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Volume 1

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DIVISION OVERVIEW

B. G. Eads

The Instrumentation and Controls (I&C) Division of Oak Ridge National Laboratory (ORNL) has continued to make major contributions to important national programs during the past 2-year period. Important research and development (R&D) activities were conducted in support of nuclear energy, national defense, advanced manufacturing, materials research, basic science, and other programs. This report describes selected efforts representative of the range of activities from this report period.

The systems engineering expertise of the Measurement and Controls Engineering Section (MACES) is again demonstrated with their many accomplishments in the U.S. Navy's advanced submarine program. MACES has become a national leader in the technology of acoustic beamformer signal processing. The special-purpose measurement and analysis systems being developed include thousands of sensors, supercomputers, parallel array processing, and the associated software.

Image processing and acoustic signal processing have continued as major growth areas for MACES. The Automated Postage Stamp Inspection System was developed by a multiorganizational team led by MACES. This system was recently recognized by ORNL and by peers in a professional society as a significant engineering achievement. Extension of this technology into new applications is progressing in a multimillion dollar program for the Federal Bureau of Investigation. The work on stamps and currency has also led to the development of a major new capability in machine vision applications for inspection of web manufacturing processes. MACES is a leader in the formation of an ORNL, university, and industry R&D consortium with this area as its research focus. Additionally, efforts are under way on a cooperative R&D agreement involving inspection of ceramic substrate material used for high-temperature electronics. The integration of optics and electro-optics into inspection and other measurement systems is a growing area of applications R&D.

Applications in manufacturing and process control are both a long-standing and continuing MACES expertise through utilization of advanced techniques and intelligent controllers. A recent example is the use of chaos analysis to develop an improved control algorithm for a fluidized-bed process. Modelling and simulation of complex processes is used as needed in development, design, and implementation of new systems. Contributions to several ORNL programs have been made in the implementation of highly effective experimental data acquisition and analysis systems. Other areas of significant activity include electromagnetic interference/compatibility studies and solutions for a variety of applications, including ORNL research reactors and commercial nuclear power plants.

The Reactor Systems Section (RSS) is focused on nuclear plant I&C and is moving into new applications and work for different sponsors. Contributions to the conceptual design effort for the Advanced Neutron Source (ANS) have been a major endeavor. The design of the I&C and computing architecture will result in ANS being a showcase for digital control technology for the nuclear industry if it is implemented as envisioned. This system will integrate the functions of plant control, safety, security, management systems, and experimental control and analysis. In support of conceptual design, an analysis effort was conducted of the very challenging criticality safety issues that arise in the refueling of this radically different reactor. Additionally, the feasibility was investigated of monitoring subcriticality during refueling by the method of ^{252}Cf-source-driven noise analysis. New temperature and flux sensors are being designed to support the continued operation of the High Flux Isotope Reactor. These sensors are expected to update these designs to take advantage of the best commercially available technology.

RSS continues to be valued as an independent agent to support the nuclear power enterprise of the

United States. Research in aging of I&C components for existing light-water reactors (LWRs) in support of the Nuclear Regulatory Commission (NRC) has continued, with expansion into qualification of I&C systems for the Advanced LWRs. Under the sponsorship of the Electric Power Research Institute, guidelines are being developed for a framework that will assure the appropriate software verification and validation for upgrade of existing nuclear plants. The unique expertise of RSS in boiling-water reactor (BWR) thermohydraulic instabilities is regularly sought by NRC. This includes conducting theoretical studies that are leading to sizable cost savings in estimation of instabilities. A theoretical basis has also been developed which is leading to the commercial development of a portable stability measurement system for routine use in BWR plants.

The history of the RSS includes application of leading-edge techniques to the dynamic modelling and simulation of nuclear plants and other complex systems. The most recent accomplishment is the development of a simulation tool that utilizes object-oriented software techniques. The resulting environment offers very rapid creation, modification, and testing of dynamic models, as was successfully demonstrated for several reactor types.

The Research Instruments Section (RIS) is a major contributor to the development of custom electronics for national and international programs in high-energy and particle physics research. These applications typically involve thousands of channels of very high speed and ultracompact electronics, which often requires radiation hardening. Work is being done in support of the Superconducting Supercollider and the Relativistic Heavy Ion Collider. In addition to applications-specific electronics, work is ongoing in detector design and detector media studies.

Electro-optics R&D continues to expand into very exciting applications. For example, RIS was asked to develop a pointing solar radiometer for the Department of Energy (DOE) Atmospheric Radiation Measurement Program. Another element of this program is the pioneering work in modelling the structure of solar spectra for gases and particles in the atmosphere. Some very challenging optical metrology has been accomplished in the application of holographic interferometry to measurement of figure quality of aspheric optical components. The newest work in this field is research in hybrid optical-electronic processing for application to a neutron imaging detector.

RIS engineers have developed a variety of diagnostic techniques and systems. This includes work in current signature analysis, interrogation of structures by microwave, and fusion diagnostics. The support of the Laboratory infrastructure of health physics monitoring and safety is a long-standing mission of RIS. This effort is carried on in collaboration with I&C's Technical Support Department and the Laboratory's health physics organizations. Several upgrades have been completed or are ongoing. Development of new health physics instruments is also a continuing activity. Recent breakthroughs in ruggedizing detectors shows promise as the basis of a new generation of radiation detectors.

The Technical Support Department (TSD) underwent many changes in addition to its name change from the Maintenance Management Department. The rigor and emphasis on compliance within DOE has led to a greater emphasis on environmental and safety issues, thereby increasing the responsibilities of TSD. The TSD staff has risen to this challenge through new team building efforts and greater personal commitment to professional development. The Department is a leader in utilization of maintenance information management systems within the organizations overseen by the DOE Oak Ridge Field Office.

1. REACTOR SYSTEMS

1.1 OVERVIEW (D. N. Fry)

The primary mission of the Reactor Systems Section (RSS) is to support ORNL and DOE in the design and development of instrumentation and controls systems for research reactors and advanced nuclear power plants. Research, development, and engineering support are provided in five areas: (1) design and evaluation of advanced control concepts, (2) real-time dynamic simulation of nuclear reactors and balance-of-plant systems, (3) design of advanced instrumentation and measurement systems, (4) development and demonstration of plant monitoring and diagnostic systems, and (5) maintenance and upgrade of instrumentation and controls (I&C) systems in ORNL research reactors. The engineering capabilities and R&D facilities of the section also support other federal agencies such as the U.S. Nuclear Regulatory Commission (NRC), the National Aeronautics and Space Administration (NASA), and the U.S. Department of Defense (DOD); the Electric Power Research Institute (EPRI); electric power utilities; and private industry. Section R&D facilities include the Advanced Controls Computer Laboratory, a system simulation and evaluation laboratory containing an Encore parallel-processing computer and a number of Sun workstations; the Controls Engineering Laboratory, which includes control module development facilities and a three-loop benchtop water simulation of a piping system used to evaluate control concepts; the Surveillance and Diagnostic Methods Development Laboratory, which uses a variety of computer platforms to develop and evaluate nuclear plant monitoring and diagnostic systems; and the Supervisory Control Development Laboratory, in which advanced hierarchical supervisory control systems for advanced reactors are developed. Support of major ORNL missions by RSS includes design of I&C systems for the Advanced Neutron Source (ANS) and upgrade of the High Flux Isotope Reactor (HFIR) and I&C Engineering support of ORNL research reactors. Highlights of recent RSS activities are described below, with some additional details provided in the following sections.

Advanced Controls

Reactor Systems has gained national and international prominence as a leader in the development of advanced control concepts. Major funding is supplied by the DOE Office of Nuclear Energy for development and demonstration of automated control of the advanced liquid metal reactor (ALMR) by means of the Power Reactor Inherently Safe Module (PRISM). Because of the capabilities and prominence gained in this work, RSS has received additional support from the Babcock and Wilcox (B&W) Nuclear Plant Owners' Group to provide control concepts for upgrade of B&W plants and from EPRI for evaluation of fault-tolerant digital control systems and development of methods to verify and validate digital control systems. RSS recently entered into a cooperative research and development agreement (CRADA) with EPRI for the study of technologies and strategies for I&C upgrades in U.S. commercial nuclear plants.

Dynamic Simulation of Reactor Systems

RSS was a pioneer in the use of analog and hybrid computers to simulate the dynamic behavior of nuclear reactors and the associated heat removal of power production systems (balance-of-plant systems). These simulations have provided crucial information to aid designers and operations personnel in understanding the dynamic interactions of the plant with its control and protection systems. All RSS digital simulation facilities that use parallel processors, engineering workstations, and personal computers are now integrated in a computer network that provides unsurpassed computing power and flexibility for real-time simulation of nuclear systems. Current activities include simulation and dynamic analysis of PRISM, the modular high-temperature gas reactor, the Canadian Deuterium Uranium Reactor (CANDU-3), the ANS reactor, and B&W commercial nuclear plants.

Instrumentation and Measurement Systems

Measurements in nuclear plants, because of the sometimes harsh temperature, flow, and radiation environments (especially in the reactor core region), require specialized instruments and measurement systems. RSS designs and evaluates such systems to meet the needs of current and future plants.

RSS has developed a very high temperature, high sensitivity neutron flux detector and associated electronics to provide startup and power monitoring for PRISM. Also, a self-calibrating prototype resistance temperature detector (RTD) thermometer for space reactor applications has been developed and tested. Subcriticality measurement is a key process in the nuclear business, from fuel processing to plant startup to spent fuel transportation and storage. Historically, subcriticality measurements have always required that measurement systems first be calibrated by operating the multiplying medium in a critical state. This requirement is obviously impossible in fuel processing and storage facilities; therefore, engineers in RSS have developed a new method to measure subcriticality based on use of a californium isotope as a source of neutrons, two detectors (neutron or gamma), and novel signal-processing methods. Accurate subcriticality measurements can be made by using this method without the need for prior calibration at critical. We recently proposed to use this methodology to monitor reactivity during fueling of the proposed ANS reactor.

Plant Monitoring and Diagnostic Systems

Safe and reliable operation of nuclear plants requires that the plant operators have accurate, timely information regarding plant status and the condition of key plant equipment and systems. The current availability of very fast computers with massive data storage capability is making it possible for engineers in RSS to develop and evaluate plant monitoring and diagnostic systems that provide timely information and advice to plant operators and maintenance personnel to assist them in plant operations. A system was developed for HFIR that uses advanced signal processing, analysis, and display techniques to inform operations personnel regarding plant status. Experience gained at HFIR is being incorporated into early design concepts for a total plant information management system for ANS. RSS is also a major participant in the newly established ORNL Diagnostic Engineering Center.

Maintenance and Upgrade of I&C Systems in ORNL Reactors

RSS has a very strong commitment to support the complete life cycle of I&C systems in ORNL research reactors. This section has played a significant role in the design, installation, and maintenance of I&C systems in all ORNL reactors. As reactor I&C systems age, it sometimes becomes difficult to maintain them because replacement parts are unavailable. We are currently providing support to the ORNL Research Reactors Division (RRD) to upgrade these I&C systems with state-of-the-art hardware. A conceptual design has been submitted to RRD for replacement of obsolete neutron flux and temperature sensors in HFIR. We are also modifying the HFIR safety system to reduce the frequency of unscheduled shutdowns caused by electromagnetic noise.

New Measurement Technologies

In addition to our mission in nuclear plant I&C, RSS has recently made a number of significant contributions in new measurement technologies. For example, we recently developed and implemented a new instrument for noninvasive measurement of the pressure in vacuum-sealed thin-wall packets. Another new development, a sampling system for subsurface in situ soil gas, should greatly facilitate characterization of DOE waste storage sites. We recently completed an exploratory study for EPRI to assess advanced pressure sensor technology for upgrade of electric power plants. These examples illustrate the RSS expertise in advanced measurements.

1.2 RESEARCH REACTOR SYSTEMS

1.2.1 New Temperature and Neutron Sensors for the High Flux Isotope Reactor

The I&C Division was requested by RRD to prepare procurement specifications for replacement RTDs and ionization chambers for the HFIR safety and servo-control channels and to design related assemblies such that the new sensors and assemblies will be compatible with existing equipment and meet all current performance requirements.

The original HFIR ionization chambers were designed as multisectioned chambers having special features that experience has shown are no longer necessary (i.e., sections for gamma compensation and for on-line chamber testing). These chambers, designated PCP-II and PCP-III, used ^{10}B-coated, parallel circular plates stacked with appropriate spacings to provide high neutron sensitivities and low gamma sensitivities in small volumes. The PCP chambers performed well, and it had been our hope that the commercial sector would manufacture this type of detector. However, because of high manufacturing costs and a limited market, no commercial organization has been willing to commit to manufacturing the PCP chambers. At today's labor rates and material charges, the cost for ORNL to fabricate the PCP chambers would also be unreasonably high.

RSS has, therefore, designed a new two-section neutron detection system using two commercial-grade ionization chambers (Fig. 1.1). The ionization chambers have cylindrical electrodes coated with ^{10}B; one chamber or section provides the safety channels (protection system) an electrical current proportional to the power of the reactor, and the second section provides a similar signal to the servo channels (automatic control system). These chambers, which are positioned side by side in a container of the same design as that of the PCP chambers, are considerably longer (sensitive length of 7.50 in. as compared with 1.88 in.) than the PCP chambers and, therefore, experience significant neutron flux gradients across their sensitive volumes when positioned in the reactor. Calculations have shown that the neutron sensitivities of the new chambers should be comparable to those of the PCP chambers and that the neutron-to-gamma current ratio is >10 in the power range. These new assemblies, designated the commercial cylindrical chambers (CCCs), will be fabricated by a commercial organization for a cost considerably less than that for fabrication of the PCP chambers.

In addition to the design of the CCCs, RSS designed a temperature measurement system for the primary loop of HFIR. As with the PCP chambers, the manufacturer of the original system was unable or unwilling to reproduce what had become an obsolete system. It became necessary and, in fact, desirable for RSS to design a new system using today's technology. This effort required the redesign of the RTD probe housings and the penetration beam assemblies into which the RTDs are inserted and to which the probe housings are attached. The new units were designed to ensure the integrity of the pressure boundary of the primary system and to provide physical protection for the sensor probes. Industry-standard four-wire platinum, 200-Ω resistance thermometers and transmitters that provide 10- to 50-mA output signals will be used. Because of the additional mass of the new probe housings, the RTD systems will have a response time of 5 s, as compared with the originally specified but unconfirmed response time of 2 s. The acceptability of the 5-s response time is being studied by RRD. Otherwise, the new RTD systems meet all performance requirements, and because of the simple design, the robust components, and the improved RTDs, longer term acceptable performance should be attainable.

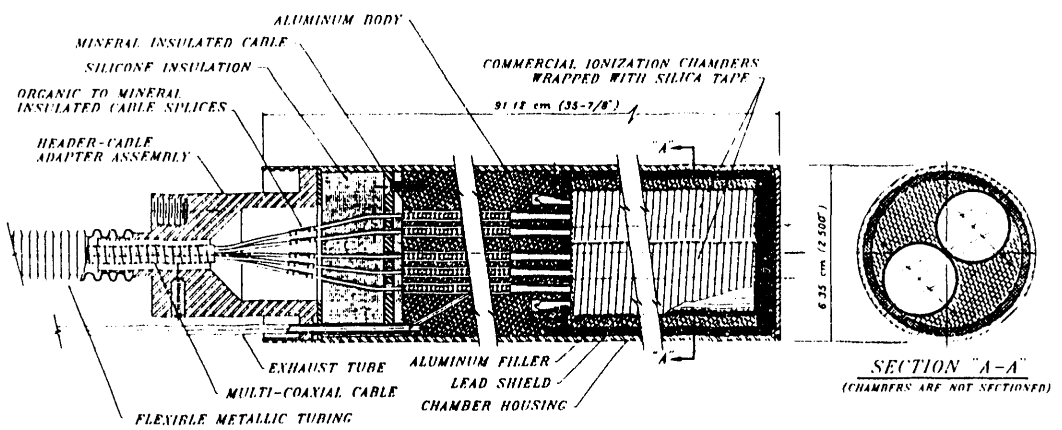


Fig. 1.1. Two-section neutron detection system using two commercial-grade ionization chambers.

1.2.2 Reactivity Monitoring During Fueling of the Proposed Advanced Neutron Source Reactor

Fueling of the proposed ANS reactor is unique in that the core is composed of two different-diameter annular fuel elements, each of which is supercritical when moderated and infinitely reflected by heavy water. The neutron multiplication factors for the upper and lower fresh fuel annuli are 1.2 and 1.1 respectively. These high neutron multiplication factors require careful design and detailed criticality safety analysis at each step of the fueling process to ensure that criticality is not a major safety issue. To maintain the fuel elements subcritical in heavy water, suitable materials must isolate the elements from the heavy water and move with each of them until their insertion into the reactor core positions where the control and safety rods can maintain subcriticality. A preliminary analysis was made of possible materials with which to isolate the fuel annuli from the heavy water reflector and internal moderator to maintain subcriticality during fuel loading. Also, ^{252}Cf-source-driven-noise analysis was evaluated as a possible method for measuring the subcriticality and verifying the refueling procedure in the critical experiments program; an additional objective was to determine whether the use of the method is appropriate during the fueling of the ANS reactor. The scope of the task reported here was limited to neutronic calculations. Other considerations such as decay heat will subsequently be evaluated. This criticality safety evaluation contributes to the more complete feasibility studies of this concept by the ANS project staff.

For this study, structural materials were chosen as isolators because their presence can be verified visually to ensure subcriticality and because they protect the fuel element from mechanical damage during the loading process. This analysis shows that either an inner SS 304 isolator or an outer aluminum isolator will isolate the fissile material from the heavy water and will maintain the neutron multiplication factor (k) below 0.95. Thus, two independent methods are available for maintaining $k < 0.95$ because both materials can be independently held in place. The thickness of isolators required to meet the shutdown criteria was determined by using the KENO–Va Monte Carlo neutron transport code. With both inner and outer isolation materials present, the calculated neutron multiplication factors for the upper and lower configurations were 0.653 ± 0.002 and 0.769 ± 0.001 respectively.

The feasibility of monitoring subcriticality during fueling was investigated by using Monte Carlo calculation of measurements by the ^{252}Cf-source-driven-noise analysis method to obtain the autopower spectral densities (APSDs), cross-power spectral densities (CPSDs), coherences, and ratios of spectral densities as a function of frequency. Calculations were performed by using the modified version of KENO Va for various stages in the refueling process such as in the interim fuel storage canal and the transfer shaft that extends down to the top of the reflector vessel. The ^{252}Cf source was located in the inner stainless steel isolator at midplane. The detectors were two 51-mm-diam, 0.53-m-long ^{3}He proportional counters located on a diameter in the outer isolator and adjacent to the outer surface of the fuel element with the detector and fuel element axes parallel. The diameter on which the source was located was perpendicular to the diameter on which the detectors were located. For this application, the ^{252}Cf source and the neutron detectors in the isolators would move with the fuel element to above the reflector tank and thus could provide continuous monitoring of the subcriticality as the fuel element is moved.

Monte Carlo criticality safety calculations have shown that the use of appropriate structural materials will maintain adequate subcriticality during the fueling of the ANS reactor. In addition, the isolators surrounding the fuel element minimize the chance of mechanical damage to the fuel elements during refueling. These analyses also indicate that the ^{252}Cf-source-driven-noise analysis method is a viable way of monitoring the subcriticality as each ANS reactor fuel element is loaded into the reactor. This method will be evaluated experimentally in the ANS critical experiments program.

1.2.3 Instrumentation, Control, and Computing Architecture for the Proposed Advanced Neutron Source Reactor

ANS is a proposed basic and applied research facility based on a powerful steady-state research reactor that will provide neutron beams for measurements and experiments in the fields of materials science and engineering, biology, chemistry, and nuclear science.

Engineers from the I&C Division, Central Engineering, and the project architect-engineer (Gilbert/Commonwealth) worked as a team to support research, development, and design efforts, leading to a 12,000-page, 340-drawing conceptual design report that includes system design descriptions, a conceptual safety analysis report, and a cost estimate. The architecture described below is a key element of this conceptual design that supports all ANS control and computing functions.

