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Sandia Laboratories Technical Capabilities:

Engineering Analysis

Sandia Laboratories

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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.

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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
Computation Systems	SAND74-0080	Physical Sciences	SAND74-0074
Design Definition and Fabrication	SAND74-0084	Safety and Reliability Assurance	SAND74-0090
Earth Sciences	SAND74-0085	Systems Analysis	SAND74-0089
Electronics	SAND74-0086	Testing	SAND74-0088
Engineering Analysis	SAND74-0087	Auxiliary Capabilities: Environmental Health, Information Sciences	SAND74-0082
Explosives, Electrochemistry, and Electromechanisms	SAND74-0081		

Compilation of
Sandia Laboratories Technical Capabilities
(SAND74-0092)

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
Professional Staff and Investment in Equipment

	Professional Staff	Investment in Equipment (in $1000)
Structural Mechanics	50	
Stress Wave Analysis	27	20
Explosives Analysis	5	-
Heat Transfer	46	100
Aerospace Engineering	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.

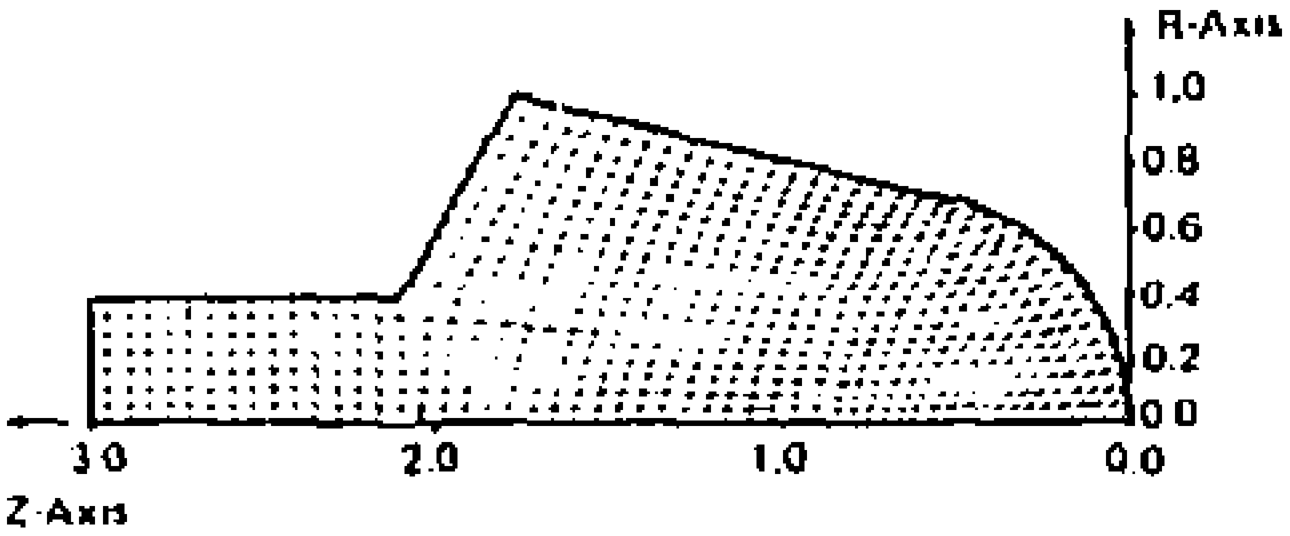

Figure 1 A finite-element mesh idealization of a graphite reentry-vehicle nosetip.

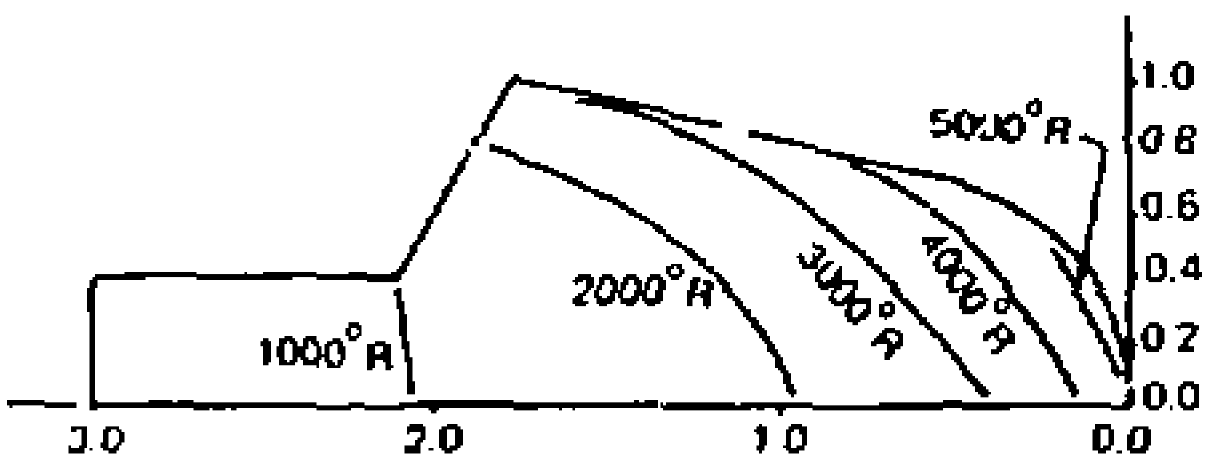

Figure 2. Thermal contours at a point in reentry.

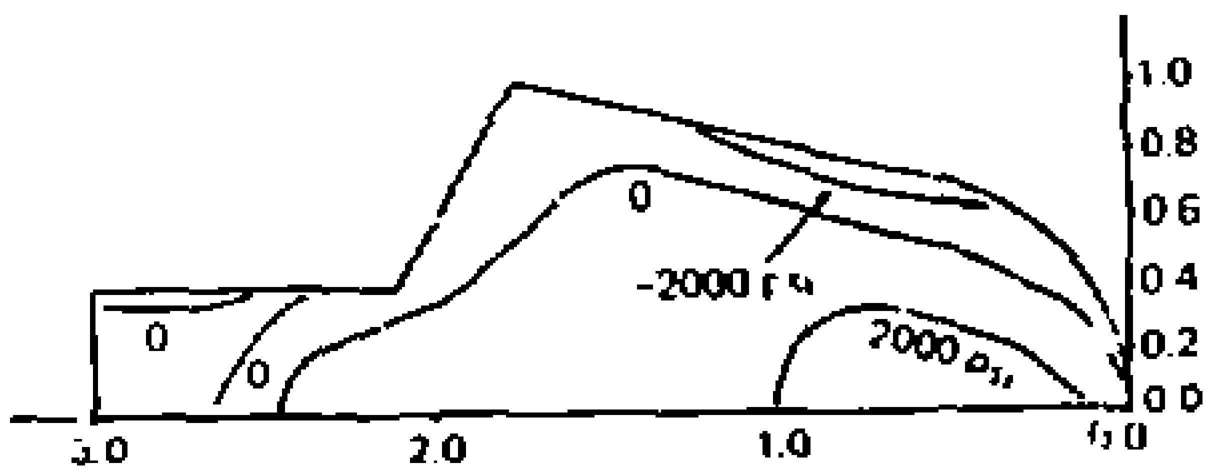

Figure 3. Thermal stresses that result from the temperatures of Figure 2.

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.

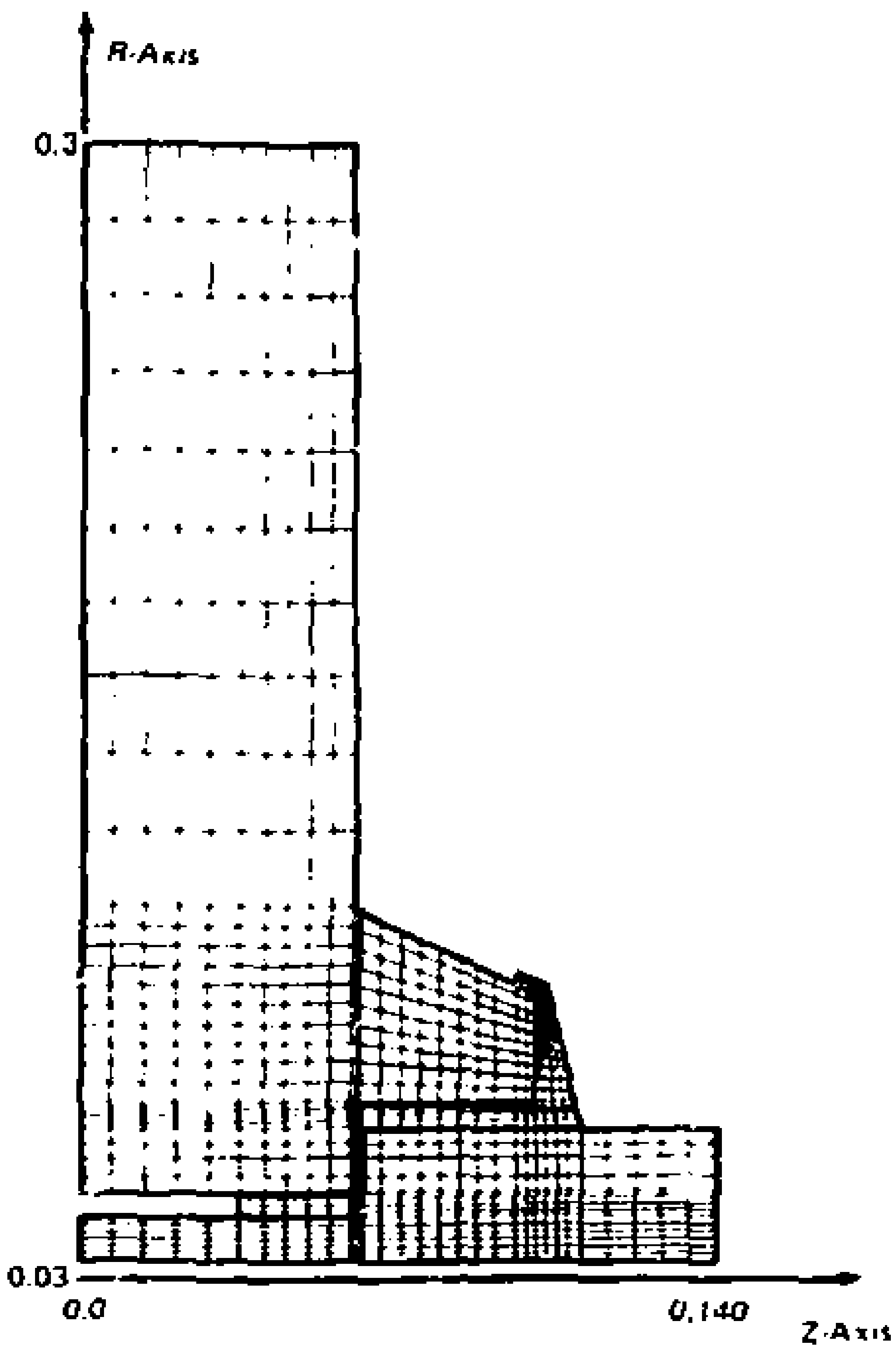

Figure 4. A finite-element mesh idealization of a ceramic-to-metal seal in a ceramic vacuum tube.

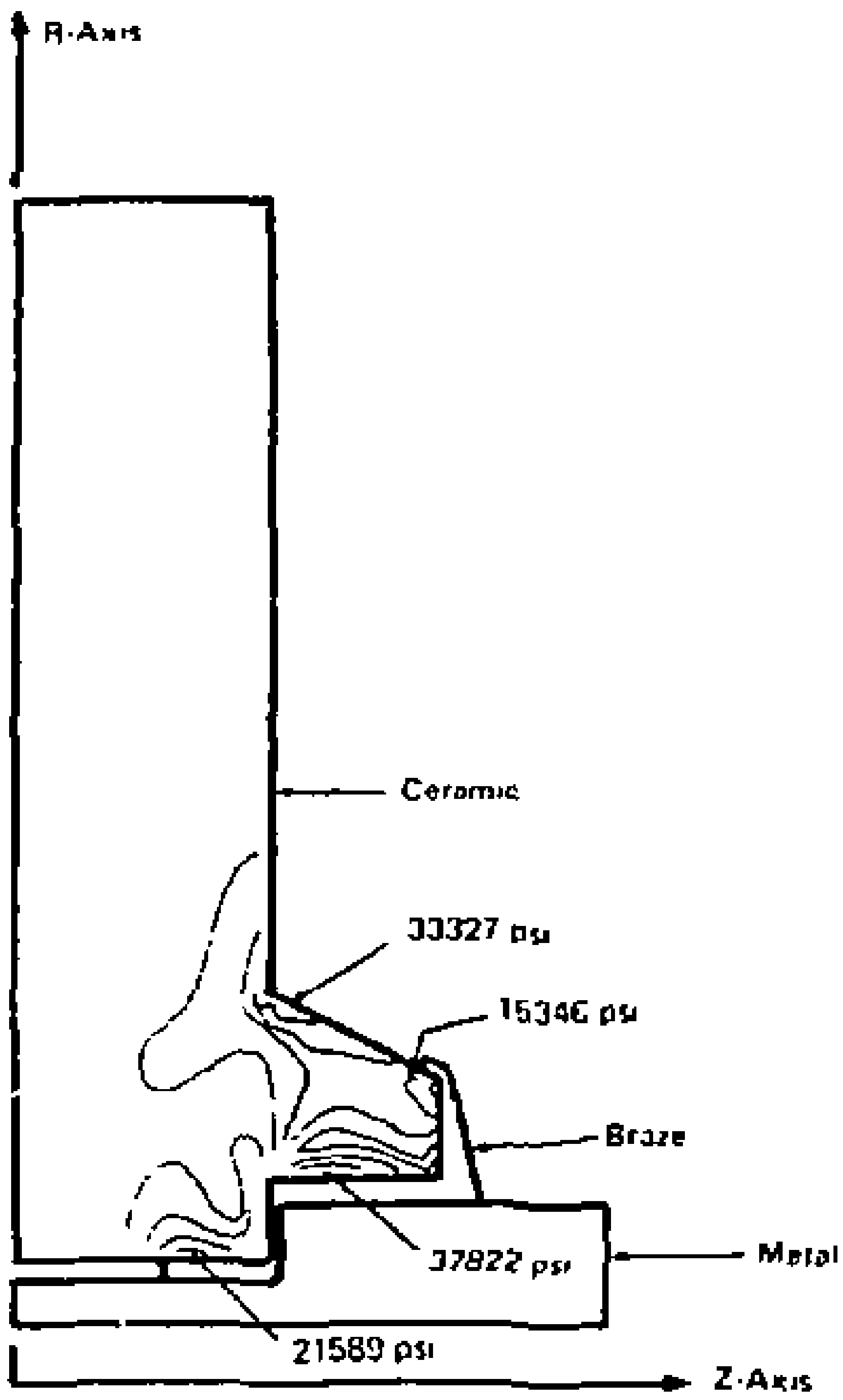

Figure 5. Maximum principal stress contours in the ceramic arising from the brazing operation used to seal the ceramic to the central metal tube.

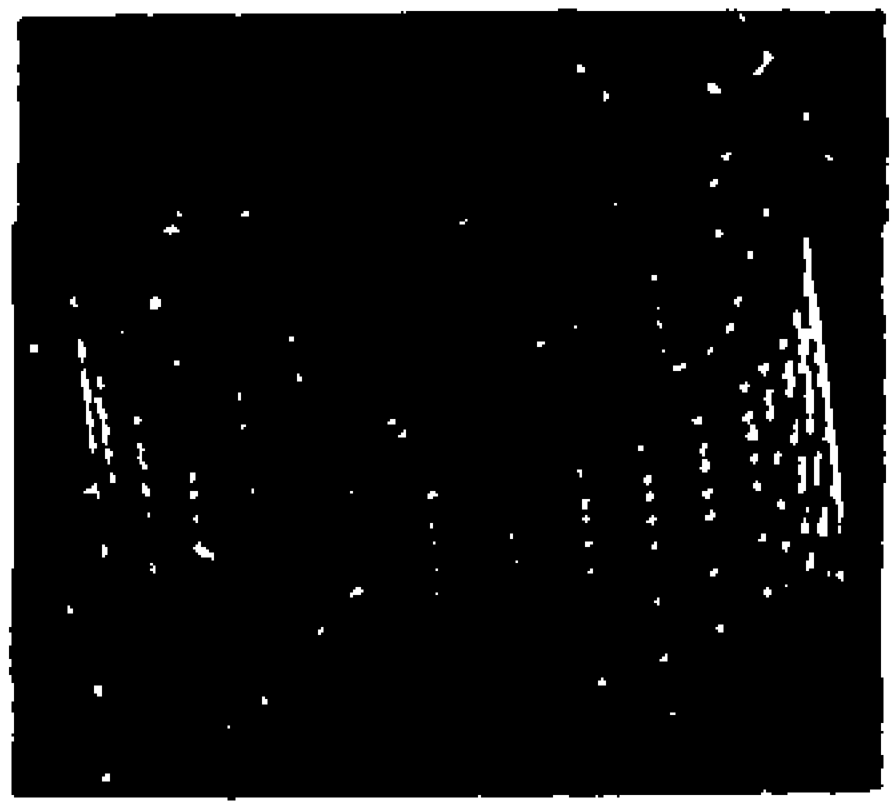

Figure 6. A three-dimensional finite-element mesh idealization of an encapsulated electrical component.

Figure 7. Deformed shape of the mesh on a plane through the structure.

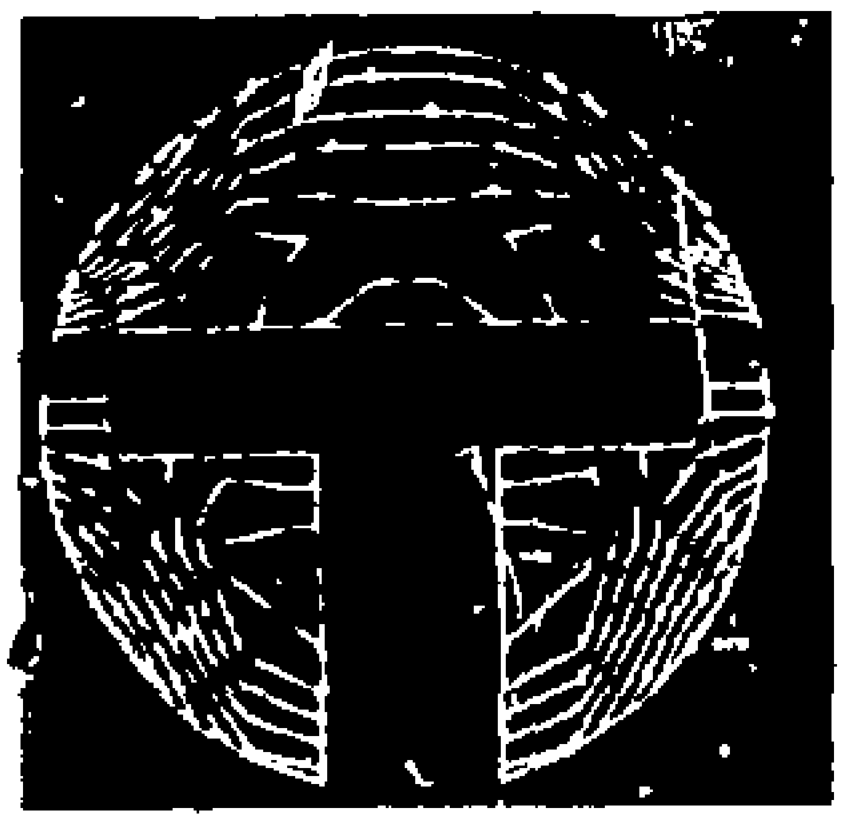

Figure 8. Maximum principal stress contours on a plane through the structure.

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.

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.

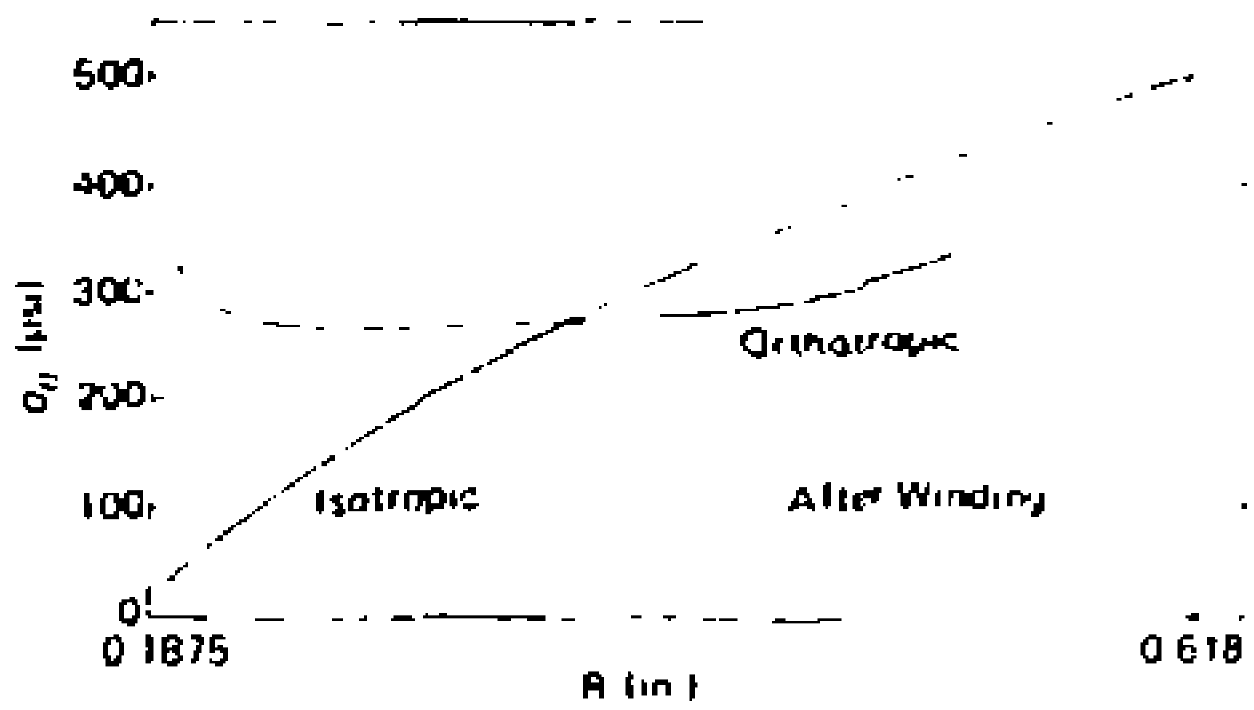

Figure 9. Circumferential stresses in the dielectric material of a wound capacitor with and without orthotropic effects, as a function of capacitor radius.

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.

