mm diameter, 0.23 kg at 1.7 km/s
      - 101-mm diameter, 0.36 kg at 1.0 km/s
      - 101-mm diameter, 0.37 kg at 0.6 km/s
    - Use
      - Constitutive equation studies
      - Spall and fracture studies
      - Instrumentation development
      - Component development studies
  - Triaxial facility
    - Capability
      - Servo-controlled, ultrastiff machine
      - 1-GPa pressure
      - 1.78 million Newtons force rating
    - Use
      - Constitutive equation studies
      - Soil/rocks studies
      - Polymers studies
      - Porous materials studies
  - Ultrasonics facility
    - Capability
      - 0.4 to 10 MHz, shock or sinusoidal modes with concurrent temperature and pressure
    - Use
      - Constitutive equation studies
      - Dispersion in composites
      - Acoustic velocities studies
      - Seismic studies

*   *   *   *   *   *   *HIGHLIGHTS*   *   *   *   *   *   *

Item 1. *Hypervelocity Particle Impact Analysis*

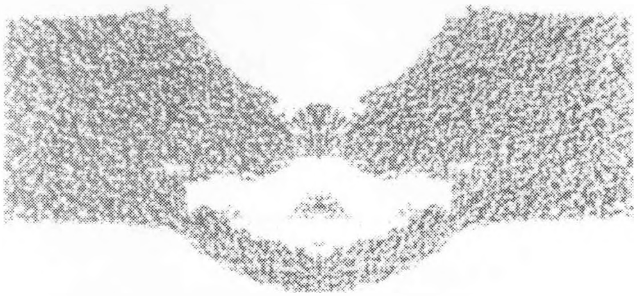
The capability of two-dimensional Lagrangian and Eulerian computer programs to solve difficult problems accurately is illustrated in this example. A 1.27-cm-thick steel armor plate is impacted by a 0.95-cm-diameter nylon sphere at 5182 m/s. The 13-GPa polymorphic phase change in iron, the correct spall strength, an accurate material failure model, and a high degree of numerical resolution are very important in the solution of this problem (Figure 1).

Studies of high-velocity impacts include predictions of damage to nuclear reactor vessels from tornado-borne debris, meteorites and fragments (such as turbine blades) dispersed in an internal accident.

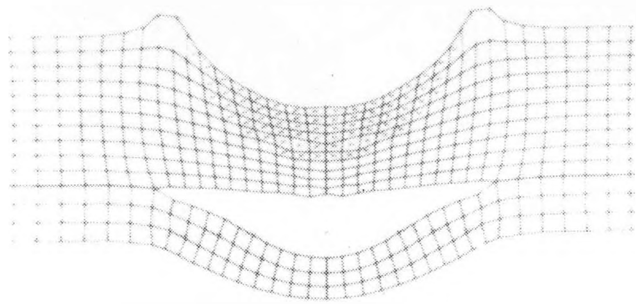
Item 2. *Safety Analysis for Containers of Radioactive Material*

The response during impact loading of the heat-source capsule (Figure 2) for a radioisotopically powered thermoelectric generator (RTG) was analyzed to determine structural integrity. The capsule consists of a fuel pellet of a radioactive isotope surrounded by distended material, which is in turn surrounded by layers of special alloys.

To predict whether the outer case of the capsule would remain intact under impact, calculations were performed with a two-dimensional wave propagation code (TOODY) capable of providing the history of deformation for each part of the RTG capsule. In one calculation the impact surface was at the spherical end; in another, at an angle with the corner of the capsule's flat end. Reduction

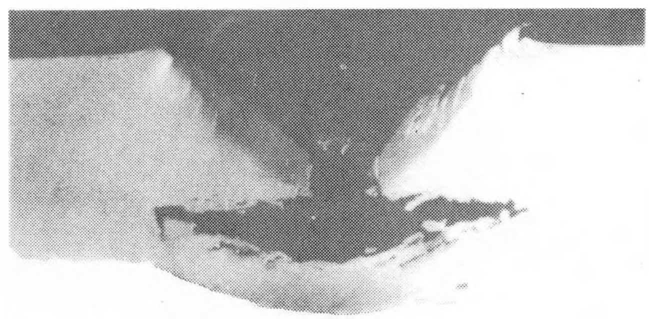


CSQ Eulerian code solution
with 13 GPa phase transition



TOODY Lagrangian code solution
with 13 GPa phase transition

CSQ Eulerian code solution
without 13 GPa phase transition



Experiment

Figure 1. Comparison of Lagrangian and Eulerian code predictions with results of hypervelocity impact experiment

SOLID DYNAMICS

in strength of the outer layer of material due to welding was modeled. Results showed that the outer structure of the capsule should remain intact and that the toxic radioisotope would not be released.

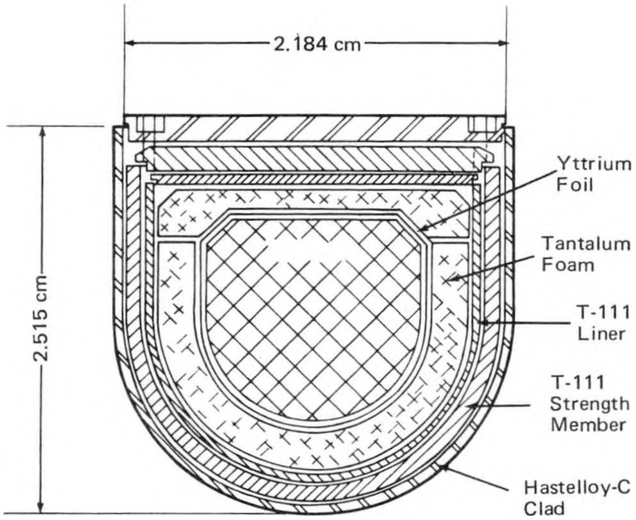


Figure 2. Heat source for radioisotopically powered thermoelectric generator

Item 3. *Dynamic Loads on Earth-Penetrating Projectiles*

In conjunction with terradynamics experiments, two-dimensional stress-wave propagation codes are employed to predict depths of penetration, deceleration histories, and dynamic loads imposed on projectiles. Constitutive relations for earth materials, determined by shock-wave and static triaxial stress experiments, have been incorporated into the TOODY two-dimensional code. Given appropriate geomaterial property data, calculations of projectile penetration are performed for single or layered media. Material response, including compaction behavior and failure, is observed, and its relation to projectile velocity, nose configuration and loads of the projectile is assessed to optimize projectile designs (Figure 3).

Item 4. *Hydraulic Jet Applications*

Hydraulic jets, both continuous and pulsed, have been studied experimentally for applications ranging from coal mining and rock tunneling to the cutting and machining of metals. The forces produced by water jets on target surfaces and predictions of target material behavior under jet action are obtained from a two-dimensional Eulerian code (CSQ) calculation (Figure 4). An inviscid, compressible, cylindrical column (2 mm in diameter) of water strikes an elastic-plastic target at a velocity of 3 km/s (with corresponding nozzle pressure of 4.5 GPa). From such a calculation pressure and velocity fields are determined in the water flow, and stress fields, regions of failure or yielding and deformation of the target material are obtained.

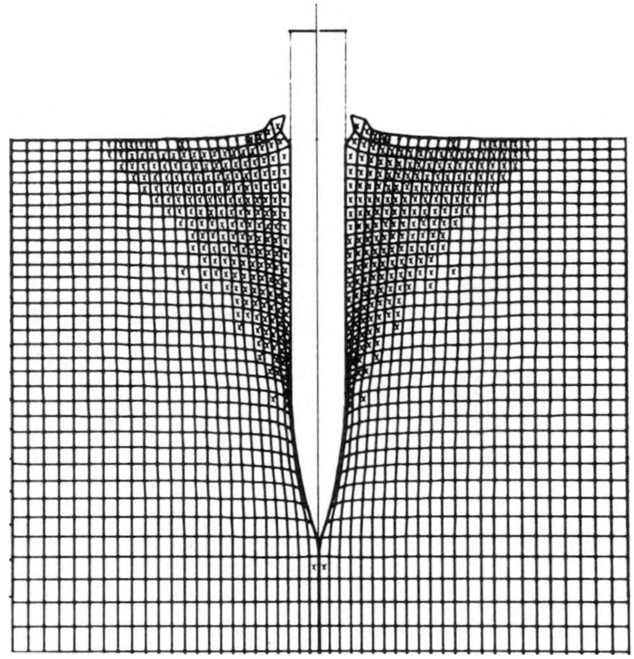


Figure 3. Regions of failure (8 msec after impact) produced in a soil medium by a 0.165-m-diameter projectile impacting at 152 m/s

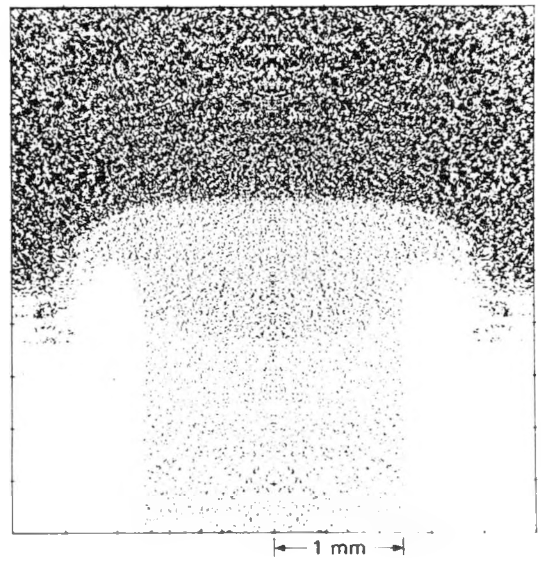


Figure 4. Fluid flow and target deformation at 0.65 μs after a 3-km/s water jet strikes an elastic-plastic target

Item 5. *Melting Time Scales*

To determine whether, under high rates of energy deposition, melting occurs on a time scale of 10^{-6} seconds or less, experimental techniques have been developed to study the behavior of materials shock-compressed to energy states at which melting should occur. Studies on both aluminum and bismuth indicate that melting does occur when these materials are shocked to high-energy states. However, the experimentally measured wave profiles are not in agreement with predictions based on rate-independent hydrodynamic calculations. This effect is shown in Figure 5, which compares the calculated and experimental particle velocity profiles on a bismuth specimen heated to 463 K and shocked to 2.4 GPa. The experimental profile is not in exact agreement with the calculation corresponding to instantaneous melting or with that for complete suppression of melting. However, the comparison does indicate that melting indeed occurs in times less than 10^{-6} second. The data allow development of equation-of-state models to describe material response in applications where energy is deposited in submicrosecond times.

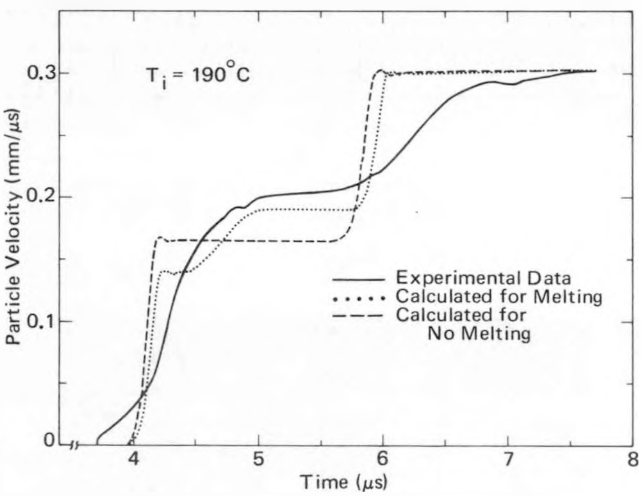


Figure 5. Measured velocity history in bismuth, shocked to a state where melting occurs, compared with equilibrium calculations

Item 6. *Stress- and Shock-Wave Measurement*

The quartz piezoelectric stress-wave gauge, with nanosecond resolution, has become a standard for shock-wave instrumentation. But a gauge is needed with larger electrical response for use in cases where the stress level and/or the signal-to-noise ratio are low. The lithium niobate gauge was developed for this purpose. The feature of lithium niobate that makes it particularly attractive is shown in Figure 6. The strain dependence of its piezoelectric polarization, as expressed by the piezoelectric coefficient, is an order of magnitude larger than that of quartz. The solid lines illustrate the nonlinear response for the large strains of interest, whereas the dashed lines represent the initial slopes. Only recently has lithium niobate become available in sufficiently large and high-quality crystals for this application. Figure 7 illustrates the quartz gauge (left) and the lithium niobate gauge (right).

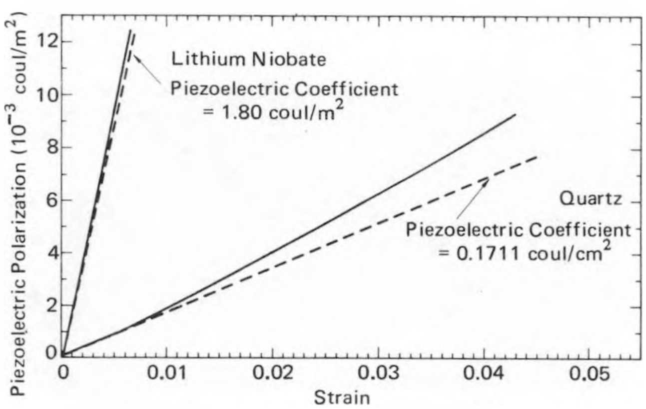


Figure 6. Piezoelectric polarization as a function of strain for lithium niobate and quartz

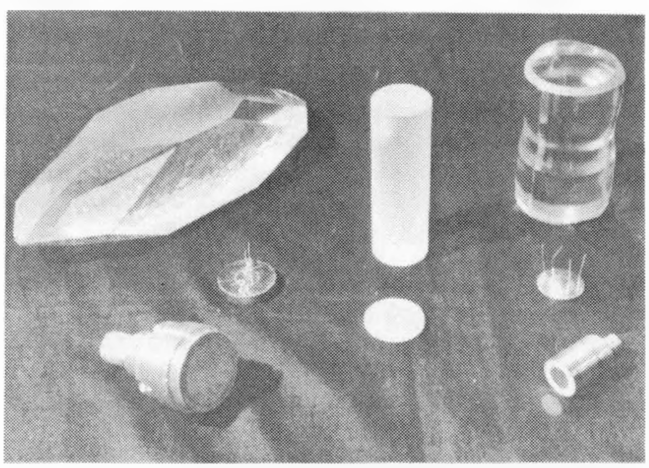


Figure 7. Crystals and stress gauges (left-to-right) of quartz, sapphire and lithium niobate

SOLID DYNAMICS

Item 7. *Armor-Plate Spall Strength*

An exploratory program has been conducted on the projectile penetration characteristics of armor plate (see Item 1). An accomplishment of the initial program was close correlation of an experimental hypervelocity penetration test with numerical wave-propagation code predictions. The success of the calculations was due to material property input based on experimental determination of the spall strength of armor plate (information not previously available). Figure 8 shows spall separation initiated in armor plate by conventional gas-gun impact experiments. The thin plate is the flyer plate, which was impacted at a velocity of 0.335 m/s against the target plate. A spall strength of 3.8 GPa was determined from this experiment.

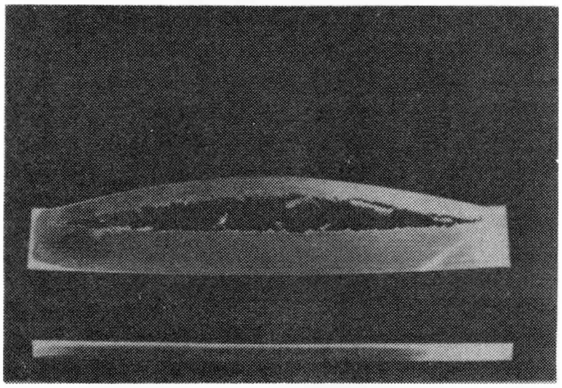


Figure 8. Spall of armor plate steel produced in experiment to determine dynamic tensile strength

Item 8. *Dynamic Mechanical Properties of Plasma-Sprayed Beryllium*

In the plasma-spraying process for forming coatings and shaped parts, powders of various materials, melted as they pass through an electric-arc plasma, are deposited on a solid substrate. This production technique, though useful, produces some rather unique mechanical properties. Splat deposition and solidification of the molten material causes an extremely layered microstructure containing thin cracks, porosity, and thermally induced residual stresses. An investigation of wave propagation in plasma-sprayed beryllium revealed that the wave structure was highly dependent on the nature of this microstructure. Further, it was shown that the dynamic mechanical properties could be changed by altering the microstructure by sintering-type heat treatments. The results of this study provided information for selecting a heat treatment that would optimize the properties of porous beryllium.

Item 9. *Constitutive Equation Modeling: Composites*

Studies of wave propagation in composites has resulted in several constitutive models. Extension of a rigorous mathematical description of a linear elastic model with microstructures to higher orders, specifying interlamellar stress and strain constraints, has led to a greater understanding of internal stress and strain fields. Still further understanding has resulted from a realistic statement of external boundary conditions and a knowledge of the role of interlaminar bond failure in governing wave propagation.

While the elastic theories aid in understanding wave propagation, a series of "homogeneous" material models have proven the most useful. These models allow nonlinear stress-strain behavior. One, for example, treats the composite as a rate-dependent solid of the Maxwell type. Excellent agreement has been obtained between calculated stress-wave profiles and laboratory experiments on a cloth-laminate quartz phenolic composite. Stresses were calculated to within 5 percent, as were the wave speeds. Further extensions of the model have been made to incorporate thermodynamics and initial porosity. In this form, the model is being used for engineering design calculations, replacing expensive and prolonged field testing.

Item 10. *Shock Initiation of Detonation in PBX-9404*

High-resolution measurements of the structure of plane waves propagated through the explosive PBX-9404 have yielded information about the rate of growth of weak shocks toward detonation. Comparison of the detailed structure of the observed wavefronts with theoretical results permits the determination of rates of release of chemical energy behind the shock and the study of the interplay between this energy release and viscoelastic dissipation of energy in controlling the growth of the wave. Information on the properties of explosives is used in developing nuclear ordnance and in safety assessments of potential accident situations involving explosives.

Item 11. *Complete Equation of State of Nitromethane*

Shock Hugoniots centered at several initial temperatures have been measured for the chemical explosive nitromethane. These results have been combined with atmospheric-pressure thermodynamic data to yield the complete equation of state of this material in regions of temperature and pressure ranging from ordinary ambients to those in detonations. This equation of state, combined with chemical kinetic data, is being applied to the study of wave propagation and initiation of detonation in this prototype homogeneous material. Equations of state for both detonated and undetonated explosives are utilized in computer codes for design and analysis of explosive components.

Item 12. *Explosion Containment*

Interest in the containment of explosions has led to the development of devices to contain the hot gaseous detonation products, high-velocity metal fragments, and other debris that may be produced when high explosives are detonated. In these devices, energy is removed from the detonation products by allowing them to do work in irreversibly compacting porous metal. The outward motion of the explosion debris and compacted metal is then arrested by the application of forces arising in a momentum trap that consists of strong reinforcing layers, either alone or in combination with shock-absorbing material. Finally, the cooled quiescent gases are contained in a pressure vessel surrounding the energy and momentum trap. In the largest-scale test to date, the detonation of 13.5 kg of explosive in a 2.1-m^3 vessel resulted in its being subjected to a pressure of only 0.48 MPa. Calculations suggest that container weight need be only some 100 times that of the explosive to be detonated (Figure 9).

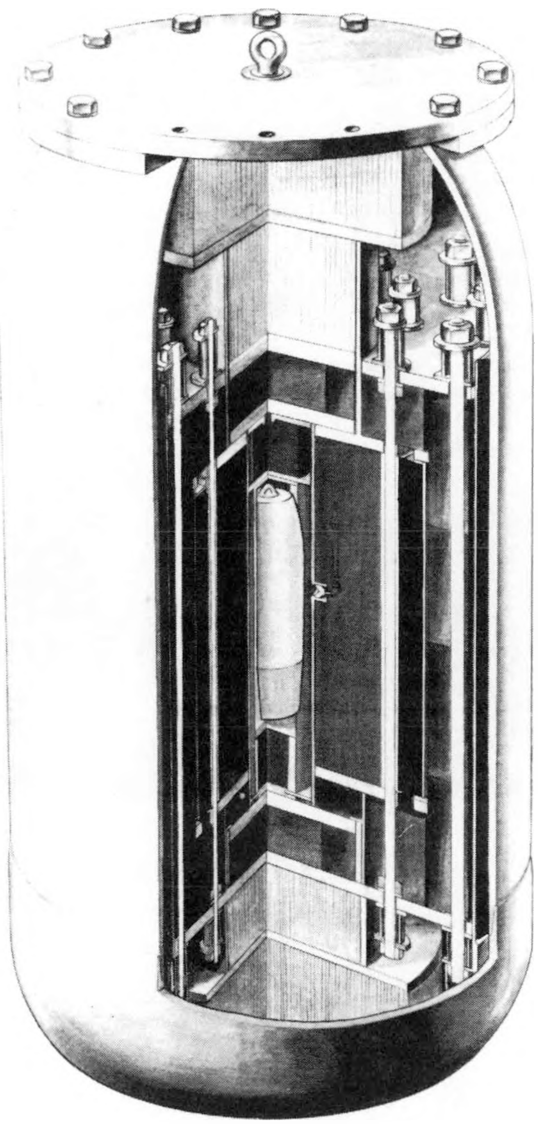


Figure 9. Prototype explosion container

Item 13. *Criteria for Electrical Initiation of Detonation in PETN*

The widespread use of granular compacts of PETN in exploding bridgewire detonators has necessitated the development of initiation criteria for this explosive. The "threshold burst current criterion" developed to meet this need takes account of both bridgewire dimensions and relevant explosive parameters.

Studies of the sensitivity of PETN to electrostatic discharges have led both to the establishment of a criterion for initiation by electrical sparks and to the development of a special class of detonators initiated by this means. These latter detonators, which have essentially the same advantages of functional precision and safety that make exploding bridgewire detonators attractive, operate on much less stored electrical energy.

Item 14. *Detonator and Firing-System Performance*

To facilitate the design of exploding-bridgewire detonator systems, models of the electrical behavior of exploding wires have been developed and data collected for some 20 wire materials. The results of this study are summarized in the form of computer codes that calculate current waveforms in circuits containing exploding wires and evaluate explosive initiation criteria that are cast in terms of the calculated current history and various detonator and explosive parameters. In addition to predicting detonator behavior, these studies of exploding-wire performance have proven useful in predicting performance of circuit fuses, metal plasma generators, and other similar devices.

SOLID DYNAMICS

Item 15. *Two-Stage Light Gas/Powder Gun Facility*

This facility, shown being prepared for a hypervelocity single-particle impact test (Figure 10), can achieve velocities of 10 km/s. The facility includes a 15-m flight range and features precise control of the flight and impact of the projectile. When used for constitutive equation work, impact planarity of flat-nosed projectiles is maintained to better than 1.0 milliradian. Instrumentation includes velocity interferometry, in-flight stereo and holography, flash x-ray and numerous electronic devices.

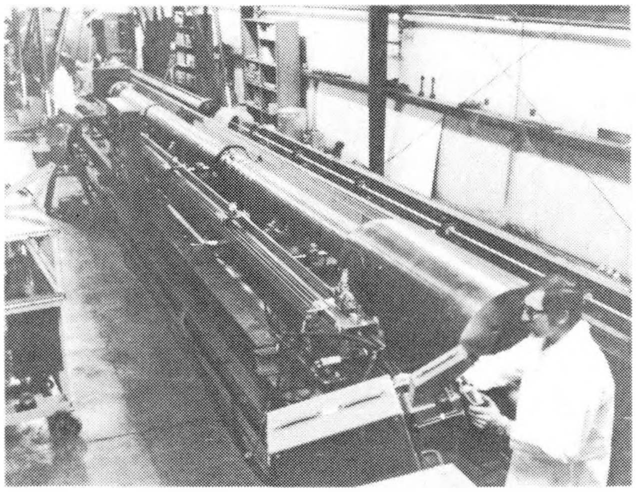


Figure 10. Two-stage light gas/powder gun facility

Item 16. *Interferometry*

A collection of laser interferometry systems has been developed which gives high resolution for studies of shock-wave phenomena and permits precise measurement of material response. Displacement interferometers resolve material displacements of fractions of the wavelength of light. Velocity interferometers have demonstrated resolution of 0.25 percent in particle (material) velocity at stresses of 25 GPa and particle velocities up to 1.3 km/s. Time resolution with these systems is a few nanoseconds.

These interferometers allow detailed investigations of the complete dynamic stress-wave loading and unloading process. They have been used to study the visco-elastic nature of polymers, showing the experimental existence of instantaneous and equilibrium response and the growth and decay of acceleration waves; the transformation kinetics of the iron polymorphic phase change occurring at 13 GPa; the internal ballistics of a two-stage light gas gun at a velocity of 3 km/s; and the velocity dispersion which occurs within the compaction wave in porous aluminum.

Item 17. *Static Triaxial Stress Studies of Oil Shale*

A computer-controlled triaxial test machine is used to study the yield and fracture behavior of anisotropic oil shales as a function of kerogen content, under various pressures. A typical result (Figure 11) illustrates the increase of volumetric strain with compressive stress unique to rocks and soils (dilatancy). This effect is the dominant feature in rocks and soils, and triaxial studies are providing the data needed to construct constitutive models. Such rock and soil models, as incorporated into the numerical codes, are being used for engineering calculations in developing earth-penetrating projectiles, in cratering, in rock drilling and blasting, and in oil-shale retort rubblization.

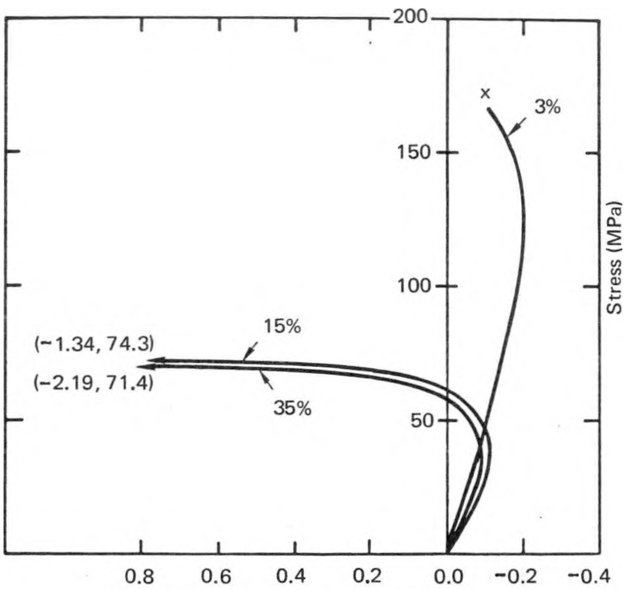


Figure 11. Axial stress-volume strain behavior of oil shale as a function of kerogen content (volume percent). Failure or fracture is denoted by X for the 3-percent shale and by the strain and stress values noted for the 15 and 35 percent shales.

INTERACTION OF RADIATION WITH MATTER

Interests in this area range from formulating and refining a basic understanding of radiation effects in solids to developing radiation-resistant devices and systems. Theoretical studies provide computer codes and methods for solving problems involving neutron, photon, and electron radiation transport through matter. These studies are supported by facilities for neutron, ion, electron, x-ray and gamma-ray irradiation of materials and devices. Major areas of research are: radiation, electronic, atomic, and molecular physics; materials and devices; and transport calculations.

Radiation Physics

In studies of the fundamental mechanisms and phenomena pertinent to the interactions of radiation with matter, special emphasis is placed on energy deposition resulting from electron irradiation, radiation effects (both transient effects and permanent damage) produced by electrons, and x- and γ-ray and neutron environments. (Items 1-3)*

Current Activities

- Radiation interactions in matter
  - Dose-depth determination for electron penetration
  - Electron transmission and backscattering
  - Bremsstrahlung production
  - Characteristic x-ray production
  - X- and γ-ray penetration
  - Positive ion sputtering
  - Neutron sputtering
  - Secondary electron emission
- Radiation effects
  - Transient effects in semiconductors and insulators
  - Permanent damage in metals, semiconductors, and insulators
  - Thermomechanical response of solid matter
  - Changes in mechanical properties of materials
- Radiation detection
  - Electron, x- and γ-ray, and neutron dose and/or fluence measurements
  - X- and γ-ray and neutron dose rate and/or flux measurements
  - Electron-beam current measurements
  - Neutron, x-, and γ-ray spectroscopy
  - Electron energy analysis and spectral determination
  - Neutron time-of-flight techniques
  - Heavy-ion energy analysis

*See Highlights, below.

Electronic, Atomic, and Molecular Physics

Programs are aimed at obtaining basic data required for understanding of particle interaction with matter. These data are directly applicable to electron-energy deposition in materials such as electron-beam-driven and heavy-ion-driven laser systems. (Item 4)

Current Activities

- Collision cross-section measurements
  - Neutrals (including metallic atoms)
  - Heavy ions (including metallic ions)
  - Electrons
- Atomic and molecular spectroscopy
  - Vacuum ultraviolet
  - Visible
  - Infrared

Materials and Devices

The materials studied include semiconductors, inorganic and organic insulators, pure metals, alloys and metal hydrides. Accelerator facilities are used to perform irradiations under controlled environments. (Items 5-7)

Current Activities

- Semiconductors and inorganic insulators
  - Lattice defect production, defect identification, and annealing in semiconductors, glasses, and oxides
  - Ion implantation modification and doping
  - Lattice location and diffusion of implanted impurities
  - Radiation effects on conductivity, carrier lifetime, and optical properties
  - Electron, neutron, ion, and γ-ray damage
  - Neutron-radiation detectors

INTERACTION OF RADIATION WITH MATTER

- Radiation effects in semiconductor devices
  - Transistors - bipolar and MOSFET
  - MNOS devices
  - Diodes
  - Solar cells
  - Light-emitting diodes
  - Microwave devices
  - Neutron-energy dependence of radiation damage
- Radiation effects on organic materials
  - Polymers
  - Organic crystals
  - Dosimetry
  - Radiation chemistry
- Metals
  - Helium ion implantation damage, bubble and blister formation, gas release; simulation of tritium decay
  - Helium and deuterium implantation and channeling lattice location
  - Ion implantation and radiation-enhanced diffusion studies
  - Theoretical and experimental studies of ion-beam simulation of neutron radiation damage
- X-ray effects
  - Extensive studies of x-ray induced shock, spallation, and energy deposition
- Theory
  - Depth distribution calculations of the energy deposited into displacement damage and ionization energy
  - Calculations of radiation damage as a function of neutron energy and comparison with experiment
  - Calculations of the mechanical response of structures following irradiation

Transport Calculation Capability

Research is directed toward the development and use of computer programs for solving neutron, photon, and electron transport problems in shielding-type studies. The objectives include the ability to treat multidimensional geometries and time-dependent effects. Analytical techniques to provide highly accurate approximate solutions for photon and electron transport problems also are being investigated. Cross-section data are being developed and maintained for input to transport calculations. (Items 8,9)

Current Activities

- Discrete ordinates transport codes
- Monte Carlo transport codes
- Analytical transport calculation techniques
- Cross-secton libraries

Atomic Wave Function Library

Many atomic properties of matter can be calculated from a knowledge of the distribution of atomic electrons about the atoms. Such information is contained in the atomic wave functions. A library of relativistic Hartree-Fock wave functions is available for calculation of desired quantities. (Item 10)

Critical Activities

- Nonrelativistic Hartree-Fock wave functions
- Relativistic Hartree-Fock wave functions

Experimental Facilities

Van de Graaff generators (400 keV and 2.0 MeV) are used for *in situ* ion implantation and ion surface analysis down to 38 K. Ion backscattering, ion-induced x rays or ion-induced nuclear reaction analysis on polycrystalline surfaces or on single-crystal surfaces employ a precision goniometer for channeling analysis.

A 2.5-MeV Van de Graaff is integrated with an 80-keV high-fluence heavy-ion implanter and a high-voltage transmission electron microscope for *in situ* ion implantation and analysis of radiation damage or alloy formation. A high-fluence heavy-ion accelerator (300 keV) supports ion implantation studies, as well as *in situ* stress and ion-induced x-ray analysis of surfaces.

A 400-keV ion accelerator is used for *in situ* mass spectrometry, scanning electron microscopy, and proton-excited x-ray analysis of surfaces.

Other facilities include a relativistic electron irradiation facility for pulsed electron irradiation, pulsed laser action, and pulsed x-ray irradiation; a pulsed x-ray facility used with an *in situ* optical spectrometer at temperatures from 4 K to room temperature; and two pulsed reactors for neutron irradiation of materials and devices.

INTERACTION OF RADIATION WITH MATTER

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Electron Energy Deposition Measurements*

In a study of energy deposition profiles for energetic electrons penetrating matter, a measurement technique has been developed which utilizes calorimeters of the same material as that under study. Thus it is not necessary to use a relative stopping power ratio correction, a quantity which can be extremely difficult to calculate. With a precision 1-MeV electron accelerator, dose-depth profiles have been measured over the energy range of 0.1 to 1.0 MeV and at normal and oblique incidence for Al and Ta. Measurements also are being performed on laminated structures and on various materials. The results obtained from this work provide a check of the accuracy of present predictive capabilities.

Item 2. *Transient Radiation Effects*

Radiation effects in materials and components are studied extensively, using pulsed accelerators. Under investigation are transient effects, ranging from photocurrent phenomena in discrete components to IEMP effects in circuits/components, and permanent effects arising from such phenomena as trapping of liberated charge carriers at surfaces or interfaces. In addition, utilization of the accelerators in the e-beam mode has facilitated studies of the transient thermomechanical response of solids subject to high-intensity, short-duration energy deposition as well as permanent damage to the material or structure resulting from spall, delamination, blowoff, etc.

Item 3. *Radiation Dosimetry*

Specialized diagnostic tools and/or techniques have been developed to characterize radiation fields (neutrons, γ- and x-rays, electrons, positive ions, etc.). This has included the development and utilization of magnetic spectrometers to measure electron and photon spectra; a specialized device, called the "Ratio Detector," to measure electron spectra on the pulsed accelerators; solid-state and proton-recoil neutron spectrometers; active neutron and photon detectors (photodiodes, PIN detectors, Compton diodes, scintillator/photomultiplier detectors, fission-couple detectors, neutron time-of-flight techniques, etc.); and passive neutron and photon detectors (foil activation techniques, TLD's, plastics/glasses, etc.). Also included has been the development of calorimetric techniques for e-beam and photon definition, as well as Rogowski coils, B_θ probes, current shunts, and capacitive and resistive voltage dividers to monitor e-beam characteristics.

Item 4. *Atomic Cross-Section Measurements*

A continuing program is providing cross-section data appropriate to the interaction of ions and neutral atoms with atoms and molecules. In this program, an ion accelerator provides atomic or molecular ions of up to 100-keV energy. Special techniques have been used to obtain ions of metals and other solid materials. Cross sections for electron capture and loss have been measured for a variety of such ions in a number of gases. Emission cross sections have been determined for ions, atoms, or molecules for interaction with atmospheric gases. This is of particular interest in connection with the physics of the upper atmosphere. This program is currently directed toward obtaining information useful in high-pressure gas laser studies.

Item 5. *Radiation-Induced Defects in Si*

Electron spin resonance (EPR) is one of the experimental tools used to study the character of defects in solids. Figure 1 shows an EPR spectrum of a radiation-induced defect in Si. The six almost evenly spaced lines about the central line are due to ^{17}O. The central line is due to ^{16}O (^{17}O is only 0.03% naturally abundant). The difficulty in observing ^{17}O interactions was overcome by ion implantation in which the ^{17}O concentration was enhanced by a factor of 10^4.

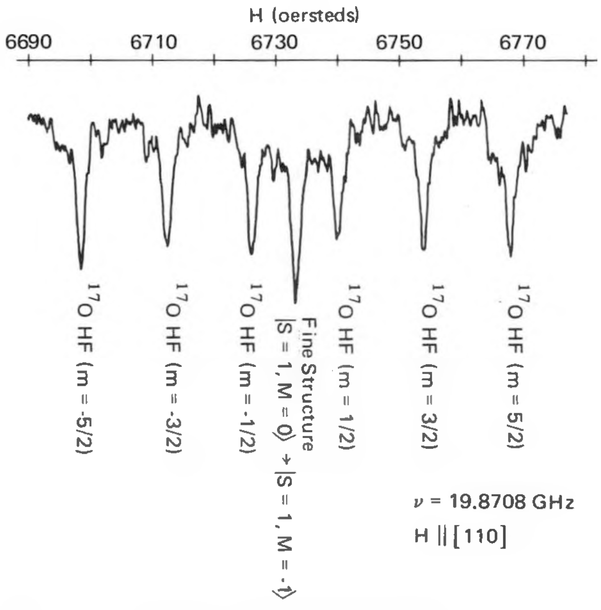


Figure 1. EPR spectrum of a radiation-induced defect in Si

INTERACTION OF RADIATION WITH MATTER

Item 6. *Semiconductor Neutron Detectors*

A method developed for measuring fast neutron fluences, useful for pulsed neutron sources, consists of detecting beta-induced electrical conductivity resulting from radioactive decay in semiconductors. It is ideally suited for high-resistivity semiconductors with large mobility-lifetime products, such as CdS. When CdS is irradiated with fast neutrons, the principal radioisotopes produced are ^{32}P and ^{115}Cd, which decay by beta emission, producing ionization (i.e., electron-hole pairs) within the semiconductor. The induced conductivity resulting from this ionization is measured. Since the radioisotope concentration is related to the incident neutron fluence, the resulting electrical changes from radioactive decay can be used as a means for neutron detection. With this detection technique fast-neutron fluences ranging from 10^{10} to 10^{17} n/cm^2 can be measured.

