Number One 1987

Oak Ridge National Laboratory review

Science Education at ORNL

THE COVER: Jill Hiemstra of St. Olaf College uses a pipette to extract metabolite from mouse skin. This work is part of a Biology Division study of skin metabolism of topically applied chemicals such as steroids. The special research environment that ORNL offers undergraduate and graduate students and faculty members is discussed in Vivian Baylor's article on ORNL's University Relations Programs on page 12.

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review

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DEPARTMENTS

OAK RIDGE NATIONAL LABORATORY

operated by Martin Marietta Energy Systems, Inc.
for the Department of Energy

The Advanced Integrated Maintenance System control room improves efficiency of remote-handling operations through the use of color graphics, touch-screen monitors, and a team of two operators. Steve Zimmerman (left) uses touch screen monitors to control peripheral equipment such as cameras and transporters, allowing Mark Noakes, the operator on the right, to move the master control arms to position the remotely located Advanced Servomanipulator. Both men are development engineers in ORNL's Instrumentation and Controls Division.

The U.S.-Japan Collaboration on Breeder Fuel Reprocessing: *ORNL's Role*

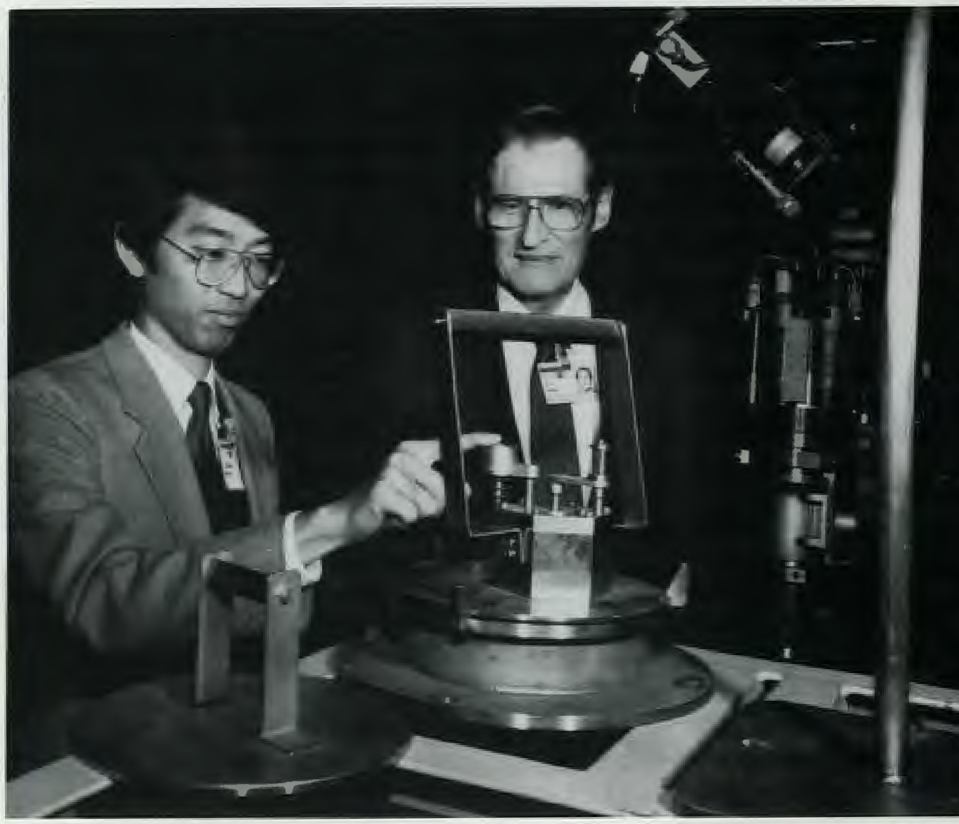
By WILLIAM D. BURCH

Over the past two decades, the United States and Japanese nuclear programs have had many ties. U.S. developments in nuclear power have been transferred to Japan through both government and commercial channels. Currently, Japan generates about 30% of its electric power by U.S.-licensed pressurized-water reactors and boiling-water reactors, and Japanese work on fast breeder reactors has evolved from U.S. programs and technology.

This technical exchange has led in the past year to a major new collaboration in breeder fuel reprocessing. The U.S. effort in this broad, long-term collaboration is centered at ORNL. The United States and Japan will cooperate in developing and demonstrating breeder reprocessing technology—isolating radioactive fission products and recovering usable uranium and plutonium from breeder reactor spent fuel.

This collaboration will focus on facilities planned by Japan for recycling fuel from their JOYO and MONJU breeder test reactors. Much of the technology under development at ORNL in the Fuel Recycle Division (FRD) for the past decade will be transferred to Japan and incorporated into those pilot-

Bill Burch has been director of ORNL's Fuel Recycle Division since it was formed in 1981. Since 1974 he has been director of the Consolidated Fuel Reprocessing Program, which directs all civilian reprocessing development activities in the United States. In this position, he is responsible for a major new collaboration between the United States and Japan to cooperate in a long-term effort to develop and demonstrate the technology for breeder reprocessing. He has been a staff member at ORNL since 1952, except for 1973 to 1974, when he worked for Union Carbide Corporation's Uranium Enrichment Associates. Before 1973 Burch served as program manager for waste programs and manager of the Transuranium Processing (TRU) Facility. In 1976 he served as technical chairman of an International Atomic Energy Agency's Workshop on the Development of Technology for Reprocessing Spent LMFBR [liquid-metal fast breeder reactor] Fuels (Leningrad). He holds a master's degree in chemical engineering from the University of Missouri at Rolla and is a graduate of the Oak Ridge School of Reactor Technology. He serves on the Fuel Cycle and Waste Management Division Executive Committee of the American Nuclear Society. Burch provides technical leadership for the U.S. Department of Energy's exchange agreements in breeder reprocessing with Japan, the United Kingdom, France, and the Federal Republic of Germany. Here, he and Eiichi Omori of Japan's Power Reactor and Nuclear Fuel Development Corporation examine a manipulator test rack on which Omori has performed some comparison tests.



plant facilities. Additional development and other activities in support of the facility design will be done at ORNL. Long-range plans include designing and building equipment that will be tested in the Japanese pilot plant.

This collaboration will allow the United States to maintain a core of expertise; ORNL technical experts can stay abreast of developments in the reprocessing field as they participate in a viable, long-term mission while the Laboratory and DOE search for future directions for advanced reactor-fuel cycle technologies. This course of action was strongly suggested by the FRD Advisory Committee two years ago. FRD staff members played a prominent role in preliminary discussions with their Japanese counterparts and in the follow-up negotiations between DOE and the Power Reactor and Nuclear Development Corporation of Japan (PNC), which is responsible for the programs there. Japan sees this collaboration as a significant addition to their rapidly developing technical capability as well as an excellent means of strengthening ties between the two countries in the nuclear arena.

Five-Year R&D Program

The initial phase of this collaboration is a five-year R&D program in which DOE and PNC will each contribute $5 million annually to support the program at ORNL. In later phases, still to be defined in detail, ORNL will participate in the design, construction, and operation of facilities in Japan. If the initial phase is productive and useful, avenues for broader involvement of the Laboratory in later stages will be opened up, including fabrication and testing of special hardware systems in which ORNL expertise will help ensure success of the pilot plant.

The United States pioneered the development of the current generation of light-water reactors (LWRs) operating in Japan and elsewhere in the world. Our country

Ji Young Chang, in his office at Tokai, Japan, is a Westinghouse employee having earlier ORNL ties. As an ORNL subcontractor assigned to the development group at the Tokai Plant for the past two years, he helped with the negotiations that led to the U.S.–Japan agreement on joint breeder fuel-reprocessing research.

Grant Stradley (left) and Burch review the technical plans they negotiated with the Japanese calling for a joint, five-year R&D program on breeder fuel reprocessing.

also historically led the world in the development of technology for closing the LWR fuel cycle, but the United States has failed to support a commercial fuel-reprocessing industry for a variety of reasons—mainly because of regulatory issues and short-term economic considerations.

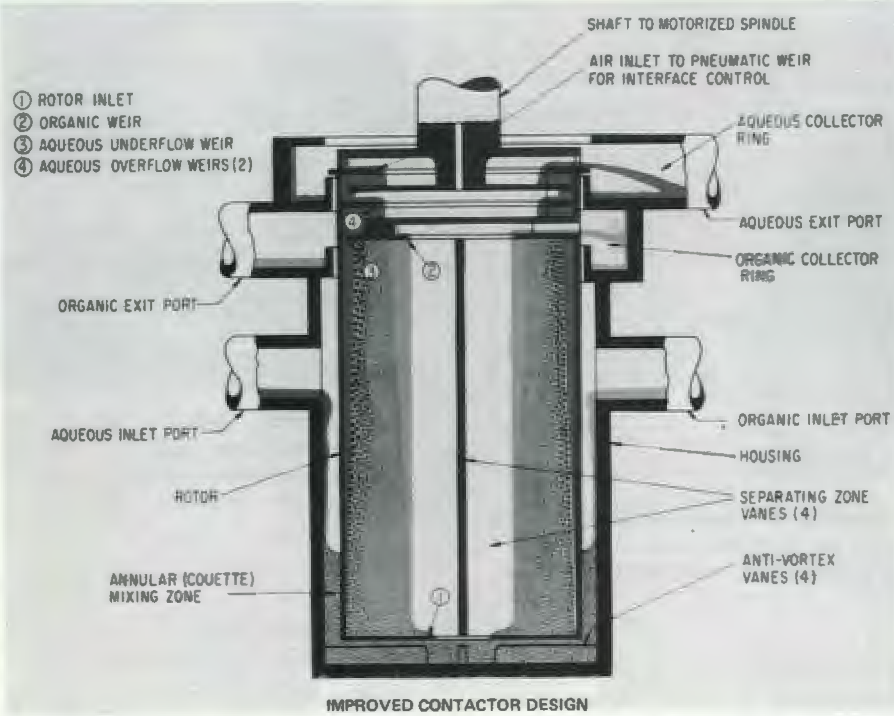
Japan, in the meantime, has built and operated a small reprocessing facility at Tokai Mura and is well on the road to building a major large commercial facility in the next decade. Japanese capabilities in this area have matured rapidly in the past five years, and the Tokai plant is operating routinely after a period of learning and problem solving. Japan began its breeder development program about ten years ago by building and operating the small test reactor JOYO. Then, Japan planned and began construction of the MONJU breeder reactor [the equivalent of our now-defunct Clinch River Breeder Reactor Project (CRBRP), the U.K. Prototype Fast Reactor, and the French PHENIX]. Operation of the MONJU breeder is scheduled to begin early in the 1990s.

Initial plans for recycling fuel from the JOYO and MONJU reactors called for an entirely new pilot plant, but the plans now focus on using a near-term Hot Experimental Test Facility (HETF) coupled to the existing Tokai plant. The initial stages of reprocessing—dismantling, shearing, and dissolution—and the first solvent-extraction cycle, in which uranium and plutonium are separated from the bulk of the fission products, would be done in HETF. Final product purification and waste management would be handled in the existing facilities. This new approach could provide most of the experience needed from a pilot-plant demonstration at substantially lower cost.

In March 1986 the United States and Japan agreed to collaborate on developing and demonstrating breeder-reactor fuel reprocessing at a Japanese fuel-recycling pilot plant, which incorporates technology developed at ORNL. The U.S. work, mostly in remote technology, is centered at ORNL.

How the Collaboration Resulted

Shaping up such a collaboration has proven to be quite a challenge. Initial informal discussions about a broad collaboration grew out of earlier technical exchanges between the United States and Japan in remote technology (e.g., remotely operating manipulators from a control room to run or repair simulated reprocessing equipment). On several occasions Japan had expressed interest in a broader exchange across the entire area of breeder reprocessing, but no clear directions or methods were seen. Then, a partnership with Japan was discussed as part of an attempt to ensure continued support for the Breeder Reactor Engineering Test Project, which was a joint effort between ORNL and Hanford Engineering Development Laboratory to recycle fuel from the Fast Flux Test Facility and the CRBRP (until its demise). When it became obvious that the United



Schematic of the improved contactor design. ORNL has led in developing a new generation of chemical engineering equipment for solvent extraction. This centrifugal contactor is used extensively for the key chemical steps in reprocessing. ORNL and collaborators have developed a new generation of simpler, smaller units that can be scaled to the size needed by the Japanese reprocessing pilot plant

Eight stages of centrifugal contactors have been fabricated as a unit to provide the extraction bank of a solvent extraction cycle. Solvent extraction is used to remove fuel, fertile material, and fission products from reprocessing solutions. Centrifugal contactors offer the advantages of rapid startup, short solution residence time, compact size, high mass transfer efficiency, and potentially lower overall system cost when compared with conventional contactors.

Technical Achievements at ORNL That Will Be Useful to Japan

Much of the breeder fuel-reprocessing R&D done at ORNL and in similar programs in other countries has focused on the initial complex mechanical steps: dismantling the stainless-steel-shrouded fuel assembly; shearing fuel pins into pieces 2.5 cm (1 in.) long; and dissolving uranium, plutonium, and fission product oxides in nitric acid (to permit recovery of fuel and fertile material, which can be recycled into a breeder reactor).

The United States, largely through ORNL, has led the world in developing the engineering-scale hardware for carrying out these steps. However, because the country has had only small breeder test reactors and limited amounts of actual fuel to handle, it has had only a limited program in reprocessing of nuclear fuel. On the other hand, France and the United Kingdom have recycled breeder fuel from all their test reactors in small-scale, hot-cell facilities.

A remote laser cutting system similar to that developed by the Consolidated Fuel Reprocessing Program at ORNL for shearing fuel assemblies will be used in the Japanese fuel reprocessing pilot plant. (It also has potential for large industrial uses requiring a high-power laser.) A carbon dioxide laser will be used to remove stainless steel shrouds around fuel assemblies by cutting them longitudinally into several pieces.

ORNL also paid special attention to designing operating equipment that would best suit the work environment, which is a large, highly radioactive remote cell. ORNL is recognized as the world leader in using innovative designs to couple process equipment to facility maintenance.

For the past five years, the head-end process equipment and related maintenance equipment have been developed in ORNL's Integrated Equipment Test Facility. The key maintenance hardware is the M-2 servomanipulator, which evolved from mechanical components made by the Central Research Laboratories Division of Sargent Industries and a new digital control system developed at ORNL (see other sidebar on the Advanced Servomanipulator).

In another achievement, ORNL has led in developing a new generation of chemical engineering equipment for solvent extraction. Called a centrifugal contactor, this equipment is used extensively for the key chemical steps in reprocessing. ORNL and collaborators have developed a new generation of simpler, smaller units, that can be scaled to the size needed by a reprocessing pilot plant. Japan's Power Reactor and Nuclear Fuel Development Corporation is particularly interested in this U.S. technology development because it will reduce the size and cost of its planned breeder fuel-reprocessing pilot plant.

ORNL's Fuel Recycle Division facility.

Technology demonstrated by ORNL's remote laser cutting system for shearing fuel assemblies will be used in the Japanese fuel reprocessing pilot plant.

States itself was not prepared to support any major facility demonstration, the potential collaboration was refocused on the Japanese program.

The final serious perturbation occurred early last year when severe budget cuts forced a disturbing choice: Japan would have to provide substantial support to the U.S. program as part of the collaboration or the United States would not continue its support. Japan still saw the overall value of the collaboration, even under such an arrangement, and agreed to the U.S. request in principle. However, forging these intentions into real governmental actions and budget decisions in a short time proved to be almost too big an undertaking. U.S. congressional action was required to support this effort. Because of the efforts of the Tennessee congressional delegation, this program was fully supported by the U.S. Congress in final budget action last year. The Japanese government made the final commitments late in the year.

Incidentally, Japanese and ORNL scientists have been collaborating on other projects, too. Since 1983, scientists from the Japan Atomic Energy Research Institute (JAERI) and ORNL have been collaborating on reactor experiments to test the ability of different materials to withstand neutron radiation damage; these materials are candidates for future fusion reactors. In March 1986, DOE and JAERI signed an agreement for a five-year, $4-million collaborative testing program for high-temperature gas-cooled reactor (HTGR) fuels; HTGR fuel particles will be made by both countries and shipped to ORNL for irradiation in the High Flux Isotope Reactor to determine how well the particles retain fission products.

The principals in shaping the breeder fuel-reprocessing collaboration in the United States have been the author, director of ORNL's Fuel Recycle Division; Fred Mynatt, ORNL associate director for Nuclear and Engineering Technologies; and David E. Bailey, director of DOE's Office of Spent Fuel and Reprocessing in Washington, D.C. Kunihiko Uematsu, a recognized expert in the field worldwide and one of the executive directors of PNC, was very supportive initially, and many other PNC executives have since become strong supporters and carried out the follow-up negotiations.

Last year J. Grant Stradley, who participated in many of the early discussions, was named program manager for the PNC collaboration. As one means of strengthening ties between the ORNL and PNC programs, on-site representatives have been assigned to facilitate communication. Ji Young Chang, a Westinghouse employee having earlier ORNL ties, has facilitated many of these negotiations as an ORNL subcontractor assigned to the development group at the Tokai Plant for the past two years.

The program is off and running. Many challenges lie ahead, but we at ORNL look forward to working with the Japanese for a long time. ornl

ORNL's Advanced Servomanipulator Attracts Industrial Interest

ORNL has designed and built a remote-controlled servomanipulator that can do work that once only humans could. The development marks the latest advance in remote-handling technology, which is being developed for use in environments hazardous to human workers.

Several companies have expressed interest in the development and are negotiating to acquire exclusive rights to further develop, manufacture, and market the device. It may be marketed first to foreign nuclear fuel cycle facilities.

The Advanced Servomanipulator (ASM) has been one of the key developments in ORNL's breeder fuel-reprocessing program. Work on servomanipulator development began about six years ago because of the need for greater dexterity in maintaining reprocessing facilities than is offered by cranes and electromechanical manipulators. The ASM is operated in ORNL's Fuel Recycle Division.

The ASM mimics the motions of human arms and hands as it repairs or replaces failed motors, corroded pipes, and other faulty components in a full-scale mock-up of a nuclear fuel-reprocessing module. Although developed for the maintenance of future nuclear fuel-reprocessing facilities, ASM technology can be adapted for other applications. It could be used to build space station modules; repair satellites; explore the ocean floor; or handle toxic chemicals, explosives, and nuclear and chemical wastes.

DOE's Consolidated Fuel Reprocessing Program, a national effort managed by ORNL to develop advanced nuclear fuel-reprocessing technologies, is responsible for the development of the ASM. The technology that led to this development is the basis for exchanges with other countries, mainly Japan and France, and is one of the key elements that led to establishing a new Robotics and Intelligent Systems Program at ORNL.

The ASM is a descendant of "master-slave manipulators," mechanical devices first built in the late 1940s to handle radioactive materials in thick, concrete hot cells. Because they were mechanically linked, these devices are limited to a fixed position. Servomanipulators, however, have freedom to move into remote areas because they are electronically linked; their "arms" and "hands" have sufficient dexterity to perform many complex remote-handling tasks.