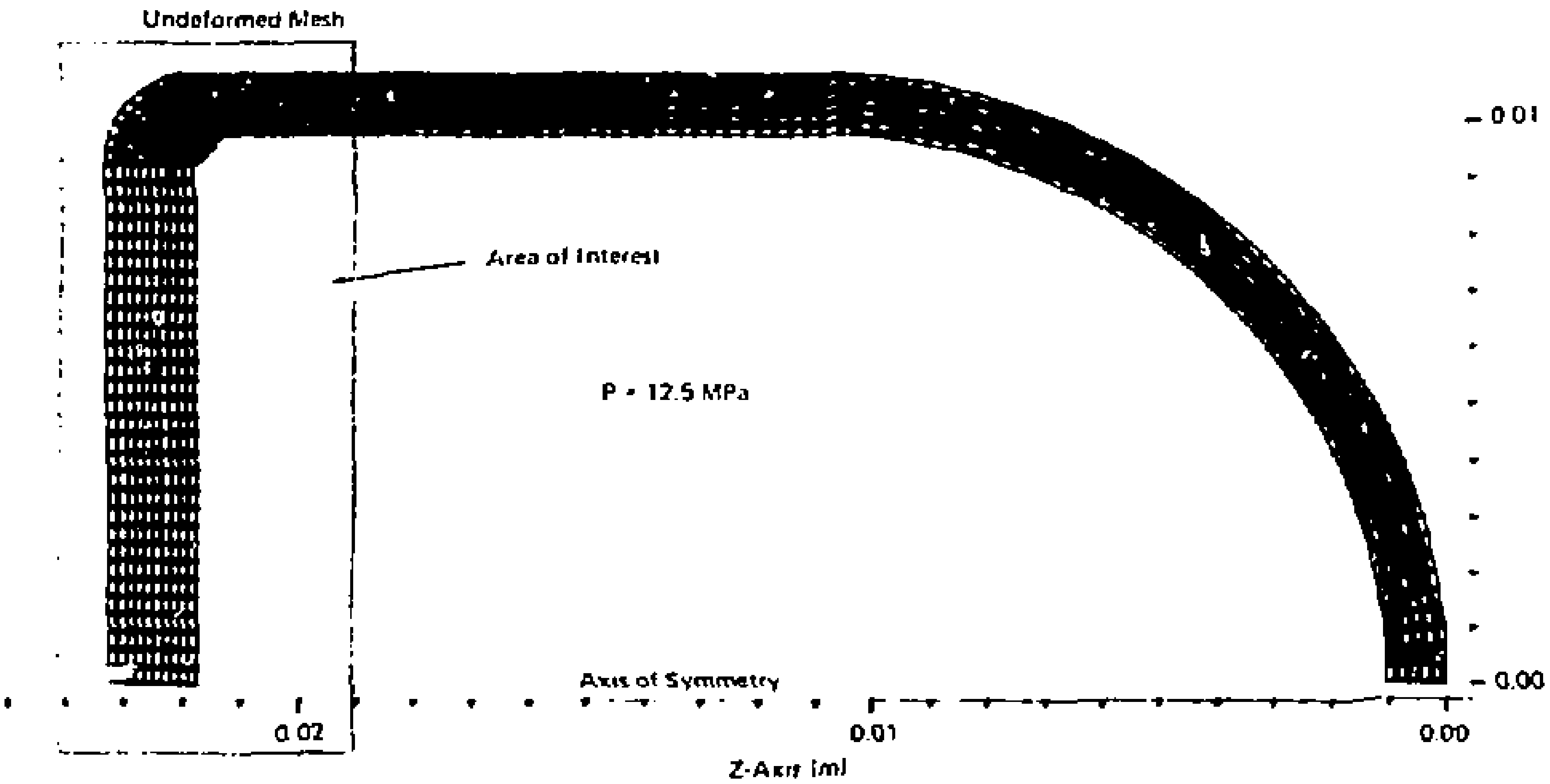

Figure 10. A finite-element mesh idealization of an axisymmetric pressure vessel.

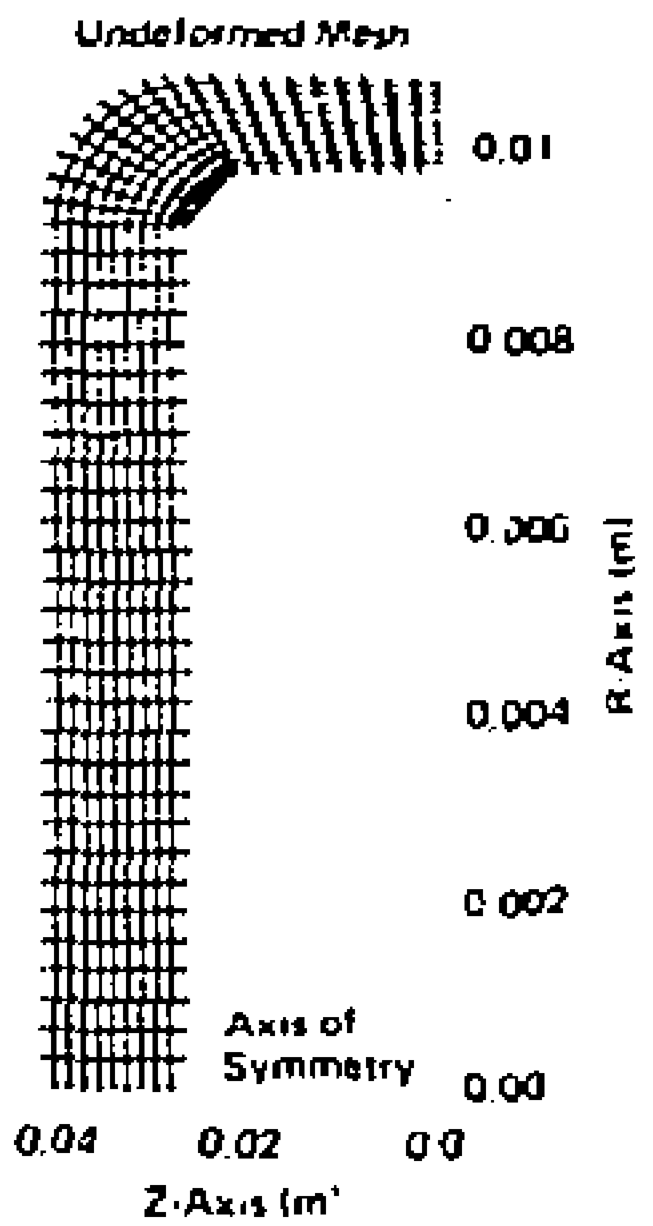

Figure 11. Finite-element mesh idealization of the area of interest in the pressure vessel of Figure 1.

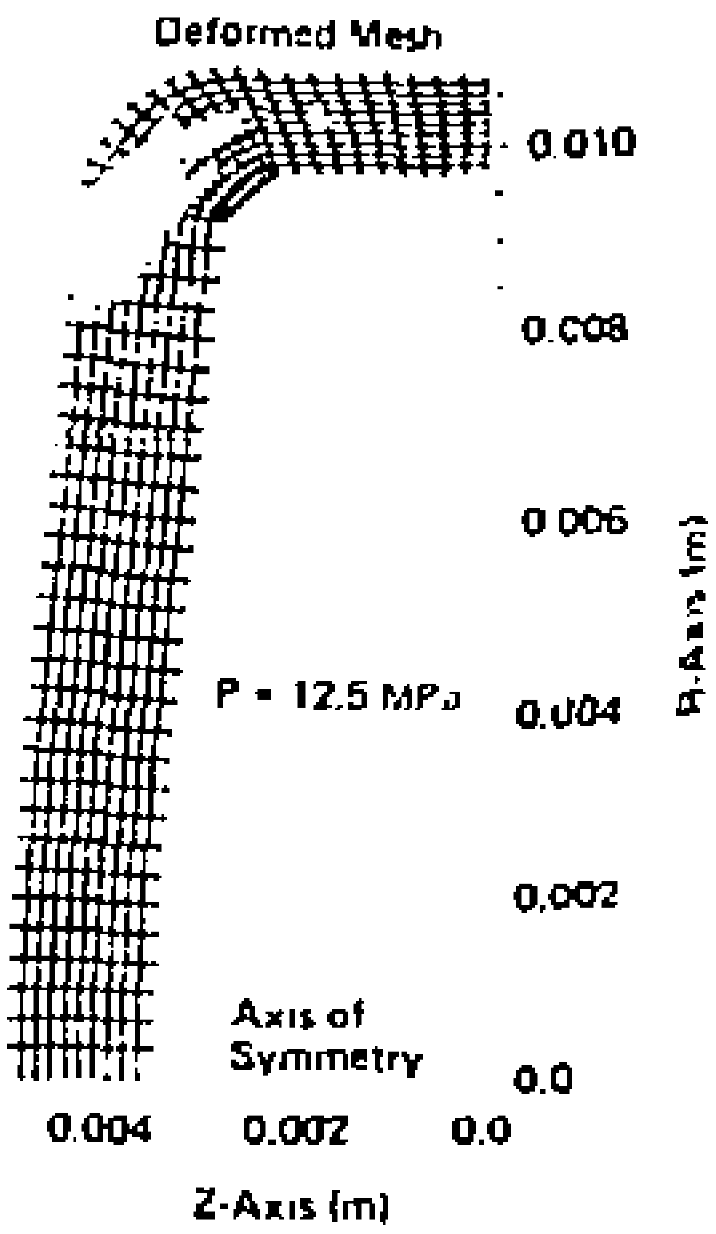

Figure 12. The deformed shape (exaggerated) of the area of interest caused by internal pressure.

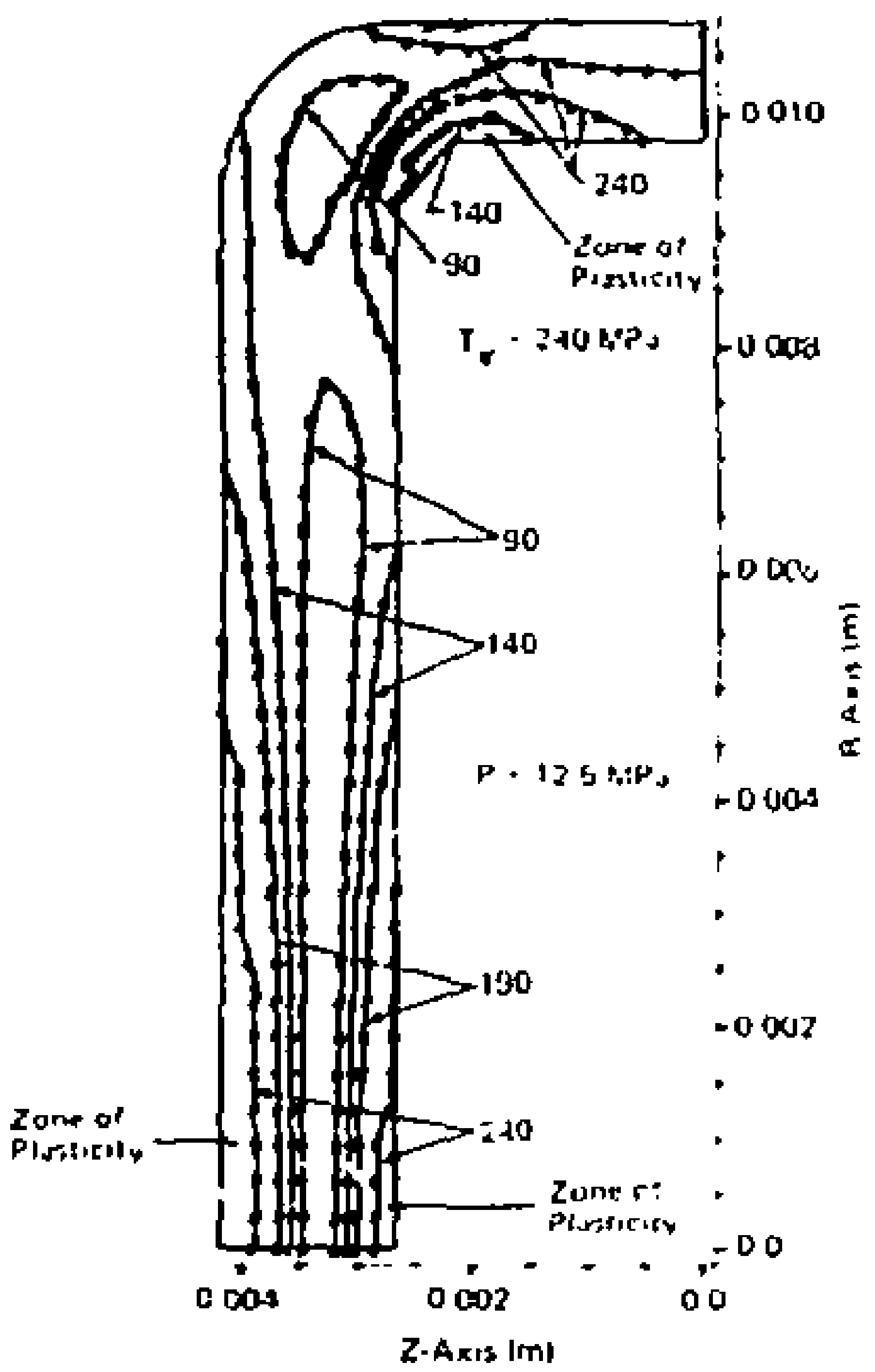

Figure 13. Stress contours developed in the area of interest by internal pressure

Item 6. *Fuel-Cask Severe-Impa[illegible]*

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

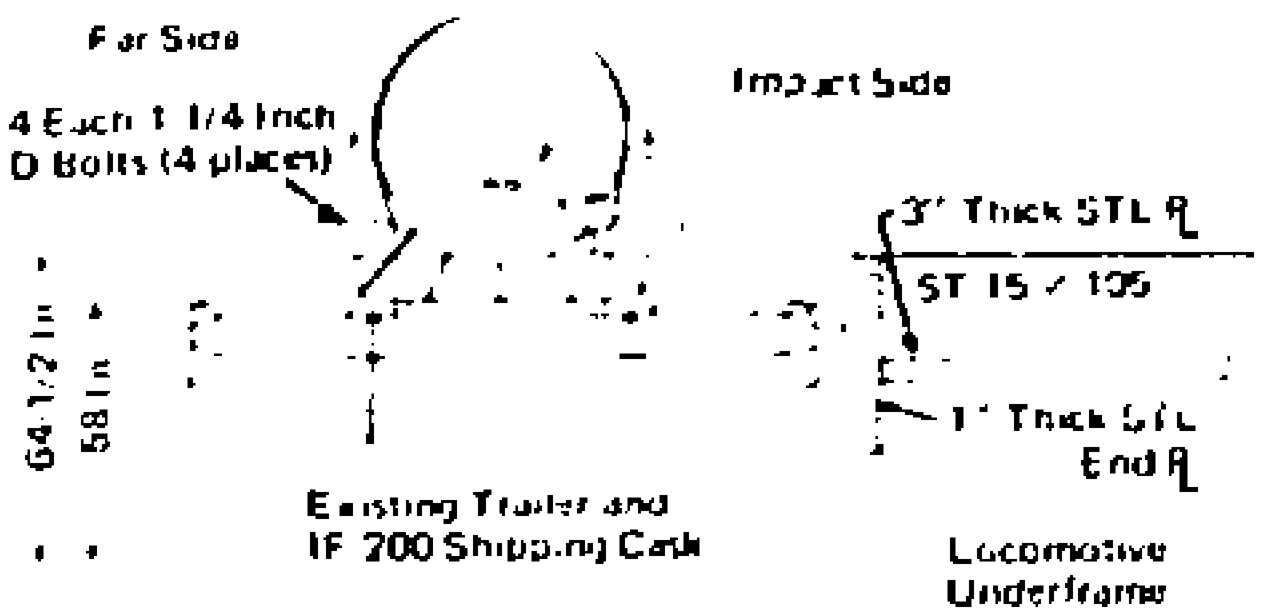

Figure 14. Position of cask and locomotive underframe at impact.

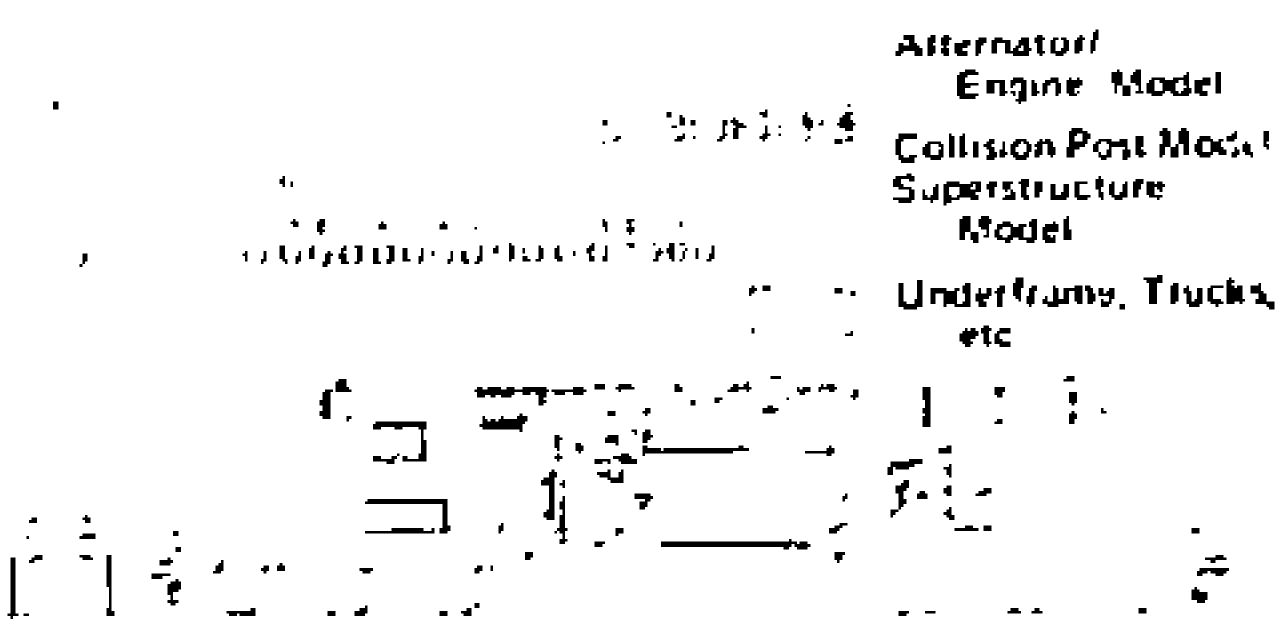

Figure 15. Spring-mass model of six axle freight locomotive.

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.

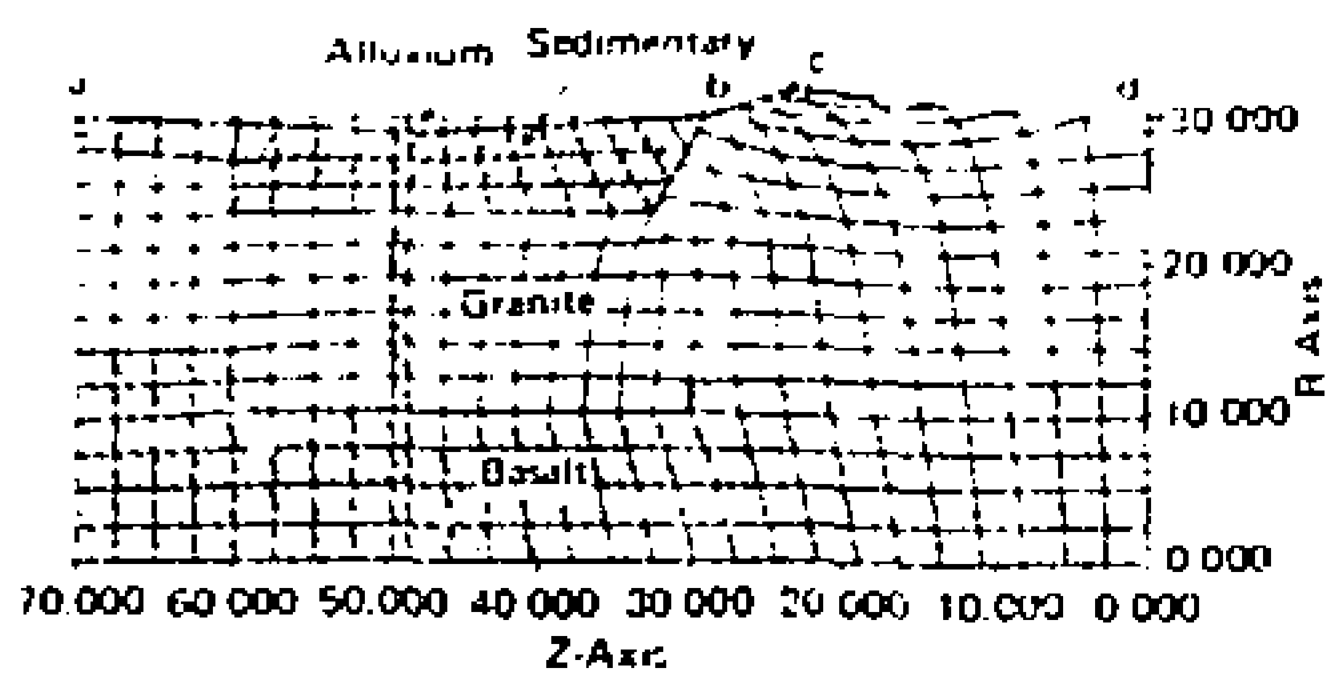

Figure 16. Central mesh area.

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.

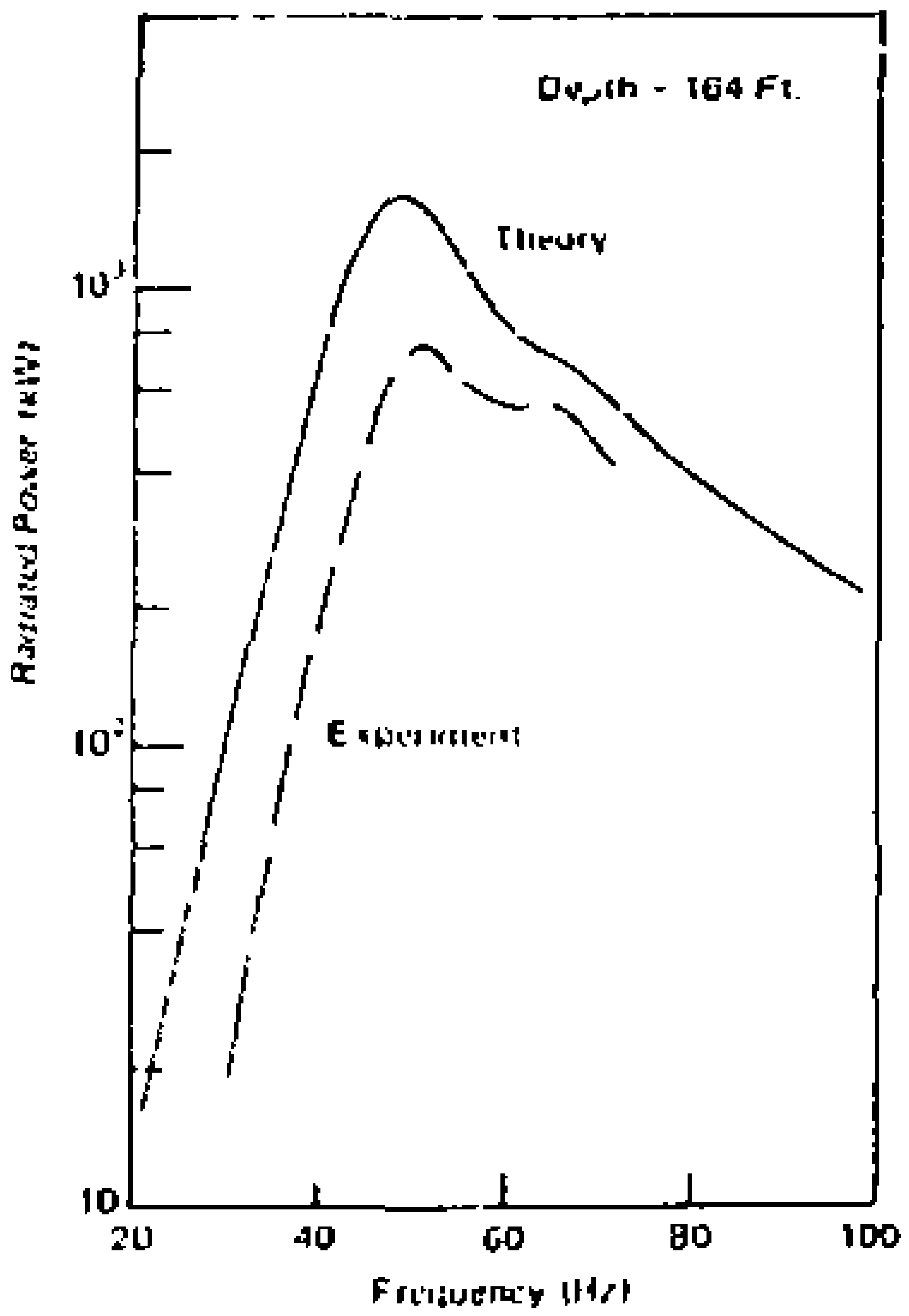

Figure 17. Radiated power versus frequency for a sound source submerged in 164 feet of fresh water.