The instrumentation, control, and computing architecture integrates computing and telecommunications systems that provide plant control, safety, security, business, and experimental computers in a manner that (1) meets ANS plant requirements, (2) is licensable, and (3) is sufficiently flexible to accommodate new technologies. The architecture implements a philosophy of using distributed control system technology as much as possible, using highly integrated operator displays, and grouping control and computing in a manner that allows the particular requirements to be addressed specifically. The architecture includes a plant data communications backbone, a reactor protection system (RPS), two plant control and data acquisition systems (PCDASs), a plant simulator, a business data handling system, a data collection system, and a security system. The plant data communication backbone uses local area networks to link these systems in such a way as to provide integrated data for operators, supervisors, and engineers, while allowing data and cabling to be segregated and isolated to meet regulations (such as for security and reactor safety) as well as to meet performance requirements. A diagram of the backbone communication system and its hubs in the ANS buildings is shown in Fig. 1.2.

RPS consists of the primary reactor shutdown system (PRSS), the secondary reactor shutdown system (SRSS), and the experiment protection system (EPS). EPS monitors experiments in the reactor and initiates controlled setback or reactor trip to protect against experiment failures that may threaten reactor safety. PRSS and SRSS are redundant, independent systems with designs similar to those of commercial reactor protection systems, but they have some requirements—most important is fast time response—that are different from those of commercial protection systems. Because some RPS requirements are different from those of commercial protection systems, the I&C Division will support development and testing of a prototype RPS. Nonsafety control and monitoring is performed by the non-Class 1E PCDAS, and safety control and monitoring is performed by the Class 1E PCDAS and RPS.

The I&C Division will provide staff as members of the ANS I&C team to prepare functional specifications, provide technical oversight, and perform research and development support for design, procurement, construction, testing, and startup.

1.3 POWER REACTOR SYSTEMS

1.3.1 Assessment of Boiling Water Reactor Stability

ORNL is recognized worldwide as a leading organization in the area of boiling-water reactor (BWR) thermohydraulic instabilities through the involvement of I&C Division personnel in research and development in this field. I&C Division efforts over the years have ranged from theoretical studies about the underlying causes of instabilities to the development and application of test techniques and devices to measure the stability of operating reactors. As part of this ongoing effort, I&C Division personnel have provided technical support to NRC staff in three general areas related to BWR stability: numerical calculations of dynamic parameters, stability tests in commercial reactors, and review of stability calculation and measurement methodologies submitted to NRC by utilities and reactor vendors. A unique ORNL capability is the LAPUR computer code, which was developed and is maintained at ORNL for NRC. LAPUR calculates reactor transfer functions in the frequency domain and estimates the stability of the reactor. LAPUR has been benchmarked successfully against a large number of reactor tests and is one of the industry-standard codes for BWR stability analyses.

Along with having a main mission to provide the technical basis for NRC reviews of industry proposals in the area of BWR stability, we have continued to be in the forefront of research and development. Among recent ORNL contributions in this area are the following highlights.

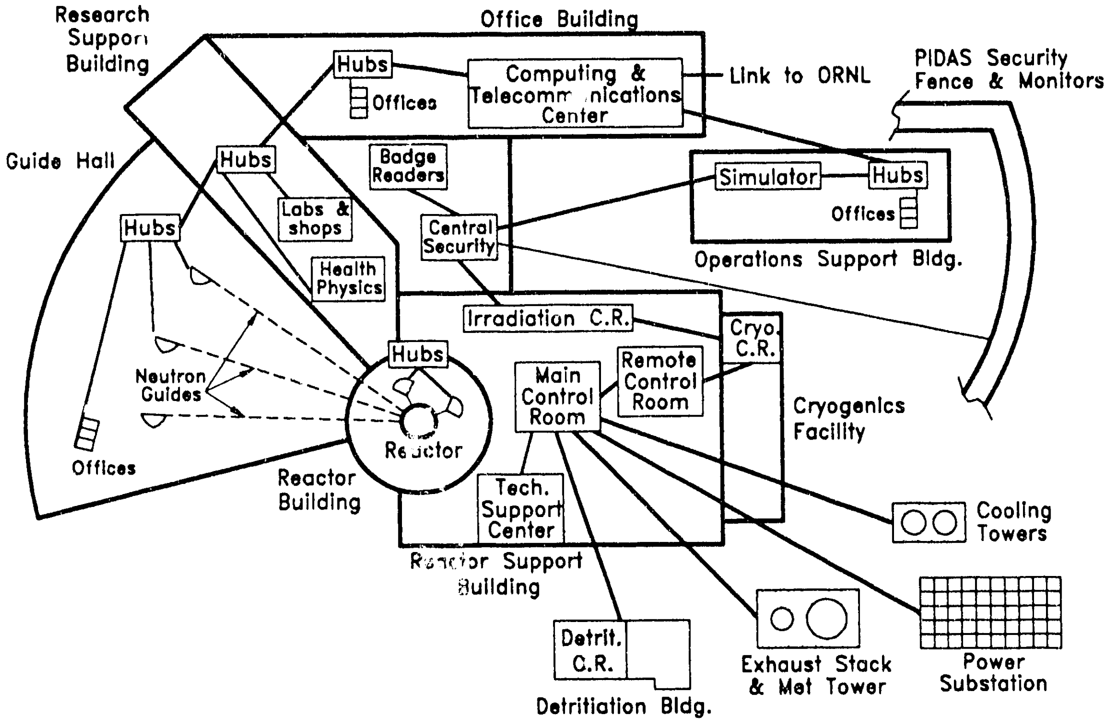


Fig. 1.2. Instrumentation, controls, and computing architecture for the Advanced Neutron Source reactor.

- Particular among theoretical developments that explain the basic mechanisms for the several types of instability that have been observed, ORNL established the theoretical basis that identified the so-called "out-of-phase instability mode" as a coupled instability between the first azimuthal mode of the neutronics and a parallel-channel type of thermohydraulic instability. This theoretical development allowed for simplified frequency-domain analyses that can estimate the stability of the out-of-phase mode with several orders of magnitude less cost than would be required by three-dimensional neutronics time-domain calculations.
- The development of techniques to obtain time-domain nonlinear information such as limit-cycle oscillation amplitude from linear frequency-domain calculations led to an upgrade of the LAPUR code, so that it now estimates the oscillation amplitude for small-amplitude limit cycles.
- Development of the theoretical basis as well as analysis techniques to estimate the stability of commercial BWRs from nonintrusive neutron noise measurements led to the development of a portable stability-measurement device that has been used in several stability tests in U.S. BWRs. The ORNL-developed algorithms are being used in the industry for on-line and off-line stability measurements and are the basic components of commercially available systems. One such system is currently used in the WNP-2 BWR of the Washington Public Power Supply System to satisfy a technical specification requirement to monitor plant stability during recirculation pump upshifts at high power.

1.3.2 Aging Assessment of Reactor Instrumentation and Protection System Components

This study, performed for NRC, examined the effects of aging on equipment performance and normal service life and concentrated on six specific instrumentation categories: indicators, sensors, controllers, transmitters, annunciators, and recorders. A basis founded on power plant practices was employed in selecting the boundaries for I&C module categories used in the study. This basis is primarily the set of modules for which plant I&C departments are responsible and which are used in systems considered *important to safety*. These categories were selected because of their importance in the operations of safety-related I&C systems and because they have not been reviewed previously by the NRC Nuclear Plant Aging Research (NPAR) program.

In accordance with the NPAR program philosophy, this study had three objectives.

1. Identify aging stressors and the likely effects of these stressors on I&C modules.
2. Identify, by examination of operational history, those safety-related I&C modules most affected by aging.
3. Identify, where possible, methods of inspection, surveillance, and monitoring that will ensure timely detection of significant aging effects prior to loss of safety function.

The approach of the study was to examine nuclear industry experiences that have affected the aging of I&C modules. This examination was accomplished by using data reported in nationwide industry databases such as Licensee Event Reports (LERs), Nuclear Plant Reliability Data System (NPRDS), and Nuclear Plant Experience (NPE). Other material used in the research included NRC Daily Headquarters Reports, NRC Daily Operating Events Reports, NRC Regional Inspection Reports, and published literature on related investigations of instrumentation aging. The Sequence Coding and Search System (SCSS) database of LER information, operated by ORNL for the NRC Office for Analysis and Evaluation of Operational Data, formed the basis for a compiled aging database for this task.

A search of operating experiences was made to cover the 5-year period 1984–88 for each of the six categories. This time span was selected because LER reporting requirements were changed in 1984 and a continuity of reporting was deemed necessary for the analysis. Each abstract was reviewed and analyzed to obtain insights into module aging failures, and then those aging events were placed into an electronic database created especially for this study. Excerpts from the NRC Daily Headquarters Reports, NRC Daily Operating Events Reports, and NRC Regional Inspection Reports were added.

A detailed analysis was then performed on the retained data. We concluded that I&C modules make a modest contribution to safety-significant events: 17% of LERs issued during 1984–88 dealt with malfunctions of I&C modules, and of this group only 28% were found to be aging related (other studies show a range of 25–50%). Of the six I&C module categories studied, indicators, sensors, and controllers account for the bulk (83%) of aging-related failures (see Table 1.1). Infant mortality appeared to be the dominant failure mode for most I&C module categories (with the exception of annunciators and recorders, which appear to fail randomly).

We also observed that I&C modules in nuclear plants are replaced as often for reasons of technological obsolescence as for aging. The issue of replacement in response to obsolescence may have far greater impact on regulatory matters in the

Table 1.1. Safety-related findings from Licensee Event Reports (LERs) (1984–88)

Instrumentation and control module category	Number of LERs retrieved for modules	Number of aging-related LERs	Percentage of aging-related LERs/aging-related total (628)	Percentage of aging-related LERs/total LERs generated (13,726)
Indicator	997	220	35	1.6
Sensor	424	199	32	1.4
Controller	397	105	17	0.8
Transmitter	296	79	12	0.6
Annunciator	101	17	3	0.1
Recorder	61	8	1	0.06
Total	2276	628	100	4.6

I&C area in the years ahead than will the issue of aging.

We recommended that monitoring of environmental stressors may be a suitable means of predicting approaching circuit failure. It may be possible to determine threshold values for aging stressors and to perform real-time measurement of these stressors.

We recommended that consideration should be given to methods that would be helpful in reducing the incidence of infant mortality and also to testing selected I&C modules for synergistic effects of aging stressors. The purpose of this latter work would not be qualification of specific equipment but rather identification and quantification of generic stress and failure relationships.

Also, consideration should be given to creating an industry-wide database dedicated to aging-related information. Earlier studies pointed out that existing databases, although reporting stressors, do not adequately identify the root-cause failure mechanisms; this current study also encountered difficulty in drawing conclusions as a result of this deficiency.

1.3.3 Qualification of Instrumentation and Control Systems for Proposed Advanced Light-Water Reactors

Instrumentation and control systems of proposed advanced light-water reactors (ALWRs) will make extensive use of digital controls, microprocessors, multiplexing, and fiber-optic signal transmission. Although the application of advanced technology in the nuclear environment is generally encouraged by NRC, the introduction of new technology—either as retrofits in existing nuclear power plants or in the design of the next generation of light-water reactors—may require development and revision of related qualification standards and guidelines. A particular concern in using digital technology stems from the susceptibility of microprocessor-based systems to the effects of electromagnetic interference (EMI) and radio-frequency interference (RFI).

Accordingly, NRC initiated two research programs in 1991 at ORNL aimed at addressing the functional and environmental qualification issues arising from the use of new technologies in the instrumentation for next-generation nuclear power plants.

The first program—*Regulatory Guidance and Acceptance Criteria for Electromagnetic Interference in Digital Systems*—is aimed at developing the technical basis on which NRC regulatory guidance on EMI and RFI susceptibility can be established. The expected change from completely analog systems to fully digital, computer-based I&C systems can be expected to yield significant benefits, including a potential for improvements in the safe and reliable operation of nuclear power plants, reduced stress on I&C components from frequent maintenance and testing cycles (due to the self-testing/diagnostic capabilities of microprocessor-based systems), and a potential for reduction in system costs and cabling (due to sharing of data transmission lines via multiplexing). However, the introduction of digital technology in safety-related systems of nuclear power plants also raises key issues relating to systems *environmental* and *functional* reliability. One issue is the trend toward higher clock frequencies, faster operating speeds, and lower logic-level voltages. The faster logic families have shown a greater susceptibility to upsets and malfunctions due to the effects of EMI and RFI. Therefore, good EMI design and installation practices need to be established to control interference sources and to ensure compatibility of digital systems in a nuclear environment. Also, a test and evaluation program needs to be established to outline the tests to be performed, the associated test methods to be followed, and the acceptance criteria to be employed to ensure that the system under test meets recommended guidelines. ORNL assistance to NRC to date has involved the development of recommendations for electromagnetic compliance in the nuclear industry.

The goal of the second program—*Qualification of Advanced Instrumentation and Control Systems*—is to develop an understanding of the technical issues involved in evaluating long-term properties and performance of *advanced* digital I&C systems proposed for use in ALWRs. Initial studies have focused on protection systems and the I&C portions of engineered safety feature systems.

Under the I&C Qualification Program, ORNL has developed an ALWR evaluation template by assembling a reasonably complete configuration of a safety channel instrument string for an ALWR and then comparing the impact of environmental stressors on that string with their effect on an equivalent string in a present-day light-water reactor. Functional issues considered in the templates include distribution of function, communication protocols, sources and delivery of electrical power, calibration and testing capabilities, and failure prediction based on environmental monitoring. The application and acceptance of digital computers in RPSs are also being reviewed in light of current standards.

1.3.4 Development of Control System Software Verification and Validation Guidelines for Commercial Nuclear Power Plants

Digital processor technology in control applications is being used ever more widely, bringing increased acceptance for its use in areas where high reliability is important. One of these areas is the control and operation of nuclear reactor facilities, especially commercial electric generating stations. Analog control systems are becoming more costly to maintain and upgrade as use of digital technology grows. For nuclear power plants, incorporating new technology is particularly difficult because of the regulatory process that must be satisfied. Rapid changes in digital processor hardware and software capabilities and the increasing variety of alternatives for design and implementation of digital control systems have produced a situation in which many new elements can be introduced simultaneously into control systems. This situation raises concerns about maintaining a high level of reliability without creating serious problems with rising costs and slipped schedules. A wide diversity of opinion had also developed about how plant control software should be verified and validated. Guidelines were needed to bring some focus to the issues and to suggest a development framework incorporating appropriate levels of verification and validation (V&V). Therefore, EPRI asked ORNL to develop software V&V guidelines. Because of common interests of DOE programs and the electric utilities, our work described below was jointly supported by EPRI and the DOE Office of New Production Reactors (Heavy Water Reactors) and the Advanced Controls Program.

A plant control system development life cycle is shown in Fig. 1.3, with much of the hardware and software development performed along separate, concurrent paths. The most important phase in this scheme is the conceptual analysis phase at the beginning. V&V are intended to be conducted in the context of a development life cycle. Verification is the process of determining whether the results of work done in one phase are correctly and completely transmitted and incorporated into the results of work done in the following phase. This information transmission most often is accomplished by using languages, terminology, symbolic representations, or diagrams in a succeeding phase different from those used in the preceding one. Verification is an ongoing activity throughout development. Validation is a process for determining that the final product satisfies the requirements specifications, which in turn must be validated against the prototypes and analyses done in the conceptual analysis phase.

We conclude that a control system developer must have control of the software development process if V&V activities are to be carried out effectively and are to have any reasonable chance of producing reliable products. The software quality assurance (QA) plan describes what management controls shall be used and references the documents describing how these controls shall be implemented. The software QA plan also describes what must be addressed in the V&V plan. Configuration management (change control) is the primary instrument used to maintain control and to track progress. It must incorporate results of program inspections, testing, and reviews. Deficiencies found must be recorded in a log maintained as a controlled document; likewise, descriptions of what was done to resolve deficiencies must be recorded.

Verification is best done by using program inspection, a variant of program walkthrough in which the composition of the inspection team and its actions are more structured and formally defined. Two types of approaches must be considered for verification: static and dynamic. Static methods direct attention to architecture, logical connections, and design issues; dynamic methods focus on function, movement and use of data, and sequence of control logic. Techniques used depend on the type of application software and life cycle phase.

Control software has many characteristics that make it quite different from most other types of software. It is in the general class of real-time software, so ability to meet deadlines is a top priority. Processes involving complex and expensive equipment must be controlled in a way that preserves the investment in it and minimizes costly or frequent maintenance. In some cases, means for mitigating the effects of a failed component by readjusting set points and flow rates are necessary. The manner in which signals from

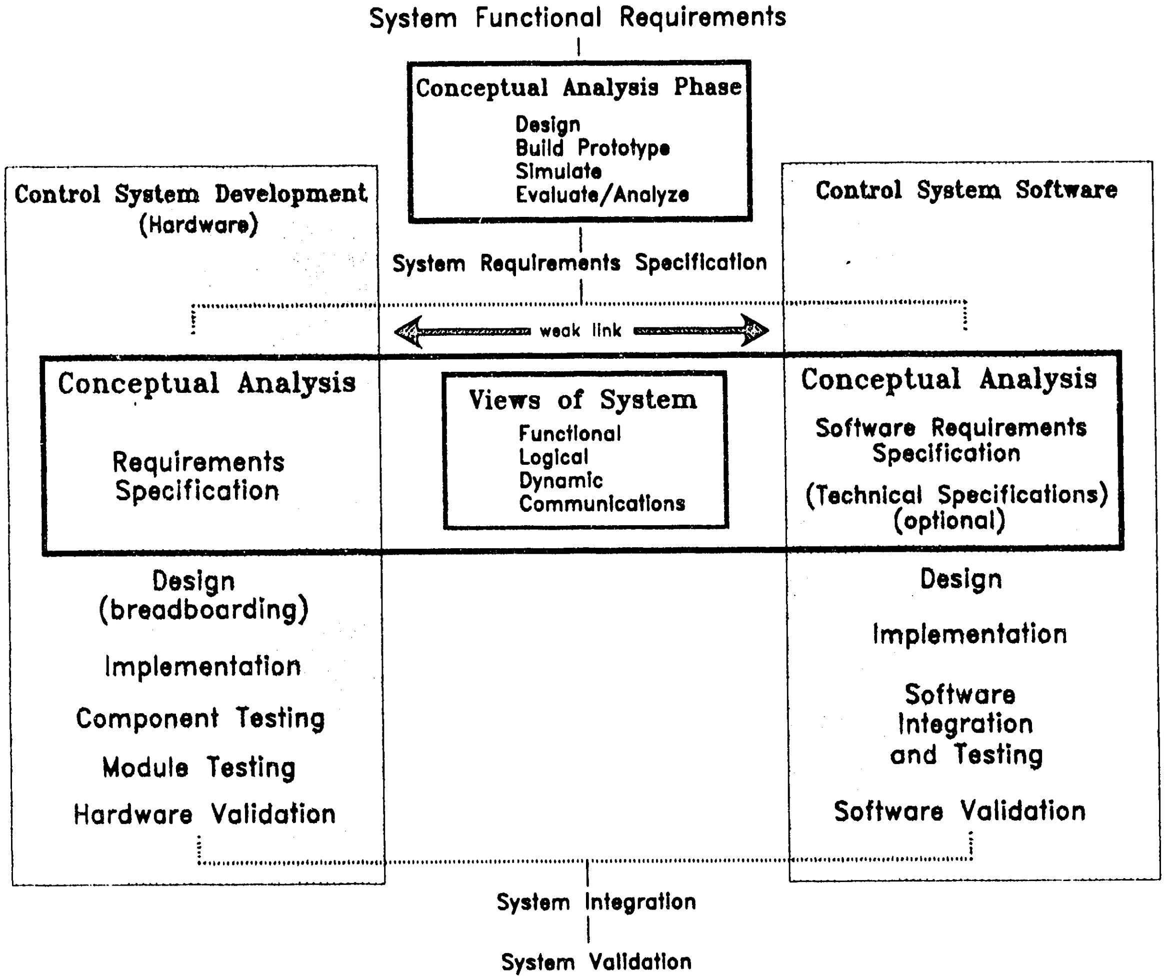


Fig. 1.3. Development life cycle for a nuclear plant digital control system.

sensors are processed and information is extracted from them adds unique characteristics to digital control systems. Unintended function is a much greater potential problem with process control software than with software used for procedures such as a structural design calculation. More verification and testing are required as a result of these additional aspects of control software.