However, earlier servomanipulator units use conventional cable-drive systems that are prone to failure; these frequent failures are costly because extensive decontamination and glove-box repair operations are required to restore the devices to working order. In addition, the early models of servomanipulators were controlled through an unwieldy signal transmission system connecting the control system with the seven motors in each arm. The wiring harness between slave and master stations might contain several hundred wires—a cumbersome arrangement for a unit that travels through large spaces performing complex maneuvers.

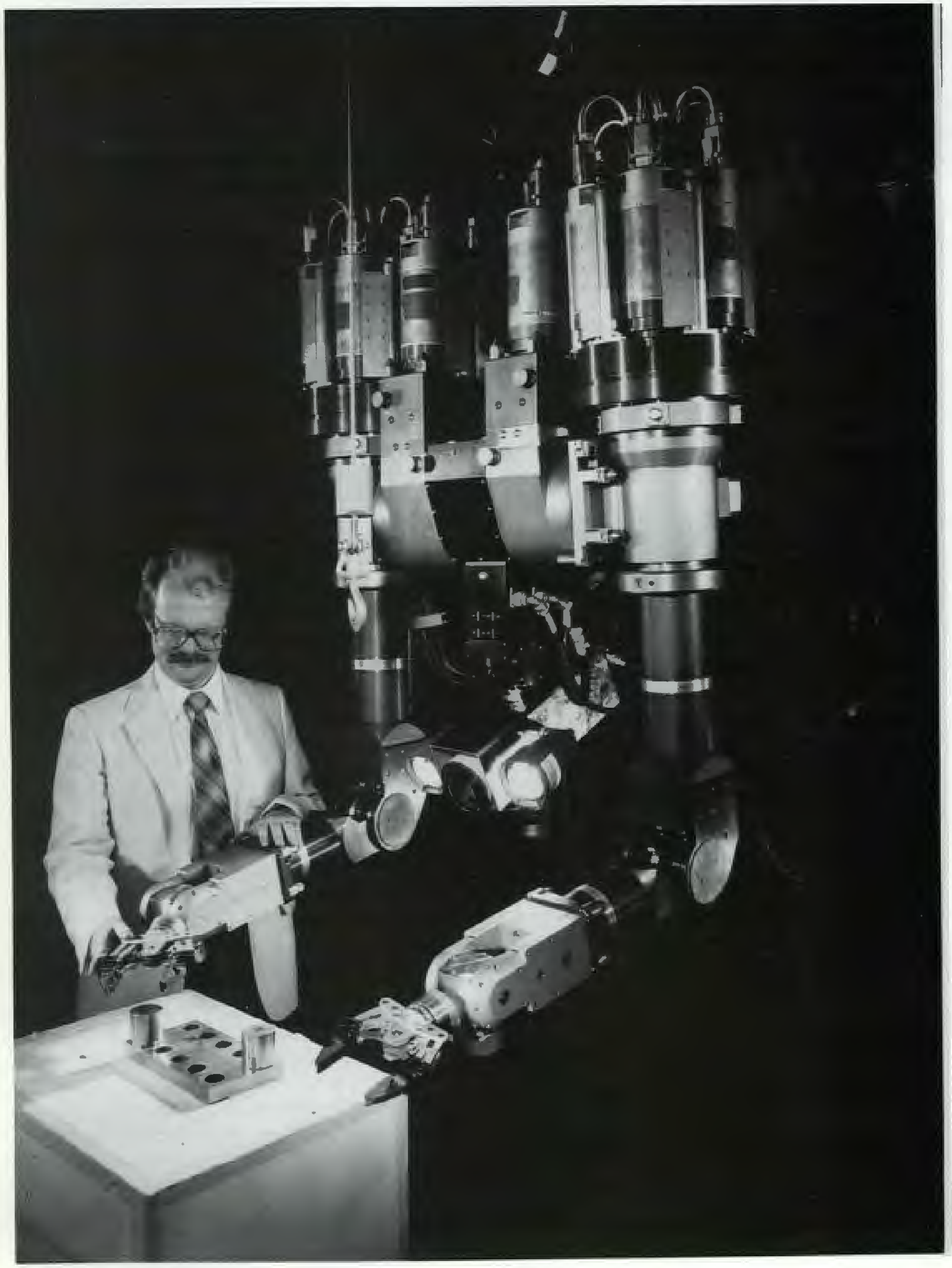
In developing the ASM, ORNL researchers overcame these two limitations. First, they solved the signal-transmission problem by using a multiplexed digital control system—the first application of such a system to a manipulator. Multiplexing—using only a few cables to transmit many electrical messages simultaneously—reduced by an order of magnitude the number of wires needed to connect the master and slave manipulators. This technical improvement of a servomanipulator was recognized in 1984 by an I-R 100 award from *Research & Development*; the award went to Joe Herndon of the Fuel Recycle Division and to Lee Martin and Paul Satterlee, both formerly of the Instrumentation and Controls Division and now involved with local private companies in this field. Several ORNL researchers are also developing several improved techniques for signal transmission using inductive coupling, laser light, and microwaves. These innovations have been incorporated and improved in the ASM.

The mobile ASM is controlled by human operators in a distant control room. Under this arrangement, the servomanipulator operator is assisted by a second operator whose main functions are to oversee the performance of tasks, which can be seen and heard by closed-circuit television cameras and a microphone. The second operator controls the movement of the overhead bridge supporting the ASM and positions and focuses the cameras. Under the new U.S.-Japan collaboration, ORNL will provide some details of the new control room design, which incorporates ASM technology, to the Power Reactor and Nuclear Development Corporation of Japan for use in one of its fuel-cycle facilities.

Second, ORNL researchers solved the problem of the fragile cable drive system by replacing it with modular torque tubes and gear trains for every drive motion. Should a failure occur in this system, the defective module can be removed and replaced by a new one using another manipulator, thus eliminating the lengthy repair time. The researchers found that the new system achieved essentially the same levels of dexterity, force feedback, and operability as the tape-driven one. For example, using either approach, a force of 0.5 kg (1 lb) applied to the slave arm can be "felt" at the master arm.

The ASM incorporates high-precision components and a sophisticated microprocessor control system to overcome gear-induced friction, inertia, and backlash, factors which make it difficult to accurately transmit feel to the human operator.

The ASM was developed under the guidance of Melvin Feldman, senior advisor to the director of the Fuel Recycle Division, and Joseph Herndon, Advanced Integrated Maintenance System (AIMS) task leader in the same division. Development support was provided by ORNL's Instrumentation and Controls Division (by a group led by Bill Hamel) and Energy Systems' Engineering Organization (by a group led by Dan Kuban). A team of craftsmen from ORNL's Plant and Equipment Division fabricated the Advanced Servomanipulator.



Joe Herndon obtains a direct "feel" of friction and backlash in the slave arm of the Advanced Servomanipulator at the Fuel Recycle Division.

awards and appointments

John Googin and **Charles D. Scott** have been named senior corporate fellows of Martin Marietta Energy Systems, Inc. This distinction, granted only once previously to William L. Russell, is the highest award that the company gives for career achievements in research and development.

Five ORNL researchers have been named corporate fellows by Energy Systems in recognition of their outstanding career achievements in science or engineering. They are **Benjamin A. Carreras, Robert N. Compton, Herbert A. Mook, Lester C. Oakes,** and **Thomas J. Wilbanks**.

Chris Bottcher, Mark Rasolt, and **C. W. White** have been named Fellows of the American Physical Society.

James E. Turner has been named a Fellow of the Health Physics Society.

Steven E. Lindberg has been appointed to the editorial board of the new book series *Advances in Environmental Science*, which is published by Springer-Verlag in Berlin, Federal Republic of Germany.

Emory D. Collins has been named section head of ORNL's Chemical Technology Division.

James S. Eldridge has been elected president of the Environmental Radiation Section of the Health Physics Society.

Kennie W. Boling has received the 1986 Leonardo da Vinci Award from the Design Engineering Division of the American Society of Mechanical Engineers.

Robert W. McClung has been elected to honorary membership in the American Society for Nondestructive Testing.

Bob Jolley has received the Distinguished Service Award from the American Chemical Society (ACS) for his participation in the activities of the ACS Division of Environmental Chemistry. He had served as assistant secretary, secretary, and chairman of the division and is now its program chairman.

Dan G. Cacuci has been named director of ORNL's new Center for Studies of Nonlinear Phenomena.

Joe Sherrod has been named ORNL environmental, safety, and health coordinator for subcontractor activities.

Ray Popp has been appointed registrar for the newly created Mouse Globin Gene Registry, which was proposed at a May 1984 international meeting in Bar Harbor, Maine. The Registry will ensure consistent nomenclature for new genes and mutants as they are discovered.

Glenn W. Suter has been appointed chairman of the 11th Symposium on Aquatic Toxicology and Hazard Assessment of the American Society for Testing and Materials.

John S. Cook is associate editor of the international journal *News in Physiological Sciences.*

Employees of the Engineering Physics and Mathematics Division received a Distinguished Safety Performance Award from Alex Zucker, Associate Director of Physical Sciences, for working more than 30 consecutive years (three million employee hours worked) without a disabling injury.

A. L. (Pete) Lotts has been appointed to the new position of director of Department of Defense Technology Programs at ORNL.

The Data and Analysis Section of the Energy Division has been transferred to the Energy Systems' Data Systems Research and Development Program managed by **Andrew Loebl**. The section members have formed the Data Systems Engineering Organization, headed by **George Dailey**.

Colin D. West has been named director of the Center for Neutron Research Project Office in ORNL's Engineering Technology Division.

Bill Corwin has been appointed manager of ORNL's Heavy Section Steel Technology Program.

Mark L. Sollenberger has been named manager of Institutional Planning at ORNL.

Paul H. Stelson has received the Jesse W. Beams Award from the Southeastern Section of the American Physical Society.

Robert L. Ullrich has received the 15th Research Award of the Radiation Research Society in recognition of his research contributions in radiation biology, particularly radiation carcinogenesis. He is the first ORNL scientist to receive this honor.

Walter Porter is president of the American Academy of Industrial Hygiene.

James Eldridge is president of the Environmental Radiation Section of the Health Physics Society.

Steiner J. Dale is a Congressional Science Fellow for a year. He is assigned to work with the U.S. House of Representatives Committee on Science, Space, and Technology and its chairman Rep. Robert A. Roe (D-N.J.).

J. Michael Ramsey has been appointed to the Editorial Advisory Board of the international journal *Progress in Analytical Spectroscopy.*

Robert J. Luxmoore has been appointed to the Editorial Review Board of the journal *Tree Physiology.* He also has been named associate editor of *Soil Science Society of America Journal.*

John R. Trabalka has received a commendation and certificate of achievement from DOE's Office of Basic Energy Sciences for his work in compiling information on the global carbon cycle.

David E. Reichle has been appointed to the Public Responsibilities Committee of the American Institute of Biological Sciences.

John Martin is president of the Nuclear and Plasma Sciences Society of the Institute of Electrical and Electronic Engineers.

C. Stephen Haase has been named to the Geochemistry and Modeling Subcommittee of the Underground Injection Practices Council.

Harold Adair is president of the International Nuclear Target Development Society.

H. Richard Kerchner has been appointed to direct the Low-Temperature Neutron Irradiation Facility; **Robert M. Nicklow**, the Neutron Scattering Facility; **C. W. White**, the Surface Modification and Characterization Collaborative Research Center; and **George Wignall**, the National Center for Small-Angle Scattering Research. These national user centers open to university, industry, and other U.S. and foreign researchers are operated by ORNL's Solid State Division.

Steve Stow has been elected Councilor of the Geological Society of America.

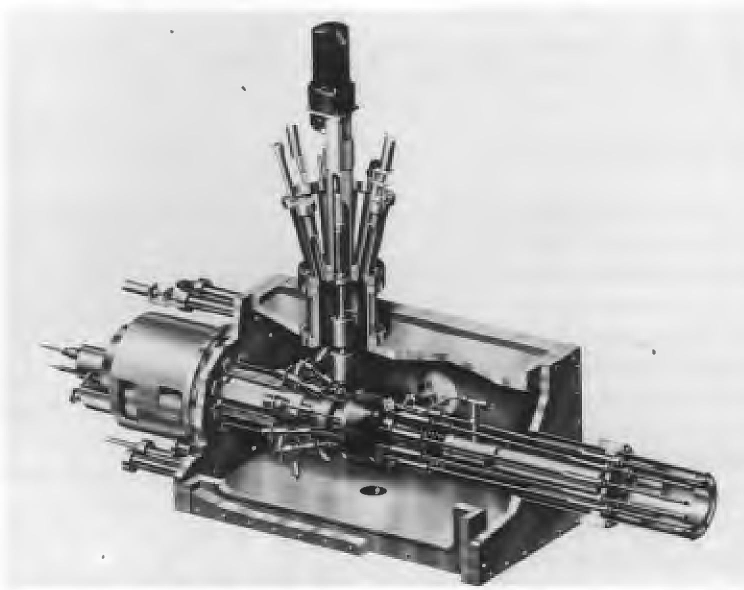
Awards and Appointments

R. B. Fitts has been named ORNL coordinator of the DOE Environmental Survey Program, whose goal is to identify potential environmental management and compliance problems at DOE sites.

B. Gordon Blaylock organized and cochaired the "Effects of Ionizing Radiation on Aquatic Organisms" workshop for the National Council on Radiation Protection and Measurement.

Nineteen entries of ORNL and Martin Marietta Energy Systems, Inc., received awards in the 1987 publications competition sponsored by the East Tennessee Chapter of the Society for Technical Communication (STC/ETC). The winners are: **Carl W. Turner**, **Charlotte E. Johnson**, and **Edgar H. Kelly**, award of distinction in the category of brochures for *A Mobile In Vivo Radiation Monitoring Laboratory*; **Charles C. Coutant**, award of distinction in trade/news articles for "Thermal Niches of Striped Bass," *Scientific American*; **Charles W. Forsberg**, **Catherine H. Shappert**, and **Donna T. Brooksbank**, award of distinction in scholarly/professional articles for "A Process Inherent Ultimate Safety Boiling Water Reactor," *Nuclear Technology* (February 1986); **Carolyn Krause** and **Bill Clark**, award of merit in scholarly/professional articles for "Managing Hazardous Waste: ORNL Examines the Options," *ORNL Review*; **V. C. Mei**, **Leroy D. Gilliam**, and **Sharon McConathy**, award of merit in scholarly/professional articles for "Theoretical Heat Pump Ground Coil Analysis with Variable Ground Farfield Boundary Conditions," *AIChE Journal* (July 1986); **Carolyn Krause** and **Bill Clark**, award of excellence in house organs for the *ORNL Review*; **Charles K. Bayne** and **Ira B. Rubin**, award of excellence in books for *Practical Experimental Designs and Optimization Methods for Chemists*; **John R. Trabalka**, **David E. Reichle**, **Vivian Jacobs**, and **Sherry Hawthorne**, award of merit in books for *The Changing Carbon Cycle: A Global Analysis*; **John R. Trabalka**, award of achievement in books for *Atmospheric Carbon Dioxide and the Global Carbon Cycle*; **Natalie E. Tarr** and **Anne K. Ragan**, award of excellence in periodic activity reports for *Environmental Sciences Division Annual Progress Report for Period Ending September 30, 1985*; **Thomas W. Oakes**, **Tina Sekula**, and **Thomas O. Tallant**, award of merit in periodic activity reports for *Environmental Surveillance of the Oak Ridge Reservation and Surrounding Environs during 1985*; **William Fulkerson** and the ORNL Energy Division staff, award of merit in periodic activity reports for *Energy Division Annual Progress Report for Period Ending September 30, 1985*; **Curtis C. Travis**, award of merit in whole periodicals for *Risk Analysis* (the international journal of the Society for Risk Analysis); **Ernest G. Silver**, **Susan E. Hughes**, and **Jean S. Smith**, award of achievement in whole periodicals for *Nuclear Safety*; User Services Staff of the Computing and Telecommunications Division, award of achievement in software manuals for *Graphics Reference Manual*; **Allyn Zerby**, **Jeanne Dole**, and **LaWanda Klobe**, award of achievement in newsletters for *The RAMbler*; **Michael P. Farrell** and **David E. Fowler**, award of achievement in newsletters for *CDIC Communications*; **E. C. Beahm**, **Donna R. Reichle**, and **B. C. Drake**, award of merit in technical reports for *Organic Iodide Formation following Nuclear Reactor Accidents*; **F. J. Zehr**, **Mary S. Guy**, and **Leroy D. Gilliam**, award of achievement in technical reports for *The Performance and Economics of Superinsulated Houses*.

ORNL and Energy Systems illustrators who received awards for industrial-technical graphics in the 1986 STC/ETC Technical Art Competition are **Michael Darnell**, Best of Show Award in art and award of distinction in mechanical illustration tone art for *Eight-Shot Pneumatic Pellet Injector*; **Sandra Schwartz**, award of excellence and award of merit in the same category for *Rf Antenna* and *ATF Coil Segment*, respectively; **Judy Neely**, award of achievement in the same category for *Advanced Toroidal Facility*; **Shawna Parrott**, award of achievement in mechanical illustration line art for "Progress in the Recovery Operations at Three Mile Island Unit 2: An Update," *Nuclear Safety*; **Jamie Payne** and **Bob Samples**, award of achievement in single-sheet design graphics line art (one or two colors) for the cover of the brochure *Stack Sampling—ORGDP*; **Frances Burkhalter**, award of excellence in single-sheet design graphics line art (three or more colors) for *Sources for Possible Loss-of-Structural Integrity Inherent to Philosophy and Nature of Six-Coil Tests*; **Shirley Boatman**, award of merit in the same category for *Purpose of Preliminary Study: Apply the NPAR Program Strategy to Safety-Related Concrete Components*; **Sandra Schwartz**, award of distinction in single-sheet design graphics tone art (one or two colors) for *Compenstation Practices & Procedures, A Manager's Handbook*; **Edgar H. Kelley, Jr.**, and **Paul D. Baker**, award of merit in the same category for the inside cover of the *PIP* brochure; **Frances Burkhalter**, award of excellence in single-sheet design graphics tone art (three or more colors) for *CNR Fuel Element Design Evolved from the Current HFIR Fuel Element*; and **Luci Bell**, award of achievement in the same category for *Results from Simulated Upper-Plenum Aerosol Transport Tests*. **Bill Clark** won three awards in the category of multiple-sheet design graphic tone art (one or two colors): award of excellence for *Surface Modification and Characterization Collaborative Research Center at Oak Ridge National Laboratory*, award of merit for *Biomedical and Environmental Sciences at Oak Ridge National Laboratory*, and award of achievement for the No. 3, 1985 issue of the ORNL *Review*.



Award-winning drawing of the Fusion Energy Division's eight-shot pneumatic pellet injector for refueling plasmas.

Vivian B. Baylor has been ORNL's University Relations Program Manager since July 1985. In this position, she serves as liaison between universities and ORNL, facilitating interactions between academe and Laboratory staff members. She manages the DOE University-Laboratory Cooperative Program at ORNL and directs activities with Historically Black Colleges and Universities for Martin Marietta Energy Systems. Before this appointment, Baylor held several other administrative and technical positions at the Laboratory and the Oak Ridge Gaseous Diffusion Plant. In 1976 she began work at ORNL as a student in the Metals and Ceramics Division, before being hired as research engineer in 1978. She published numerous papers on her research on corrosion in coal liquefaction systems. For six months she was assigned to DOE Headquarters in Washington, D.C., as the Fossil Energy Programmatic Liaison.