Item 7. *Blister Formation From Radiation Damage in Controlled Thermonuclear Reactor Materials*

Ion implantation is being used to study radiation-induced blister formation in metals. Figure 2 is a scanning electron micrograph of blister formation on vanadium for a dose of 4 x 10^{18}He atoms/cm^2 implanted at a temperature of 400°C. The bcc metals of Nb, V, and Mo and their alloys are likely candidates for construction of first-wall, divertor, and collector elements in controlled thermonuclear reactor designs.

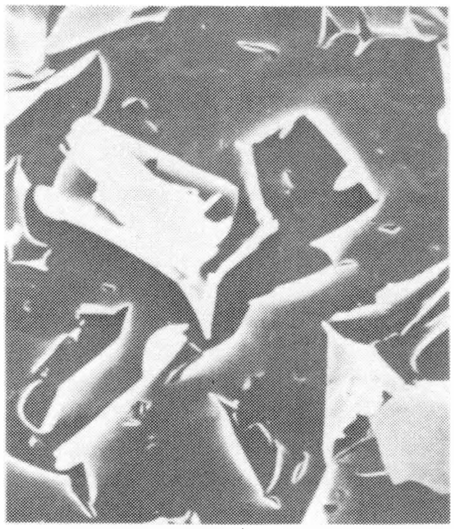


Figure 2. Scanning electron micrograph of blister formation on vanadium from implanted He ions

Item 8. *The DINT Computer Program*

A computer program called DINT generates the multigroup cross-section tables required to solve photon transport problems by the method of discrete ordinates. Its unique feature is the assumption that the photon scattering is describable by the physics of the coherent and incoherent scattering processes. When used with any of the well-known discrete-ordinates transport codes, the cross-section tables produced by DINT include in the transport calculation all the important photon-matter interaction processes.

Item 9. *Analytical Methods in Electron Transport*

Analytical methods have been developed that treat a number of calculational aspects of fast electron transport near a material/vacuum or material/material interface. Such calculations are required in studies of radiation vulnerability and diagnostics, certain aspects of laser-induced fusion, high-energy electron beam machines, and other areas. Algebraic formulae—developed for the number of electrons driven out of a surface by an arbitrary photon flux, for their distribution in energy and angle, and for the accompanying emission of low-energy secondaries—provide a valuable alternative to sophisticated, but complex and expensive, Monte Carlo techniques.

Item 10. *Low-Energy Electron Scattering Cross Sections*

Calculations which account for the scattering of electrons as they penetrate matter depend on knowledge of the probability that electrons will be scattered in various directions. This information, as expressed by the differential scattering cross section, is accurately known for electron energies greater than $(Z/3)^{4/3}$ keV, where Z is the atomic number of the material. A computational effort has been successful in which relativistic Hartree-Fock atomic wave functions were used in a theoretical formalism to determine more accurate low-energy differential elastic electron scattering cross sections. These new cross sections have yielded calculated results for electron interaction information that agree better with experiment than previous results.

LASER FUSION

Programs in laser physics research are aimed toward the development of high-power lasers required for laser fusion and for studies of the response of materials subjected to high-intensity radiation environments. To this end fundamental studies are being pursued in atomic and molecular physics; solid-state, gas, and chemical laser physics; laser-plasma physics; laser fusion theory, and laser propagation theory. Capabilities and facilities are available for laser fusion research, laser development, laser pulse-power research and development, and for basic studies of chemical reaction rates, energy transfer processes, atomic lifetimes, and high-power optical phenomena.

Solid-State Laser Systems

Programs are aimed at understanding the physics involved in the design, construction, and usefulness of large solid-state laser systems. Quantitative measurements of nonlinear indices of refraction of transparent materials have been made, with emphasis on laser materials. Other pertinent laser parameters also can be measured, such as relaxation rates of inverted populations, beam divergence, and beam spatial and temporal profiles. (Items 1,2)*

Current Activities

- Laser diagnostics
  - Fast photodiodes
  - Integrating photodiodes
  - Calorimeters
  - Picosecond streak camera
  - Beam profile
- Optical isolators
  - Pockells cells
  - Faraday rotators
- Pulse width control
  - Mode locking
  - Q-switching
  - Gated pulse techniques

Gas Laser Systems

Programs are aimed at identifying and studying gaseous media which may be capable of supplying very high laser intensities for pellet implosions. (Item 3)

Current Activities

- Iodine laser development studies
- Atomic physics
  - Lifetimes
  - Energy transfer
  - Reaction rates
  - Pressure broadening
- Excited-state energy storage
  - Efficiency
  - Extraction
- Electron-beam-energy deposition in gases

Gas Laser Physics

Programs are directed toward investigating the feasibility of developing gas laser systems in which pumping energy is delivered to the system through the use of high-intensity electron-beam photons or heavy ions. (Items 4 - 6)

Current Activities

- Electron-beam excitation of gas laser systems
- Evaluation of gas laser system performance
  - Gas fluorescence and spectroscopy
  - Gain measurements
  - Output energy/power determination
- Modeling of gas laser systems
- Nuclear-reaction-product excitation of gas laser systems

Chemical Laser Systems

Chemical laser programs are aimed at utilizing chemical reactions for the production of laser energy. Special emphasis has been placed on time-resolved mass spectrometry for the interpretation of chemical reactions in the gas phase, as well as on developing vacuum and gas handling of systems. An effort has been made to develop expertise in optics and spectroscopy as pertinent to laser research. (Items 7,8)

*See Highlights, below.

LASER FUSION

Current Activities

- High-frequency laser development
- Mass spectrometry
  - Quadrapole mass filters
  - Time-of-flight mass spectrometers
- Vacuum and gas handling systems
  - Stainless-steel and glass systems
  - Gas handling of explosive or very reactive gases
  - Light absorption
  - Scattered, transmitted, and reflected light spectra
- Diagnostics
  - X-ray spectrometer
  - X-ray pinhole cameras
  - Thomson parabola ion analyzers
  - Picosecond streak camera
  - 20-keV ion probe
  - Magnetic electron spectrometer
  - Fast-neutron spectrometer
  - Picosecond holographic interferometer
  - Transmitted and reflected light photodiodes
  - Infrared spectrometer
  - Magnetic probes
- Laser-fusion theory
  - 2-D light propagation code
  - 2-D magnetohydrodynamic codes for target dynamics with self-magnetic fields
  - Transport calculations for instability-produced electrons
  - Combined theory for e-beam propagation and light output for high-pressure gas lasers
  - 1-D Lagrangian target dynamics codes, including multiphase equations of state
  - Nonlinear laser absorption theory

Theoretical Atomic and Molecular Physics

The research in theoretical atomic and molecular physics and chemistry emphasizes the gas phase. Particular attention is being given to the influence of rotational and vibrational excitation on the probability of electronic excitations, induced and spontaneous dissociation, and association of molecules. Investigations are being extended into the realm of gas discharge physics and the theory of electron-beam-excited gas discharge lasers. (Item 9)

Current Activities

- Electronic excitation and charge exchange in atom-atom collisions
- Auger, x-ray and related inner-shell processes
- Electron and photon collisions with atoms and molecules
- *Ab initio* calculation of the potential energy curves and properties of diatomic molecules

Laser Plasma Physics

The purpose of this program is to experimentally study laser-produced plasma phenomena resulting from high-power laser irradiation of spherical and slab targets. Basic laser-plasma studies are being conducted with the Sandia 4-beam laser in the energy region of 200-400 joules. Plasma diagnostics necessary for these studies have been developed. (Item 10)

Current Activities

- Measurements
  - Plasma temperatures
  - Neutron production
  - Shock propagation, compression
  - X-ray yields
  - High-energy electrons
  - Ion energy, charge, mass
  - Magnetic fields
  - Plasma potentials

Laser Light Propagation and Target Interaction Theory

Research is directed toward two basic problems. First, what is the important physics governing laser light propagation, amplification, diffraction, and focusing in a variety of lasing media, including Nd:glass and various high-pressure gases? Second, what are the mechanisms responsible for light absorption by various targets and what are the anticipated target dynamics? These problems are being addressed as part of the national program in laser fusion.

Current Activities

- Basic physics
  - Laser light characteristics
  - Focusing methodology
- Mechanisms
  - Light absorption
  - Target dynamics

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Four-Beam Laser System*

An Nd^{3+}:glass laser system (Figure 1) has been designed, constructed, and tested which gives four parallel beams for laser fusion studies. To date, 200 joules in a 1.8-nsec FWHM pulse have been delivered to CD_2 spherical targets. This laser is also used for large laser system engineering studies and applications.

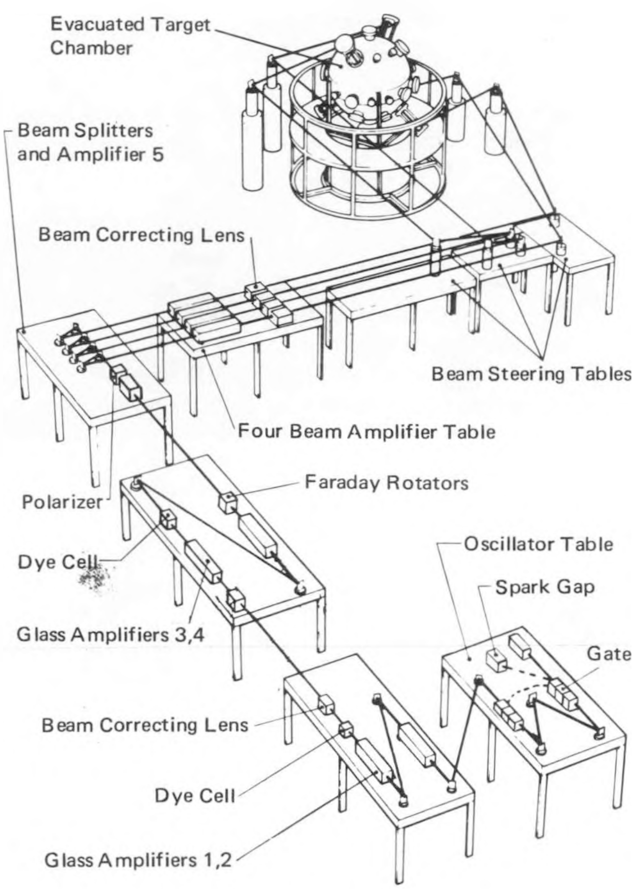


Figure 1. Four-beam laser system

Item 2. *Nonlinear Optical Studies*

An investigation is being conducted into the measurement of nonlinear indices of refraction of transparent materials with greater accuracy (±5%) than previously available. To date, the nonlinear index n_2 of 10 important laser materials such as laser glass have been measured. These studies are concentrated on obtaining a basic understanding of these important optical processes.

Item 3. *Dissociation Lasers*

There is a class of lasers in which either the upper-energy or the lower-energy laser level is repulsive. The limitations of this type of laser have been identified. The lower-energy case is particularly interesting, since population inversion is guaranteed and net gain should be obtainable. In the noble gases the upper-energy level is the lowest bound diatomic level and the lower-energy level is the repulsive diatomic ground state. In helium the center wavelength of the transition is ~600 Å and in xenon it is ≈1720 Å. By using different noble gases it may be possible to make a tunable laser at wavelengths between 500 Å and 1800 Å. Studies have demonstrated that the xenon system can support net gain at wavelengths near 1720 Å.

Item 4. *Cold-Cathode Electron-Beam-Stabilized Discharges*

Electron beams have been shown to be very effective in stabilizing discharges in gases. The electron beam is used to produce copious quantities of free electrons and an external voltage is applied to cause avalanching. The voltage is maintained low enough, however, to avoid breakdown or arc formation. Large volumes of gases can be uniformly excited in this manner. A parametric study has been performed, using a large (10-cm x 100-cm) electron beam (½ amp/cm²) from a cold-cathode vacuum diode (200 keV), to ionize $He/N_2/CO_2$ mixtures of gases at atmospheric pressures (Figure 2). Spatially uniform excited mediums were produced (Figure 3). The optical gain and performance of the CO_2 laser were measured.

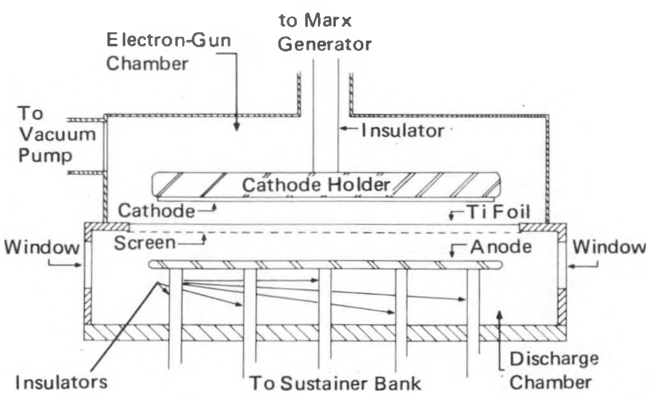


Figure 2. Schematic of cold-cathode vacuum diode and discharge chamber

LASER FUSION

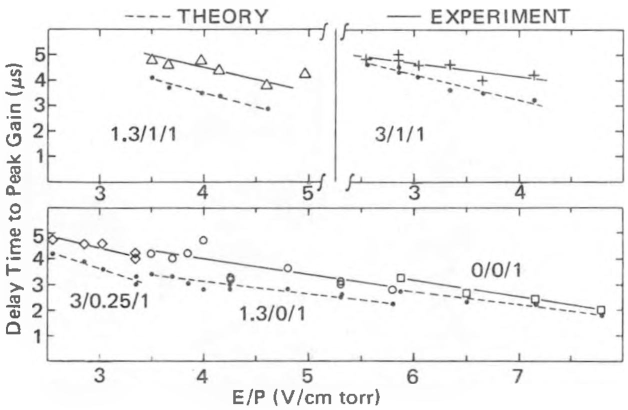


Figure 3. Typical data obtained with the cold-cathode electron-beam-stabilized CO_2 laser (p = 1 atm); $He/N_2/CO_2$ = 1.3/1/1

Item 5. *CO_2 Laser Operation*

A CO_2 laser has been made to operate with the use of the Sandia Pulsed Reactor II, a fast-burst reactor, as a driving source. The neutrons from the reactor were utilized in either the $He^3(n,p)H^3$ reaction or U^{235} fission process, with the reaction products providing ionization in the gas mixture. In the latter case the uranium was in the form of a U_3O_8 film deposited on the inner wall of the laser cell. Studies currently in progress include He-Ne, argon and CO, as well as chemical systems.

Item 6. *Lasing in N_2 Gas*

A model has been developed which quantitatively describes the lasing occurring in N_2 gas when it is subjected to an intense pulse of high-energy electrons. This model accounts for the return current in the cell required to maintain electrical neutrality, and the major feature is the excitation of the $C^3\pi$ state of N_2 by the return-current electrons which have been accelerated in the transient electric field created by the e-beam propagation process.

Item 7. *Electron-Beam Excitation of Chemical Lasers*

Electron beams are attractive for ignition of chemically active media because large volumes can be uniformly ignited in times much shorter than normal burn times. Studies have shown that a very efficient HF laser can be produced by using intense electron beams to ignite $SF_6 + C_2H_6$ mixtures (Figure 4). Conversion efficiency from deposited electron-beam energy to super-radiant laser outputs was as high as 16%.

Item 8. *Behavior of Methyl Radicals*

Programs have been conducted utilizing mass spectrometry to study the behavior of methyl radicals, since the characterization of this transient species has important implications for chemical lasers. Programs are also being conducted to investigate reactions involving very reactive components such as tetrafluorohydrazine.

Studies have been completed pertaining to the chemical dynamics of hydrogen fluoride chemical lasers and iodine photodissociation lasers.

Models for laser systems have been developed and, on the basis of experiment, it appears that the chemical lasers are generally understood for practical purposes.

Item 9. *Atomic and Molecular Studies*

Photo effect and Auger rates have been calculated for all inner shells of elements in the Periodic Table. Through a practical method developed for replacing inner shells of complex diatomic molecules by an effective potential, molecular properties can be quantitatively determined for very heavy systems. A new semiclassical theory of low-energy atom-atom collisions makes calculations on many-electron systems practical. A theory derived for the influence of vibration and rotation on the electronic excitation and spontaneous dissociation of molecules was derived (in excellent agreement with experiment) which shows that vibration and rotation can dramatically alter the interactions of a molecule with its surroundings.

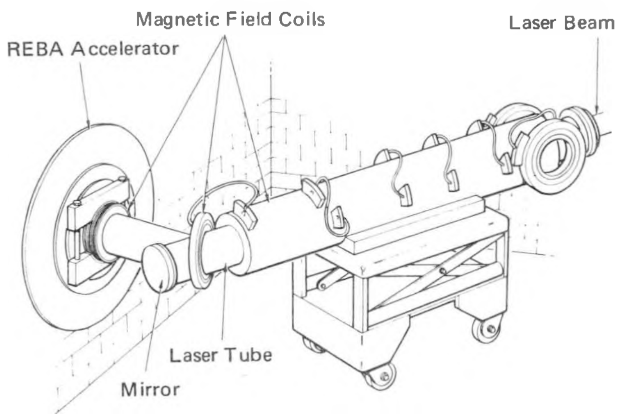


Figure 4. Schematic of laser tube assembly used with the relativistic electron beam accelerator to excite a large-volume chemical laser

Item 10. *Laser Irradiation of Deuteride Spheres*

Experiments have been conducted with 150-190-micrometer-diameter carbon deuteride spheres irradiated by four laser beams. The beams were incident upon the spheres in a tetrahedral geometry which provided a uniform irradiation, provided the focal spot was approximately equal to the sphere diameter (Figure 5). Energy on target has exceeded 50 joules per beam in a 2-nsec pulse for an average power density over the surface of the spheres of 10^{12} - 10^{13} watts/cm^2. Irradiation symmetry has been studied with x-ray pinhole photography. K-edge filter x-ray spectrometers, Thomson parabola ion analyzers, Faraday cups and fast-neutron detectors have been used to study plasma properties. In lower-energy, single-beam experiments, plasma expansion dynamics have been studied with picosecond holography and x-ray spectra. Plasma potential measurements have been made with a 20 keV ion-beam probe.

Data from these experiments are contributing to the AEC's laser fusion program.

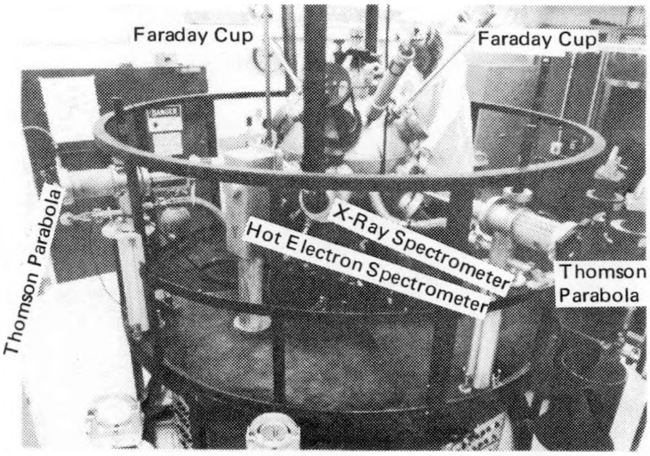


Figure 5. Target chamber and associated diagnostic equipment

RELATIVISTIC ELECTRON BEAM RESEARCH

Research in relativistic electron-beam phenomena is concerned primarily with electron-beam fusion and advanced applications of pulsed power technology. Newly developed capabilities to generate and focus high-intensity beams of electrons are being exploited in pulsed fusion research, in laser excitation, in nuclear effects studies, and in the collective acceleration of ions to ultrahigh energies.

The study of the physics of electron beam production in vacuum diodes utilizes a variety of experimental techniques, including laser diagnostics and computer modeling with multidimensional numerical codes. Plasma formation at both the anode and the cathode surfaces in the vacuum diode has been shown to strongly influence diode impedance and beam dynamics. Experiments in focusing beams to power densities of 10^{13} watts per square centimeter are oriented toward demonstrating the electron-beam fusion concept and developing a pulsed fusion reactor based on the heating and compression of deuterium-tritium pellets. Much of the work is aimed at providing a technical basis for demonstrating the feasibility of electron-beam-induced and laser-induced fusion. Advanced ultrashort-pulse relativistic beam generators are actively under development for use in pulsed fusion studies.

Major areas of research include the production and control of relativistic electron beams and their interaction with plasma; electron beam pulse power research and technology, accelerator development and applications, and fusion physics.

Relativistic Electron Beam Production

Programs are aimed at understanding the physical processes involved in the production and control of high-current (megampere, megavolt) relativistic electron beams. To accomplish this work, diagnostic techniques have been developed to measure high-energy densities. (Item 1)*

Current Activities

- High-current relativistic electron beam diodes
  - Design
  - Nanosecond current and voltage diagnostics at megampere and megavolt levels
- Plasma phenomena in diodes
  - External production of diode plasmas for beam control
  - Ion acceleration in diode plasmas
  - Neutron production in high-current diodes
- Diagnostics
  - Pulsed laser holographic interferometry
  - Thomson scattering
  - Optical measurements
  - Faraday rotation
  - X-ray photography

*See Highlights, below.

Electron-Beam Fusion

The Relativistic Electron Beam (REB) Fusion Program has as its goal to produce a controlled thermonuclear fusion reaction through implosion and heating of DT-containing pellets, to provide the basis for a fusion power source. The program is being pursued through an extensive effort in accelerator technology, experimental beam and plasma physics, analytical and numerical theoretical studies, and system analyses. The potential advantage of REB-induced fusion is its relatively high efficiency and low cost.

The AEC REB Fusion Program, which is centered at Sandia with support from other AEC labs, is aimed at demonstrating the feasibility of this approach through the execution of large-scale experiments to produce significant neutron yields. These experiments are being scaled up over a continuing program with the goal of achieving scientific breakeven in the early 1980's. (Item 2)

Relativistic Electron Beam Control

The objectives of these programs are to understand the generation of high-intensity electron beams and to develop techniques for the effective transport and control of these beams. Associated with this is the requirement to understand the interaction of high-intensity relativistic electron beams with plasmas and external fields. (Item 3)

Current Activities

- Electron beam physics
  - Beam generation
  - Beam transport and control (with and without external fields)
- Electron-beam/plasma interactions

Interaction of Relativistic Electron Beams With Plasma

Studies of the interaction of high-current relativistic electron beams with plasmas are concerned with the production of plasmas with temperatures in the thermonuclear regime, and with understanding the processes by which intense beams of high-energy ions are produced when high-current electron beams interact with neutral gases.

Basic theoretical studies of the production, propagation, focusing, and energy deposition of relativistic electron beams are being pursued, in the context of using these beams as energy sources for controlled thermonuclear fusion. Both analytical methods and numerical codes have been developed for use in these investigations. The physical models employed range from the collisionless plasma simulation approach to the collision-dominated fluid descriptions appropriate to hydromagnetic flow. (Item 4)

Current Activities

- Propagation of relativistic electron beams in neutral gases and plasmas
  - Beam transport and control (with and without external fields)
  - Heating of solid DT targets
- Collisionless models
  - Electron-beam strong focusing models
  - Analytic plasma-wave mode coupling theory
  - 1-D relativistic beam-plasma interaction codes
  - 2-D time-independent beam propagation and background ionization calculations
  - 2-D diode simulations
- Fluid models
  - Analytic envelope equation for beam focusing
  - Calculation of ambipolar diffusion and Debye sheath formation
  - 1-D Lagrangian multitemperature hydrodynamics codes including thermal and radiation diffusion
  - 2-D Eulerian hydromagnetics codes

RELATIVISTIC ELECTRON BEAM RESEARCH

Pulse Power Research and Technology

This program is directed toward establishing a basis for technology and a fundamental understanding of important processes to deliver 10^{14} watts of electrical power for generating intense electron beams. Research has been conducted with the aim of developing accelerators for use in nuclear effects studies and has recently been extended to new applications in electron-beam fusion. Other applications using the same technology are fusion plasma heating, electromagnetic pulse generators, portable x-ray machines, electron-beam rock tunneling, and lightning simulators. This program, which began in 1966, has resulted in 14 different accelerators being designed, fabricated, and placed in operation, the largest being a 10^{12}-watt, 10-megavolt unit. A 10^{13}-watt accelerator is now under development. (Item 5)

Current Activities

- Megavolt switching
  - High-current switching in liquids, gases, and dielectrics
  - Nanosecond synchronization
  - Low-inductance switches
  - Fast triggering modes
- Energy storage
  - Low-inductance Marx generators
  - Nanosecond synchronization
  - Megajoule energy storage
  - Inductive energy storage
  - Fast energy storage
- Dielectric breakdown
  - High-energy density media
  - Vacuum interface
  - Electrode properties

Accelerator Development

Continued development and improvement of accelerator capabilities is required to satisfy ever increasing program requirements as well as to allow for more effective source utilization. This includes activity in such areas as modification and improvement of accelerator components, electron-beam generation, transport and control, x-ray converter design and development, and the development and improvement of associated instrumentation and diagnostics. Activities in these areas promote pulsed accelerator simulation capabilities and provide experimental capabilities for investigating the feasibility of electron-beam fusion and accelerating the development of fusion technology. (Items 6-9)

RELATIVISTIC ELECTRON BEAM RESEARCH

Current Activities

Design and evaluation of accelerator components
Electron-beam generation
  Diode design and development
Electron-beam transport and control
  Neutral gas focusing
  Beam control with guide bodies
  External field beam control
Bremsstrahlung converter design and development
  Advanced "thin" target design
  Standard "thick" target design
Accelerator diagnostics and instrumentation development
  Electron-beam calorimetry
Voltage monitors - resistive and capacitive dividers
Current monitors - Rogowski coils, resistive shunts, and Faraday cups
Advanced instrumentation development - digital equipment for direct data acquisition and reduction

Accelerator Applications

High-current pulsed electron accelerators are used in the study of transient radiation effects in electronic components and circuits, permanent radiation damage to devices and circuits, and basic studies of the response of semiconductors to intense short-duration pulses of ionizing radiation. The thermomechanical response of materials and/or structures through conditions of melt and vaporization also are investigated, as are radiation-induced changes in the mechanical properties of materials. These sources, which provide the potential energy sources for electron-beam fusion, are also used as energy sources for pumping gas lasers and for plasma heating studies. In support of these applications, instrumentation and data-acquisition capabilities and experimental techniques have been developed.

Current Activities

Experiment-related accelerator output optimization
Data acquisition for and conduct of experiments
  Experiment design
  Experiment diagnostics and instrumentation
  Data acquisition and reduction
  Radiation detection
Flash x-ray, pulsed electron-beam, and steady-state-electron, positive-ion, and neutron exposures
Operation and maintenance of accelerator systems

Nuclear Physics

Various techniques, and the nuclear data they generate, are used in studies of electron-beam accelerator diode behavior and in the investigation of the phenomenon of ion acceleration accompanying electron-beam generation and/or transport.

Current Activities

Nuclear spectroscopy
Photo-neutron-induced reactions
Heavy-ion-induced nuclear reactions
Activation analysis

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Plasma Measurements*

Pulsed laser holographic interferometry has been used to measure plasma density and motion in the diodes of high-current relativistic electron-beam accelerators. The photograph (Figure 1) shows a reconstruction of a hologram taken on the Relativistic Electron Beam Accelerator (REBA). A pointed glass rod cathode about 6 mm in diameter is at the left and a planar anode at the right. Each fringe indicates an increase of plasma electron density along the optical path of the laser of $\sim 10^{17}/cm^2$. Abel inversion of the density contours gives the radial variation of plasma density as a function of axial position. Variations of intensity of the fringes provides a measure of the plasma velocity.

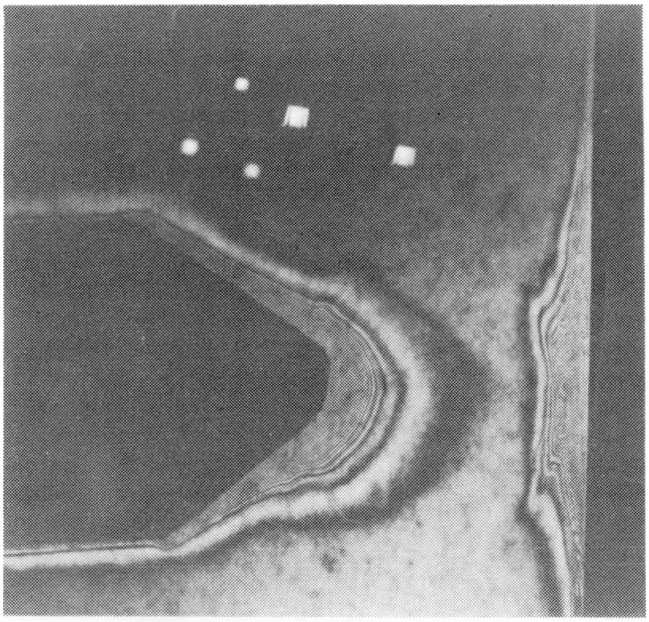


Figure 1. Reconstruction of hologram taken on the REBA accelerator

Item 2. *Pellet Implosion Studies*

In the Sandia concept for pellet implosion, beams from two separate sources are focused onto a spherical pellet. Initial tests are being carried out on the Hydra accelerator, which employs two synchronously fired pulse lines to deliver two beams to a hollow gold spherical shell mounted in a common anode (Figure 2). Self x-ray photographs of the target indicate the uniformity of irradiation, which is found to be quite good (Figure 3). In actual fusion experiments this shell will be filled with deuterium-tritium (D-T) gas and the implosion of the shell by the ablating outer surface will compress and heat the D-T to thermonuclear temperatures. Present studies are concentrating on the efficiency of beam concentration and energy deposition and the dynamics of imploding spherical targets.

Item 3. *Electron-Beam Control*

Electron beams have been effectively controlled through the use of strong axial magnetic guide fields in the anode-cathode and drift regions. The external field, by inhibiting the self-pinching mechanisms in the diode, leads to the generation of a "cooler beam" and to lower-impedance diode operation.

By this method, beam energy losses in the radial direction are greatly reduced. Efficient propagation of moderate-to-high current beams has been achieved for external field strengths of 5 to 20 kilogauss under conditions of good electric and magnetic neutralization. The radial focusing of such beams under similar conditions has been attained by using a single-ended magnetic mirror (up to 3:1 ratio) with efficient energy transport to a useful target area.

Item 4. *Diode Calculations*

The potential use of high-current relativistic electron beam machines in controlled thermonuclear fusion depends on the ability to focus the electrons onto a small target. Because of the difficulties associated with transporting high-current beams, beam focusing within the diode region is an attractive alternative. Two-dimensional direct particle simulation codes have been constructed and employed to understand the physical mechanisms responsible for the strong focusing observed in plasma-filled diodes. A model consistent with almost all of the measured results has been formulated with the assistance of the codes. The generality of the codes has allowed them to be applied to a wide variety of electron device experiments, including neutron generating tubes and very small gas ionizer tubes.

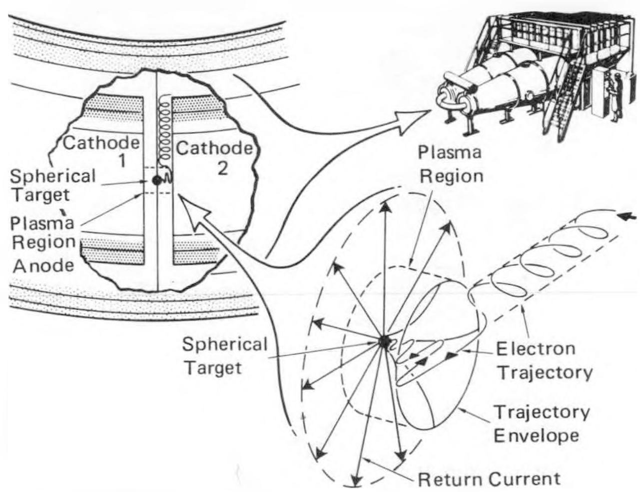


Figure 2. Mechanism of imploding the spherical pellet

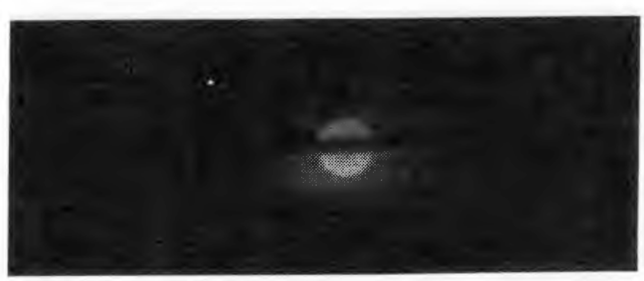


Figure 3. Anode-mounted spherical target used in pellet implosion studies

RELATIVISTIC ELECTRON BEAM RESEARCH

The accompanying computer simulation output (Figure 4) shows an example of a high-current beam pinching in a plasma, which is produced in some experiments by exploding a thin wire running between the cathode and anode in the vacuum diode. The electrons are injected into the plasma with a distribution determined from a separate simulation of the portion of the diode, which does not contain plasma. The self-magnetic field of the beam combines with the diode electric field to produce a very tightly focused beam at the anode. The computed current densities of 5 to 10 megamperes per square centimeter are consistent with experimental measurements.

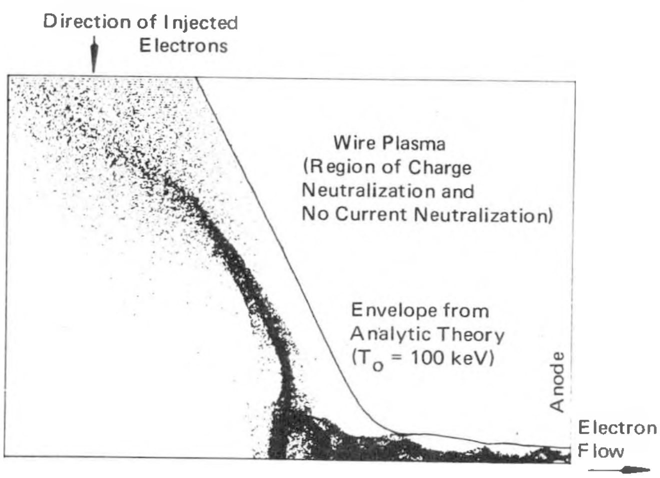


Figure 4. Computer simulation of a high-current beam pinching in a plasma

Item 5. *Accelerators*

Accelerators which have been developed operate from 0.3 to 12 megavolts and current levels up to 1 megampere. Pulse durations of 2-10 x 10^{-8} seconds are typical. One of the largest accelerators (Hermes) has been in operation since 1968 (Figure 5). Its maximum output has been 150 kilojoules delivered in a single 10^{-7}-second pulse. Hermes employs an oil-dielectric-insulated Marx generator and pulse-forming line with a self-breakdown oil switch and a multistage-insulator beam-forming diode.

The most recent addition to the electron-beam facility is Hydra, completed in 1972 (Figure 6). Hydra can produce two 1-megavolt, 0.5-megamp electron beams with an 80-nsec pulse duration. It uses water pulse-forming lines with synchronized triggered gas switches operating at 3 megavolts.

A program is under way to develop an accelerator capable of 10^{13} watts with a 5 nsec risetime. The projected pulse duration of 20 nsec will provide greatly improved capabilities for the first feasibility studies of the electron-beam fusion concepts and for nuclear-weapon effects studies.

Item 6. *Sheet Beams*

To provide for transverse electron-beam injection into a high-pressure gas laser cell, a diode has been designed for the REBA accelerator that produces large-area electron beams. With prepulse electric fields minimized, very uniform and highly stable beams have been generated. This approach can furnish average energy fluences ranging from 1 to 10 cal/cm^2.

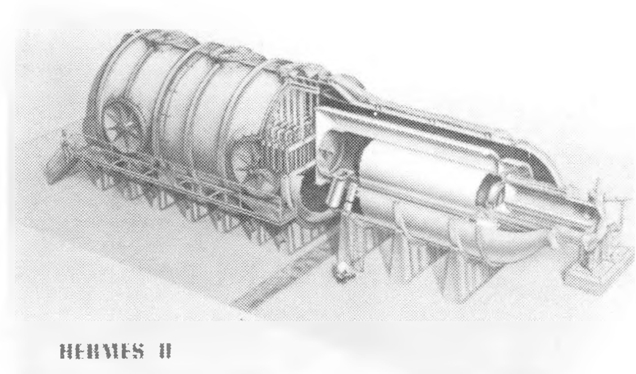


Figure 5. Hermes accelerator

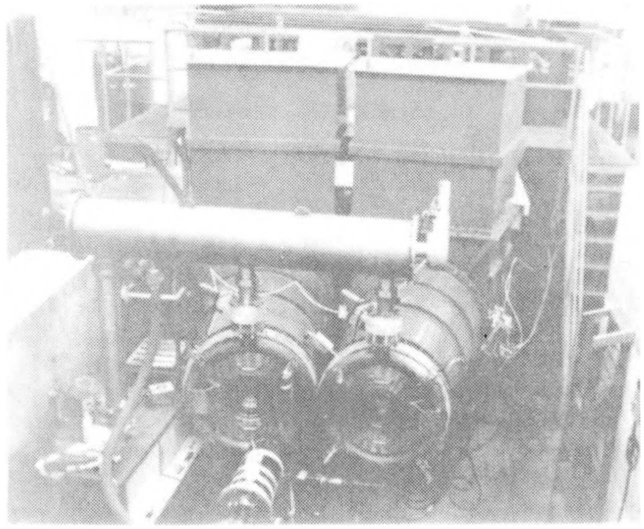


Figure 6. Hydra accelerator

Item 7. *Drift-Chamber Beam Control*

Collective propagation of a high-intensity relativistic electron beam in a neutral gas is strongly dependent on gas pressure; this allows for a wide variation in beam fluence to be realized through pressure variation alone. A technique of beam control has been developed for the electron beam generated by the REBA accelerator which utilizes a two-pressure drift chamber of conical configuration. The chamber geometry was selected so as to approximate the e-beam entrance conditions. Using this technique, energy fluences of up to 500 cal/cm^2 over approximately 3 cm^2 have been achieved; this corresponds to a useful targeted transport efficiency of 50 to 75 percent.