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 links with greatly different 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 p[illegible]s 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).

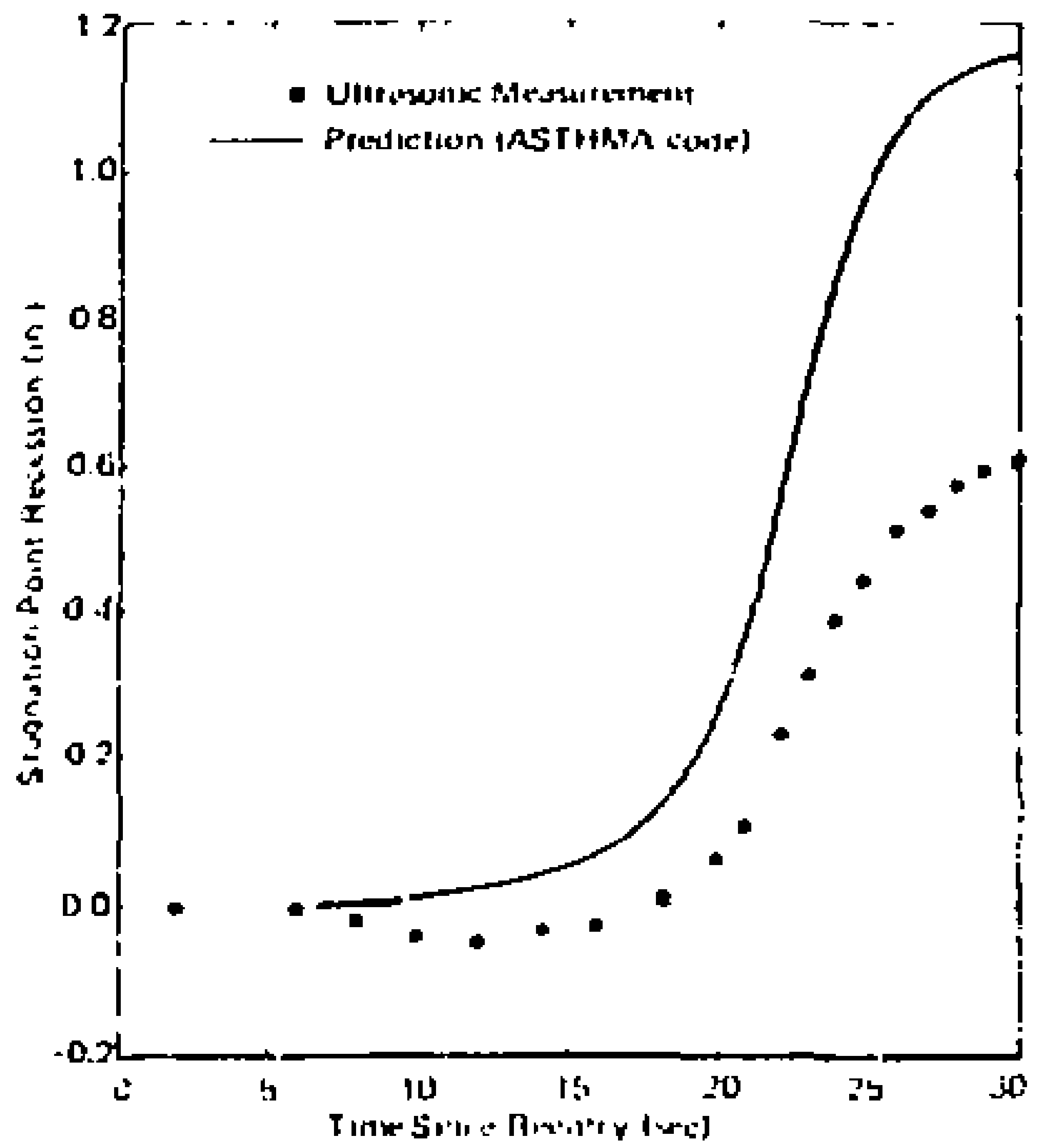

Figure 18. Ultrasonically measured and predicted (ASTHMA code) stagnation point recession histories.

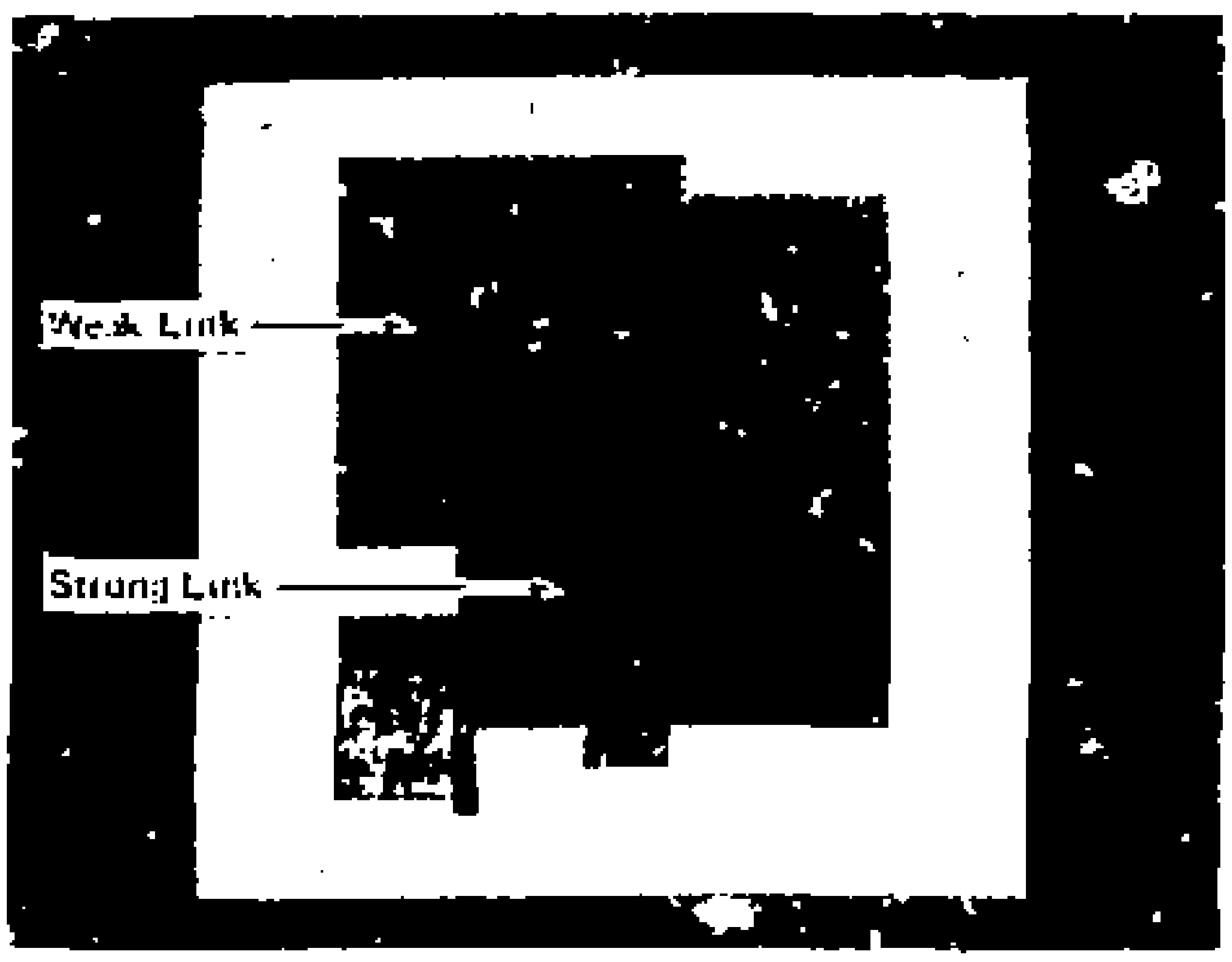

Figure 19 A two dimensional cross section of an electronics package showing the relative positions of various pieces.

STRUCTURAL MECHANICS

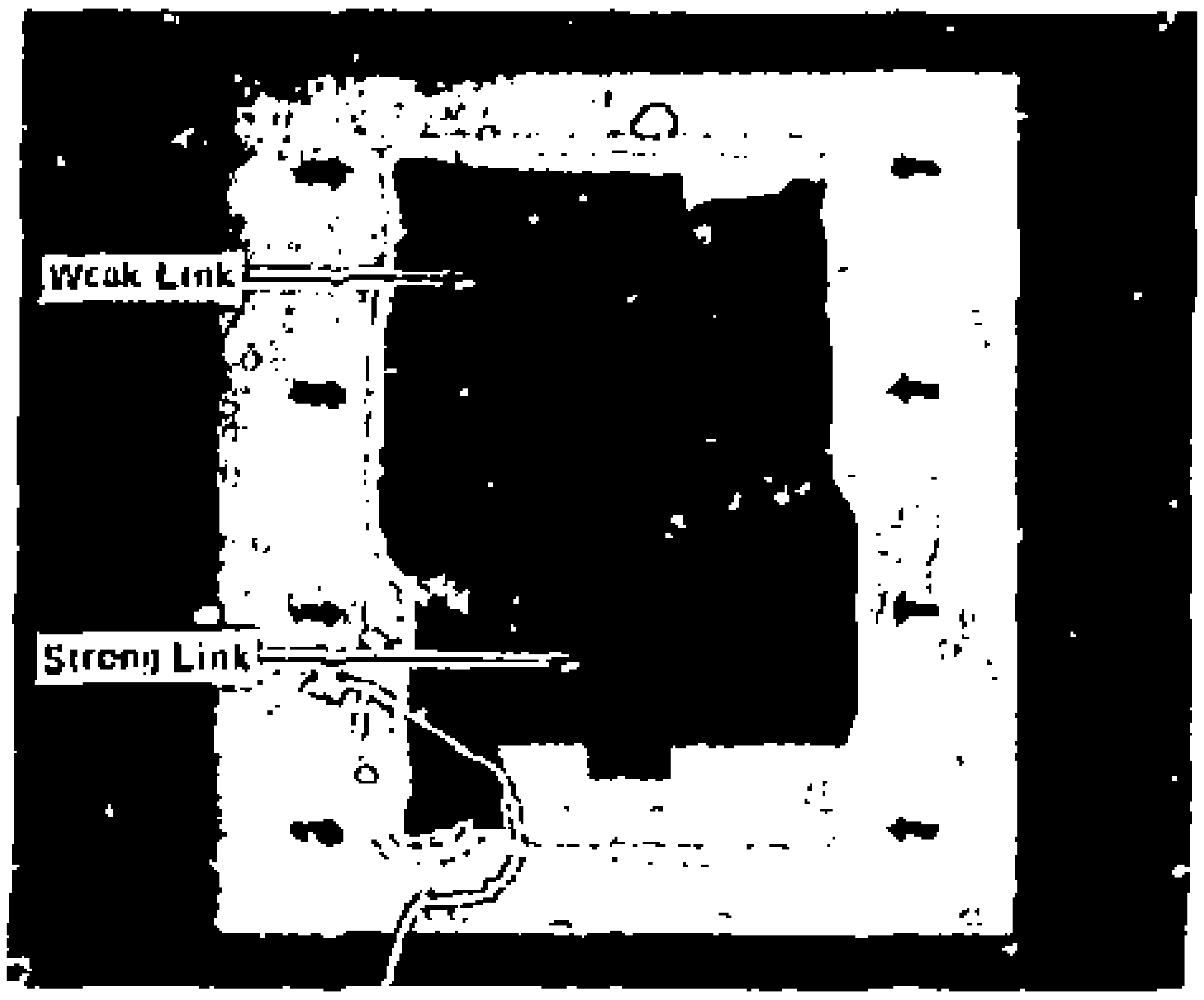

Figure 20 The result of applying a dynamic crush load. Note the greater crush of the weak link in relation to the strong link.

Item 14. *Numerical Time Integration 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 Latheta and as well as modal decomposition and integration are used in various structural codes.

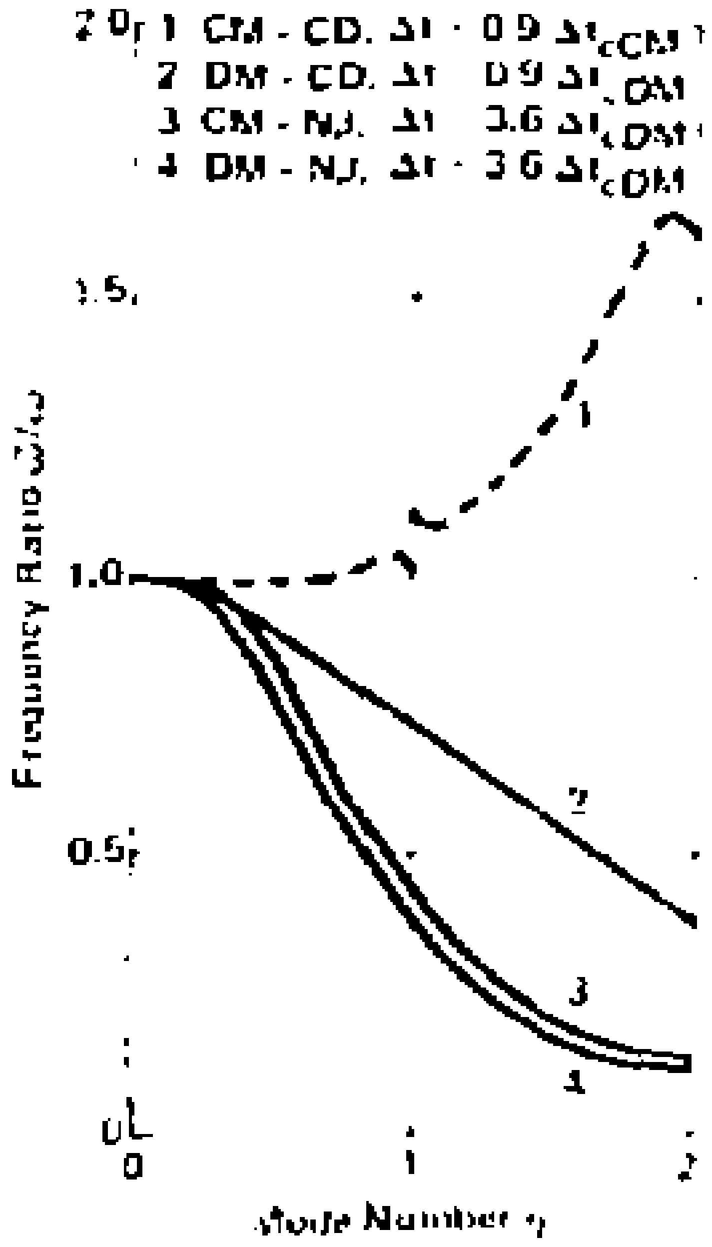

Figure 21. The ratio of computed frequency to exact frequency versus nondimensional mode number for central difference (CD) and Newmark β (N,β), β = 1/4, time integrations combined with consistent mass (CM) and diagonal mass (DM) finite element discretizations of the beam equation using cubic displacement assumptions.

Item 15. *Two-Surface Plasticity Theory*

A plasticity theory has been developed to describe the moderate rate loading of metals. This 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

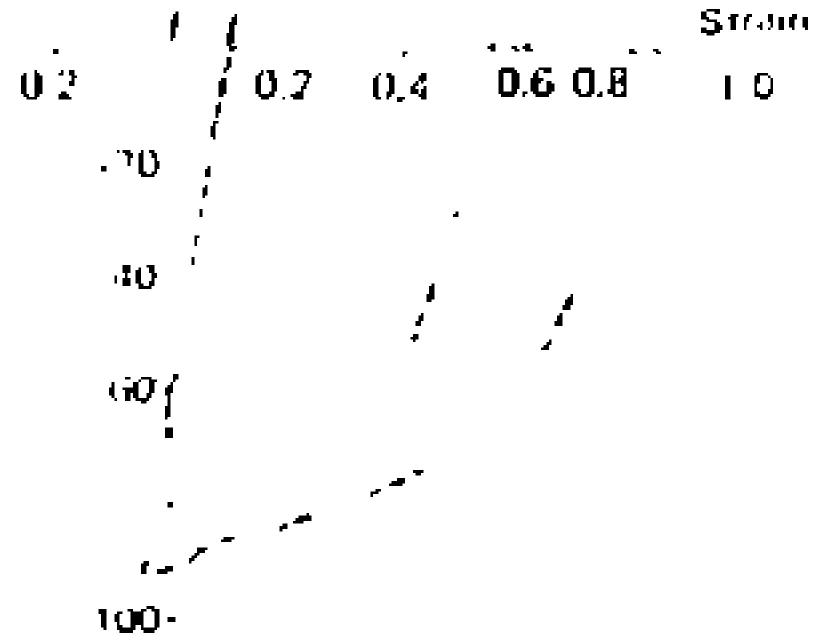

Figure 22 Uniaxial stress-strain curve for 6061-O aluminum (solid line) compared with theory (dashed line).

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.

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,

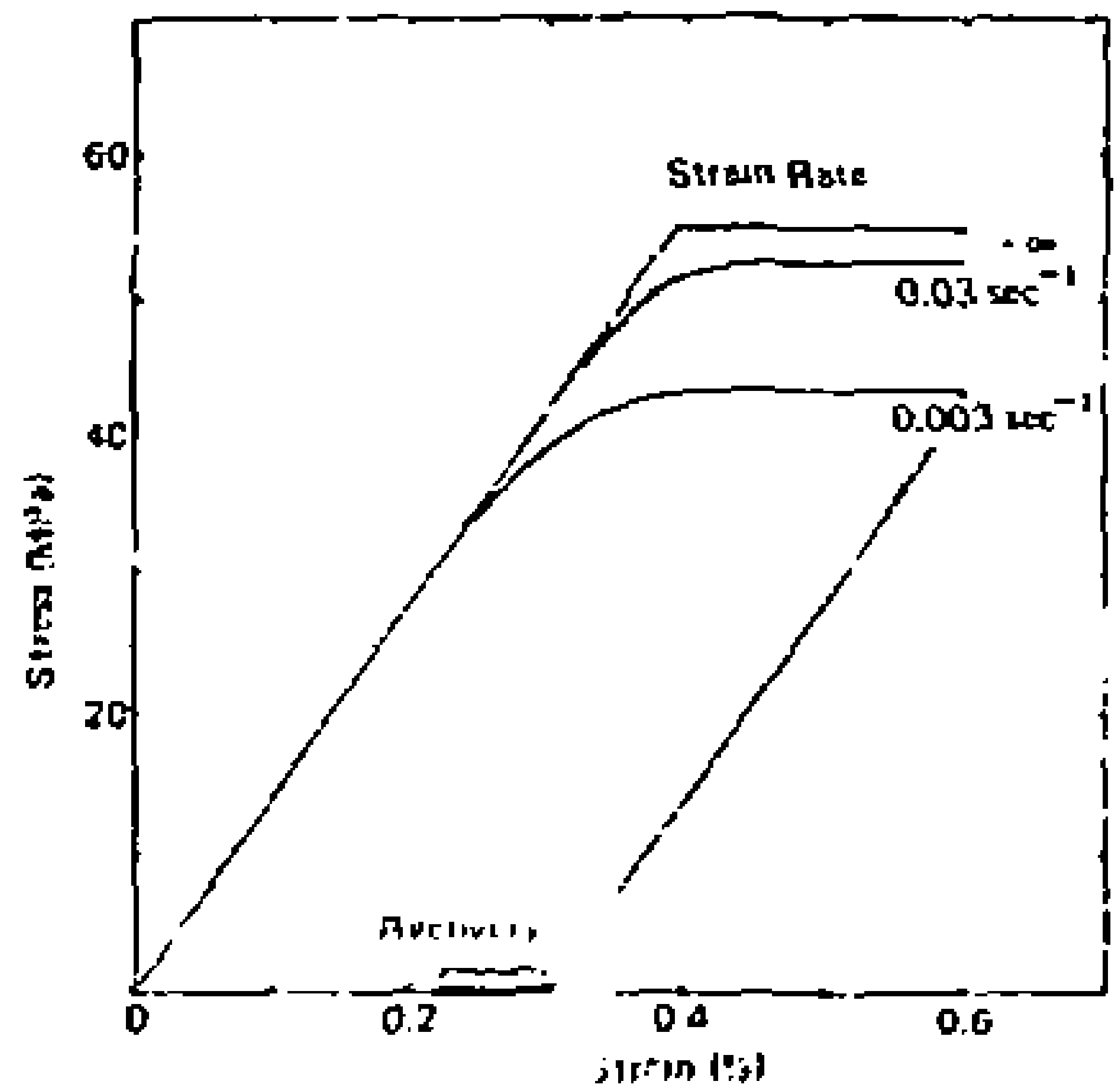

Figure 23. Stress-versus-strain behavior at various strain rates for a time-dependent plasticity model which also incorporates recovery or annealing.

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 153 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)*

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

*See Highlights below.

STRESS-WAVE ANALYSIS

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.

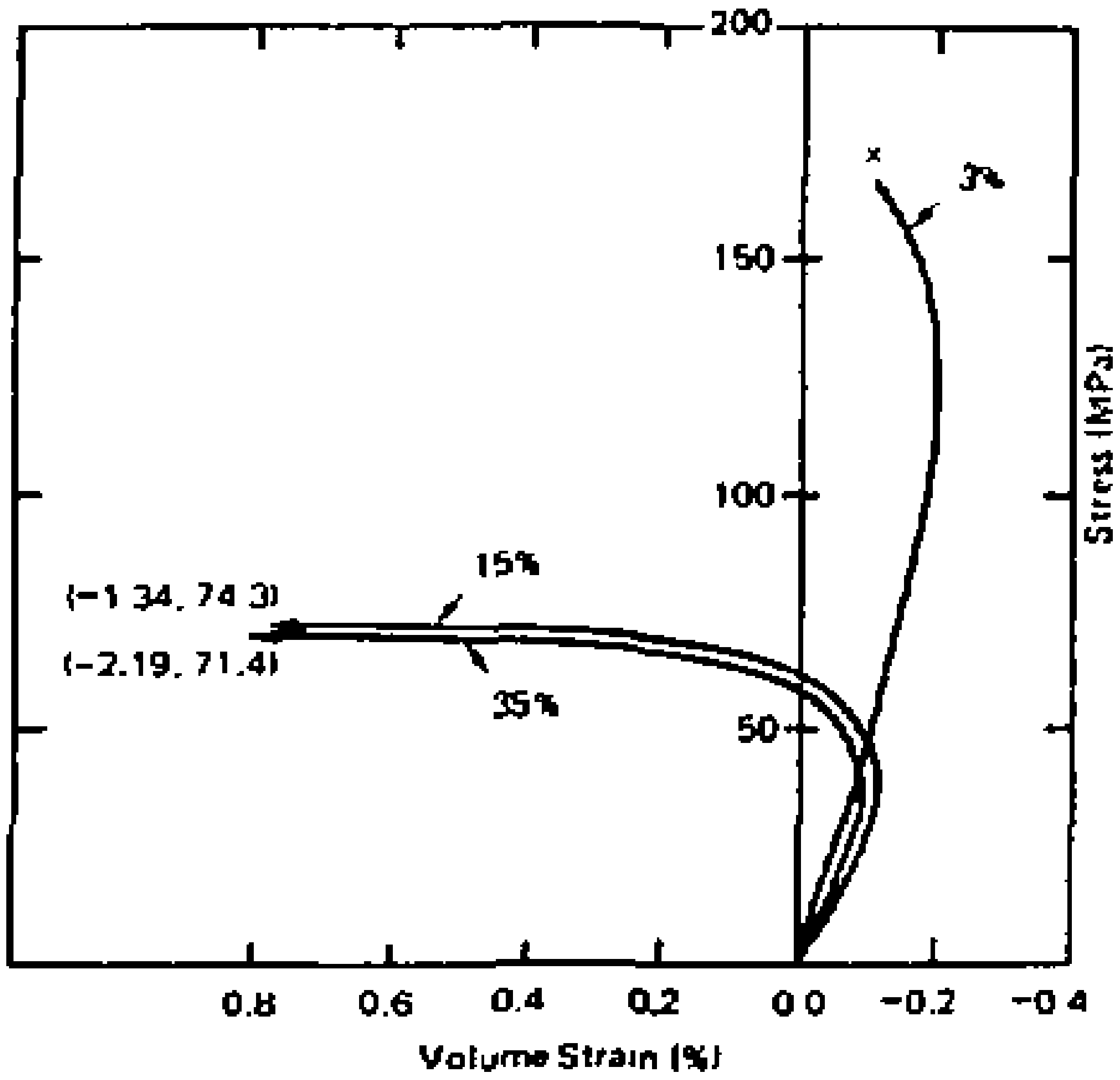

Figure 2. Axial stress volume strain behavior of oil shale as a function of kerogen content (volume percent). Failure or fracture is denoted by X for the 3-percent shale and by the strain and stress values noted for the 15 and 35 percent shales.