Expectations for the future include introduction of mathematical notations and the use of symbols to represent a control system design, greater use of automation to perform routine tasks, and much more extensive use of networked computers to manage all forms of information needed to operate a power plant. All of these are software intensive; all will require V&V; and all should contribute to safer, more productive, and more reliable plant operations.

1.3.5 Development of a Generalized Object-Oriented Simulation Environment

A Generalized Object-Oriented Simulation Environment (GOOSE) is being developed as part of the Advanced Controls Program at ORNL to aid in the simulation of advanced reactors. Although GOOSE development is geared toward reactors, it can be used to simulate any dynamic system. Dynamic models can be created, modified, and tested quickly and easily. The dynamic capabilities of GOOSE allow the user to change model parameters without recompilation. The environment also provides access to powerful tools such as numerical integration packages, graphical displays, and on-line help. Additional tools are available in GOOSE, including a dynamic plotting package, a real-time simulator, and a Jacobian matrix solver.

GOOSE is written in the Objective-C programming language and runs on UNIX and DOS operating systems. The object-oriented approach to simulation used in GOOSE combines modularity with the additional features of precompilation, optimization, and testing of individual modules and the incorporation of model validation rules. Once a library of classes has been defined and compiled, complete models can be built and modified freely and easily without recompilation of the component models.

The GOOSE software package consists of three basic elements: a Class Developer, an Environment Builder, and a Runtime Environment. The Class Developer provides a user-friendly environment for creating classes of the model components. It produces the necessary source code and on-line help files for each class definition; thus, although the user does not have to know anything about object-oriented programming to use any of the GOOSE tools, the class definitions are converted into an object-oriented environment. The source code and help files produced by the Class Developer are available to the user and to other GOOSE tools. The purpose of the class definition is to define the structure and behavior of objects that belong to the class being defined. Recompilation is necessary only if a class definition is modified, and in that case, only the modified class needs to be recompiled.

After the Class Developer has been used to specify and compile the class definition, the user can create a customized simulation environment by using the GOOSE Environment Builder. The Environment Builder creates an executable simulation environment, called a Runtime Environment, that includes those classes specified by the user. In addition to files and classes specified by the user, the Environment Builder will include all classes on which the user-specified classes depend as well as plotting libraries. When a class definition is changed, the Environment Builder is used to relink new and modified classes into an executable Runtime Environment.

The Runtime Environment allows the user to build, modify, and execute the model through the dynamic creation, connection, modification, and deletion of model objects from the classes included in the environment. Unless new classes need to be defined or old class definitions are modified, a user will need to use only the Runtime Environment. GOOSE models are extremely portable in that once Runtime Environments have been created on different hardware platforms, models (objects, connections, initial conditions, present conditions, etc.) can be transferred to other platforms without recompilation, thus allowing the user to continue developing, testing, and modifying the model on either machine.

The versatility and modularity of GOOSE have enabled the production of simulation environments for numerous reactors relatively quickly and, in some cases, even to use the same class definitions for some standard components of each model. GOOSE has been used for a reactor training simulator and to simulate the advanced liquid metal reactor, modular high-temperature gas-cooled reactor, Advanced Neutron Source reactor, pressurized-water reactor, and Canadian deuterium uranium (CANDU) reactor. Some of the graphical features of GOOSE can be seen in the CANDU displays shown in Fig. 1.4.

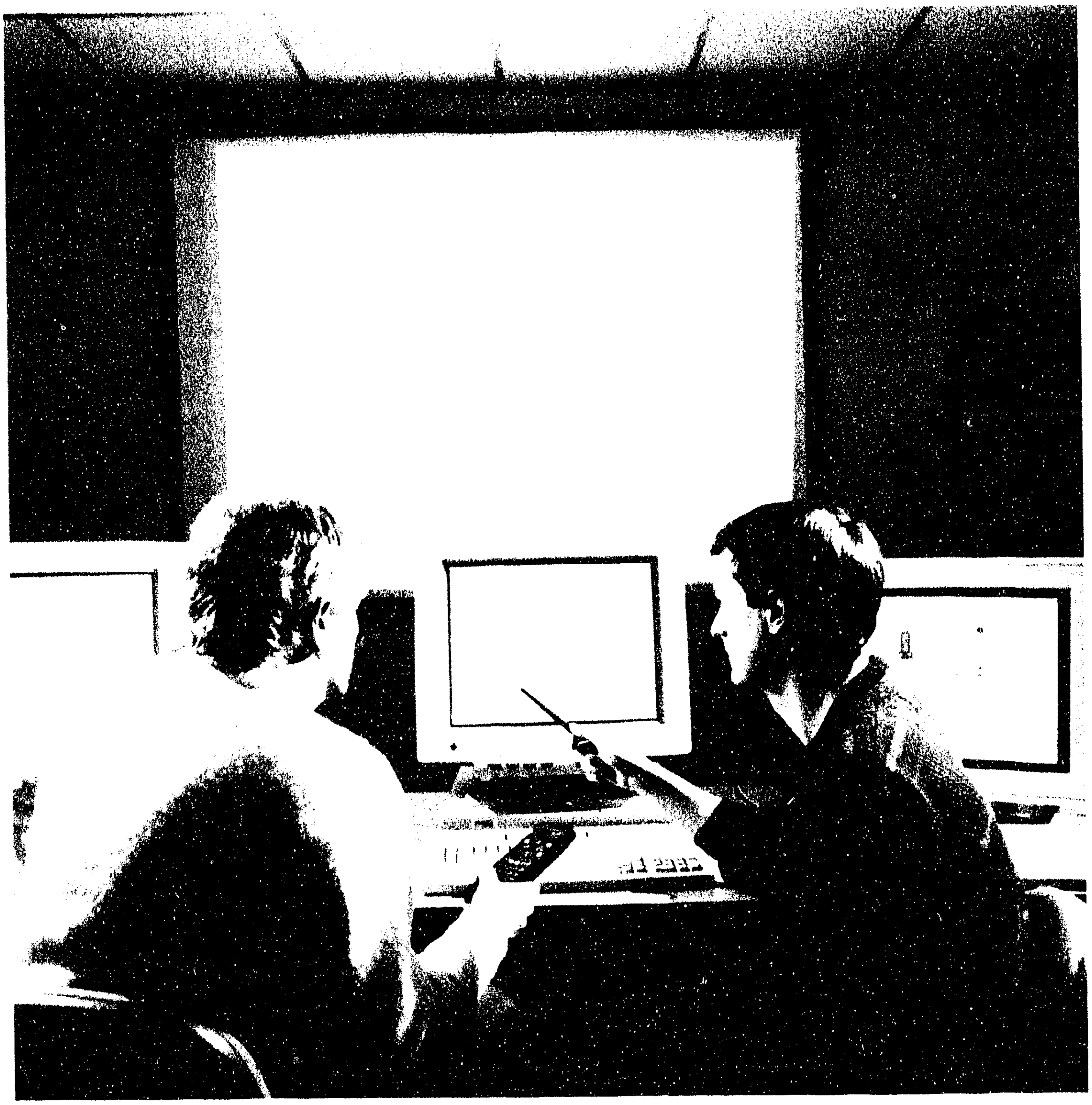


Fig. 1.4. Photograph showing graphical features of Generalized Object-Oriented Simulation Environment in the Canadian deuterium uranium reactor.

2. RESEARCH INSTRUMENTS

2.1 OVERVIEW (H. R. Brashear)

The Research Instruments Section (RIS) performs research, development, design, and fabrication of sensors, instruments, and measurement systems and applies them to measurement challenges of national importance. Strong theoretical and analytical analysis capabilities are frequently the foundation for the direction of the research. On that foundation, creation of unique methodologies and unusual approaches are often necessary before instruments or systems are developed. Once the development phase is completed, design, fabrication, and testing are accomplished to produce working hardware for either one-of-a-kind instruments, instrument systems, or prototypes. Within RIS there is a continuing emphasis on measurements for nuclear physics, particle physics, and health physics. RIS has diversified into other measurement science areas such as acoustics, optical metrology, atmospheric physics, plasma physics, hybrid optical/electronic information processing, containerless metallurgical processing, robotics, communication, and diagnostics.

Extremely challenging R&D activities encompassing electronics and detection media for the Superconductor Super Collider (SSC) are being addressed. Both the Sodenoidal Detector Collaboration (SDC) and Gammas, Electronics, Muons (GEM) Detector Collaborations are funding work within the RIS. In addition to the SSC R&D, RIS is playing a lead role in application-specific integrated circuit (ASIC) R&D in the Photon Electron New Heavy Ion eXperiment (PHENIX) for the Relativistic Heavy Ion Collider (RHIC). Electronic R&D encompasses circuits using commercially available discrete components and RIS-developed ASICs. In R&D for both colliders, staff members are helping pioneer advances in performance, functional integration, compactness, power, and radiation hardness.

RIS has established an extensive ASIC development capability. At the heart of this capability is a suite of more than 100 integrated software packages used to design, synthesize, model, verify, and generate test vectors. Expertise exists to develop analog and digital circuits (bipolar or complementary metal-oxide semiconductor) with implementation in silicon or gallium arsenide. Approximately 25 different circuits are fabricated annually through various foundries; and more than 85% of the first-time-fabrication ASICs worked. In the past 2 years, two of the fabrication runs were conducted on precommercial foundry fabrication runs. One of these runs was a beta-test of that foundry's software. Staff members have been sought after to establish ASIC development capabilities at various federal sites.

Many novel radio-frequency developments, including variable-frequency microwave furnaces, microwave nondestructive testing apparatuses, and current signature analysis tools, have brought attention to the staff.

Electro-optics activities have increased dramatically in the past 2 years. Activities range from alpha-particle diagnostics in plasmas to optical metrology to hybrid optical/electronic information processing to atmospheric physics. Two new electro-optics laboratories—a prototype laboratory and a hybrid optical/electronic processing laboratory—have been established, and two other laboratories are in the planning stage.

A new thrust of the section is in the area of cooperative research and development agreements (CRADAs) with industry. Three CRADAs are either funded or approved for funding. One is in the area of automobile engine control with a major automobile manufacturer. Others are in nondestructive testing using microwave technology and in developing ASICs for a small commercial health-care instrument company to improve dose measurements for patients in radiation therapy.

A second new thrust is microinstrumentation. Two separate projects have been completed in which the sizes of measuring instruments have been drastically reduced, one through the use of ASICs. These are the predecessors and the first steps toward nanoinstrumentation.

Staff members have been recognized as recipients of the prestigious R&D 100 award and the Advanced Technology Award. A National Management Association award was granted to a first-line supervisor. The Martin Marietta Awards Night brought five technical awards and one administrative award to RIS staff. Two staff members were recognized through the Martin Marietta Significant Event Award. Staff members have served or have been asked to serve in several technical forums such as guest editor for the Institute of Electrical and Electronics Engineers Nuclear Science Symposium and chairperson of the Optical Systems Session at the 22nd Southeastern Symposium on System Theory. Twenty-seven patent disclosures were submitted, thirteen patent applications were filed, and seven patents were awarded. In addition to the patent awards, both licensing support awards and unlicensable invention awards were received.

RIS staff continues teaming with a multitude of different disciplines within the I&C Division, within ORNL, and in collaborations with other institutions to bring to bear the appropriate and best expertise in solving measurement challenges.

2.2 RADIATION AND ENVIRONMENTAL MONITORING

2.2.1 Health Physics Portable Instrument Upgrade

During FY 1991 and FY 1992, RIS technical staff completed the ORNL health physics portable instruments upgrade. Portable instruments and detectors were procured and qualified for field use as contamination survey and dose rate survey instruments. Instruments included in this upgrade program were Bicron Surveyor-MX count-rate meters (used with pancake and side-window Geiger-Müller tube probes and low-profile, large-area alpha scintillation probes); Eberline gas-flow alpha-contamination survey meters; Bicron Micro-REM high-sensitivity gamma dose-rate survey meters; Bicron RSO-5 gamma dose-rate meters; Nuclear Research Corporation CP-10 and CP-1000 high-range gamma dose-rate meters; Nuclear Research Corporation NP-2A neutron dose-rate meters; Automess Model 6150 extended-probe dose-rate meters; and Bicron Analyst survey meters with 2 × 2 NaI scintillometer probes.

The instruments were qualified by subjecting them to a series of tests performed according to ANSI N42.17A. The data from these tests established baseline performance capabilities for each particular instrument. Instruments were tested for stability vs temperature and humidity, for insensitivity to vibration and radio-frequency interference, and for time-independent performance.

The detectors and probes used with the new portable health physics instruments were also qualified by subjecting them to a series of tests performed according to ANSI N42.17A. Such separate qualification is needed because these parts must be replaced frequently on portable instruments. To rapidly quantify detector performance, an automated system was developed. This system is capable of determining exact operating voltage and count-rate sensitivity for multiple detectors in a single operation and produces graphical records of the detector performance. This record supports the decision to either use or reject a detector.

To support the calibration and maintenance of Bicron Surveyor-MX count-rate meters, which represent >50% of the portable instrument inventory, an automated calibrator and diagnostic instrument was designed and built. The use of this instrument greatly decreases the time needed to calibrate and maintain these instruments. This development is described in Sect. 4.4 of this report.

2.2.2 Navy RADIAC Development Program

During FY 1991 and FY 1992, the most significant achievement of the Navy Radiation Detection, Indication, and Computation (RADIAC) Development Program was the completion of the development of the Multifunction RADIAC (MFR) and the transfer of its technology to industry. Industry, in turn, will produce MFR for the U.S. Navy. MFR is an advanced microprocessor-controlled radiation survey instrument. Currently, it is in the final stages of advanced prototyping by a private corporation; and engineering support was provided for successful transfer of the MFR technology to that corporation.

I&C Division personnel have developed an advanced check source set for the Navy to use specifically with MFR. A prototype set was delivered to the Navy. This set includes various 10 CFR Pt. 20-exempt quantity sources arranged in an aluminum storage case with detector footprints machined around each source. This check source set is to be used to check proper operation of MFR without having to attach radioactive sources to individual RADIACs.

Another significant advance made in the past two years is the development of the Ruggedized Contamination Detector (RCD) technology. This technology is a major breakthrough in radiation detector design and is the basis of a new generation of radiation detectors. These devices are not only chemically and physically rugged, but they outperform all commercially available detectors according to U.S. Army tests. The RCD technology was licensed to a private corporation through Energy Systems Technology Transfer in August 1991 for use in commercial instrumentation.

An improved design for a condensate tritium monitor was developed and demonstrated by using a flow-through NE102 (plastic) sponge scintillator combined with dual photomultiplier tubes. This improved design, together with the associated electronics, enables the detection of 1 nCi/mL of tritium in water with only a 5-min sampling time.

2.3 DETECTOR RESEARCH AND DEVELOPMENT FOR LARGE COLLIDING PARTICLE-BEAM ACCELERATORS

Members of the Monolithic Systems Development Group within RIS have participated in detector research and development for the Superconducting Super Collider (SSC) near Dallas and the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL). The main contributions of RIS personnel have been in application-specific electronics, detector design, and detector media studies.

2.3.1 Superconducting Super Collider

Two major detector collaborations were formed to design, build, and operate large detectors for SSC. One of these is the Solenoidal Detector Collaboration (SDC); the other is the Gammas, Electrons, and Muons (GEM) Collaboration.

2.3.1.1 Solenoid Detector Collaboration

Readout electronics were developed for the outer tracking subsystem. This subsystem consists of ~150,000 strawtube drift chamber detectors. The 4-mm-diam, 4-m-long strawtubes are packed tightly together into strawtube modules with 160 straws per module. Each strawtube module attaches to the end of a readout module consisting of 160 channels of readout electronics. In this way, the signal from each straw is fed to a preamplifier, shaping circuit, and discriminator. The readout module has a trapezoidal cross section and a volume of only 341 cm^3. Not only the electronics but also high-voltage bias distribution and decoupling capacitors and resistors are included in these small readout modules. The electronics are mounted in leadless chip carriers containing eight channels of readout electronics per carrier. Small, custom high-voltage capacitors were developed by a commercial vendor to meet the demanding space constraints. The prototype high-density readout module assembly shown in Fig. 2.1 takes advantage of six-layer printed circuit boards (some with blind vias). The first of these readout modules will be used with prototype detectors now being constructed and tested at Duke University, the University of Indiana, and the University of Colorado.

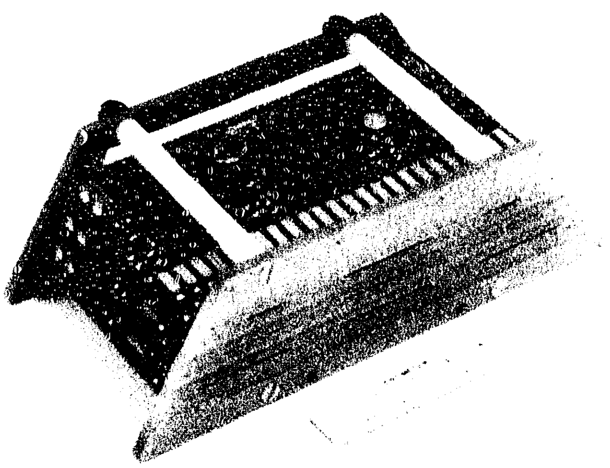


Fig. 2.1. High-density readout modules (prototype shown here) are required to meet the demanding space constraints of the strawtube outer tracker subsystem.

2.3.1.2 GEM Collaboration

The GEM Collaboration, which is to design the second major detector authorized by the SSC

Laboratory, near Dallas, is composed of former members of the L*, EMPACT, and TEXAS collaborations.

Electronics were developed for all parts of the GEM detector from the central tracker, preradiator, EM calorimeters, and hadron calorimeter to the muon endcap chambers. The technologies employed range from custom radiation-resistant analog complementary metal-oxide semiconductor (CMOS) to thin-film hybrid preamplifiers, shaping amplifiers, and fast discriminator circuitry. The custom bipolar monolithic front-end circuits were included in beam tests. There have been partnerships between RIS and many universities and national laboratories, including BNL, Boston University, Princeton, Columbia, California Institute of Technology, and the Universities of California–San Diego, Indiana, Mississippi, Oregon, Pittsburgh, Tennessee, Washington, and others.

Central Tracker Integrating Pad Chamber. The central tracker pad chambers will require radiation-hardened analog memory to store discrete events occurring every 16 ns until the trigger decision is made about 4 μs later. Because of its central location, the electronics will be subjected to high-neutron and high-particle fluxes and yearly doses of 10 Mrad. The initial design is complete, and plans are being made for a radiation hardened integrated circuit fabrication run.

Silicon Electromagnetic Calorimetry. Nine ORNL custom integrated circuits were designed as possible solutions to the preamplifier requirements for the harsh SSC environment. The first-generation custom integrated circuit was fabricated by using a VTC, Inc., bipolar, dielectrically isolated sidewall process. The second-generation designs were fabricated by using the Harris Semiconductor Very High Frequency Process (VHFP), which is a 20-V dielectrically isolated bipolar process.

Three different preamplifier architectures were produced with the Harris process. One uses a folded-cascode input stage; another uses a differential input stage; and the third uses current feedback. The performances of these three designs were compared in terms of noise, resistance to gamma radiation, power consumption, and minimization of external components. The folded-cascode input stage was superior in all respects. Each silicon chip contains four preamplifiers.