Item 8. *Converter Designs for the Pulsed Electron Beam Accelerator, Hydra*

Bremsstrahlung converter designs, in both thick and thin target configurations, have been developed for the Hydra accelerator. The designs have led to useful exposure capabilities of about 5 cal/g over exposure areas of 10 cm^2 with magnetic field control of the beam, and of 5 cm^2 without magnetic field control. These capabilities correspond to beam energies in the range of 12 to 15 kJ, or about half the beam energy potential of Hydra.

Item 9. *Accelerator Capabilities*

The pulsed electron accelerators so far developed have the fluence capabilities shown in Table I.* These exposure capabilities are among the most intense available in the US.

*See items above for descriptions of the accelerators REBA, Hermes II, and Hydra.

TABLE I

Exposure Capabilities

Source	REBA	Hermes II	Hydra
Bremsstrahlung Mode			
Energy (MeV)	3.0	10.0	0.9
Pulse width (ns)	50	60	100
Dose (krad)	15	50 (300)*	5 cal/g
Dose rate (r/s)	3×10^{11}	8×10^{11} (6×10^{12})*	–
Area (cm^2)	50	300 (20)*	5
Electron Beam Mode			
Energy (MeV)	3.0 (1.0)*	10.0	0.9
Fluence (cal/cm^2)	400 (300)*	700	400
Dose (cal/g)	400 (1000)*	300	2000
Area (cm^2)	3 (3)*	15	5

*Alternate mode of operation.

RESEARCH REACTORS

Reactor research activities range from development of new reactor concepts and facilities to basic studies of the response of materials and components to transient and steady-state neutron and gamma radiation. Models have been formulated for describing elastic, plastic, and elastic viscoplastic fuel-material behavior, dynamic failure in fuels and fuel claddings, constitutive relations, and chemical reactions. Methods have been developed for assessing and predicting radiation effects, including computer codes for calculating thermomechanical shock and stress-wave propagation, and theoretical models for the dynamic response of materials and material damage. This theoretical and experimental work is supported by the use of the pulse reactors, gamma facilities, conventional static and dynamic loading devices, remote metallography, and hot cells. Major areas of research are the characterization of fuels and facilities, and correlation of this information with projected utilization.

The reactor facilities are also used to support research and development programs for Sandia and other agencies that require a transient neutron environment. In this supportive role, facility personnel supply expertise in experiment design, source optimization, experiment diagnostics, and data retrieval and reduction.

Transient Effects on Fuels

Research is aimed at characterizing the dynamic response of fuel materials subjected to pulsed radiation, and the determination of constitutive equations. Of specific interest are themomechanical interactions and the resulting stresses, physical interactions between fuels and coolants, and the description of explosive disassemblies of fuel elements.

Constitutive models, together with numerical codes and material-property data, are used in the design of experiments and engineering and safety problems. Measurements also are made to empirically determine the constitutive equations. Instrumentation is developed to measure the response of materials and assemblies during transient loading. (Items 1,2)*

Current Activities

- Constitutive Models
  - Oxide fuels
    - Through-melt and vaporization models
  - Metal fuels
    - Elastic models
    - Plastic models
    - Elastic-viscoplastic models
  - Fuel cladding
    - Stress/failure models
  - Fuel-coolant
    - Heat-transfer models
    - Boiling models
- Diagnostic techniques
  - In-pile optical pyrometers
  - Calorimetric systems
  - High-speed data acquisition
- Code inventory
  - Discrete ordinates:
    - DTF-IV, TWOTRAN
  - Monte Carlo:
    - SORS, JUGADOR, KENO II
  - Diffusion:
    - EXTERMINATOR, AIM-6
  - Kinetics:
    - KOKIEL, POWER-Z, RAMP
- In-pile techniques
  - Liquid sodium loop development
  - Containment of explosions
  - Neutron filters/spectrum modification
- Safety analysis methodology
  - Dose potential/risk modeling
  - Standards development
  - Fission-product generation and transport codes: FISSP-CLOUD
- Heat transfer and fluid flow
  - Hydrogen liberation from hydrided fuels
  - Heat transfer at elevated temperatures
  - Cladding and gap-conductance modeling
  - Convective and boiling heat transfer

Facilities and Utilization

To support the programs in transient radiation effects, facilities have been developed for producing pulse neutron and gamma radiation for pre- and post-test analysis. As adjuncts, radiation sources, instrumentation, and data-acquisition techniques have been developed.

*See Highlights, below.

There are programs aimed at source enhancement through modification of existing sources and through new-source construction. (Items 3-5)

Facilities

- Existing source capabilities
  - Annular Core Pulse Reactor (ACPR)
    - 4.7-msec pulse width
    - 1.3-msec initial power transient
    - 1.7×10^{15} n/cm^2, E > 10 keV
    - 10^6 rad (H_2O) gamma dose/pulse
    - 9-inch-dia x 12-inch-high irradiation cavity
    - 300 kW steady-state power (600-kW approval expected)
  - Sandia Pulsed Reactor (SPR) II
    - 50-μsec pulse width
    - 14-μsec initial power transient
    - 8×10^{14} n/cm^2, E > 10 keV
    - 2×10^5 rad (H_2O) gamma dose/pulse
    - 1-1/2-inch-dia x 8-inch-high irradiation cavity
    - 3 kW steady-state power
  - Gamma Irradiation Facility (GIF)
    - Cobalt and cesium gamma sources
    - 10^4 to 2×10^5 rad (H_2O)/min peak rates
- New-source development
  - ACPR upgrade
    - 4.7-msec pulse width
    - 1.3-msec initial power transient
    - 4×10^{15} n/cm^2, E > 10 keV
    - 9-inch-dia x 21-inch-high irradiation cavity
    - 2-inch-dia in-pile experiment loops
    - 2-MW steady-state power
  - SPR III
    - 50-μsec pulse width
    - 14-μsec initial power transient
    - 6×10^{14} n/cm^2, E > 10 keV
    - 7-inch-dia x 12-inch high irradiation cavity
    - 15-kW steady-state power
- Specialized major developed facilities
  - Neutron radiography facility (nondestructive testing)
    - Capabilities
      - ~1-mil resolution
      - Length-to-diameter ratios of 65 - 500
      - ~10^3 cm^2 exposure areas
      - Neutron beam flux > 2×10^5 n/cm^2-sec
      - Neutron/gamma ratio > 10^6 n/cm^2-mr
    - Use
      - Resolution of cracks and voids in materials
      - Nonpropagating explosive detonation
      - Separation of dissimilar explosive materials
      - Pulse radiography
        - Detonation propagation in explosives
        - Transient mixing behavior of high-pressure gases
  - Fissionable material metallurgy and chemistry facility
    - Capabilities
      - Remote metallography
      - Hot cells
      - Remote sample preparation
      - Vacuum encapsulation
      - Vacuum high-temperature tensile tests
      - Phase-stability analysis
      - Chemistry determination
      - Aluminum ion plating
      - Handling and storage of fissionable materials
    - Uses
      - Pre- and post-test analysis of irradiated materials
      - Weapon material research and development
      - Impurity effects studies
      - Casting/fabrication techniques
      - Material property studies
      - Sample preparation
      - Sample-failure phenomenology
  - Photoelasticity modeling facility
    - Capabilities
      - Many-point compressive or tensile loading of models
      - Stress-riser determination
    - Uses
      - Design of minimum-stress component configuration
      - Selection of constituent materials
      - Computer code model verification
  - Operation of radiation sources
    - Experiment-related output optimization
    - Data acquisition for, and conduct of, experiments
      - Experiment design
      - Experiment diagnostics and instrumentation
      - Data acquisition and reduction
      - Radiation detection
    - Operation procedure and maintenance of sources

Radiation Effects

Research is aimed at characterizing the response of materials and components to radiation. Programs are to determine radiation effects on electronic systems, on the dynamic properties of materials, on biological systems, and on the dynamic structural response of fissionable materials (Item 6).

Activities

- Dynamic fissionable material properties
- Composite fissionable material response
- Compatibility of irradiated materials
- Modeling of material behavior
  - Changes in static properties caused by radiation
  - Laser pumping and enhancement
  - Thermo-radiation sterilization

RESEARCH REACTORS

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *UO_2 Fuel-Pellet Stress*

The Annular Core Pulse Reactor is used as the transient driver to determine stress levels in the cladding of uranium dioxide fuel pellets as a way of simulating a superprompt critical excursion in a liquid-metal fast breeder reactor. Melt temperatures (~2800°C) have been achieved and thermal gradients measured by intrinsic thermocouples and in-pile optical pyrometers.

Projected energy depositions in excess of 1400 cal/gm in enriched UO_2 pellets will be used to study the constitutive relations.

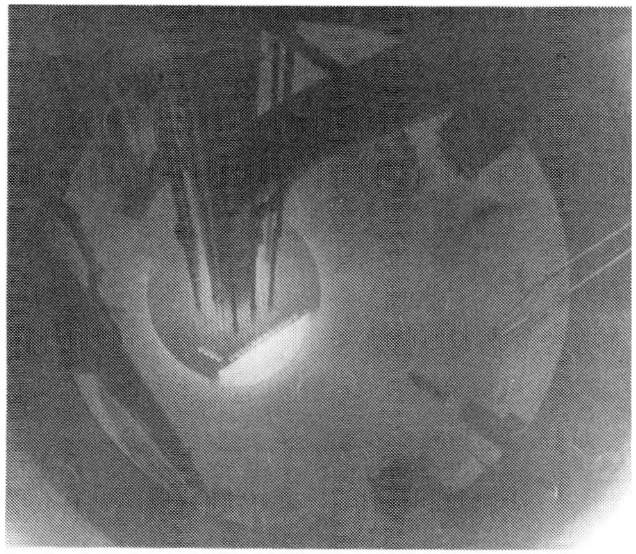


Figure 2. Core of the Annular Core Pulse Reactor (ACPR)

Item 2. *ACPR Steady-State Power Increase*

Preliminary 600-kW testing has shown a distinct increase in heat conductance as a function of fuel temperature (Figure 1). The increased heat conductance is caused by hydrogen liberation from the fuel to the fuel-clad gap, which markedly increases gap conductance. As a result of the increased heat transfer, permissible levels of steady-state operation could be substantially increased.

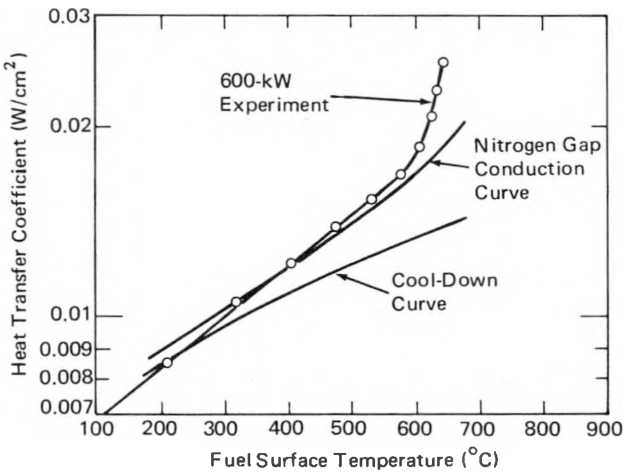


Figure 1. Increased gap conductance caused by hydrogen liberation from the fuel to the fuel-clad gap, resulting in increased heat transfer

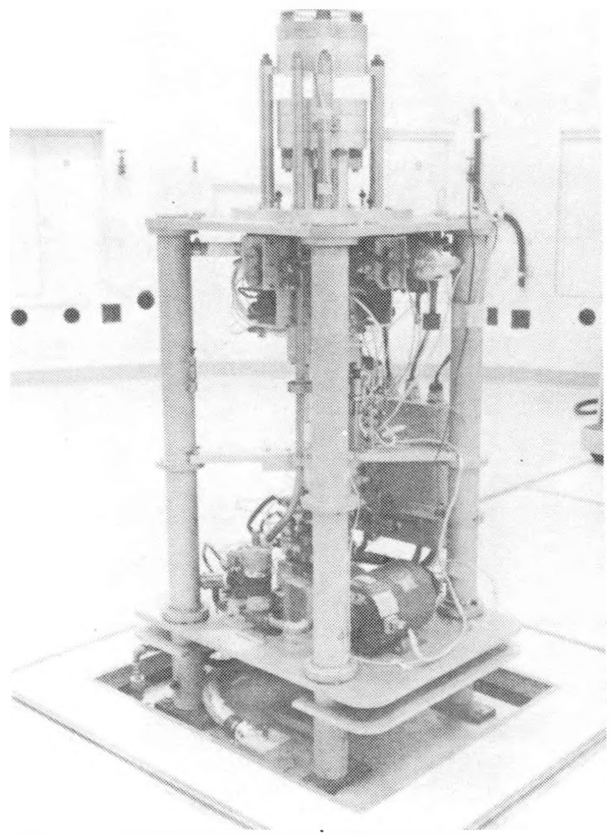


Figure 3. Sandia Pulse Reactor II (SPR II)

Item 3. *Radiation Sources*

Existing radiation sources are shown in Figures 2, 3, and 4; the pulse sources represent the state-of-the-art for transient neutron irradiation.

Item 4. *SPR II Fuel Failure*

Investigation of failures of SPR II fuel components has revealed a number of fabrication and chemistry deficiencies: casting voids, incomplete alloying, and high impurity content, particularly carbon. It was concluded that fuel-element cracking resulted from an almost continuous brittle grain-boundary region identified as uranium carbides. In Figure 5a, uranium carbide precipitates can be seen in the grain boundaries of gamma-phase uranium-10 w/o molybdenum. The burst-reactor fuel-plate alloy was cast at 1300°C and annealed at 950°C for 12 hours. The precipitates of uranium carbide along the gamma grain boundaries resulted in brittle fracture during rapid heating of the fuel plate. Tight controls have been established for fabrication of SPR III fuel components, which should result in longer fuel life.

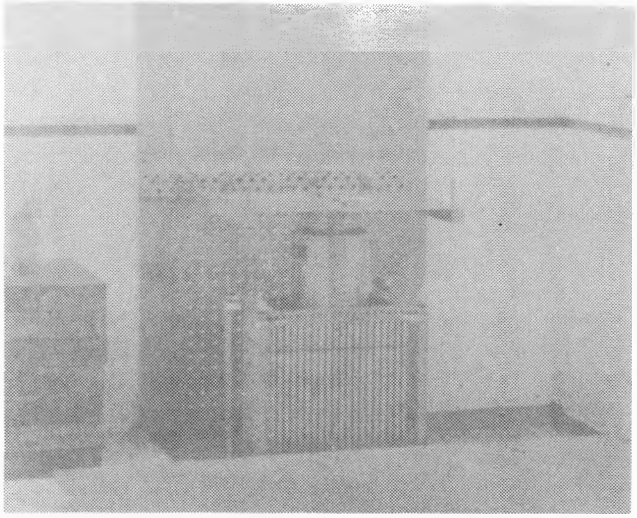
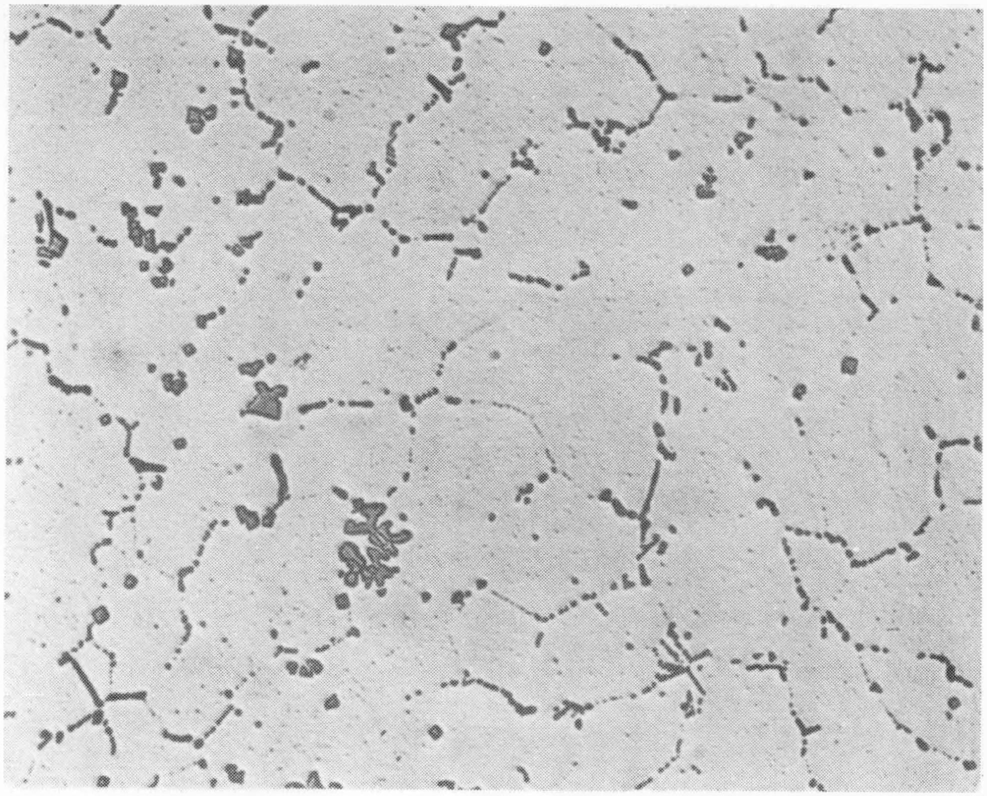


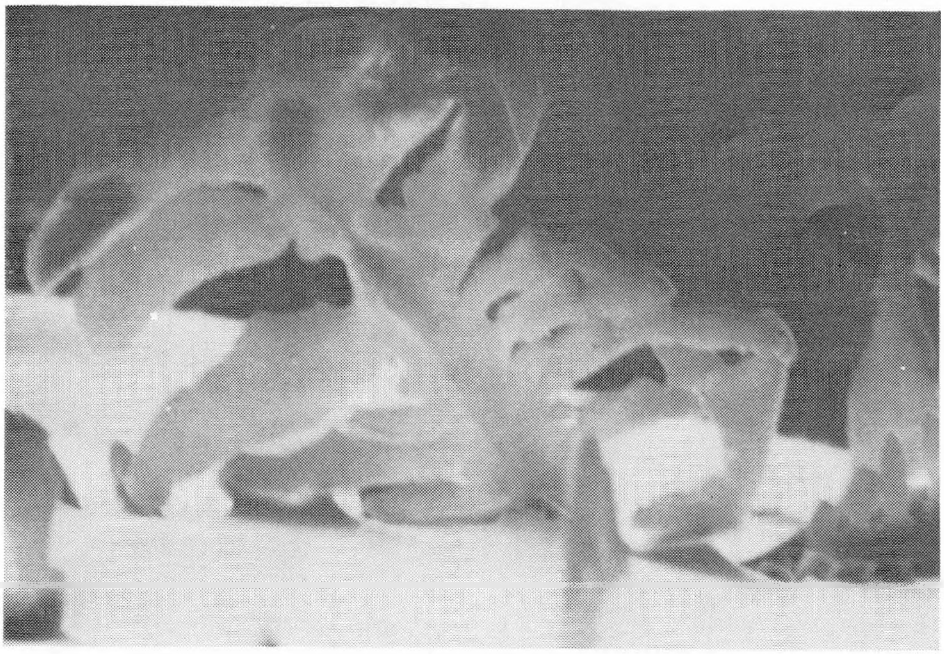
Figure 4. Gamma Irradiation Facility (GIF)



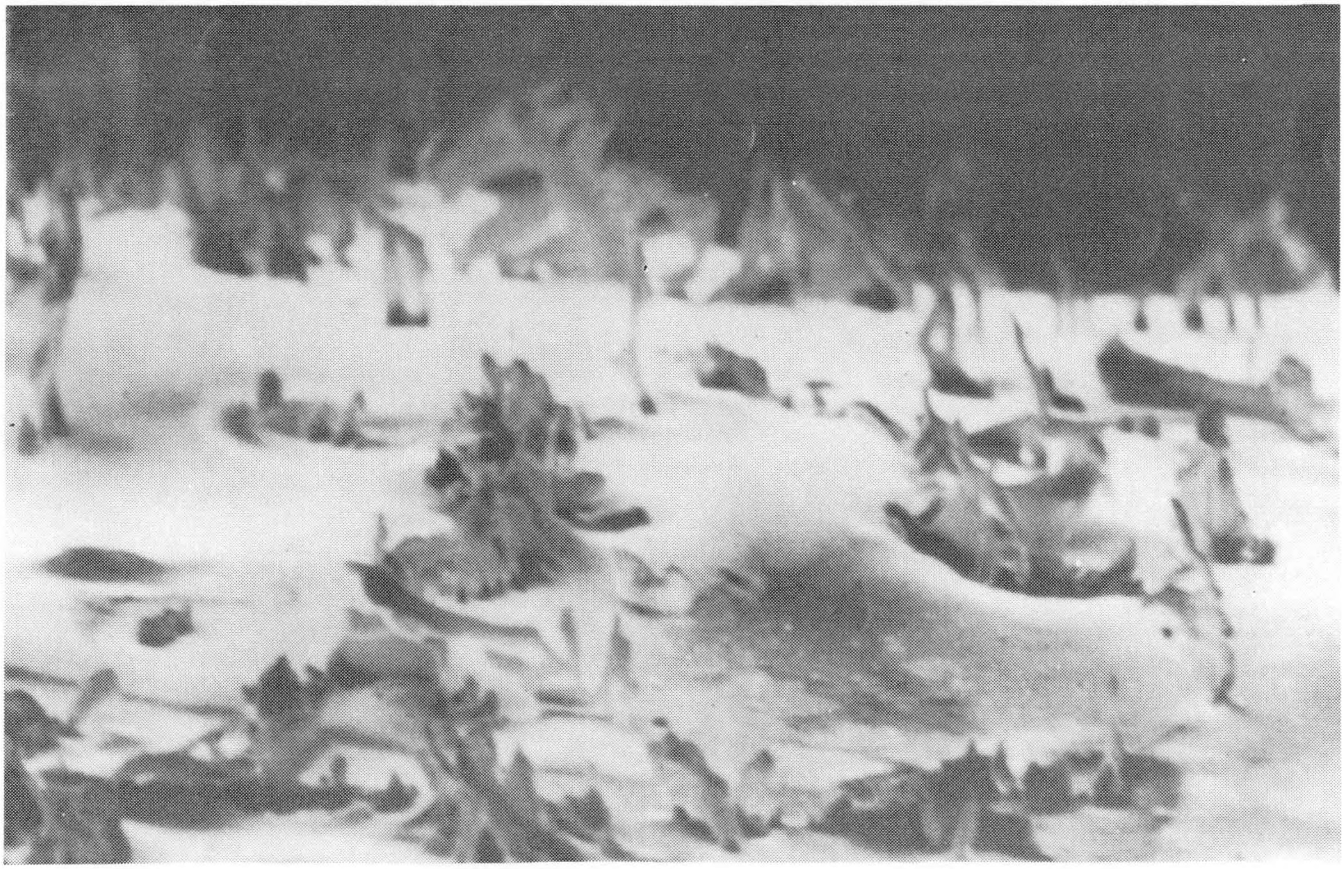
a. An optical photomicrograph shows the alloy in the as-polished condition before electro-etching but after exposure to air. The air darkened the uranium-carbide precipitates.

Figure 5. Three magnifications of uranium-carbide precipitates forming a grain-boundary region in a fuel element

RESEARCH REACTORS



b. The scanning electron micrograph shows the uranium-carbide phase in relief after the matrix was heavily electroetched in alcohol - 5% hydrochloric acid (1300X)



c. The dendritic structure of the uranium carbide grain boundary phase is shown (500X)

Figure 5. (Concluded)

Item 5. *Neutron Radiography*

Neutron radiography capabilities have been developed to provide resolution to ~1 mil, with length-to-diameter ratios of 65 to 500. Extensive nondestructive testing continues in the areas of explosive technology and development, and in fuel material research in conjunction with reactor safety programs. Typical radiography capabilities and uses are illustrated in Figure 6.

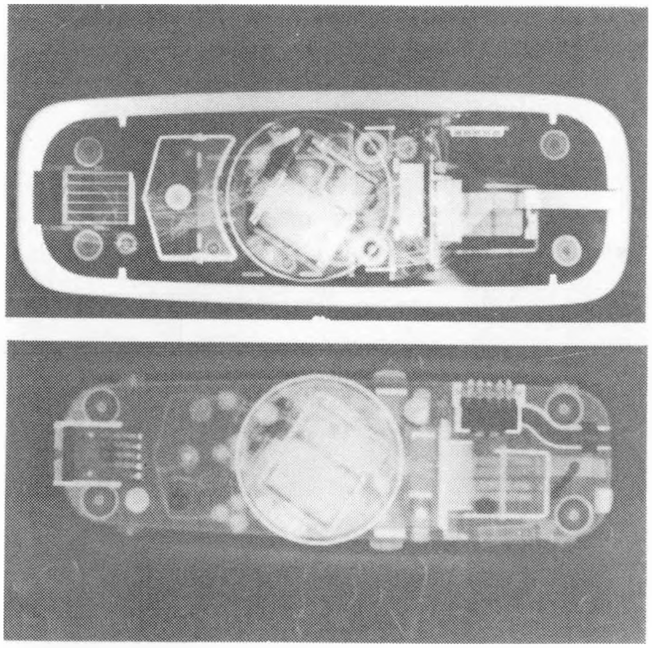


Figure 6. Comparison of neutron radiograph (top) with an x-ray of a Princess telephone

Item 6. *Dynamic Fuel Response*

An experimental technique has been developed with which to determine several temperature-dependent properties of fissile materials under rapid fission heating (~80 to 200 μsec) using a fast-burst reactor. The speed of sound, modulus of elasticity, thermal expansion, and internal friction of the material are determined as a function of temperature by measuring the magnitude and duration of the induced oscillations (Figure 7).

Item 7. *Fast-Reactor Safety Studies*

Research related to fast-reactor safety is being performed using the ACPR and SPR II to provide fuel-heating conditions corresponding to hypothetical LMFBR accident conditions. These studies include determination of the behavior of LMFBR fuel pins subjected to extreme excursions as well as investigations of heat removal from hypothetical post-accident fuel debris. Other studies now underway include investigations of (1) the effective equations of state of fresh and irradiated LMFBR fuels, (2) fuel-coolant interactions for both oxides and advanced LMFBR fuels (carbides and nitrides) and (3) facility needs for future safety-related research.

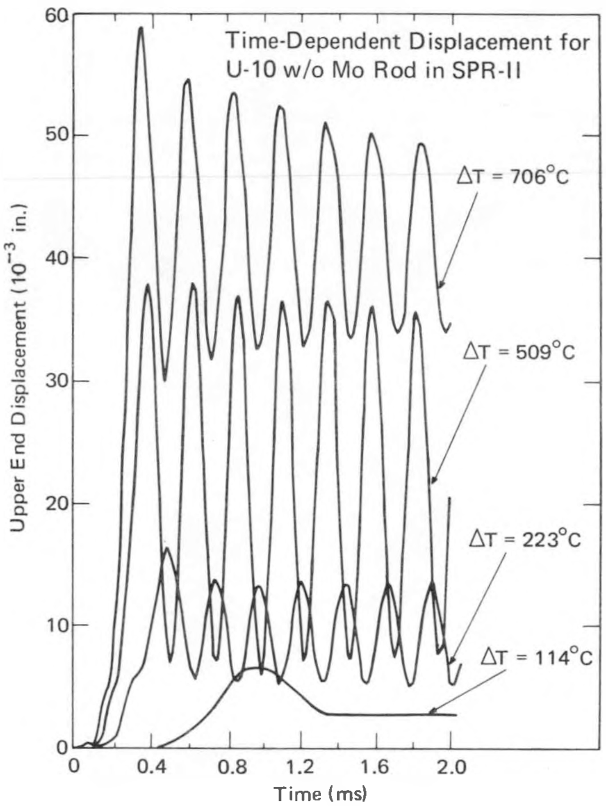


Figure 7. Profile of uranium-10 w/o molybdenum rod expansion with time as a function of fuel-temperature rise

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Sandia Laboratories Technical Capabilities

Safety and Reliability Assurance

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115
and Livermore, California 94550 for the United States Energy Research
and Development Administration under Contract AT(29—1)-789

SAFETY AND RELIABILITY ASSURANCE

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SANDIA LABORATORIES TECHNICAL CAPABILITIES

SAFETY AND RELIABILITY ASSURANCE

ABSTRACT

This report characterizes the safety and reliability assurance capabilities at Sandia Laboratories. Selected applications of these capabilities are presented to illustrate the extent to which they can be applied in research and development programs.

SAFETY AND RELIABILITY ASSURANCE*

Safety and reliability responsibilities have necessitated the development of analytical and measurement techniques for evaluating behavior of systems in normal and abnormal environments. As a result of these evaluations, designs are sometimes modified or new design concepts introduced. Many of the systems evaluated have requirements for high reliability and utmost safety. Assessment technologies emphasize extensive use of computational models and data from simulation experiments and tests at subassembly and lower levels. This is necessary because full-scale demonstrations in anticipated final-use conditions are often denied by international agreements, an by ecological or economic considerations.

Safety and reliability studies are performed on such projects as nuclear weapons, conventional weapon subassemblies, nuclear power reactors, special transport vehicles and ground-based and satellite sensor systems.

Both safety and reliability functions are conducted by specialists outside the project groups to encourage independence of viewpoint and approach to assessment.

Safety and Reliability Assurance Staff

	Professional Staff
Safety	
Safety Assessment Technology	5
Safety Assurance Analysis	7
System Safety Studies	9
Reliability	
Reliability Assessment	21
Statistical Design and Analysis	8
Human Factors Analysis	3
Quality Control	2

*Compiled September 1975

SAFETY

Exacting nuclear-safety requirements have necessitated the generation of a technical specialty for predicting system response in accidents and other abnormal situations and for innovative designs of electrical and mechanical systems. Acceptable levels of risk are so low as to be outside the realm of everyday experience. Risk assessment, specific design guidance, and system review by technical safety experts are among activities performed.

Safety Assessment Technology Development

Safety assessment is concerned with unwanted events whose consequences are potentially serious nationally or internationally. The causes of such events tend to be abnormal or unpredictable physical stimuli (e.g., accidents) or malevolent behavior of persons or groups. Design philosophies coupled with assessment techniques have been developed to treat these threats. Assessment techniques are either analytical models or adversary simulation--an experimental approach using a team acting with the skills and tools of potential attackers. (Items 1,2)*

Current Activities

- Fault-tree modeling
  - Hazard identification
  - Risk assessment
- Computational code development
  - Large fault trees
  - General Boolean
  - Other probability-related
- Adversary simulation
- Theft or accident scenarios
  - Generation and credibility determination
  - Effectiveness priority ranking
  - Effects evaluation
  - Contravention or prevention techniques

*See Highlights, below.

Safety-Assurance Analysis

Independent studies are conducted to determine whether design concepts proposed by design groups are based on acceptable safety principles. Emphasis is placed on techniques for recognizing and evaluating system responses in accident situations.

Current Activities

- Safety analyses are performed on systems composed of:
  - Electronic, mechanical, electromechanical, and electrochemical components
  - Environment-sensing and human-operated safety subsystems
- Analyses of systems and safety-critical components include:
  - Comparison of safety requirements and safety approach
  - Review of design drawings, specifications, and manufacturing processes
  - Physical examination of representative models
  - Review of verification plans to compare actual performance with predicted response
  - Fault-tree analyses
  - Review and analyses of test data
  - Unique-signal analyses
  - Normal and abnormal environment analyses

SAFETY

System Safety Studies

Both the Energy Research and Development Administration and the Department of Defense require formal safety studies on complex systems to be used in military and testing operations. Sandia evaluates these systems and provides expertise to the formally constituted safety study groups. Methodology has been developed to detect weaknesses in materials and procedures at the major system level.

Current Activities

Participate in safety studies and reviews with the military services on complete weapon systems.

Participate as a member of safety study groups that make recommendations to ERDA management on improving safety in:
- Activities at nuclear test sites.
- Assembly and disassembly in weapon plants.

Maintain capability to respond to nuclear accidents, thefts, or bomb threats.

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Exclusion-Region/Weak-Link/ Strong-Link Concept*

A design concept has been evolved in which a combination of design features is used to achieve a predictably safe response of an ordnance electrical system in normal and abnormal environments.* Reductions are obtained in the total portion of the system to be protected and in the number of components about which there are nuclear safety concerns. A salient feature is a special region of the ordnance system that contains safety-critical components designed to respond to abnormal environments in a predictably safe manner.

The exclusion region, as this area is called, contains selected elements (weak links) vital to the operation of the electrical system, and two or more accident-resistant unique-signal switches (strong links). All circuits to the weak links are interrupted by open contacts of the strong links. The weak and strong links are colocated and arranged so that they will respond sequentially and predictably to assure safe system response if the system is subjected to abnormal environments. Specifically, the weak links will become inoperable and render the weapon system inoperable before the strong links fail to maintain electrical isolation.

*Abnormal environments includes, e. g., fires, crushing, impact, high-velocity particle penetration, immersion in deep water, or electrical surges caused by lightning.

Nuclear safety in abnormal environments is achieved even though premature signals may appear at the input of the exclusion region, and even though the abnormal environment is imprecisely defined. The use of unique signals to actuate safety-critical components within the exclusion region eliminates the need to evaluate power supplies, signal sources whether normal or modified by malfunctions, wiring outside the exclusion region, the duration of threat signals, and changes in system design. The approach permits verification of system safety by analysis and test at reasonable resource expenditure levels.

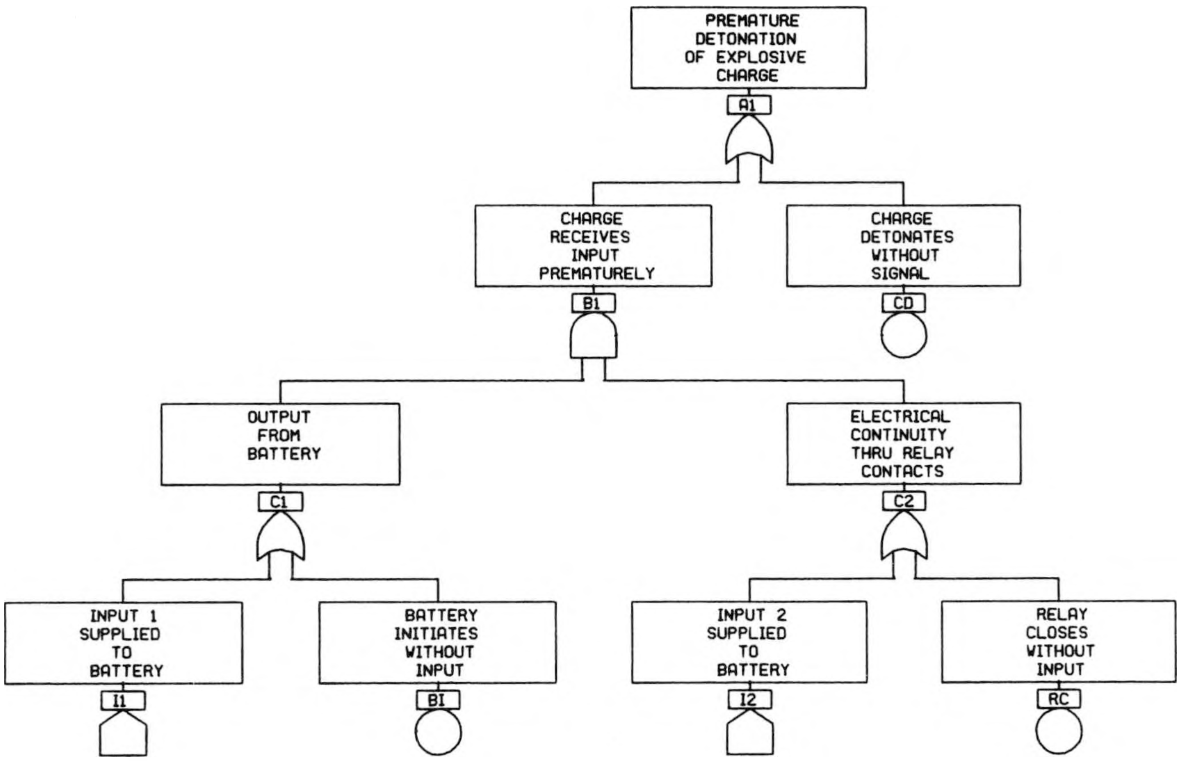
Item 2. *Fault-Tree Analysis*

This type of analysis is used as the principal logic modeling technique for assessing system safety. Extensive computer programs have been developed that provide a capability for evaluating large fault trees both qualitatively (event equations) and quantitatively (probability calculations). Sample outputs from these programs are illustrated in Figure 1. A fault-tree program was used to draw the small fault tree. The equations were derived from the fault tree using the Set Equation Transformation System computer code. The equation shown is for event A1 as a function of only primary events. Several methods have been developed to perform sensitivity analyses to identify important primary events, or combinations of events,

SAFETY

on both qualitative and quantitative importance criteria. Typical system fault trees consist of a few hundreds of basic events and up to several thousand sum-of-products terms in the simplified system equation.