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.

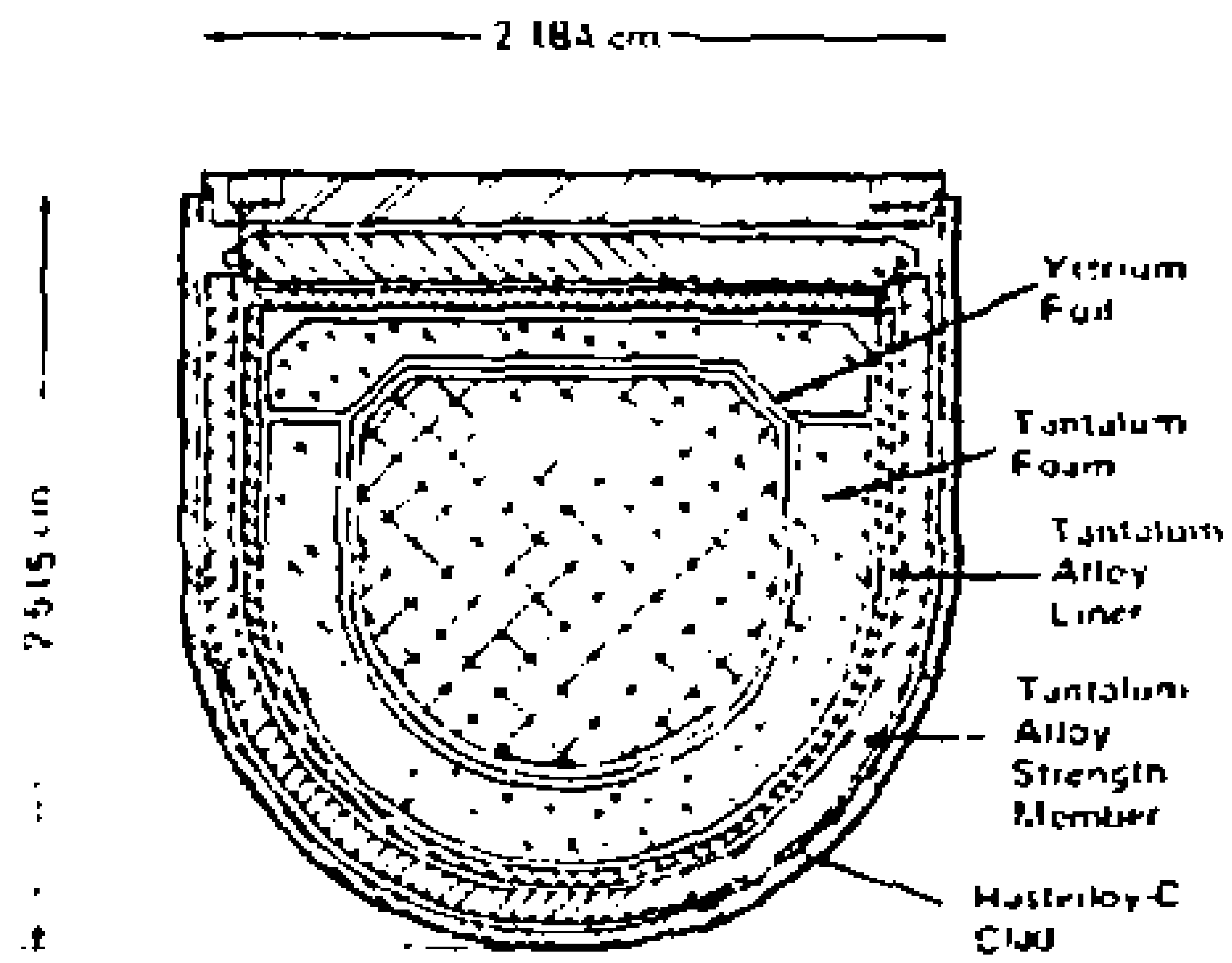

Figure 3. Heat source for radioisotopically powered thermoelectric generator

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.

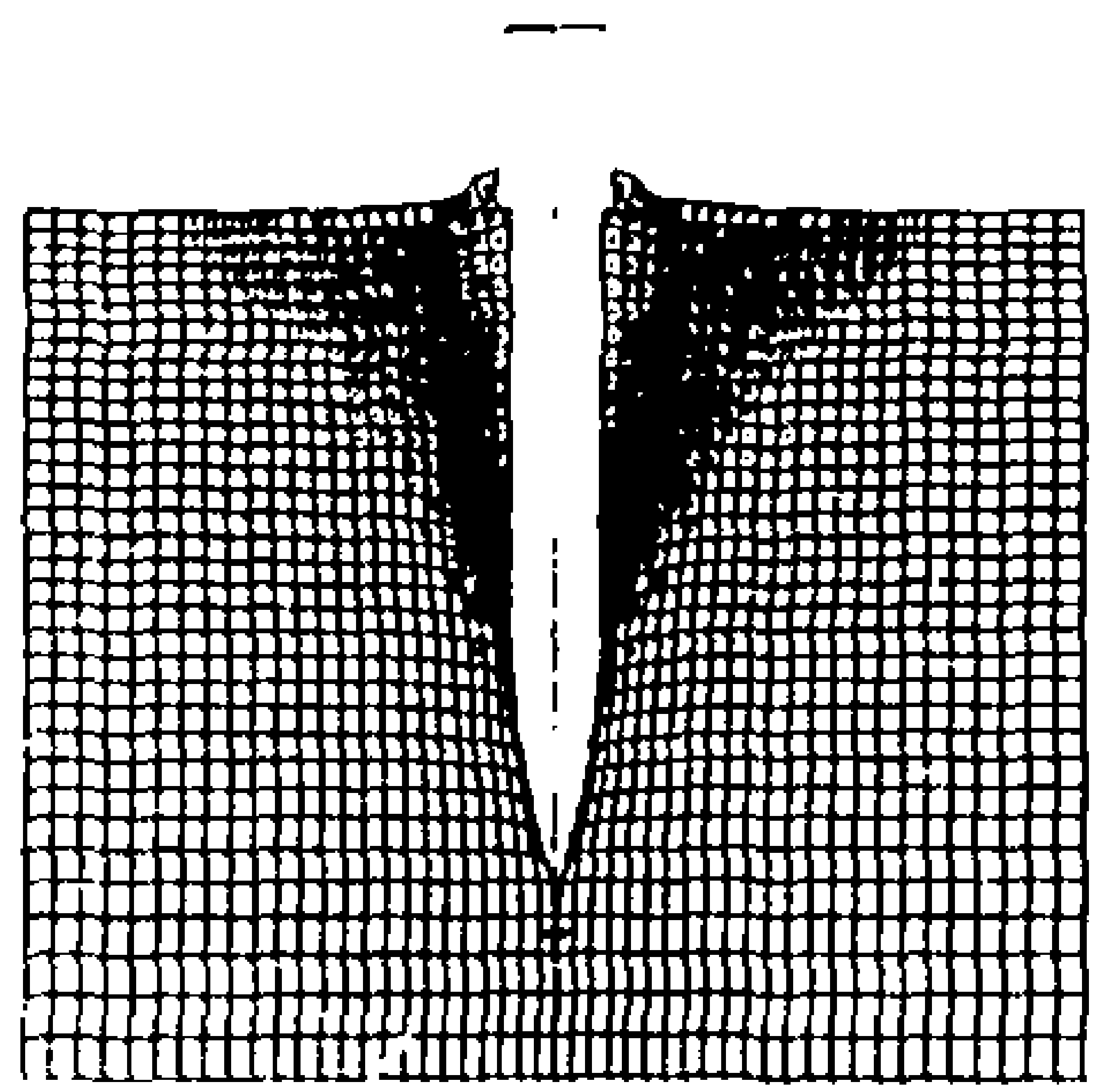

Figure 4. Regions of failure (8 msec after impact) produced in a soil medium by a 0.165 m diameter projectile impacting at 152 m/s.

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.

ENGINEERING ANALYSIS

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	Critical Temperature (°C) 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.

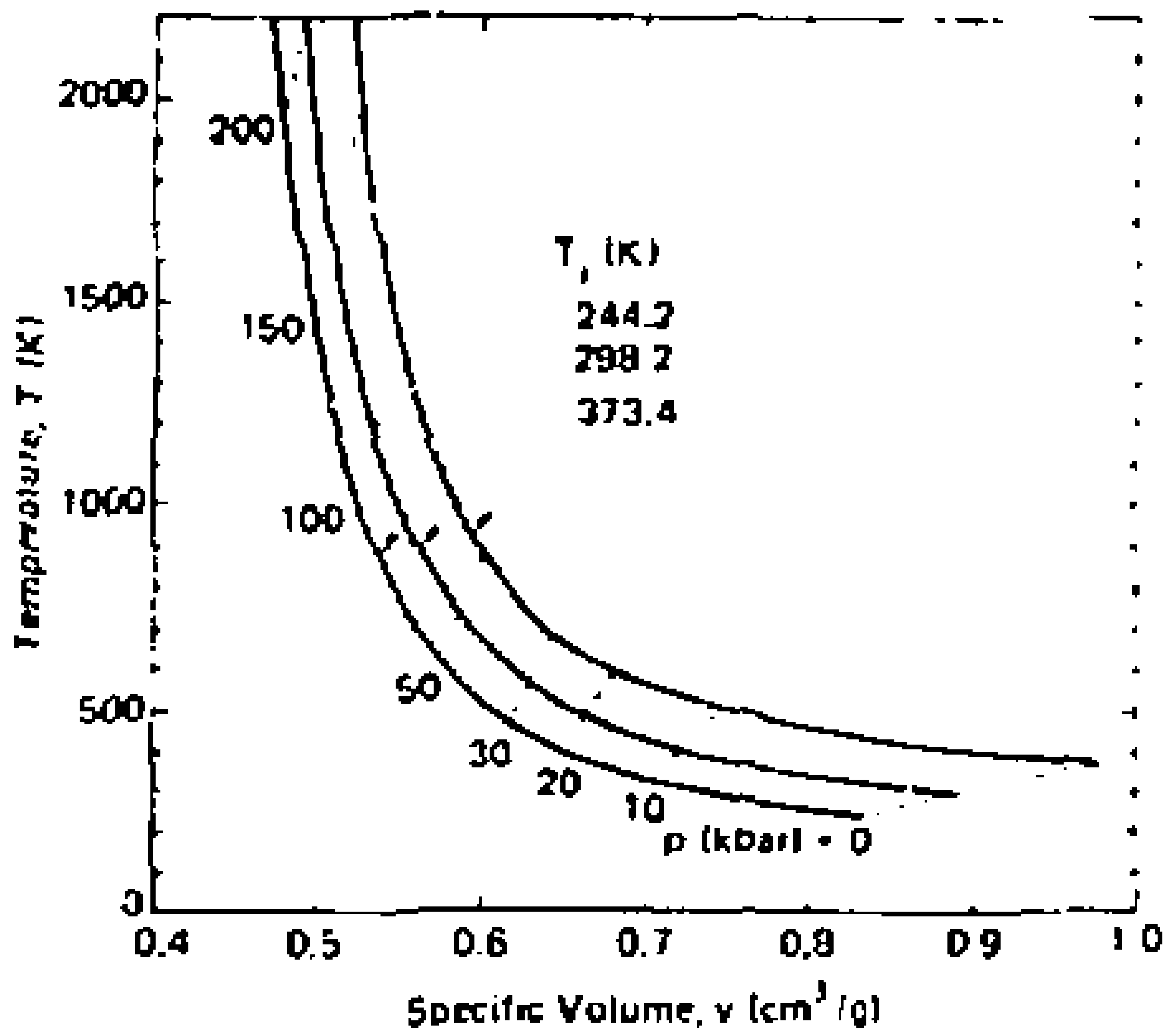

Figure 1. Temperature-specific volume states achievable behind shock waves of various strengths for three values of the initial temperature.

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.

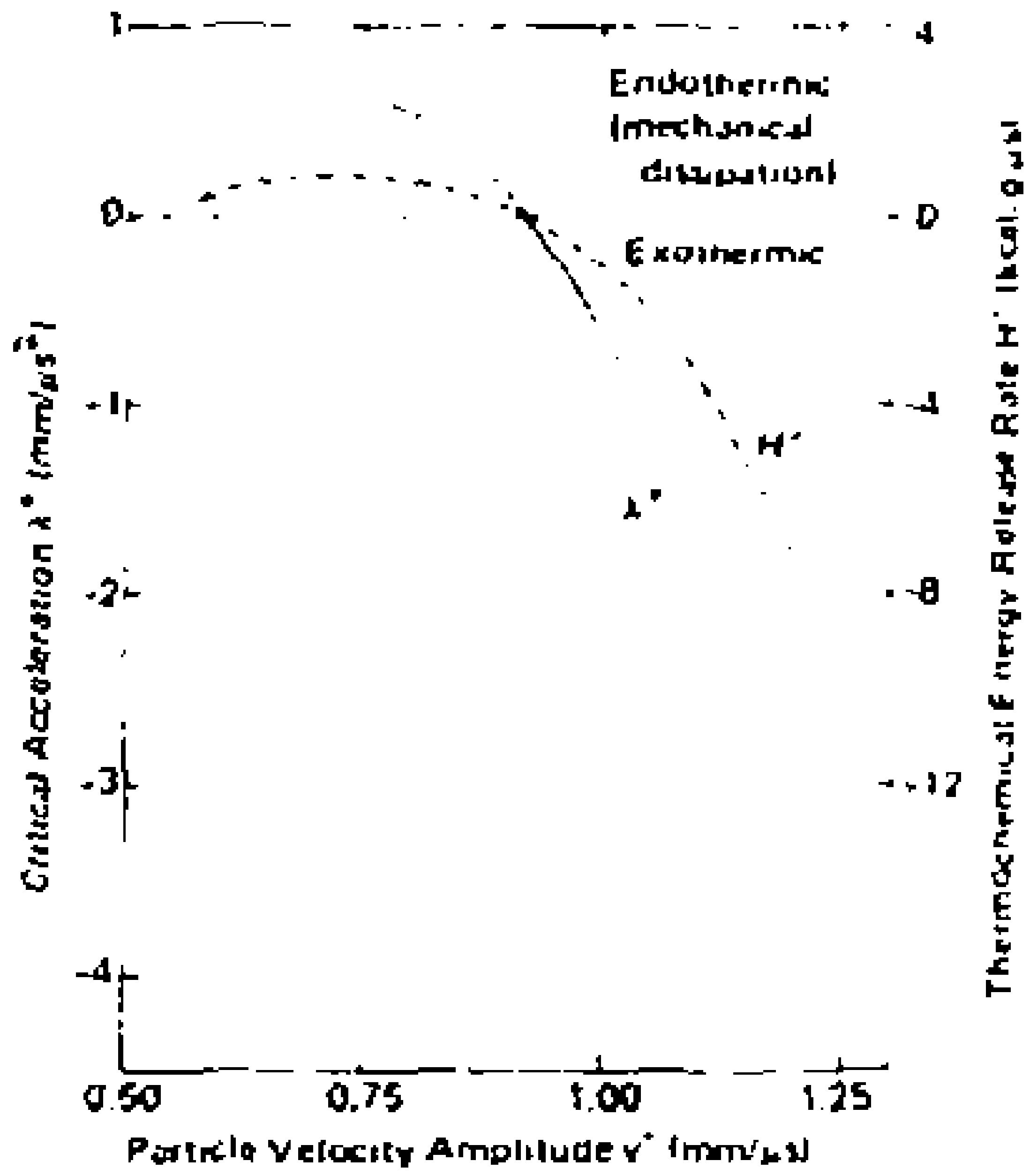

Figure 2. Acceleration behind shocks of varying strengths that separates the region in which the shock grows in strength from that in which it decays. Also shown is the energy release rate at the critical condition corresponding to steady wave propagation.

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.

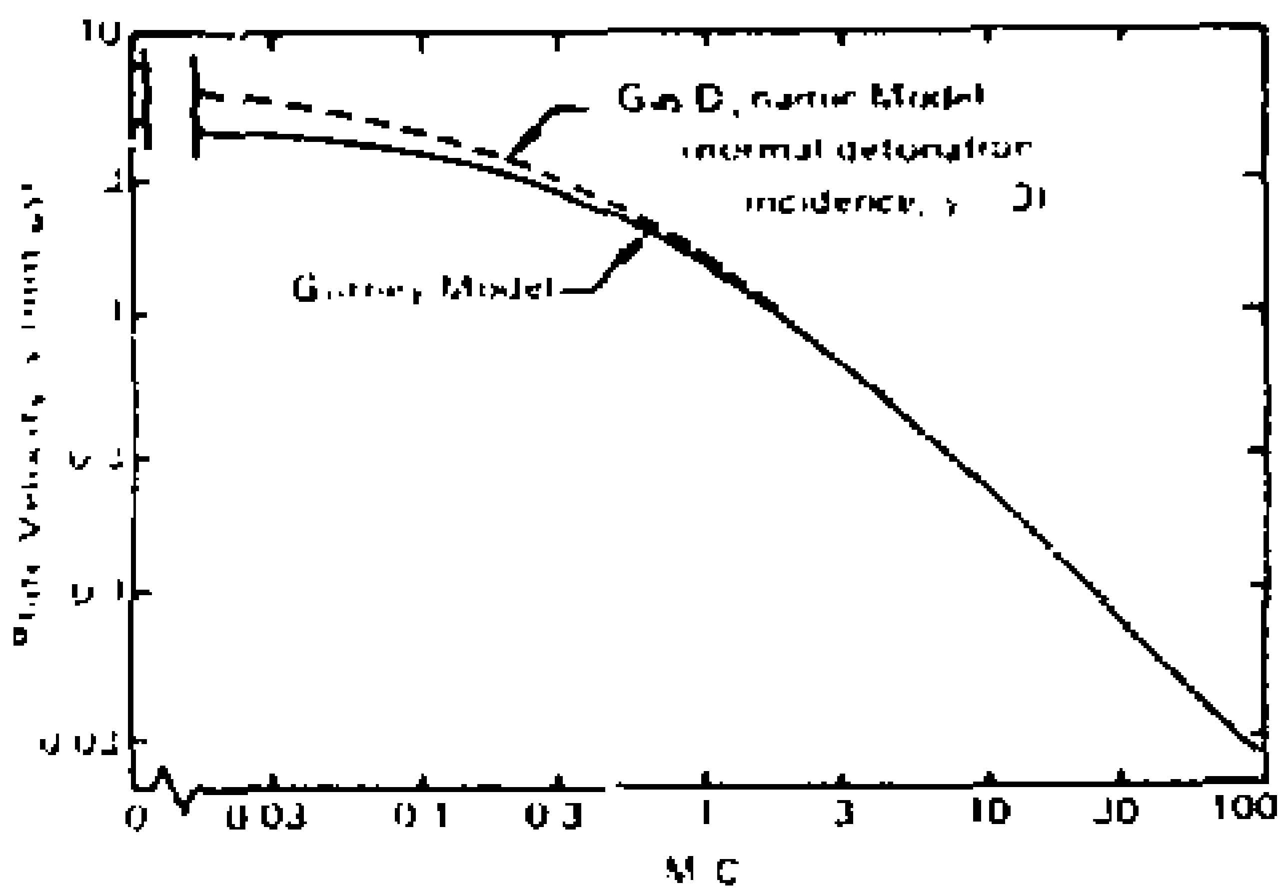

Figure 3. Gas dynamic and Gurney predictions of the velocity of explosively driven plates for various ratios of plate mass, M, to charge mass, C, of composition B explosive.

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

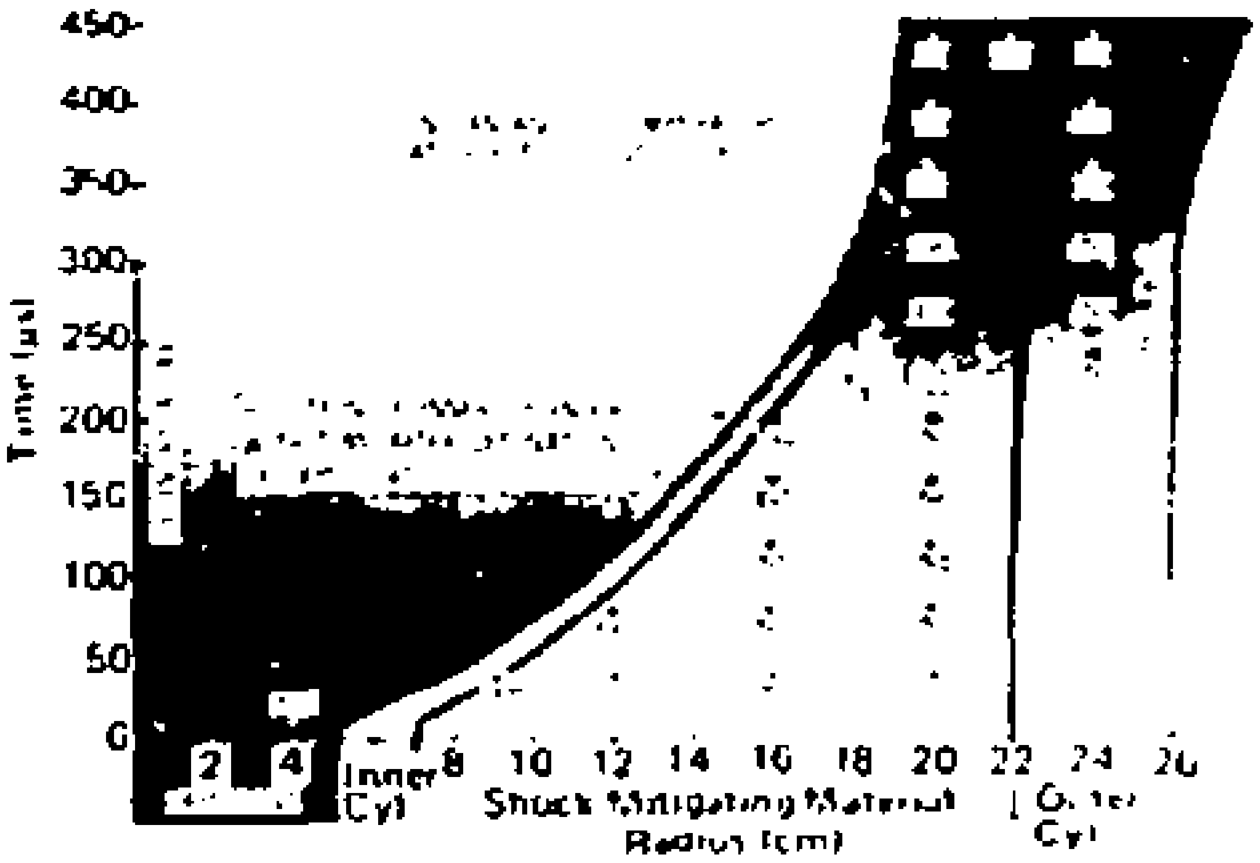

Figure 4. The position of the various parts of a containment vessel subsequent to the detonation of the enclosed explosive and selected temperatures are shown.