These ORNL quad-preamplifier chips have been used in beam tests of a large area array (0.5 by 0.5 m) at the Institute for Theoretical and Experimental Physics (ITEP) in Moscow and with an array comprising pads and strips at the Alternating Gradient Synchrotron at BNL. Over 2000 of these quad-preamplifier chips (8000 channels) are currently being incorporated in a prototype Silicon Electromagnetic Calorimeter detector.

Scintillating Calorimeters. Materials studies were made for two calorimetry options. The initial study was of the chemical compatibility between liquid scintillators and wavelength-shifting optical fibers that were proposed for a scintillator-based hadron calorimeter. In addition to chemical compatibility, radiation damage studies were also made of the fibers in air, inert gas, and scintillation cocktails.

When the liquid scintillator option was rejected in favor of a scintillating fiber (spaghetti) calorimeter, radiation damage experiments were redirected from wavelength-shifting fibers to scintillating fibers. The damage studies were conducted at ORNL and at BNL.

2.3.2 Relativistic Heavy Ion Collider

The photon electron new heavy ion experiment (PHENIX) detector is one of two large detectors planned for RHIC. Its primary role is to study the physics associated with photons and leptons, and it should be capable of exploiting the highest luminosities envisioned for RHIC.

PHENIX is composed of at least four subsystems, including an electromagnetic calorimeter, a muon system, a time-of-flight system, and a vertex tracking system. PHENIX work began approximately three years ago and has continued to grow. Early work on PHENIX involved the development of fast custom preamplifiers for gas pad chambers. These electronics were fabricated in both CMOS and bipolar processes. In addition to the preamplifiers, random-access analog memories and analog-to-digital converters (ADCs) were also fabricated. The goal of these early developments was to integrate a complete readout chain through digitization on a single chip. This goal was achieved with the chip containing four independent readout channels. Each channel consists of a preamplifier, a shaper, and a 16-deep analog memory. The data were then multiplexed into an 8-bit ADC for digitization.

During the past three years, the PHENIX project has expanded to include development of readout electronics for two other subsystems—the silicon strip vertex detector and the lead-glass calorimeter. In addition, development of the overall detector timing system has begun. Finally, ORNL has been given the extremely important task of coordinating all the custom integrated circuit developments for PHENIX.

2.4 PHOTONICS

Photonics research and development include advanced metrology, optical and fiber-optic sensors, optical processing, spectral radiometry and photometry, atmospheric optics, and geometric optics. Currently, two laboratories exist—a prototype/staging area supporting a diverse range of programs and an optical processing laboratory supporting work in automated inspection and advanced detectors for the High Flux Isotope Reactor and the proposed Advanced Neutron Source reactor.

2.4.1 Atmospheric Optics Research and Development

I&C Division work in atmospheric optics supports the DOE Atmospheric Radiation Measurement (ARM) Program. ARM is implementing a number of highly instrumented measurement sites called Cloud and Radiation Testbed (CART) sites around the globe for testing general circulation models that predict climate and climate changes. Two tasks are being performed in support of this work. One task is the spectral inversion of shortwave radiometric data to extract aerosol, ozone, and water vapor concentrations. The second task is the development of a shortwave pointing radiometer instrument for installation at the CART sites.

2.4.1.1 Atmospheric Modeling

The spectral inversion work for ARM supports radiometer measurements made by ORNL and State University of New York at Albany. To solve the inversion problem, a priori knowledge of the structure of the solar spectrum is necessary. To provide this prior knowledge, a parameterized model of the atmosphere, based on the principles of atmospheric physics, is employed to determine the particle sizes and concentrations of the constituent gases in the atmosphere. A computer code such as LOWTRAN7 provides the detailed spectral structure (e.g., absorption bands, Rayleigh scattering) for each of the constituent gases and particles (e.g., aerosols, ozone, water vapor) that may be in the atmosphere. Then, with this spectral structure and the measured irradiance data, a least-squares estimate of the model parameters is obtained by singular value decomposition, a particularly robust mathematical procedure. Three results of this work are significant. One result is that concentrations and particle size distributions of trace gases and particles in the atmosphere can be estimated from shortwave measurements. Another result is that the solar spectrum can be reconstructed for wavelengths more closely spaced than those of the original irradiance data. The third result is that an optimum set of wavelengths giving the most accurate reconstruction of the solar spectrum over the region of interest can be determined for a radiometer instrument design.

2.4.1.2 Solar Radiometer Development

Also in support of ARM, RIS technical staff are developing a general-purpose shortwave (0.415- to 2.16-μm) pointing solar radiometer with a 1° field of view. The instrument will be used in four operating modes at the CART sites to make (1) solar extinction measurements quantifying aerosol, water vapor, and ozone; (2) solar aureole measurements by an almucantar scan measuring aerosol distributions; (3) zenith angle measurements in the near infrared for cloud studies; and (4) all-sky scan measurements that support the calibration of an all-sky imager for cloud coverage measurements and the calibration of a multifilter shadowband radiometer.

The shortwave radiometer consists of a front-end two-stage sunshade with coated baffles, an aperture, a precision optimized achromatic lens, a chopper wheel, an integrating cavity, and eight photodetectors (six silicon detectors, one germanium detector, and one indium arsinide detector). These components are shown in Fig. 2.2. Stray light rejection, a critical requirement of this radiometer, is provided by the front-end sunshade while radiance from the sun is collected by using the lens and the integrating cavity. A removable aperture allows the instrument to make measurements pointing directly into the sun as well as away from it.

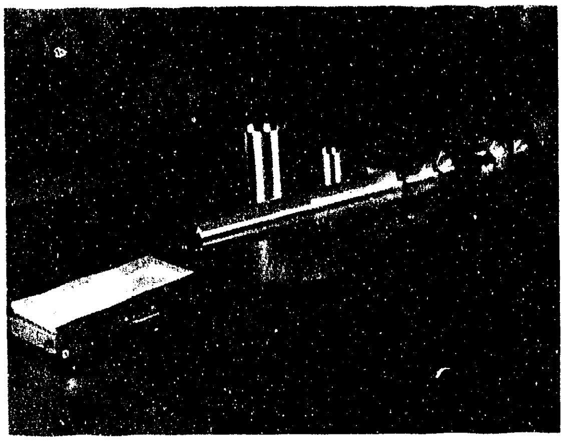


Fig. 2.2. ORNL shortwave pointing solar radiometer.

2.4.2 Hybrid Optical-Electronic Processing

Existing neutron imaging detectors have limited count rates. To some extent, this limitation is inherent in the detector design, and to some extent, it results from the limitations of the electronics. The popular multiwire proportional counter is limited by gas recombination to a count rate of $<10^5$ n/s over the entire array; and the neutron Anger camera, even though improved with new fiber-optic encoding methods, can image only 10^6 n/s over a limited array. New cold neutron sources are being designed that will provide neutron fluxes greatly exceeding the rates accommodated by these imaging techniques. For these reasons, a new type of neutron imaging detector with a resolution of 2 to 5 mm and a count rate capability of 10^6 n/s per pixel element is being developed. Optical and electronic processing are combined to increase the throughput of this advanced detector system while simplifying computing requirements. This combination is accomplished by placing a scintillator screen ahead of an optical image processor and by placing a detector array after it.

Scintillation detectors offer several advantages over intrinsically limited gaseous and semiconductor detectors currently used for position sensing and imaging. They have high rate capacity ($>10^6$ s^{-1}), small parallax error because of the thin material used in fabrication, good localization of charged-particle tracks for high spatial resolution, and the ability to be fabricated into virtually any shape. Scintillators have an extra advantage over other media in that they can be tailored to specific wavelengths to match solid state photodetectors. Recently, the inherent advantages of the conventional scintillator have been extended by a new technique for designing a scintillation screen that provides very efficient coupling to the optics system. The new screens were optimized for particle size, phosphor content and ratio, screen thickness, and gamma sensitivity.

In Optical Processing Enhanced Real-Time Advanced Detection (OPERAD), light from the scintillator is imaged onto an optical processor by a low f-number Cassegrain telescope. To minimize spherical aberration and coma, the shape of the two mirror surfaces is aspheric. The telescope is designed to be constructed from a diamond-turned, 60-cm-diam concave primary mirror with a 16-cm-diam convex secondary mirror spaced from the primary by 45 cm.

The optical processor design consists of a pair of anamorphic imaging systems. Each of these systems is designed to collect all the light in a plane along one dimension (e.g., the vertical dimension) and image all that light along a line in the orthogonal dimension — in this case, the horizontal dimension. A cylindrical mirror is a simple example of an anamorphic system.

The output of each anamorphic imaging system is focused onto a linear photodetector array. As a result of using optical processing, the needed number of photodetectors is reduced from n^2 for an n by n pixel image to $2n$. Each photodetector is coupled to a charge-sensitive preamplifier followed by a pulse-shaping circuit with a 500-ns time constant. A discriminator follows each pulse-shaping circuit. The preamplifier and shaping circuits are individually constructed on 2- by 2-in. circuit boards. These boards are mounted on a 10- by 12-in. motherboard along with a board for the photodetector array, discriminators, and connectors for power and outputs to a digital coincidence circuit.

2.4.3 Holographic Interferometry for On-line Differential Aspheric Figure Metrology

The measurement of aspheric figure quality is one of the most challenging areas of optical metrology. Traditional interferometric techniques, ranging from null testing configurations for conicoids to the use of diffractive null correctors, are expensive and time consuming. Alternately, on-line aspheric metrology can significantly reduce the cost of producing aspheric optical components, allowing them to be corrected and qualified without ever removing them from the manufacturing station. However, the manufacturing environment is seldom conducive to the use of specialized test systems requiring precision multiaxis alignment control.

RIS engineers are investigating the new technique of holographic interferometry, which provides a viable solution to the on-line measurement problem. The procedure requires one laboratory measurement of the optic prior to fixturing it for final figuring at the manufacturing station. This laboratory measurement characterizes the errors in the optic and produces an error map showing the magnitude and location of each error. The holographic interferometer is then used to store an in situ reference of the optic as it appears at its manufacturing station. This reference wavefront includes any extraneous aberrations introduced by windows, fixturing, and minor misalignments and can be reproduced by the hologram at any subsequent time for comparison.

During the manufacturing process, this technique permits direct differential measurement of the optical figure—independent of any extraneous aberrations present in the configuration. As the errors in the optic are corrected, the reflected wavefront from the optic is interfered with by the diffracted reference wavefront from the hologram. This interference produces a differential measurement map that emerges as the complement of the original error map and provides guidance for the manufacturing process. The instrument prototype is shown in Fig. 2.3.

2.5 DIAGNOSTICS

RIS engineers have continued the development of instrumentation and techniques to characterize materials and systems. Work on current signature analysis (CSA) for rotating machinery continued and was extended to other electrical devices. A technique to measure the velocity distribution of the alpha particles in a fusion plasma was developed and tested. The I&C Division began development of a device to examine the internal characteristics of civil structures by using microwave technology. In addition, a specialized instrument to test health physics instruments was developed.

2.5.1 Motor Current Signature Analysis

Motor CSA is proving to be a valuable tool in characterizing motor loads. This technology is being aggressively developed from both a theoretical and an application viewpoint.

2.5.1.1 Theoretical Studies

The basis of motor CSA technology is that variations in the mechanical load presented to a motor will produce corresponding changes in motor shaft speed and, thereby, result in amplitude, phase, and frequency modulations of the current drawn by the motor from its power source. To forge a tighter link between observed motor current (the dependent variable) and shaft speed (the independent variable), equations have been derived that describe the relationship between motor shaft speed fluctuations and stator current fluctuations when the shaft speed is perturbed by any cause. Differential equations and basic electromagnetic equations, rather than phasors, were emphasized in the derivation.

Then, from these equations, motor current waveforms were calculated for a shaft speed consisting of the sum of a constant and two sinusoids. The constant was taken as 59 Hz, and the two modulation frequencies were 13 and 17 Hz. Two shaft speeds were used rather than one so that intermodulation effects could be studied.

Next, the waveforms that would result after amplitude demodulation and frequency demodulation were calculated. From the Fourier spectra of these waveforms, it was concluded that frequency demodulation is potentially a much better method to detect shaft speed fluctuations than is amplitude demodulation but that nonaliasing methods of frequency demodulation are needed.

2.5.1.2 Applications

The RIS effort in CSA applications focuses on analog demodulation techniques because it was found that, typically, the ratio of the power-line amplitude to the sideband amplitude exceeds the capabilities of ADCs in existing digital signal-processing analyzers.

At the Portsmouth Gaseous Diffusion Plant, the CSA system operates on current samples from 1700-hp motors. Software-directed trending and pattern-recognition algorithms provide reliable detection of the blade-damaging rotating-stall

Fig. 2.3. Holographic interferometry prototype.

operation and provide indications of several other abnormal types of compressor operation.

A second CSA system was developed and installed at Portsmouth to facilitate improved uranium-front monitoring near the top of the plant. Approximately 80 centrifugal compressor motors in the top isotopic and purge cascade areas are monitored and trended by using signals acquired from the central-room ammeter loops. Later phases of this multiyear program will eventually provide a real-time display of the molecular-weight gradient in this critical area of the plant.

Additional CSA applications studies have been conducted on a variety of shipboard systems under U.S. Navy funding. The results caused the Navy to request the fabrication of two upgraded portable CSA data-acquisition systems.

Because of past successes of discrete analog motor current demodulation circuitry and because of its potentially wide application, a single-chip, analog motor-current demodulator is being developed.

2.5.2 Alpha Particle Plasma Diagnostics

During the past year, RIS engineers developed a new system for measuring alpha particle velocity distribution in fusion reactor plasmas. Such a measurement is needed because the kinetic energy from the fusion product alpha particles must be redeposited into the plasma to sustain the fusion reaction, and the slowing rate of the alpha particles reflects the rate of energy redeposition to the plasma fuel.

The new diagnostic is based on small-angle scattering of carbon dioxide (CO_2) laser light from plasma alpha particles. A high-power CO_2 laser (~10^6 W) with a pulse width of 1.5 μs is directed into a burning plasma experiment. A low-noise heterodyne receiver with a bandwidth of 2 GHz and an optics system collects light scattered from the alpha particles at an angle of ~1.0°. The line broadening of the scattered light yields the velocity and energy distribution of the alpha particles.

Because no alpha-particle-producing plasmas are available, the feasibility of the technique was determined by the measurement of a resonant electron plasma feature with small-angle scattering. The scattering of laser light from alpha particles in a burning plasma at small angles is very similar to scattering from a resonant plasma electron feature in a nonburning plasma, both in scattered power level and in spectral broadening. The results of this experiment are shown in Fig. 2.4, where the scattered power is plotted as a function of electron density. The data in Fig. 2.4 show that the agreement between theory and experiment is excellent.

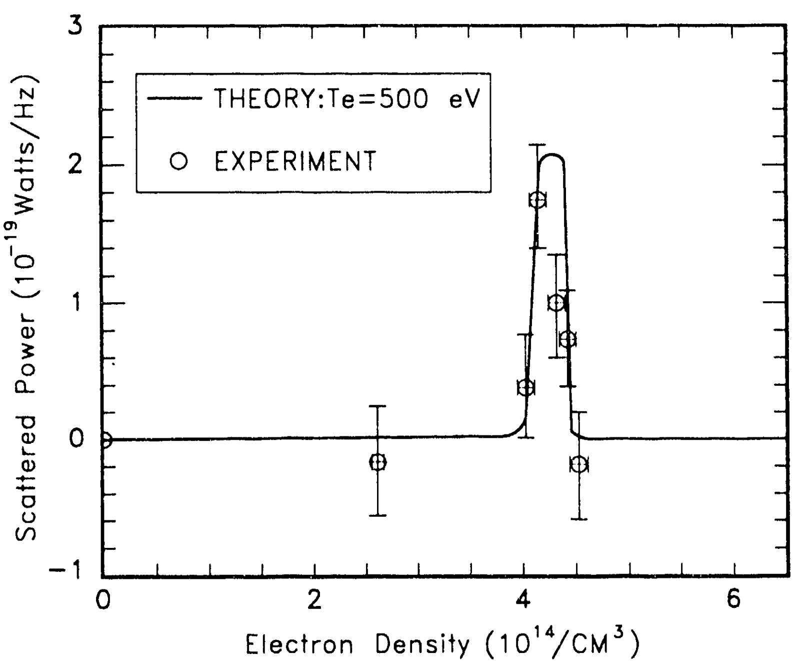


Fig. 2.4. The measured small-angle scattering data closely follow the calculated data.

2.5.3 Nondestructive Wall-Inspection Probe

A prototype microwave wall-inspection probe, the first inexpensive handheld instrument capable of nondestructive evaluation of a certain class of architectural structures, was developed by RIS staff. By using microwaves in the 8- to 12-GHz range, this probing instrument can detect subsurface characteristics in concrete, brick, wood, and other building materials to depths in excess of 12 in. The microwave wall probe was developed to test a wide variety of structures that cannot be properly evaluated with established technologies because of their surface characteristics, limited accessibility, and other physical constraints.

The device interrogates a structure from a single side by transmitting a low-power microwave signal into the surface at some angle of incidence and receiving the reflected signal on the same side of the structure. This device eliminates the need for access to both sides of the wall, which is necessary with transmission-type measurements such as radiography, where the source of radiation and the detector must be on opposite sides of the structure under test. The microwave signal is partially reflected at each internal boundary of different dielectric constant, giving a composite reflection that contains information from each internal layer. This approach is not hindered by voids or minor density differences within the structure that degrade the performance of ultrasonic testers and make interpretation difficult.

The reflected composite signal is compared in phase and amplitude with those of the transmitted signal, and that reading is considered the "signature" of the structure under test. When the signature of the test structure matches the standard signature, the structure is considered normal. When the test signature differs from the standard, an anomaly is thereby identified. By varying parameters such as frequency, angle of incidence, or separation between transmitting and receiving horns, the system can be customized for a wide variety of structures.

The wall probe is currently being field tested, and preliminary extensions of this technology to the determination of the internal characteristics of other building materials looks promising.

2.5.4 Automated Testing System for Health Physics Survey Instruments

The manual testing, adjustment, and calibration of ORNL health physics instruments is a repetitive and time-consuming process that requires a significant amount of labor. RIS engineers designed a microprocessor-based, automated tester to assist technicians in test and calibration of over 500 Bicron Surveyor-MX instruments at ORNL. Instrument goals were reduction of labor required for testing; increased reliability of the test and adjustment procedures; and, by streamlining the record keeping associated with the instrument calibration, increased accountability.

Testers guide users through an alignment procedure, control the operating modes of the unit under test, inject stimulus signals, record response signals, and prompt the user to make necessary adjustments by using a graphic display panel. The instrument identification number and the badge number of the user are also recorded by bar codes. Several self-contained tester stations can operate simultaneously and independently.

The file server system can service multiple stations operated in parallel by polling the tester stations periodically and uploading calibration and adjustment data sets from the tester stations as they are generated. This system produces printed calibration reports, exports records to the central instrument maintenance database system, and enables review and analysis of historical records.

2.6 INSTRUMENT DEVELOPMENT

Readily available low-cost microprocessor chips, nonvolatile memories, and liquid crystal display panels, along with a generous selection of integrated circuits with programmable functions, allow a systems approach to instrument design with software-driven operation functions easily selected and altered from a front panel display. The cavitation monitor built for the David Taylor Research Center [renamed Carderock Division, Naval Surface Warfare Center (CD/NSWC)] and the Modular Electromagnetic Levitator (MEL) metal solidification pyrometer are impressive examples of this technology. Large circuit, high data rate, low power, and small size and weight can be achieved in custom-designed application-specific integrated circuits (ASICs). The miniaturized multichannel scaler is an excellent example of the achievements enabled by ASICs. Custom printed circuit boards used with commercial microprocessor controllers, standard signal buses, and backplanes with a wide selection of commercial interface cards speed the implementation of custom instrumentation systems. The Bonneville Power Authority breaker monitor is an example of this instrumentation technology.