The codes, which were developed to handle generic logic problems, are also finding increasing application in evaluating other logic models used in system safety and security analysis.




```
A1  =  (  BI  v  I1  )  ^  (  RC  v  I2  )  v  CD
       1             1     1              1
```

TERM NUMBER	NUMBER OF LITERALS	A1 =
1	1	CD v
2	2	BI ^ RC v
3	2	BI ^ I2 v
4	2	I1 ^ RC v
5	2	I1 ^ I2

Figure 1. Fault-tree analysis

RELIABILITY

A technology has been developed to assure that reliability requirements are met for systems including those that must withstand severe use environments after long periods of dormancy. Mathematical models are developed to facilitate evaluation of design reliability, comparison of alternate designs, and identification of potential reliability problem areas.

High reliability requirements, along with testing restrictions, have necessitated development of a methodology that allows reliability to be assessed on the basis of data taken at various levels of assembly and from a variety of test programs over the life cycle of the system. The methodology relies upon engineering analysis to determine the applicability of the data for reliability assessment while mathematical models allow these data to be combined.

Reliability Assessment

The basic function of reliability engineering is to assess the probability that an operational system will function properly in the intended use environment, including consideration of the human element. Failure-oriented analyses are performed for systems, subsystems, system elements, and human performance to assure that: designs are capable of achieving the required reliability and comply with established reliability and human-factors principles, and enough of the right types of tests are performed to be compatible with the reliability requirements.

Allocation or apportioning studies are performed during feasibility and preliminary design phases to optimize the rationing of acceptable system unreliability among system elements. Reliability assessments are performed at final design and over the life cycle to evaluate compliance with requirements. (Items 1,2)*

Current Activities

- Failure-mode, effects, and criticality analyses are performed on subassemblies composed of:
  - Structures
  - Components
    - Electronic
    - Mechanical
    - Explosives
    - Electrochemical
    - Electromechanical
- Model development
  - Block-diagram representations of complex components, subassemblies and systems (logic models)
  - Probability-tree diagramming
  - Probability-of-failure equations (mathematical models) for subassemblies and systems
- Component and subassembly evaluation and test
  - Failure analysis
  - Generation of specific failure rates
  - Derivation and application of generic failure rates

*See Highlights, below.

Statistical Design and Analysis

Techniques of statistical design and analysis are used to direct the collection and guide the interpretation of component and system test data.

Current Activities

- Statistical design
  - Experimental designs, e.g., randomized blocks, Latin squares
  - Life tests
  - Acceptance sampling
  - Calibration studies
  - Response surfaces
- Statistical analysis
  - Linear and non-linear regression
  - Probit and logit
  - Distribution theory
  - Non-parametric
  - Tolerance and prediction limits
  - Statistical computer programming
  - Monte Carlo
  - Probability theory

RELIABILITY

Human Factors Analysis

Human factors techniques are employed to develop specifications and design concepts relating to the impact of the human interface with the total system to improve operability, maintainability, reliability, safety, and security.

Current Activities

Task analysis
- Observation
- Interview
- Self performance
- Error rate and criticality analysis

Questionnaire design and analysis
Psychological scaling
Probability-tree diagramming
Design of data-collection methods for task performance factors
Design and analysis of laboratory and field experiments to evaluate human performance ance

Quality-Control Engineering

Quality-control engineering activity is devoted to developing quality-control techniques for the specification, design, and evaluation of production processes that will economically meet and maintain the level of quality required.

Current Activities

Development of simplified approaches to provide operator control of the process at the required quality level.
Development of a mathematical technique in which tooling and measurement errors are minimized by setting the position of the "virtual coordinate system" of a part coincident with the coordinate system of the machine with which it is to be processed or measured.

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Reliability Assessment*

Reliability assessment for weapons includes consideration of the effects of delivery and use environments. Sometimes satisfactory assessment requires special analytical techniques. For example, one multipurpose weapon is required to operate at some time after impacting any of several hard irregular targets.* A computerized analysis technique was developed that involves a probabilistic approach to selection of trajectory and target conditions; the result is a plot of system reliability as a function of release height for each general target type. The probabilistic approach properly weights the small likelihood that extreme values of all undesirable delivery and target conditions will occur simultaneously, and takes advantage of the higher (more probable) reliabilities associated with nominal impact conditions.

*Examples include military command centers, railroad marshalling yards, dams, bridges, and industrial complexes.

The computer program has three basic parts: a trajectory-simulation routine predicts weapon trajectory angle and velocity; the target-analysis routine determines the likelihood of impact on various types of surfaces within the target complex; and the reliability-function routine describes weapon reliability as a function of angle, velocity, and impact-surface combinations supplied by the other two routines. Using these routines and their associated inputs, many missions are simulated (using Monte Carlo techniques for input selection) until distributions of reliability vs. release height are well defined for each type of target complex.

Item 2. *Quantitative Evaluation of Human Reliability*

Quantitative evaluation of overall weapon-system reliability or safety involves modeling the reliability of human operators in the system. The human component is given quantitative consideration comparable to that given to other components. The model furnishes a way of predicting human error rates and of evaluating the degradation of a man/machine system likely to be caused by human errors in association with equipment functioning, operational procedures, and other characteristics that influence system behavior.

The basic tool used in such modeling is probability-tree diagramming (Figure 2). Branching in the tree is used to show different events as well as different conditions or influences on these events. Thus, values assigned to the events depicted by the tree limbs are conditional probabilities. The Greek symbols represent non-human system events and the English letters represent human events, the small letters indicating correct performance and capital letters incorrect performance. The three major branches represent different stress levels under which the human tasks were to be performed.

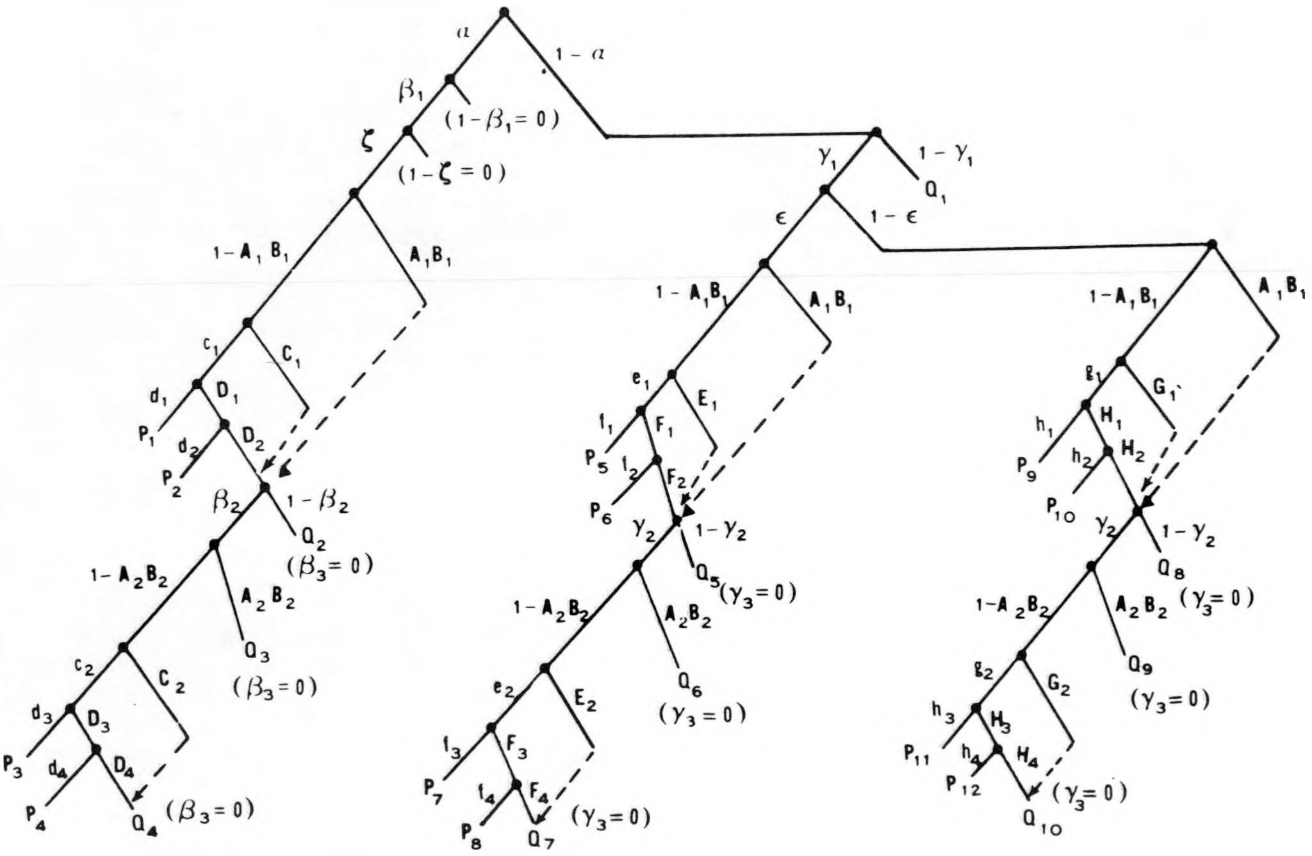


Figure 2. Probability tree illustrating branching technique.

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SYSTEMS ANALYSIS

Sandia Laboratories Technical Capabilities

Systems Analysis

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115
and Livermore, California 94550 for the United States Energy Research
and Development Administration under Contract AT (29-1)-789

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SANDIA LABORATORIES TECHNICAL CAPABILITIES

SYSTEMS ANALYSIS

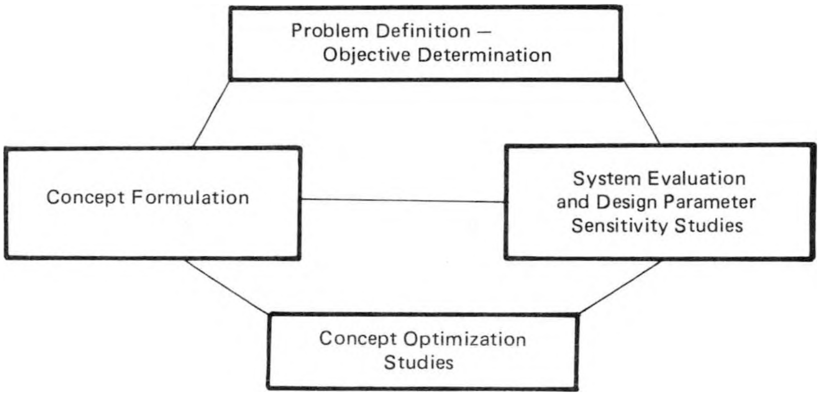
ABSTRACT

This report characterizes the systems analysis capabilities at Sandia Laboratories. Selected applications of these capabilities are presented to illustrate the extent to which they can be applied in research and development programs.

SYSTEMS ANALYSIS*

The objective of the systems analysis activities is to aid in deciding among alternative systems and concepts. This is accomplished by evaluating the relative utility and costs of the competing options within the appropriate environment. Areas of active study include nuclear and conventional weapon systems, energy extraction and conversion, environmental analysis, security systems for both weapons and materials in the nuclear fuel cycles, and biological systems. Typically, the studies seek to evaluate tne relative worth of new concepts and to provide an understanding of parameter sensitivities that can lead to system improvements.

The outline below describes the major steps in almost every system study.



The systems analysis function may begin at any point in this schematic and may feed back to previous steps as indicated. The object of such iterations is to formulate, evaluate, and/or optimize a system or alternative systems on the basis of a common set of objectives. In addition to identifying system options or alternatives the studies typically provide early insight into critical technology requirements.

Most studies conducted in the systems analysis groups require a number of disciplines. The following table summarizes the composition of the Systems Analysis staff according to academic background. Members of the staff have broad interests in addition to their major specialty.

Systems Analysis Technical Staff

Number of Professional Staff	62
Distribution of Academic Backgrounds	Percent
Electrical Engineering	35
Mathematics	27
Mechanical and Nuclear Engineering	23
Physics	10
Other	5

*Compiled March 1975.

PROBLEM DEFINITION AND ASSESSMENT

The objective of the Systems Analysis group is to critically examine the feasibility of proposed research and development programs. The most favorable of these are selected for further study. Primary consideration in these studies is given to the application and implementation of the total system. The first undertaking is to clearly define the problem to be addressed and to develop qualitative and quantitative descriptions of the objectives. In parallel with this step a preliminary assessment is made of the adequacy of existing systems to meet the objectives.

Determination of Need

System requirements are identified. A basic understanding of the problem at hand and possible justifications of existing or new systems are sought. In addition, an understanding of the design and operation of systems under consideration is required so that they can be compared on the basis of consistent measure of performance. (Items 1,2)*

Current Investigations

- Aircraft survivability analyses
- Transportation systems for weapons and nuclear material
- Standoff weapon systems
- Nuclear options for precision guided missiles
- Earth-penetrating warheads for tactical missiles
- Nuclear-burst monitoring systems
- Secure storage systems for weapons and nuclear material

Objective Definition

The objectives or performance criteria of a system are defined to furnish a basis for comparison with alternative systems. Typically the objective must contain measures of system "cost" as well as measures of "benefit." (Items 3,4)

Current Activities

- Worth of underground reactor siting
- Military effectiveness and collateral damage potential of tactical weapons
- Worth of nuclear power parks
- Linear programming objectives for energy resource allocation

Studies of the Adequacy of Existing Systems

Thorough understanding of the adequacy of existing systems is important since the fundamental justification for new systems frequently resides there. Determination of the adequacy of existing systems is based upon a knowledge of their objectives, and usually requires consideration of all aspects of any given system. Emphasis is first placed on finding solutions that capitalize on existing hardware, manpower, and organizational assets, since such solutions usually imply relatively low cost and short lead times. (Items 5-7)

Current Activities

- Evaluation of current antisubmarine weapons
- Evaluation of the jam resistance of radar fuzes
- Security system response-force analysis
- Shipment accident frequency analysis
- Strategic potential of forward-based systems
- Collateral-damage analyses
- Evaluation of security systems

*See Highlights below. The majority of systems analysis studies are weapon-related, and cannot be discussed in an unclassified publication. Consequently, the highlights presented in the following pages of systems analysis activities, predominantly dealing with security and energy matters, do not accurately reflect the amount of effort associated with weapons.

PROBLEM DEFINITION AND ASSESSMENT

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Aircraft Survivability Analyses*

The proliferation and improved effectiveness of modern air defense systems have caused attention to be focused on potential inadequacies of both fighter-bomber tactics and weapons. The Middle East war, for example, showed that a combination of SAM and antiaircraft artillery systems can effectively counter deep-strike operations.

An important measure of the effectiveness of new tactics (e.g., low-altitude penetration, electronic countermeasures, or maneuvers) or new weapons (e.g., defense-suppression or self-defense missiles) is the probability of aircraft survival against prescribed defenses. Figure 1 is a typical result from an analysis that shows a preference for standoff weapons, especially for delivery by aircraft at low speeds. Estimation of these probabilities required trajectory analyses of aircraft, bombs, and defense missiles using computer simulation of guidance-and-control dynamics and probabilistic analyses of antiaircraft gunfire. These analyses included target vulnerability models and projectile dynamics. It was assumed that both tactics had equivalent results. Such studies help identify not only system needs, but desirable characteristics as well.

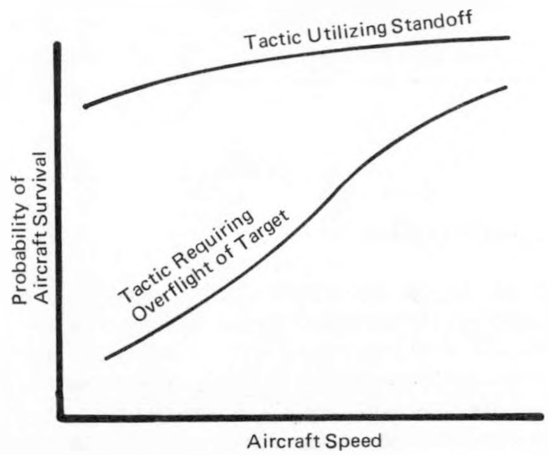


Figure 1. Aircraft survivability as a function of speed and tactics

Item 2. *Transportation Systems for Weapons and Nuclear Material*

Transportation methods for nuclear weapons and materials have been analyzed in an effort to identify vulnerabilities to diversion or sabotage. Destruct options, surveillance systems, the physical vulnerability of carrier vehicles, and other factors were considered. The studies provided a better understanding of the adequacy of current transportation methods, as well as of possible attack characteristics. Several concepts were identified which, through improved communications and diversion deterrents, offer increased shipment security. These were demonstrated by exploratory development groups and several were adopted. An integral part of the transportation studies has been the consideration of safety.

Item 3. *Underground Reactor Siting*

Proponents of underground siting maintain that this technique enhances safety and security, making it possible to locate power-generating stations near load centers, thereby reducing delivery costs. To clarify benefits of underground siting, the following objective has been defined for a system study: minimize the cost of delivered power and maximize acceptance of underground siting relative to other types of siting. Variables are (1) the cost of electrical power produced by an underground system, and (2) acceptance of underground siting on the basis of benefits gained. Both variables are functions of

1. Engineering considerations such as reactor type; geology; seismology and meteorology; construction techniques, and containment methodology,

2. Special safety considerations relating to accident and sabotage possibilities, and

3. System considerations such as fuel, power, and radiation waste transport; waste-heat transport and use, and load definition.

With this definition of the objective, a foundation has been laid for further studies.

Item 4. *Linear Programming Applied to Energy Resource Allocation*

Linear programming models have been developed for studying allocation of energy resources. The models include efficiencies of energy conversion, delivery, and use. Energy source interchangeability is permitted where feasible. The

PROBLEM DEFINITION AND ASSESSMENT

objective sought by the models can be varied among such things as minimizing or maximizing the use of a particular energy source, or maximizing the efficiency with which energies are used.

As an example, an oil embargo in 1974 prompted interest in reducing oil usage. Linear programming, with the objective of minimizing oil consumption, was used to delineate areas of potential savings and to estimate their magnitude.

Item 5. *Response-Force Analysis*

Response-force options are analyzed. A computer code was developed to estimate the time required for response groups (e.g., state police) to reach given locations along routes used in shipping nuclear weapons. Typical code output is shown in Figure 2. Such techniques allow rapid determination of the adequacy of current and postulated response-force basing and equipment.

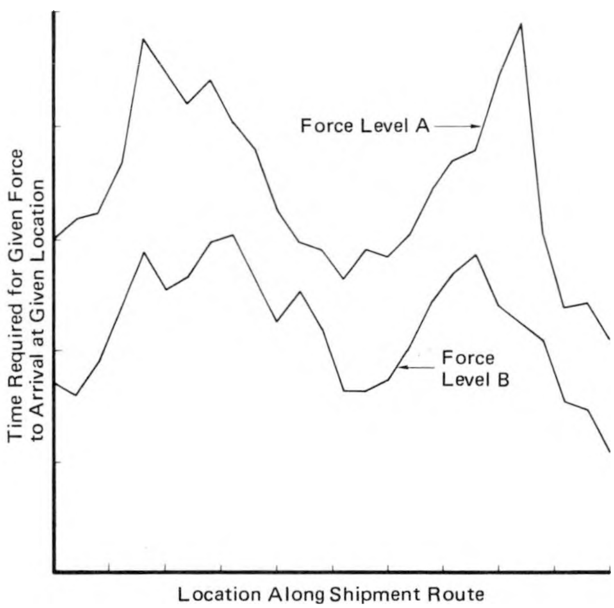


Figure 2. Schematic of a time of response of protection agencies along a typical shipping route

Item 6. *Collateral-Damage Analyses*

New and existing weapons are evaluated to permit prediction not only of military effectiveness but of the risk of collateral (undesired) damage, especially when military targets to be attacked are near civilian population centers.

Figure 3 illustrates the relative magnitude of collateral-damage hazard. For reliable destruction of military targets, high levels of airblast or radiation are typically required, yet much lower levels pose a threat to exposed people, lightly constructed buildings, and other nonmilitary assets.

Collateral damage is dependent on weapon delivery accuracy, fuzing, burst environment (air, surface, or subsurface), and warhead design. Once the yield required for a target has been established, weapon energy released in the forms of x-rays, neutrons, gamma rays, and debris are determined, based on calculations and nuclear test data. The transport of this energy through the atmosphere and soil, and its effect on nonmilitary people and objects, determines the severity of collateral hazard.

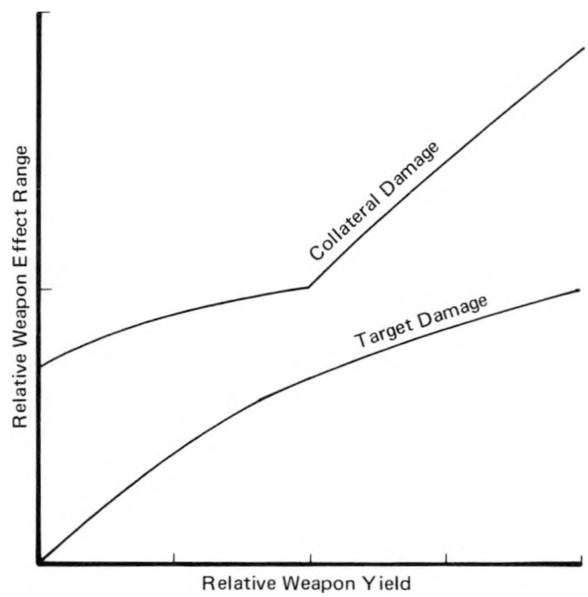


Figure 3. A schematic representation of collateral (undesirable) and target damage with relation to the range and yield of a weapon system

Item 7. *Evaluation of Security Systems*

The adequacy of security systems is evaluated. A security system is defined as the total effort – guards, physical barriers, and detection devices – needed to prevent access to the materials of interest. An effective way to make such an evaluation is to perform Adversary Simulation studies by (1) selecting one or more teams of individuals whose knowledge, equipment, and expertise approximate the various threats postulated; (2) assigning the teams to develop attack concepts for defeating a specified security system; and (3) carefully evaluating these concepts to identify possible defects in the system. Vulnerabilities disclosed by this procedure are called to the attention of the system designers, and solutions are again subjected to Adversary Simulations.

Such studies have been made of complete security systems (e.g., nuclear-material transport and storage systems) and to components of security systems.

CONCEPT FORMULATION

This activity has two phases: generation of new concepts, and conceptual engineering. The purpose of both is to identify alternative ways to accomplish a desired objective, once the need for a new system has been established and its objective defined.

Concept Generation

This phase involves a thorough study of the requirements imposed by a given objective. Care is taken to separate real demands and constraints from those stemming from tradition or technological limitations. This usually requires a thorough knowledge of states of the art in numerous technological areas. (Items 1-4)*

Current Activities

Energy extraction from magma
Earth-penetrating weapons
Underground storage of weapons or nuclear material
High-level reactor waste disposal
Solar energy conversion

*See Highlights below.

Conceptual Engineering

After a potentially attractive concept has been identified, an analytical model of the system is constructed. This is done to establish basic feasibility, to assure compatibility of subsystems and component parts, and to identify parameters that are most significant in determining system performance. (Items 5,6)

Current Activities

Maneuvering reentry vehicles
Artillery-launched rockets
Electron-beam fusion reactors
Oil-shale recovery systems
New drilling and excavation systems
Height-of-burst measurement systems

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Energy Extraction From Magma*

A concept generated in response to the energy need is magma energy extraction, which involves extracting thermal energy from liquid magma sources lying below volcanos or other geothermal anomalies. Since these sources typically have temperatures greater than 1000°C, they could provide large amounts of high-quality energy. In a single cubic mile of such material, the extractable energy is conceivably adequate to run several 1000-MW electric plants for tens of years. The concept involves locating suitable magma sources, drilling holes into them, and installing heat exchangers to continually transfer heat from the magma to a power plant on the surface.

The magmatic energy concept was first studied analytically to determine critical design parameters. Then an experimental effort was initiated to determine the applicability of current materials and liquid convective heat transfer codes. At this juncture, both the analytic studies and the experimental results indicate that the extraction of energy from magma is a viable concept.

Item 2. *Earth Penetrating Weapons*

Weapon-effects studies reveal that cratering efficiency can be greatly improved through the use of subsurface bursts, which require much lower yields to create a crater of given size than do surface bursts. Collateral damage resulting from fallout, prompt radiation, and airblast is substantially attenuated by this concept. Analyses have established design characteristics for earth penetrating weapons, their usefulness, and their probability of penetrating various geological areas. Typical trade-off studies are illustrated in Figure 1.

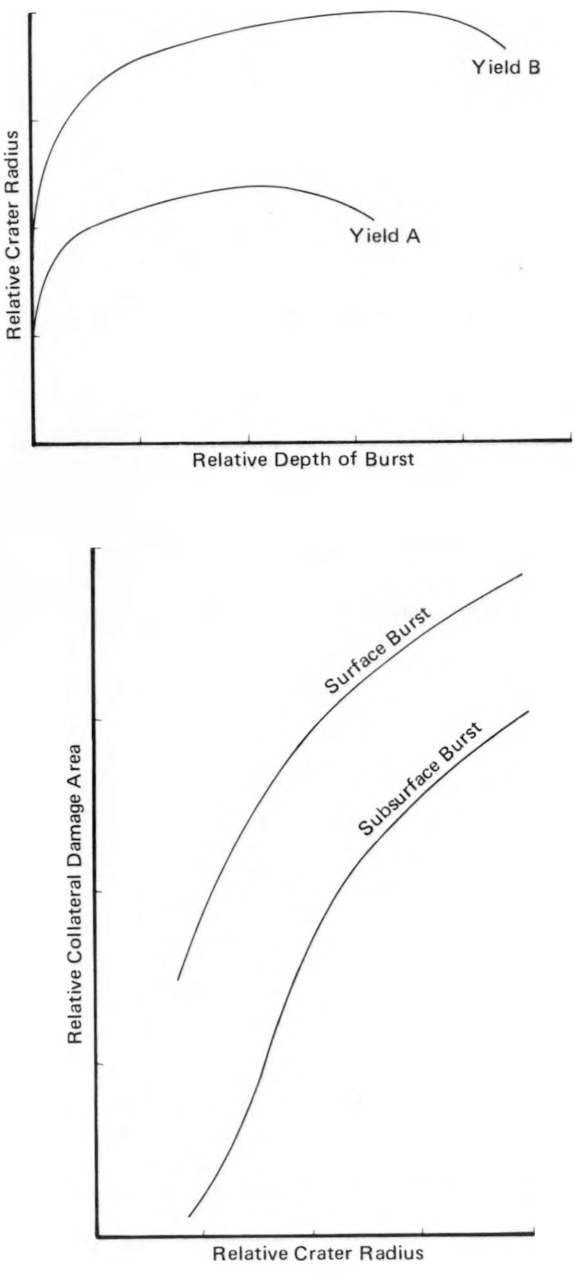


Figure 1. Trade-off studies

Item 3. *Underground Storage of Weapons or Nuclear Materials*

A concept has been developed that involves drilling and casing a deep hole of reasonably small diameter to create a secure underground vault for weapons or nuclear materials (Figure 2). Access to the vault is controlled through the use of a security door operated by a buried coded switch. All other features necessary for a complete security system were conceptually designed and evaluated.

The study of this and other alternative storage concepts was prompted by increasing concern about possible terrorist threats and by the desirability of eliminating the need for a large, readily available, full-time guard force, such as is demanded by present storage methods.

Critical factors relating to weapon storage that were studied include potential security threats, safety, initial and operating costs, vulnerability, logistics, and future flexibility.

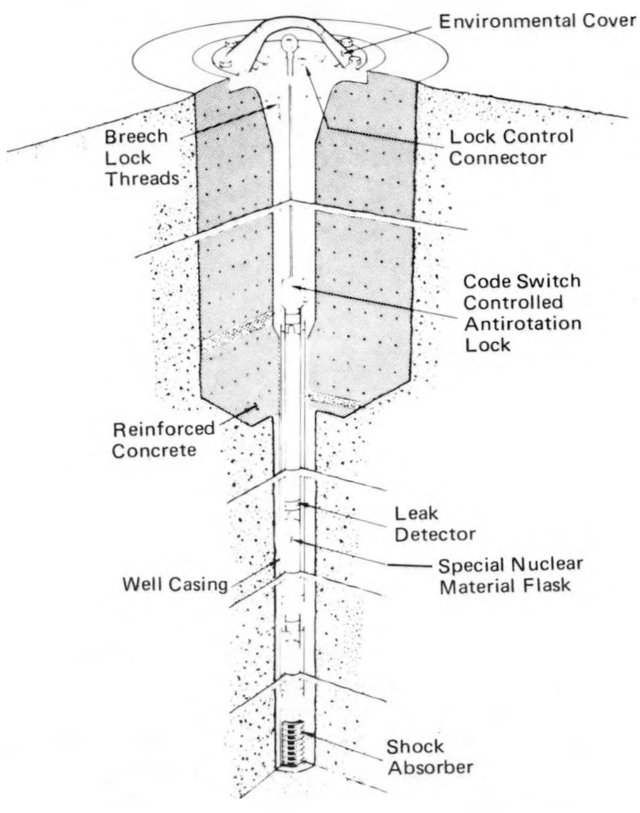


Figure 2. Underground vault for nuclear materials

3

CONCEPT FORMULATION

Item 4. *Mars Penetrator*

On the basis of technology developed by Sandia for earth-penetrating weapons, a penetrator is proposed for the instrumented exploration of Mars planned by the National Aeronautics and Space Administration. The penetrator concept offers several advantages over a vehicle designed to make a soft landing. First, several penetrometers can be released from a single Mars orbiter, allowing investigation of multiple sites on the planet from a single mission. Second, the penetrator allows measurement of the thermal gradient and mass properties of the planet's crust—both impossible with a soft lander—as well as accurate seismic studies. Third, the penetrator would not have to rely on a soft landing or withstand the Martian environment over an extended period of time; consequently its cost would be much less than that of a soft lander, its lifetime longer, and its probability of success higher. A complete description of the Mars penetrator is being developed.

Item 5. *Electron-Beam Fusion Reactors*

The use of relativistic electron beams (REB's) to compress deuterium-tritium (D-T) fuel pellets to thermonuclear burn conditions appears distinctly possible. The concept involves the use of large, annular, hollow cathodes to focus the beams on the fuel pellet (Figure 3). One objective of recent system studies has been to evaluate the feasibility and cost of producing electric power by REB fusion. A baseline engineering design of an operating REB fusion reactor has been formulated. Much of the work in progress involves the integration of conceptual designs of protected reactor walls, energy recovery systems, tritium production and recovery systems, D-T pellet coating recovery systems, and energy storage systems. This integration facilitates an understanding of total system efficiency, material resource availability, radiation damage mechanisms, and vacuum pumping limits.

Item 6. *Height-of-Burst Measurements*

A technique has been proposed for determining the altitude of an endoatmospheric nuclear event from a satellite. The basis of the concept is the use of atmospheric absorption of light to indicate the distance over which the light has traveled. Light from the burst is observed at wavelengths that are both strongly and weakly absorbed in the atmosphere. Through the observation of differences in power levels recorded in the various wavelength bands, the burst altitude can be determined.

Conceptual engineering involved selecting the optimal spectral band and the optimum optical collection area. Optical radiation characteristics of nuclear detonations were modeled on empirical formulas that characterize U.S. nuclear events. Atmospheric transmission as a function of wavelength was calculated. Optical power received at the satellite was computed as a function of burst altitude and nadir angle; uncertainty in measurement of the power difference was determined as a function of the signal-to-noise ratio in the optical sensors. The expected error in altitude measurement was investigated parametrically, and system elements were chosen to minimize this error.

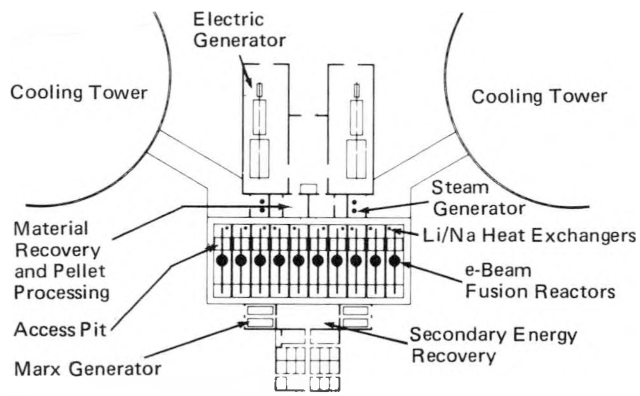


Figure 3. Conceptual design of relativistic electron beam power generation plant

SYSTEM EVALUATION

Systems or concepts are evaluated on the basis of their objectives. In some instances the system analysis group may carry a problem all the way from definition to evaluation. In other cases a previously defined problem with an objective and a potential solution may be brought to the group by others for evaluation. This evaluation may result in the formulation of additional concepts or a restructuring of the problem and its objective. Iterations continue until an acceptable solution is found or the problem is abandoned.

Model Development

Both analytical closed-form techniques and numerical methods designed for digital computers are employed for the mathematical modeling of technical systems or concepts. Simulations of systems or concepts may involve both statistical and deterministic approaches and may be either static or dynamic. (Items 1-7)*

Current Modeling Activities

- Weapon-related modeling
  - Nuclear effects
  - Collateral damage
  - Antiaircraft defenses
  - Reentry-vehicle dynamics
  - Terrain correlation guidance
  - Inertial guidance
  - Reentry-vehicle and satellite vulnerability
  - Technological assessment of foreign weapon systems
  - Acoustic discrimination in air and water
- Energy-related modeling
  - Oil-shale processing
  - Reactor safety
  - Solar thermal and wind-energy systems
  - Geothermal energy extraction
  - Waste-heat utilization
  - Burial of reactor waste in bedrock
  - Fusion reactors
  - Reactor siting
  - Waste reprocessing plant siting
  - Environmental impact of liquid-metal fast breeder reactors
  - Biological inactivation
  - Conservation/resource allocation

*See Highlights below.

Cost/Benefit Analyses

Some system evaluations are made that require a dual indication of performance that may be broadly classified as cost/benefit analysis. In a literal sense the "cost" of a system is the resource outlay required to achieve some level of performance, and the "benefit" is the accumulated value or worth of the performance. (Items 8,9)

Current Cost/Benefit Analyses

- In-situ oil shale processing
- Underground weapon storage
- Extended-range bomb delivery
- Central and total-energy solar power systems
- Deep rock nuclear waste disposal
- Wind-powered fresh water condensation system

Sensitivity Analyses

Systems and concepts are evaluated not only to obtain a figure of merit or a calculated performance index but also to determine factors on parameters to which the performance index is most sensitive. Once these critical features are determined, the system can be modified to improve its performance. Often a sensitivity analysis not only leads to improvements in a single concept but also indicates directions for future research and development. (Items 10,11)

Current Areas of Analysis

- Acoustic sensing of jet aircraft
- Accuracy of maneuvering and ballistic reentry vehicles
- Response time for reaction forces
- Accuracy of terrain correlation guidance
- Plutonium toxicity associated with the liquid metal fast breeder reactor fuel cycle
- Weapon and nuclear material security confidence vs cost

SYSTEM EVALUATION

Collateral-damage minimization
Electrical power transportation costs
Cost of waste-heat transportation
Storage requirements for solar thermal and wind energy systems
Cost of improved drilling technology
Cost of in-situ oil-shale processing

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Aircraft and Tactical Missiles Versus SAM Defenses*

The interactions of aircraft and tactical missiles with surface-to-air missile (SAM) defenses have been extensively modeled in engagement simulations. SAM system characteristics are derived from intelligence sources, supplemented as necessary by engineering judgment and knowledge of design practice.

Using defense models and a figure of merit (number of weapons required to achieve some level of damage, or probability of penetrating the defense with a single weapon), it is possible to assess the sensitivity of results to variations in system characteristics.

The degree of detail incorporated in the model is chosen in conformance with the study phase of interest. In the conceptual stages simple deterministic models are often adequate, while in the optimization phase detailed dynamic engagement models including missile-guidance and body-response calculations are frequently required.

Item 2. *Impact of Breeder Reactors on the Environment*

The problem of plutonium toxicity associated with releases from the liquid-metal fast breeder reactor (LMFBR) fuel cycle is being studied via a dynamic simulation model of man and his environment. The model simulates the release of characterized plutonium compounds from various sites of the total fuel cycle, dispersal of the material within the environment (air, water, plants, animals, etc.), and the uptake and excretion of the material by man, all as a function of time.

In addition to inhalation and ingestion by man, the model also includes transport of the material through the various human pathways as influenced by particle size, solubility, and kinetic rate parameters. This allows determination of the integrated accumulation of plutonium and its daughter products for any organ in the body for the expected lifetime of the man. With this information the risks of both genetic and somatic damage can be estimated. Modified versions of the model can be used to study other environmental health problems.

Item 3. *Vulnerability Models*

Extensive models have been developed to investigate all facets of reentry-vehicle vulnerability to both endo- and exoatmospheric nuclear bursts. The prompt and delayed effects associated with blast, neutrons, x-rays, gamma-rays, electromagnetic pulses, and electrons are treated. The models can be used to estimate kill probability of a complete system or malfunction probability for specific subsystems and components. Many of the computer codes involved are also applicable to vulnerability studies of satellites and aircraft.

Item 4. *Biological Inactivation Modeling*

In its effort to improve methods for sterilizing heat-sensitive components and systems, Sandia's Biosciences Research Group has found that combined treatments of heat and ionizing radiation result in the synergistic inactivation of bacteria, viruses, and other biological entities. Since no biomathematical models existed to explain this phenomenon, dynamic models were developed, based on well-founded physical principles, to provide an interpretive framework for experimental data and to give direction for further efforts in this area.