She holds B.A. degrees in political science and English from Virginia Polytechnic Institute and State University and a B.S. degree in metallurgical engineering from the University of Tennessee at Knoxville, where she completed course requirements toward an M.S. degree. She serves on national committees for the National Association of Corrosion Engineers and the American Society for Metals.

National Laboratories and Science Education: *The University Relations Programs at ORNL*

By VIVIAN B. BAYLOR

The United States aspires to lead the world in scientific discovery and technological innovation, yet a nationwide shortage of homegrown scientists and engineers is forecast. The percentage of U.S. students who are inadequately educated in science and mathematics continues to rise, and those who are trained in these fields may not be prepared well enough to compete with the next generation of foreign scientists (see sidebar). In the hope of reversing these unfortunate trends, the federal government has turned to its national laboratories for help.

The Department of Energy's national laboratories have long played an important role in educating and training students through many programs that provide research experience. National laboratories are a significant resource for colleges and universities: they house state-of-the-art equipment that university personnel may use, and many of their well-qualified staff members are eager to work with university personnel. National laboratories usually provide a research experience for students and faculty members that cannot be duplicated in the university environment.

Why does Oak Ridge National Laboratory want to work with

ORNL and other national laboratories play a significant role in the education and training of university students and in providing unique research experiences for university faculty. To improve science education and encourage more U.S. students to choose technical careers, ORNL has developed new programs for undergraduate and precollege education.

The Crisis in U.S. Science and Mathematics Education

What is the crisis in mathematics and science education in the United States? Why is the U. S. Department of Energy (and Oak Ridge National Laboratory) so committed to helping solve it? The crisis is a matter of insufficient quantity and quality. Not enough U. S. students are pursuing degrees in science- and mathematics-related disciplines; as a result, a nationwide shortage of scientists and engineers is projected in an era when the United States is trying to lead the world in technology innovation. In addition, Americans interested in science and mathematics are prepared inadequately to compete with the next generation of foreign scientists, who seem to receive (and learn) much more by the time they graduate from high school than do U.S. youth.

DOE is concerned about the crisis because of manpower projections. They indicate that the Department will be competing for a dwindling supply of well-trained, qualified U.S. scientists and engineers to perform energy-related research. ORNL has much the same concern; continuing to hire the best and brightest scientists and engineers may be increasingly difficult here as the pool of candidates decreases.

A 1985 report[1] from the National Science Board of the National Science Foundation provides considerable quantitative information describing the changing state of U. S. science and technology and science and mathematics education. From 1974 to 1983, the number of entering U.S. freshmen electing to major in science and engineering fell from 33.4% to 32%, although more of these freshmen in 1983 (37%) than in 1974 (30%) stated a desire to obtain master's degrees. The 1983 graduate school enrollment showed an increase of 18% over that in 1975; however, over the last decade, the number of bachelor's, master's, and doctoral degrees awarded in science and engineering disciplines has remained stable.

Meanwhile, the proportion of foreign Ph.D. candidates in all science and engineering fields at U.S. universities has risen from 20% in 1972 to 26% in 1984, including increases from 14% in 1977 to 37% in 1984 in computer sciences and from 33% in 1972 to 56% in 1984 in engineering. Although an increasing number of these foreign doctoral students plans to stay in the United States (from 51% in 1972 to 60% in 1984), the long-term effects of their employment on U.S. science and technology remains unclear. For example, concerns have been raised about the quality of undergraduate programs with a large proportion of foreign graduate teaching assistants and faculty members who cannot readily explain difficult concepts in English.

Although the decreasing proportion of U.S. citizens in science and engineering is causing some concern, the precollege statistics show even more alarming trends that could adversely affect future U.S. college enrollments and manpower pools. Again, the quality of science and mathematics instruction and the quantity of recipients are concerns. The report states that "during a time when science and technology are playing an increasingly important role in the lives of all citizens, the average high school student knows comparatively less about these subjects" in 1982 than in 1970 based on achievement scores. Furthermore, the last time most high school students are exposed to science is in tenth grade. And, over the last three decades, the number of high school students enrolled in precollege science courses has dropped substantially from 54% to 44%.

Comparative studies show that American high school students "take substantially less coursework in science and mathematics than students in other highly developed countries such as Japan, West Germany, East Germany, and the Soviet Union." Another alarming figure shows that even the best U. S. students do not compare well with other nations' students; by the end of the 12th grade, for example, American students who had taken calculus equaled only the mean performance of mathematics students who were seniors in foreign high schools.

Although it is clear to many that a crisis exists, the causes and solutions are still being debated and are much too complex to address here. Meanwhile, ORNL is playing a role in trying to address some of these issues through an expanded university relations program. The program includes a number of new precollege activities aimed at enriching the curricula through both exposing teachers to new scientific research and exposing students to science at earlier ages. Our hope is that students will learn to enjoy and appreciate the stimulation of scientific investigation as they choose their career paths.—*V.B.B.*

[1]National Science Board, *Science Indicators: The 1985 Report*, National Science Foundation Report to Congress and The White House, 1985.

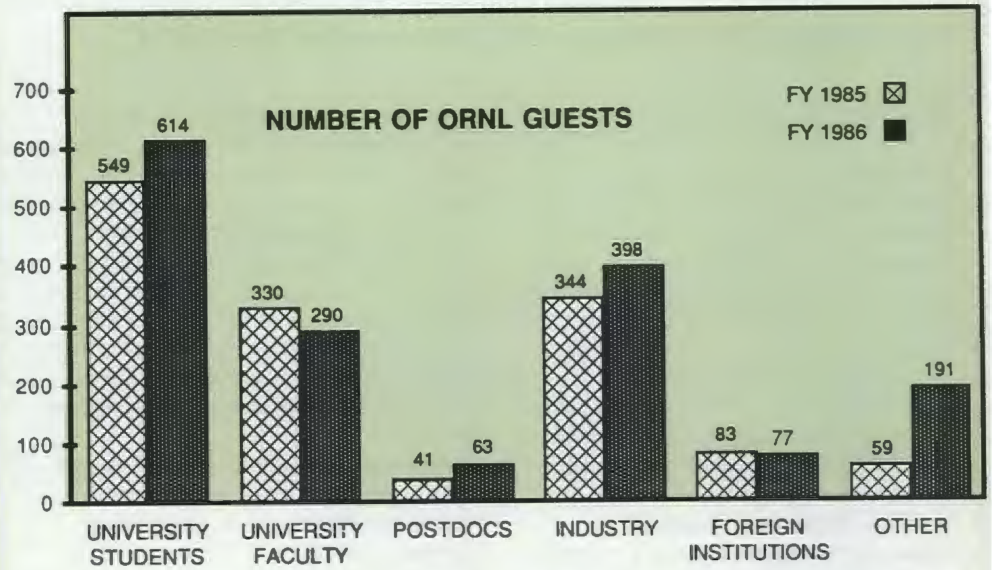
universities? Here are several reasons why it is in the best interest of both the nation and ORNL that the Laboratory has strong collaborative relationships with universities:

- DOE's manpower projections indicate that the demand for well-qualified, trained scientists and engineers will continue to increase, particularly in fields such as health physics and computer science. At the same time, only a stable number of science and engineering doctorates will be awarded. A particular concern is that the number of doctorates awarded to U.S. citizens is decreasing. In 1984, 56% of the Ph.D. candidates in engineering at U.S. universities were foreigners, over 30% of whom will return home to work. The percentage of foreign Ph.D. candidates in computer sciences has risen from 14% in 1977 to 37% in 1984. To ensure enough personnel to perform energy-related research, DOE has a comprehensive program to improve both the quality of science education and to increase the number of students electing to study science. The national laboratories play an integral role in this program by working with educational institutions to improve their research capabilities and train students for careers in research.

• Working with universities is a cost-effective way to help achieve ORNL's programmatic goals. ORNL awards numerous research and development (R&D) subcontracts to universities (described in more detail later in this article) that sponsor research on campus in support of Laboratory missions. In addition, a number of programs coordinated through the University Relations Office allow students and faculty to participate in research at the Laboratory at a cost below that of hiring regular staff.

• In addition to being cost-effective, university personnel perform quality research and can make substantial contributions to ORNL missions. Working with university personnel helps fulfill ORNL's technology transfer objectives. Not only can we train students on state-of-the-art instrumentation and acquaint them with programs on the cutting edge of science, but we can also learn from the students and faculty who work with us. A recent example of the value of university participants in our programs is the contribution made by a former graduate student, Russell Becker, and a current postdoctoral appointee, James G. Mantovani, to the design, construction, and operation of the scanning-tunneling microscope—the only one of its kind in the Southeast—in the Health and Safety Research Division.

Over the two decades that



Over 60% of guest researchers at ORNL are university-based, producing more than 300 person-years of program assistance.

ORNL has hosted undergraduate students on academic-year science semester programs, several students have made substantive contributions to ORNL projects that later were patented or received I•R 100 awards from *Research & Development* magazine. Many ORNL divisions have long-standing collaborative research projects with internationally recognized university faculty members. Their contributions not only help keep ORNL from becoming insular, but also validate our research techniques and results.

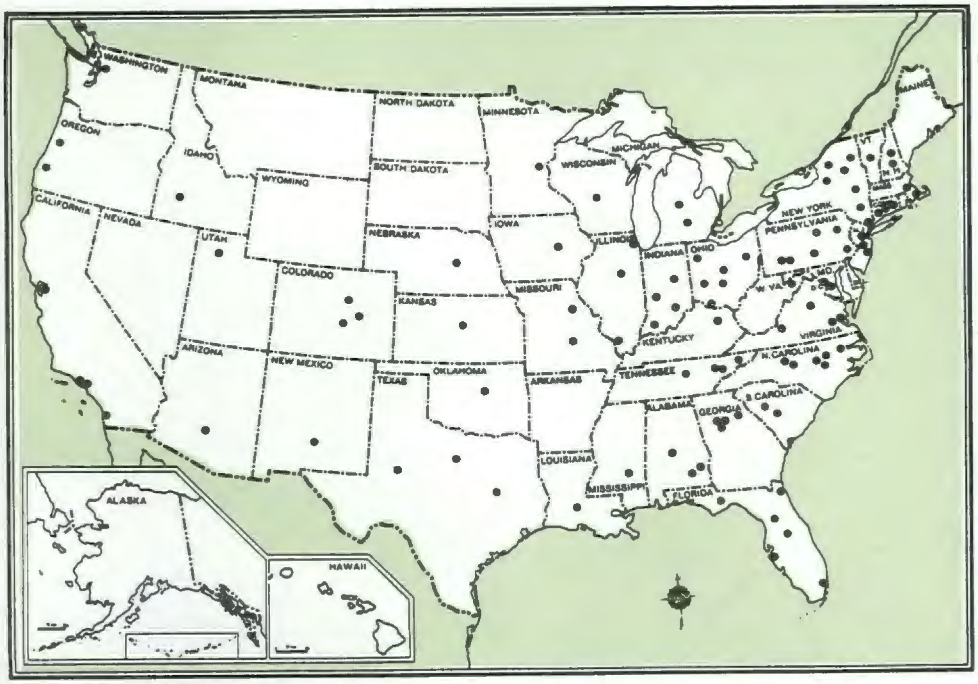
1000 University Guests a Year

Each year ORNL hosts about 1000 university-affiliated guests, either as undergraduate and graduate students, faculty members, or postgraduate appointees. Most visit for short-term research projects, but about one-third are assigned full time to ORNL divisions for research that may last up to one or two years, producing about 300 person-years of program assistance annually. They are hosted by the Laboratory through a variety of mechanisms.

ORNL interacts with universities through awarding R&D subcontracts, encouraging short-term research in ORNL's national user facilities and other resources, supervising students and collaborating with faculty members on research participation appointments, donating and loaning personnel and equipment resources, and establishing close collaborations with specific universities and university consortia.

University Subcontracts

ORNL awards about 250 R&D subcontracts to more than 100 universities annually. The amount of money spent on university subcontracts has increased steadily since 1981 to $17.7 million in fiscal year (FY) 1986—about 3.7% of ORNL's operating budget. This figure is substantially higher than the subcontracting total at any of the other DOE laboratories; in FY 1985, the amount of money spent by ORNL on university subcontracts accounted for 30% of the total cost of DOE laboratory subcontracts with universities.



ORNL had R&D subcontracts with more than 100 universities in FY 1986 for a total expenditure of $17.7 million.

A subcontract generally sponsors research on campus, but it may also provide student internships or faculty appointments to perform research at ORNL. About 30% of the Laboratory's subcontracts are with the University of Tennessee at Knoxville, including the cost for the joint appointments under the Distinguished Scientist Program (discussed later in this article). In FY 1986, universities in 38 states, Puerto Rico, and Canada received research funding from ORNL. Six historically black colleges and universities (HBCUs) were among the recipients of subcontracted funds.

User Facilities and Resources

ORNL is the home of 13 DOE User Facilities and Resources. These facilities offer unique opportunities for outside researchers to perform experiments on state-of-the-art equipment at minimal cost. Many of the facilities are supported by separate operational funds, and users need pay only their travel and housing costs. These resources include the Holifield Heavy-Ion Research Facility, the National Center for Small-Angle Scattering Research (sponsored by DOE and the National Science Foundation), the Surface Modification and Characterization Collaborative Research Center, and the Oak Ridge National Environmental Research Park. Of the non-ORNL participants using these facilities over the last five years, around 60% come from universities; in FY 1986, 320 university researchers performed experiments in ORNL's national user facilities.

In addition to the officially designated centers, other ORNL unique resources are sometimes available to university researchers. These include the Walker Branch Watershed (one of the best in the nation for ecological studies), supercomputing capabilities provided by a Cray X-MP and two 64-node parallel processors, and advanced electron microscopes and analytical equipment (including a new Fourier Transform Mass Spectrometer).

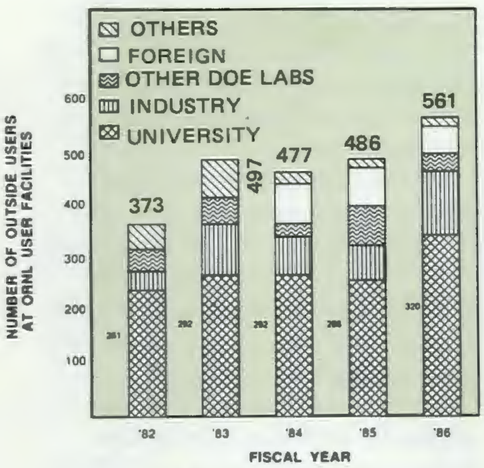
Arrangements to use these resources are made directly with research staff members or through the University Relations Office. Oak Ridge Associated Universities (ORAU) Research Travel Contracts help support travel costs for university faculty and graduate students. Additional programs supporting travel costs for HBCU researchers include Minority Institution Research Travel (MIRT) and Very Important Small Institution Travel Support (VISITS). The supported visitors may perform experiments at user facilities and resources or consult with ORNL staff members about common research interests.

Research Participation Appointments

Many university personnel receive training or perform experiments using ORNL's state-of-the-art resources while they are research participants. In FY 1986, 175 undergraduate and graduate students, 20 postgraduates, and 35 faculty members were appointed research participants through University Relations programs. In addition, almost 300 students and faculty members received research travel contracts for short-term research visits.

Undergraduate Student Programs

Several undergraduate student programs are worth mentioning in more detail because they are popular, unique, or new. The Technology Internship Program (TIP) provides training opportunities for students pursuing an associate degree. Two very



ORNL user facilities and resources serve an increasing number of outside researchers each year.

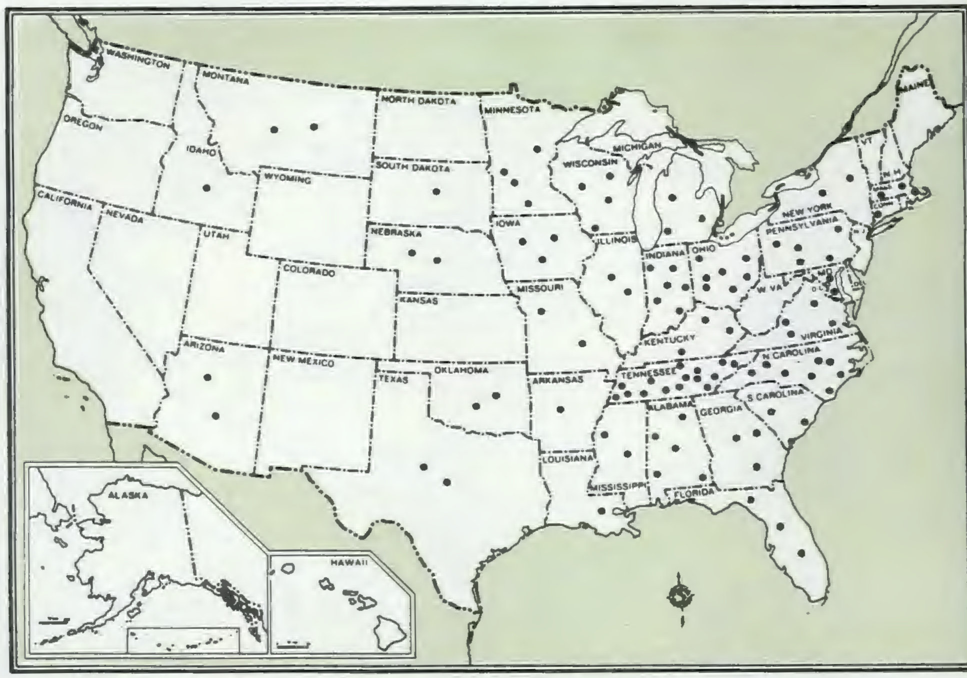
successful programs for undergraduates are the Student Research Participation Program (for rising seniors only for ten-week summer appointments) and the Oak Ridge Science Semester (ORSS) Program, an academic-year research participation program.

Under the ORSS program, selected upperclass students attending colleges that are members of the Great Lakes Colleges Association/Associated Colleges of the Midwest (GLCA/ACM) and the Southern College University Union (SCUU) spend a semester at ORNL performing research and taking courses for credit taught by resident faculty members from the consortia.

Another noteworthy undergraduate program is the Special Summer Program, which provides opportunities for undergraduate students from HBCUs to participate in research as early as the freshman year; many of these students are rehired for the following summers through graduation.

Graduate Student Programs

Graduate student programs also receive considerable attention at



FY 1986 research participants came from more than 100 colleges and universities across the nation.

ORNL. Graduate interns are hired through the Summer Research Internship Program, designed for graduate students having a minimum grade point average of 3.5 out of 4.0. Two participants in the Summer Research Internship program who have become high achievers at ORNL are Dan Robbins, manager of the Information Resources Organization of Energy Systems, and Herman Postma, Energy Systems vice-president and ORNL director.