2.6.1 Miniaturized Multichannel Scaler for a Fluorescence Measurement System

A prototype miniature multichannel scaler was built to demonstrate the feasibility of miniaturizing the multichannel scaler function. This miniature scaler is needed for well-monitoring instrumentation used to determine the concentration of uranium in well water by applying nonionizing radiation.

The multichannel scaler initiates the data acquisition cycle by sending a trigger pulse to a laser, which is the excitation source for the water sample. The scaler counts and stores the resulting photomultiplier tube pulses in a programmable configuration. Count rates of up to 70 MHz are feasible. The host system can then retrieve these data from the multichannel scaler and process the information. The prototype unit supports all communications necessary for programming the unit and uploading data to a host system.

The prototype multichannel scaler instrument is built around a custom-designed embedded microcontroller unit. This unit includes resources for program execution, data storage, input/output control, communication, and data acquisition and control functions for the custom multichannel scaler chip (MCSC). Most of the design effort was focused on the development of a general-purpose ASIC MCSC designed to facilitate testing.

2.6.2 Improved Cavitation Monitoring Device

The Improved Cavitation Monitoring Device (ICMD), or Cavitation Monitor, was developed for the David Taylor Research Center (renamed CD/NSWC) and the Naval Sea Systems Command. The goal of the ICMD program was to develop a stand-alone instrument to detect the onset of propeller cavitation on existing U.S. Navy submarines.

For many years submarine commanders had needed an automated means of accurately self-detecting cavitation before it becomes detectable by other submarines. Cavitation is an extremely undesirable source of noise in otherwise quiet submarines because it can be used to locate and identify a submarine from a great distance. Cavitation monitoring is currently performed by trained sonarmen and by a monitoring computer subsystem. Neither method is optimal. The sonarmen require training and are prone to fatigue and error. The computer subsystem is inaccurate and not very sensitive. ICMD, on the other hand, is portable, relatively inexpensive, easily configured for any type vessel, extremely sensitive, and completely programmable and reconfigurable.

ICMD relies on a detection algorithm that is a dramatic departure from existing methods of artificial cavitation detection including the method used by the computer subsystem. This improved detection method permits ICMD to detect cavitation before it becomes audible and enables cavitation-free operation of U.S. submarines.

2.6.3 Modular Electromagnetic Levitator

A small containerless processor is being developed for the Marshall Space Flight Center, National Aeronautics and Space Administration (NASA), to demonstrate that high-temperature metals, those with melting points >2500°C, can be precisely positioned in space and melted without the use of containers. Containerless processing of high-temperature materials makes it possible to study high-purity metals because no crucible is present to contaminate samples. The microgravity of space flight offers the opportunity to study absolutely quiet samples with no gravitational forces to cause convection currents in the melted metal.

In support of this work, a high-efficiency modular electromagnetic levitator (MEL) is being developed. In the past, power limitations on the space shuttle coupled with relatively low efficiencies of available electromagnetic levitators have made containerless melting of high-temperature metals difficult. The efficiency of the previous electromagnetic levitator experiment flown on the shuttle in 1982 was about 3%. The efficiency of MEL, however, is 36%.

Spherical samples of Ag, Al, Au, Pb, and Inconel (trade name of Inco Alloys International, Inc.), 5 mm in diam, were levitated during a KC-135 microgravity flight to ensure that the system was adequate for future flights. On the next KC-135 flight, a three-turn heating coil will be placed between the levitation coils to melt and solidify niobium during the 20 s of microgravity.

Principal investigators are anxious to measure the temperature and the solidification velocity of 5-mm niobium spheres undercooled in space. A special pyrometer and two high-speed light meters have been designed and fabricated to function with multiple-channel scopes to record the recalescence to obtain recrystallization at the top and bottom of levitated samples while in flight on the KC-135. This equipment is part of the total experiment package, shown in Fig. 2.5, fabricated at ORNL this year for the Marshall Space Flight Center, NASA. Principal investigators will use this hardware for flights on the KC-135 to learn more about microgravity experiments before other experiments can be done on the space shuttle.

2.6.4 Substation Reliability-Centered Maintenance for Bonneville Power Administration

RIS engineers have participated in the Substation Reliability-Centered Maintenance project, which will enable the monitoring of high-voltage transformers and circuit breakers to allow effective scheduling of maintenance resources. This project began with a request for recommendations regarding computer communications for the project. As these recommendations were being developed, the need for a circuit breaker monitor became apparent, and none was commercially available. When the transformer monitor vendor was unwilling to develop a breaker monitor, a proposed design was accepted by Bonneville Power Administration. A prototype under development will monitor two

Fig. 2.5. Experiment package was flown on a KC-135 microgravity flight.

breakers for indications of mechanism wear, operation history, and contact stress. The monitor will collect data on circuit breaker operations and transfer the data on demand to the Reliability-Centered Maintenance Workstation, where they will be analyzed and ultimately compared with data from similar breakers throughout the power system.

2.6.5 Ultrasonic Tomography Instrument Development

With the collaboration of researchers from the ORNL Energy Division, I&C Division staff have developed a portable geophysics instrument system for underground imaging applications. The system is designed to aid in the location of underground objects and geological features by using minimally disruptive methods.

The system is composed of a linear array of hydrophones, a PC-based data-acquisition system, and an acoustic source. The acoustic source is applied linearly along the area surface. The hydrophone array is placed vertically in the ground in an encased hole filled with water for good acoustic coupling to the earth. Imaging data are acquired by firing the acoustic source and acquiring real-time data from the hydrophone sensors. Data from the sensors are processed at the control PC, and a two-dimensional plot showing relative sound wave propagation speeds in the earth is produced. With only limited knowledge of the target object or geological feature, the user can discriminate between the target and the surrounding earth.

This instrument system has been successfully used for locating tunnels, waste burial pits, archaeological elements, and dinosaur bones.

2.7 APPLICATION-SPECIFIC INTEGRATED-CIRCUIT DEVELOPMENT

The use of ASICs provides extensive value-added benefit to many projects. To support development of ASICs, a solid base of expertise (~12 staff members) has been built in the use of silicon-based integrated-circuit technologies both for custom analog and digital designs. Expertise is also being established in custom gallium arsenide (GaAs) integrated-circuit designs. These technologies have proven extremely useful in many recent applications, including a whole-arm collision-avoidance system for robot control, miniaturized analytical instrumentation, a microwave oscillator, and a reduced instruction-time execution microcontroller architecture. In many of the applications, complete systems have been implemented on a single chip. For other systems, the ASIC chip is used with other components to form the system solution. One such system solution is shown in Fig. 2.6. Most fabrication continues to be done through the Metal-Oxide-Semiconductor Implementation Service (MOSIS); however, runs have been made directly with foundries that offer specific processes unavailable through MOSIS, and additional fabrication runs are planned with other foundries.

Developing and fabricating the circuits is only one facet of the overall process. Testing and testability have become extremely important issues. A set of sophisticated test equipment that allows designers to completely characterize the dc and ac performance of their circuits has been acquired. In the case of digital circuits, the

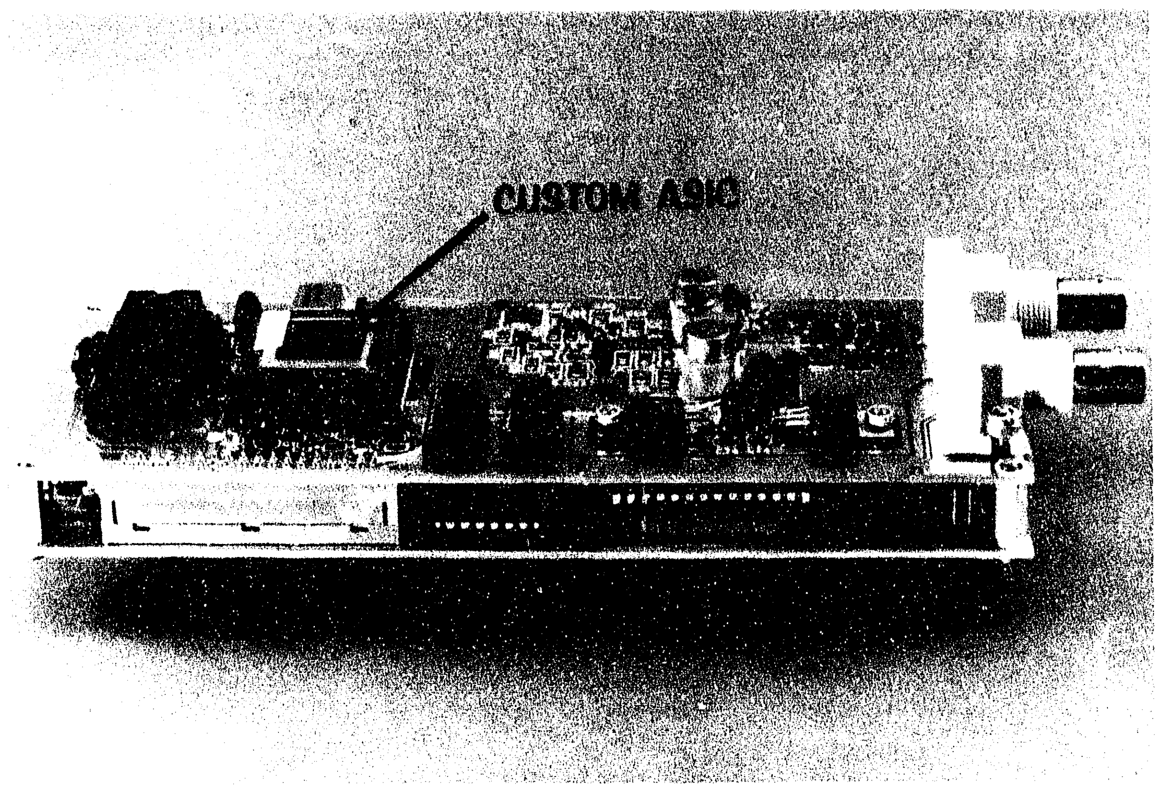


Fig. 2.6. Custom ASIC allows benchtop instrument functionality to be implemented in an inexpensive, miniaturized, portable package.

capability to apply the same test vectors used during the design to test the actual hardware has been added recently. Finally, expertise is available to support the complete development cycle from conception to final hardware test and checkout.

3. MEASUREMENT AND CONTROLS ENGINEERING

3.1 OVERVIEW (D. W. McDonald)

The Measurement and Controls Engineering Section (MACES) specializes in systems engineering of state-of-the-art equipment and software and addresses technical problems of national significance. Our management staff targets national concerns where technical solutions requiring advanced approaches are appropriate and applies our resources to develop funding and then to develop technical solutions in these targeted areas. Our technical staff maintains an in-depth knowledge of the state of the commercial art, which allows us to integrate very high performance systems. We are often the Beta test site for new products and likewise often integrate low-serial-number devices into our systems. This innovativeness requires a technical staff of uncommon technical depth and breadth. Our technical staff is also involved in investigating new theoretical approaches to extending our measurement and control capabilities. These new approaches are applied as soon as practical into our mainstream engineering activities.

Over the past 2 years, the annual section activity has been about $15M per year. Our financial plan—commitments from our Work for Others (WFO) sponsors—has a carryover that is presently at $17M. We have identified $5M in new funding which we expect during the coming year. The section has grown by 10% in the past year, and we expect a 6% growth for the coming year. Our strong financial health in the face of rapidly declining federal funding is a tribute to the excellent performance of our technical staff in meeting and exceeding the expectations of our sponsors and to the aggressive efforts of our management staff in identifying and developing new opportunities. We are expecting level funding from DOE and from the U.S. Department of Defense, U.S. Department of Justice, and National Aeronautics and Space Administration sponsors. We expect our biggest growth areas in the next 2 years to be in industrial interactions, primarily through cooperative research and development agreements (CRADAs) and in the transportation area in support of federal intelligent vehicle and smart highway system programs.

The section staff was honored with many awards and other instruments of recognition. Among the highlights, the Tennessee Society of Professional Engineers presented us with its Outstanding Engineering Achievement Award for the Automated Postage Stamp Inspection System we developed for the U.S. Department of the Treasury's Bureau of Engraving and Printing (BEP). The same system was recognized as one of the top ten technical achievements at ORNL during 1991. ORNL also recognized the Acoustic Measurements Facilities Improvement Project, Phase I, as one of the top ten technical achievements at the Laboratory during 1990. The Instrument Society of America (ISA) presented the Mills Dean II Award to G. N. Miller for his contributions to the Test Measurement Division of ISA. In 1991 J. M. Jansen was named Small Business Advocate of the Year by Energy Systems and also won the National Management Association's Human Resources Development Award. Energy Systems recognized the Large Cavitation Channel Data Acquisition and Analysis System (LCCDAAS) for a Significant Event Award in 1992 and also recognized R. S. Thomas with a Significant Event Award in 1991 for his leadership of a U.S. Navy team in quickly restoring an important research vessel to operation following an experimental mishap. D. A. Clayton and W. W. Manges both received letters of commendation for managerial performance from the Energy Systems WFO Program.

The fields of measurement science and controls technology are very broad. The sample projects we have chosen to highlight our work over the past 2 years reflect that breadth. We have subdivided our presentations into five areas: signal processing, advanced manufacturing, defense and space systems, nuclear systems, and environmental remediation. Many projects that were significant in their impact and innovation simply could not be included because of space limitations. For the most part, the projects highlighted in this report are major projects that spanned most of the past 2 years.

3.2 ADVANCED MANUFACTURING

3.2.1 Optics MODIL Program

The objective of the Optics Manufacturing Operations Development and Integration Laboratory (Optics MODIL) is to develop and integrate emerging technologies into manufacturing processes of precision optical components and to facilitate the transfer of this technology to the optics industry to support future defense production requirements.

The I&C Division is responsible for metrology and its integration into the manufacturing process. One of the most time-consuming and expensive tasks in the fabrication of precision optics is the measurement of the figure (shape) and finish of the surfaces. The figure of a typical precision mirror must be controlled to within a fraction of a wavelength of light and the finish to within a few angstroms. Measurements at this level have traditionally required the part to be removed from the fabrication machine and taken to a specialized metrology laboratory for interferometric or other optical measurement techniques. Usually, several iterations between the metrology laboratory and the fabrication machine are required before the specified tolerances are achieved. A primary goal of the MODIL metrology program is to develop methods for making these measurements while the part is still installed on the fabrication machine.

The primary metrology effort during this reporting period has been directed toward on-process figure measurement of aspheric mirrors.

Conventional phase interferometry for figure measurements of spherical or flat surfaces is well developed and commercially available. Several difficulties arise when applying this method to measure aspheres or to make measurements in a manufacturing environment. The requirement for accurate alignment and vibration sensitivity severely limits the on-process application of phase interferometry even for simple surfaces. Two different approaches for on-process interferometers are being developed for overcoming these problems. The first is a *differential* interferometer that uses a holographic image for measuring figure changes during the fabrication process. The second is a *polarization shearing* interferometer, a common path design sufficiently stable for operation in relatively high-vibration environments.

In addition, we are investigating the technique of using the built-in interferometers of the diamond turning machine along with a linear variable differential transformer probe to measure the coordinates of points on the surface after the machining operation. Another method uses a Scanning Hartmann Measuring Device, an adaptation of the classical Hartmann test for optical systems. This device uses a laser beam to scan the surface and a position-sensitive detector to measure the position of the reflected beam. The slope of the surface at each point is computed from the position data and integrated to determine the surface profile. Figure 3.1 shows the Scanning Hartmann Measuring Device in operation.

I&C Division personnel are also developing control concepts for ion beam milling. Ion milling of optical components is a superior alternative to mechanical polishing. An ion beam gun is used to sputter surface material from an optical workpiece inside a vacuum chamber. The surface removal effect of the ion beam is controlled by moving the gun through a grid of points over the surface of the optic with a computer-controlled translation stage. At each point, the beam dwells for a period of time. Determination of the dwell times is a challenging problem in two-dimensional signal processing. The dwell times are computed with an array processor by solving an ill-conditioned system of linear equations by using the concept of the singular-value decomposition of a matrix. This approach was pioneered by the I&C Division and offers significant advantages compared with techniques used by others.

3.2.2 Web Inspection Consortium

ORNL, The University of Tennessee (UT), and industrial partners have organized a Web Inspection Consortium with the objective of advancing the state of the art in web inspection technology through joint government- and industry-funded generic R&D. Web products are those produced in continuous rolls and are represented by most textile, paper, plastic, and metal processes. The activities of the consortium will include technology development, education, and technology transfer.

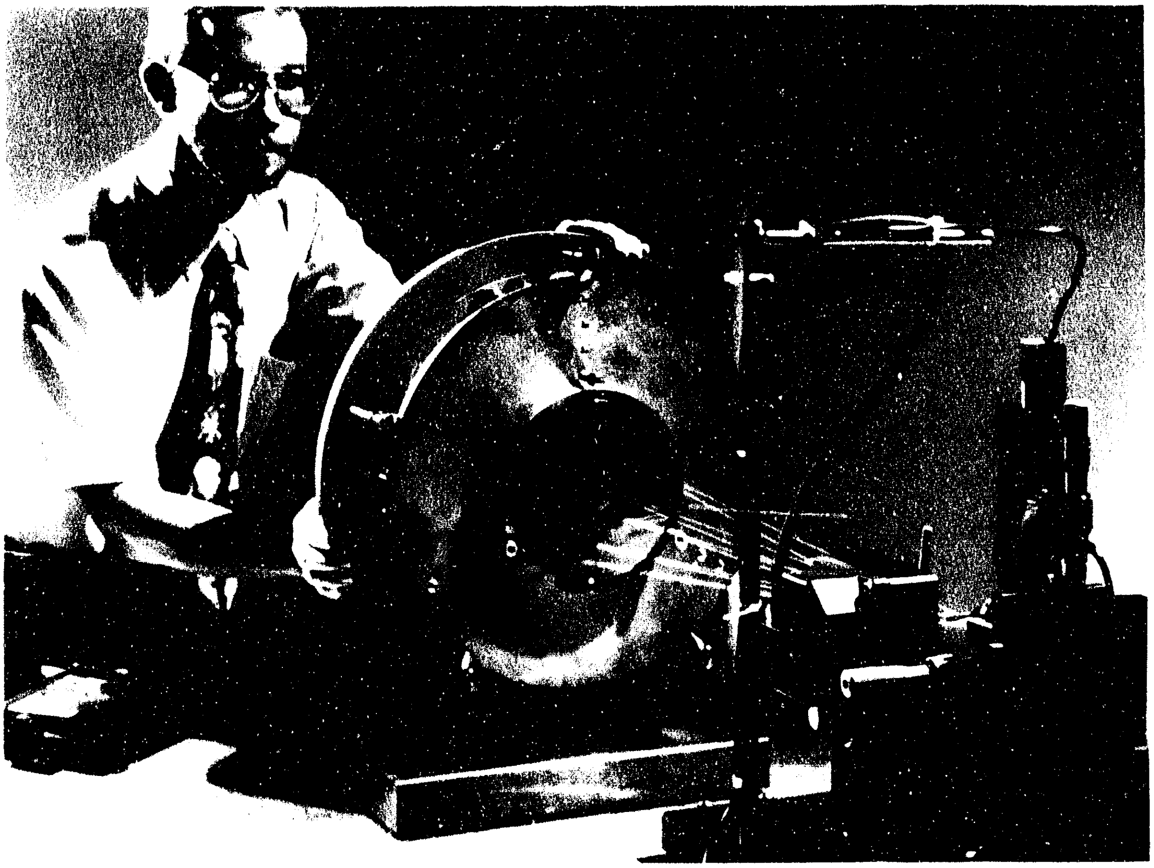


Fig. 3.1. The Scanning Hartmann Measuring Device measuring the figure of a large spherical mirror.

The Web Inspection Consortium is organized under the auspices of the UT Measurement and Control Engineering Center (MCEC). By combining the substantial resources of UT, ORNL, and the industrial partners, this consortium will work to achieve national preeminence in web inspection. The R&D agenda is determined by the Consortium Advisory Board (composed of representatives of the members). The participation of major U.S. manufacturers of web-based products and web inspection equipment suppliers will ensure a research agenda relevant to U.S. industry and will provide a direct mechanism for technology transfer to private industry.