The result has been an inactivation rate parameter model that describes pure thermal inactivation, pure radiation inactivation, and a heat-sensitive radiation-induced inactivation related to free-radical dynamics. Complete generalization of this model suggests that all biological entities may be synergistically inactivated by composite environments of heat and ionizing radiation. The model can project these conditions for any biological system with a known nucleic acid molecular weight. Typical results, along with experimentally confirmed points, are shown in Figure 1.

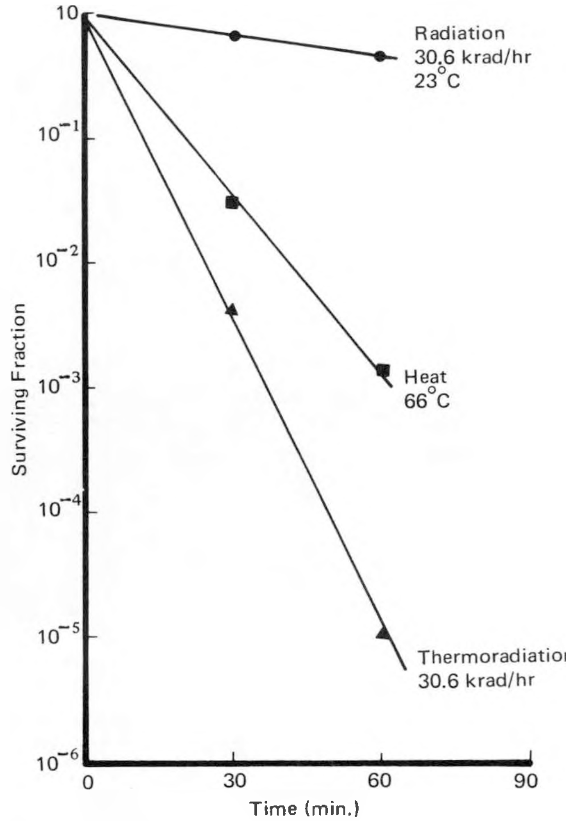


Figure 1. The inactivation of bacteria of the synergistic effects of heat and radiation is depicted as a function of time.

Item 5. *Thermal Insulation Model*

A thermal model was developed to aid in the design or modification of cellular insulation for packing, architectural, or other applications. A computer program based on the model determines the effects of wall material, cell structure and size, cover gas, pressure, and temperature on the conductivity of the insulation. The contributions of each heat-transfer mechanism with each insulation/environment combination are computed to indicate where improvements can be made and which changes would have the greatest effect.

The program can be used to predict conductivities of existing insulations in environments in which they have not been tested and to determine their suitability for new applications.

The program has also been used to design refractory insulation. The predicted and actual conductivity of the insulation are shown in Figure 2.

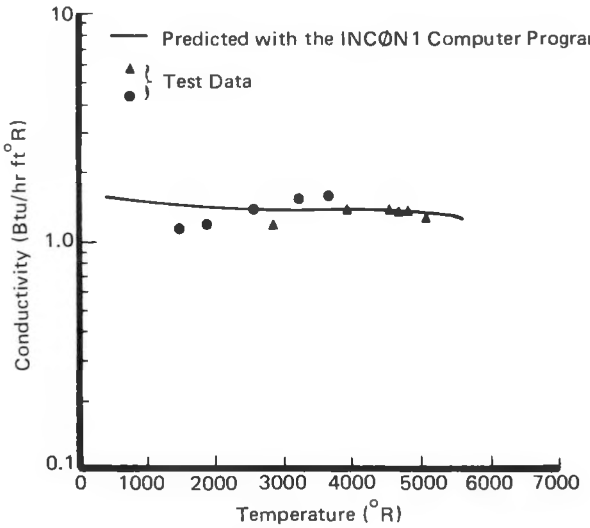


Figure 2. Thermal conductivity of graphitized processed cork

Item 6. *Composite Target Model*

Mathematical target models are formulated for use in assessing the battlefield potential of nuclear weapons and in planning for the selective and precise use of explosive energy. Frequently this model must treat a composite target as a collection of clusters of target elements, or subtargets, with each constituting a worthwhile target for small weapons.

The principal variables that affect the choice of optimal aimpoints within a composite target are:

1. Yields, number, and accuracy of weapons to be used,

2. Geometry of the array of target elements and their directional vulnerability, and the

3. Military value of individual target elements and their proximity to civilian population centers.

The composite target model has proved to be a useful analytical tool. Given data with respect to the above principal input variables, the following results are obtained:

1. A recommended set of aimpoints (optimal aimpoints),

SYSTEM EVALUATION

2. Expected numbers of elements of different types that will be damaged to the required level,

3. Probability that each target element will be damaged as required, and

4. Expected area on which effects impinge in nearby population centers.

Item 7. *Solar Thermal System Model*

A solar total-energy system is being developed to provide the electrical, heating, and cooling needs of a specified building which will also be used as an engineering evaluation center.

Models of both components and subsystems are made to facilitate cost tradeoffs with performance. A particular area of involvement has been with solar collectors and collector arrays. A detailed model of flat-plate collectors has been developed that allows comparisons with focused collectors. The model calculates system efficiency based on solar input and heat losses resulting from conduction, convection, and radiation. An arbitrary number of layers can be considered as well as such parameters as optical and collector absorptance properties. The analytical model has been experimentally verified.

Item 8. *Deep Rock Nuclear Waste Disposal*

A deep-rock disposal concept is being developed in which solidified uncontained high-level radioactive wastes would be placed in holes drilled deep in bedrock. Heat generated by the wastes will melt the waste and the surrounding rock, and the two will be mixed by convection currents. After several years, heat generation decays and the liquid resolidifies into a low-solubility matrix.

A cost analysis of this scheme took into account drilling, casing, and refilling the hole, and handling as well as monitoring equipment. Cost would be about 0.0005 mill/kWh, which appears negligible compared to the total cost of electricity. Since preliminary indications are that the concept is safe, permanent, and economically feasible, it has been selected for detailed exploratory development.

Item 9. *A Wind-Powered Fresh-Water Condensation System*

A system for use on Pacific atolls has been designed that would use cold ocean water (50°F 1000 feet below the surface) to cool the warm moist Pacific air below its dew point while blowing through a heat exchanger, thus providing fresh water. The warmed sea water contains nutrients that could support mariculture and hydroponics. To take advantage of the 13-knot (minimum) winds that blow 50 percent of the time in that area, power for pumping the water would be derived from a specially designed wind turbine that is under development. While pumping, the turbine could also generate electricity for other uses.

Costs of the wind-powered system were determined by amortization of the piping, pumps, wind turbine, generator, heat exchanger, and other equipment over the life of the system. Unit costs for the derived benefits were compared with costs of alternate methods, and decisions about system implementation were based upon cost effectiveness.

Item 10. *Acoustic Sensing of Jet Aircraft*

In determining major sensitivities in the concept of identifying aircraft using acoustical techniques, current interest centers around measurements of signal zero-crossing density, i.e., the number of times the input signal crosses through zero per unit time. A method using the time history of this parameter has proved successful for identifying jet aircraft under limited test conditions.

The dominant sound source for unquieted jet aircraft operating at or near full power is the turbulent flow of the jet exhaust itself. This source, which produces random noise, is assumed to approximate a continuous normal process. As such, the expected value of its zero-crossing density, λ, for positive-direction crossings only, can be found by

$$\lambda = \frac{1}{2\pi}\left[\frac{\int_{w_1}^{w_2} w^2 S(w)\,dw}{\int_{w_1}^{w_2} S(w)\,dw}\right]^{1/2}$$

where

$S(w)$ = sensor input signal power spectrum
w = frequency - radians/seconds
w_1, w_2 = sensor bandwidth limits.

As these equations indicate, the expected zero-crossing density depends on the input power spectrum. Models have been developed to reveal how source characteristics, propagation, and background noise will affect this spectrum.

Results for various ambient "white" noise levels are shown in Figure 3, indicating that even low white-noise levels can influence the time history signature of λ.

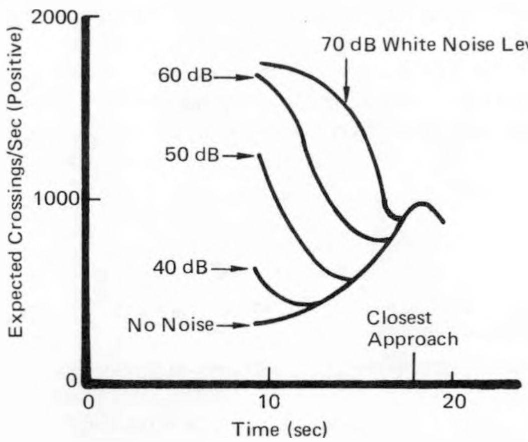


Figure 3. Mirage IV calculated zero crossings with white-noise background (sensor located 300 feet offset from flight path)

Item 11. *Cost of In-Situ Oil-Shale Processing*

In a recent study of in-situ oil-shale processing economics, a major objective was to determine the sensitivity of product cost to parameters influencing cost of the process. A complete extraction configuration was formulated, and schedules of capital and operating expenses were developed. A simulation of the operation of the retorting process was developed based upon all parameters affecting operational efficiency.

These models were integrated into a computer code which calculates the oil price necessary to allow a defined discounted cash flow rate of return for investments in the defined process, using nominal values for all expenses and operating efficiencies. Variation of each parameter allowed calculation of the accompanying variation in oil price necessary to maintain the required rate of investment return. This procedure identified parameters to which the cost of the product is most sensitive, indicated subsystem areas in which engineering development will be most beneficial, and showed process parameters on which basic research would be most helpful. Typical outputs are shown below.

Cost Sensitivity of Shale-Oil Price
to Dominant Input Parameters
(50,000 Barrels per Day, Basic Model)

Parameter	Nominal Value	Percent Cost Reduction From 10% Improvement
Retort height	1000 ft	9.77
Retort volume	10^7 ft^3	9.68
Shale quality	0.60 bbl/ton	9.68
Retort efficiency	0.60	9.68
Retort excavation cost	0.15 \$/ft^3	2.69
Void fraction	0.2	2.44
Retort rubblization	19 x 10^6 \$	1.71
Operating power and fuels	6 x 10^6 \$	0.49
Operating labor	4.7 x 10^6 \$	0.49
Central shafts	12.69 x 10^6 \$	0.49

CONCEPT OPTIMIZATION

In this process, which is the final step in most system analyses, a set of subsystems and/or parameters is identified that provides an extremum of performance functions under the defined constraints. In this phase the completeness of identification and appropriateness of objective definition are of prime importance.

Determination of Extrema

For large or complex systems, determination of a global extremum is often impractical or impossible, and a local extremum about a defined operating point is found as a compromise. Since such complexity is often encountered, the optimization procedure usually involves an iterative process of reformulating the system relative to a number of feasible operating points, each of which is accompanied by an optimization. (Items 1-5)*

Current Activities

- Strategic weapon allocation and targeting
- Design of radioisotopic thermal generators
- Energy storage requirements
- Guidance systems
- Waste heat transportation

*See Highlights below.

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Energy Transmission Networks*

A study is being made of supplying both electrical and thermal energy from nuclear power plants to a set of demand centers. Thermal demand can be met either by electricity to operate heat pumps or by hot water derived from the plant's steam system.

With the nonlinear economies of scale associated with energy production and distribution taken into account, a heuristic program was developed to determine the most economic routing of the network, avoiding restricted regions. An example of results is shown in Figure 1.

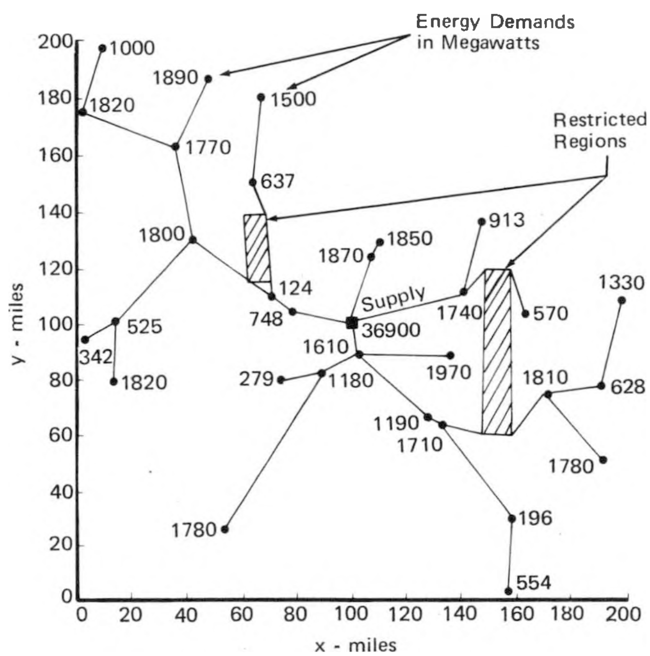


Figure 1. Energy transmission network

Item 2. *Use of Wind Power in Utility Grids*

The Darrieus vertical-axis wind turbine is being investigated for use in the synchronous wind-powered generation of electricity coupled into an existing electrical utility grid. One feature of the Darrieus turbine is that for a given design, generated power never exceeds some maximum value under any wind conditions. Thus, unlike conventional horizontal-axis wind turbines, no means such as blade pitch control are needed to assure that the power rating of a generator is not exceeded. A model has been constructed which determines for a given maximum power and annual wind distribution the radius and rotational speed that will maximize annual energy production. Figure 2 shows optimal turbine designs for a particular set of aerodynamic characteristics. Once the most efficient Darrieus turbine designs have been found, cost comparisons will be made against horizontal-axis turbines.

Item 3. *Reactor Fuel Reprocessing Plant Location-Allocation*

Using the locations and fuel requirements of 99 nuclear reactors, a heuristic method was developed determining the number, capacity, and location of reactor fuel reprocessing plants to minimize total reprocessing costs.

Minimum-cost solutions can be obtained for a stipulated number of reprocessing plants with either specified or unspecified capacity.

Item 4. *Guidance-System Analyses*

In determining the delivery accuracy of weapon systems, simulation analyses are used for system optimization, comparison of alternatives, and estimation of performance. Radar systems have received particular attention, among them track/command and seeker systems as well as terrain-sensing systems. Analyses include probabilistic studies of terrain as it provides clutter to some systems and information to others.

Item 5. *Waste-Heat Transportation*

Various domestic, industrial and agricultural uses have been suggested for the vast amounts of heat rejected by electric power plants. A general parametric model of a steam power plant and a two-way underground hot water transmission system has been constructed. It contains cost models for extracting energy from the power plant, and complete capital and operating expense models for transporting the hot water a given distance (Figure 3). All heat losses and gains are accounted for. The complete model is embedded in a computational routine that minimizes the total cost of delivered energy by selecting the correct set of system design parameters for a given transportation distance, delivery temperature and power requirement.

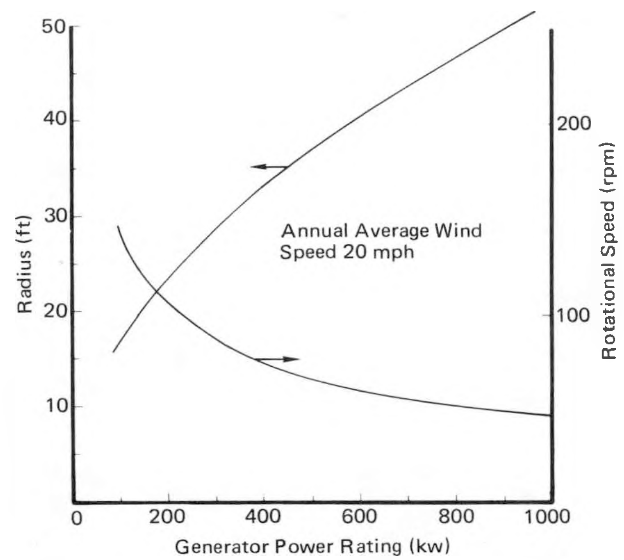


Figure 2. Darrieus wind turbine design to maximize the annual energy production

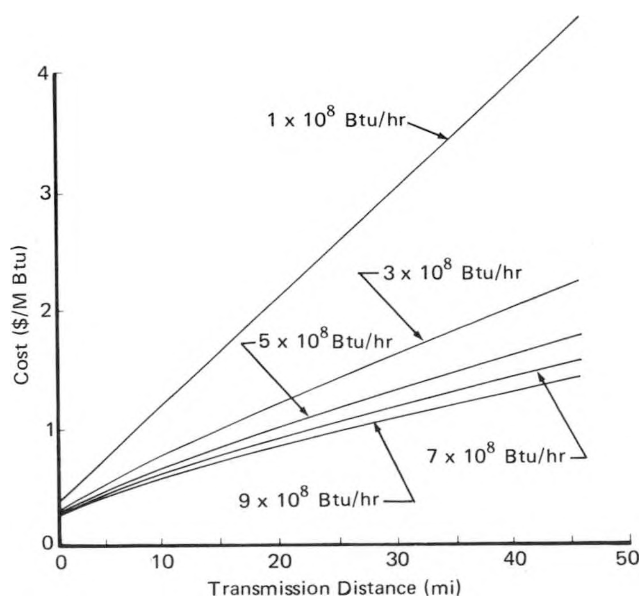


Figure 3. Optimal costs for nuclear power plant waste heat purchase and transmission

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TESTING

Sandia Laboratories Technical Capabilities

Testing

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115
and Livermore, California 94550 for the United States Energy Research
and Development Administration under Contract AT(29—1)-789

SAND-74-0088
Unlimited Release
Printed September 1975

SANDIA LABORATORIES TECHNICAL CAPABILITIES

TESTING

ABSTRACT

This report characterizes the testing capabilities at Sandia Laboratories. Selected applications of these capabilities are presented to illustrate the extent to which they can be applied in research and development programs.

TESTING*

Extensive test facilities have been developed to simulate mechanical, thermal, hydrodynamic, electromagnetic, and radiation environments. Research, development, and evaluation testing facilities are used to explore new concepts and to evaluate proposed and existing designs. Facilities include shock, vibration, surface impulse, blast loads, thermal, aerodynamic, underwater, and electromagnetic for the simulation of environments. Radiation sources have been developed to provide a simulation of nuclear effects tests. Pulse reactors provide a mixed neutron-gamma exposure. Steady-state neutron and gamma irradiation are provide by a neutron generator and ^{60}CO and ^{137}Cs radiation sources. Bremsstrahlung x-ray and electron beam exposures are performed using the pulse accelerators. Test facilities used primarily in support of the Laboratories' exploratory research and development effort are wind tunnels, plasma jets, shock tubes, and flight simulators to support aerodynamic testing, and high-velocity gas guns, and explosively and magnetically driven flyer plate facilities to support the materials characterization effort in solid dynamics and structural studies. Materials, structures, components, and entire integrated systems are evaluated using a wide variety of nondestructive testing techniques such as flash x-ray, acoustic emission, laser holometry, ultrasonics, and x-ray and neutron radiography. Field-testing capabilities include mobile instrumentation vans that can be deployed worldwide, a rocket-launching facility at Kauai in Hawaii, an isolated area at Nevada Test Site for underground nuclear testing, and the Tonopah Test Range for a wide variety of aerodynamic testing.

In addition to providing test facilities for engineering programs, the responsibility of the testing function includes anticipating future test requirements and integrating test plans with project, research, and advanced development organizations for the design of meaningful test programs.

Only test facilities that are common to several programs are discussed in this section. Facilities to support special objectives or single programs are omitted here, but are described in other sections of the Technical Capabilities report.

Testing Technical Staff and
Investment in Equipment

	Professional Staff	Investment in Equipment ($1000)
Environmental Simulation	72	37,210
Mechanical Loading		
Radiation Loading		
Research, Development, and Evaluation	55	8,275
Aero Testing		
Material Response		
Nondestructive Testing		
Field Testing	61	30,500
Tonopah Test Range		
Nevada Test Site		
Kauai Test Facility		
Mobile Testing		

*Compiled April 1975

ENVIRONMENTAL SIMULATION

The purpose of this function is to furnish research, design, and development engineers with test results that encompass anticipated handling and use environments. To support the requirement for a wide variety of stimuli, test facilities have been established that simulate various environments including several types of mechanical loading (static, shock or impact, acceleration, vibration, and surface impulse) and radiation loadings (thermal, electromagnetic, neutron, x-rays, electron, and gamma rays).†

Mechanical Loading

Research and development test facilities are used to simulate several types of mechanical loading. The dynamic simulation testing capability consists of a variety of shock-testing machines, including electrodynamic and hydraulic vibration actuators. These machines are computer-controlled for sinusoidal and random vibration, and shock-controlled pulses. Other mechanical loading facilities provide for earth-penetration testing, surface-impulse simulation, acceleration/time signatures, blast loading, and explosives testing. Combined environments can also be simulated, such as temperature plus vibration or impact, or vibration during acceleration. Underwater facilities provide the capability for water-entry testing as well as high-speed hydrodynamic investigations.

New test techniques, test control methods, data acquisition and analysis systems, and instrumentation are continuously being developed to improve simulation capabilities. The facilities are adaptable to particular test requirements.

Static Mechanical Loads

Static loading tests are performed to determine the ability of structures to resist loadings expected in use and to satisfy the needs of fundamental research with respect to material properties. Loadings can be induced from external point sources, from area loads as in hydrostatic pressurization, and from inertial body forces such as sustained acceleration. Facilities can accomodate a broad spectrum of loading conditions and test item sizes. Some combinations of external point loading and body force loading are possible, and on some equipment, tests can be conducted at temperatures other than ambient. (Item 1)*

Current Facilities

- Centrifuges
- Tension-compression testing machines
- Load frames
- Hydrostatic pressure chambers
- Creep high temperature testers

Shock or Impact Loading

Shock-controlled pulse or impact testing is used to evaluate the structural and functional integrity of components, subsystems, and entire systems to a prescribed transient response. Transient response techniques are also used in combination with analytical and numerical techniques to determine mechanical properties of materials. Techniques and facilities have been developed to provide a wide range of shock-controlled pulse shapes. (Items 2-9)

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† Test facilities are presented only under the generic headings indicating their use. Detailed descriptions of the simulation facilities mentioned in this section are available in the Sandia publication "Environmental Test Facilities," June 1972.

* See Highlights below.

ENVIRONMENTAL SIMULATION

Current Facilities

Actuators
Drop towers
Shock machine
Flyer plates
Air guns
Centrifuges
Rockets
Rocket sleds
Aerial cable
Blast tubes
Earth penetrators

Surface Impulse Loading

Facilities have been developed for loading material samples, structural shapes, and full-scale systems with short-duration (1 to 10 μs) pressure pulses. Stress waves generated by an impulse in combination with structural response may lead to major structural and material damage. Explosives and explosively or magnetically driven flyer plates have been developed to simulate radiation-induced blowoff impulse and to determine stress-strain relations for structural materials under high strain rates. Electron-beam irradiation is also used to simulate transient surface-loading conditions on small material samples. (Items 10-11)

Current Facilities

Light-initiated explosives
Mesh-initiated explosives
Propagating explosives
Gas driven flyer plates
Explosively driven flyer plates
Magnetically driven flyer plates
Electroexplosives
Electron beams

Random and Sinusoidal Vibration

Vibration tests are performed on components, subsystems, and entire systems either to determine the response of the configuration to a specified level of excitation, or to define excitation levels and spectra that induce failure. Vibration testing is also used to determine the response and resonance frequencies of configurations to a low-level specified excitation spectrum for analytical modeling purposes.

Vibration facilities are composed of electrodynamic drivers supplied by electronic amplifiers under programmed servo control. Options include swept sinusoidal, random, swept sinusoidal on random background, and swept random on random background.

Control capability consists of analog techniques for sinusoidal excitation, digital methods for random excitation, and analytical techniques for transfer function determination. Analyses are generated in quasi-real time with plots of power spectral density, shock spectra, transmissibility, transfer function, and Fourier spectra versus frequency, as well as printouts of eigenvalues and spatial eigenvectors. (Item 12)

Current Facilities

Electrodynamic shaker drivers
Hydraulic actuators
Spectral density analyzer/equalizer

Acceleration/Time Loading

In the design and qualification of some components and subsystems, a major requirement is that they withstand acceleration loading for a specified time. Acceleration/time profile testing is used to properly exercise inertial devices and to determine their ability to measure acceleration, velocity, or distance. Missile launch, in flight reentry conditions, staging, parachute deployment, and other such conditions can be duplicated or simulated. Emphasis is placed on reentry simulation for the test of inertial devices, but other noninertial items are tested, especially where systems interact with inertial devices. A rocket sled track, available for testing large items, can be used with advantage to simulate effects of missile launch and staging. (Items 13,14)

Current Facilities

Centrifuges
Rockets
Rocket sleds

Explosives Firing

Facilities with explosive load limits to several thousand kilograms are in operation. Instrumentation available includes oscilloscopes, tape and disk recorders, high-speed framing and streak cameras, flash x-ray, and a time-resolved spectrograph.

ENVIRONMENTAL SIMULATION

Current Activities

Tests on explosive systems
- Shock
- Vibration
- Temperature
- Humidity
- Pressure
- High-speed spin

Tests utilizing explosive systems
- Flyer plates
- Containment
- Pulse power sources
- Component qualification
- Overpressure
- Vulnerability
- Electrically initiated plane wave generators
- Cratering
- Response of materials to shock loading

Underwater Testing

Technologies and facilities have been developed to study phenomena related to high-velocity hydrodynamics and pressure effects. Full-scale and model entry studies are conducted in water tunnels. The rocket-sled track is used for larger or higher-velocity full-scale water-entry studies. (Item 15)

Current Facilities

- Water impact
- Water tunnels
- Rocket-sled track

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *7.6-Metre-Radius Centrifuge*

The distribution of internal loads in a complex structure subjected to combined axial, lateral, and bending loads can be determined using the centrifuge to apply a steady-state acceleration field in conjunction with hydraulic jacks used to apply local bending moments. This centrifuge has a radius of 7.6 metres and can accelerate an 8-ton specimen to 100 x earth gravity (Figure 1). Specimens of less weight can be accelerated to a maximum of 250 x gravity within the dynamic load rating of 1.6×10^6 gravity-pounds. Specimens being tested can be concurrently subjected to temperatures from -65 to 350°F and vibration frequencies from 10 to 3000 Hz.

Item 2. *Earth Impact Testing*

The effects of earth impact on air-dropped munitions can be simulated using a rocket pull-down technique developed at the aerial cable facility. Before development of this technique such detailed evaluations of full-scale systems could only be made statically with pre-positioned munitions, since airdrop accuracy is not sufficient to reliably position munitions in an instrumented arena.

A 1200-kg fuel-air explosive was tested using this technique. The munition was raised by a hoisting line to a release point on the overhead cable. Two towing lines ran from the munition to the impact point in the center of the instrumentation arena. Guide tubes buried under the target area redirected the towing lines to a rocket sled at the end of a track as shown in Figure 2. The release point on the overhead cable was selected to provide the desired impact angle of 70 degrees. Impact velocity was 250 m/s. Ground and overhead cameras recorded aerosol growth rate until detonation by pre-positioned ground initiators. Yield was determined from pressure transducers in the target arena.

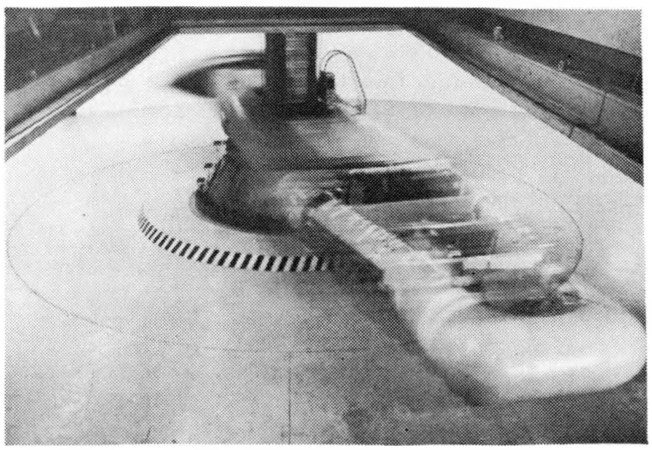


Figure 1. 7.6-metre-radius centrifuge

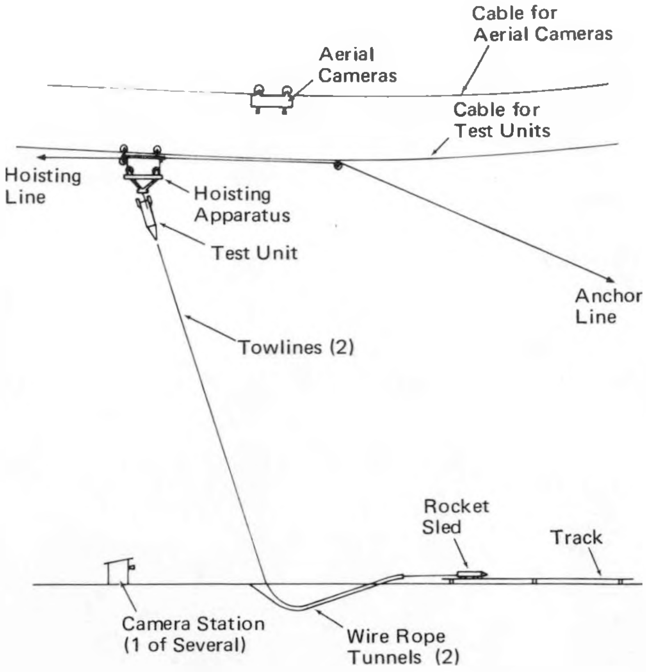


Figure 2. Aerial cable facility

This facility is used to impact masses of up to 10,000 kg into almost any target material; earth, water, concrete, steel, even trees. Impact velocities of 300 m/s have been achieved with lesser masses. Facility capability is limited to combinations of mass and velocity that have a maximum kinetic energy of 40 MJ.

Item 3. *Pneumatic Actuator Facility*

Mechanical shock tests were conducted using the pneumatic actuator facility (Figure 3) to produce a programmed acceleration loading profile that simulated the environment resulting from blast loading. The actuator was used in the thrust column driven sled mode for this test series. This mode consists of an air-driven actuator applying a force through a piston-driven thrust column to a sled mounted between two rails 610 mm apart. The maximum force that can be applied to the sled is 2.45 MN with a maximum stroke of 0.9 metre. Velocities available range from 80 m/s with a 115-kg sled to 40 m/s with a 900-kg sled. Accelerations up to 2000 x gravity may be obtained using this sled mode.

To achieve higher accelerations or a short-duration shock pulse, the actuator can be used in a two-sled impact test mode. In this method the actuator imparts a velocity to the first sled which impacts a second sled via a mechanism that controls the forces between the sleds. Up to

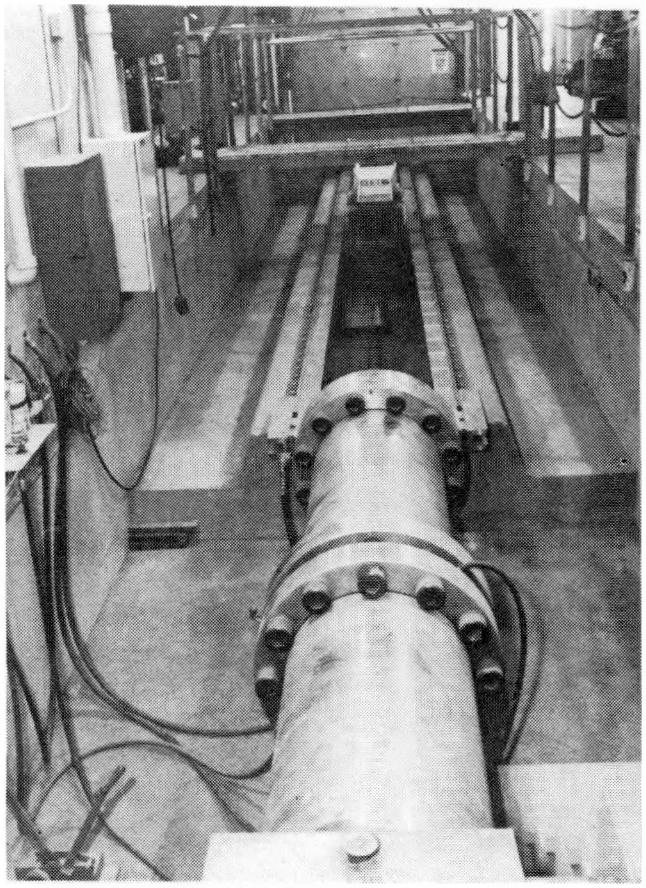


Figure 3. Pneumatic actuator facility

10,000 x gravity can thus be applied to a test specimen on the second sled. Other test methods involving multiple sleds and force programmers have been developed to simulate various field environmental conditions.

Item 4. *Explosively Propelled Flyer Plates*

Studies of the effects of oblique impact on the structural integrity of complete systems, or of nonplanar stress waves on gage response, and many other experiments in which objects are subjected to nonsimultaneous loading conditions, can be conducted using massive flyer plates of plastic or metal accelerated by solid explosives to high velocities with low rotational rates. A test specimen can be positioned at any point along the flight path to allow the plate to rotate the desired amount before impact. Thus, any angle between the velocity vector and surface normal may be obtained to simulate oblique impacts. Plates weighing up to 10 kg have been employed at velocities from 1.5 to 4.0 mm/μs.

ENVIRONMENTAL SIMULATION

Item 5. *Centrifuge Impact*

The energy-absorbing capabilities of insulation materials can be evaluated using the 10.7-metre-radius centrifuge. A test specimen is secured to the end of the centrifuge arm by a cable. When the centrifuge is stabilized, with the specimen traveling at the desired impact velocity, the cable is cut, allowing the specimen to travel freely into a 14,000-pound steel target. Hardwire instrumentation is used to measure deceleration forces on the specimen during impact.

The facility can provide impacts from 10 to 550 ft/s, with a maximum velocity of 210 ft/s on a 10,000-pound test specimen.

Item 6. *Blast Testing*

The effect of a blast-wave environment enveloping a structure (tank, car, building, reentry vehicle) can be studied using a shock tube to produce the desired shock wave. One such tube is 1.8 metres in diameter and 61 metres long, with a driving charge of high explosives at one end and the experiment at the other. Detonation of the explosive produces an aerodynamic shock wave which moves down the tube to envelop the experiment (Figure 4). In a typical experiment, a charge of 150 kg of PETN explosive in the form of primacord is used in the shock driver section at a loading density of 11 kg/m. At this density the explosive energy is contained by the driver.

Blast overpressures of 1.4 MPa and 0.5 MPa can be generated in the 1.8-m and 5.8-m test sections, respectively. Other shock tubes up to 2 m in diameter are available for generating blast pressures up to 4 MPa. These, however, are driven by larger explosive charges with energy densities that cannot be contained. Thus, a driver section must be expended with each test.

Item 7. *Earth Penetration Testing*

Terradynamics deals with the motion of soil and other solid materials, and with forces acting on bodies in motion relative to those materials. Terradynamics studies have resulted in analyses of earth penetration, and a field test program that has yielded projectile deceleration/time data and penetration performance in materials ranging from saturated clay to competent limestone. Projectile penetration can be used for environmental testing of components. The penetration event can generate high-deceleration long-time duration loading profiles that cannot be attained in the laboratory. Current capabilities consist of air launch at free-fall and boosted velocities, track launch and horizontal impact up to 1.2 km/s (4000 fps), and portable recoilless-gun accelerators.

The Davis Gun, a smooth-bore recoilless reaction-mass gun, can be used to fire a 304.8-mm (12-inch)-diameter instrumented projectile vertically downward into man-made or earth targets at velocities to 457.3 m/s (1500 fps) [for a 455-kg (1000-lb) penetrator] or 914.6 m/s (3000 fps) [for a 136-kg (300-lb) penetrator] (Figure 5a and b). The air gun can vertically launch 76.2-mm (3.0-inch) diameter, 6.14-kg (13.5-lb) instrumented projectiles into man-made or natural earth targets at velocities to 198 m/s (650 fps). A 25.5-kg (56-lb) projectile can attain velocities to 99 m/s (325 fps).