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.

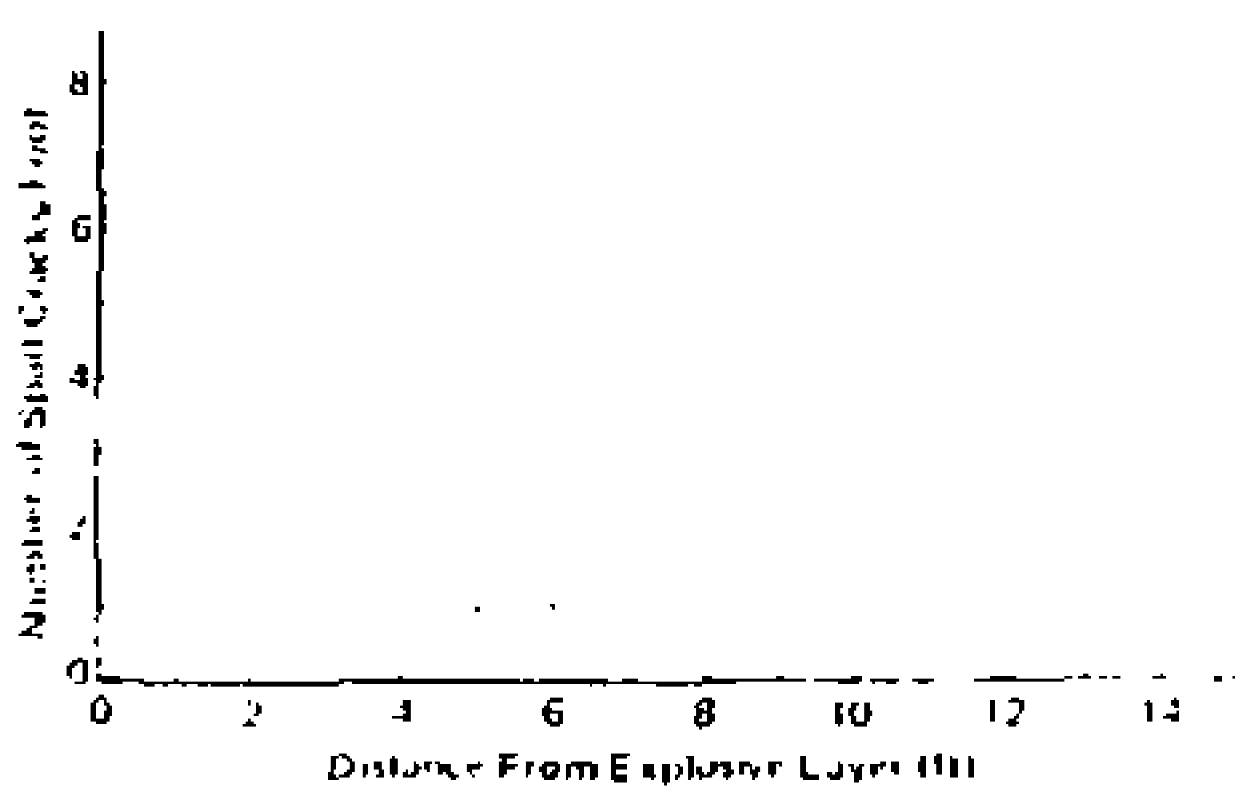

Figure 5. Spall induced fracturization as a function of the thickness of the oil shale layer.

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

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

*See Highlights below.

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

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.

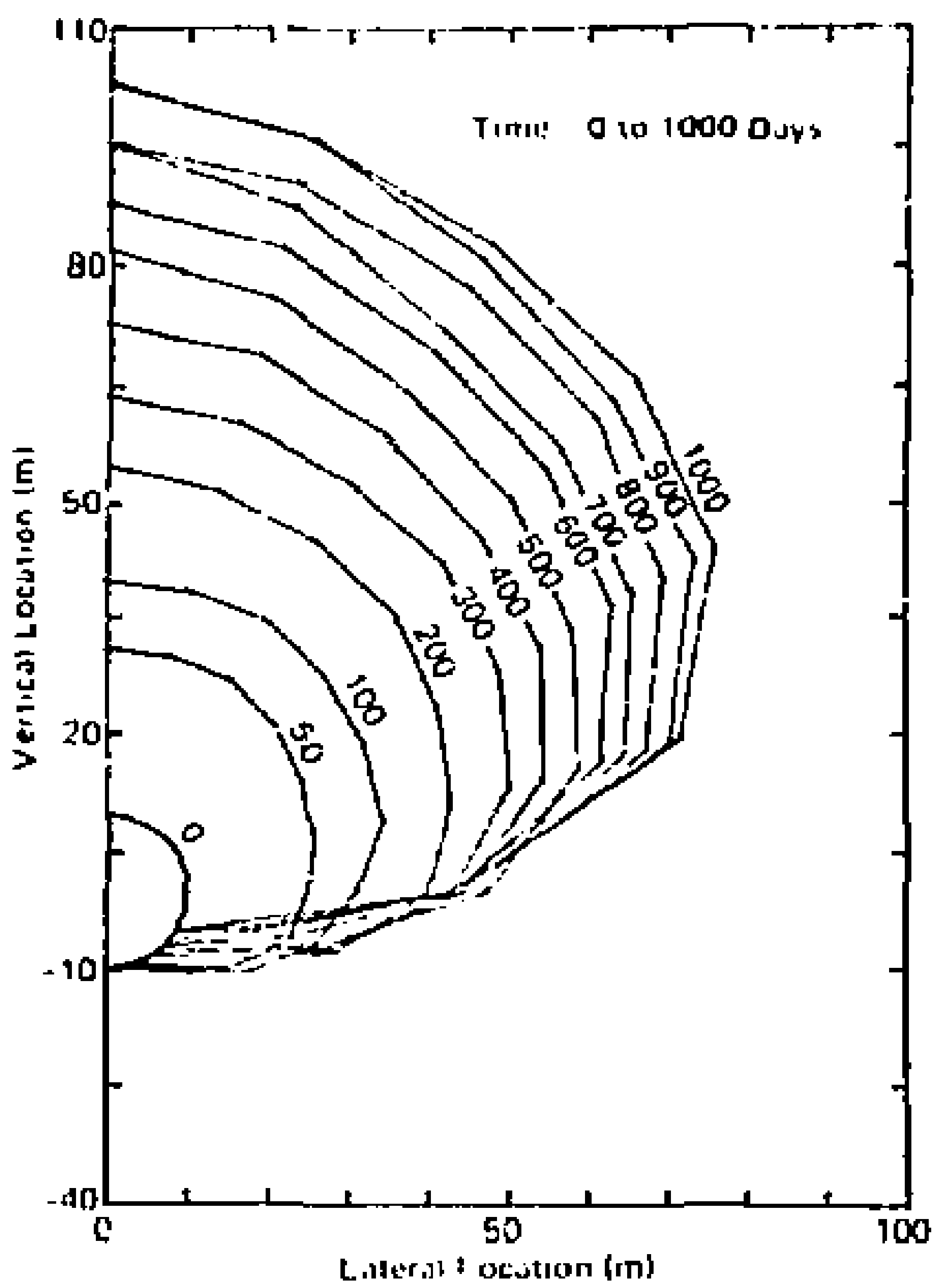

Figure 1. The growth of the solid/liquid interface is shown for the simulated disposal of radioactive waste in deeply buried rock.

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.

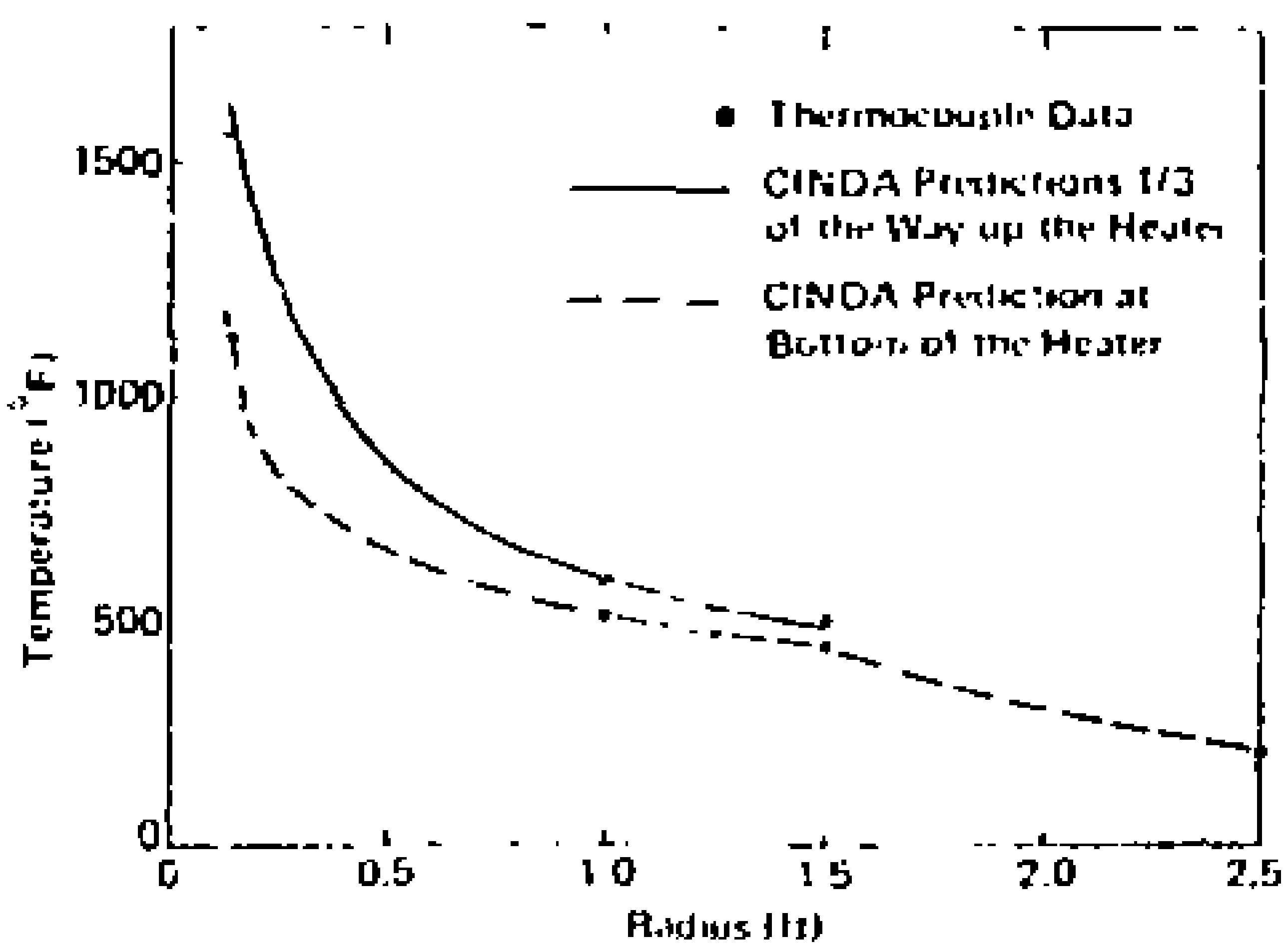

Figure 2. Predicted and measured temperatures, 25 days into the test.

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.

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 5. Melted region caused by a cylindrical heat source in a tube of solidified glycerin.

Figure 6. Migration of a molten region caused by convective effects in a tube of solidified glycerin.

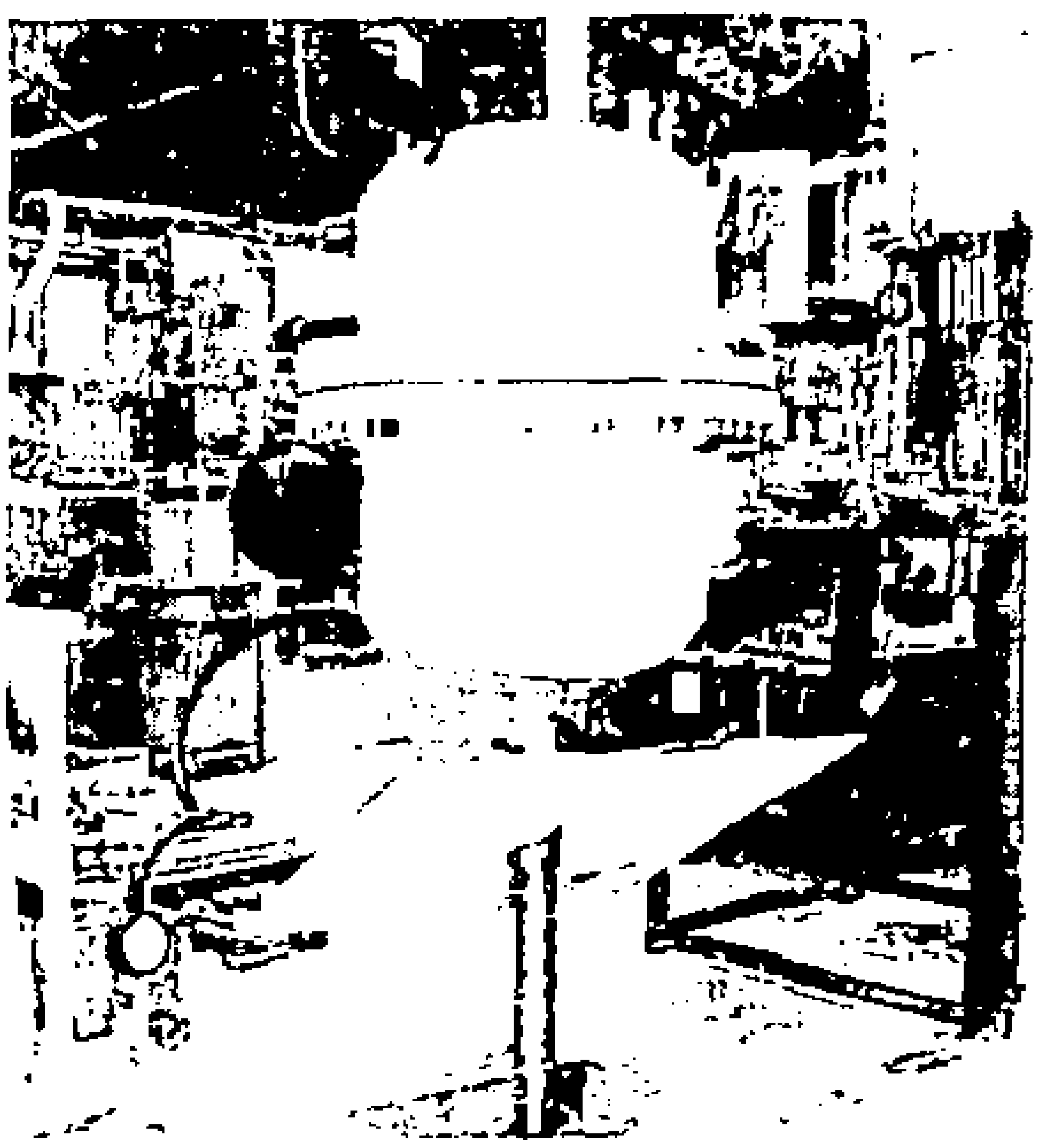

Figure 7. Single-tube boiler used in the molten lava/heat extraction experiment.

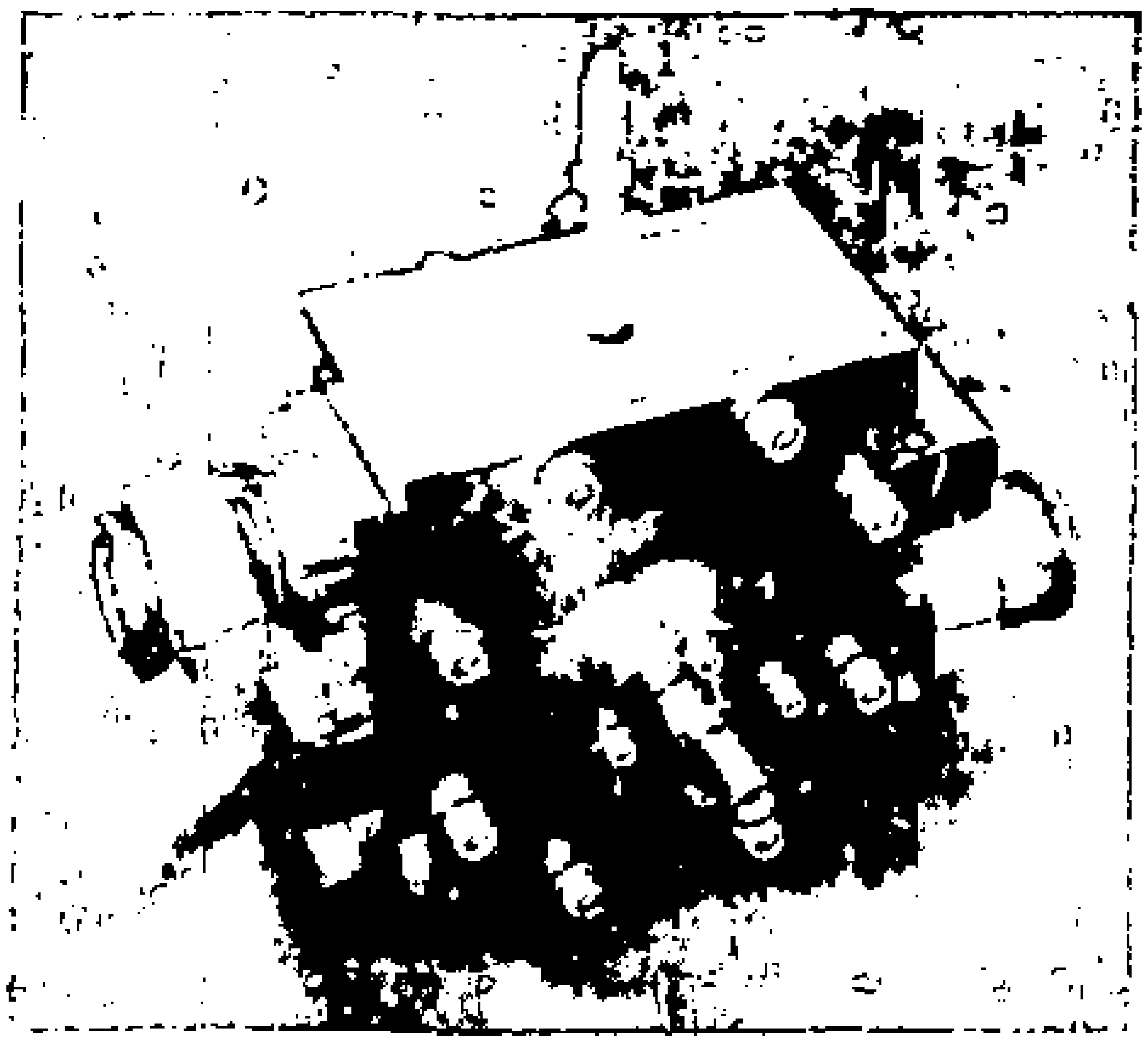

Figure 8. Vane turbine for molten lava/heat extraction experiment.

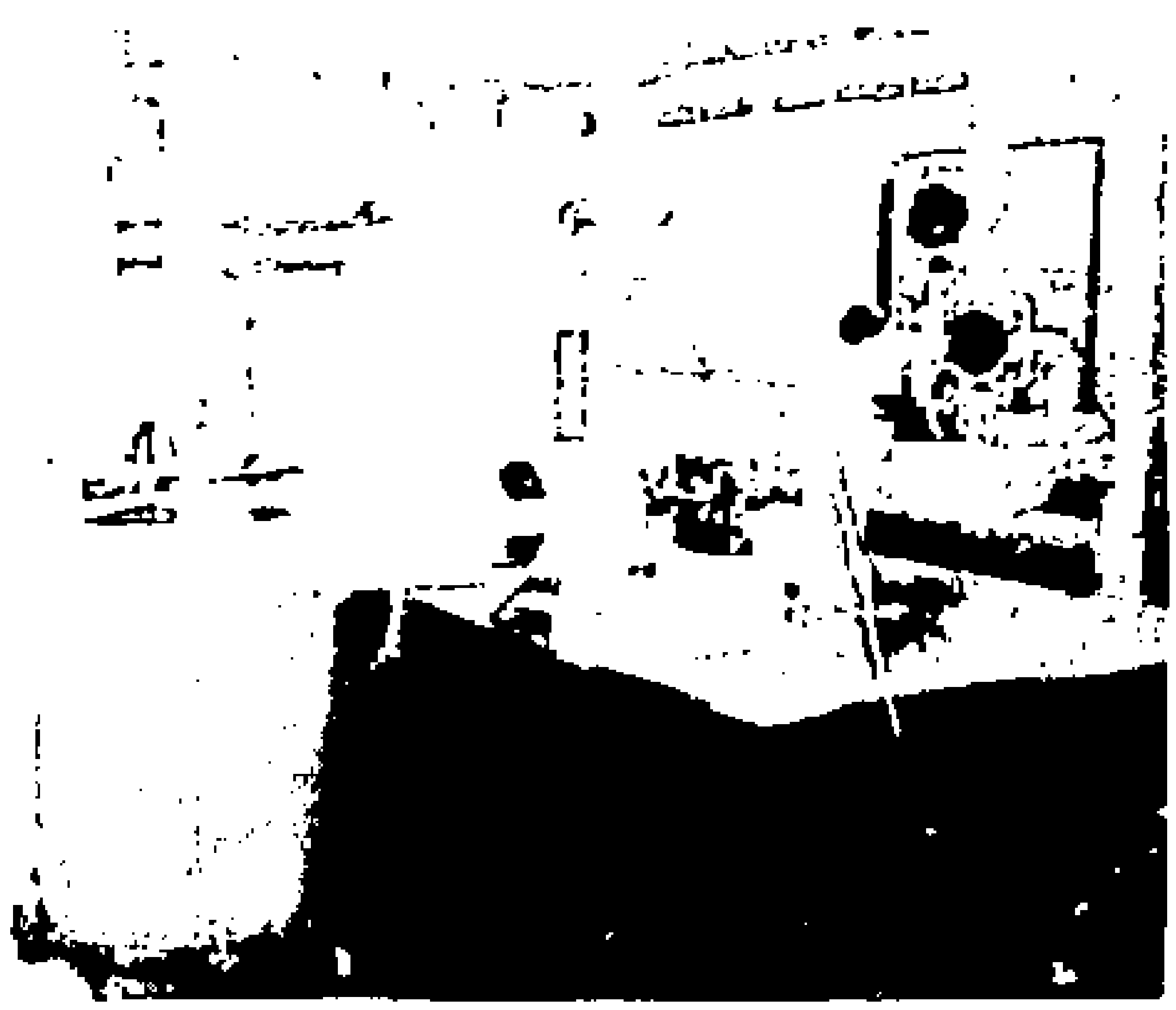

Figure 9. Vane turbine in steam cycle test bed.