Graduate students can perform prethesis and thesis research through several other programs. ORNL has hosted a number of students for summer practicum experience who have been awarded DOE Fellowships. Although thesis research can be sponsored by ORNL R&D subcontracts, it is also the objective of the Laboratory Graduate Participation (LGP) Program. Students selected for this program perform thesis research full time for up to two years under the direction of a graduate committee composed of ORNL and university representatives. Selection for this program is very competitive; typically fewer than ten appointments are made annually, and all candidates must be approved by the ORNL Graduate Fellow Selection Panel, a committee composed of professional staff members representing all ORNL research and technical divisions. The panel also is responsible for approving postmasters and postdoctoral applicants appointed through the Postgraduate Research Training Program.

ORNL's Impact on Campus

ORNL sponsors a considerable number of research projects at colleges and universities through R&D subcontracts, thereby supporting faculty, graduate students, and support staff. Occasionally, as part of the cost of sponsoring research, these subcontracts allow purchase of

Robert Coleman, a student at Chattanooga State Technical Community College, uses a sodium-iodide scintillation detector to determine whether a soil sample is contaminated with mercury, uranium, radium, or cesium. He participated in the Technology Internship Program at ORNL, where he was assigned to the Health and Safety Research Division.

modern research equipment, which is on every university's "wish list." Recent changes in DOE policy allow equipment purchased under subcontract for less than $5000 to remain the property of the school upon termination of the work (previously all equipment had to be returned unless it was too costly to transport).

ORNL also participates in the DOE Excess Research Laboratory Equipment (ERLE) program, which allows colleges and universities to obtain excess equipment for the cost of transportation only. The equipment, which ranges from small detectors to sophisticated analytical instruments, may be new, used, or in need of repair. University personnel can access the ERLE computer data base, which is updated monthly, and have equipment held until they can submit proposals for its use. ORNL also lends and donates excess equipment to universities directly, though DOE restrictions make this difficult.

Besides equipment resources, ORNL works with academic institutions to improve their educational programs and research capabilities by donating personnel time and resources. ORNL staff members (75 to 100 a year) frequently give seminars at universities across the nation, either through ad hoc invitations from faculty members or formal programs such as the ORAU Traveling Lecture Program and the Industrial Research Institute (IRI) Visiting Scientist Program.

Many ORNL staff members have adjunct affiliations with universities, teaching classes and collaborating on faculty research projects. Some 25 to 30 adjunct professors from ORNL receive compensation under official appointments from the University of Tennessee, but many others donate their teaching talents to institutions such as Knoxville College, Tennessee Technological University, and Roane State Community College. ORNL staff members also teach short courses as part of ORAU's manpower training programs sponsored by DOE; these classes are attended by students from colleges throughout the country. ORNL also assists faculty members by making critical reviews of proposals and manuscripts and organizing joint meetings and conferences.

The needs of resource-poor HBCUs also receive special attention. In FY 1985, Energy Systems donated a VAX 11/70 computer to Knoxville College, which is now the cornerstone of a new joint venture with the minority-owned MAXIMA Corporation to provide data

Jennifer Dyke, a student in the Oak Ridge Science Semester Program from DePauw University, prepares a sample for analysis by gas chromatography as part of her research assignment in the Analytical Chemistry Division.

services. Energy Systems has also helped Knoxville College by donating library books and sending teams of volunteers to assist with major maintenance projects. Knoxville College also has received several R&D contracts.

We are helping several HBCUs develop programs that are relevant to energy research manpower needs for the future, including a health physics technology program at Fort Valley State College in Fort Valley, Georgia. To formalize our commitment to improve resources, ORNL signed a memorandum of understanding (MOU) with Atlanta University in 1983 that was tied to a subcontract award of $565,000 over three years to improve their research capabilities in plasma physics. A similar MOU with Tuskegee University, with initial emphasis in environmental sciences, is expected to be signed in 1987. Other HBCUs that we are working with include North Carolina A&T University, Southern University, and Alabama A&M University.

ORNL and UTK

Formal collaborative agreements, such as memoranda of understanding, are unusual vehicles for ORNL–university interactions. Most agreements are much more informal. The only other current MOU is with the University of Tennessee at Knoxville (UTK), which was initiated as part of the Science Alliance, the state-sponsored Center of Excellence at UTK under the auspices of Tennessee's Better Schools Program. The purpose of the Science Alliance is to encourage expansion of research collaborations between ORNL and UTK, thus fostering a unique environment for research training. Many different activities fall under the program's umbrella, but the most visible one is the Distinguished Scientist Program. This program's purpose is to attract scientists of high national and international stature to strengthen R&D in the region.

The scientists selected hold a tenured full professor position at UTK and an appointment as a senior research scientist at the Laboratory; the costs are shared between the two. Five Distinguished Scientists began appointments in FY 1986; one began his appointment earlier. In FY 1987 three others have signed acceptances, bringing the total to nine.

Other Science Alliance activities include a summer research program and the development of joint graduate programs, including a new master of science program in biotechnology. ORNL is also working with UTK to develop a graduate program in measurement and control engineering.

Although Science Alliance activities are relatively new, they are based on a long-standing history of collaboration between ORNL and UTK. In addition to the large proportion of subcontracted funding at UTK and the adjunct appointments for ORNL staff, many UTK faculty members have served as consultants and research participants at ORNL. ORNL staff members have served on UTK advisory committees, and UTK staff members have played a similar advisory role at ORNL. Many ORNL staff members have taken advantage of the UTK Resident Graduate Program in Oak Ridge, which offers evening courses to those pursuing advanced degrees in a variety of scientific and engineering disciplines.

Rhonda K. Jones, a student from Fort Valley State College, collects data for population monitoring on the rare plant Delphinium exaltatum. *The plant is located in one of the Oak Ridge Reservation's new state-registered natural areas, which contains probably the world's largest population of this species. Jones was a participant in the Special Summer Program at ORNL, which offers summer employment for talented undergraduates attending historically black colleges and universities. Fort Valley State College in Georgia administers a DOE-sponsored program that encourages outstanding students to pursue energy-related careers.*

Perhaps the least known, yet one of the strongest, joint programs has been the two UTK graduate schools located at ORNL. Both are in their second decade. Housed in ORNL's Biology Division at the Y-12 Plant, the UTK Oak Ridge Graduate School of Biomedical Sciences (ORGSBS) offers full-time graduate study for M.S. and Ph.D. degrees and for postdoctoral training for about 50 persons a year.

The other UTK graduate program in Oak Ridge is the Graduate Program in Ecology within ORNL's Environmental Sciences Division (ESD). Similar to ORGSBS, opportunities are available for about 15 persons a year for full-time graduate study leading to both the M.S. and Ph.D. degrees as well as postdoctoral research training.

Other Collaborations

Many other long-standing close collaborations between ORNL and universities also exist because of mutual research interests. Most of

A joint academic outreach planning committee, composed of ORAU and ORNL staff members, has been formed to integrate communications and collaborative functions. Members include, from left, William Felling, Oak Ridge Associated Universities (ORAU) executive director; Chester R. Richmond, associate director for Biomedical and Environmental Sciences, who oversees ORNL's University Relations Office; Vivian Baylor, manager of ORNL's University Relations Office; Alfred Wohlpart, chairman of ORAU's University Programs Division; and James L. Gumnick, university relations director for ORAU.

these involve outstanding departments at premier research institutions and include active exchanges of students and faculty members. An example of this sort of research partnership was detailed in the *Review* article by Glenn R. Young (Vol. 18, No. 4, 1985) that described pion emission experiments designed and performed in collaboration with personnel associated with the State University of New York at Stony Brook and Michigan State University. About one-third of the R&D subcontract annual expenditures goes to support collaborative research at 20 colleges and universities that would make many "best" lists, such as the Massachusetts Institute of Technology, the University of Illinois, and the University of California at Berkeley. These institutions each average more than four subcontract awards valued at over $60,000 each.

ORNL also has close relationships with several university consortia. ORNL's long-standing collaboration with ORAU on educational programs has been strengthened through the implementation of several new joint programs as well as joint university outreach activities. In FY 1986, ORNL moved closer to the Southeastern Universities Research Association (SURA), another consortium of major universities in the Southeast, through staff members serving on the Board of Trustees and on various committees. We are examining the possibility of linking ORNL to the computer network SURANet, which has a node at UTK, so that university personnel can access ORNL's computer resources. SURANet is sponsored by the National Science Foundation (NSF).

Precollege Education

Besides increasing the traditional interactions with universities, ORNL is expanding the university relations programs to include precollege activities. Much of the interest in precollege programs stems from a renewed commitment by the federal government to science and mathematics education, including addressing concerns about quantity and quality of courses at both college and precollege levels. As a result of several studies by agencies such as the White House Office of Science and Technology Policy and the NSF, federal officials have expressed dismay over the current state of mathematics and science education. Declining enrollment in university mathematics and science courses, especially of U.S. citizens (including minority students), and generally poor precollege preparation for technical studies have been cited as problems. Within the past several years, DOE has recognized that these problems may affect our nation's future ability to compete in international research arenas. In response, DOE has started several precollege programs for both students and teachers.

ORNL has also responded to the calls for action by starting several precollege activities, organized and managed jointly by University Relations and Public Relations staff members. Although several programs have existed for many years to show the Laboratory to high school students and teachers (e.g., the Junior Science and Humanities Symposium and ORNL as a field-trip resource), in FY 1985 several new programs were started to increase teacher participation in the Laboratory's research. In the summer of 1985, 14 high school teachers participated in the pilot Summer Field Experience Program, which allowed them to assist ORNL researchers for six weeks. During that time, they were exposed to sophisticated laboratory techniques and equipment that would otherwise not have been available to them; they also absorbed scientific information that could be transferred back to the classroom.

As a follow-up effort, ORNL hosted 11 secondary school teachers in the summer of 1986 as part of the three-year NSF-sponsored program at ORAU called Science Teachers Research Involvement for Vital Education (STRIVE). STRIVE participants worked with ORNL researchers for eight weeks, while also participating in workshops conducted by UTK staff members to improve their teaching skills. ORNL staff members continue to be involved in two other components of the program—donating time for a fall seminar series and scientist visits to schools. Also, beginning in FY 1986, ORNL participated in the national Residence in Science and Technology (REST) Program, which offers summer research appointments to teachers selected nationally.

Several new programs have also been implemented for high school students. In the summer of 1985, DOE sponsored a two-week honors workshop at Lawrence Livermore National Laboratory in computer sciences. One student from each state was selected to participate. As a complement to this workshop, 20 students from high schools throughout Tennessee participated in a one-week workshop at ORNL during the same time. Produced in cooperation with ORAU and UTK, the workshop provided tours, demonstrations, and hands-on experience in computer

Don Morrison of Maryville High School was one of 14 high school science and mathematics teachers who participated in the 1985 Summer Field Experience at ORNL. Morrison, who was assigned to ORNL's Holifield Heavy-Ion Research Facility, is shown here checking sodium iodide detectors used in the Spin Spectrometer to detect gamma rays emitted by nuclear collisions.

applications. ORNL expects to be the site of one of the national workshops in FY 1988, with a focus on environmental sciences.

In FY 1986, ORNL implemented another new program for exceptional high school students, called the Special Honors Study Program. It allows students to conduct a study project at the Laboratory under the supervision of an ORNL staff member in an area of special interest to them. Two students were appointed in 1986, and several more are expected in 1987. One student who started his project here in 1986 is Albert Wong, an Oak Ridge High School senior. In January 1987, he was named one of 40 national winners in the annual Westinghouse Science Talent Search, and in March he placed third in the prestigious competition and received a $15,000 scholarship. His winning project focuses on neural networks and mathematical models. Wong was assisted by Al Geist, a computer scientist in ORNL's Engineering Physics and Mathematics Division, and ORHS math teacher Benita Albert. He is the son of Cheuk-Yin Wong, a theoretical physicist in the Physics Division.

As part of this increased focus on precollege activities, we are also expanding one of the most visible and successful precollege programs—the Ecological Study Center (ESC) of the Oak Ridge National Environmental Research Park. ESC offers half-day field-study modules that provide students of all ages with the opportunity for hands-on learning in the environmental sciences. These include fallen-tree study, stream ecology, study of small mammal niches, and predator awareness.

A very successful citizens advisory group has collaborated

Marcella Cranford, Knoxville veterinarian and consultant to ORNL's Ecological Study Center, demonstrates to elementary students that snakes are not "so wet and slimy after all." The Ecological Study Center presents field-study modules to students and teachers as part of ORNL's increasing precollege activities. Recently, one module was adapted for presentation to handicapped children.

Dan Kuban (center) of the Energy Systems Engineering Organization shows Clint Miles and Ashley Melton a viewgraph of the results of robotics work at ORNL sponsored by the National Aeronautics and Space Administration. The youths are students at Bowers Elementary School in Harriman. During February, Kuban and Tom Burgess of ORNL's Fuel Recycle Division made 13 presentations at area elementary schools as a part of Tennessee Space Week activities. During their presentations, the two engineers demonstrated a one-fifth scale model of the Manned Maneuvering Unit built by Martin Marietta Corporation and showed viewgraphs and videotapes to more than 1400 children.

with the Fermi National Accelerator Laboratory for a number of years to put together precollege programs. Called Friends of Fermilab Association (FFLA), the group identifies community needs and seeks funding from private and federal agencies to implement programs that call on the resources of the Fermilab to address their educational objectives. When ORNL began implementing new precollege activities in FY 1985, most were in response to perceived national needs; however, we also recognized that community involvement with the Laboratory should play an important role in our precollege activities. As a result, in cooperation with ORAU, we invited the president of FFLA to speak to a group of area citizens in the hope that a similar organization could be formed in Oak Ridge that could help guide precollege program development in accordance with area needs. The nucleus of the group formed at that meeting, and several activities have since occurred, including a needs assessment workshop in January 1987 conducted with the assistance of FFLA personnel. A critical need identified was the establishment of a resource center for area teachers; we are working with the group to determine how ORNL might help address this need.

Summary

The precollege and university relations programs at ORNL will continue to grow significantly in the future. We will continue to involve new groups in our activities, implement new programs to meet needs, and improve our education and training activities. ORNL currently offers an impressive catalog of programs, but there are always opportunities for new initiatives. For example, we expect to hire high school teachers and selected high school students during the summer under new internship programs. The number of university research participants is expected to increase considerably in FY 1988 with the implementation of a new DOE-sponsored nationwide program called Science and Engineering Research Semesters, modeled after the successful academic-year programs like the GLCA/ACM Oak Ridge Science Semester. We also plan collaborations that will provide research opportunities for midshipmen from the U. S. Naval Academy and students and faculty members from Hispanic colleges and universities. The one program in the most demand that can never be implemented, however, would provide summer employment to all the college student relatives of Energy Systems employees. They

ORNL's Berea College Alumni Get High Marks

ORNL contributes to colleges and universities by training students in a laboratory setting and providing unique research experiences for faculty members. However, colleges and universities also contribute to ORNL through the education of students who later become productive members of ORNL's research and management staff.

One small college whose alumni at ORNL have had an unusually outstanding track record is Berea College in Berea, Kentucky. Berea College has highly motivated students for several reasons. It promotes equality of opportunity for all students; it requires all students to work 10 to 15 hours a week to help support the college operation, and it accepts only students whose parents' income is below a certain middle-class limit.

ORNL has a division director and a former division director who attended Berea College: Jim Barker, director of the Personnel Division, and John Auxier, former director of the Health Physics Division. Two Energy Systems corporate fellows are Berea College alumni. They are Sam Hurst and Bob Compton. Both are also I-R 100 award winners. Hurst shared an I-R 100 award in 1984 for development of a rare-gas atom counter. Compton, a senior research staff member of the Health and Safety Research Division (HASRD), shared an I-R 100 award in 1983 for his work in developing an ultraviolet vacuum spectrometer; in 1986 he received the annual Excellence in Research Award from HASRD for his studies of the spectroscopy of negative ions using novel experimental techniques.

Hurst and Auxier, who both took early retirement, are well known in the area as entrepreneurs. Hurst has founded Atom Sciences, Inc., and Elographics, Inc. (which recently was sold to Raychem Corporation), and Auxier organized and became president of his own company, Applied Sciences, Inc., now part of IT Corporation. Auxier will receive an honorary doctorate from Berea College this year.

Other Berea College alumni at ORNL are Delno Ausmus, shift superintendent in the Laboratory Protection Division; R. L. Cline, staff engineer in the Operations Division; Sherri J. Cotter, research associate in HASRD; B. Z. Egan, senior development staff member in the Chemical Technology Division; Gordon Jones, engineering specialist in the Environment and Safety Analysis Organization of Energy Systems; Betty Maskewitz, director of the Radiation Shielding Information Center in the Engineering Physics and Mathematics Division; Marvin Payne, senior research staff member in HASRD; Candice Strickler, technical librarian in the Information Resources Organization (IRO); Dennis Strickler, computing specialist in the Computing and Telecommunications Organization; and Mary Uziel, technical information analyst in IRO.

Jim Barker doesn't have a degree from Berea College but took several college courses there for high-school credit while attending the Berea Academy during his junior and senior years. At the time he roomed with Hurst, who was attending the college. "Sam and I had incompatible schedules," he laughs. "He liked to stay up late and study. But I had to go to bed early since I had to get up by 5 a.m. to work in a commercial bakery." Barker says that what he remembers best about Berea College is the "quality and dedication of the teaching staff."

must qualify and compete on an equal footing for the available positions with all the other applicants.

Program development, implementation, and management are not the only significant activities of the University Relations Office; we also spend much time providing information. University personnel frequently call us seeking technical contacts who share their research interests (e.g., "Who should I talk to about two-phase flow in nuclear reactors?"), and ORNL staff members frequently call with questions about program opportunities (e.g., "What is the best way to hire this student for the summer?"). We also travel frequently to universities and university-sponsored meetings and give presentations on ORNL and the University Relations programs. The ORNL program has also elicited the interest of Department of Defense (DOD) laboratories; as a result, in October 1986 we presented a workshop on our programs to DOD representatives and are following up with site visits.

The University Relations Office underwent some rather drastic changes in the spring of 1985 when it was restructured and moved from the Personnel Division to the Central Management Offices Division. It now reports to Chester Richmond, associate director for Biomedical and Environmental Sciences, who also serves as director for University Relations at ORNL. The move was made to give the University Relations Program more focus and visibility. As a result of the changes, many of the functions formerly performed by the University Relations Office continue to be performed by Personnel staff, such as services for guests and foreign nationals, while the role of University Relations Office staff in program development, implementation, and management and as university liaison increased.

Major initiatives within the past two years, including expanded programs with HBCUs and in precollege education, have resulted in an expanding program. The ORNL University Relations Program will continue to grow and serve as a model for other federal laboratories and corporations in their efforts to offer new research experiences for university faculty members and improve the education of the nation's youth. ornl

take a number

By V. R. R. Uppuluri

Divisibility by 7

Whether a number of three digits or more is divisible by 7 can be determined by one of two procedures. In the case of a three-digit number, multiply the first digit by 2 and the second digit by 3 and add these products to the third digit. Put another way, if the number is represented as abc, the formula is $2a + 3b + c$. Next, determine whether the sum of this formula is divisible by 7. If it is, then the three-digit number is divisible by 7.

Try the procedure on 658. In this case, $(2 \times \mathbf{6}) + (3 \times \mathbf{5}) + \mathbf{8} = 35$, which is divisible by 7. Thus, 658 is divisible by 7. The procedure also verifies that 785 is not divisible by 7 because $(2 \times \mathbf{7}) + (3 \times \mathbf{8}) + \mathbf{5}$ is 43, which is not divisible by 7.