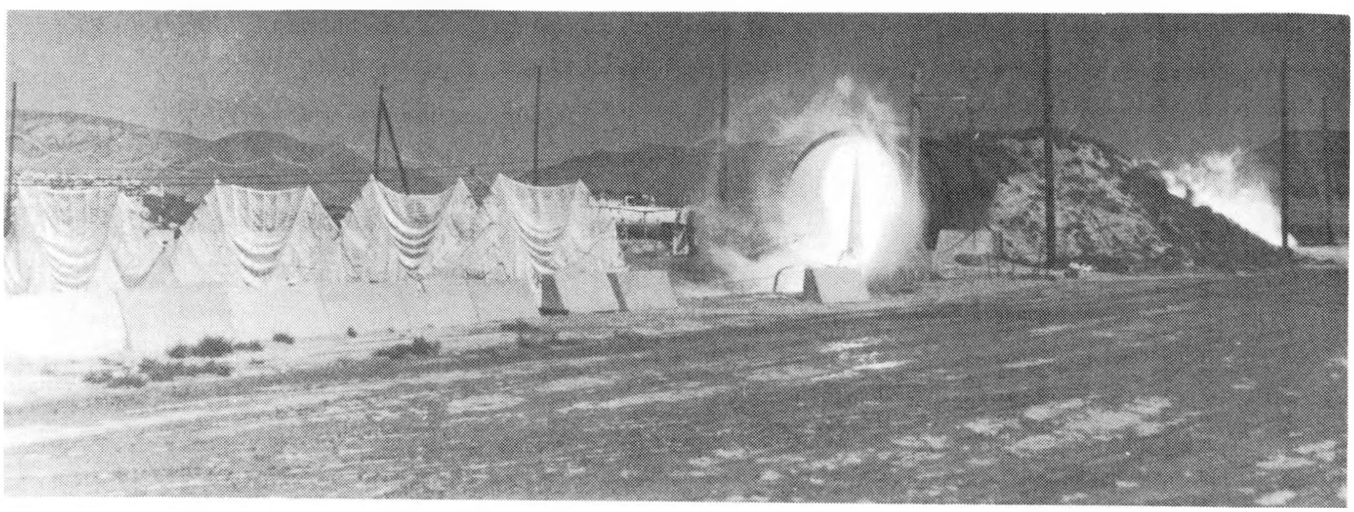
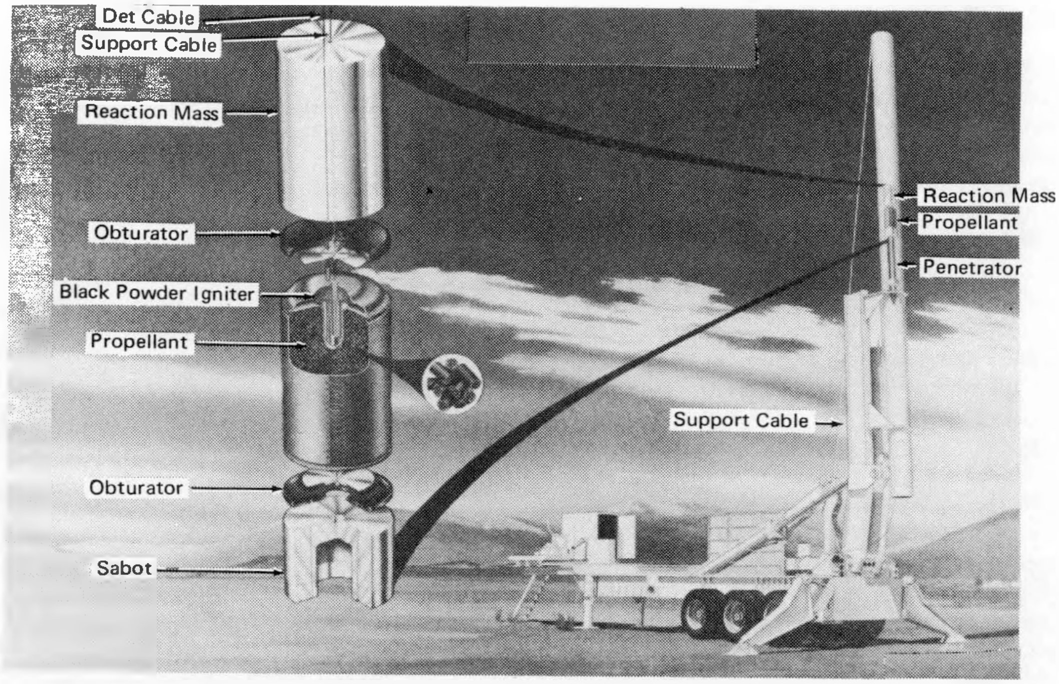
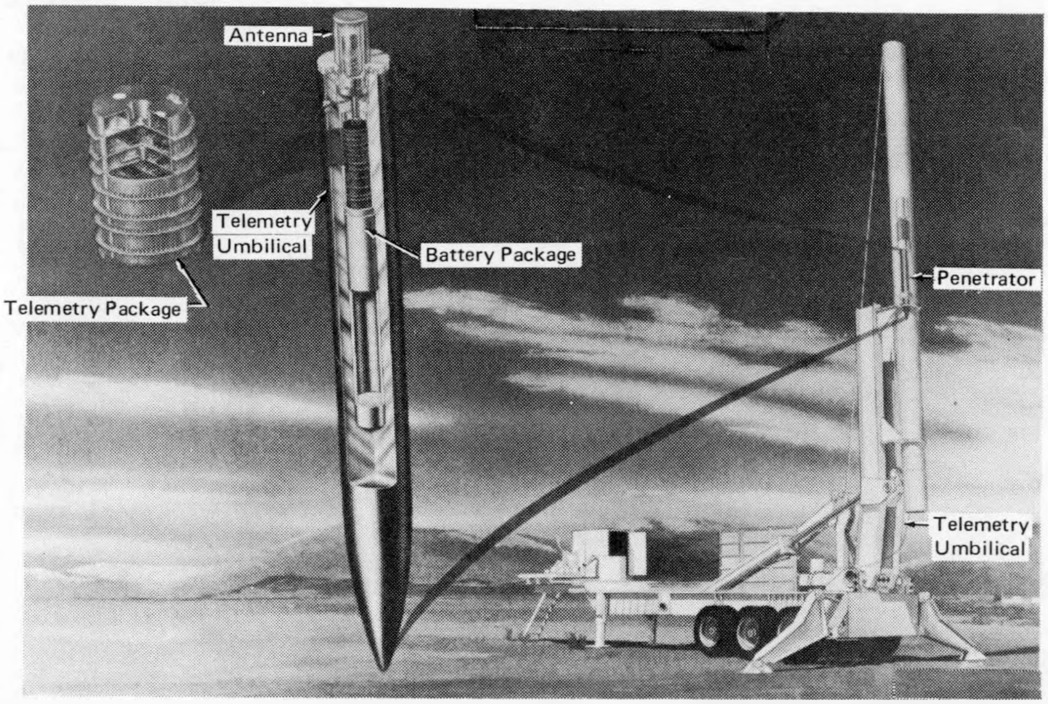


Figure 4. Blast testing of a missile system in a shock tube



a. Earth penetrator propulsion system



b. Earth penetrator

Figure 5. Terradynamic earth penetrator systems

ENVIRONMENTAL SIMULATION

Item 8. *Programmed Transient Testing*

Computers are used to program transient acceleration tests on vibration machines. Typically, a desired environment is defined as a shock spectrum or a specific time history representing the environment in which the specimen will be used, or a combination of damped sinusoids. The computer is used to generate the excitation transient including corrections to bring the final velocity and displacement to zero so that physical constraints imposed by the exciter are met with minimum distortion of the desired transient. Typical of simulated field shocks are missile stage separation, parachute ejection, and handling and transportation environments.

A computer is used to replace the trial-and-error approach of successive approximation with comparison of output to input by transfer functions. As applied, the computer generates a known calibration pulse into the electronic amplifier, monitors the test input point acceleration, does a complex Fourier analysis of both, calculates a complex transfer function in the frequency domain for the complete system, and applies the inverse transfer function to the desired output to arrive at a corrected input time domain excitation that will generate the precise desired test acceleration input. The computer is then used to evaluate the test at various locations on the specimen. Plotted analytical results can be presented in near-real time as transfer functions between any two points, and shock or Fourier spectra versus frequency in two dimensions or, where appropriate, also against time in three dimensions. Setup, test, and analysis are based upon a sound theoretical approach using the capabilities of the digital computer; as a result, relatively inexpensive tests can be conducted with short turnaround times.

Item 9. *Computer-Controlled Shock Testing*

Data acquisition and analysis capabilities have been instituted to improve data quality and turnaround time of shock testing. Control of all parameters, data annotation, and test setup can either be done remotely at the test facility or in the computer room via a computer display terminal featuring interactive graphics and a hard-copy unit. A 32-thousand core disc-based minicomputer system can take up to eight channels of analog data directly through its 200-thousand words per second analog-to-digital converter on disc or can digitize any number of channels from analog magnetic tape recordings. Data are presented as complete annotated plots of original pulse and velocity change versus time; complex Fourier spectrum, shock spectrum, complex transfer function versus frequency, and special data desired by the test requester such as strain versus displacement.

Item 10. *Magnetically Driven Flyer Plates*

Surface impulse can be applied to structural shapes with magnetically driven flyer plates. Energy up to 750 kJ stored in capacitor banks is used to propel the plates. Cylindrical or conical structures with base diameters of ~0.4 m can be laterally impulse-loaded up to ~1200 $\text{Pa·cm}^2\text{·s}$. Typical measurements include strain, acceleration, displacement, and high-speed photographic coverage.

Item 11. *Impulse Simulation*

A technique for simulating transient surface-loading effects uses the light-sensitive explosive silver-acetylide/silver-nitrate, which can be spray-painted on any surface. The desired explosive distribution is obtained by spraying through a mask and rotating the specimen between spray passes. The explosive is detonated by an intense flash of light. Extremely thin layers of explosive can thus be detonated simultaneously.

The test facility permits the remote handling and firing of a 1-kg explosive charge sprayed over a 1-m^2 surface. Impulse levels may range from 10 Pa to over 1000 Pa with load rise times of ~1 μs. Strain, acceleration, displacement, x-ray, and high-speed camera measurements are obtained. Equipment for recording 80 data channels is available. Spray-painted explosives are particularly useful for structures with irregular surfaces or where step discontinuities in impulse complicate loading.

Item 12. *Random-Vibration Testing*

Since random-vibration testing is computerized for improved control accuracy, the time required for preparing a test is reduced. Side advantages of considerable significance are the near real-time data analysis and the power spectral density plots obtained. Control spectra may be of any form that can be represented by straight-line segments and may range from 0.5 Hz to over 3 kHz with rms forces of up to 155.7-thousand Newtons (35,000 pounds) and displacements to 200 mm (7.87 inches) at the low frequencies. The computer systems function with up to 1024 discrete frequency lines in either pseudo or true random mode. Capability is available on the minicomputer system to perform spatial modal analysis resulting in eigenvector or eigenvalues at monitored points. This technique allows development of mathematical models of a subsystem package.

Item 13. *Acceleration and Deceleration Simulation*

The centrifuge-computer combination facility is an automated, precise, accurate, and very repeatable system designed for the test of inertial devices. Performance is optimized for the test of 4.5-kg (10-lb) packages at a radius of 0.6 m (2 ft), but much heavier devices can be tested at radii up to 0.9 m (3 ft). Peak speed is 52 rad/s (500 rpm).

The system can provide controlled rates from 61 mm/s^3 (0.00062 g/s) linear ramps to the worst expected reentry condition. Standard software allows the generation of polynomials up to order 6 and linear ramps through computerized commands. Nonstandard programming can be written if required for either control or data analysis.

Up to eight switch functions can be monitored by the computer with the acceleration at function times measured with accuracies of five significant figures. Repeatability of the time profile can be as good as 1 ms in a 10-s program. Acceleration/time integrals can be measured with 0.1 percent accuracy. Test environments from 200 K (-100°F) to 366 K (+200°F) are available with no degradation specifications.

Item 14. *Vulnerability of Structures to Airborne Objects*

A test facility used to evaluate the vulnerability of structures to tornado-borne objects has been completed and evaluated. Among objects successfully thrown at the structure are 12-foot x 4-inch x 12-inch wooden planks at 200 mph; 3-inch-diameter pipe 10 feet long at 100 mph, and a 3000-pound car at 50 mph.

The capability of the facility includes subjecting concrete slabs 17 by 17 feet square, and up to 24 inches thick, to the impact of tornado-generated missiles of any variety. For instance, telephone poles at velocities of 150 mph, pipe to 300 mph, planks to 300 mph, etc., can be accelerated into concrete slabs or any other material (Figure 6).

Item 15. *Water Testing*

A test series was conducted using the maximum capabilities of the water impact facility to experimentally determine the submarine trajectory of a weapon entering the water at a 30-degree angle of attack, a pitch angle of 10 degrees, and a velocity of 400 fps, while spinning at 20,000 rpm. The model used was 1/5 scale.

Figure 6. Automobile impact into a concrete wall

A turnaround water-impact test technique has been developed using the rocket sled to accelerate a water tank up to velocities of 609.8 m/s (2000 fps) prior to impact with full-scale systems. Water tunnel (Figure 7) capabilities include velocities up to 167.7 m/s (550 fps) in a 152.4-mm (6-inch)-diameter test section. Test duration is approximately 5 seconds. Force, and pressure measurements are possible within the test section and photographic coverage of the test specimen is available. Models up to 15.88 mm (5/8 inch) in diameter can be used for drag, cavitation, and underwater cavity analyses.

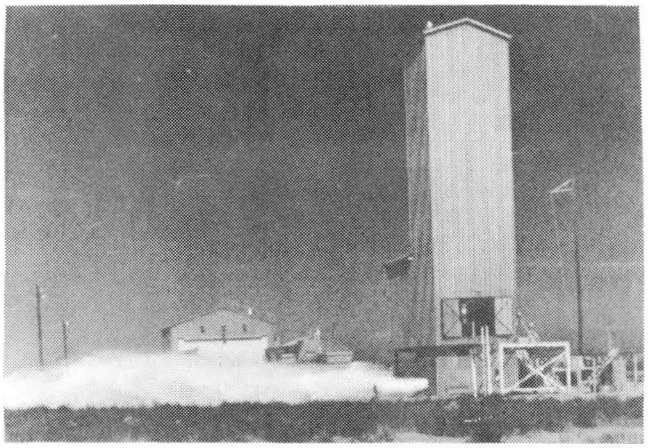


Figure 7. Vertical water tunnel

ENVIRONMENTAL SIMULATION

Radiation Loading

Facilities have been developed for producing various forms of radiation in which to investigate the response of materials, components, and systems. Combined or isolated levels of neutrons and gamma rays are obtained from pulse nuclear research reactors; steady-state gamma rays are produced by cobalt and cesium sources; Bremsstrahlung x-rays and electron beams are generated by pulse accelerators; thermal loading is produced by a radiant heat facility, and various sources of low-level electromagnetic energy are used. The radiation fields and their effects are defined by radiation and beam transport studies and measured by appropriate instrumentation. The facilities are used in support of nuclear weapon studies, nuclear reactor safety research, and nuclear fusion research using lasers and electron beams to generate the required physical conditions.

Pulse Reactors

Pulse reactors are designed to produce bursts of high-intensity neutrons and gamma rays. Experimental techniques and instrumentation are developed to study the response of electronic circuits, structures, and materials including fissionable and explosive materials. The facilities are also used to produce neutrons for radiographic evaluation of components and for simulating conditions for studying the response of nuclear-power reactor components to abnormal transient conditions. (Items 1-5)*

Current Capabilities

Annular core pulse reactor (ACPR)
- Pulse mode
  - 4.7-ms pulse width (FWHM)
  - 1.3-ms initial power transient
  - 1.7×10^{15} n/cm^2, E > 10 keV
  - 10^6 rad (H_2O) gamma dose/pulse
  - 9-inch-dia x 12-inch-high irradiation cavity
- Steady-state mode
  - 300 kW steady-state power (600 kW approval expected)
  - 5×10^{12} n/cm^2/s, E > 10 keV

Neutron radiography
- 10^8 n/cm^2 s thermal at maximum steady-state power
- 3×10^9 n/cm^2 thermal in pulse mode
- 65 to 500 L/D ratios

Sandia pulse reactor (SPR) II
- Metal core, hard energy spectrum (350 keV peak)
- 1.5-inch-dia x 8-inch-high central irradiation cavity
- 1×10^{15} n/cm^2, E > 10 keV
- 40-μs pulse width (FWHM)
- 2×10^5 rad (H_2O) gamma dose/pulse
- 3 kW steady-state power

Sandia pulse reactor (SPR) III
- Metal core, hard energy spectrum (350 keV peak)
- 7-inch-dia x 12-inch-high central irradiation cavity
- 1×10^{15} n/cm^2, E > 10 keV
- 40-μs pulse width (FWHM)
- 2×10^5 rad (H_2O) gamma dose/pulse
- 15-kW steady-state power

Pulse Accelerators

These accelerators are used to generate intense short pulses of ionizing radiation for the study of the transient effects of x-rays on electronic components and circuits, permanent radiation damage to electronic devices and circuit parts, and the responses of nonconductors. Also studied are the thermomechanical responses of materials and structures through melting and vaporization, and radiation-induced changes in the physical structure of materials. The accelerators are also used to generate electron beams for producing fusion, pumping gas lasers, and heating plasmas. (Items 6,7)

*See Highlights, below.

Current Capabilities

Source	REBA*	Hermes II	Hydra*
Bremsstrahlung Mode			
Energy (MeV)	3.0	10.0	0.9
Pulse width (ns)	50	60	100
Dose (krad)	15	50 (300)**	5 cal/g
Dose rate (r/s)	3×10^{11}	8×10^{11} (6×10^{12})**	–
Area (cm^2)	50	300 (20)**	5
Electron Beam Mode			
Energy (MeV)	3.0 (1.0)**	10.0	0.9
Fluence (cal/cm^2	400 (300)**	700	400
Dose (cal/g)	400 (1000)**	300	2000
Area (cm^2)	3 (3)**	15	5

*REBA — Relativistic Electron Beam Accelerator. Hermes II and Hydra — Electron-beam accelerators; for further detail see Physical Sciences, SAND74-0074.

**Alternate mode of operation.

Steady-State Sources

Steady-state neutron and gamma irradiation facilities and associated experimental techniques and instrumentation support studies of radiation effects in electronic components and circuits, biological effects of radiation, gamma sterilization, and other programs for which an intense neutron or gamma source is required. (Item 8)

Current Facilities

Gamma irradiation facility (GIF)
 Cobalt and cesium gamma sources
 10^4 to 2×10^5 rad (H_2O)/min peak rates
Neutron generator

ENVIRONMENTAL SIMULATION

Thermal Testing

High-temperature facilities have been developed to study thermal loadings of materials, components, and systems. Temperature profiles can be simulated using tungsten-filament quartz-tube lamps or graphite resistance heaters. Earth orbital decay reentry heat-transfer conditions can be simulated in the arc tunnel with accurate duplication of stagnation enthalpy and reentry pressure profile. Solar heating can be simulated with either tungsten-filament lamps or carbon-arc devices, which provide a close spectral match where absorption and reflection properties are important. (Items 9,10)

Current Facilities

Radiant heat
Arc tunnel
Ovens
Climatic chambers

Electromagnetic Testing

Electromagnetic radiation testing is used to investigate the effects of communication and radar transmissions on electrical systems. Low-level radiation facilities have been developed to establish the transfer functions between incident and induced electromagnetic fields or currents in cables inside electrical systems. In addition, laboratory techniques have been developed to induce system failure by direct illumination of electronics packages. The combination of the radiation-facility-measured transfer function and the laboratory-induced failures provides sufficient information to certify electrical systems.

Electromagnetic pulse testing is the basis for studies of the effect of electromagnetic energy generated by direct transient radiation on electrical components. The high currents induced by the rate of change of the transient radiation pulse are capable of burning out discrete components in electrical systems. Both facilities and laboratory techniques have been developed to investigate this transient failure mechanism in electrical systems.

Current Facilities

Electromagnetic radiation
Electromagnetic pulse
Lightning
Static electricity

ENVIRONMENTAL SIMULATION

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Annular Core Pulse Reactor (ACPR)*

The ACPR (Figure 1) provides high radiation levels for the study of both steady-state and transient irradiation effects. A large central cavity allows in-pile testing of most full-size assemblies; maximum-yield pulses can be obtained at 20-minute intervals. Radiation experiments on electrical components have been conducted. A program of reactor safety studies is under way with emphasis on uranium dioxide equation-of-state analysis.

Figure 1. Reactor core for the annular core pulse reactor (ACPR)

Item 2. *Sandia Pulse Reactor II (SPR II)*

SPR II (Figure 2) is used in a variety of basic and applied research programs including radiation effects in materials and electronic devices; dynamic response of composite materials; pulse reactor fuel-material studies; neutron-pulse laser systems; electrical component response, and degradation tests. Maximum-yield pulses can be obtained at 1-1/2 hour intervals.

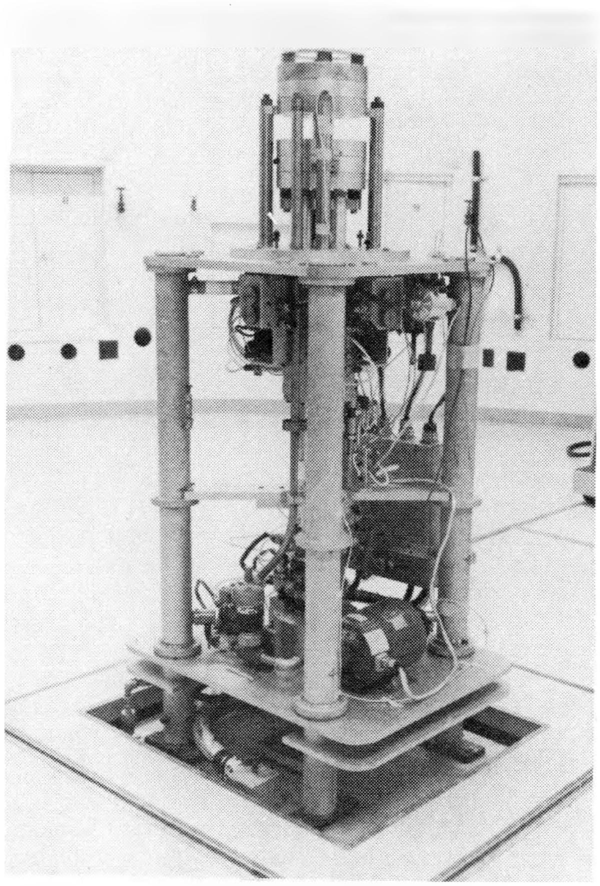


Figure 2. Sandia Pulse Reactor II (SPR II)

Item 3. *Reactor Fuel Metallurgy and Chemistry*

Investigation of failures of Sandia Pulse Reactor (SPR II) components revealed a number of problem areas which alone or in combination contributed to the failures and reflected inadequate or no controls in fabrication of the components. Faults included casting voids, incomplete alloying, and high impurity content, primarily of carbon. In particular, it was concluded that cracking of the fuel plates was caused by the almost continuous brittle grain-boundary phase identified as uranium carbides. Information obtained from the studies has been used to design the next generation of pulse reactors.

Item 4. *Quality Assurance*

A quality-assurance program is applied to the design, fabrication, construction, and testing of all new structures, systems, or components required for a new pulse reactor facility, and to modifications of existing structures, systems, and components. Requirements imposed by the Quality Assurance program apply to all activities affecting the safety-related function of these structures, systems, and components, including design, procurement, fabrication, handling, shipping, storing, cleaning, erecting, installing, inspecting, testing, operating, maintaining, repairing, refueling, and modifying. The program comprises all planned and systematic actions necessary to provide confidence that the reactor can be safely operated and maintained.

Item 5. *Nondestructive Testing*

Neutron radiography is used to investigate explosive-component development and to complement x-radiography. Separations of dissimilar explosive materials, as well as cracks, voids, bridgewire failures, and nonpropagating detonations, are evaluated with resolution to 1 mil. Other applications include the use of hydrogenous materials or materials with high thermal neutron cross sections placed inside high-Z containers for the purpose of detecting broken, displaced, or missing material. Pulsed neutron radiography (motion picture) capabilities are developed to investigate the transient mixing behavior of gases at high pressures and to observe detonating and propagating explosives. Activation analyses of isotopes in the central cavity and in the pneumatic shuttle system are techniques developed to investigate isotopes of long and short half-lives, respectively. Typical irradiation under various neutron spectra ranges from 10^{14} nvt to 1.0 to 10^{17} nvt steady-state accumulation and to 3×10^{15} nvt pulsed.

Item 6. *Accelerator Applications*

Radiation effects in materials and components are studied extensively using pulse accelerators. Areas investigated include transient effects in devices and components ranging from photo-current measurements in discrete components to induced electromagnetic pulse effects in circuits and components, and permanent effects in devices caused by such phenomena as trapping of liberated charge carriers at surfaces and interfaces. Use of accelerators in the e-beam mode has made possible studies of the transient thermomechanical response of solids subjected to high-intensity, short-duration energy deposition as well as permanent damage to a material or structure resulting from spall, delamination, and blowoff of surface material.

Item 7. *Diagnostics Development*

Specialized diagnostic tools and techniques have been developed to characterize radiation fields (i.e., neutrons, gamma and x-rays, electrons, and positive ions). This effort has included the development and use of magnetic spectrometers to measure electron and photon spectra, and a specialized device to measure electron spectra on the pulse accelerators. Other techniques used to measure radiation environments are solid-state and photon-recoil spectrometers, active neutron and photon detectors (photodiodes, p-type intrinsic n-type detectors), Compton diodes, scintillator/photomultiplier detectors, fission-couple detectors (foil activation techniques, thermoluminescent detectors, and plastics/glasses). Also included has been the development of calorimetric techniques for e-beam and photon definition, as well as Rogowski coils, B_θ probes, current shunts, and capacitive and resistive voltage dividers to monitor e-beam characteristics.

Item 8. *Gamma Irradiation Facility (GIF)*

The GIF contains two independent shielded cells containing a 10^5 Curie ^{60}Co source and a 2×10^5 Curie ^{137}Cs source. The facility has been used extensively in radiation-effects studies as well as in programs dealing with sterilization techniques for blood, milk, and sewer wastes.

Item 9. *Radiant Heat Facility*

The radiant-heat facility provides a means of conducting controlled high-intensity transient heat input testing of full-scale units by regulating the electrical power fed to radiant-heat emitters. The facility consists of power controller units, power transformers, programmer-computer units, control consoles, data recorders, and heater assemblies. The heater assemblies are infrared heat lamps and graphite radiators in various configurations.

Test space available	500 ft^2
Access door opening	10-ft wide x 12-ft high
Programmed specimen temperature range	200° to 2800°F
Programmed specimen heat-flow range	0 to 500 Btu/ft^2-s
Peak controlled heater power	19,200 kW (20 s)
Minimum rise-time to full power	2 seconds
Output voltages available	2400, 600, 480, 240, 120 V
Explosive limits	Only self-contained HE units allowed

ENVIRONMENTAL SIMULATION

For testing smaller units, a portable radiant-heat cabinet is also available which may be precisely controlled at low power.

Item 10. *Reentry Heating Simulation*

An arc-tunnel facility has been used to generate high temperatures at high heating rates (311 to 811 K/s; 100 to 1000°F/sec) for the evaluation of high-temperature insulation used in advanced reentry vehicles. Performance of the insulation is both time- and temperature-dependent. Insulation samples were sandwiched between a graphite disc 3.18 mm (1/8 inch) thick, heated by the arc jet, and an aluminum disc simulating the reentry vehicle substructure. The complete reentry heating profile was simulated by testing in an argon jet to achieve heating rates encountered during the laminar flow regime; then the jet was switched to nitrogen and the power level increased to simulate transition to turbulent-flow heating rates. Temperatures were measured at the front and back faces of the insulation during the test.

RESEARCH, DEVELOPMENT, AND EVALUATION TESTING

In a number of technical disciplines, test facilities are used concurrently for experimental research, the development of advanced engineering hardware, and design evaluation. Such is the case with facilities used in the aeroscience, material-response, and nondestructive-testing technologies.

Aero Testing

Facilities developed for aerospace testing include wind tunnels, plasma jets, shock tubes, and flight simulators. Full-scale flight vehicles are used to achieve certain test conditions.

Wind Tunnels

Wind tunnels are used to determine aerodynamic characteristics of flight vehicles and to investigate complex flow phenomena. Facilities include a trisonic wind tunnel in which the test section is 30 x 30 cm, and a hypersonic wind tunnel with a test section 45 cm in diameter. Flow Mach numbers of 0.7 to 14.0 can be obtained. Instrumentation includes precision strain-gage balances, pressure transducers, heat-transfer gages, displacement indicators, shadowgraph optics, electron-beam devices and hot-wire probes. Data are recorded and operations controlled by a high-speed data acquisition and control system. (Item 1)*

Current Activities

- Scaled-model tests
  - Force and moment
  - Pressure distribution
  - Heat transfer
  - Flow-field definition
  - Dynamic stability
- Hypersonic boundary-layer studies
- Instrumentation development

Plasmajets

Plasmajet equipment provides conditions of stagnation enthalpy and pressure that simulate the aerothermodynamic environment encountered by reentry vehicles. The Laboratories' 5-megawatt facility can provide total enthalpies from 5 to 50 kJ/g depending upon nozzle, stagnation pressure, and type of arc-heater. Similar enthalpies can be obtained with the 2-megawatt facility; its nozzles are smaller, but maximum stagnation pressure is an order of magnitude greater. (Item 2)

Current Activities

- Material ablation and development tests
  - Nosetip
  - Aft heatshield
  - Antenna windows
- Radio frequency propagation studies
- Flow diagnostics

Shock Tube

Shock tubes are used in molecular laser studies. The 500-kilojoule arc-driven tube can provide shock-wave velocities up to 15 km/s into a 1-Torr test gas. The driven section is 30 cm in diameter by 11 metres long. The driver has an inside bore of 10 cm and a maximum arc length of 77 cm.

Current Activities

- High-temperature chemical kinetics
- Blast-wave physics

Flight Simulators

Analog and hybrid (analog/digital) computer equipment is used to simulate flight characteristics. This equipment can be interfaced to three-axis angular-motion simulators on which hardware is mounted and subjected to the angular velocities and accelerations experienced in flight. (Item 3)

*See Highlights, below.

RESEARCH, DEVELOPMENT, AND EVALUATION TESTING

Current Activities

Six-degree-of-freedom flight simulations
Guidance and control system development
Component testing in real time

Flight Test Vehicles

Special-purpose flight vehicles are developed to complement ground-based facilities in order to achieve certain test conditions. Depending on conditions desired, these vehicles are rocket-boosted, dropped from aircraft, or launched from sleds or guns. (Item 4)

Current Activities

Flight configuration studies
- Stability
- Performance
- Guidance and control

Parachute deployment studies
Boundary-layer transition studies
Reentry vehicle heatshield development
Nosetip-erosion investigations

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Scaled-Model Tests*

Wind-tunnel facilities complement analytical and numerical methods in the determination of aerodynamic forces and moments acting on flight vehicle configurations. Shown in Figure 1 is a high-performance sounding-rocket model installed in the trisonic wind tunnel. Aerodynamic loads imposed upon the model during tunnel operation are measured by a precision strain-gage balance positioned within the model.

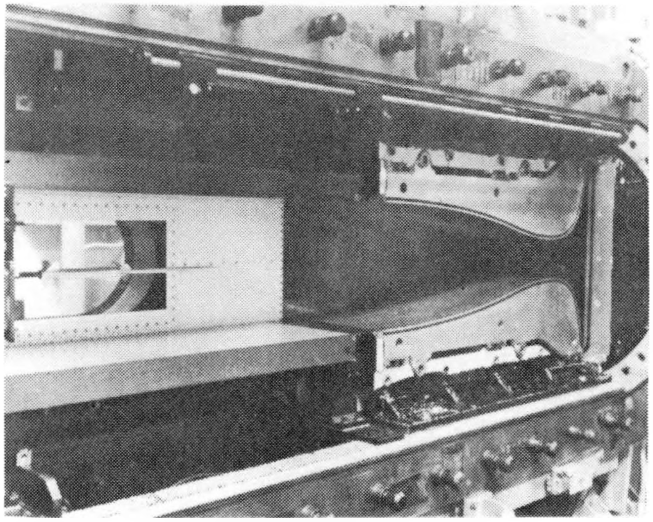


Figure 1. Trisonic wind tunnel

Item 2. *Material Ablation Tests*

An example of ablation testing in the 5-megawatt plasmajet facility is illustrated in Figure 2. In this test, reentry-vehicle nosetip material is subjected to plasma flow with an enthalpy of 45 kJ/g and stagnation pressure of 0.1 atm.

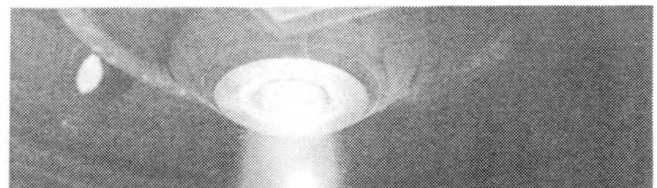


Figure 2. Ablation test in 5-megawatt plasmajet

Item 3. *Flight Control Hardware Testing*

Control systems are designed to provide missile configurations with prescribed maneuvering capability. Before flight, the control hardware package is tested on the Carco three-axis flight-motion simulator as shown in Figure 3. The simulator is driven by an appropriately programmed hybrid computer linked to the control hardware.

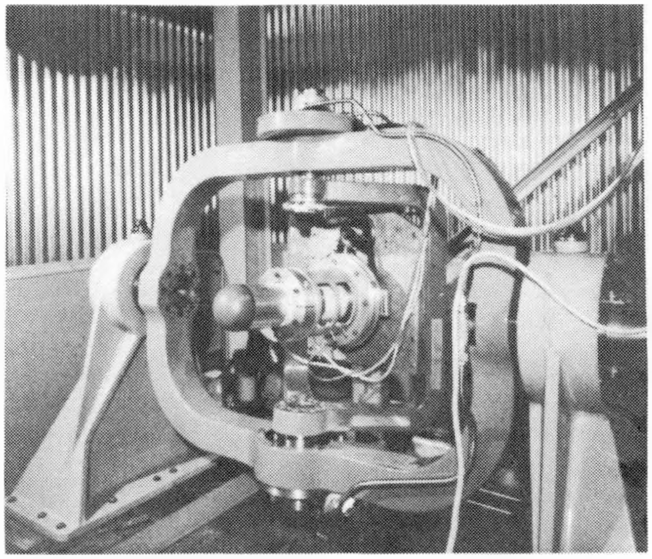


Figure 3. Control system test on motion simulator

Item 4. *Parachute System Proof Tests*

Weapon parachute systems are designed to operate without failure at a dynamic pressure 25 percent greater than the maximum operational level. To proof-test at this condition, rocket-boosted parachute test vehicles are used. The vehicle shown in Figure 4 was designed to test deployment of a 5.2-meter-diameter ribbon parachute at a dynamic pressure of 130,000 newtons per square meter.

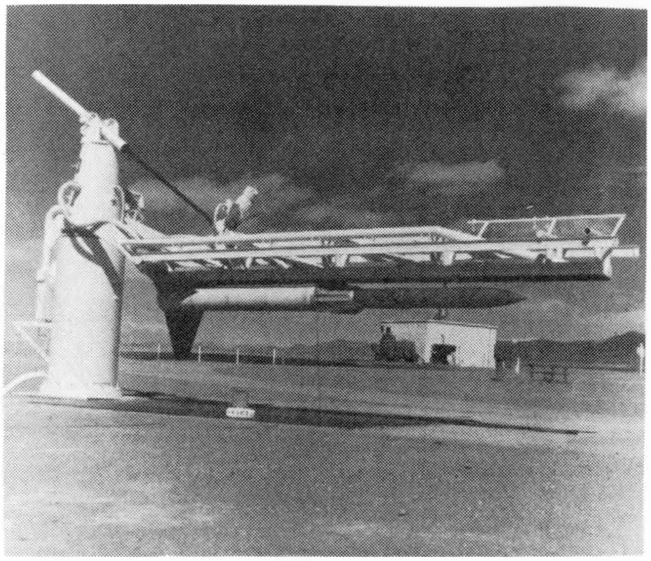


Figure 4. Parachute test vehicle

RESEARCH, DEVELOPMENT, AND EVALUATION TESTING

Material Response

Facilities exist to measure mechanical and thermal response of materials over wide ranges of temperatures, pressures, and loading rates to satisfy the needs of component and structural design evaluation. In addition to conventional mechanical testing including creep, stress relaxation, cyclic fatigue, static loads, and high strain rates over a wide temperature range, specialized test techniques and instrumentation have been developed for high pressures, combined stresses, very high temperatures, and extreme strain rates. Ultrasonic test facilities are used to determine sound velocities to high temperatures and pressures, and to determine accurate dispersion and attenuation curves for very lossy materials. Thermal capacity, diffusivity, and emissivity tests can also be made over a wide temperature range. Special capabilities have been developed to measure material responses at extreme pressures and temperatures using precision high-velocity impacts, high-power pulse lasers, and large pulse electron-beam machines.

Dynamic Mechanical Properties

A plate-impact test has been developed, together with high-resolution instrumentation, to provide quantitative data for material response at the highest strain rates that can be sustained in materials. A variety of compressed-air and propellant-driven gun facilities permits launching of flat flyer plates for planar impact against stationary target plates. Quartz stress gages or laser interferometers capable of nanosecond time resolution allow measurement of the fine structure of loading shock waves and unloading release waves from which dynamic yield strengths, relaxation spectra, polymorphic phase-change kinetics, melting kinetics, high-pressure equations of state, and dynamic spall fracture data are deduced.

A variety of ultrasonic test facilities provides routine sound-speed measurements over wide ranges of temperature and pressure. Both pulse echo and interferometric methods can be used. In addition, facilities have been developed with the wide frequency and high powers necessary to accurately determine dispersion and absorption curves for lossy materials. These have been used successfully with porous materials, polymers, and laminated and fibrous composites. (Items 1,2)*

Current Facilities

Gun driven flyer-plate facilities
- Impact velocities to 5 km/s
- Strain rates to 10^8/s
- Shock pressures to 1.0 TPa
- Shock temperatures to 10^4 K

Ultrasonic facilities
- Low temperatures to 1 K
- High temperatures to 600 K
- Static high pressures to 3 MPa

*See Highlights, below.