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

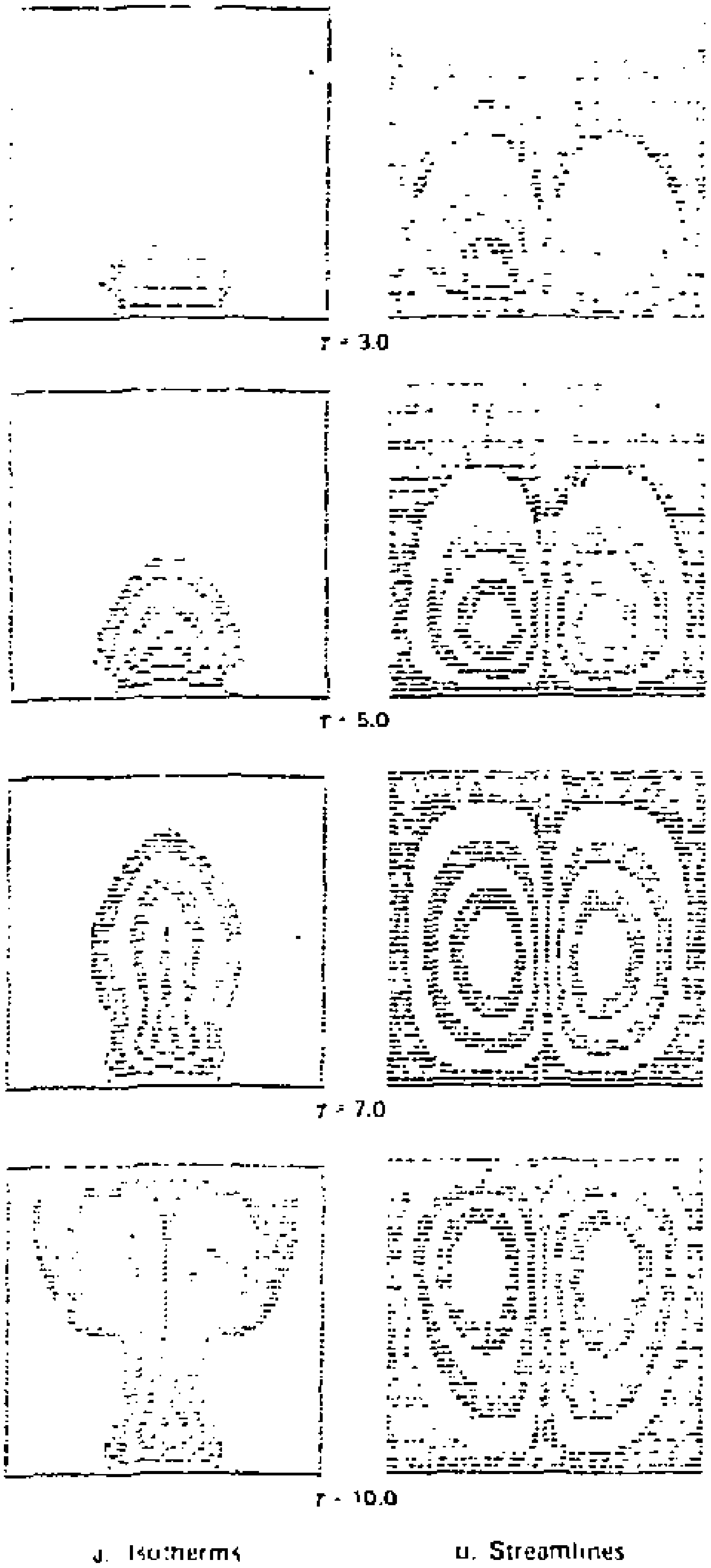

Figure 10. Computer-generated isotherm and streamline profiles for a simulated cable-tray fire in a nuclear reactor.

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.

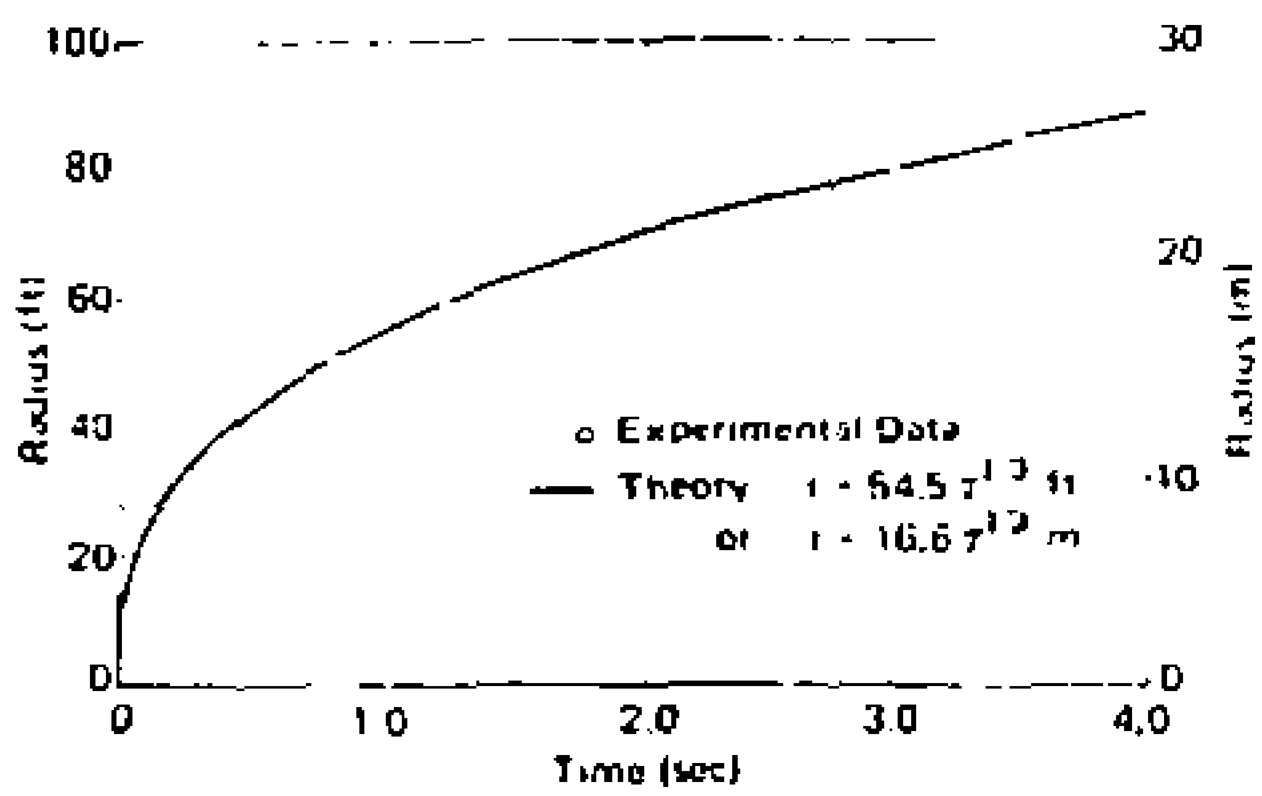

Figure 11. Cloud growth for sudden release of 930 pounds of propane.

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.

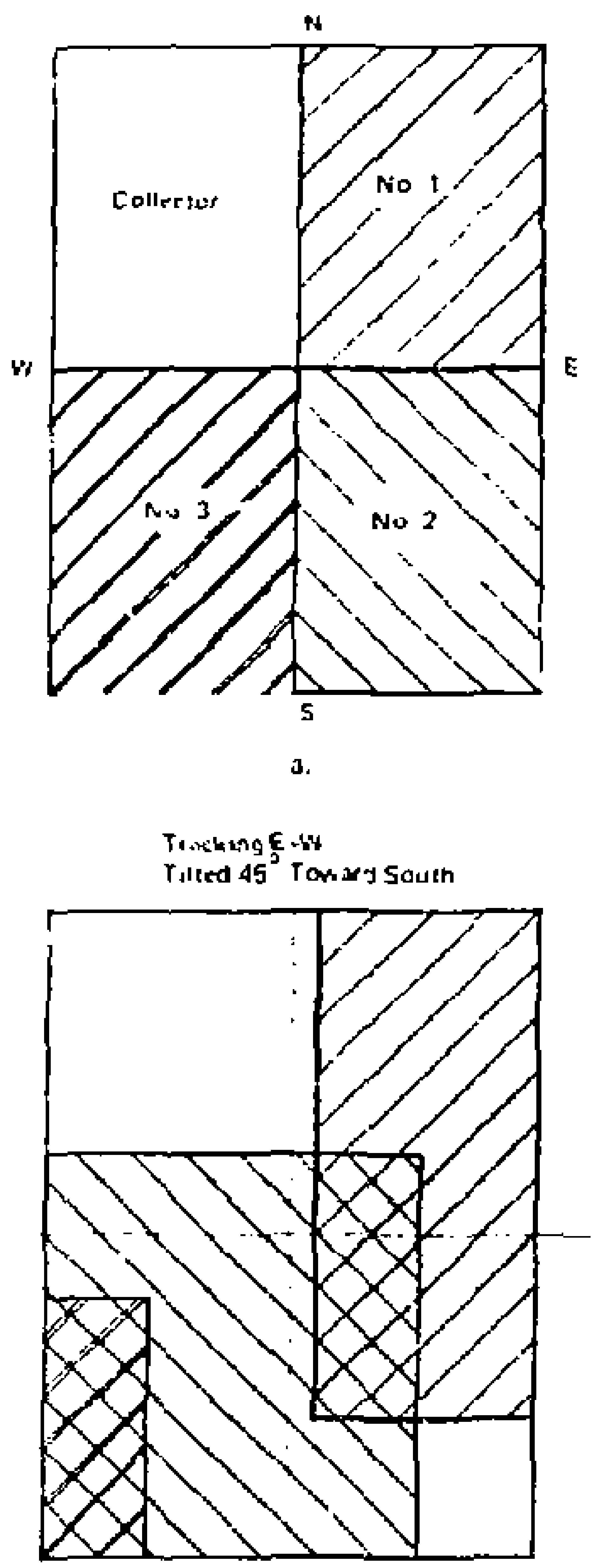

Figure 12. Computer-generated shadow pattern on a solar collector produced by shadowing from adjacent collectors.

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.

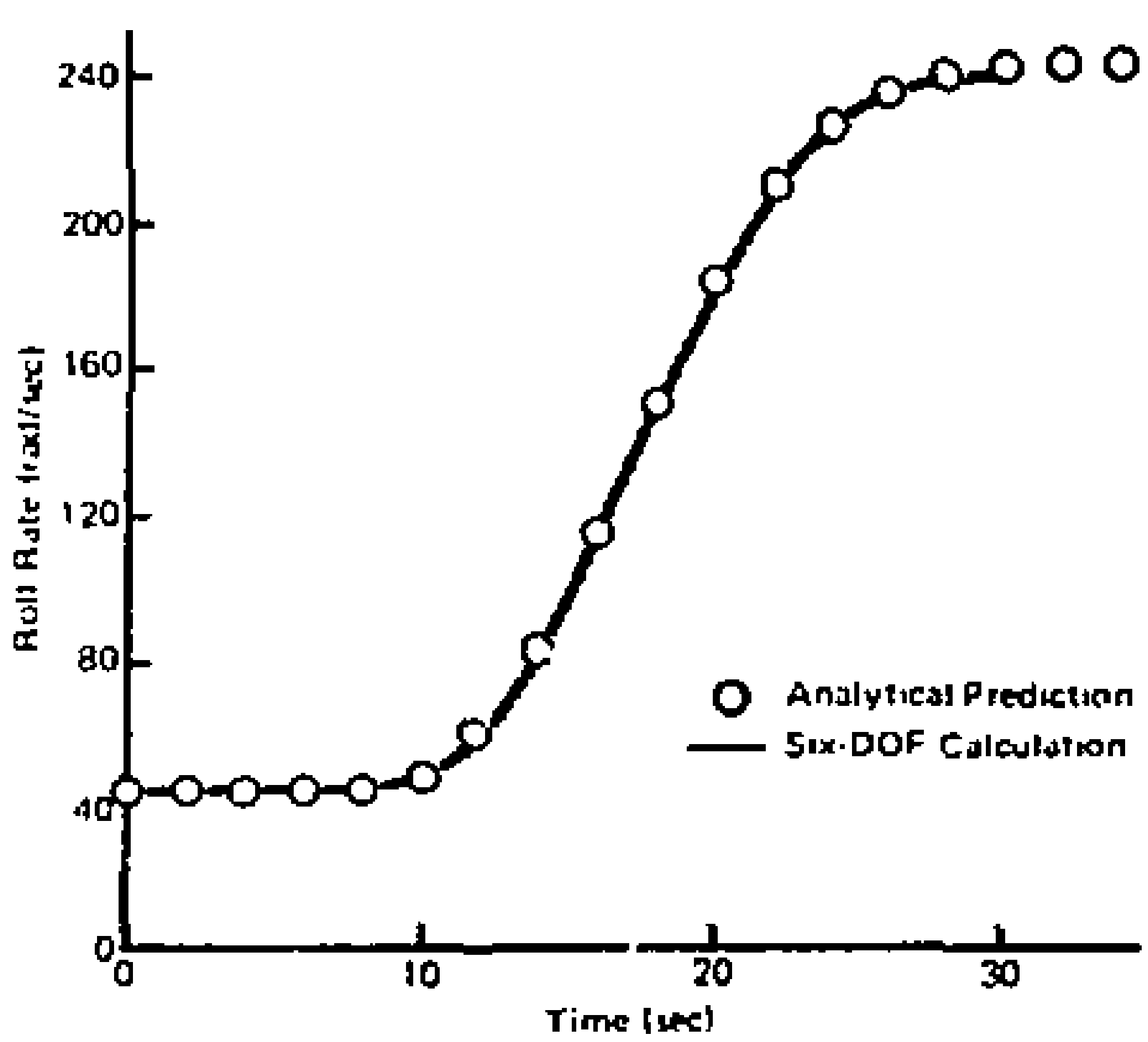

Figure 1. Example of mass asymmetry effect on reentry-vehicle roll rate.

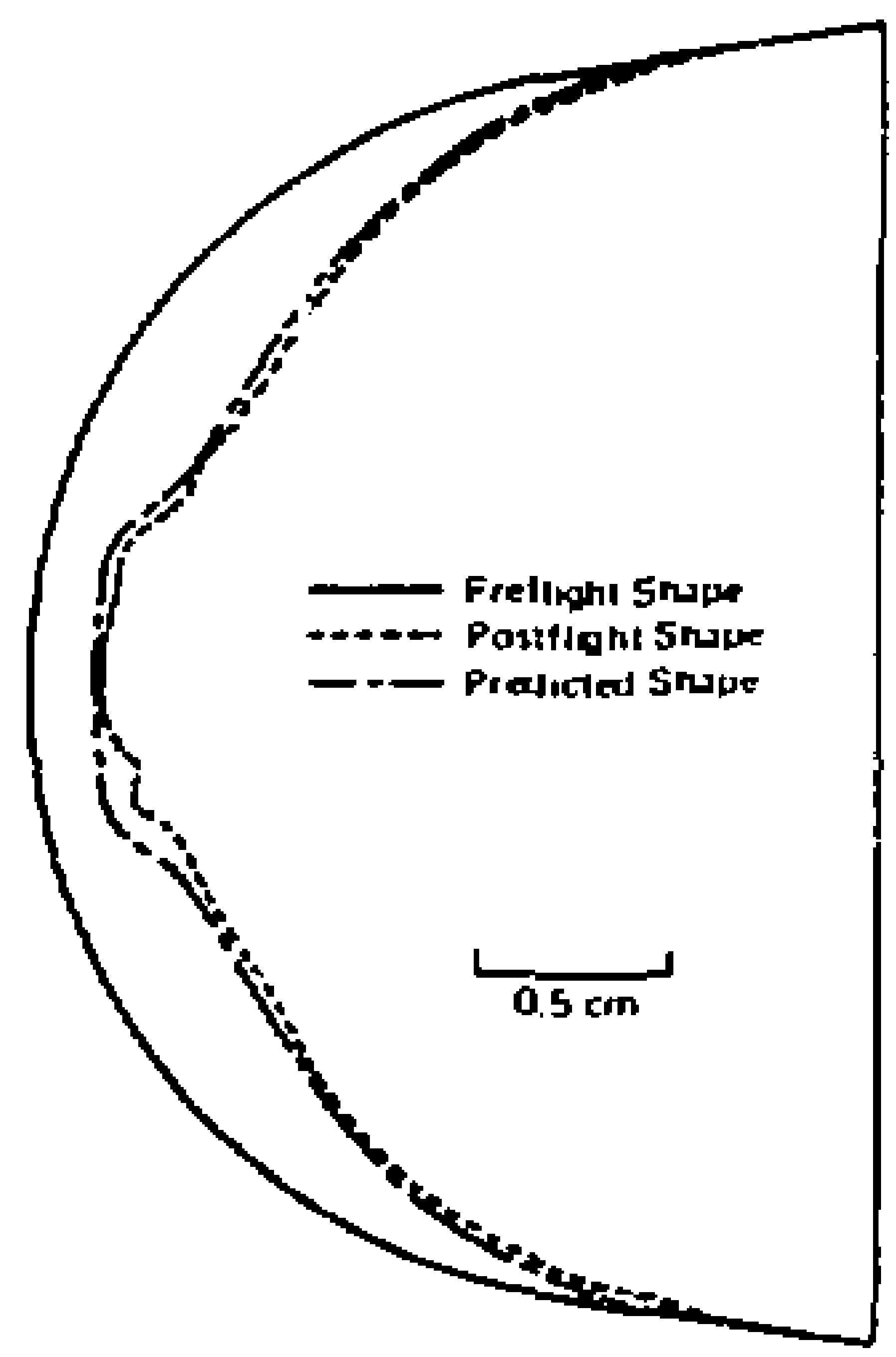

Figure 2. Comparison of predicted and actual nosetip recession.

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

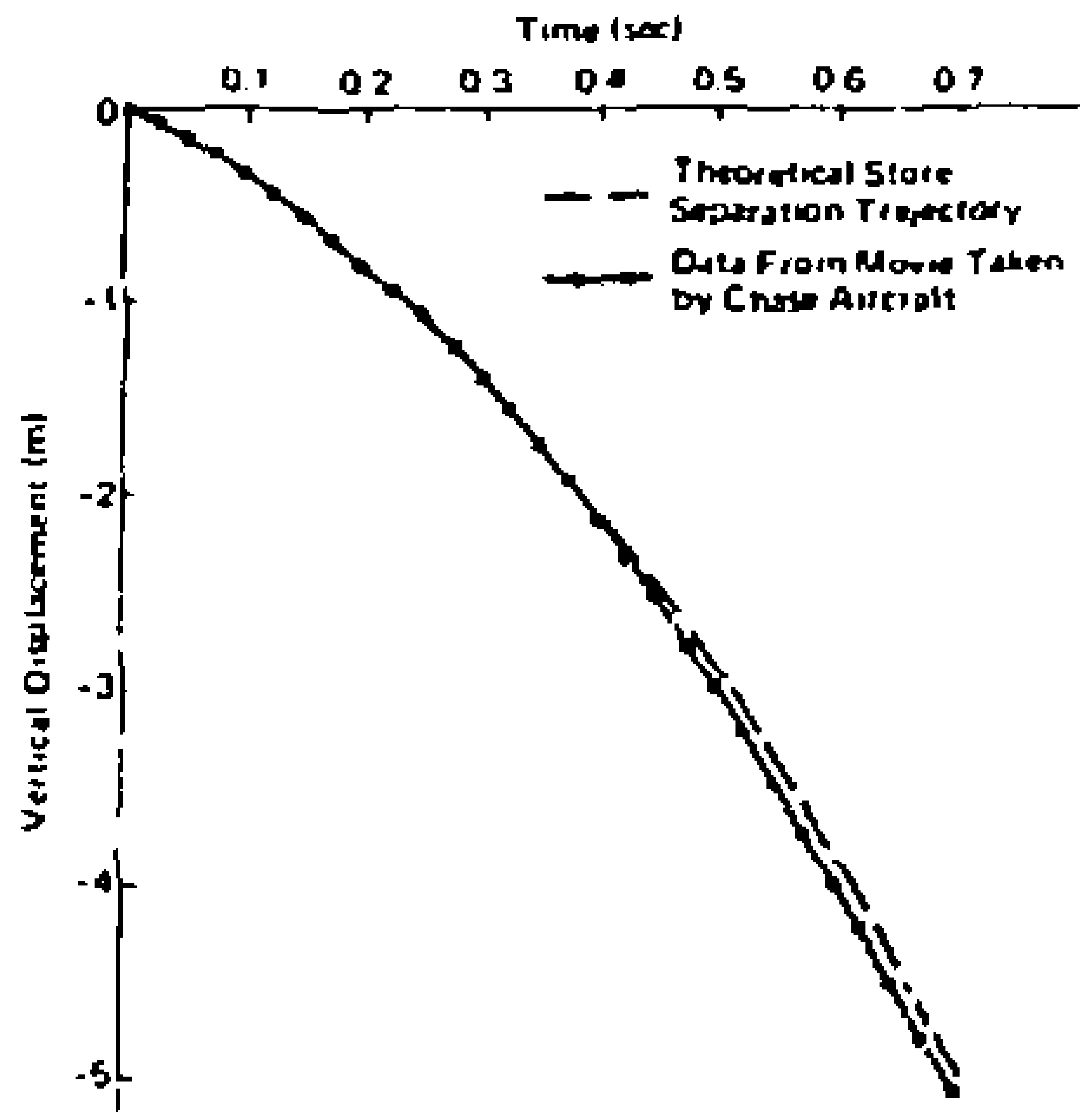

Figure 3. Comparison of theoretical and observed trajectories for a canard-controlled missile ejected from an F-4 aircraft (Mach number = 0.7 at 4600 metres altitude).

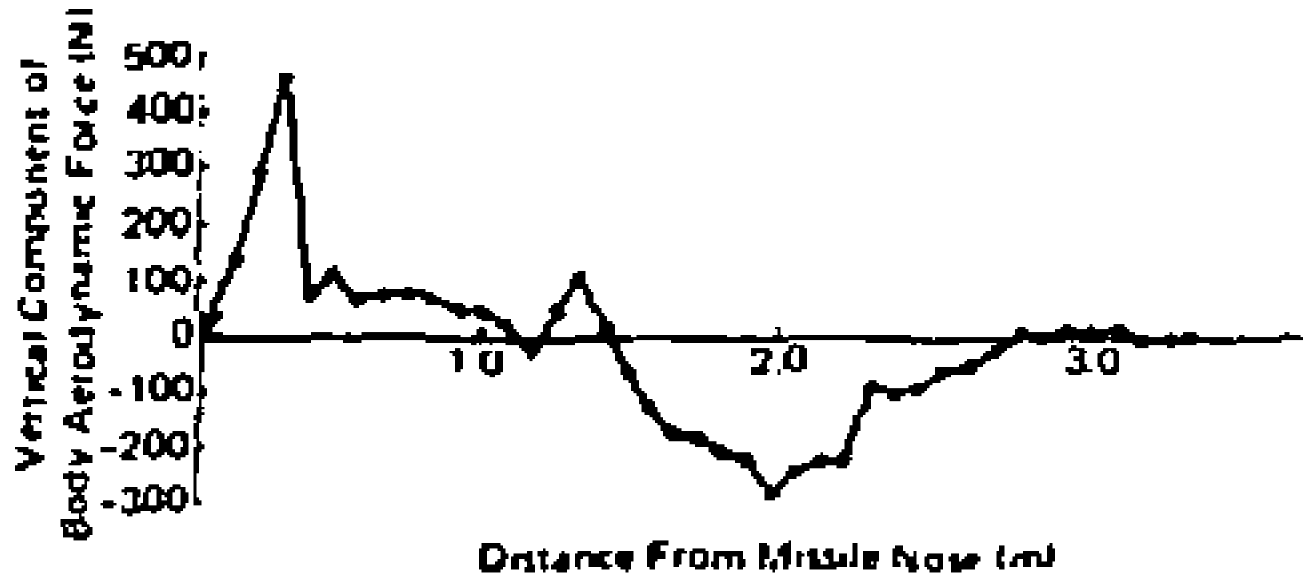

Figure 4. Calculated vertical component of aerodynamic load distribution along the body of a canard controlled missile on an F-4 aircraft (Mach number = 0.95, 4 g symmetric pullup at 2100 *metres altitude).*

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.