A different procedure can be used to determine whether any number of four digits or more is divisible by 7. Write down the last three digits of the number from left to right. Subtract from this three-digit number the next set of digits and then add the next set. Continue to alternate between subtracting and adding. If the result is divisible by 7, so is the number.

If we try this procedure on the five-digit number 91,336, we get $336 - 91 = 245$. Because 245 is divisible by 7, it can be concluded that 91,336 is divisible by 7. Indeed, a calculator check shows that $91{,}336 \div 7 = 13{,}048$.

Consider 64,236,928, a seven-digit number. Applying the procedure, we obtain $928 - 236 + 64 = 756$. Because 756 is divisible by 7, it can be concluded that the original number is divisible by 7. A check with the calculator shows that $64{,}236{,}928 \div 7 = 9{,}176{,}704$.

This procedure is particularly useful for rapidly determining whether very large numbers are divisible by 7.

True Only for One Pair

The sum of 2^m and 3^n can be a perfect square only if $m = 4$ and $n = 2$. If m and n equal other natural numbers, $2^m + 3^n$ can never be a perfect square.

news notes

HFIR kept idle for studies of radiation damage

In May 1986, several weeks after the Chernobyl reactor accident, ORNL Director Herman Postma became uneasy about the reactors at ORNL and requested a committee to probe their safety. One committee, headed by Don Trauger of the Central Management Offices Division, found evidence that the pressure vessel of the High Flux Isotope Reactor had been embrittled. When the reactor was shut down for refueling and maintenance November 14, it was decided to keep it idle for a prolonged period to determine what actions must be taken to resume its safe operation. The extended shutdown was announced November 20.

The 100-MW HFIR is ORNL's largest reactor and one of the best sources of high-flux neutrons in the world; the 21-year-old reactor has long been used for isotope production, neutron-scattering experiments, and materials-irradiation tests.

In October 1986 sample specimens of the HFIR vessel's carbon steel alloy that had been removed from the vessel in October 1983 were analyzed and found to show signs of radiation-induced embrittlement. After HFIR was shut down November 14, more specimens were removed from the vessel and analyzed. They, too, showed signs of embrittlement.

An ORNL advisory committee, headed by Dick Cheverton of the Engineering Technology Division and Randy Nanstad of the Metals and Ceramics Division, was formed immediately to review data from the analyses and recommend any needed changes. Based on this information, the committee was to determine whether more analyses, corrective actions, or changes in reactor operating procedures were needed to ensure HFIR's safe operation.

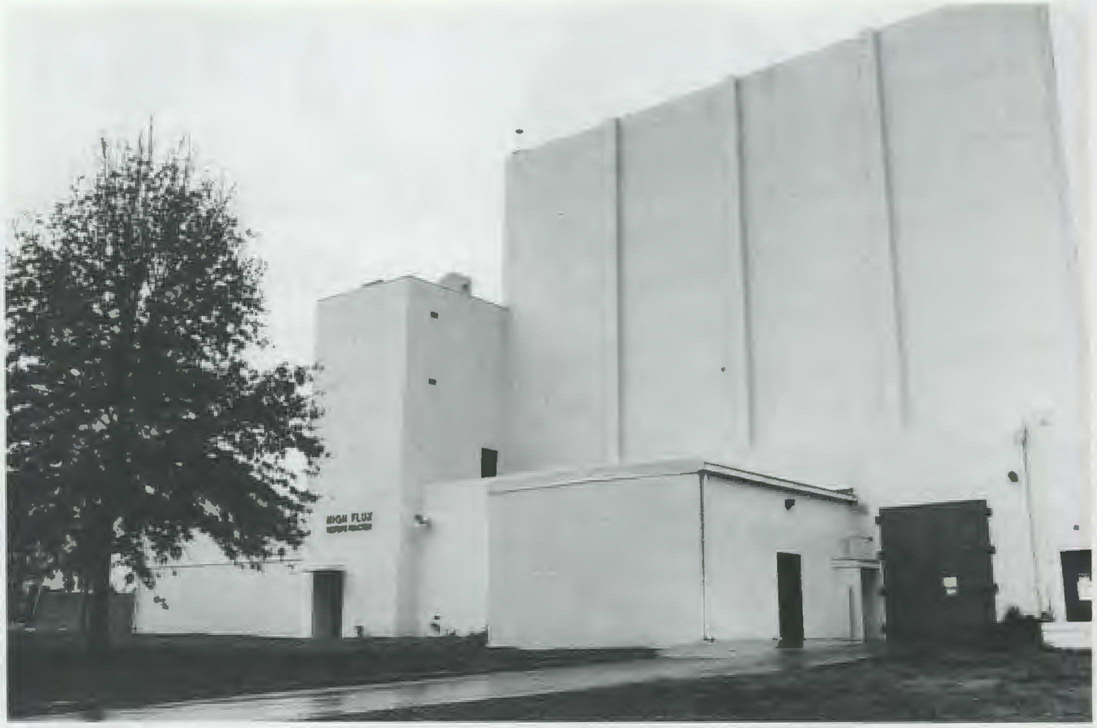
The committee has considered short-term fixes that could extend the reactor vessel's operating life. Such fixes include heating the pressure vessel to high temperatures to anneal out the radiation damage and then operating the reactor at lower power or pressure. The committee has also been examining a possible long-term fix: replacing the pressure vessel with a new one, an action that could take several years.

After extensive study, it was revealed in February 1987 that the estimated remaining life of the reactor pressure vessel ranges from 3.7 to 8 years.

The impacts of an extended shutdown of the HFIR have been cushioned by the availability of the Oak Ridge Research Reactor (ORR). The ORR had been scheduled to be closed at the end of fiscal-year 1986 but got a reprieve when DOE decided to use it for low-enriched uranium experiments to be conducted by Argonne National Laboratory.

Two HFIR-produced radioisotopes— iridium-192 and gadolinium-153—are now being produced at the ORR (see following story). HFIR's shutdown will have relatively little impact on production of californium-252 (for treating cancer and inspecting aircraft welds) unless it exceeds nine months.

Users of the National Small-Angle Scattering Center at the HFIR can perform some small-angle neutron scattering experiments at ORR even though the neutron flux is at least an order of magnitude lower. The center normally has 95 users a year and from two to eight users a week. Irradiation of capsules for the U.S.-Japan materials-irradiation experiments had been completed at the HFIR before the shutdown, and



ORNL's High Flux Isotope Reactor has been shut down indefinitely because of an embrittled pressure vessel. The reactor is now being extensively studied by DOE and Energy Systems. Results of one study indicate that the remaining life of the vessel ranges from 3.7 to 8 years.

future experiments could be done at the ORR (although the rate of neutron-induced damage in samples at ORR is half as fast as that produced at HFIR).

Today, eight U.S. Department of Energy and Martin Marietta Energy Systems committees are studying management and technical issues related to the HFIR. Pete Lotts, director of Defense Technologies at ORNL, is coordinating ORNL's response to information needs and recommendations of the eight study teams. One of DOE's six investigations of the HFIR's problems seeks to determine the reason for the three-year delay in analyzing samples from the vessel wall. This investigation is being carried out by a team headed by John Rothrock, director of the Quality Assurance Division of DOE's Oak Ridge Operations. Mary Walker, DOE's assistant secretary for safety, environment and health, heads three safety-related investigations of HFIR, one of which cannot be conducted until the HFIR is back in operation.

ORR, INEL, and BNL reactors produced isotopes in demand

Several radioisotopes that had been produced at the HFIR are being produced at other reactors during its prolonged shutdown. Iridium-192, which is in demand for surveys of heavy-section steel and pipelines, is being produced at the ORR and the Advanced Test Reactor (ATR) at the Idaho National Engineering Laboratory. Gadolinium-153, used in bone scans to detect osteoporosis, is being produced at the ORR and may also be produced at the ATR if the demand for the isotope picks up. ORNL will decide soon whether to send europium targets to Idaho Falls for neutron irradiation to make additional gadolinium-153.

Arrangements have been made for the High Flux Beam Reactor at Brookhaven National Laboratory to produce osmium-191, which decays to iridium-191*m*, a short-lived product that safely images heart defects. Osmium-191 is needed by physicians using prototypes of the improved iridium generator developed by ORNL's Nuclear Medicine Group to obtain iridium-191*m* for tests of human patients. In particular, the isotope is needed by a hospital in Belgium and by the University of California at Los Angeles–Harbor Medical Center, whose Human Use Committee recently gave approval for the first tests on U.S. patients of iridium-191*m* from the new generator.

Although these reactors will help DOE meet the demands for these special radioisotopes, they do not perform the job as fast as the 100-MW HFIR. Because the ORR is a 30-MW reactor, it produces fewer neutrons per unit volume than the HFIR. Thus, it will take about 9 weeks to make gadolinium-153 in the ORR, compared with 3 weeks in the HFIR. Osmium-191, which was produced in 3 days at the HFIR, can be made in 10 days at the HFBR because the HFBR's neutron flux is one-third that of the HFIR.

On March 26, 1987, DOE ordered ORNL to shut down the ORR, the Bulk Shielding Reactor, the Health Physics Research Reactor, and the Tower Shielding Facility because of concerns about reactor management.

Eighth UT-ORNL Distinguished Scientist named

A physicist widely regarded as one of the leading U.S. atomic collision theorists has accepted a joint appointment under the University of Tennessee-ORNL Distinguished Scientist Program. Joseph H. Macek, professor at the University of Nebraska, becomes the eighth appointee to one of the dual teaching and research positions. The program was established in 1984 to attract to this area a select number of scientists of national and international stature.

Macek is to begin his tenure in mid-1988, after a year in Europe under a research fellowship sponsored by the West German government. His appointment will be in the Department of Physics at UT Knoxville and the Physics Division at ORNL.

ORNL helps EPA assess acidity of U.S. lakes

The percentages of lakes that are acidic and that have a low capacity for neutralizing inputs of acids are presented in a new report co-authored by an ORNL staff member. Paul Kanciruk of the Environmental Sciences Division and two staff members of Science Applications International Corporation have completed a three-volume report entitled *Characteristics of Lakes in the Eastern United States*. This work is part of a series summarizing results of the National Surface Water Survey recently conducted by the U.S. Environmental Protection Agency.

ORNL has helped the lake study, which is sponsored by the National Acid Precipitation Assessment Program, by providing data-base management and statistical support. More than 1600 lakes from Maine to Wisconsin to Florida were sampled in the fall of 1984. Helicopters were used to speed sample collection and reach lakes inaccessible by road. In the fall of 1985, more than 900 lakes in the West were sampled; technicians had to reach some of these lakes by horseback and on foot because of wilderness restrictions. Kanciruk recently assisted in the completion of the western lake report, which supplements the eastern lake report.

ORNL researchers assist U.S. Border Patrol

Researchers in ORNL's Instrumentation and Controls (I&C) Division are developing a sophisticated system for retrieving information from sensors to help the U.S. Border Patrol stem the tide of illegal aliens. The system will provide a uniform communications link between Border Patrol stations and remote detection devices near sensitive borders.

Using multiple sensors, the system will count pedestrians and vehicles and map their directions. The information relayed to the Border Patrol will indicate the most probable locations of illegal traffic to which agents should be dispatched.

According to Ed Madden, leader of I&C's computer systems development group, "The system will connect an array of existing electronic detection equipment and provide automated, interactive dispatching and path analysis functions to assist Border Patrol agents in controlling and reporting on illegal traffic." ORNL's work is a result of an interagency agreement between DOE and the Immigration and Naturalization Service.

Record budget submitted to the 100th Congress

President Reagan's proposed trillion-dollar budget for fiscal-year (FY) 1988 seeks significant spending cuts for most federal departments, including DOE. However, it includes substantial increases for the Strategic Defense Initiative (SDI), which supports some work at ORNL. About $13.9 billion (up from $12.6 billion in FY 1987) is requested for DOE.

In the budget proposal submitted to the 100th Congress in January 1987, DOE funding would decline from $10.6 to $10.2 billion; however, it would rise in later years because of increased spending for nuclear weapons production. The federal budget projects a $107 billion deficit, which is well under the guidelines set in the Gramm-Rudman-Hollings Balanced Budget and Deficit Reduction Law of 1985.

Under the proposed budget, ORNL funding would increase by $10 million to $460 million in FY 1988. The ORNL budget request reflects increases for the physical sciences and waste management facility improvements and cutbacks for other programs. According to Joe Lenhard, assistant manager for Energy Research and Development at DOE's Oak Ridge Operations, "We have done handsomely in a year of gross austerity."

The proposed ORNL budget includes a $3 million increase over the FY 1987 budgeted amount for physical research, to $70 million, including $3 million for the Center for Neutron Research; a $5 million decrease for fusion energy research to $40 million, which reflects completion of the Large Coil Test Facility; a $4 million increase for defense waste-related work to $29 million; a $1 million increase for conservation and renewable energy research to $45 million; and a $3 million increase for SDI programs to $7 million.

ORNL programs whose funding is unchanged for the coming fiscal year include nuclear energy, the Environmental Restoration Facility Upgrade, and life sciences research.

Thermoelectric generator is largest in the world

The largest single unit of a separated radioisotope ever assembled for transport and use is currently undergoing tests in ORNL's Operations Division. The unit is a radioisotope thermoelectric generator (RTG), which produces electricity by converting the heat from the decay of more than a million curies of strontium-90 (^{90}Sr). According to Chuck Ottinger of the Operations Division, "The unit produces approximately 7500 watts of thermal energy, which is converted into more than 600 watts of electricity."

The ^{90}Sr, a by-product of nuclear reactor fuel, is in the form of solid, high-density pellets of strontium fluoride contained in three welded-metal source containers. Each of the three sources is more than 50% larger than any previously made single ^{90}Sr source. The ^{90}Sr was recovered and purified at DOE production facilities at Hanford, Washington, and then shipped to ORNL for fabrication of the RTG. The RTG could be used to power

ORNL's radioisotope thermoelectric generator is ready to be loaded with heat sources. Standing by is David Carroll of ORNL's Operations Division.

systems that detect and analyze seismic activity and underground nuclear explosions.

Nitrogen cause of soil leaching in the Smokies?

Excessive amounts of nitrogen, as well as sulfur, from atmospheric deposition (including acid rain) and other natural sources may be the chief cause of leaching in soils in the Great Smoky Mountains. The nitric acid produced in the soil plays a major role in the leaching of aluminum and nutrients needed to support the growth of beech and spruce trees in the Smokies.

Sulfate plays a significant role as well but is often of secondary importance to nitrate in causing this leaching loss. It is not known whether the aluminum leaching caused by nitrate and sulfate is sufficiently high to cause toxicity to vegetation.

These preliminary conclusions were drawn recently by Dale Johnson and colleagues in ORNL's Environmental Sciences Division. The results suggest that sulfur oxides from fossil-fuel combustion may not be a major contributor to soil acidity and that installation of expensive emission controls on coal power plants would not guarantee a reduction in soil acidification in the Smokies.

In soil solutions from three sites near Clingman's Dome, Johnson found that nitrate is frequently the dominant ion. The high nitrate amounts, he said, suggest that the trees and other vegetation have more nitrogen than they can use. The excess nitrogen results in luxuriant ammonium supplies to nitrifying bacteria, which convert ammonium to nitric acid.

"The source of the high amount of nitrogen is unknown," says Johnson. "We speculate that possible sources include atmospheric inputs caused by nitrogen oxide emissions from vehicle exhaust, high rates of decomposition of nitrogen-rich soil organic matter, or a disturbance such as hog rooting or insect attack, both of which have been known to occur in the Smokies."

Johnson's four-year research project is part of the Integrated Forest Study, a multisite investigation to determine the sources of excessive soil acidity and the mechanisms by which it robs trees of needed nutrients. The study is supported by the Electric Power Research Institute.

TECHNOLOGY TRANSFER BRIEFS

Energy Systems' technology transfer progress report

Since Energy Systems became manager of DOE facilities in Oak Ridge and Paducah in 1984, the number of technology transfer staff members has increased from two to ten. In the past, many of the responsibilities for technology transfer that were carried out informally by research staff members are now being handled by professionals in the Office of Technology Applications (OTA).

According to Bill Carpenter, vice-president for technology applications, "Centralizing the technology transfer function has resulted in a more productive program. Now research staff members need to be involved only in the technical aspects of the transfer process because OTA staff members take care of contacting and conducting negotiations with clients."

In the past year OTA focused its efforts on developing a licensing policy and identifying industrial contacts who could benefit from ORNL's unique research-and-development capabilities through joint agreements, user facilities, personnel exchanges, work-for-others agreements, or licensing.

In FY 1986, Energy Systems' technology-transfer achievements include the following: 21 technologies were transferred to 148 organizations; six spin-off companies were started by employees; eight technologies were licensed to industry; $150,000 in up-front licensing fees were received; three I-R 100 awards were received for new inventions; three university-laboratory-industry centers were formed; $21,900 were awarded to Energy Systems inventors for filing patents; and 55 work-for-others agreements worth a total of $6.3 million were contracted.

Innovations continue to abound at ORNL. This year ORNL submitted a record 43 entries in the I-R 100 competition sponsored by *Research & Development* magazine.

License agreement signed with Future Tech Corp.

Energy Systems has signed a service supplier license agreement with Future Tech Corporation of Oak Ridge to provide services to end users of a computer software system developed at Oak Ridge Gaseous Diffusion Plant.

The Analytical Laboratory Information System, known as AnaLIS, recently was installed at ORNL and the Portsmouth Gaseous Diffusion Plant and is accessible to other DOE installations through telecommunications.

Under the license agreement, Future Tech Corporation will provide installation, training, updates, improvements, and error corrections for the copyrighted system.

AnaLIS enables an analytical chemist to record quickly the results of an analysis just performed or to retrieve data on several million analyses performed previously.

View of the turbine hall and, from left, Reactor Units 1 through 4 at the Chernobyl complex in the Soviet Union. In the foreground is the Pripyat River.

SPECIAL SECTION:

ORNL Follows the Chernobyl Accident from Afar

By CAROLYN KRAUSE

On April 26, 1986, a pair of explosions at a reactor at Chernobyl in the Soviet Union lofted into the atmosphere large amounts of radioactivity that would be detected around the world. Radioactive releases into the atmosphere included cesium-134, cesium-137, and iodine-131, much of which fell on other countries in Europe. More than 30 people died as a result of the accident.

The Chernobyl accident, the world's worst nuclear power plant disaster, stirred up fear and anxiety on the part of the Soviet and European public and caused worldwide disaffection with nuclear power. Among scientists and engineers, including many at Oak Ridge National Laboratory, it also aroused considerable interest and prompted scientific studies.

"Back Calculations"

Shortly after the Chernobyl accident, ORNL scientists began making analyses on their own initiative. The first calculations were made by Owen Hoffman of

Map showing the location of the Chernobyl nuclear power plant in the Ukraine.

ORNL's Environmental Sciences Division (ESD), who had been in touch with colleagues in Sweden. (The Soviet Union delayed announcing that the accident had occurred, but the news reached the West when Swedish scientists concluded that a Soviet accident was the source of the high radiation levels being detected in Sweden.)