Static Mechanical Properties

Facilities have been developed for testing materials under states of combined stress. Static or low-rate tests involving biaxial stresses (via tension or compression, external or internal pressurization, and torque loading of tubular specimens) are applied to materials such as structural metals to determine combined stress-yield surfaces, and to composites to determine combined stress-failure envelopes. Static or low-rate confined compression tests, involving so-called triaxial loading within a static high-pressure vessel, have been applied to measure failure envelopes and strength of rocks. Both biaxial and triaxial machines have computer feedback control, allowing sophisticated programming of loading paths as well as direct computer-controlled data acquisition and reduction. (Item 3)

Current Activities

Biaxial facilities
- 800 kN end load
- 70 MPa pressure
- 8 kN·m torque

Triaxial facilities
- 1.8 MN end load
- 1.0 GPa pressure

RESEARCH, DEVELOPMENT, AND EVALUATION TESTING

Thermal Mechanical Properties

Test capabilities exist for determining all conventional mechanical properties and some unconventional ones. Creep and stress relaxation tests can be made on metals, polymers, ceramics, and composites under controlled temperature and atmosphere environments. Conventional uniaxial stress-strain properties can be obtained at temperatures from that of liquid nitrogen to the melting points of refractory metals. In addition, feedback-controlled, time-dependent thermo-mechanical environments can be applied to electrically conducting materials during which mechanical properties can be obtained as a function of the history of temperature and stress or strain.

Stress-corrosion cracking tests are performed in a variety of environments with controlled humidity and in pressurized liquid. These can also be used in fracture-mechanics studies except for molten salts and pressurized liquids. (Item 4)

Current Facilities

Uniaxial loading facilities
- Load - 800 kN
- Strain rate - 10^{-5} to 10^{2}/s
- Temperatures - 65 to 3000 K
- Pressures - 10^{-6} Pa to 100 MPa

Thermal Properties

Techniques and facilities have been developed for obtaining data on various thermal properties required for system design and application. A major feature of these facilities is their capacity to make rapid measurements on a large number of samples and a wide variety of materials. Current studies involve determining thermal diffusivities, specific heats, and optical properties of molten refractory materials. Studies are also under way on optical and radiative properties.

Current Facilities

- Thermal conductivity
- Thermal diffusivity
- Thermal expansion
- Enthalpy and specific heat
- Optical absorptance, reflection, and transmission
- Total hemispherical emittance

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Interior Ballistics of Two-Stage Light Gas Gun*

Experiments to measure projectile velocity-time histories in a two-stage light gas gun during launch have been made using a Sandia-developed instrument that measures velocity by laser interferometer. Two sample velocity-time histories for identical gun loadings in Figure 1 illustrate the essential features and demonstrate experimental reproducibility. The interferometer is capable of an accuracy with 0.1 percent of the final launch velocity, which in Figure 1 is close to 5 km/s, and a time resolution of 5 μs for the entire launch duration, which in this case was in excess of 2 ms. The inset shows the early portions of the records on an expanded time base, which exhibit discrete steps because of shock reverberation in the propellant gas. Direct measurement of projectile velocity with unusually high accuracy, together with fine time resolution for an extended recording time, has added a valuable new tool for the detailed study of interior ballistics. For example, it is possible to observe projectile failure in the gun tube during launch, and deduce precise conditions under which failure occurs.

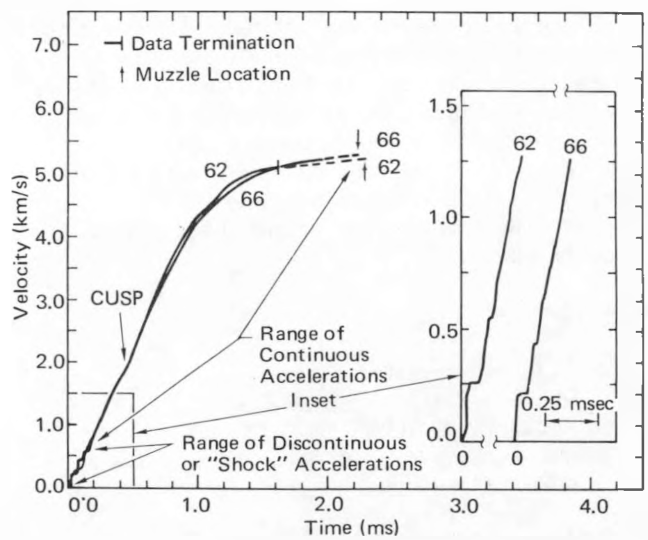


Figure 1. Velocity time histories showing experimental reproducibility

RESEARCH, DEVELOPMENT, AND EVALUATION TESTING

Item 2. *Ultrasonic Measurement System*

An ultrasonic system has been developed at Sandia which measures the velocity and attenuation of an acoustic wave as it travels through a material. The frequency range of the wave may be varied from 0.3 to 5.0 MHz and the temperature of the sample may be varied from -25° to 125°C. This system has proven particularly useful in obtaining low-amplitude, high-strain-rate mechanical characterizations of two classes of materials: (1) those that are viscoelastic in nature and (2) heterogeneous materials whose internal geometry disperses waves as they propagate through the material. For the first class, the system is used in a "direct transmission" configuration to obtain velocity and attenuation data at several discrete frequencies over a wide range of temperatures. Using the principle of time-temperature superposition and standard viscoelastic transformations, these data may be used to obtain a "master curve" viscoelastic characterization of the material. These master curves may take several related forms, the most common being velocity versus frequency and relaxation modulus versus time. A typical example of a velocity master curve is shown in Figure 2 for the solid polymer polymethyl methacrylate. For the second class of materials, the system is used in a "water-bath" configuration to obtain dispersion spectra at constant temperature over a range of frequencies. These data map the first pass band of the material and may, depending on the specific material, map the second pass band as well.

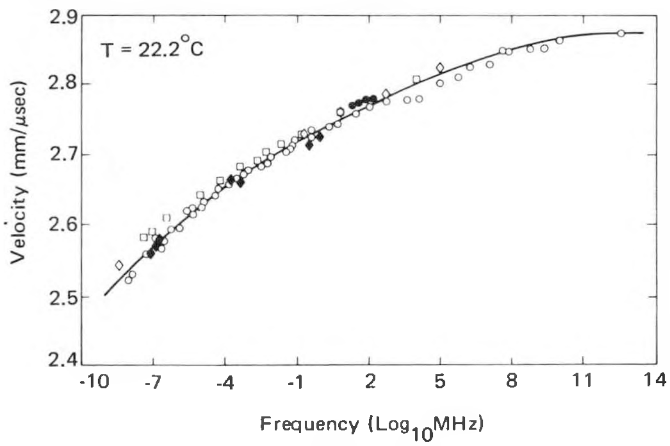


Figure 2. Wave velocity in polymethyl methacrylate as functions of frequency

Item 3. *Triaxial Test Facility*

The computer-controlled triaxial facility is especially adapted for the study of the yield and fracture surfaces of materials with complicated anisotropic constitutive response such as rocks and porous materials (Figure 3). Very rapid response is obtained through a combination of PDP 11/10 computer-activated servo controls and extreme machine stiffness.

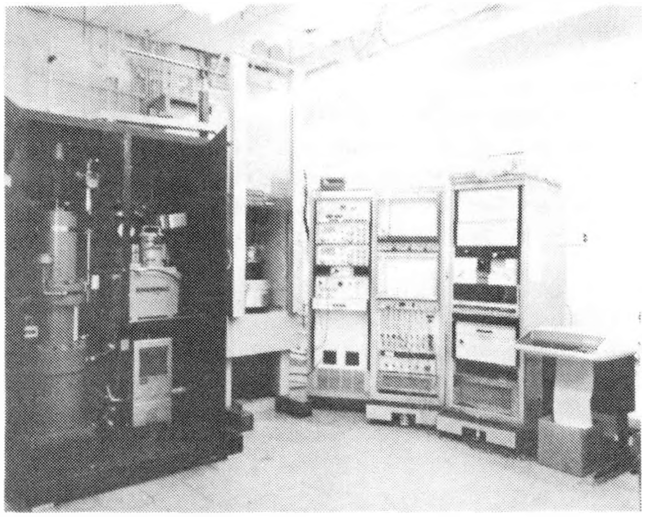


Figure 3. Triaxial test facility

The facility has three pressure vessels (70 MPa, 200 MPa, 1 GPa), each with electrical feedthroughs, an axial loading ram, and a separate pressure-intensifying system. The load frame is rated for 1.78 MN (400 Kip) load, 7.0×10^9 N/m (40×10^6 lb/in.) stiffness, and 2.94 cm/s (1.16 in./s) loading rate.

Two computers are used with the facility for data acquisition and real-time control of test parameters. A PDP 8/1 computer with 64 input channels for analog-to-digital conversion is used when only data acquisition is required. A PDP 11/10 computer is used for real-time control of both pressure and load systems. It has ten channels of analog-to-digital conversion and two high-speed input/output devices.

Both computers output raw test data for transfer over phone lines to a large PDP 10 computer. Data are then reduced with specialized computer codes and plotted on a Tektronic 4010 display terminal. This data management permits data from one test to be reduced and plotted almost simultaneously with the test, so that it can be used on an immediately succeeding test.

Item 4. *High-Temperature Mechanical Properties*

The mechanical properties of graphitic materials at very high temperautres are being determined after the materials have been heated to the desired temperature within a few seconds and at strain rates up to approximately 10 per second. The technique employs self-resistance heating of a tensile or compressive specimen by passing a high electrical current through it in a preprogrammed, feedback-controlled heating cycle and then mechanically loading the specimen monotonically or cyclically through a predetermined stress or deformation history. Load and strain are monitored electronically and optically so that constitutive relations and fundamental deformation mechanisms for arbitrary thermal and mechanical histories can be determined. Transient heating and cyclic loading tests can be used to simulate nuclear reactor transient environments in studying the response of component materials such as cladding, stainless-steel hardware, or pressure-vessel steel.

To prevent thermal conduction along the specimen and into the end grips from producing large temperature gradients in the specimen, the graphite grips are heated separately by RF induction to create "thermal barriers" (Figure 4).

Strain is determined by optically tracking 3 to 5 μm-thick TaC targets sputtered onto specimens that are illuminated by an argon laser. The optical trackers view through narrow-band interference filters to block specimen incandescence. The technique has general applicability for studying the thermomechanical behavior of any conducting material subjected to particular thermal and deformation histories, including cyclic loading, thermal ratcheting, and creep. Graphite sublimation temperatures can be reached in a few seconds under controlled conditions.

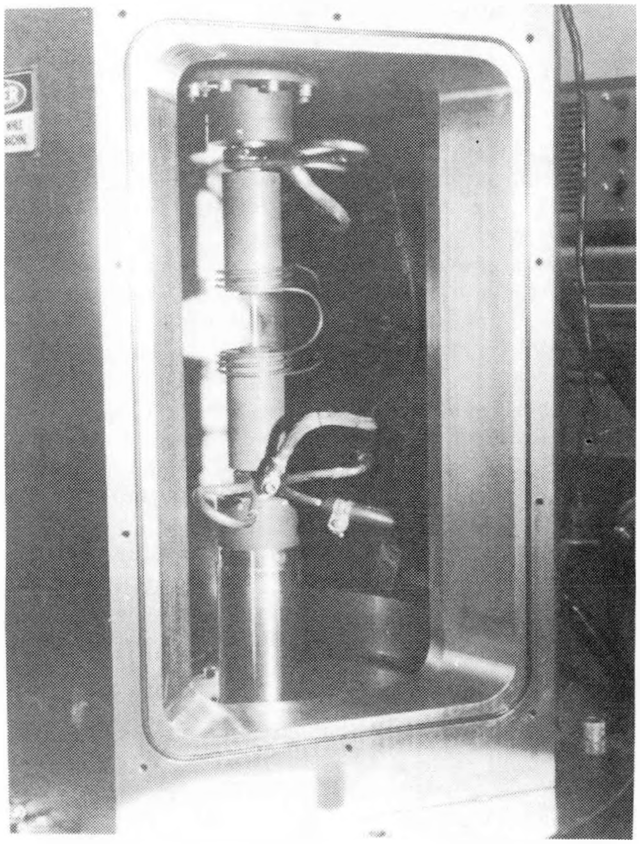


Figure 4. Hign temperature mechanical properties test machine

4

RESEARCH, DEVELOPMENT, AND EVALUATION TESTING

Nondestructive Testing

Nondestructive testing (NDT) methods are used for locating defects and for quality-control purposes, with emphasis given to techniques for characterizing materials and assessing structural integrity. Acoustic emission, neutron radiography, and laser holometry techniques have been developed while the usefulness of older NDT methods such as radiography and ultrasonics has been extended by image enhancement and automated data acquisition and analysis.

Radiation Test Methods

Information on the uniformity of material properties and the location of subsurface defects is provided to materials, component, and structural groups. Radiation test methods are used to interrogate the internal structures of test items. Special techniques such as microradiography, slit radiography, laminography, and infrared microscopic scans are used. (Item 1)*

Current Techniques

- X-radiography (5 kV to 10 MV)
- Isotope gamma radiography (^{60}Co, ^{192}Ir)
- Neutron radiography (pulsed research reactor)
- Radiation gaging (density x thickness -- 10 to 300 kV)
- X-ray Vidicon (fluoroscopy)
- Flash radiography (100 to 600 kV)
- Differential x-ray diffractometry
- Infrared thermography (micro and macro)
- Liquid crystals

Acoustical Test Methods

Ultrasonic, eddy current, and acoustic emission techniques are available to detect flaws and material-property variations. Both manual and computerized data acquisition modes are available to allow complete data analysis. (Items 2,3)

Current Techniques

- Commercial standard and high-energy ultrasonic testing systems interfaced with an interactive data-analysis mini-computer system.
- Commercial and special eddy-current test systems interfaced with mini-computer system
- Multiple-channel triangulation acoustic emission system

*See Highlights below.

Optical Test Methods

Sensitive test methods are used to measure variations in material properties and stress concentrations. Holographic interferometry is used to detect small flaws within the thickness of a material which perturb deformation of the surface of a loaded structure. Small surface perturbations are detected using an automated system-analysis technique involving a low-light-level TV camera. A Fourier transform optical system is used to enhance x-radiographs, and neutron radiographs are used for detecting flaws. (Items 4,5).

Current Techniques

- Automated quantitative holographic interferometry system using continuous-wave and pulsed lasers
- Fourier transform optical system for enhancing radiographs

Other NDT Methods

Special requirements, such as locating discrete surface defects, evaluating weldments, and determining leak rates of hermetically sealed containers, are met by applying NDT methods that do not fall in the classifications cited above. Microscopic surface defects can be imaged using visible and ultraviolet dye penetrants or by spreading magnetic particles on ferromagnetic materials. Leak testing and gas analysis are performed using both commercial and specially designed equipment. Precision leak testing to 10^{-12} cc/s requirements is done using a krypton-85 radioactive gas system. Measurements made with NDT techniques are converted into quantitative form using image-enhancement techniques and digitization methods. Three PDP-11 minicomputers with common interfaces and magnetic tape recording modes have been coupled with such diverse NDT methods as ultrasonics, radiation gaging, eddy current, acoustic emission, and holometry. (Item 6)

RESEARCH, DEVELOPMENT, AND EVALUATION TESTING

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Neutron Radiography*

Neutron radiography has proven to be a valuable NDT method for examining certain classes of materials such as plastics, explosives, and composites. Two types of facilities have been developed to serve the needs of the materials, component, and system groups. One type uses thermalized neutrons from existing research reactors such as the Annular Core Pulsed Reactor, while the other uses a small californium-252 radioisotope which continuously emits large numbers of neutrons and has a half-life of 2-1/2 years. Both types have permitted state-of-the-art resolutions on radiographs of a variety of componentry and have helped to solve design and processing problems undetectable with conventional x-radiography. Neutron radiography has the ability to detect the oil level in an inertial switch. Other applications include the detection of hydrogen embrittlement, density of explosive loadings, and the radiographic imaging of gases such as hydrogen and helium-3.

Item 2. *Acoustic Emission Capabilities in Nondestructive Testing*

Equipment has been developed for locating flaws in small test items by triangulation, which is performed with an 8-channel system that uses a PDP-11 minicomputer for real-time data acquisition, display, and frequency analysis.

Acoustic emission has also been used for studies to determine the switching mode of amorphous semiconductors, for evaluation of rocket-vehicle damage during static qualifying tests, and for pressure-vessel proof tests for safety purposes.

Item 3. *Nondestructive Testing Data-Acquisition, Analysis, and Display Systems*

General-purpose data-acquisition systems based upon PDP-11 minicomputers are used with precision modular fixturing for evaluating test shapes. Test methods include ultrasonic pulse echo, ultrasonic velocity, ultrasonic attenuation, eddy current (surface and through transmission), radiation gaging, acoustic emission, and holographic interferometry. Software exists for such analyses as determining the best position in which to machine a part from a billet, contouring of data, and statistical analysis of data.

Item 4. *Automated Holometry*

Surface deformations are displayed by holographic interferometry, with recorded fringes automated and digitized through interactive controls. Strain calculations can be made rapidly and accurately. The automated system requires the use of a low-light-level camera, a minicomputer, a CRT display, and extensive computer programming. Deformations of simple shapes can be calculated using the minicomputer while more involved calculations are performed on a CDC 6600, since the fringe locations are recorded on IBM-compatible magnetic tape.

Item 5. *Infrared Techniques*

Infrared scanning is applied to both micro- and macro-sized test objects to map thermal contours and to locate discrete defects that reduce component life. The technique is used to scan large objects such as full scale flight vehicles and small objects such as hybrid circuit devices. Automated data-acquisition processes and analytic methods have been developed to allow convenient and meaningful analyses. Unwanted concentrations of heat are located using an infrared microscope and automated scanning table to evaluate heat-sink efficiencies in a hybrid circuit element. Scaled contour plots showing iso-temperature lines are produced on a minicomputer test system that controls power to the hybrid scanning process, and finally calculates and displays the contour lines. Similar operations can be performed on macro-sized objects using a large-scale infrared scanning camera.

Item 6. *Kryptron-85 Leak Detection in Sealed Components*

A leak detector using a diluted radioactive gas (1 to 2 percent ^{85}Kr and nitrogen) measures extremely small leaks (to 10^{-13} cc/s) in hermetically sealed components such as transistors. Components to be tested are placed in a pressure tank which is then sealed, evacuated, and pressurized with diluted ^{85}Kr gas. The radioactive gas diffuses into any existing leaks in the components. After a prescribed "soaking" period, the diluted gas is pumped out of the tank and stored for reuse. Components with leaks retain some radioactive atoms, which emit gamma radiation. Components are inspected with a suitable radiation counter, which indicates leak rates as a function of measured radiation.

FIELD TESTING

Test facilities are maintained in areas appropriate for the kinds of testing to be conducted. The Tonopah Test Range in central Nevada is used for flight and trajectory studies, rocket static tests, hard and soft-target airdrops of weapon systems, and high-altitude rocket and reentry-body studies. The Nevada Test Site in southern Nevada is used by this laboratory primarily for investigating the effects of nuclear detonations on materials, structures, components, and complete weapon systems. Radiation diagnostics, seismic, and ground-motion studies are also conducted. Many nonnuclear tests requiring a controlled environment are conducted at both sites. The Kauai Test Facility on Kauai, Hawaii, uses the Pacific Missile Range and its rocket-launching capability for high-altitude scientific research and reentry-vehicle studies. In addition to fixed-base testing, field-test operations are conducted at other locations around the world because of special environment demands. The testing technologies required to support these worldwide test operations have been translated into a substantial inventory of test support equipment, the nuclei of which are mobile data-acquisition systems consisting primarily of airborne telemetry systems and transportable recording vans capable of recording large amounts of high-frequency data and processing it for analysis.

Tonopah Test Range

This range is operated by Sandia for development and operational tests and evaluations of weapon systems. When not required for ERDA tests, the range is available on a reimbursable basis to other government agencies and defense contractors.

Situated along a series of dry lake beds between two mountain ranges in central Nevada, the range occupies about 625 square miles of controlled area ideally suited for a variety of field-test operations. The range features controlled airspace, physical remoteness, a relatively quiet radio-frequency environment, an atmosphere of low optical reflectivity, and operational versatility.

Facilities

To cope with diversified testing activities, Tonopah Test Range has acquired a large variety of complete facilities, both fixed and mobile. As testing requirements change, facilities are updated and modified to meet new situations. (Items 1-5)*

*See Highlights below.

Current Facilities

- Rocket and missile launch sites
- Guns for acceleration testing
- Precision tracking systems
- Optical data acquisition
- Electronic data acquisition
- Meteorological information
- Data processing
- Photographic services
- Target areas
- Landing field for aircraft
- Recovery equipment

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Rocket and Missile Launching Area*

The Tonopah Test Range (TTR) has complete facilities for handling, storing, assembling, firing and recovering rockets whose aeroballistic performance meets conditions prescribed for range safety. The four launchers available are capable of handling the Honest John, Nike, Strypi and Nike-Tomahawk classes of rockets.

Two blockhouses containing monitoring, checkout, and firing equipment are complemented by remotely located telemetry and precision electronic and optical tracking systems. In addition, a large variety of sequential photographic instrumentation is available to permanently record rocket behavior during certain portions of the trajectory.

Support buildings in the general vicinity of the launchers include three assembly buildings providing secure working areas for test units containing explosives. The explosive working areas conform to all safety standards and include a continuous static monitoring system with automatic alarms. One building is equipped with washdown and containment equipment for use in the event of hazardous material dispersion.

Fourteen bunkers for storage of explosives vary in capacity from 22.7 kilograms (50 lb) to a maximum of 22,680 kilograms (50,000 lb). Approved equipment for transporting and handling explosive and hazardous material is available. Personnel are specially trained in handling such materials.

High-performance/high-altitude (600,000 feet) rockets supporting scientific research in solar-flare and stellar x-ray activity have been launched and recovered. In addition, a high-performance (12,000 ft/s), low altitude (20,000 ft msl) capability has permitted development of the Sandia-designed TATER rocket (12,000 ft/s at apogee) to carry test units associated with reentry-body studies.

Item 2. *Gun Test Facility*

This test facility, consisting of two 155-mm and two 8-inch guns, provides a flexible, low-cost method of conducting acceleration (21,000 x gravity axial) tests of unit and instrumentation hardware. The guns have firing elevation ranges of 0 to 90 degrees. Miniature radio-frequency telemetry systems have been developed that can operate and survive within a projectile during accelerations of up to 21,000 ft/s^2, which corresponds to muzzle velocities in excess of 3000 ft/s. Typically, 155-mm and 8-inch shells are fired at elevation angles of 86 degrees to altitudes in excess of 70,000 ft, at which point a parachute system is deployed to provide soft recovery for test items within the projectile.

Item 3. *Precision Tracking Systems*

Two types of precision tracking systems (radar and Contraves cinetheodolites) are used to acquire position, velocity, acceleration, attitude, and limited event data. The radar network consists of two 1-megawatt, 5400 to 5900 MHz, and two 250-kilowatt, 8500 to 9600 MHz, precision tracking radars. These systems collect trajectory position data for approximately 150 miles along the flight path of test vehicles and provide operational data in real time for range use. Six fixed and three mobile Contraves cinetheodolites form a network to obtain metric photo data. Test-unit elevation and azimuth information is recorded on 35-mm film.

Item 4. *Data Acquisition*

Optical:

Sequential engineering photographic records are obtained by two tracking telescopes designed and built by Sandia. The Newtonian-type telescopes, with prime focal lengths of 298.5 cm, are pivotally supported in azimuth mounts so the telescopes can track in elevation and azimuth. Four of the systems are mobile and can be moved to optimum range locations to improve data quality. The long-focal-length lenses are temperature-corrected and are kept in focus with radar data to provide excellent images of targets at extreme distances.

A small, highly mobile tracking mount, capable of much higher tracking rates, carries a 304.8-mm Newtonian telescope with a focal length of 152 cm. It also features special photographic instrumentation for high-speed impact data. Both the azimuth-elevation tracking telescopes and the impact telescope are kept in focus with radar data and are temperature-corrected.

Electronic:

Three mobile and three fixed radio-frequency (225 to 260 MHz, 1435 to 1540 MHz, 2200 to 2300 MHz) telemetry stations are equipped with various combinations of receiving, display, and recording equipment, with magnetic tape recording responses up to 1.5 MHz. Special telemetry requirements such as operation at frequencies other than those normally assigned to the range can also be accommodated.

FIELD TESTING

Item 5. *Target Areas*

Range topography and soil composition offer range users the choice of several targets with a variety of earth conditions. The string of dry lake beds through the center of the range is the target series used when hard-packed, clay-base soil is desired. Other locations provide sand and sand-clay mixtures, as well as gravel, rocky, or solid-rock impact areas.

There is a circular 1-foot-thick 4000-psi concrete target at the south end of the main lake, surrounded by numerous data-gathering stations designed to provide detailed impact data.

Air-dropped test units vary in shape from twice cigarette-pack size (air-deliverable electronic countermeasures) to ballistic shapes exceeding 12 feet in length. Test-unit velocity has ranged from 2000 to 100 ft/s for parachute-retarded vehicles. Delivery aircraft vary from low-performance propeller-driven types to B-52 jet-bombers with release altitudes between 50 and 55,000 feet above ground level.

Nevada Test Site

The Nevada Test Site was established so that nuclear-weapon development and effects experiments could be conducted in a controlled manner to ensure the safety of both test participants and the public. Sandia has complete access to all its resources and services within established rules, regulations, and practices. The test site is located in southern Nevada in a basin-and-range topographic environment. The operational test areas of the site are located approximately 150 kilometers northwest of Las Vegas, the closest contact with industry, public transportation, and commerce.

Facilities

Administrative headquarters for the overall test site are at Mercury, Nevada, where living quarters, utilities, recreation facilities, warehouse facilities, and administrative offices are located. Sandia maintains permanent facilities in both Mercury and in the forward testing areas to support its field-test operations at the Nevada Test Site. In addition to the fleet of data-acquisition trailers, these facilities include electronics maintenance shops, parts storage, photographic labs, and a complete machine shop. Sandia also maintains facilities in the testing areas where experiments are assembled and checked out. Some assembly areas contain heavy-duty assembly equipment and are supported by a portable machine shop. (Items 1-5)*

*See Highlights below

Current Activities

- Nuclear
  - Radiation diagnostics
  - Ground motion
  - Effects measurements
  - Transducer development
  - Test-bed design
  - High-fluence test technique development
  - Arming and firing
  - Containment studies
  - Containment hardware development
- Nonnuclear
  - Soil pore pressure measurements
  - Structural response measurements
  - Ground motion
  - Hydrofracturing

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Data Acquisition Systems*

In support of underground test programs investigating nuclear effects, Sandia has established a capability to acquire large amounts of high-speed data on a one-time basis at the Nevada Test Site. This capability consists of approximately 500 channels with 1-kHz response and 1000 channels of FM-FM multiplexed magnetic tape recording with frequency response from 20 to 400 kHz. Approximately 300 oscilloscopes are also available. This recording capability is completely mobile in a fleet of approximately two dozen trailers (Figure 1 and Table I). Each recording trailer has its own diesel-powered generators, self-contained environmental systems, programmable control and playback system, and remote operation capability. Fixed-based installations are also used with equivalent recording and playback capabilities.

Sandia is updating its mobile recording capability from analog to digital. The new digital system will be completely programmable by varying the frequency response of the recording channel as a function of time relative to the start of a recording period. Each trailer will be set up to handle from 250 to 500 channels of information with frequency response to approximately 100 MHz. Duration of recording is highly dependent on frequency response.

A mobile downhole TV system involves lowering a 6-inch video camera in a wet or dry hole to depths of 6000 feet in temperatures up to 140°F. Pan and tilt options as well as directional readouts are available. A 4-inch camera is available for depths to 2500 feet.

FIELD TESTING

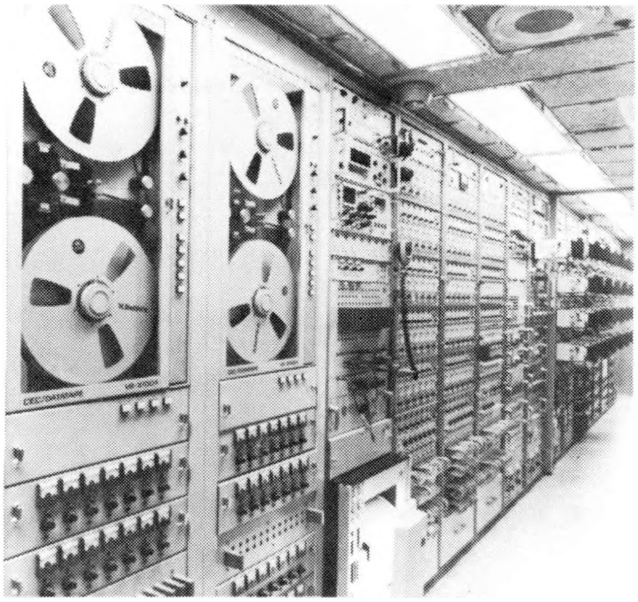


Figure 1. Typical multichannel instrumentation in mobile station for recording of underground test data

TABLE I

Trailer Number	Multiplex Channels Frequency Response (kHz) 1	20	50	500	Oscilloscope Channels Frequency Response (MHz) ≤100	≥100
B-20		72		12	16	
B-21		7		14	18	5
B-22		11	58	12	16	
B-23	100	91				
B-25		91		10	16	
B-38		11	58	12		4
B-51						16
B-61		42		12	15	25
B-62		42		12	27	13
B-63		42		12	20	14
B-69			63	12	21	7
B-72		11	63	12	14	14
L-31		91			17	
L-32		91		12	15	
B-74	96				16	
B-3	96					
B-4	50					
B-17	172					
F-27				10	16	
Totals	514	602	242	142	227	98

Item 2. *Radiation Diagnostics*

Radiation-output diagnostic measurements are made to define the free-field environment of x-rays, gamma rays, and neutrons on nuclear-weapon effects tests. Activities range from the inception of new measurement techniques, through the design, calibration, fielding, data analysis, and reporting of results. Laboratory equipment includes x-ray generators, both direct current and pulsed; counting and recording apparatus and multichannel analyzers; oscilloscopes, power supplies, and optical spectrophotometers.

Item 3. *Effects Measurements*

Measuring the response of a material, a component, or a whole structure during exposure to a nuclear-detonation environment is a prime activity. Typical measurements include temperature, pressure, hydrodynamic shock stress, structural strain, velocity, and acceleration of materials and structures. Special techniques were developed to make measurements in an intense radiation environment. These included modification of the quartz shock-pressure gage, and development of a linear-velocity transducer to measure the momentum imparted to a material by radiation.

Item 4. *Ground-Motion Measurements*

Three components of ground surface motion are routinely measured on selected underground nuclear detonations. The measurements are made from surface ground zero out to distances several times the burial depth of the explosion. Ground shock pressure has been measured with ytterbium and lithium niobate gages from about 3 kilobars to less than 100 bars. Ground motions with peak accelerations between 10^5 and 10^{-2} x gravity and peak velocities between 10^2 and 10^{-3} m/s have been measured.

Item 5. *Test Facility Design*

A nuclear-effects test requires the design and fabrication of an underground facility that must conform to many exacting scientific requirements as well as to severe geo-political regulations requiring complete containment of the environment resulting from the nuclear detonation. Stemming and containment features and experiment-protection systems are designed by using information obtained from ground-motion and radiation diagnostics from previous tests as inputs to one- and two-dimensional hydrodynamic computer codes. Criteria for the design and construction of the test bed are established from the analysis.

Kauai Test Facility

Sandia maintains a permanent test facility at the Pacific Missile Range installation on Kauai, Hawaii, with resources for complete assembly, checkout, and launching of sounding rockets, plus a capability for receiving and playing back telemetry data. Both the Pacific Missile Range and the nearby National Aeronautics and Space Administration installation have facilities for tracking rockets and recording data. The Pacific Range also provides aircraft and ships to recover payloads after some tests.

Test facilities exist for developing and testing high-altitude rocket systems used to study reentry-vehicle characteristics and atmospheric effects caused by nuclear reactions and radiation emissions from stars.

Mobile Testing

Limited numbers of tests that must be conducted at specific global locations are supported by mobile test facilities. Test series of this type have included undersea recovery of a nuclear reactor, Arctic icepack depth measurements, penetration studies using recoilless rifles, rocket launch checkout and undersea recovery, and remote-site rocket launches.

Facilities

The mobile facilities are self-contained and include power, communications, and instrumentation. Instrumentation includes measurement techniques such as geophonics and hydrophonics, seismology, and meteorology equipment; and analytical tools for analyzing thermal and chemical properties. Auxiliary equipment exists to transport personnel and equipment and to operate in severe environments. (Items 1-5)*

*See Highlights below.

Current Facilities

- Data-acquisition systems
- Photographic equipment
- Data-display systems
- Data-evaluation systems
- Hydrophones
- Surveying equipment
- Aircraft position-control equipment
- Communication systems
- Aircraft
- All-terrain vehicles
- Drilling equipment

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Ice-Penetration Studies*

Measurements have been made of the mechanism of penetration into most types of ice by free-falling test vehicles. Operating conditions have included fresh-water ice, annual ice, and multiyear pack ice in the Bering Straits, Beaufort Sea, Baffin Bay, the ice cap north of Greenland, and frozen lakes from sea level to 7000 feet MSL. Aircraft are used to deliver the test vehicles. Telemetry and real-time data analysis is performed on the ground as well as in the drop aircraft. Impact control is provided by an in-house optical system that can be located anywhere that a man can be stationed.

FIELD TESTING

Item 2. *Terradynamic Studies*

The 8- and 12-inch recoilless rifle systems, and closed-breech compressed-air and gun systems, have been fielded in environments from swamps to Rocky Mountain stone for test-vehicle implant measurements. Typically these operations include high-speed photometric measurements of velocity and shock-wave phenomena. Telemetry includes in-barrel and subsurface data to obtain a complete acceleration profile. Prelaunch calibration and near-real-time computer analysis of the data is provided for both time- and frequency-shared telemetry systems. Test-vehicle velocities have ranged from 200 feet per second to Mach 3. Vehicles are recovered after test and the ground is restored to its original condition. Administrative and logistics services provided by the testing organizations include movement, storage, and handling of explosives, real-estate rentals, surveillance radars, geological logging, and life-support systems.

Item 3. *Undersea Nuclear Power Generator Recovery*

A polar-orbit payload launched southward from Vandenberg Air Force Base veered off course shortly after launch and was destroyed. The payload contained a nuclear isotopic power source that had to be located and recovered. Normal naval search systems failed to locate the debris in the Point Conception area. Within 2 weeks, Sandia assembled a hydrophone system with a plotting board similar to that available in a tracking radar station, put it aboard a chartered vessel, controlled a chartered research submarine bottom search, and located the generator for a successful and safe recovery.

Item 4. *Rocket Test Support*

Test support includes airborne and shipboard recording of telemetry, prelaunch calibration of instrumentation systems, near-real-time data analysis, underwater hydrophone measurements, and deep-sea recovery. These types of tests have been performed from the Atlantic to the Caribbean, the Gulf of Mexico, the western US shoreline (San Diego to Vancouver), and to the Pacific to Johnston Atoll.

Item 5. *Major Rocket Systems*

The mobile remote range facilities provide specialized prelaunch calibration and data analysis of payloads for major missile systems, some associated with weapons and others with research in geophysical phenomena. Launches have been made from such remote areas as the southern tip of Brazil and above the Arctic Circle. National range facilities are used whenever possible to supplement Sandia's specialized instrumentation requirements. High-pressure and vacuum-system technologies have been important parts of the calibration systems. Complex time- and frequency-shared RF telemetry systems are involved in most missile tests. The typical telemetry system checkout facility, including computer system, is packaged in a 10 x 40 foot trailer and is valued at about $800,000. When necessary, the trailer is equipped with air-to-ground and ship-to-shore communications for coordination and control of associated aircraft and ship instrumentation.

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Sandia Laboratories Technical Capabilities

Auxiliary Capabilities

Environmental Health
Information Science

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115
and Livermore, California 94550 for the United States Energy Research
and Development Administration under Contract AT(29–1)-789

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SANDIA LABORATORIES TECHNICAL CAPABILITIES

AUXILIARY CAPABILITIES

ENVIRONMENTAL HEALTH
INFORMATION SCIENCE

ABSTRACT

This report characterizes some of the auxiliary capabilities at Sandia Laboratories. These auxiliary capabilities provide essential support to the line organizations.

ENVIRONMENTAL HEALTH

ABSTRACT

This report characterizes the environmental health capabilities at Sandia Laboratories. Selected applications of these capabilities are presented to illustrate the extent to which they can be applied in research and development programs.

ENVIRONMENTAL HEALTH*

The primary responsibility of the environmental health function is the evaluation and control of hazardous materials and conditions. The evaluation and control of toxic materials, nonionizing radiation such as laser beams and microwaves, and ionizing radiation such as from radiation machines and radioactive sources, are examples of the activities of environmental health programs. A chemical laboratory is operated for the analysis of toxic and radioactive substances and for the bioassay program to provide an index of internal exposure of personnel to toxic and radioactive materials. Instrumentation support and development is provided for environmental health activities. A dosimetry program is maintained to measure personnel exposure to external ionizing radiation. A radiation counting laboratory is maintained. Reentry safety control and effluent documentation support are provided for underground nuclear tests at the Nevada Test Site.

Environmental Health Laboratory

Professional Staff	Investment in Equipment (in $1000)
18	$926

*Compiled February 1975

Hazard Control

Programs are aimed at evaluating potential hazards to personnel that may exist in current and proposed research and development activities. Emphasis is placed on maintaining the state of the art in personnel-protection techniques.