3.2.3 Web Stamp Inspection System

MACES engineers completed the development of a modular, on-line printed web inspection system in support of BEP. The objectives in the system development were fourfold: (1) establish postage stamp quality standards that can be utilized by automated stamp inspection equipment, (2) develop on-line sensors capable of measuring stamp characteristics that influence the perceived quality, (3) determine the requirements for integrating the inspection system into the existing stamp manufacturing system, and (4) fabricate the prototype stamp inspection system for installation at BEP.

The program was funded at $6M and involved the prototype development of two major systems: (1) printed web quality monitoring and (2) web perforation monitoring. The first system mounts directly on the printing press to monitor key features as the web is printed. These features include (1) color-to-color and press-to-press registration; (2) color fidelity; (3) printing defects such as streaks, spots, and voids; (4) print width; and (5) web velocity.

The second system mounts directly on the web perforation equipment to gauge the horizontal and vertical registration of the perforations relative to the printed stamp image.

Both systems were designed to operate at full production speeds of up to 600 ft/min and to provide real-time parametric displays on large-screen color monitors. Additional capabilities include the on-line, on-demand preparation of detailed hard-copy graphic reports of web quality based on an entire roll. The reports were keyed to the length of the roll to allow for prompt review and removal of spoilage.

This program culminated in the delivery of the two systems to BEP for installation and testing.

3.2.4 Fingerprint Image Capture System

The Federal Bureau of Investigation (FBI) has undertaken a major revitalization effort that will result in a substantial upgrade of its services. The Criminal Justice Information Services Division is developing a new system known as the Integrated Automated Fingerprint Identification System (IAFIS) to modernize its ability to establish the identity of individuals on the basis of fingerprints. The heart of the IAFIS system will be the FBI Image Transmission Network (ITN/FBI), which will provide the framework for processing identification requests in a paperless environment within FBI. Implementation of ITN/FBI will require conversion of the existing FBI Fingerprint Card Master File to digital image format. This conversion must be completed before ITN/FBI can become fully functional. The conversion will require a high-speed, high-resolution Fingerprint Image Capture System (FICS) to generate digital fingerprint images of sufficient resolution and quality to allow accurate comparison of images by fingerprint examiners.

The development of a prototype FICS is being carried out through an interagency agreement between FBI and DOE. MACES engineers have the lead responsibility for the development of the prototype FICS. Functions that must be performed by the prototype FICS include transporting fingerprint cards past imaging equipment, acquiring a digital image of both sides of the card, buffering the images during processing, presenting the images on video monitors for verifying specific text information against FBI computerized records, and compressing and storing the image information on media suitable for future use by ITN/FBI. The throughput requirements for the system dictate an average data transmission and processing rate of 8.4 MB/s.

A low-speed image capture system that generates high-resolution, high-quality images has been developed to generate test data for the ITN/FBI prototype (Fig. 3.2). A conceptual design for the full-speed FICS prototype has also been developed. The target date for completion of the FICS prototype development is July 1993.

The I&C Division is also providing technical support to develop a prototype Fingerprint Processing Workstation (FPW) for the ITN/FBI prototype. FPW will allow presentation and manipulation of fingerprint images to aid experts in performing all steps necessary to process an identification request.

3.3 SIGNAL PROCESSING

3.3.1 Large Cavitation Channel Data Acquisition and Analysis System

A $5.2M signal-processing system was developed and installed in the U.S. Navy Large Cavitation Channel (LCC) in Memphis, Tennessee, in June 1991. Navy certification procedures continue to verify that performance meets or exceeds expectations. Previous reports detailed the architecture, data flows, signal characteristics, and performance goals. The performance of the near-field beamformer, the focus of this report, continues to represent the state of the art in real-time processing of acoustic signals in a noise-laden, enclosed facility such as LCC (Fig. 3.3). The analysis performed, the techniques used, and the architecture implemented work together to provide a capability that exists nowhere else in Navy R&D facilities.

The LCCDAAS beamformer is a spatial filter whose primary function is to reduce ambient noise by performing directional measurement. Directivity, achieved by time-shifting signals from an array of hydrophones and summing, provides constructive interference, thus improving the signal-to-noise ratio (SNR) of the measurement system compared with that achieved with omnidirectional techniques. Traditionally, both analog and digital beamformers assume both a linear array of hydrophones and far-field conditions that imply plane-wave signals. Furthermore, existing beamformers have a real-time acoustic bandwidth typically <5 kHz. The LCCDAAS beamformer has a real-time acoustic bandwidth of 20 kHz for multiple-array geometries of up to 45 elements. Because of near-field effects inherent to the operating environment (Fig. 3.3), the degree of time shift for each array element is derived from

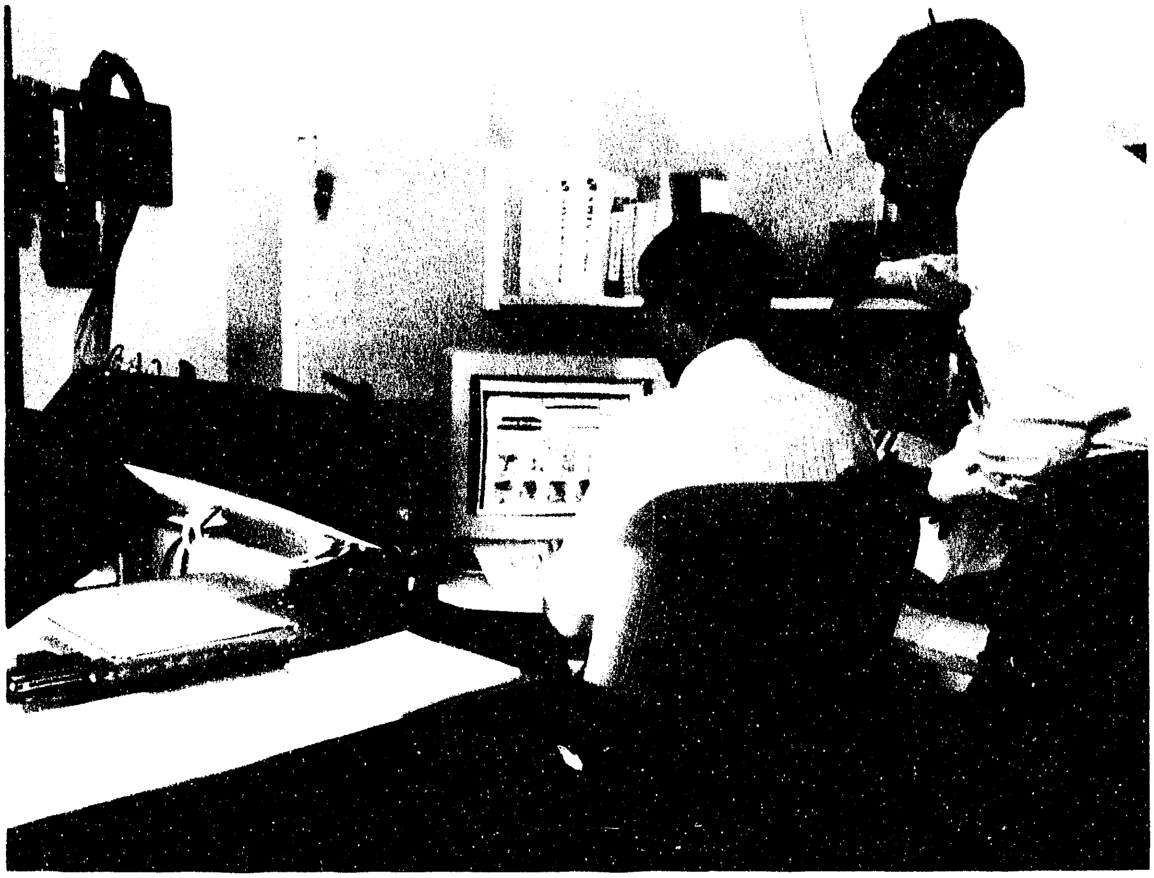


Fig. 3.2. Image Transmission Network/Federal Bureau of Investigation prototype Image Capture System.

a near-field point-source model rather than from a plane-wave model.

Signals from the hydrophone array are transformed to 15-bit time series by an analog-to-digital converter (ADC). The time series is collected by a single Star Technology, Inc., ST-50 array processor and then distributed across three additional ST-50 array processors to obtain a pipeline process operating at 9.2 MB/s. To achieve a high degree of directivity, an interpolation algorithm executing in the array processors performs a 20:1 increase in the ADC sampling rate. The algorithm implements a polyphase filter structure for a finite-impulse response interpolator, which provides a computational savings factor of 20 over zero padding for the beamforming operation. In addition to the savings, the polyphase structure provides frequency-independent array shading for improving side-lobe levels without using additional computational resources.

3.3.2 The Sonar Signal Analysis System

The Sonar Signal Analysis System (SoSAS) has been enhanced to allow analysts to perform after-the-fact beamforming on acoustic emissions data gathered from towed arrays attached to submarines. To demonstrate the feasibility of after-the-fact beamforming, a minimal interim digital system with only individual elements from arrays was integrated into SoSAS. After-the-fact beamforming/tracking provides the analyst with the ability to locate and track multiple targets from the array data. Previously, when studying data from arrays, analysts were limited to preformed beams focused in a predetermined direction. A full-function digital system based on the MIL-STD-2179 high-density digital recorder is currently being developed so that data from higher bandwidth sensors and individual elements from several arrays can be acquired and processed.

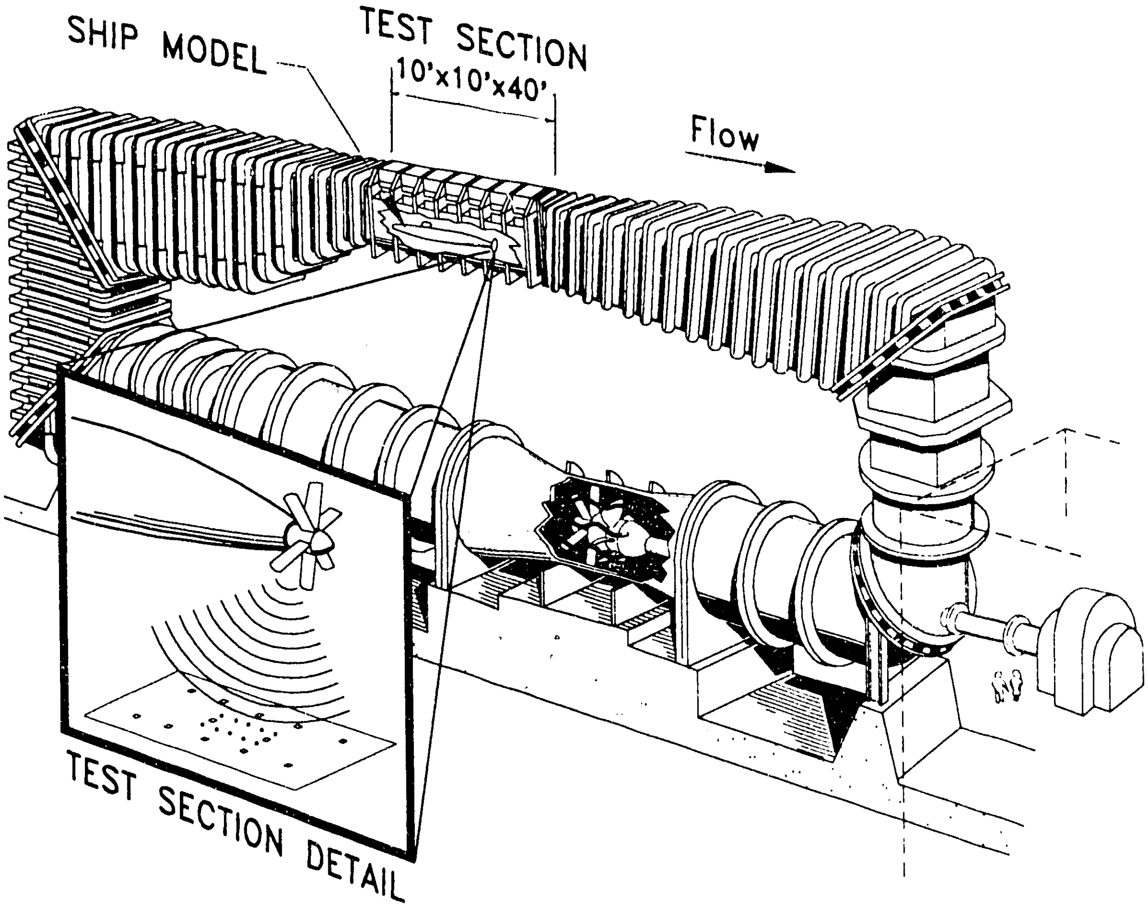


Fig. 3.3. Large cavitation channel.

Although different data sources have been added, the main mission of SoSAS has remained to provide the U.S. Navy with a tool to investigate new techniques for acquiring and analyzing information from sonar equipment and towed arrays.

Three new major software functions, previously performed either external to the SoSAS system or in SoSAS hardware during the acquisition process, were developed. These three functions are decommutating/formatting sensor data, performing beamforming/tracking operations, and converting sample rates so that results are easily compared (i.e., integration periods, frequency resolution, and bandwidth) with historical data. Decommutating/formatting sensor data allows selection of desired signals for a particular array and aperture from the incoming data stream. The second new function allows after-the-fact beamforming/tracking. To aid in the initialization of the tracker, a two-dimensional fast Fourier transform (FFT) is performed on the sensor data to produce a k-omega plot. The k-omega plot provides the analyst with a snapshot of all targets by forming beams in all possible directions. Once an initial bearing estimate has been obtained, the SoSAS linear-steered tracker and beamformer tracks the target. The third new function performs a sample-rate conversion on the beamformed results so that processed data can be compared with historical data as well as with data collected from SoSAS Phase I. The sample-rate conversion function takes advantage of the relative low bandwidth of the array data to reduce the computational complexity. By using innovative techniques, the computation requirements for the sample-rate conversion were reduced by a factor of 35 to 1.

3.3.3 Wavelet Transform

As a part of the Laboratory directed R&D project "Automated Inspection Methods," MACES personnel are employing adaptive wavelet transforms, specific to the class of images being examined, for automatic generation of features that provide a basis for material type and flaw classification. In addition, a new type of neural network has been developed, embodying many of the prevalent models as special cases, for classifying the wavelet-generated features. These two results form the core of a system that can distinguish subtle differences in web materials as well as classify and identify specific process flaws as they show up in the product.

3.3.4 Optical Processing

Under the Laboratory directed R&D project "Automated Inspection Methods," a coherent optical processor was developed that allows one to simultaneously measure the power spectrum of an image and spatially filter the image. The optical system (Fig. 3.4) applies the two-dimensional, Fourier transforming property of a lens used with coherent illumination. By using the optical processor, general, two-dimensional, spatially invariant linear operations (such as convolutions and correlations) can be performed in parallel.

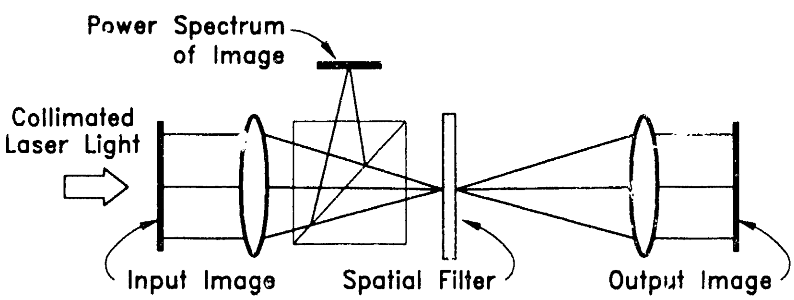


Fig. 3.4. Output plane of optical-wavelet-transformed image.

A spatial filter was designed to optically implement a wavelet transform. The wavelet transform provides a method to analyze an image at multiple spatial resolutions. By using the spatial filter, the optical system forms multiple bandpass filtered images similar to the images produced by a two-dimensional wavelet transform with a circularly symmetric kernel. Four separate images are formed simultaneously in the output plane for parallel readout. The wavelet images can then be used for image analysis in automated inspection applications.

3.3.5 Self-Tuning Controller Algorithm Evaluation

Tuning process controllers used to be a difficult and time-consuming task, but in the past few years, several manufacturers have incorporated self-tuning algorithms into their controllers to automatically tune the proportional-integral-derivative (PID) controller parameters. Researchers at Sunderland Polytechnic, Sunderland, England, developed three such self-tuning algorithms to work in conjunction with the Bristol-Babcock, Inc., PID control module. These algorithms are based on closed-loop cycling theory, pattern recognition theory, and model-based theory. Bristol-Babcock asked MACES engineers to evaluate these self-tuning control algorithms prior to their commercial implementation. I&C Division engineers developed the process simulations needed to test the algorithms; tested the performance and robustness of each algorithm; and provided a written independent investigative report comparing, contrasting, and recommending improvements to each of the three algorithms.

The tests demonstrated that some effective single-loop adaptive control techniques have been developed that can be used to adequately control many processes. Although it is certain that single-loop self-tuning controllers will not be enough to solve every process control problem, it may be possible to meet some increased demands and achieve better process control results simply by using one of these single-loop advanced control techniques.

3.4 ENVIRONMENTAL REMEDIATION AND WASTE MINIMIZATION

3.4.1 Fluid-Bed Upgrade Using Chaos Analysis

A fluid bed is a vessel in which granular or powdered solids are made to behave like a liquid by passing a gas upward through the solids in the vessel. Fluid beds are used in the conversion of certain materials into an appropriate form. When done properly, efficient reactions occur, material usage needs are reduced, and waste generation is minimized. This particular process required two fluid beds in series—one for reduction and one for conversion. To control the process for efficient material production and waste minimization, several conflicting criteria must be balanced. The conflicts can be resolved by controlling the reagent gas flow and employing a complementary function to control a diluent gas flow. The total gas flow is the fluidization demand determined by means of a Fluidization Indicator Module (FIM). Analysis of the fluid bed by using deterministic chaos led to the development of FIM. From the deterministic chaos analysis, it was found that the variation in the fluid-bed pressure signal with proper signal processing would indicate the amount of fluidization in the bed. By using the pressure signal, the total gas flow can be controlled to meet the conflicting criteria and to yield efficient material production and minimize waste products of excess gas and unreacted raw materials. This control strategy has been simulated with a fluid-bed process model, and results indicate that the design will function extremely well.

3.4.2 Waste Remediation Data Acquisition

A field-deployable data acquisition system was developed to assist in understanding and modeling the in situ vitrification (ISV) process, which employs high-voltage electrode heating techniques to encapsulate buried wastes in a stable, durable, glass structure. The data acquisition system provides real-time, graphical information from a variety of measurements within the harsh, electromagnetic-interference-plagued environment of the vitrified melt including temperature, pressure, heat flux, and various electrochemical parameters. Data obtained with the system have allowed researchers to improve models of the ISV process, leading to significant cost reductions of this and related in situ soil-remediation efforts.

Adaptations of the In Situ Data Acquisition System have been implemented for various other data acquisition efforts, including a technology demonstration for site remediation of buried waste sites at the Portsmouth Gaseous Diffusion Plant. Adaptability of this software package and its self-documenting nature led to a rapid installation of the system. This implementation and later data analysis proved extremely beneficial to the project purpose of developing a remediation plan best suited for the site conditions. A preliminary evaluation suggests that $85M will be saved by implementing this technology.

3.4.3 Saltless Direct Oxide Reduction Automation

MACES is supporting the Oak Ridge Y-12 Plant Development Division in an important development program called Saltless Direct Oxide Reduction (SDOR), which, if successful, will form an important processing section in the reconfigured weapons complex, Complex 21. SDOR provides a means of converting uranium dioxide powder to pure uranium metal with greatly reduced contaminated waste generation while using reactants less toxic than those produced with existing methods. In addition, human exposure to airborne contaminants can be eliminated; criticality safety can be addressed more rigorously; nuclear material accountability can be maintained more efficiently; and smaller, less expensive systems will be required.