By taking into account wind velocity and the distance traveled by fission products between Chernobyl and Sweden, Hoffman made "back calculations" to determine the time of the accident—information that the Soviets did not release until later. He determined that the day of the accident was April 25, a day earlier than it actually occurred. Hoffman and colleagues simply assumed a trajectory of 1600 to 2400 km (1000 to 1500 miles) for the winds and an average wind velocity of 24 to 32 km/h (15 to 20 mph), suggesting that it would take approximately two to four days for the radioactive cloud to reach Sweden. The average of these values is three days—thus, the estimated date of April 25. The same date was proposed by scientists at Studsvik, Sweden. The Soviets later announced that the accident had occurred on April 26 at 1:24 a.m.

A group in ORNL's Chemical Technology Division (CTD) also "back calculated" the time of the accident. Allen Croff used the ORNL-developed computer code called ORIGEN to estimate the radionuclide inventory in the Chernobyl core. Ed Beahm, Dick Lorenz, Morris Osborne, and George Parker called European colleagues to obtain estimates of airborne concentrations and fallout measurements for various countries. Combining this information with Croff's inventory calculations and radionuclide decay times, the scientists calculated the time of the accident within 30 min of the time announced by the Soviets days later.

Knowing the reactor power level immediately preceding the accident was thought to be important in determining its cause. Lorenz and Toshi Yamashita of CTD made an independent analysis to determine the time of the Chernobyl reactor shutdown. Their analysis was based on concentrations of iodine-131 (^{131}I) and ^{133}I measured in Finland and on estimates of Croff's fission product inventories. Lorenz and Yamashita calculated that the relative amounts of ^{131}I and ^{133}I corresponded to a time for shutdown from full power at about 9 h before the accident occurred. The actual shutdown schedule, according to the Soviets, was a stepped reduction to low power beginning 24.3 h before the accident.

When news of the Chernobyl nuclear accident was first announced in April 1986, ORNL scientists made calculations to determine about when the accident had occurred. Other ORNL scientists helped model the accident and used information on fission-product concentrations in Europe to determine the chemical conditions affecting the two releases of radioactivity from the stricken reactor. Since then, ORNL scientists have been analyzing environmental radiation data from Europe and the Soviet Union.

Local Monitoring

Two weeks after the accident, scientists in the Laboratory's ESD

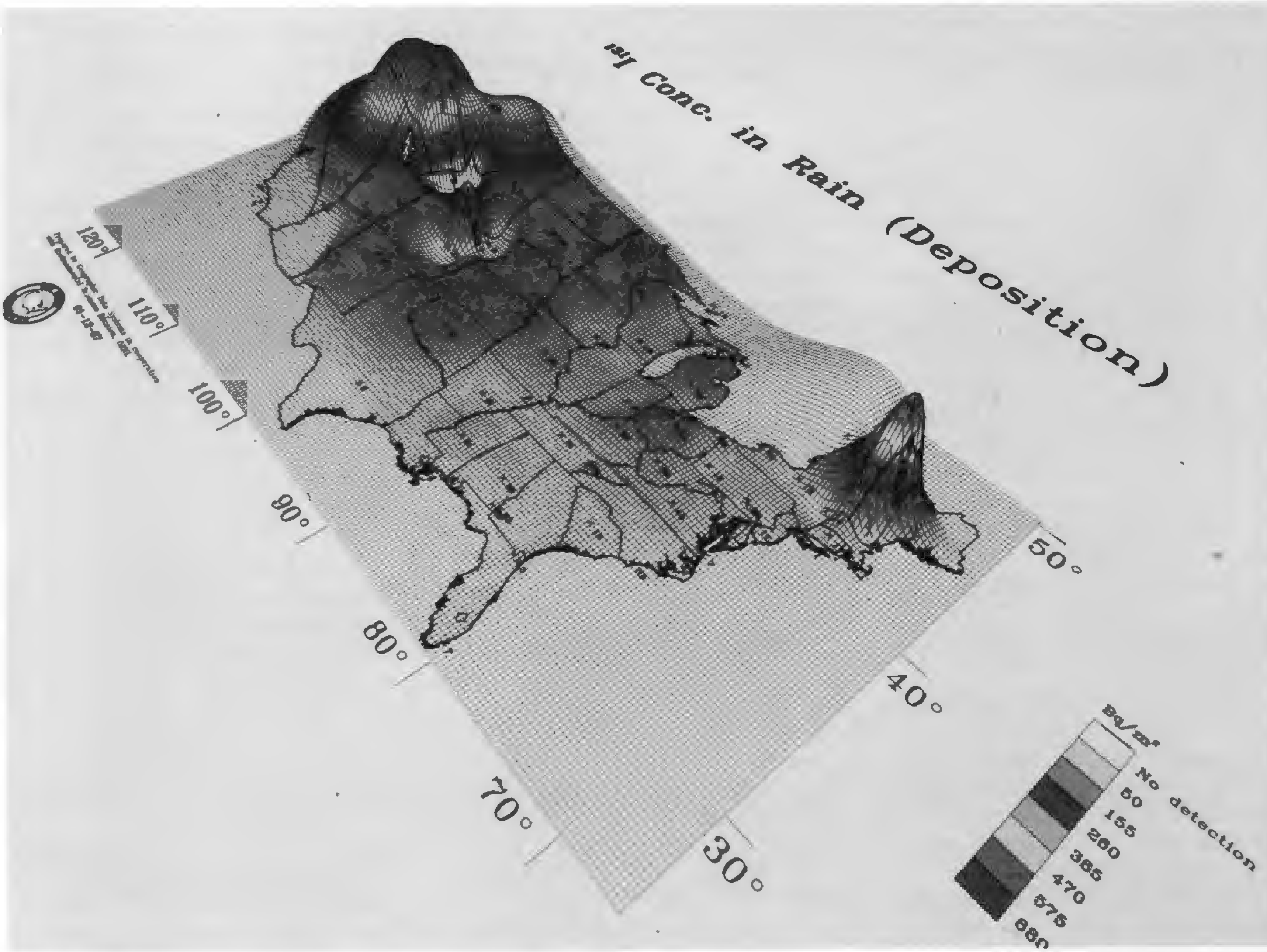
After the Chernobyl fallout reached the United States, scientists measured the changing iodine-131 concentrations deposited by rain. The two-dimensional map and the three-dimensional computer plot (right) show that radionuclide deposits were greatest in the Northwest and New England.

helped DOE obtain information on Oak Ridge-area fallout from the Chernobyl accident. Hoffman kept track of varying radiation levels throughout the world and correlated them with levels measured locally. When ESD scientists heard about the accident, I. Lauren Larsen proposed that Chernobyl fallout could be measured in rain and vegetation in Tennessee. He was the first person at ORNL to collect samples of rain and vegetation and later helped organize a volunteer effort within ESD to obtain samples of vegetation and milk. For example, Nelson Edwards supplied milk samples from his own cow, and Leroy West of the Plant and Equipment Division obtained milk from neighbors' farms for analysis. Bob Cook collected rainwater and vegetation from the Great Smoky Mountains National Park. Ernie Bondietti and Jerry Brantley analyzed the particle-size distribution of the Chernobyl radionuclides using a cascade impactor air sampler; his results have been published as a note in *Nature*.

The data obtained on Chernobyl fallout may help ORNL ecologists determine whether naturally occurring radionuclides are useful as tracers in measuring the amount of submicron aerosols transferred from the atmosphere to vegetation. ORNL analyses have already shown strong correlations between cosmogenic beryllium-7 (^{7}Be) and the Chernobyl radionuclides in rain and vegetation. These preliminary results indicate that measurements of natural ^{7}Be may be used as a surrogate to quantify the rain-to-vegetation transfer for a variety of other materials potentially dispersed in the atmosphere as submicron particulates.

ORNL and the IAEA Meeting

In June ORNL responded to a DOE request to assemble a team to model the various systems of the Chernobyl reactor in enough detail to better understand the accident. Under the direction of Les Oakes of ORNL's Instrumentation and Controls Division, team members were selected from ORNL and other DOE national laboratories—namely, Argonne, Brookhaven, and Pacific



These maps were originally produced in color. The key in the black-and-white version is misleading because the darkest tones do not represent the highest concentrations (red) of iodine-131.

Northwest. One purpose of this work was to better prepare U.S. delegates to understand the Soviet report on the accident to be presented at the International Atomic Energy Agency (IAEA) meeting in August in Vienna, Austria. The results of the modeling agreed well with the information about the accident provided by the Soviets, suggesting that extensive dynamic analyses of a verified model increase understanding of a reactor system and could have helped the Soviet operators identify problems that arose from using the reactor in an unconventional way.

On July 24, the Soviets announced that the explosion that caused the Chernobyl accident resulted from a poorly planned experiment. The experiment was to determine whether useful electricity could be generated from the inertial energy of a turbine generator during the seconds following a sudden reactor shutdown.

During the week of August 18, a team of Oak Ridge scientists were in Washington reviewing the Soviet report on the Chernobyl accident. The team included Tony Malinauskas, Tom Kress, Oakes, and Hoffman of ORNL and Clarence Lushbaugh of Oak Ridge Associated Universities. The Oak Ridge team studied the report's assertions about the accident sequence, the magnitude and types of radioactivity released, and possible health effects.

The following week, Kress was in Vienna as a representative of the IAEA for a Soviet briefing on the accident. Before the briefing, the Soviet officials announced at a Moscow press conference that a series of "unbelievable" blunders led to the Chernobyl disaster. The mistakes included reducing the reactor's power output below permissible levels, switching off two automatic-shutdown mechanisms, and switching off the emergency backup cooling system.

During the week of August 25 when Kress was in Vienna, the Soviets revealed that half of their 18 RBMK reactors of the Chernobyl type (light-water-cooled, graphite-moderated) had been shut down for safety modifications. The changes included improving training and procedures, installing additional neutron absorber rods, and inserting devices that limit how far the control rods can be withdrawn. Kress stayed a second week in Vienna to help write an IAEA report on the Soviet briefing.

ORNL Predictions Valid

On September 4, Malinauskas, director of Nuclear Regulatory Commission (NRC) programs at ORNL, revealed the results of some new ORNL work on the Chernobyl accident at a meeting of the Oak Ridge chapter of the American Institute of Chemical Engineers. Malinauskas reported that early detective work by ORNL's Dick Lorenz, Toshi Yamashita, and colleagues indicated that the Chernobyl accident released two separate kinds of radioactivity releases. The first release, which was carried to Sweden and Finland, was rich in particulates and apparently occurred when the explosion caused fuel pellets to fragment.

The material released several days later, which was transported to western Europe, was found to contain large amounts of the fission products ruthenium, molybdenum, and tellurium. Releases of these materials were increased by the oxidizing atmosphere resulting from the oxidation of the fuel during the graphite moderator fire. Particulates containing the fission products zirconium, niobium, and neodymium were present in much lower concentrations in the second release than in the material released the first day of the accident. These inferences by Lorenz's group, made on the basis of fission products deposited in Europe, were verified later by the Soviet report on the accident.

Malinauskas noted that the Chernobyl accident released some 10 million curies (10 MCi) of ^{131}I, compared with only 15 Ci from the 1979 Three Mile Island accident; the moral, he said, is this: "If you're going to have a severe-core-damage accident, make sure the fission-product escape pathway is intercepted by water and make sure the containment holds."

On September 26, Kress gave a seminar on "Chernobyl from a Vienna Perspective." He said that the Soviet scientists offered three possible explanations for the decisions by the reactor operators to violate operating and test procedures, such as continuing the experiment at the prohibited low-power levels. They may have (1) been unaware of how dangerous the situation had become, (2) been overconfident because the Chernobyl reactors up until then had the best operating record in the Soviet Union, or (3) felt pressured to make the turbogenerator experiment succeed. (If it didn't, they could not try it again for a year, thus disappointing the outside group of experimenters.)

In November, Chet Richmond, associate director for Biomedical and Environmental Sciences at ORNL, was invited by the IAEA to assist the agency in developing a coordinated research program for calculating radiation dose per unit intake for the general public. Gordon Blaylock of ESD was also invited by the IAEA during that month to assess the effects of radioactivity on the nonhuman components of the ecosystem. Hoffman and Stan Auerbach, former ESD director, also traveled to Europe on Chernobyl-related research missions.

Today, ORNL has an on-line data base containing information about U.S. radiation levels in the aftermath of the Chernobyl accident. Air, precipitation, and milk samples collected from April 29 to July 15 at scattered Environmental Protection Agency (EPA) monitoring sites have provided the data. Using the EPA data base and ORNL's Geographic Data Systems, Pete Lesslie and Dick Durfee of the Computing and Telecommunications Division have generated maps that graphically represent the levels of Chernobyl radioactive fallout in the United States.

Richmond is a member of the Task Group on Health and Environmental Aspects of the Soviet Nuclear Accident for DOE's Office of Health and Environmental Research; Richmond is chairing the Task Group's Committee on Research on the Validation of Predictive Models. Lesslie, Hoffman, Blaylock, and Keith Eckerman are ORNL members of the committee. The committee's objectives include evaluating Chernobyl accident data gathered worldwide to identify needs for additional data and critical research issues for an integrated assessment of the impacts of the Chernobyl accident. Chernobyl-related reports from potential collaborators in Europe, Japan, and China are being catalogued in a computer data base by Park Owen of ORNL's Biology Division.

According to Fred Mynatt, associate director for Nuclear and Engineering Technologies at ORNL, "The major impact in the United States of the Chernobyl accident thus far is that the startup of four newly completed light-water reactors has been delayed because of intensified state intervention on the grounds that emergency planning is inadequate. Other effects are that Congress is less inclined to continue cutting the NRC research budget and congressional advocates of advanced reactor development have become more supportive of the development of modular reactors having passive safety features. However, the lack of a sense of urgency for increasing U.S. capacity to generate electricity continues to postpone any real concern about advancing nuclear power."

Today the radioactive remains of the disabled reactor are entombed, and two of the four reactors at the Chernobyl complex are back in operation. These reactors are apparently badly needed to meet the Soviet Union's demand for electricity. ornl

SPECIAL SECTION:

The Chernobyl Accident: *Causes and Consequences*

By ANTHONY MALINAUSKAS, JOEL BUCHANAN, and RICHARD LORENZ

On April 26, 1986, an explosion occurred at the newest of four operating nuclear reactors at the Chernobyl complex in the Soviet Union. Its occurrence signaled the worst disaster in the world's nuclear industry. However, the accident also prompted an international technical exchange of almost unprecedented magnitude; this exchange culminated in a meeting at the International Atomic Energy Agency (IAEA) in Vienna during the week of August 25, 1986. The meeting was attended by more than 540 official

The control room of Chernobyl Reactor Unit 4.

representatives from 51 countries and 20 international organizations.

Information gleaned from that technical exchange is the subject of this article. We describe the Chernobyl reactor, which differs significantly from commercial U.S. reactors, present the accident scenario advanced by the Russian delegation, and discuss observations that we have made concerning fission product releases.

The Accident

At 1:24 a.m. on April 26, 1986, two explosions, one immediately following the other, signaled the beginning of the worst disaster in the commercial production of nuclear power worldwide. The accident occurred in the newest of four operating reactors at Chernobyl, which lies about 130 km (80 miles) north of Kiev. As of early January 1987, the accident reportedly caused 31 deaths, all involving site workers or members of emergency response crews, and hospitalized about 200 persons who showed symptoms of acute radiation syndrome. Economic losses are estimated at about $3 billion.

The disabled reactor, now entombed in concrete, was a boiling water reactor (BWR) cooled by light water and moderated by graphite; unlike BWRs in the West, it operated without an external steel-and-concrete containment dome. A description of the reactor's design is presented in the sidebar.

The course, cause, and consequences of the accident were described by a group of Soviet experts at a special Post-Accident Review Meeting, which was held August 25 through 29 at the IAEA in Vienna.

Causes of the Accident

The world's worst nuclear power plant accident resulted from a combination of factors: a poorly planned and executed experiment, a reactor that is difficult to control under slightly abnormal conditions, and inadvertent errors and deliberate violations of safety regulations by the reactor operators.

The purpose of the experiment that gave rise to the accident at the Chernobyl nuclear reactor was to determine the feasibility of supplying electrical power to selected reactor components from the mechanical inertia of a reactor turbogenerator during turbine coastdown. It was thought that the turbine's residual energy could be used to operate cooling-water pumps for a brief time in the event of a loss of electrical power at the site (a "station blackout"). Similar tests, conducted in 1982 and 1984, were unsuccessful because the generator output decreased much more rapidly than the inertial energy of the turbine rotor. The new test was designed to determine whether the rapid decline in output could be averted by changing the generator's voltage-regulation system.

At 1:00 a.m. on April 25, 1986, the reactor operators began to reduce the reactor power in preparation for a planned shutdown of the reactor for maintenance. At 1:05 p.m., when the 3200 MW(th)

The Chernobyl reactor accident prompted an international technical exchange of almost unprecedented magnitude; this exchange culminated in a meeting at the International Atomic Energy Agency in Vienna, Austria, during the week of August 25, 1986. This article summarizes information presented by the Soviets on the causes and consequences of the accident and discusses ORNL predictions, later verified, about the chemical conditions present during the two major releases of radioactivity from the stricken reactor.

The RBMK-1000 Reactor: A Look at Its Design Features

The stricken reactor, Unit 4, is one of four reactors that were operating at the Chernobyl site at the time of the accident. (Two additional reactors were under construction.) Each of these reactors is a graphite-moderated, water-cooled reactor of the RBMK-1000 design; each is capable of producing 1000 MW of electrical energy at full power.

The core of the Chernobyl-4 reactor is a vertical cylinder 11.8 m in diameter and 7 m high. It is formed from 2488 graphite blocks that measure 0.25 × 0.25 × 7 m. The massive graphite moderator weighs 1700 metric tons. The blocks are assembled into columns having axial cylindrical openings into which are inserted 1661 fuel channels and 211 channels that house the control rods of the control and protection system. The in-core portion of each fuel channel is made of a zirconium alloy containing 2.5% niobium; it is 88 mm in diameter and has a wall thickness of 4 mm. Outside the core, the zirconium alloy tubes are connected by a vacuum diffusion welding process to corrosion-resistant steel tubing. The control rod channels are similar in fabrication to the fuel channels but have a wall thickness of 3 mm.

Each fuel channel penetrating the graphite moderator contains a fuel assembly consisting of two 3.5-m-long subassemblies. The subassemblies, in turn, are composed of 18 fuel rods arranged in two concentric rings. The fuel rods consist of a stack of sintered uranium dioxide pellets, each 11.5 mm in diameter and 15 mm long, which are reactor was at 1600 MW(th)—50% of its rated power, one of the two turbogenerators was disconnected from the circuit and shut down. The electrical system was then rearranged so that electrical power for the reactor's own needs (including four of the six operating main circulation pumps used for cooling the reactor core) was being supplied by the turbogenerator to be used in the experiment. The plan was to conduct the experiment when the power level of the reactor had dropped to 700 to 1000 MW(th).

At 2:00 p.m., the operators shut off the reactor's emergency cooling system in accordance with the test program procedures. However, the reactor shutdown operations were then interrupted in response to a request to keep the reactor on the electrical grid. The reactor was thus permitted to supply power to

encased in a zirconium alloy tube containing 1% niobium; the tube is 0.825 mm thick and has an outer diameter of 13.6 mm. The individual fuel rods are welded in a helium atmosphere.