Current Activities

- Toxic materials
  - Atmosphere sampling for gaseous and particulate matter
  - Particle-size analysis
  - Toxicity evaluation
- Nonionizing radiation
  - Microwaves
  - Lasers
  - Thermal effects
  - Ultraviolet and infrared light
- Ionizing radiation
  - Electron-beam fusion
  - Laser fusion
  - Radioisotope thermoelectric generators
  - High-energy pulsed x-ray machines
  - Pulsed research reactors
  - Mixed fission-product hot-cell work
  - Plutonium-in-air dispersal studies
  - Shielding calculations
- Noise
  - Industrial
- Sanitation
  - Food service
  - Potable water quality

Analytical Chemistry

Analytical methods are employed to determine qualitatively and quantitatively trace levels of chemical contaminants in air, solids, and liquids. (Item 1)*

Current Activities

- Analytical programs
  - Urine bioassay
  - Air, water, soil, and vegetation samples
  - Trace-metal analysis
  - Proprietary product identification
  - Method development
- Analytical methods
  - Atomic absorption spectrophotometry
  - Emission spectrography
  - Visible, ultraviolet, and infrared spectrophotometry
  - Gas chromatography
  - Fluorimetry
  - X-ray fluorescence spectrometry
  - Liquid scintillation spectrometry
  - Alpha and gamma-ray spectrometry
  - Classical wet chemistry
- Typical analyses
  - Heavy metals
  - Beryllium
  - Organic solvents and compounds
  - Tritium
  - Actinides
  - Fission products
  - Halogens
  - Air pollutants

Radiation Dosimetry

Thermoluminescent dosimeters are employed to quantize beta, gamma, and neutron personnel exposures over wide ranges. The exposed dosimeters are packaged in a way that permits automatic exposure readings, and a computer program is used for data reduction, record keeping, and report generation. It is also possible to measure high dose levels and rates by the use of activation materials such as gold, indium, and copper. (Item 2)

Current Activities

- Thermoluminescent dosimetry
  - Gamma
  - Beta
  - Neutron
- Criticality dosimetry
  - High-level gamma
  - High-level beta
  - High-level neutron
- Applications
  - Personnel
  - Area
  - Device
  - Environment
  - Accident

Instrumentation Development

Health protection equipment has been developed when needed devices were not available commercially. Most development has to do with special ionizing-radiation detection equipment and electronic accessories for laboratory operations. (Items 3-5)

*See Highlights below.

Current Activities

Plutonium-wound counter
Tritium-in-air monitor
Shock-hardened gamma detectors
Multichannel data handling
High-dose-rate nonsaturating detectors
Forward-light-scattering photometer

Radiation Counting Laboratory

A radiation counting laboratory is maintained to routinely investigate radioactive samples with activities in the picocurie range. Both qualitative and quantitative determinations are made. Automated counting systems are available for gross alpha and beta, alpha spectrum, and liquid scintillation counting. Punch tape data in the ASCI II code are generated for computer reduction. Low-background shields are available. (Item 6)

Current Activities

Liquid scintillation
Alpha spectrometer
Beta spectrometer
Gamma spectrometer
X-ray fluorescence
Gross alpha and beta multisample counters
Low-level counting enclosures

Reentry Safety and Effluent Documentation

Experience has been gained in evaluating the extremely hostile environments associated with the underground testing of nuclear devices. Data from instrumentation are used to evaluate several environmental conditions such as high radiation and tunnel failure, to document "source terms" and released amounts of radioisotopes, and to develop procedures for safely reentering and rehabilitating a facility. The capability is available for working in and/or with high radiation-exposure levels, gross contamination, explosive-gas atmospheres, and highly toxic materials. (Refer to Item 1)

Current Activities

High-level radiation contamination
  Surface reentry
  Underground reentry
  Long-term facility rehabilitation
  Decontamination
  Long-line (greater than 1 mile) gas sampling
    and component characterization
Radiation-source term determination
  Gases
  Megacurie activities
Effluent documentation of released gases
Instrumentation hardening and multiple
  remote-readout capabilities

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Remote Gas Sampling*

After an underground test of a nuclear device, the gaseous environment is analyzed for the presence of toxic elements before personnel are allowed to reenter the test area. A system has been devised in which gas samples are drawn from the most distant parts of each side drift and other critical points, and are transmitted through piping to a portable laboratory where they are analyzed by means of a gas chromatograph. Explosive mixtures of flammable gases also have been measured on several occasions.

The long-line sampling system (Figure 1) has been used on 16 test events, during each of which 20 to 30 atmospheric samples were analyzed.

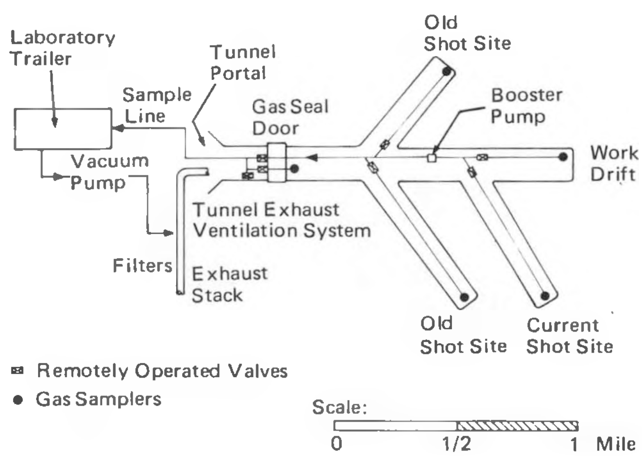

Figure 1. Long-line sampling system

Item 2. *Thermoluminescent Dosimeters (TLD's)*

A continuing radiation dosimetry program has been developed to monitor and document significant personnel exposures to beta, gamma, and/or neutron radiation. The system is based on uniquely identified thermoluminescent dosimeter packages (Figure 2) that can be automatically evaluated and reported in computer-compatible format. The computer reduces the data and performs accounting functions.

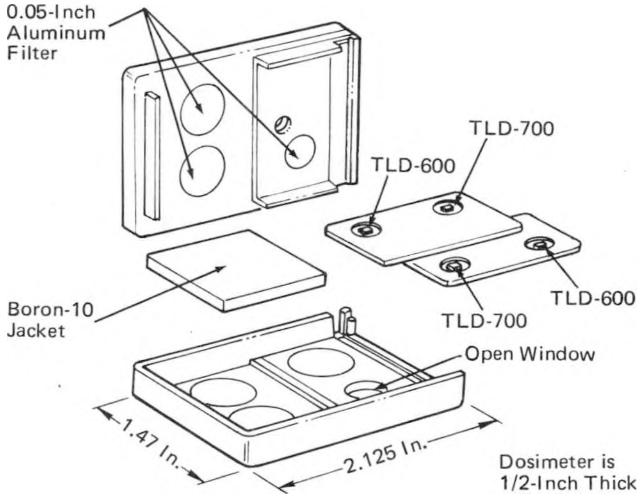

Figure 2. Thermoluminescent dosimeter cards and holder. (TLD-600 dosimeters are neutron- and gamma-sensitive; TLD-700's are gamma-sensitive and neutron-insensitive.)

Item 3. *Shock/Temperature-Hardened Radiation Sensors*

Enclosures housing radiation-detectors and associated cabling have been designed and used to allow placement and long-term survival (of the order of days) of radiation sensors in the near vicinity of underground nuclear detonations. Sensors without this hardening could not survive stresses in the region where tunnel collapse occurs. About 70% of the sensors are now routinely recovered, usually in sufficiently good condition to be used on later tests.

The enclosures are designed to maintain sensor temperature below 65°C for at least 30 minutes in an atmosphere of 300°C and 600 psi.

Item 4. *Pulsed Neutron Detector*

A device was needed that would provide the health physicist a direct measurement in rem (roentgen equivalent, man) of single or multiple short bursts of neutrons. The system developed to answer that need (Figure 3) uses activation of rhodium metal by thermal and epithermal neutrons present at the center of a 10-inch spherical moderator. The resulting beta activity of the rhodium is detected by use of a plastic fluor in intimate contact with the metal.

The detector and its attendant conventional electronics provide a stable pulse-counting system that is semiportable. The equipment has been calibrated with pulses as short as 7×10^{-6} second and has a sensitivity as low as 5×10^{-5} rem. It is used around pulsed research reactors and in neutron-generator tube applications.

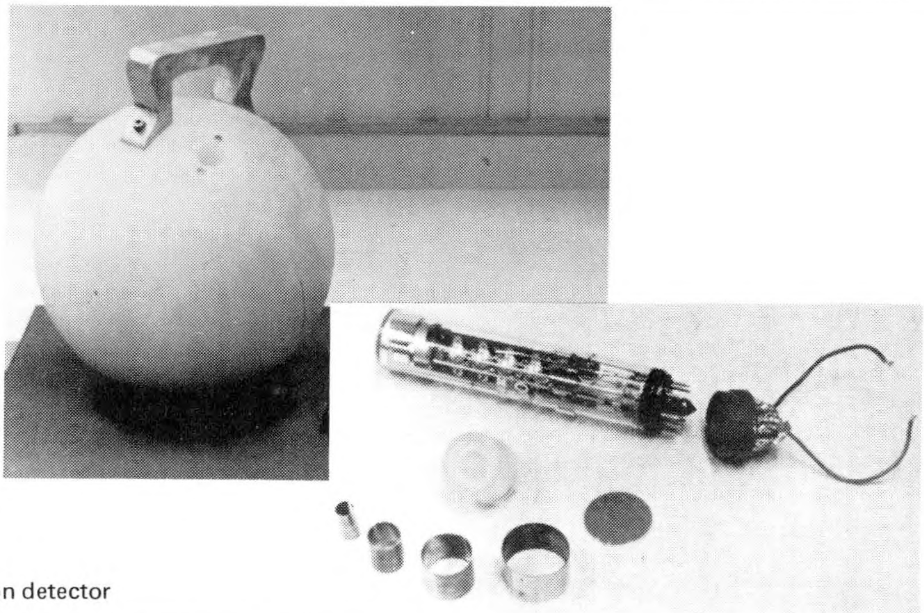

Figure 3. Pulsed neutron detector

Item 5. *Increased Sensitivity for a Forward-Light-Scattering Photometer*

A commercial smoke photometer for testing high-efficiency particulate air filters was improved by Sandia. The photometer was modified to collect forward-scattered light at angles greater than 20 degrees from the center axis, and to reduce stray light at lesser angles. It has been shown that peak intensity is attained at angles greater than 20 degrees (Figure 4).

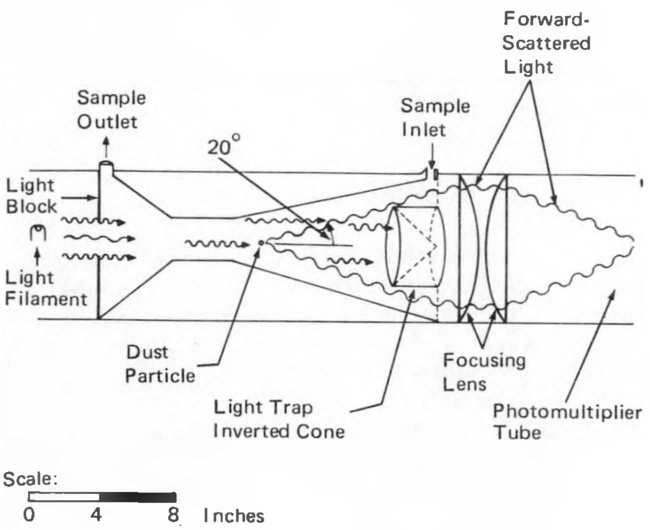

Figure 4. 20-degree angle forward-light-scattering chamber

Item 6. *Automated Alpha Spectrometry System*

Precise alpha spectrometry is normally performed under vacuum, and therefore is not compatible with conventional automated sample changers. A system has been developed that rotates samples into counting position without loss of the vacuum in the counting chamber. Information from the system is processed by multiple single-channel and/or multichannel analyzers with computer data-reduction capabilities.

The system (Figure 5) has a minimum detectability level of 3×10^{-8} μCi.

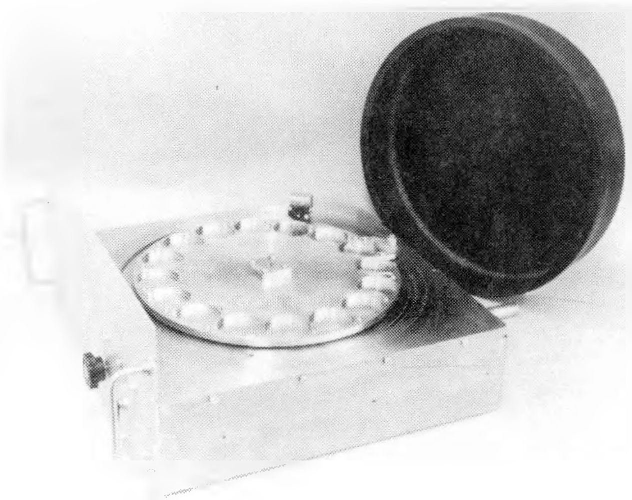

Figure 5. Automated alpha spectrum system

INFORMATION SCIENCE

ABSTRACT

This report characterizes the information science capabilities at Sandia Laboratories. Selected applications of these capabilities are presented to illustrate the extent to which they can be applied in research and development programs.

INFORMATION SCIENCE*

The information science activity functions within the framework of Sandia Laboratories' technical libraries. Information science is oriented toward the efficient dissemination of information to technical and administrative personnel. Computerized systems are used to collect, process, and circulate books, reports, and other literature. Current awareness, reference, translation, and literature-search services are also provided.

Information Science Staff

	Staff	Clerical Support
Computer Management of Materials	5	39
Current Awareness Services	4	2
Reference and Translation Services	6	5

*Compiled May 1975

Computer Management of Materials

The computerized material-management system contains records of all library holdings and generates required processing lists and forms. System programs provide on-line input to and retrieval from the master file, on-line circulation transactions, and batch output of catalogs, inventory lists, overdue notices, purchase orders, claim notices, and special reports. (Items 1,2)*

Current Activities

- Master file maintenance
  - File searching (on-line)
    - Dictionary entry using random access by various keys
    - Boolean search logic
    - Display of complete master file record
  - Input editing (on-line)
    - Format editing of additions and modifications
    - Retrievable output to disk update file
  - File updating (batch)
- Circulation transactions
  - Circulation record searching (on-line)
    - Entry by borrower name or by call number
    - Display of current status
  - Input of current transactions (on-line)

Current Awareness Services

The goal of these services is to bring technical and administrative personnel into contact with elements of current literature that could influence laboratory studies. This is done by means of widely disseminated notifications about the availability of new and pertinent material. The process is called the current awareness service.

Sources for current awareness announcements are new book and report acquisitions, recently published journal articles and conference papers, prepublication notices of journal articles and conference papers, and publication announcements of government reports. Services available include a computerized selective dissemination of information process using individualized interest profiles, and printed library publications (most of them computer-generated). Efforts are made not only to inform the using public of new material but to make this material immediately available. (Item 3)

Current Activities

- Selective dissemination of information
  - User-interest profiles of Boolean keyword combinations
  - Computer matching with any or all data bases
    - Journal articles
    - Library book and report acquisitions
    - ERDA reports
    - DOD reports
  - Search narrowing within fixed subject areas
- Computer-generated publications
  - Library accessions
  - Current journal articles in physics

*See Highlights below.

Reference and Translation Services

Reference services are aimed at providing prompt replies to technical and administrative questions. Toward this end, subject specialists of the reference staff keep abreast of scientific interests by reading technical and progress reports, attending colloquia, and acquiring information from technical personnel. On the basis of this background they select material for the collection, conduct literature searches, prepare formal bibliographies and state-of-the-art surveys, and organize special collections. Reference personnel also function as consultants to groups wishing to organize their own information resources, provide translations of foreign language material, and arrange for interlibrary loans of special material. (Items 4-6)

Current Activities

- Computerized searches
  - ERDA data bases via telecommunications network (RECON)
  - Library book file via teletype console link to Univac-1108
- Specialized data centers
  - Computer-indexed information centers file
  - Service contracts with bibliographic data centers
- Special collections and data bases
  - Environmental projects data base
  - Computer codes data base
  - Energy resource center
  - Terradynamics map file
- Consultation services
  - Referrals to sources of technical expertise
  - Referrals to sources of materials
  - Generation of indexes, manual or computerized
  - Circulation systems, manual or computerized
- Translation services
  - Obtaining foreign-language material
  - Service contracts with translation agencies
  - In-house services
    - Oral reading
    - Foreign correspondence
    - Submissions to foreign-language journals
    - Formal translations

* * * * * * *HIGHLIGHTS* * * * * * *

Item 1. *Operations Overview*

The data in Table I indicate the size and value in dollars of the technical library operation. In an average month the library processes approximately 6800 new items and circulates approximately 6700 items. The computerized material-management system that controls these items is depicted in Figure 1. It integrates all functions previously performed by manual operations.

Item 2. *Input Editing (On-Line)*

To speed processing of new library acquisitions and purchase orders, transactions against the master file are processed daily. The input of new data to the master file takes place in two stages: on-line keying to a disk file followed by batch-mode updating of the master file. Items in the temporary disk file may be retrieved at any time until the batch update takes place. This description deals with the on-line editing portion.

Input procedures are of two types: addition of a new family of records for a new title, or modification (or deletion) of records for a title already in the master file. Input of new records or changes to existing records may be made in any sequence; records that pass the edit stage are sorted for placement in the update file on disk.

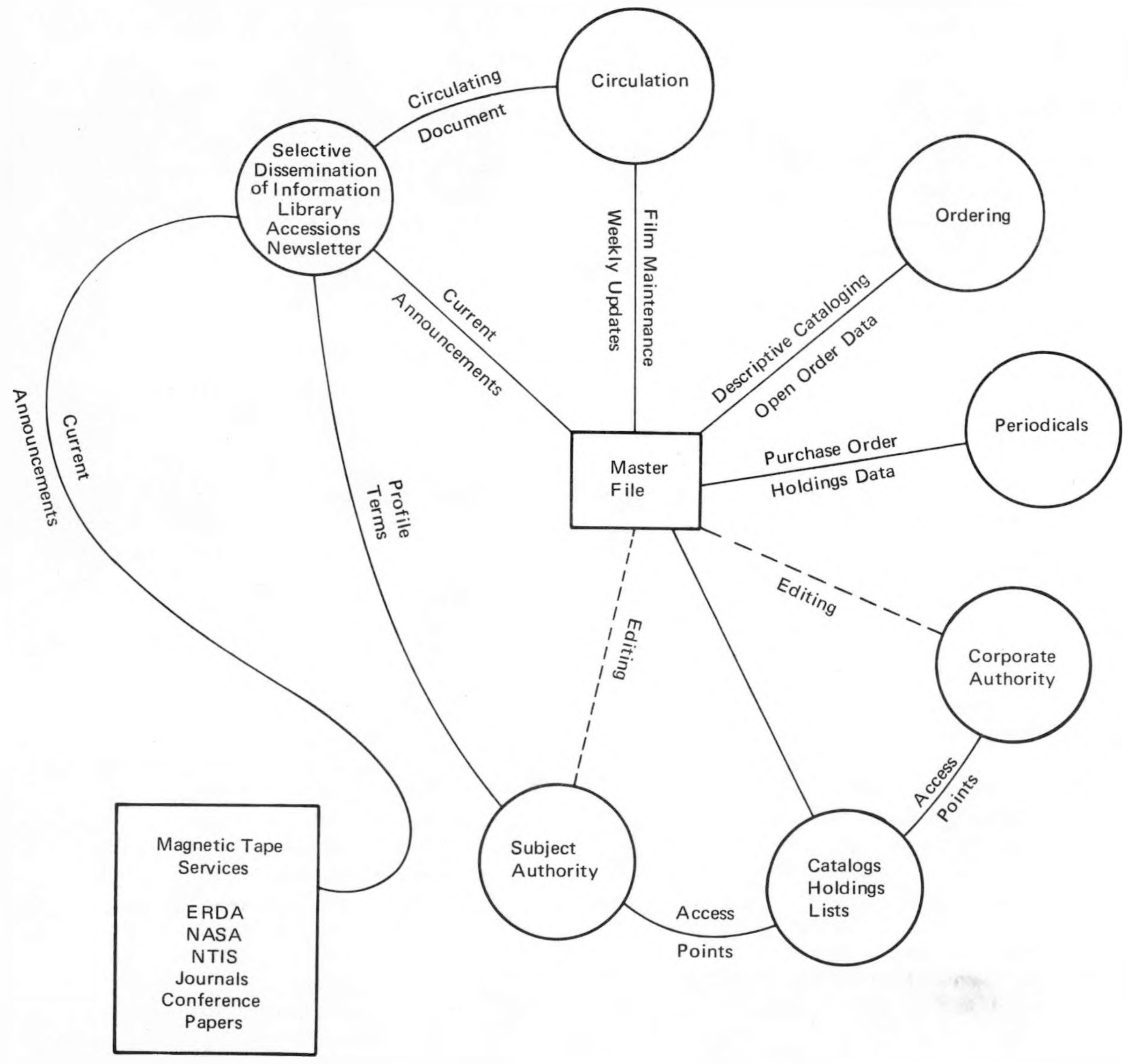

Figure 1. Integrated Livermore/Albuquerque library system

TABLE I

Collection Size and Value, Equipment Investment, and Service Contracts

Collection	Size	Approximate Value	Equipment (excluding facilities, furniture, and shelving)		Service Contracts	
Books:	47,000	$587,500	Microform readers:	$ 34,300	Computer tape services (annual):	$14,000
Paper reports:	119,000	$450,500	Microform storage:	$ 18,000	Bibliographic search services (annual):	$ 5,000
Microfiche reports:	420,000	$870,000	Computer terminals:	$ 17,000	Translation services (annual)	$ 1,000
Periodical volumes:	34,000	$800,000	Computer time (annual):	$120,000		
Periodical subscriptions:	2,000					
Periodical microfilm		$ 60,000				
Titles:	220					
Reels:	3,700					

Data in each line or field should contain specific types of information, depending on the line number or field position. This information is machine edited before the record is released to sorting. For example, in the call-number field, each position of the number is checked to see whether it is alphabetic, numeric, or a dash, depending on the position. Any character that does not conform in type to that expected for the position is referenced with an asterisk. The incorrect entry with underscoring is displayed on the on-line terminal as shown in Figure 2, and will only be released to the disk file after appropriate corrections have been made.

Item 3. *Selective Dissemination of Information Algorithm*

Individualized current awareness announcements are generated weekly by computer to inform recipients about new books, reports, conference papers, and journal articles that match their interest profiles. These profiles consist of Boolean combinations of subject categories, authors, and keywords. The term-matching algorithm developed for this Selective Dissemination of Information (SDI) system depends on enumeration of the profile terms into 8-character numeric strings. The Boolean "or" operation is defined by terms enumerated into the same 8-character string. Boolean "and" (or "not") combinations of the profile terms are represented by 8-character composites. An example is given in Figure 3.

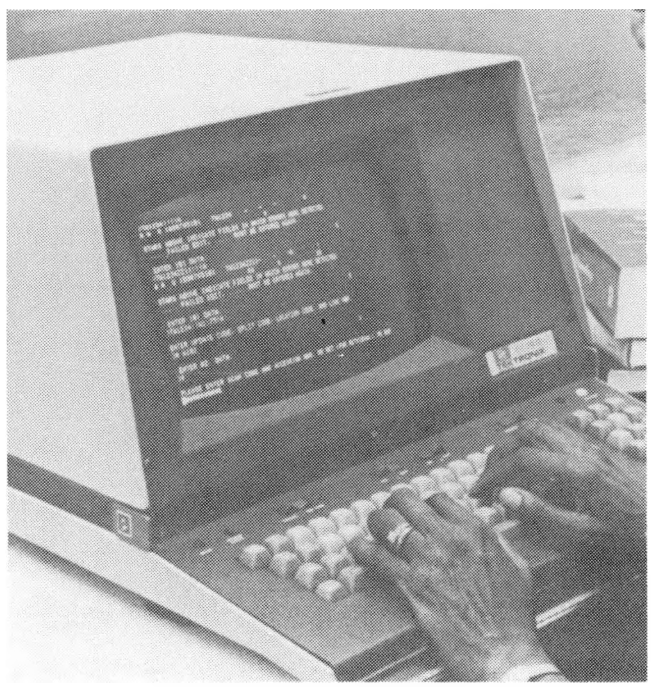

Figure 2. On-line modification of data files

Terms	Enumerated Terms	Boolean Combinations
Fracture	20000000	21200000
Steel	01000000	
Embrittlement	20000000	
Hydrogen	00200000	
Jones JP	30000000	31200000
Alloys	01200000	
Metallurgy	01200000	
Corrosion	90000000	90000000

Combination 21200000 = (Fracture or Embrittlement) and (Steel and Hydrogen) or (Fracture or Embrittlement) and (Alloys or Metallurgy)

Combination 31200000 = Jones JP and (Alloys or Metallurgy) or Jones JP and (Steel and Hydrogen)

Figure 3. Example of machine representation of Boolean combinations of Selective Dissemination of Information profile terms

At the time this computer program is run the SDI profiles containing alphanumeric terms, the enumerated value of these terms, and the enumerated Boolean combinations are processed against one of the SDI data bases. As each record or group of records representing a particular book, report, or journal citation is read in, the alphanumeric profile terms are matched against corresponding terms in the appropriate field (title word, author, etc.). If matches are found, the enumerated strings representing those terms are flagged. Then each character in the first Boolean pattern is matched against "ored" flagged strings. If every character in the pattern can be found in its designated location in the first flagged string, the citation is output as a "hit." If not, the next Boolean pattern is tried until all are exhausted. This algorithm allows both complex and simple Boolean combinations to be represented in just a few 8-character patterns. Highly specific or broadly general interest profiles can be written with facility.

Item 4. *Computerized Searches (On-Line)*

On-line searching of computerized data banks allows technical personnel and the library staff to compile bibliographies or locate single citations in a fraction of the time needed with manual methods. The library has two on-line retrospective search systems: the RECON system sponsored by ERDA, and the ASTORS* system. ASTORS is a user interactive program written in COBOL, and it makes use of the Index-Sequential/Random-Access capability. It uses two disk data files: an alphanumeric dictionary file that contains 304,000 records, each consisting of a search key and a master file entry number, and the master book file, which contains 393,000 records representing 39,000 book titles. The search keys available are author name, subject term, title word, and Library of Congress classification number.

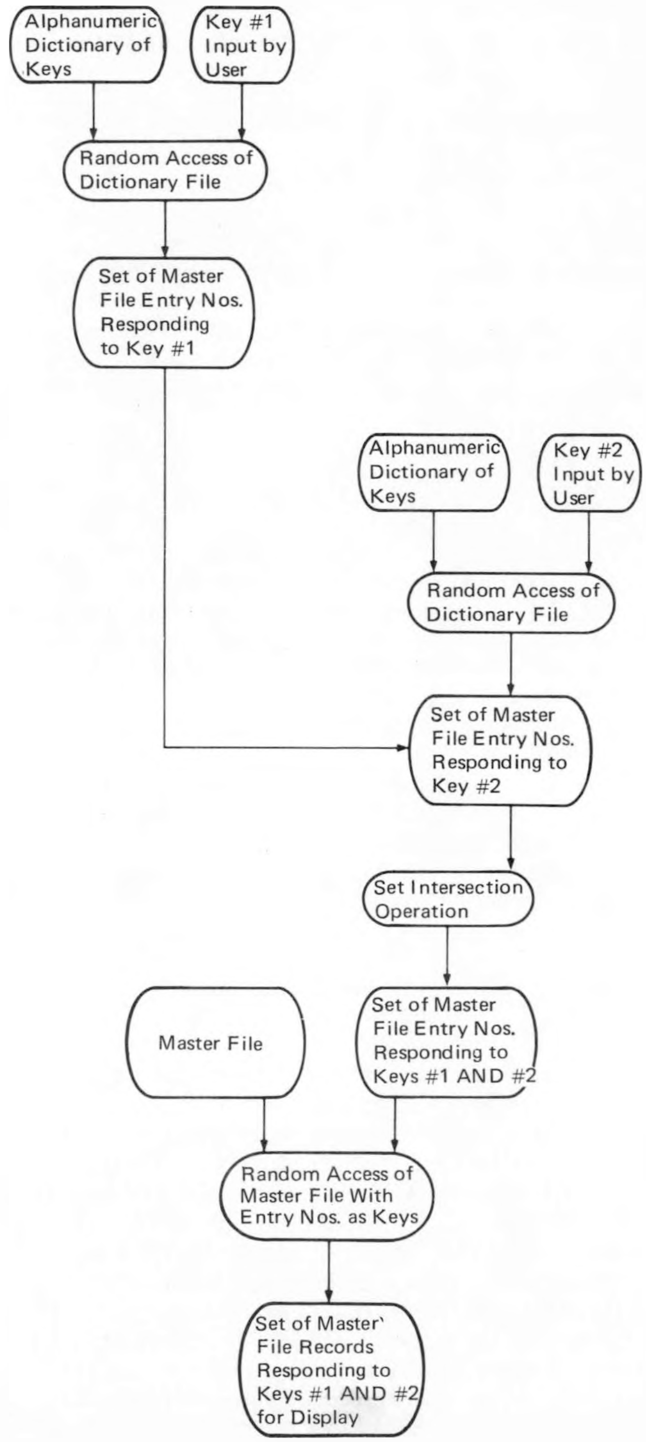

Figure 4. Illustration of ASTORS search with Boolean "and" condition

*Author-subject-title on-line retrieval system.

The chief advantage of the system is the rapid retrieval of book titles that fit user criteria. This is accomplished through Boolean search statements that combine search keys to eliminate all but the desired titles. For example, there may be 500 titles indexed by the term METALS and 200 by the term FRACTURE, but only 20 titles indexed by both these terms. Response to search requests is immediate (< 1 second). The flow diagram in Figure 4 depicts the program logic for a search using a Boolean AND statement.

Item 5. *Terradynamics Map File*

The library's reference group organized a data file for the study of Terradynamics; i.e., phenomena attendant upon earth penetration by high-velocity projectiles. Detailed maps (in 8,000 sheets) of the geology, soils, and topography of 27 Eurasian countries were selected, acquired, classified, and catalogued in the library's master file. Coding permits the extraction of a specialized, computer-generated index of countries, subject words, title words, publishers, and authors. The map files are managed and maintained by the Terradynamics organization, while the Reference group follows the state of knowledge and provides continuing selection of new materials.

Item 6. *Energy Resource Center*

The reference staff has organized a special collection of energy-related materials designed to provide background and current information to technical personnel. The collection contains basic bibliographies, current newsletters, an archive of journal articles, and a display of new library acquisitions.

A weekly-published Library News Bulletin announces new receivals and journal articles in the energy field. A computer-generated keyword index to items announced in the bulletin provides a bibliographic tool for retrieving items in the rapidly growing energy collection. A sample page from this index is shown in Figure 6.

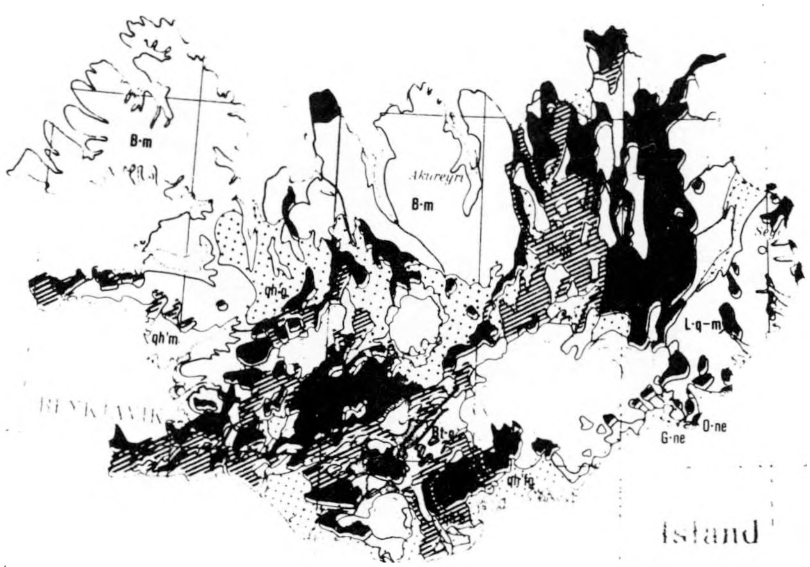

Figure 5. The Iceland section of a geologic map of Europe

Sandia Laborat

NEWS BULLETIN INDEX 05/06/75

LAND-USE	> 750120B	SEISMIC HAZARDS AND LAND-USE PLANNING
LARGE-SCALE	> 750210J	UTILITIES EYE LARGE-SCALE ENERGY STORAGE
LASER	> 750326J	NUCL : LONDON CONFERENCE HEARS OPTIMISTIC TALK ABOUT LASER ENRICHMENT
	> 750312J	NUCL : ERDA AWARDS A $350,000 LASER FUSION CONTRACT TO KMS
	> 750106J	LASER FUSION : ONE MILEPOST PASSED - MILLIONS MORE TO GO
	> 750120J	POSSIBILITY OF CONSTRUCTION OF A HIGH-POWER LASER UTILIZING AMPLIFICATION OF DIVERGING LIGHT BEAMS
LEVEL	> 750305R	MANAGEMENT OF COMMERCIAL HIGH LEVEL AND TRANS - URANIUM CONTAMINATED RADIOACTIVE WASTES
LIGHT	> 750120J	POSSIBILITY OF CONSTRUCTION OF A HIGH-POWER LASER UTILIZING AMPLIFICATION OF DIVERGING LIGHT BEAMS
LIMITATION	> 750203J	STRATEGIC ARMS LIMITATION I : THE DECADES OF FRUSTRATION
LIQUEFACTION	> 750203B	COAL GASIFICATION AND LIQUEFACTION SYMPOSIUM , UNIVERSITY OF PITTSBURGH , PITTSBURGH , PENN. , AUG
LIQUID	> 750326R	PROPOSED FINAL ENVIRONMENTAL STATEMENT : LIQUID METAL FAST BREEDER REACTOR PROGRAM
LMFBR	> 750127J	THE LMFBR : THE ONLY ANSWER
LOAD	> 750219J	SOLAR HEAT GAIN THROUGH WALLS AND ROOFS FOR COOLING LOAD CALCULATIONS
	> 750312J	SOLA : SOLAR HEAT GAIN THROUGH WALLS AND ROOFS FOR COOLING LOAD CALCULATIONS
LOCK	> 750210B	LOCK SECURITY
LOG	> 750219J	EVALUATING OIL SHALE BY LOG ANALYSIS
LONDON	> 750326J	NUCL : LONDON CONFERENCE HEARS OPTIMISTIC TALK ABOUT LASER ENRICHMENT
LOOK	> 750319J	NATU : FOUR CORNERS RATES ANOTHER LOOK
	> 750113J	PROJECT INDEPENDENCE : A CRITICAL LOOK
	> 750106J	TAKE A LOOK AT THE FIRST
LOS	> 750312R	THE REGIONAL IMPACTS OF NEAR - TERM TRANSPORTATION ALTERNATIVES : A CASE STUDY OF LOS ANGELES
MACERALS	> 750210J	CHEMICAL STRUCTURE AND PROPERTIES OF COAL XXII - BEHAVIOR OF INDIVIDUAL MACERALS AND BLENDS IN THE
MAGMA	> 750120R	HEAT EXTRACTION FROM A MAGMA RESERVOIR
MANAGEMENT	> 750305R	MANAGEMENT OF COMMERCIAL HIGH LEVEL AND TRANS - URANIUM CONTAMINATED RADIOACTIVE WASTES
	> 750305J	WAST : RISK ANALYSIS OF NUCLEAR WASTE MANAGEMENT SYSTEMS
MANDATORY	> 750113J	MANDATORY CONSERVATION COMING SOON IN THE U.S.
MANTLE	> 750319J	GENE : THE EARTH'S MANTLE
MARKETS	> 750120B	COAL-ASSOCIATED MINERALS OF THE UNITED STATES , PART 6 : WESTERNCOAL-ASSOCIATED MINERAL OCCURRENCE
MATE	>	MATE MATERIALS-RECYCLING
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	> 750210R	PROCEEDINGS OF THE 4TH INTERNATIONAL SYMPOSIUM ON PACKAGING AND TRANSPORTATION OF RADIOACTIVE MATE
	> 750210B	CRITICAL IMPORTED MATERIALS . A SPECIAL REPORT OF THE COUNCIL ON INTERNATIONAL ECONOMIC POLICY
MATERIALS-RE	>	MATE MATERIALS-RECYCLING
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MAXIMUM	> 750226R	AN ELECTRICAL SYSTEM FOR EXTRACTING MAXIMUM POWER FROM THE WIND
MEANS	> 750219J	FEASIBILITY AND ECONOMICS OF CONDITIONING RECIRCULATED GREENHOUSE AIR BY MEANS OF EVAPORATIVE COOL
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MECHANISMS	> 750210J	SOME ARTICLES ON COAL MECHANISMS OF COAL PYROLYSIS ONE - ON THENATURE AND KINETICS OF DEVOLATILIZ
MEDIATOR	> 750305J	HYDR : HYDROGEN : A FUTURE ENERGY MEDIATOR :
MEDIUM	> 750305J	GENE : NUCLEAR FORCES FOR MEDIUM POWERS . PARTS 2 AND 3 : STRATEGIC REQUIREMENTS AND OPTIONS
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MESA	> 750127J	MINING COAL ON BLACK MESA
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MEXICO	> 750203J	POSSIBLE DIVERSION OF MISSISSIPPI RIVER WATER TO TEXAS AND NEW MEXICO
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MICROSCOPE	> 750219J	ERTS PUTS THE WHOLE EARTH UNDER A MICROSCOPE

Figure 6. News Bulletin weekly index for energy logics