The I&C Division role in the SDOR program primarily concerns the automation of a variety of batch chemical processing steps. Automation of the SDOR process poses interesting design challenges not normally found in industry. I&C Division engineers, working closely with Development Division staff, have designed a unique automation strategy for SDOR processing that addresses these challenges. This strategy includes two circular-platform, inert-atmosphere glove boxes, each with a centrally mounted seven-degree-of-freedom robotic manipulator. Special material-control interlocks connect glove-box sections and control-material ingress and egress for maintaining criticality safety and atmospheric integrity.

3.4.4 West Valley Transfer Cart Control System

The I&C Division designed a communications and control system for a remotely controlled transfer cart in support of the DOE West Valley site, West Valley, New York. The cart, used to transfer radioactive waste cylinders between hot cells at the West Valley site, travels on tracks connecting four cells; the cart receives radio frequency transmitted control signals.

The rf system designed by the I&C Division for the transfer cart includes two cart antennas and four facility antennas (one in each cell of the cart path). The antennas are set up in a diversity selection mode whereby the strongest signal received by the cart or facility is selected. In this manner, if one antenna is in an rf null due to the metal-lined walls of the hot cell, another antenna can still be used for communications. Wideband spreading of the modulated digital control signals is used so that if a null occurs in a narrow frequency range, the digital signal can still be recovered from the remainder of the frequency band. Finally, an algorithm is used on the cart controller that will enable the cart to keep traveling a few inches if it stops receiving valid commands and if the last valid command it received was to drive. If both cart antennas are in a null, the additional few inches of travel will allow the cart to drive out of the null.

A control module was designed and integrated into the cart. The control module contains lead shielding to protect the communications and control electronics from high levels of radiation. Because human access to the cart is limited, the control module was designed to facilitate remote removal and replacement of either the battery pack or the whole control module by using overhead cranes.

An engineer console collects status information from the cart, battery charger, and doors for diagnostic information and historic operating logs. The engineer console, which is not used for day-to-day operation of the cart or charger, can be used for higher level commands to the system such as rebooting the cart computer, changing cart speed, and enabling/disabling facility antennas and will also be used to maintain facility-side control programs.

3.5 NUCLEAR SYSTEMS

3.5.1 Process Simulator/Trainer

Using costly operating plant equipment to test new computer-controlled systems or to train employees is sometimes a risky undertaking that could result in expensive process wastes and downtime for repairs. MACES engineers have developed a generic industrial process simulator/trainer that can be used as a surrogate plant to facilitate off-site configuration and verification of system hardware and software and to train operators to use new systems without disturbing the on-line process.

The focus of recent work has been to simulate the UF_6 freezer/sublimer process at the Paducah Gaseous Diffusion Plant. The gaseous diffusion process operates efficiently over a wide range of production capacities. Because the power drawn by the equipment is proportional to the process inventory level, large savings can be realized by operating the plant at higher capacities when less expensive power is available. Power swings can be effected by freezing UF_6 out of the process (power decrease) or subliming UF_6 back into the process (power increase). Thus, the primary components of Paducah's new cost-effective process inventory control system are the freezer/sublimer units. Although the original process development work focused on simulating the freezers/sublimers, the system can be easily duplicated and customized according to customer needs, including those of the pulp and paper, chemical, wastewater processing, automotive, textile, power, pharmaceutical, and aerospace industries.

Process simulations developed by the I&C Division have been verified and validated with actual plant process data. These efforts have proven to be indispensable to our customers in plant design and modification, control system engineering, operational scenario analysis, and operator training.

3.5.2 Fuel Disassembly System

In a nuclear-fuel reprocessing plant, a shroud must be remotely removed from spent-fuel bundle assemblies with minimal damage to the fuel pins inside. The Fuel Disassembly System uses a laser to cut the shroud away from the bundle. Because the fuel assembly must be handled and positioned numerous times during the disassembly process, the control system was designed to ensure that the movements were completed correctly through feedback of position indicators and to provide interlocks to prevent spatial conflicts with the various pieces of equipment. The laser cutting process required real-time, three-axis control by closed-loop servomotor control systems for positioning the fuel and for positioning the laser focal point. These servo systems incorporated state-of-the-art digital signal-processing techniques to obtain real-time control. A measurement system, an active follower, was devised to allow the laser focal point to "track" the shroud surface. With the focal point of the laser on the shroud surface, a much more efficient cut is made with less danger of damaging the fuel pin underneath the shroud surface. The combination of the three-axis control and the innovative active follower allows the shroud to be removed with minimal fuel-pin damage.

3.5.3 Dissolver/Process Measurement and Controls

As part of the operations of a nuclear-fuel reprocessing plant, the fuel must be dissolved in a nitric acid bath. A continuous rotary dissolver was designed to more efficiently dissolve the fuel and provide more constant product and off-gas flow streams. To achieve this higher efficiency over previous batch processes, appropriate monitoring and control were required. A dynamic model of the complicated process was developed that describes the chemical reactions, thermal-hydraulics, and mechanical motions. The modeling results helped determine the required measurements and their locations as well as heat input requirements for efficient temperature control and dissolution.

State-of-the-art motor control was used to precisely control the motion of the dissolver to ensure proper feeding and discharging of the processed fuel. In addition, a unique measurement system that included a cam on the dissolver shaft and fixed proximity sensors was developed to indicate the drum position. All sensors and actuators were designed to operate in a high nuclear radiation environment with nitric acid vapors present. A prototype continuous rotary dissolver has operated effectively with significant improvements in dissolution rates, which, in turn, has resulted in a higher quality product.

3.5.4 NRC Regulatory Guidance on the Susceptibility of Digital Systems to Electromagnetic Interference

ORNL and the I&C Division are supporting the U.S. Nuclear Regulatory Commission (NRC) in establishing regulatory guidance to address the susceptibility of digital systems to electromagnetic inteference (EMI). NRC concern stems from the safety-related issues that need to be addressed with the application of digital instrumentation and control systems in nuclear power plants. Manufacturers of digital circuits are incorporating increasingly higher clock frequencies, faster operating speeds, and lower logic voltage levels into their designs. In turn, the faster digital logic families have shown a greater susceptibility to upsets and malfunctions due to the effects of EMI.

MACES engineers are developing the technical basis on which NRC regulatory guidance can be established. This process includes the establishment of good EMI design and installation practices to control interference sources and their impact on nearby circuits and systems; a test and evaluation program to outline the tests to be performed, the associated test methods to be followed, and adequate acceptance criteria to ensure that the circuit or system under test meets the recommended guidelines; and a periodic maintenance program to assess whether the recommended EMI practices are being adhered to as part of routine plant operation.

3.6 DEFENSE AND SPACE SYSTEMS

3.6.1 Acoustic Measurements Facilities Improvement Program, Phase II

The Caderock Division, Naval Surface Warfare Center (CD/NSWC), through an interagency agreement, has tasked the I&C Division to develop a state-of-the-art prototype acoustic measurement system to support testing and operation of advanced submarine designs that will begin in FY 1995. Key features of this system include a high-gain acoustic array, its associated data telemetry system, and a beamforming system. These systems will operate in real time to produce accurate measurements and dynamic images of the acoustic emissions from test vessels that would otherwise be hidden within the ambient sea noise.

The high-gain array (HGA) system consists of two large cylindrical arrays of precisely positioned hydrophones and the electronics required to acquire, digitize, and telemeter their signals to shipboard analysis systems (Fig. 3.5). Each array of more than 1300 sensors covers a total acoustic frequency range spanning five octaves. Aggregate data rates for each array exceed 1.1 Gbit/s. In addition, a wide dynamic range (>100 dB) is provided to allow the shipboard processing systems to detect and analyze target emissions many times quieter than the ambient ocean noise.

Application of several state-of-the-art technologies has enabled the program to reach these performance levels. Rigorous testing by the I&C Division was performed to obtain sufficient confidence in these new and largely unproven

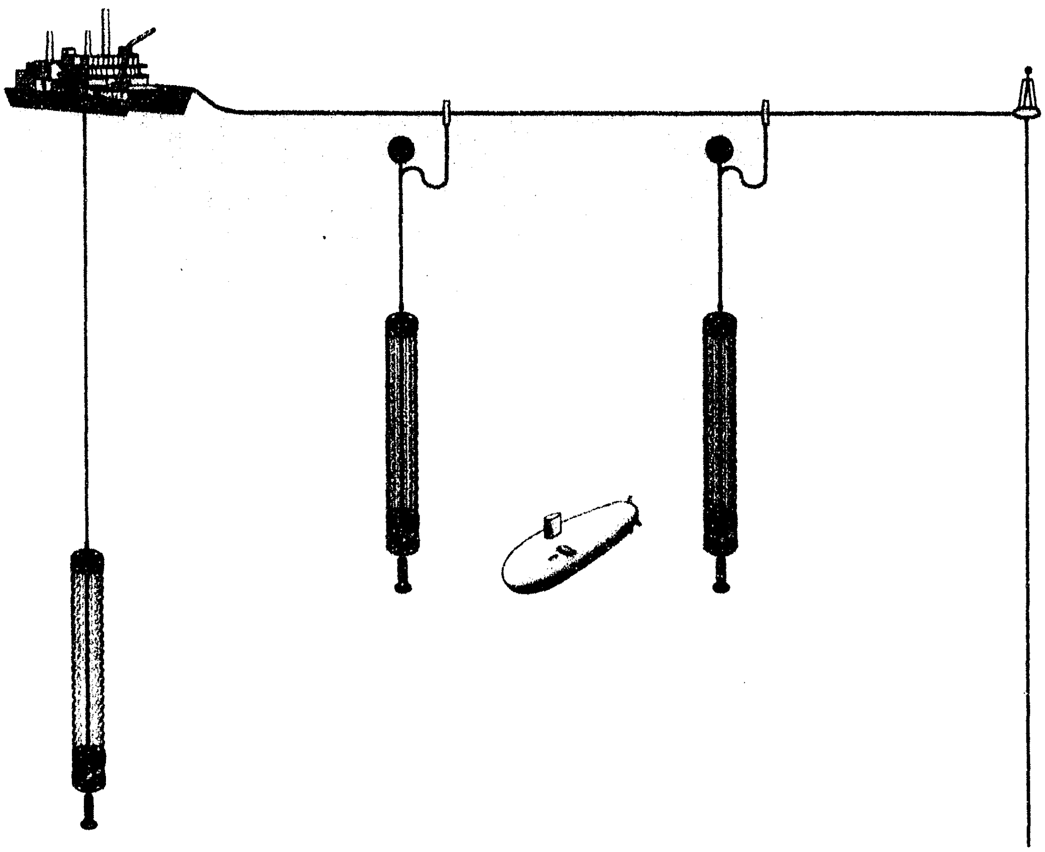


Fig. 3.5. Acoustic Measurements Facilities Improvement Program, Phase II, high-gain array system.

technologies. High-speed, high-resolution signal digitization, high-voltage dc power distribution, and very high speed data multiplexing were recognized early in the program to be critical to the design of a system that met all performance requirements. Components with the potential to fulfill these functions had recently become available commercially, but issues relating to performance, compatibility, and reliability had to be resolved before the program could commit to their use.

Sigma-delta ADC techniques have been known since the 1960s but have become practical for most applications only recently because of rapid advances in integrated-circuit digital signal-processing technology. Offering a combination of speed, accuracy, low power consumption, and relaxed antialias filter requirements not obtainable with other technologies, sigma-delta conversion was by far the most promising technology for digitizing the thousands of HGA hydrophone signals.

Conventional circuit powering techniques are not feasible for the HGA electronics because of the large distance between the shipboard power source and the arrays. Extensive testing has proven that a technique called linear postregulation solves the output noise problem and that isolating the conversion components into separate pressure vessels prevents EMI. Tests were also conducted to verify that submerged dc/dc converters will not emit significant acoustic energy in the frequency range of interest.

Early program studies showed that the use of fiber-optic data links was the most feasible method of transferring data from the underwater electronics to the shipboard processing system. To take advantage of the large data capacity of the optical data telemetry system, digitized signals from hundreds of hydrophones had to be multiplexed into a single serial data stream for transmission. A new data multiplexer based on gallium arsenide semiconductor technology provided a single-chip solution, but because the device was so new, insufficient reliability data were available. Several of the devices were operated at elevated ambient temperatures for over a year, accumulating nearly a million accelerated-lifetime hours of operation with no device failures to date.

Designs for circuitry covering the lower two octaves of the HGA frequency range have been completed, prototyped, and tested. A subcontractor is now fabricating the circuit boards and chassis. Design of most of the high-frequency circuitry is complete, and prototype assemblies are being built and tested. Requirements for interfacing HGA to the beamformer system are being defined.

The beamforming and signal-processing system will receive data from the two arrays of underwater sensors and digitally beamform and process the data to produce calibrated sound pressure level measurements of the radiated energy of the test vessel. Data products of this system include 92 precision measurement beams for each array that can be used for continuous real-time spectral analysis and high-resolution acoustic images of the test vessel area. Images are used to verify that proper beam-target tracking synchronization exists and to detect unwanted acoustic hot spots in the background area. Because the anticipated acoustic emissions are expected to be significantly quieter than the ambient sea noise, the system must simultaneously process signals from more than 2000 sensors in the arrays to produce the required measurement in real time. The incoming data rate from the arrays will be ~144 MB/s, sustained. Data will be stored for subsequent retrieval and analysis both with the system and at other facilities.

This system will be developed at ORNL and delivered and installed aboard the USNS Hayes, a ship-based laboratory operated by CD/NSWC. One-half of the system will be installed in early FY 1994, and the other half will be installed in early FY 1995.

3.6.2 Corps Command Group Vehicle

During Operation Desert Storm, corps-level commanders conducted operations from Heavy High Mobility Multipurpose Vehicles with the help of cellular telephones and lap-top computers. This experience underscored the need for a self-contained autonomous mobile command and control post from which a commanding general can perform. The commander in chief of the U.S. Army in Europe embarked on a development program to introduce advanced technologies that would enhance mobile battle management and information display and dissemination technologies into the battlefield command and control structure. In support of this research, MACES engineers developed the Corps Command Group Vehicle (CCGV).

CCGV is a mobile platform that can be fully operational in less than 7 min after forward displacement. Its critical technologies include hardened, high-resolution, large and medium screen displays for battlefield management, a communications network that supports FM and satellite links as well as video teleconferencing, and a local area network combat computer suite linking the Army's Maneuver Controls System with two operations-planning workstations and a second node comprising the Army's Standard Tactile Army Command and Control Station and a single intelligence workstation. Included in the development is a split, 20-kV, three-phase system providing power to CCGV and its environmental control unit.

CCGV has been operational since December 1991 and has successfully participated in three exercises.

3.6.3 Lithium Process Recovery Distributed Control System Installation for Chemical and Metal Forming Operations

Much of the modernization effort at the Oak Ridge Y-12 Plant Weapons Components Facility has focused on the integration of distributed control systems (DCSs) and data acquisition systems into plantwide database management systems. MACES engineers have worked closely with other organizations to develop and implement the system integration strategy in the Lithium Operations and Metal Preparation divisions. For example, a software system to provide part-tracking and data-collection functions not available in commercially available DCS software was developed that integrates information from presses and heat-treat furnaces into a common database and provides near paperless operation and tracking of many manufacturing processes in the metal-forming areas of the Y-12 Plant. Members of the I&C Division have also served on the multidivisional Shop Floor Data Integration Team. This team is responsible for planning the implementation of the Consilium WorkStream manufacturing resource planning software purchased to integrate Y-12 Plant operations.

MACES engineers had the technical lead on the multidisciplinary procurement and evaluation team responsible for selecting the new $1.1M DCS for all permanent installations to be done by lithium process recovery (LPR). The I&C Division is responsible for the instrumentation and process design for all the LPR wet chemistry operations, including the half-heavy water treatment, neutralization, evaporation, and crystallization processes as well as the annealing/outgassing oven integration effort.

3.6.4 Smart Isolated Port Switch

A Smart Isolated Port Switch (SIPS) was developed that provides the capability to switch a personal computer (PC) serial communication port between two remote systems (computers or networks) of differing security classification levels conveniently and without (1) coupling electromagnetic emanations from one remote system to the other, (2) inadvertently making data from one system accessible by the other, or (3) mistakenly having a mismatch of the classification level of the magnetic media being used by the system.

When the user activates the switch in the desired position, SIPS detects the new switch position; turns power off to the PC and peripherals; and after a short delay, turns power on (system sanitizing), causing the PC system to reboot. Then, PC communication with SIPS determines the position of the switch and verifies whether the magnetic media classification is correct for the selected network. The user is alerted to change the media if necessary and verifies the new media. SIPS then connects to the selected network and finishes the system initialization process.

3.6.5 OTDR-Based Strain Measurement

There is considerable interest in in situ measurement of strain in military structures. Optical time-domain reflectometry (OTDR) in an optical fiber is a simple and rugged technique for measuring strain. ORNL has constructed several OTDR-based, submillimeter-resolution, strain-measurement systems from off-the-shelf components. Repeatable resolution of changes in time of flight within ±1 ps has been observed. By using a 1-m-long single-mode fiber as a strain gauge and observing the time of flight between Fresnel reflections off both cleaved ends, a repeatable sensitiv[illegible] 200 microstrains has been observed. With the [illegible] fiber connecting the legs of a 90 to 10% tap-off coupler to form a loop, a repeatable sensitivity of 80 microstrains has been observed. A fiber-optic loop embedded in a composite sample allows the system to successfully measure strain in the sample. The system is being modified to improve the repeatable sensitivity to <20 microstrains for a 1-m-long gauge fiber.

4. TECHNICAL SUPPORT DEPARTMENT

4.1 OVERVIEW (D. R. Miller)

The Technical Support Department (TSD) of the I&C Division continues to maintain, as a primary responsibility, an instrument technician population focused on the support of ORNL-managed electronic equipment. During this report period, the instrument technician staff of about 100 hourly staff was directly supported by ~50 salaried staff. TSD is responsible for all electronic equipment maintenance support at ORNL. In most cases, this support is provided directly by our staff. In some cases, because the equipment is very specialized or because of contractual agreements, the equipment is subcontracted to original-equipment manufacturers or second-source vendors for maintenance. This subcontracting is approved jointly by TSD and the program supported.

TSD has experienced much change during the past 2 years. Accompanying our new name (previously Maintenance Management Department) has been a deliberate and visible effort to raise standards and empower staff. Historically, TSD has worked as a partner with I&C engineering sections to provide cradle-to-grave instrumentation service to ORNL. As DOE has shifted from a programmatic focus to one of environmental and safety, the resulting guidelines and rules have placed much more visibility on TSD activities. This increased responsibility required greater emphasis on strategic planning and formality of processes to ensure a continued cost-effective and responsive maintenance program. In addition, several new DOE orders have been directed specifically to maintenance activities of its contractors. Although the I&C Division has no direct capital asset support responsibility, it does have a significant shared role in maintaining an extensive array of scientific equipment and ensuring ample performance margins for environmental-, safety-, and health-related equipment. During the past 2 years, TSD has devoted significant effort to the analysis of requirements from DOE and our internal programmatic technology challenges. This has resulted in the creation of the most formal technical training structure since the demise of the apprentice program in the 1970s. Initiatives in radiation protection system support, field engineering, operating safety requirements, facility support, fabrication, reactor support, and personal computer service have grown into highly successful regular, fully integrated elements of our operation.

The competitive posture of TSD has always been important. During 1991, we embarked on a major new initiative with respect to competitiveness. The effort was given the title *TSD 2000*. Major elements of the initiative are Total Quality Management, timely job-specific personnel evaluation and training (reported separately), greater emphasis on empowered work teams, and supervisor training to foster coaching and counseling of employees rather than the traditional lead, guide, and direct philosophy of the past.