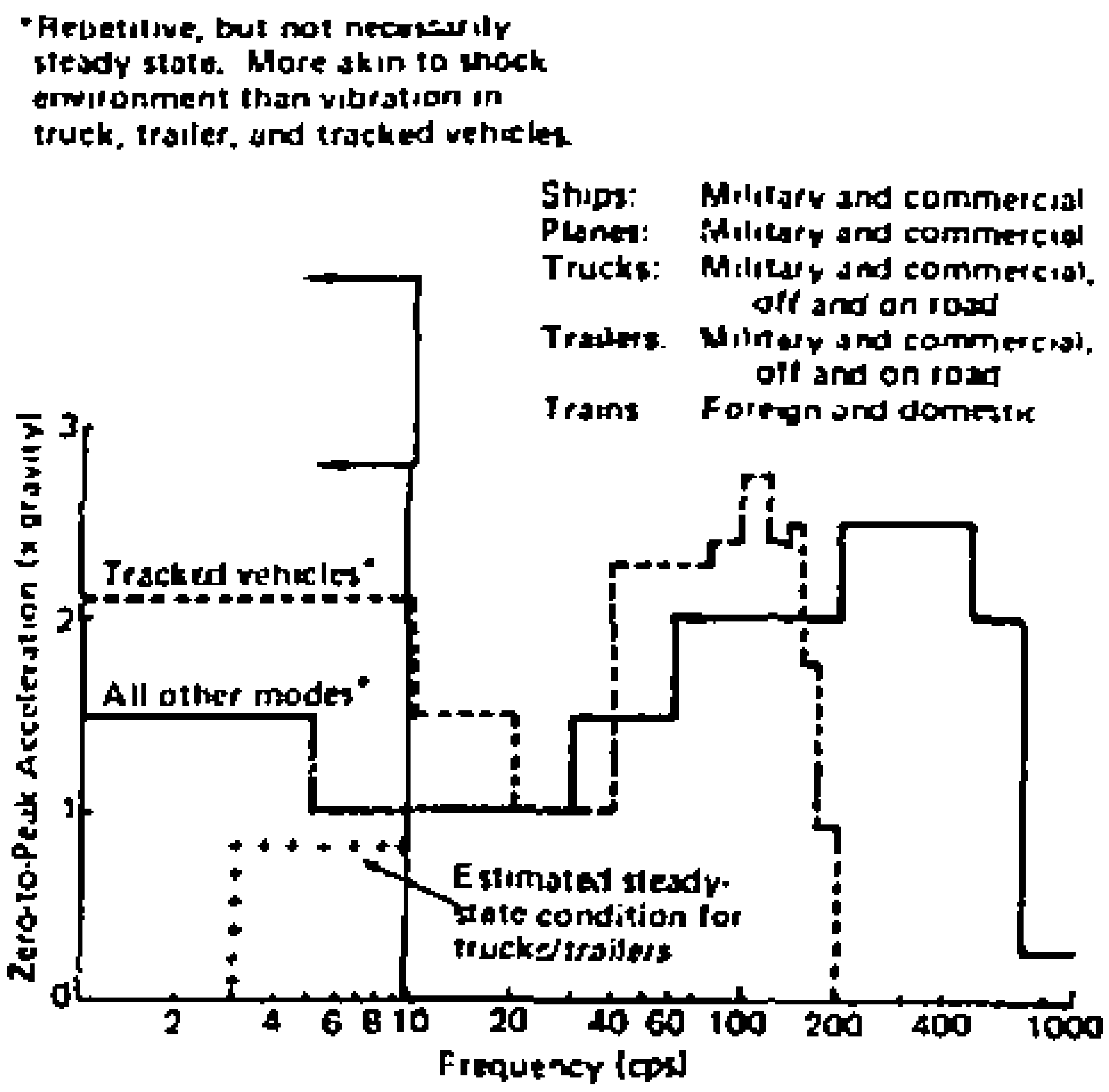

Figure 1. Envelope of 90-percent probable extreme vibration environment experienced by cargo in all modes of transport.

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_a/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.

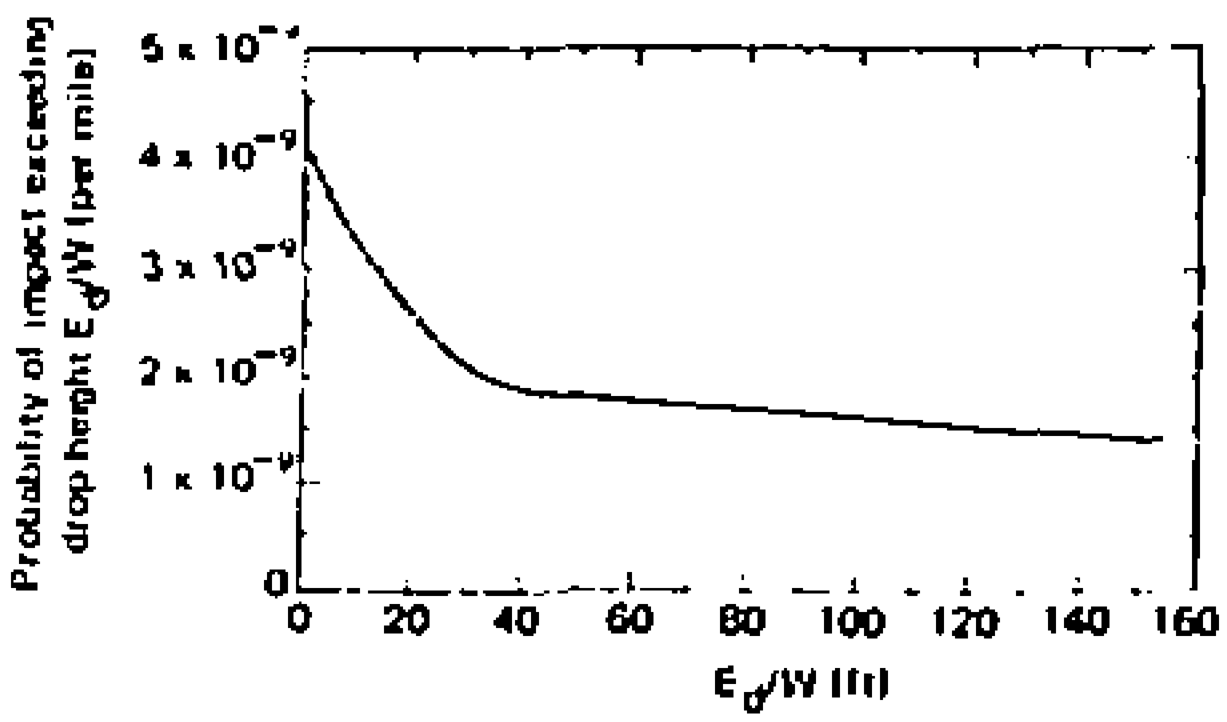

Figure 2. Probability of an aircraft accident producing an impact exceeding a given drop height, E_d/W, per aircraft mile.

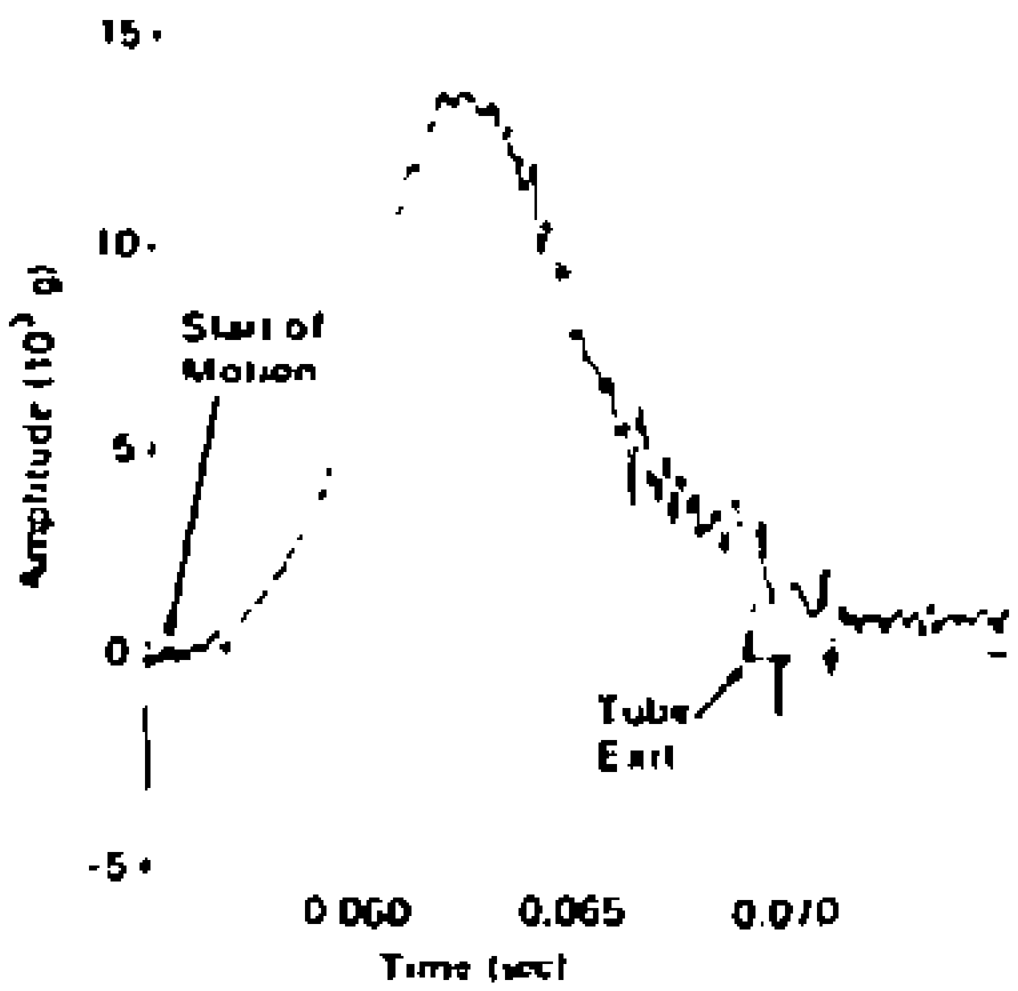

Figure 3. Axial acceleration of a projectile in 155 mm gun tube.

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

• • • • • • *HIGHLIGHTS* • • • • • •

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.

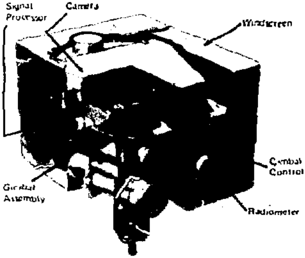

Figure 1. A low-cost, lightweight camera stabilization platform developed for shipboard application.

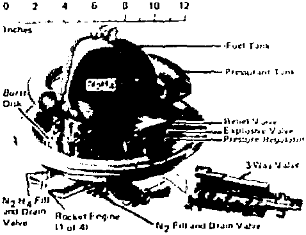

Figure 2. Rocket engine module.

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 microelectronic 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

ELECTRICAL ENGINEERING

HIGHLIGHTS

Item 1. *Analysis of Electrical Circuits Containing Exploding Wires*

A computer code has been developed to predict the behavior of lumped-parameter electrical circuits in which the resistance value of one or more elements is strongly affected by Joule heating. The code performs a numerical integration of the system of ordinary differential equations that describes circuit behavior. At each time-step of this integration the resistance values are updated using experimentally determined dependencies of resistivity on action $g = \int i^2 dt$. These resistivity functions have been measured for 23 metals, and are entered in the computer memory in tabular form.

The code has been applied to the design of firing systems for exploding-bridgewire detonators, to the prediction of circuit overload behavior resulting from fuse failure, and to other situations where Joule heating is of importance. Both tabular and graphic outputs are provided; an example of the latter appears in Figure 1, for the problem of discharge of a 4-μF capacitor bank charged to 250 V through a gold wire 0.0015 inch in diameter.

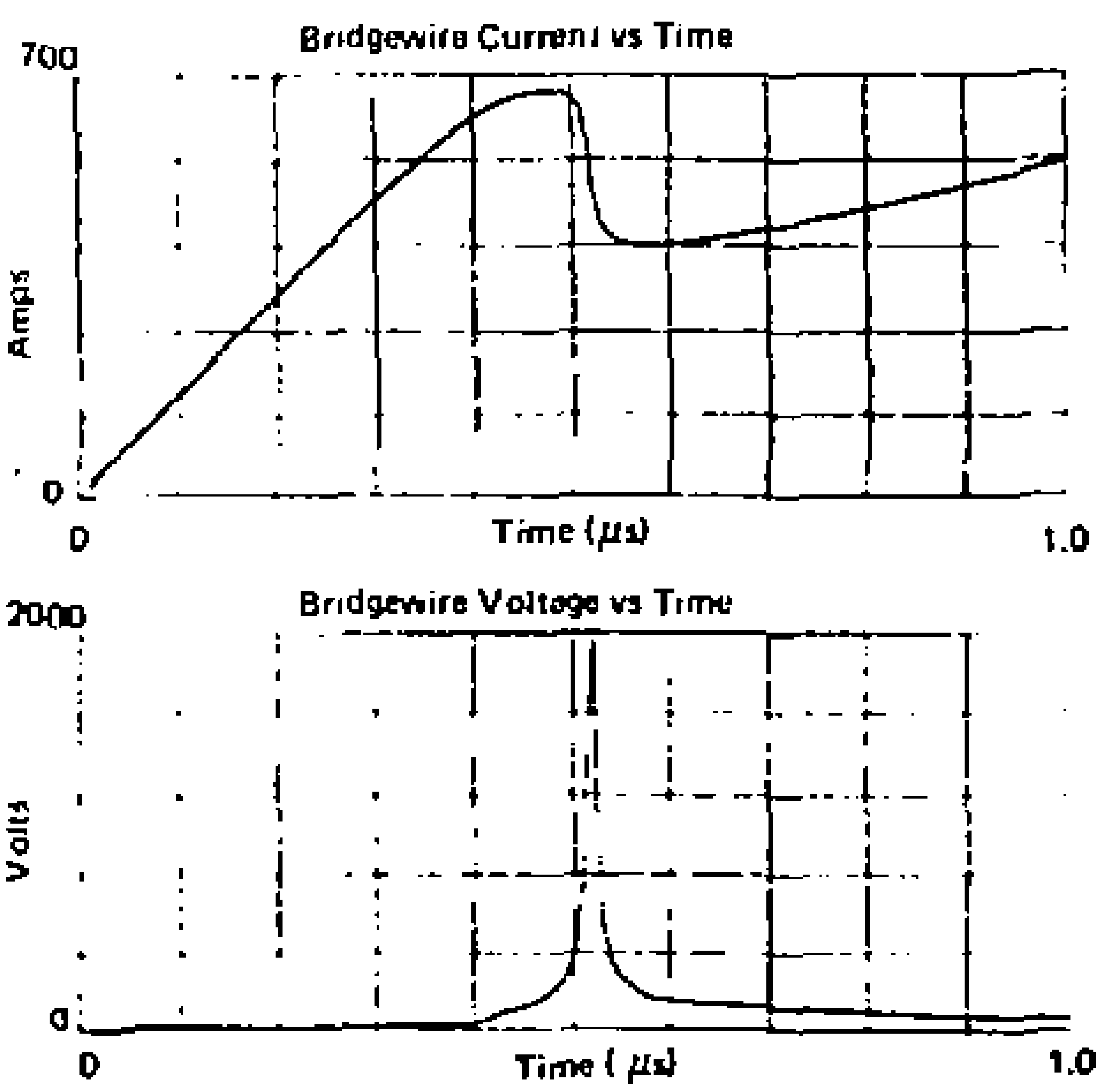

Figure 1. Computer program graphical output results for the analysis of a 1 μF, 1 μH, 0.1 ohm, 1000-volt capacitor discharge system exploding a 0.038 mm diameter by 1 mm long gold wire.

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.

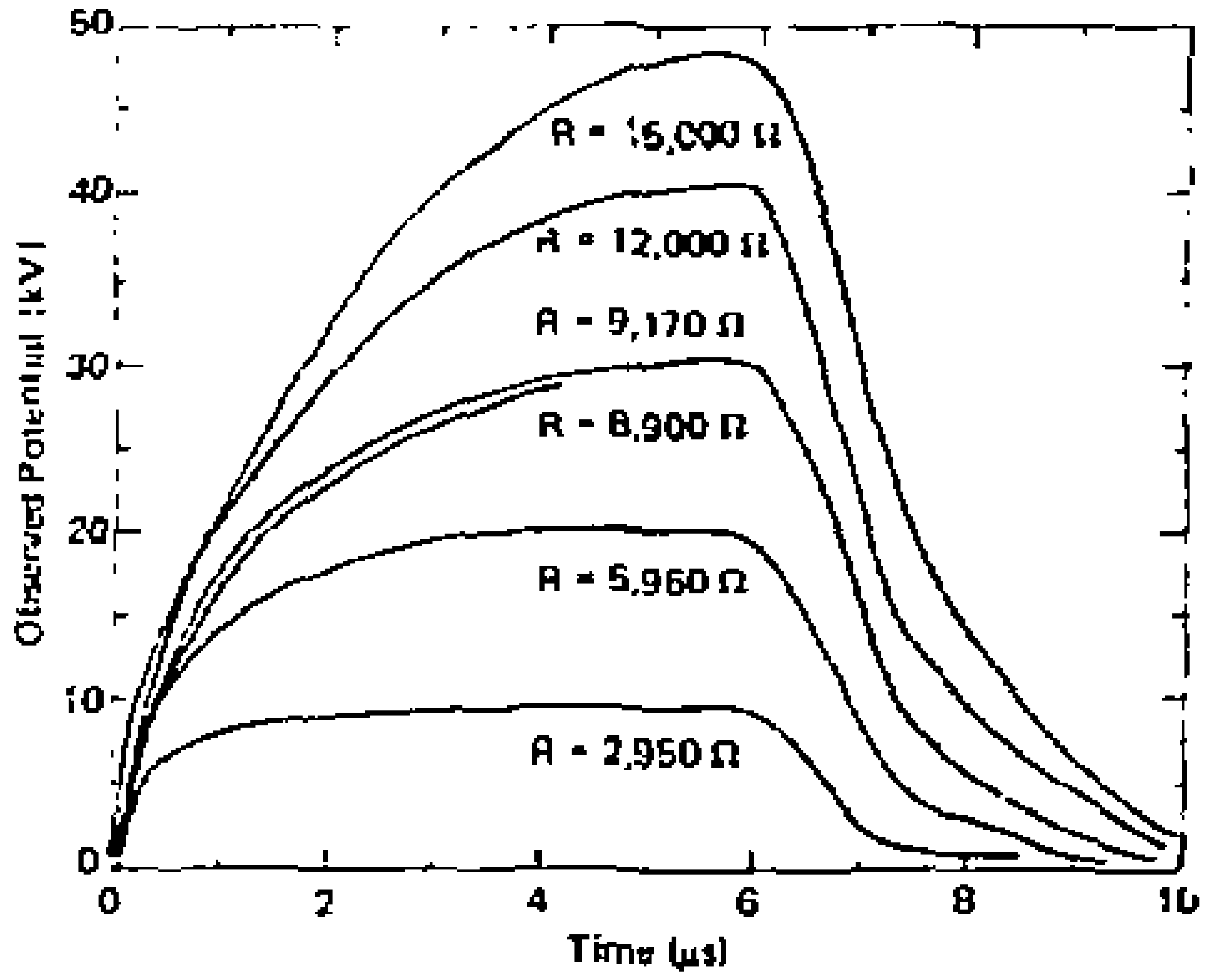

Figure 2. Electrical response of a shock-wave compressed ferroelectric ceramic.

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).

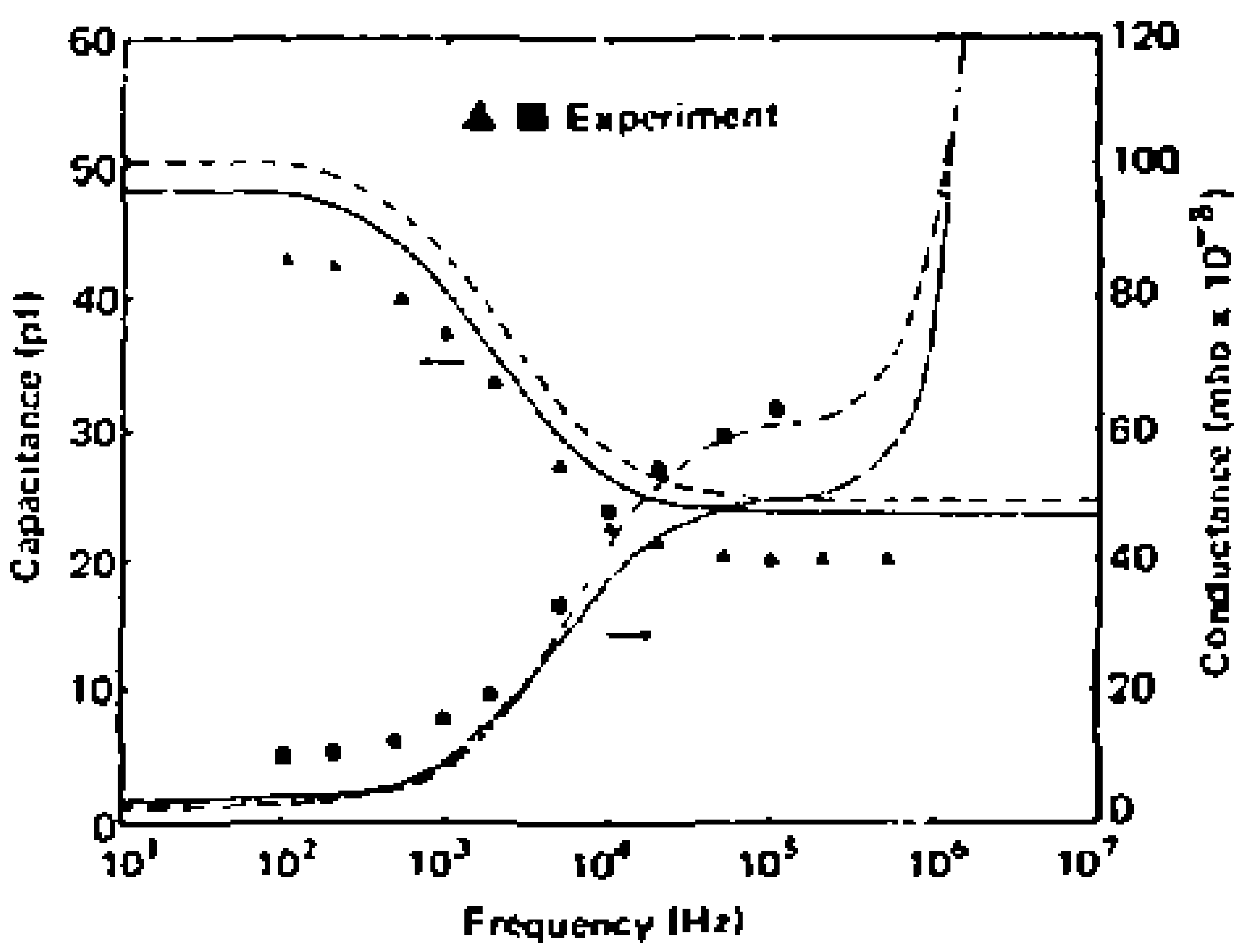

Figure 3. Calculated capacitance and conductance as a function of frequency for a gold doped diode at zero bias (N_t = 9.0 x 10^{14} cm^{-3}).