The core is cooled through two independent coolant circuits. In each circuit, cooling water is delivered to the bottoms of the fuel channels by three main circulating pumps (a fourth is in standby). The water enters the fuel channel at a temperature of about 270°C and flows upward through the fuel assembly, where it is heated to saturation temperature. In the final one-third of its transit through the channel, it is partially evaporated to a maximum steam content of 20%. The steam-water mixture exits the core at a temperature of 284°C and goes to one of two steam separators in the circuit. The steam is then transported to the appropriate turbine.

Condensate from the turbine is mixed with coolant in the steam separators, and this mixture is returned to the suction of the main circulating pumps. These pumps discharge into dispensing headers, which in turn feed batches of smaller piping that deliver the coolant to the fuel channels. A separate cooling system circulates water down through the control-rod channels; this system provides additional cooling for the graphite, which normally operates at a temperature of about 700°C.

The entire core is enclosed in a thin cylindrical steel vessel through which a helium-nitrogen gas mixture flows continuously; in this manner, heat transfer within the reactor vault is improved, and oxidation of the graphite by air is prevented.

The reactor vault is housed in a concrete pit, whereas other primary circuit components, such as the steam separators, main circulating pumps, and coolant-dispensing headers, are located in separate concrete chambers that surround the reactor. The base of the reactor building contains a two-tiered pressure-suppression system designed to mitigate the consequences of coolant-circuit-piping failures by condensing the resultant steam in a suppression pool.

At the time of the accident, the fuel of Chernobyl Reactor Unit 4 was enriched uranium (U) containing 2% fissionable ^{235}U. At this level of enrichment, the core reactivity responds positively to a decrease in the density of the water coolant—that is, a power surge can result from excessive boiling or loss of coolant. This "positive void coefficient" feature, which is not characteristic of commercial U.S. reactors, played a prominent role in the accident.

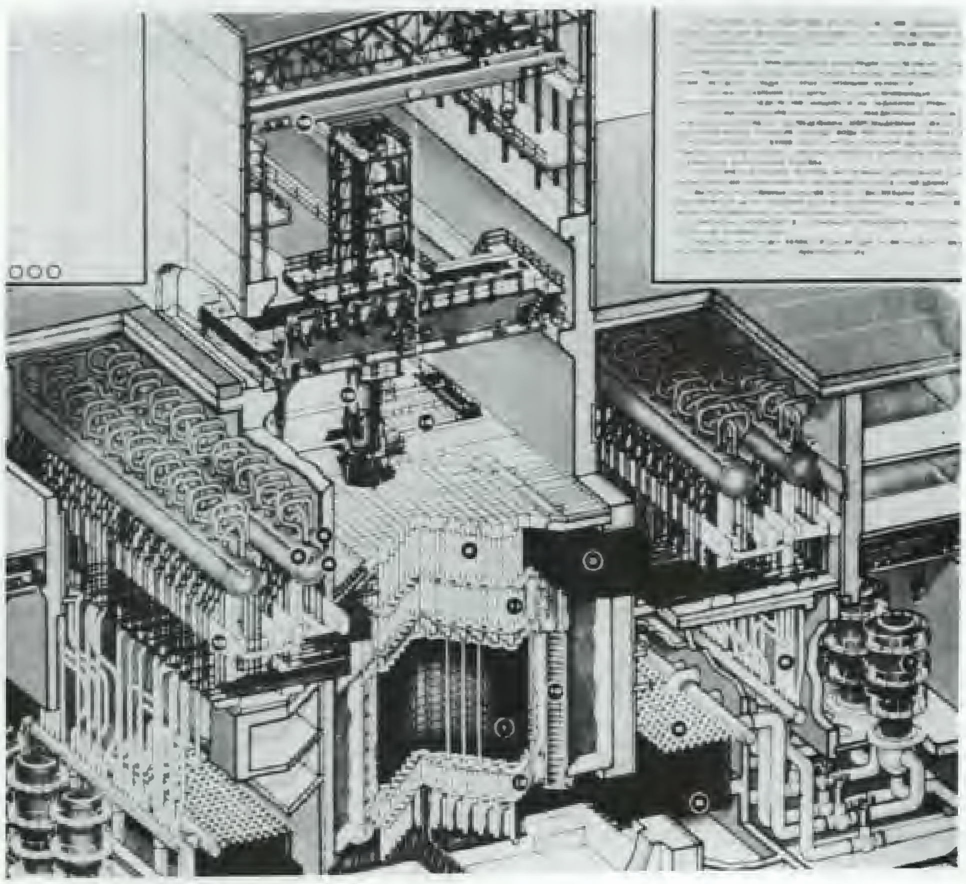
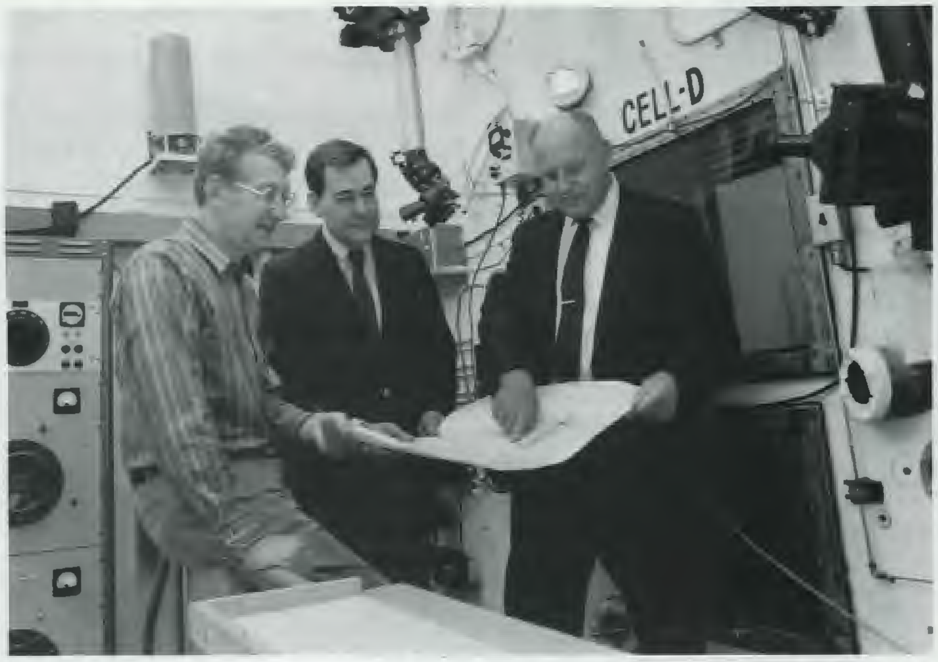


Diagram of RBMK-1000, a Chernobyl-type reactor.

the grid while its emergency cooling system remained inactivated—a clear violation of operating procedures.

The interruption in the power reduction operations had no immediate effect on the accident; however, it did result in a deviation from normal power reduction procedures, which ultimately caused a perturbation in the equilibrium of the fission product xenon. Xenon, a



Tony Malinauskas (right) is director of Nuclear Regulatory Commission (NRC) programs at ORNL. In 1985 he received the prestigious Ernest Orlando Lawrence Memorial Award from the Department of Energy for his outstanding contributions to the analysis of fission-product movement in light-water reactors. His studies helped explain why radioactive iodine releases from the Three Mile Island (TMI) reactor accident were smaller than expected. For this work in 1981, he also received an American Nuclear Society Special Award for Advancement in Nuclear Technology in Response to Three Mile Island. He has a Ph.D. degree in physical chemistry from the Massachusetts Institute of Technology. In 1962 he joined ORNL's research staff; from 1973 to 1983 he headed the Chemical Development Section of the Chemical Technology Division. He serves on the editorial board of *Separation Science and Technology* and is president of the Oak Ridge Chapter of Sigma Xi.

Joel R. Buchanan (center) is a section head in ORNL's Engineering Technology Division, where he is director of the Nuclear Operations Analysis Center (NOAC). His responsibilities include managing projects for the NRC involving the analysis and evaluation of nuclear reactor operations and safety. He received a B.S. degree in chemical engineering from Vanderbilt University in 1951 and a certificate from the Oak Ridge School of Reactor Technology in 1963. Buchanan came to ORNL in 1953 to help develop the aqueous homogeneous reactor concept and operate a test reactor. He joined the Engineering Technology Division in 1962 following a stint in the Materials Chemistry and Chemical Technology divisions. He was a founder of the Nuclear Safety Information Center in 1963 and the following year attended the Atoms for Peace Conference in Geneva, Switzerland. He has managed a number of reactor safety projects, and following the TMI accident, he was assigned to the Electric Power Research Institute in Palo Alto, California, to assist in analyzing the accident and establishing the industry's Nuclear Operations Analysis Center. He continues to edit the section on "General Safety Considerations" in *Nuclear Safety*—NOAC's journal.

Richard A. Lorenz (left) supervises the NRC's light-water reactor (LWR) severe-accident research programs conducted in the Chemical Development Section of ORNL's Chemical Technology Division. These activities include studies of fission product release from commercial irradiated fuel, iodine behavior in reactor containment, and aerosol deposition and resuspension. Lorenz came to ORNL in 1951 after receiving a B.S. degree in chemical engineering from Iowa State University. After conducting in-reactor corrosion studies for the Homogeneous Reactor Project, he began a career in 1960 in LWR reactor safety studies, including experiments on fission product release. He initiated the series of tests still used today for measuring fission product release from commercial irradiated LWR fuel. He has been the principal architect of a number of fission product release models. From his studies of the TMI-2 accident's fission product release, he provided core temperature estimates published in the *Report of the President's Commission on the Accident at Three Mile Island*. He also estimated the amount of krypton-85 remaining in TMI-2 fuel rods and modeled cesium release and transport in the primary system.

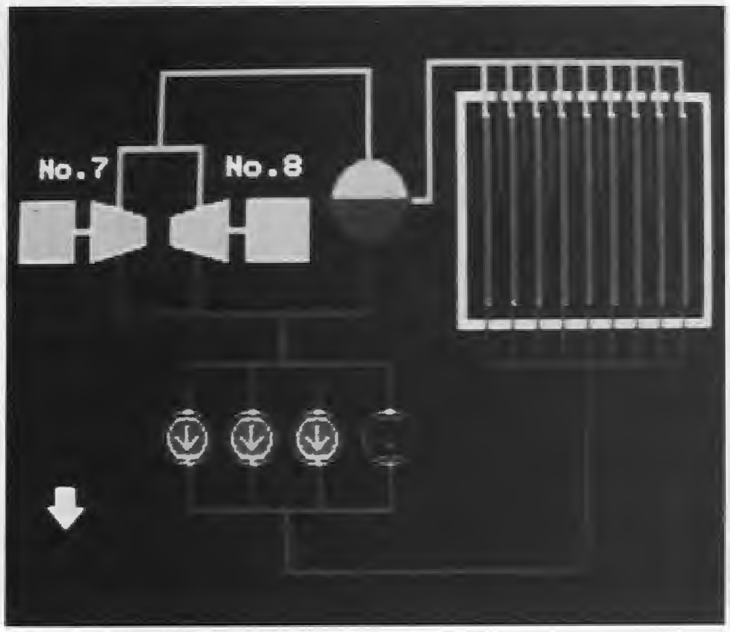
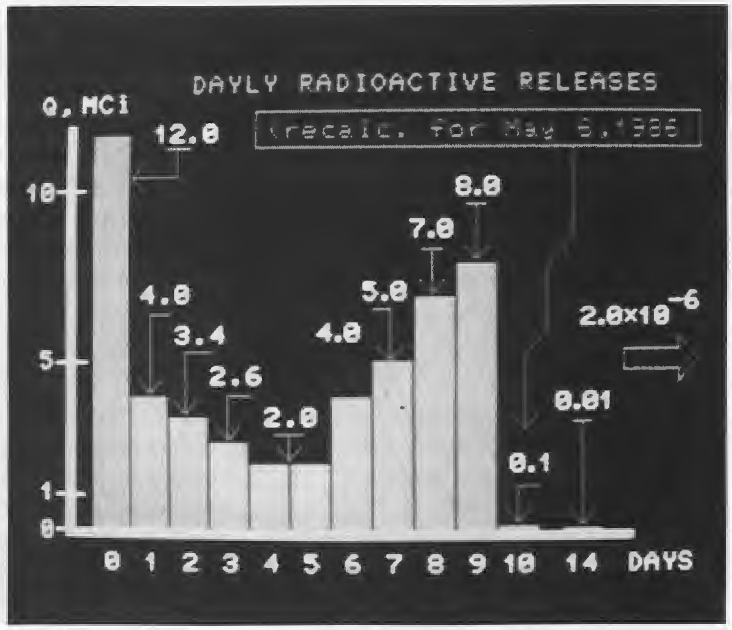


Diagram of the Chernobyl RBMK-1000 primary cooling circuit.



Soviet data for the radioactivity released as a function of days following the accident.

by-product of iodine decay, slows down the nuclear chain reaction, causing the power output to plummet. Because the power level dropped so quickly from 1600 to 30 MW(th) as a result of an operational error involving a required transfer from local to global power control, the excess xenon was not "burned out," or converted to other isotopes by absorption of neutrons. Because the reactor was poisoned by the xenon buildup, the operators pulled out all the control rods to stimulate fission. At 1:00 a.m. on April 26, they stabilized the reactor, but at a power level of only 200 MW(th), not the desired test level of 700 to 1000 MW(th).

By 1:07 a.m., two standby main circulation pumps were put into operation to support the experiment. At this point, two pumps in each circuit were being powered from the test turbogenerator and the remainder from another power source. Because the reactor power was considerably less than the level originally planned for the test, the hydraulic resistance of the core and piping was lower; as a result, when all eight circulation pumps were put into operation, some of the pumps were delivering water at flow rates exceeding permissible values—a further violation of operational procedures.

The increased flow of coolant through the core resulted in lowered reactivity and changes in pressure and water level in the steam separators. The operators tried manually to keep the pressure and water levels in the steam separators within the operational limits; when these efforts failed, they blocked the signals from the pressure and the water-level sensors to the automatic shutdown system to allow the experiment to proceed. As a result, an important part of the emergency shutdown system was inactivated.

During this time, the control rods were also being withdrawn to maintain reactivity in the core. At 1:22:30 a.m., the operators noted that the reactivity reserve margin was considerably less than the minimum permissible—that is, the core was approaching the dangerous state in which the reactor control system could no longer shut down the reactor quickly. This condition alone warranted immediate shutdown of the reactor but was ignored.

Just before the start of the experiment, the operators abruptly reduced the flow of makeup water to maintain steam pressure. This condition would eventually increase the reactivity in the core because of the positive void coefficient. [The positive void coefficient is a characteristic of the Chernobyl-type reactors that leads to an increase in the fission reaction rate and power output as the density of cooling water decreases (e.g., through loss of cooling water or excessive boiling). In most U.S. reactor designs, the loss of coolant has the opposite effect of quenching the fission reaction and reducing the power output.]

The operators also disarmed the control system that would have triggered an automatic shutdown when the steam supply to the test turbogenerator was stopped. The operators committed this violation to avert a reactor shutdown to allow another attempt at the experiment.

Finally, at 1:23:04 a.m., the operators shut off the steam supply to the turbogenerator, and the coastdown began. The system steam pressure began to rise because the coolant flow was decreasing as power to the four pumps being fed by the test turbogenerator decreased as the generator ran down. Thus, the operators had to cope with too little cooling water—just the opposite of the problem they had earlier.

As a result, a small increase in reactor power produced a higher rate of boiling and formed larger voids than would be expected from an equivalent change during normal operation. In addition, because of the positive void coefficient, a power surge occurred. Since the control rods were almost completely withdrawn, a runaway condition existed. To deal with a reactor out of control, the operators tried to shut down the nuclear reactions by reinserting all control rods into the core at 1:23:40 a.m., but the response came too late. At about 1:24 a.m., two explosions were heard, one after the other, and fragments of burning material shot into the air above the reactor building.

Two possible causes of the explosions have been proposed. First, the initial explosion is thought to have resulted from simple rapid overpressurization of the coolant system because of the coolant-power mismatch followed by fragmentation of the fuel and its rapid ejection into whatever coolant remained. The second explosion—a steam explosion—then resulted from the interaction of the hot fuel with the water coolant.

According to the second hypothesis, fuel fragmentation and the resultant fuel-coolant interaction were responsible for the initial explosion, which tore the core apart. The second explosion then resulted from the detonation of the hydrogen formed from the reaction of the zirconium alloy with steam (which had been mixed with air in the reactor building during the first explosion). The explosions, regardless of their nature, caused the initial releases of radioactivity to occur at a high elevation rather than at ground level. Unfortunately, the explosions also destroyed all systems designed to cool the disrupted core.

Consequences of the Accident

As a result of the accident, the massive graphite moderator began to burn, and the hot radioactive material released from the reactor caused 30 fires. For five days, materials were dropped from military helicopters on the exposed core. The materials included boron compounds (to prevent recriticality), dolomite (to produce carbon dioxide as it heated, thus keeping oxygen away from the burning graphite), lead (to provide shielding), and sand and clay (to act as a filter for the aerosols and fission products). On May 2, the graphite fire was extinguished.

After the initial release of radioactivity on April 26, the rate of release of fission products gradually decreased and, between April 30 and May 1, appeared to level off at about one-sixth the rate measured on the day of the accident. However, on May 2, an increase in fission-product release began to occur, reaching a peak on May 5 that was believed to equal about 75% of the April 26 release. (The Soviet scientists corrected their results for radioactive decay using May 6 as the basis. Thus, the amount of radioactive material actually released on May 5 was considerably less than 75% of the April 26 release.) On May 6, after injecting nitrogen into the space beneath the reactor, the Soviet scientists greatly reduced the rate of escape of fission products into the environment. On May 23, the release rate was estimated to be about 20 curies (Ci) per day.

At ORNL we studied the distribution of fission products in samples of the radioactive fallout in Scandinavia and Western Europe. From this analysis (conducted with the help of George Parker of the Chemical Technology Division), we concluded that the initial release, which was transported to Scandinavia, showed that the fuel had fragmented under chemically reducing conditions. The fallout over Western Europe, however, which was characteristic of fission product releases from Chernobyl about April 28, had unusually high concentrations of the fission products ruthenium, molybdenum, and tellurium. In addition, particulates that were released after the initial event were found to contain the fission products zirconium, niobium, and neodymium in much lower concentrations than in the material released during the first day of the accident. This altered distribution suggested the chemical environment had changed to oxidizing conditions (as evidenced by the burning graphite).

The Soviets estimated that about 3% of the fuel inventory (and its associated fission products) had been released into the environment. In addition, releases of the entire inventories of the noble gases (krypton and xenon) were believed to have occurred, along with 10 to 20% of the inventories of the moderately volatile fission products—iodine (I), cesium (Cs), and tellurium (Te).