A highly visible and successful foundation stone of the TSD management system is the Maintenance, Accountability, Jobs, and Inventory Control (MAJIC) computer-based information system. Significant system upgrades were accomplished during this review period. The MAJIC Committee responded to customer and regulatory requirements by developing new criteria for the system. The result was significant expansion of the data input and reports capability. More detailed reports can be extracted from the maintenance history of equipment than was earlier possible. A second major improvement is generation of special notification letters and reports needed by equipment owners. These improvements are primarily the result of teamwork between the MAJIC Advisory Committee and our Systems Development Team.

The I&C TSD remains responsive to ORNL programmatic needs and to DOE orders. It is important to note that our success is primarily due to the relatively unfettered ability to quickly assess changing needs and to respond in a cost-effective manner. The Department and I&C engineering management teamwork continue to be the best overall process to develop support structures for ORNL through a responsive and cost-effective process.

4.2 BASELINE EVALUATION PROGRAM

Driven by DOE orders, numerous other regulatory requirements, and the desire to provide users with superior service, TSD ensures that all of its employees remain current in the disciplines necessary to perform their tasks. Because the duties demanded of instrument technicians—in contrast to those of other skilled crafts—are rapidly becoming more technical and more varied, TSD has undertaken a historic initiative in the concept of technical training. Seven specialized categories of the instrument technician discipline have been identified, resulting in training programs tailored to the needs of each individual technician. By administering a Baseline Evaluation Test to all technicians, individual areas of technical strength and weakness are ascertained and then plotted against a matrix that profiles the technical attributes characteristic of the specialized category of each technician. A training curriculum that avoids teaching skills already mastered or unneeded is then customized for each individual.

4.3 INSTRUMENTATION FOR ENVIRONMENTAL STUDIES

Environmental studies often require unique, specialized instrumentation that is unavailable commercially. TSD field shops are regularly requested to assist researchers in creating systems for data collection. Collecting data in the field requires instrumentation that combines the latest technology with compactness, portability, low cost, and light weight.

TSD designed a chlorine analyzer system to assist researchers in studying the effects of high chlorine levels suspected of contributing to fish kills in the East Fork of Poplar Creek. This system (Fig 4.1) enables researchers to learn more about this phenomenon by measuring and recording pH, water temperature, conductivity, light levels, and chlorine concentration with sensitivity in the 0- to 0.5-ppm range. The system consists of a datalogger, pH and conductivity meters, a thermometer, a quantum sensor, and a chlorine analyzer.

A mercury vapor sampler was designed by TSD to provide accurate and stable airflow for the measurement of mercury fluxes. The six-port system measures and controls the flow rate of sample air through a trap and records the information through a datalogger to detect the amount of mercury vapor in the air. The system was recently tested at the ORNL Walker Branch Watershed with plans for future use in Sweden and Florida.

We designed a data-acquisition system for use in an experiment to study the greenhouse effect due to elevated atmospheric CO_2 levels on American beech and sugar maple trees. The system consists of a datalogger; a multiplexer; and a personal computer that measures air temperature, relative humidity, and soil temperature and offers real-time graphic monitoring of all sensor inputs and data storage. Resistive heaters and evaporative coolers are used to maintain temperature levels. The CO_2 is controlled by hand valves and is maintained at 150 ppm above ambient levels.

In response to a Tiger Team finding, TSD coordinated a massive effort to relocate the environmental sampling activities at the ORNL Sewage Treatment Plant to a separate facility. The existing Parshall flume was reformed to original specifications, eliminating the need for the purchase and installation of a new flume. A staff gauge was installed in the stilling well for the flume as a benchmark for environmental and sewage treatment flow activities. A further enhancement was the addition of a TSD-developed CPU-based data system to provide low-cost expansion as future upgrades in flow-measurement technology become available.

4.4 AUTOMATED HEALTH PHYSICS INSTRUMENT TESTING SYSTEM

The manual testing, adjustment, and calibration of health physics instruments are repetitive and time-consuming processes. These process demands combined with an increasing demand for health physics instrumentation have produced a need for an automated testing system. TSD recognized the opportunity to transfer existing technology to our maintenance activities to a significant advantage. The Department sponsored a development effort by the Research Instrument Section to design an automatic device that could calibrate the

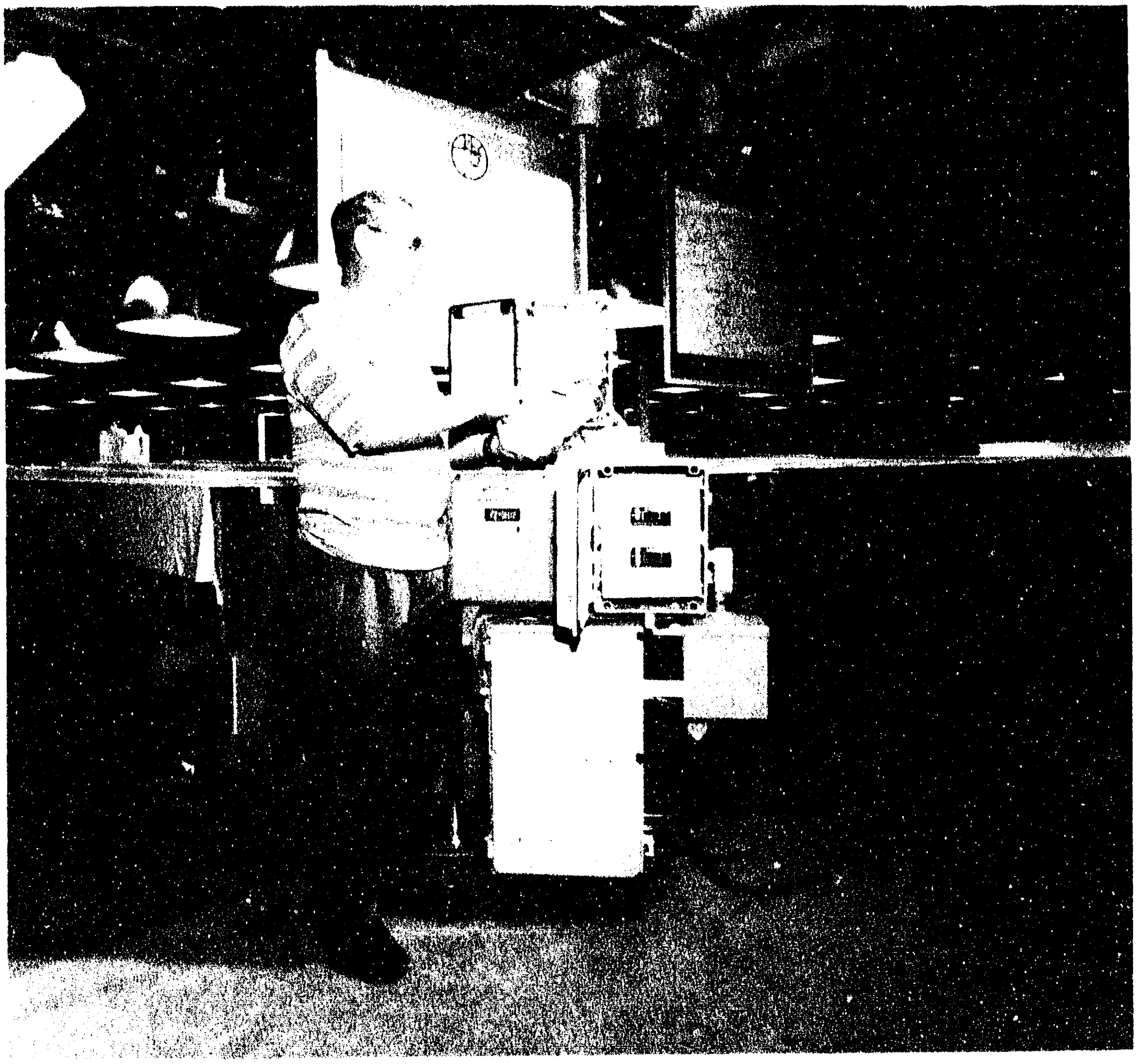


Fig. 4.1. Chlorine analyzer system.

commonly used Bicron Surveyor instrument. The result was a field shop system that was able to

- reduce hands-on technician time,
- ensure test procedure uniformity and accuracy,
- allow technicians to concentrate on instrument repair, and
- automate record-keeping.

The working prototype of the testing station was demonstrated for the Tiger Team in November 1990 and for the I&C Advisory Committee in March 1991. Full field implementation began in August 1991.

The automated testing system was targeted for use with the Bicron Surveyor-MX. This survey instrument is the preferred ORNL inventory model. More than 650 of these instruments have been acquired, and 473 older stationary friskers are being replaced with the Bicrons.

The microprocessor-based testing station (Fig 4.2) incorporates all the hardware and firmware necessary to execute the instrument testing and adjustment procedures by using a display panel and function keys for operator interaction. Four operational stations in the repair shop transmit the results of test procedures to a host computer system for archival and report generation.

The system has operated successfully for more than a year. The host computer contains a database that reads and translates bar-coded information and

Fig. 4.2. Automated health physics instrument testing system.

formats the information needed for completion of the test reports. Technicians are now able to scan a list of bar-coded comments to enhance test reports. In most cases, a technician simply signs the completed data sheet. The automated data sheet generation and the ability to electronically transmit test results to the mainframe computer have significantly reduced overall calibration and data input time.

4.5 HFIR MATERIALS IRRADIATION FACILITIES CONTROL AND MONITORING

HFIR, which produces isotopes, is a vital tool for research requiring neutron bombardment of materials. These experiments are accomplished by inserting the materials to be tested into the HFIR Materials Irradiation Facility (MIF). For years, MIF was equipped with electromechanical protection relay modules to automatically reduce reactor power to prevent overheating of experiments. Using programmable logic controllers, a Research Support Group (RSG) team developed a modern computer-based experiment protection system (Fig 4.3) that can monitor several experiments simultaneously and assist in data monitoring and report generation should the host controller-logger fail. If necessary, the new system can generate histograms, trend graphs, text reports, and alarm histories. The safety monitoring task is unaffected by report generation.

The new system requires significantly less maintenance and is more versatile. Because it accepts both analog and discrete signal inputs, both of which can be multiplexed, fewer signal cables are required. The system can automatically calculate conversions for input data, thereby providing better accuracy in control and monitoring. Data validation can be done from different levels of access priority, and each computer-based module has a *watchdog* system that provides a continuous on-line check for proper hardware and software operation.

4.6 HEAVY-SECTION STEEL IRRADIATION TECHNOLOGY

Heavy-Section Steel Irradiation (HSSI) technology experimentation is a long-standing NRC program performed by ORNL to study the embrittlement of reactor vessel materials. These experiments, conducted by the Engineering Technology Division, are abetted by a data acquisition and control system developed by the TSD Research Support Group. Located at the Phoenix Ford Reactor at the University of Michigan, these experiments require that steel specimens inside an aluminum capsule be maintained at a constant temperature during bombardment with fast neutrons.

RSG personnel devised a system (Fig 4.4) that allows the Michigan experiments to be controlled and monitored remotely from a computer terminal at ORNL. In addition to being provided with an inventory of spare parts and drawings, personnel at the Ford Reactor were trained in the system's on-site maintenance and proper response to alarms.

Fig. 4.3. Materials Irradiation Facility (MIF) control module.

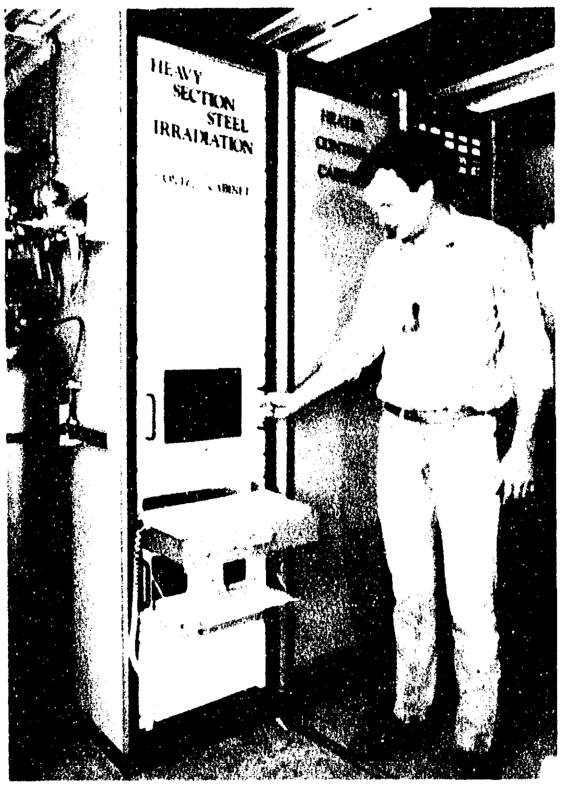


Fig. 4.4. HSSI control cabinet.

PATENTS

Instumentation and Controls Division Patent Applications Filed and Patents Issued July 1, 1990, Through June 30, 1992

ESID No.	Name	Description	Patent No. and date
		Patents Issued	
158-X	H. R. Brashear M. S. Blair M. L. Bauer C. H. Nowlin J. E. Phelps	Ultrasonic Ranging and Data Telemetry System	4,924,450 May 8, 1990
468-X	L. H. Thacker	Ionizing Radiation Detector	4,963,747 October 16, 1990
253-X	S. F. Smith D. W. Hendrix	Demodulation Circuit for AC Motor Current Spectral Analysis	4,978,909 December 18, 1990
462-X	D. D. Falter K. G. Falter K. H. Valentine	Infrared System for Monitoring Movement of Objects	5,012,113 April 30, 1991
522-X	R. L. Shepard T. V. Blalock L. C. Maxey M. J. Roberts	Optical Johnson Noise Thermometer	5,098,197 March 24, 1992
514-X	M. L. Bauer M. M. Chiles S. A. McElhaney	Scintillation Assembly for Alpha Radiation Detection and Method for Making the Assembly	5,149,971 September 22, 1992
		Patent Applications Filed	
513-X	I. L. Larson M. M. Chiles V. C. Miller	Apparatus for Detecting Spontaneous Radiation from Substances in Fluids	
779-X	R. J. Lauf D. W. Bible	Variable Frequency Microwave Furnace	

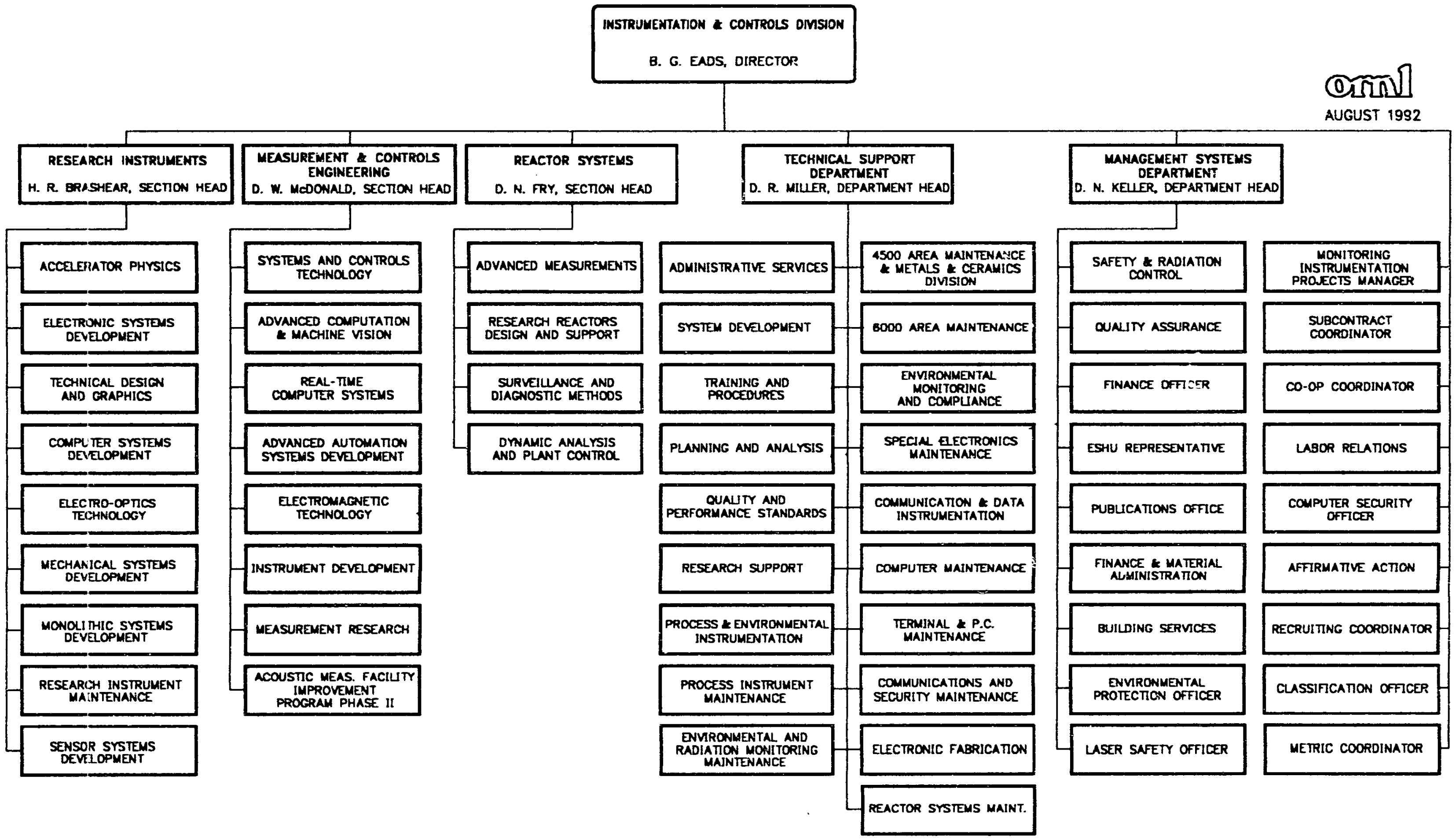
ESID No.	Name	Description	Patent No. and date
843-K	K. W. Tobin J. D. Muhs J. K. Jordan J. V. LaForge	Fiber Optic Vehicle Identification Sensor System	
865-X	D. W. Bible J. A. Moore R. J. Lauf	Personnel Address System	
778-X	R. J. Lauf D. W. Bible A. Zucker	Personnel Accountability System	
574-X	R. J. Lauf B. S. Hoffheins D. A. Costanza	Solid State Electrochemical pH Sensor	
770-X	C. L. Britton, Jr. A. L. Wintenberg	Method and Apparatus for Providing Pulse Pile-Up Correction in Charge Quantizing Radiation Detection System	
871-X	M. M. Chiles S. A. McElhaney	Unitary Scintillation Detector and System	
953-X	L. C. Maxey	An Automated Interferometric Alignment System for Paraboloidal Mirrors	
867-X	T. G. Kollie L. H. Thacker H. A. Fine	Instrument for Measurement of Vacuum in Sealed Thin Wall Packets	
929-X	B. S. Hoffheins R. J. Lauf	Rapid Fuel Analyzer	

TECHNOLOGY TRANSFER

The following developments have been licensed to private industry through the Martin Marietta Energy Systems Technology Transfer Program.

An instrument for the measurement of the pressure in vacuum-sealed thin-wall packets, developed by the Reactor Systems Section of the Instrumentation and Controls (I&C) Division and the Materials Thermal Analyses Group of the Metals and Ceramics (M&C) Division, has attracted the attention of the commercial sector. The instrument was developed for the nondestructive measurement of the internal pressure of sealed, evacuated panels of superinsulation being developed at ORNL. This technology can also be used to measure vacuum-sealed packets of pharmaceuticals, food-stuffs, chemicals, etc. Through the Technology Transfer Office of Martin Marietta Energy Systems, Vacu-panel, Inc., has signed a limited license agreement for the purpose of evaluating the performance capabilities of the instrument and determining the potential market for such an instrument. The inventors of the instrument are L. H. Thacker, I&C Division, and T. G. Kollie, M&C Division.

The Research Instruments Section licensed the ruggedized alpha detector to Dosimeter Corporation in August 1991. This technology was developed for the Navy RADIAC Program. The alpha detector replaces the conventional Mylar detector with a physically and chemically durable aluminum hardcoat.



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