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

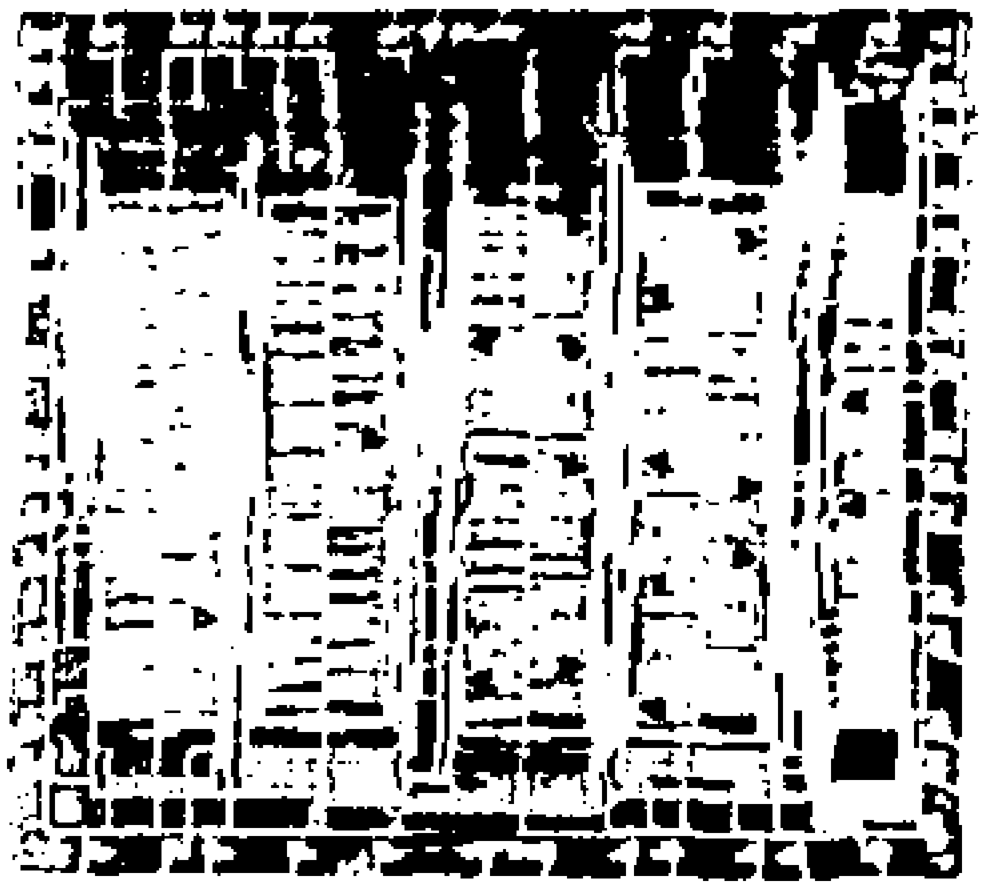

Figure 4. Photograph of timer integrated circuit (chip is 0.55 x 0.59 cm).

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.

ELECTRICAL ENGINEERING

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.

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

• • • • • • HIGHLIGHTS • • • • • •

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.

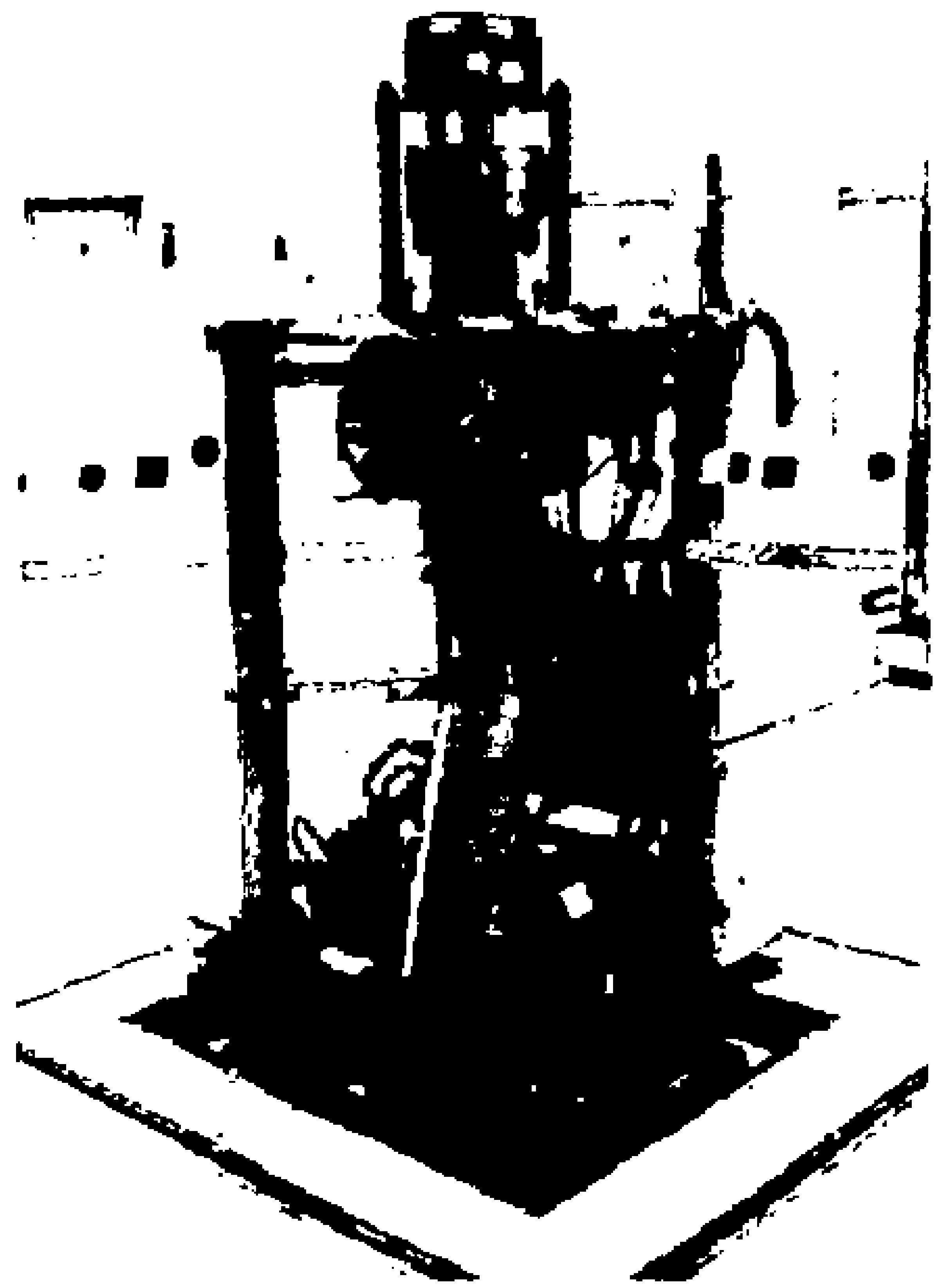

Figure 2. Sandia pulsed reactor II.

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.

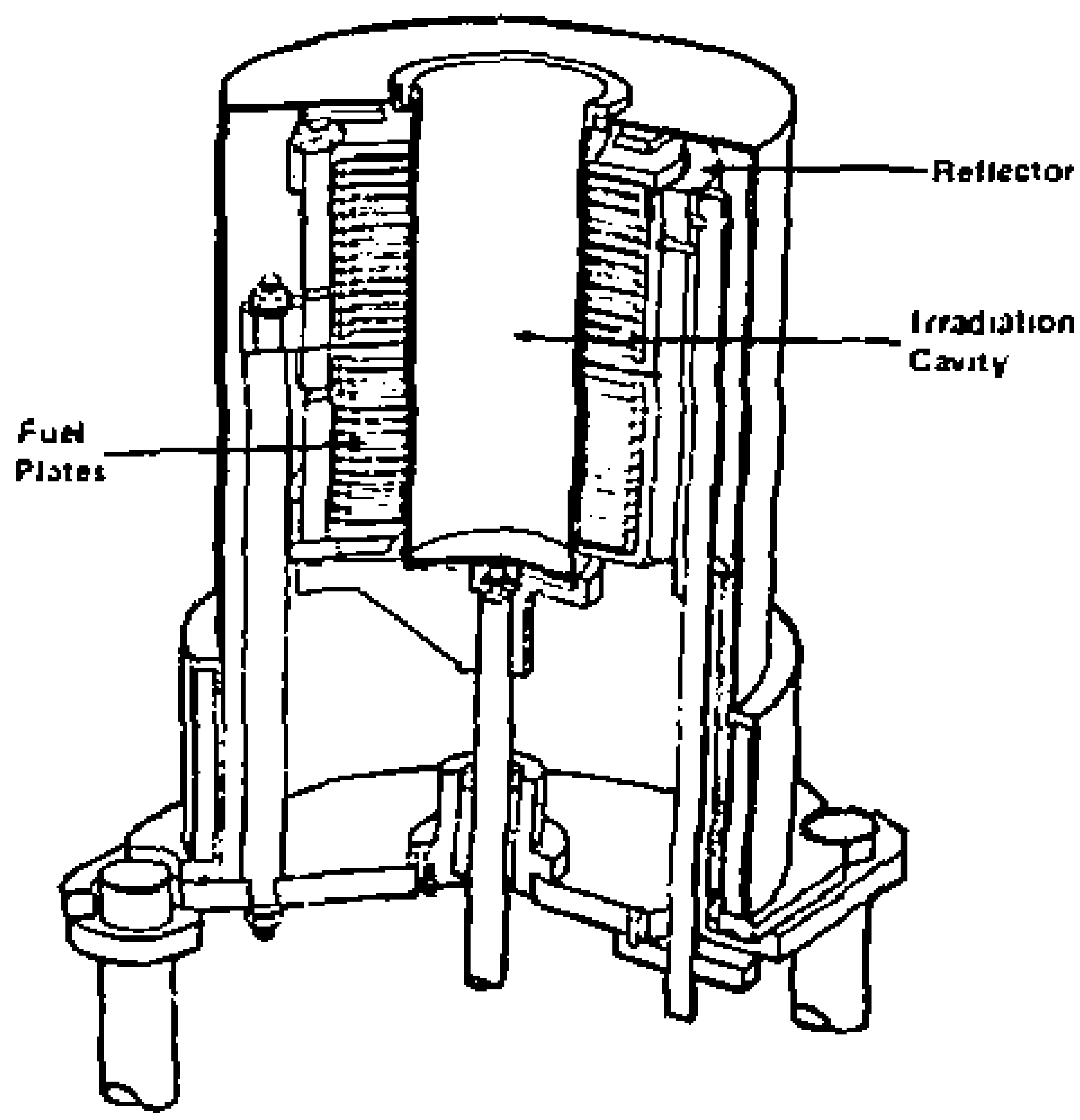

Figure 3. Sandia pulsed reactor III.

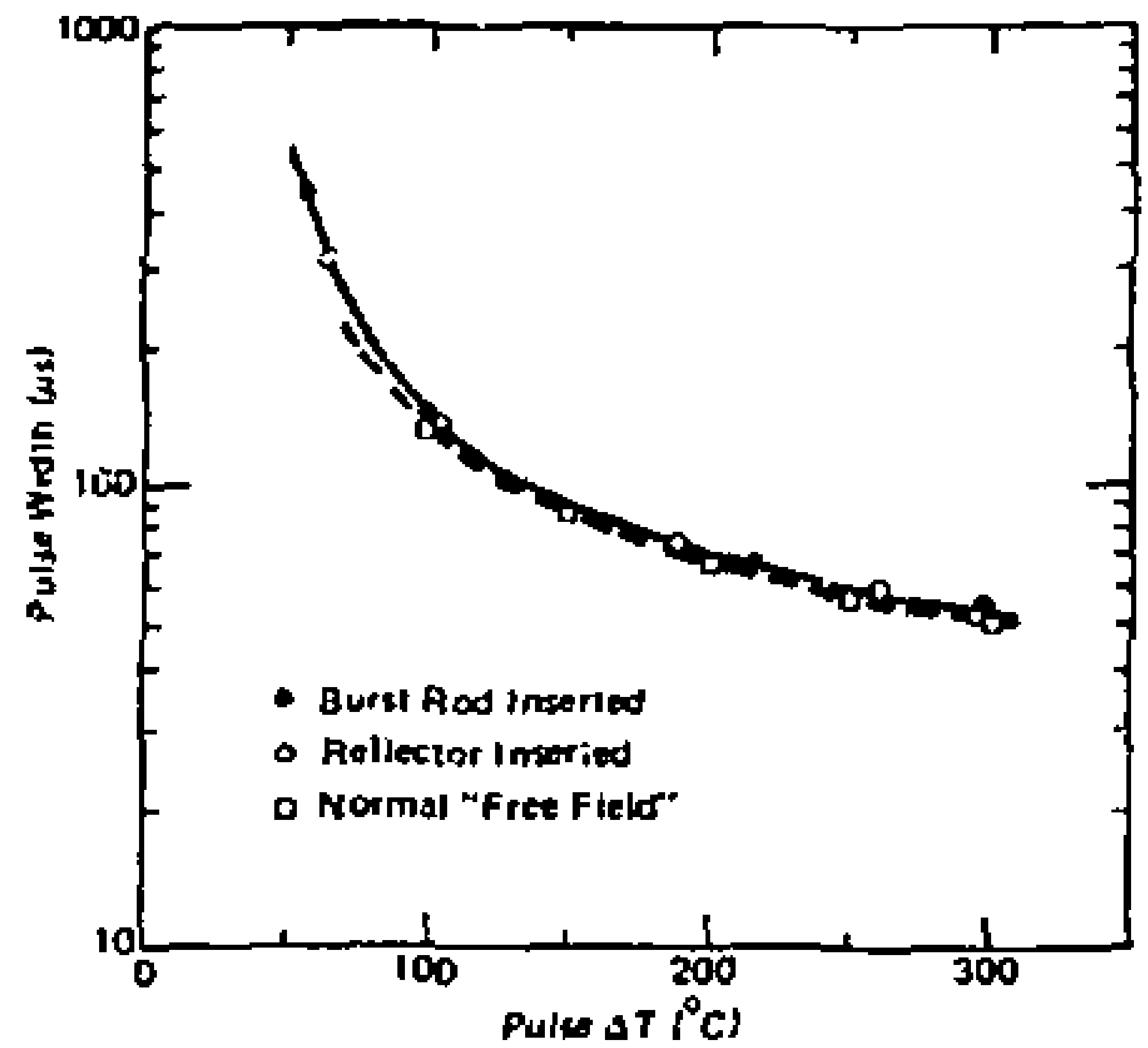

Figure 4. Results of pulsed reflector experiment.

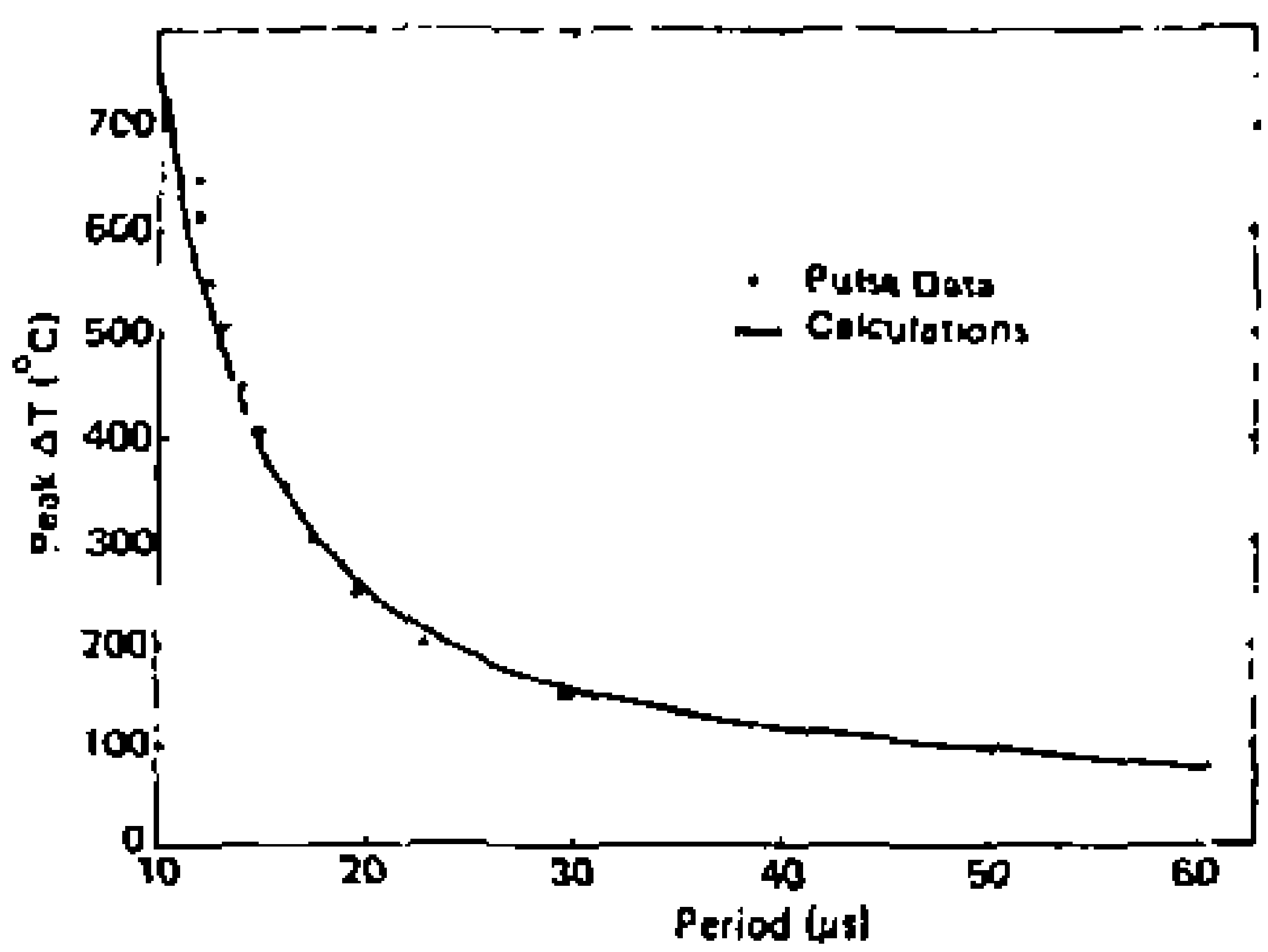

Figure 5. Yield vs period.

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
  - Light-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

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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, at 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 breech 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, [illegible] flow in the inlet-outlet nozzles was calculated for [illegible] 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 onshore 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.

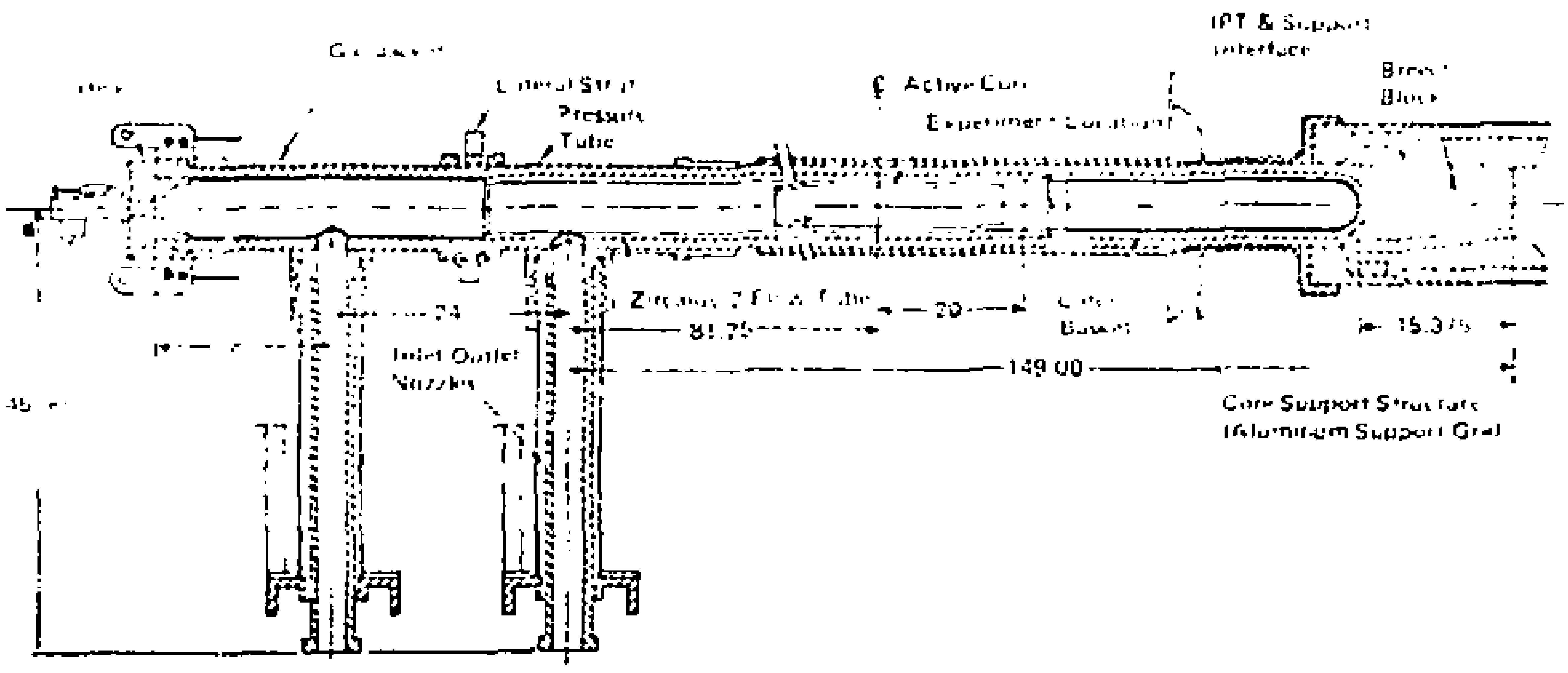

Figure 1. Axial cross-section of in-pile tube.

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 cracking
- 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

MATERIAL PROPERTIES

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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).

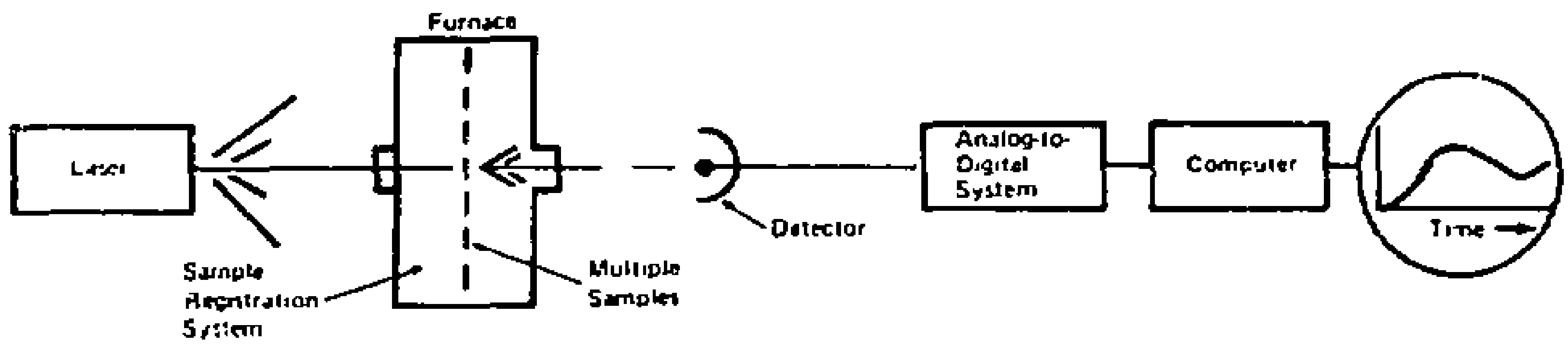

Figure 3 Pulsed thermal diffusivity measurements.