The estimate of 100% release of the noble gas inventory is not consistent with the release of only about 20% of the I and Cs nuclides (unless we are seriously underestimating the effects of "natural processes" in attenuating the source terms for these species). ORNL's studies of fission product release from overheated fuel indicate that the fractions of noble gases, I, and Cs released under severe core damage conditions should be identical. Thus, either only about 20% of the noble gas inventories were actually released during the accident at Chernobyl, or the entire inventories of the Cs and I fission products were also released from the core, with about four-fifths of these amounts being retained on surfaces within the destroyed reactor building. The former possibility appears to be more probable.

As a result of the Chernobyl accident, some 7 million Ci of ^{131}I (decay corrected to May 6, 1986) and, more significantly, about 1.5 million Ci of ^{134}Cs and ^{137}Cs were estimated to have been released into the environment. By contrast, the Three Mile Island (TMI) accident released only about 15 Ci of ^{131}I and no detectable releases of radioactive cesium. At TMI, the escape pathway for fission products was intercepted by water, and significant delay processes existed because the containment remained intact; at Chernobyl, the explosions within the core and possibly within the containment building resulted in the escape of fission products from the core directly into the biosphere. Because of the long half-lives of the cesium isotopes (two years for ^{134}Cs and 30 years for ^{137}Cs), the extent to which these fission products can be extracted from or stabilized in the environment will determine the habitability of the area around the Chernobyl complex.

Conclusion

Not uncharacteristically, details concerning the Chernobyl accident were slow to be released by the Soviets. Indeed, the first indication to the West of an accident involving a Soviet nuclear reactor was released by Swedish experts following detection of radioactive fallout over Scandinavia almost two days after the actual event. The continued lack of information from knowledgeable sources prompted rampant speculation about the nature of the accident, its consequences, and the status of the reactor site. No doubt some of the speculation would have been unnecessary had the Russian technical community responded promptly by providing information as it became available.

On the other hand, and in a move that appears to have no parallel in modern history, the Soviet government agreed to present its study of the causes and consequences of the Chernobyl accident to the international community through the IAEA and to subject its experts to questioning by their international colleagues. (By contrast, although two major investigations of a similar nature were made of the Three Mile Island accident, neither of these, *The Report of the President's Commission* and the *Report of the Nuclear Regulatory Commission's Special Inquiry Group*, had been submitted in as formal a way to the international community.) The meeting of the IAEA highlighted the need for broad technical exchanges concerning nuclear reactor safety, accident response, and radioactivity decontamination.

Radioactivity from the Chernobyl accident was detected around the world. In this sense, the Chernobyl fallout, like acid rain resulting from the production of electrical energy from fossil fuels, reminds us that communities of the world are interrelated—that is, the actions of one community affect communities far away. The consequences of sophisticated technological advances have given new meaning to the words penned over 350 years ago by John Donne:

"No man is an island, entire of itself; every man is a piece of the continent, a part of the main; if a clod be washed away by the sea, Europe is the less, as well as if a promontory were, as well as if a manor of thy friends or of thine own were; any man's death diminishes me, because I am involved in mankind; and therefore never send to know for whom the bell tolls; it tolls for thee." - Devotions XVII (1624) ornl

Shield covers on top of the core and the refueling machine in the background at the damaged Chernobyl reactor.

BOOKS

Our Radiant World, By *David W. Lillie, Iowa State University Press, Ames, Iowa (1986), 215 pp. Reviewed by Carolyn Krause,* Review *editor.*

Fear of radiation is about as pervasive as radiation these days. One way to alleviate that fear is to appeal to reason by putting radiation and its sources, including nuclear power, into perspective. David W. Lillie, an independent energy consultant and author, does just that.

Lillie, who worked for 25 years as a staff scientist for General Electric Research and Development Center in Schenectady, New York, and later for the U.S. Atomic Energy Commission in Washington, D.C., speaks eloquently to the general reader about a variety of risks. Writes he: "Almost all parts of the spectrum can be useful to us, and some parts are essential. Similarly almost all parts in too great intensity can be harmful: bright light can cause blindness, thermal radiation can burn, and gamma rays and X rays at high levels can do serious biological damage."

His discussions of nuclear power and reactor accidents are forthright and understandable. However, according to Tony Malinauskas, director of Nuclear Regulatory Commission programs at ORNL, Lillie's views about the Three Mile Island (TMI) accident are partly in error.

According to Lillie, the TMI accident "has shown that fuel disintegration short of melting but induced by reaction with steam at very high temperatures can also release substantial quantities of radioactivity."

Says Malinauskas, "Lillie incorrectly infers little fuel melting in the TMI accident. A substantial part of the core was severely degraded and a fairly significant fraction was molten during the course of the accident. This finding is consistent with the estimates of relatively large releases of fission products (~60% of the noble-gas and cesium nuclides) that were made immediately after the accident.

Lillie writes that new studies indicate that the number of deaths for a worst possible accident would range from 0 to 330 (not 3300 as predicted in Norman Rasmussen's report). He defines a worst possible accident as a low-probability case, believed to occur only once every million years in a world of 1000 reactors. (This part of the book was written before the Chernobyl reactor accident, which has resulted in 31 deaths to date.)

To put the reactor risks in perspective, Lillie makes these observations:

"In the past 100 years the greatest single man-made accident was the methyl isocyanate gas leak on December 3, 1984, in Bhopal, India, where it is estimated that over 2000 were killed and 200,000 made ill. Even those who apparently recovered may suffer life-shortening side effects. The failure of a dam in Johnstown, Pennsylvania, in 1889 cost about 2000 lives; the explosion of a French munitions ship in the harbor at Halifax, Nova Scotia, in 1917 killed over 1600 people; the sinking of the *Titanic* in 1912 cost 1500 lives; and automobiles kill about 55,000 people every year in the United States alone."

"For additional perspective we need to look at the magnitude of natural disasters over which man has no control. Six thousand people died in the Galveston hurricane in 1900, and in the period 1900–1972, 12,577 deaths in total were attributed to hurricanes. The San Francisco earthquake killed about 750 people in 1906, falls kill 18,000 people per year, and there is always the possibility of a major meteorite striking a large city.

"Adding this all up we conclude that the consequences of a worst possible nuclear accident, while severe, are less than those of other natural or man-made catastrophes that have been or will be experienced. . . We need to focus all our technical expertise on ensuring the safety of nuclear plants, but we do not need to abandon the benefits of nuclear power because of the risks inherent in the reactors themselves."

Lillie also provides an afterword on the Chernobyl accident, which occurred on April 26, 1986; unfortunately it was written on May 26, several months before the Soviet report came out. But, according to Malinauskas, "Lillie correctly captured the more plausible speculations concerning the cause of the Chernobyl accident when the addendum was written. He correctly notes that, if a hydrogen explosion did occur, it had to take place in the reactor building, not within the core itself.

"Lillie was not too far afield in postulating a reactivity excursion or a power-cooling mismatch as the initiating event. We now know that the accident began as a reactivity transient, caused in part by the insertion of control rods, not their sudden withdrawal, as he surmises. Like everyone else at the time, he failed to grasp the significance of the positive void coefficient, a characteristic of the Chernobyl-type reactors. Similarly, he overstated the health effects that would probably result. However, Lillie was right on the mark in his assessment of the situation at the time of the accident and of its aftermath."

Readers may be confused by Lillie's statement on page 51 that

"New isotope separation plants will use gas centrifuge technology instead of gaseous diffusion." That may be the case in Europe or if private industry takes over uranium enrichment in the United States; but under current plans, if the U.S. government decides to use advanced enrichment technology, it has already selected the atomic vapor laser isotope separation, or AVLIS, technology, not the advanced gas centrifuge approach.

Lillie's book is especially appealing to the lay reader because he demonstrates the value of radiation (medical diagnosis and treatment, for example) and describes ways to protect against hazardous levels. He tells us how to guard against possible radiation releases from television sets and microwave ovens and advises us to use adequate ventilation to keep indoor radon at safe levels.

In his chapter on nuclear arsenals, he urges citizens to learn about the effects of nuclear weapons so they can protect themselves if a war occurs. He advises readers to peruse *The Effects of Nuclear Weapons* by Samuel Glasstone (who was an Oak Ridge resident at the time of his death in 1986) and obtain and learn to use a radiation detection instrument.

Oak Ridgers should be interested in Lillie's observations about the Oak Ridge Y-12 Plant radiation accident in 1958. In this incident, eight men received substantial doses of neutrons and gamma rays after inadvertently adding enriched uranium to a drum, creating a critical mass. Lillie reports that psychological and follow-up physical examinations revealed that "fear of radiation effects may have caused more long-term harm than the radiation itself, a point important to all of us."

So, what is the bottom line? Should we worry about all the low-level ionizing radiation around us, from cosmic rays to dental X rays to radiation from high-voltage lines, decaying uranium in soil and building materials, and nuclear power plants? Lillie concludes that genetic effects from radiation are not a major concern. But he adds that a definite link exists between low levels of radiation and the induction of cancer. Then he puts this statement into perspective. "The effect is small," he writes, "and is of lesser consequences than that from many other causes such as carcinogenic chemicals, variations in body chemistry, possible viruses, and other as yet unidentified initiators."

In a world where fear of radiation seems much more prevalent than understanding, *Our Radiant World* makes an important contribution. Its greatest value is that it puts to rest needless fears by making its readers "radiation literate."

Books in Print

The following books were written or edited by ORNL staff members (whose names are in boldface).

Positive Feedback in Natural Systems, by **D. L. DeAngelis**, **W. M. Post**, and **C. C. Travis**, Springer-Verlag, Berlin, Federal Republic of Germany, 1986.

A Hierarchical Concept of Ecosystems, by **R. V. O'Neill**, **D. L. DeAngelis**, J. B. Wade, T. F. H. Allen, Princeton University Press, Princeton, New Jersey, 1986.

Hypercube Multiprocessors 1986, ed. **Michael T. Heath**, Proceedings of the First Conference on Hypercube Multiprocessors, Society for Industrial and Applied Mathematics, Philadelphia, 1986.

Analytical Chemistry Instrumentation, ed. **W. R. Laing**, Proceedings of the Conference on Analytical Chemistry in Energy Technology, Lewis Publishers, Chelsea, Michigan, 1986

Boundary Value Problems in Abstract Kinetic Theory by W. Greenberg, C. van der Mee, and **V. Protopopescu**, Birkhauser-Verlag, Basel, Switzerland, 1987.

Acid Deposition and the Acidification of Soils and Waters, by **J. O. Reuss** and **D. W. Johnson**, Springer-Verlag, New York, 1986.

Atoms, Radiation, and Radiation Protection, by **James E. Turner**, Pergamon Press, Elmsford, New York, 1986.

Impacts of Hazardous Technology: The Psycho-social Effects of Restarting TMI-1, by **John Sorensen**, **Jon Soderstrom**, **Emily Copenhaver**, **Sam Carnes**, and Robert Bolin, State University of New York Press, New York, 1986.

The Changing Carbon Cycle: A Global Analysis, ed. **John R. Trabalka** and **David E. Reichle**, Springer-Verlag, New York, 1986.

Atmospheric Carbon Dioxide and the Global Carbon Cycle, ed. **John Trabalka**, U.S. Department of Energy, Washington, D.C., 1985.

SPECIAL SECTION:

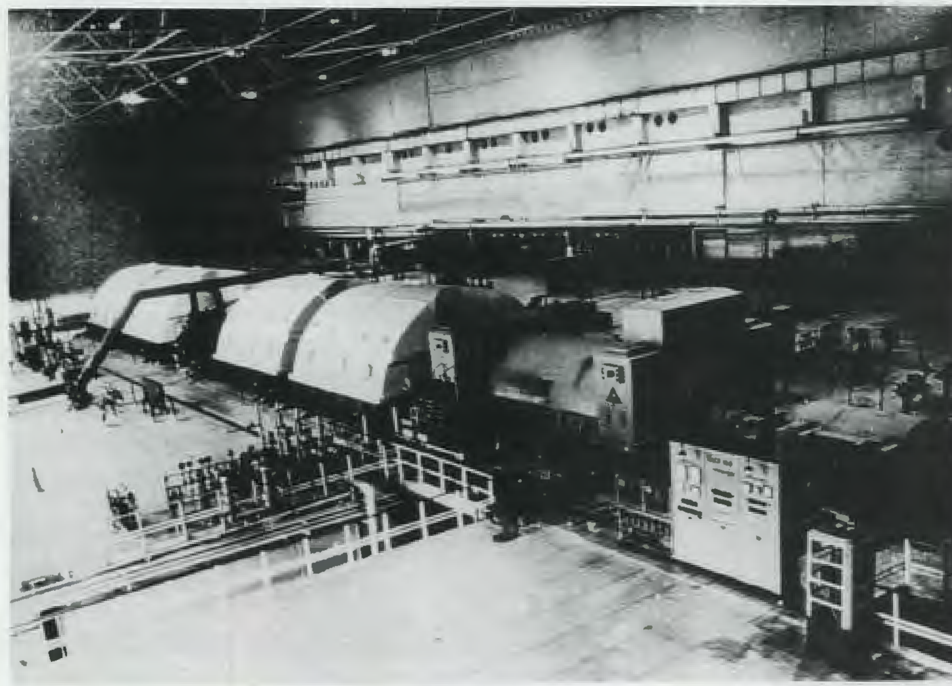
Chernobyl from a Vienna Perspective: *The Soviet View of the Accident*

By THOMAS S. KRESS

When I received a call from a member of the International Nuclear Safety Advisory Group asking if I would be willing to serve as an expert consultant to the International Atomic Energy Agency (IAEA) at the August 1986 meeting in Vienna on the Chernobyl reactor accident, it took me about a microsecond to say yes. The first step was to embark on an intense personal crash course on the accident and the RBMK type of reactor at the Chernobyl complex. The information about reactor characteristics and design that I was able to obtain before the meeting was of much value, but news reports, including rumors about the nature of the accident and its causes, proved to be almost no help at all.

The much anticipated Soviet report on the accident finally arrived at the Department of Energy Headquarters about a week before the Vienna meeting, scheduled for August 25–29. The DOE staff in charge of coordinating the U.S. effort called in a team of translators, who completed an English version of the 400-page report over the weekend for a hastily called review meeting that took place over the next three days.

I was, of course, elated to have the chance to study the Soviet report a whole week in advance of the Vienna meeting. The report was very thorough and detailed. However, because of subtleties in language that sometimes do not come across accurately in translations, the report contained a number of ambiguous and unclear passages. It also contained some astonishingly resounding and dramatic passages such as the following one describing the excursion itself:



The experiment was conducted on turbogenerator No. 8, shown here.

"Shortly after the beginning of the experiment, the reactor power began to rise slowly. At 1:23:40, the unit shift foreman gave the order to press button AZ-5, which would send all control and scram rods into the core. The rods fell, but after a

The Chernobyl reactor accident resulted from a combination of elements: an experiment conducted without authorization and without an adequate safety review, severe violations of operating and test procedures, and operator errors. All of these elements interacted with the particular design characteristics of the RBMK reactor—notably the positive void coefficient, a slow and ineffective emergency control system, and the ineffectiveness of the containment—to a catastrophic end.

View of Reactor Units 3 and 4 at the Chernobyl complex. The accident occurred at Unit 4.

few seconds, a number of shocks were felt, and the operator saw that the absorber rods had halted without plunging fully to the lower stops. He then cut off the current to the sleeves of the servo drives so that the rods would fall into the core under their own weight. According to observers outside Unit 4, at about 1:24 there occurred two explosions one after the other; burning lumps of material and sparks shot into the air above the reactor, some of which fell onto the roof of the machine room and started a fire."

The problems of language, as well as the complexity of the RBMK reactor and the Chernobyl accident, evoked a number of questions. In fact, after the remarkably open and candid presentations by the Soviet team at the Vienna meeting, written questions were solicited from the more than 500 international nuclear safety experts in attendance, and more than 400 such questions were received. In addition, the filled-to-capacity press conferences that followed each day's meetings could easily have continued late into the night had the chairman not insisted on closing the sessions.

Personally, I gained considerable respect for both the tenacity and the competence of the news media representatives. In particular, one newsman was so determined to "get the story right" that on three separate occasions he spent at least three additional hours at a restaurant with me and another technical expert learning all he could about nuclear reactors and the accident itself. During those three night sessions, he received the basics of a senior-level course on reactor physics focused on the RBMK type of reactor.

Reactor Flaws

The Chernobyl RBMK-1000 reactor has what I would consider to be at least three major design deficiencies: (1) a weak and ineffective containment, (2) a positive void coefficient of reactivity, and (3) neutronic stability and control problems at low power and a relatively slow-acting shutdown system.

The reactor, however, has a degree of containment. It has a number of separate volumes housing the major parts of the primary system; these volumes have one-way valves, allowing some pressure relief between volumes. The various steam relief lines eventually vent into a two-layer pressure-suppression pool, which condenses the steam. The "weak-link" in this confinement system is the steel shell housing the reactor space itself. This region has a maximum design pressure of only 27 psia (by contrast, a BWR Mark I drywell has a design pressure of about 70 psia). In addition, the volume and vent rate from this reactor space is intended to compensate for the water and steam blowdown from a complete failure of only one of the pressure tubes into that region.

The neutronic characteristic of the RBMK reactor that has evoked the most comment and concern is

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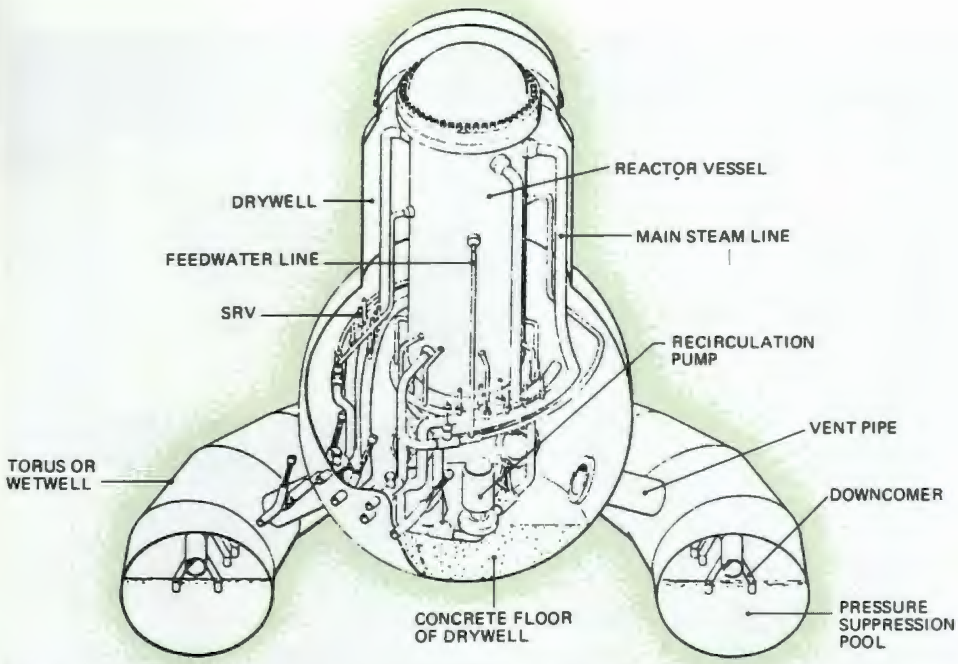
its positive void coefficient: as coolant boiling increases and the average void in the core increases, reactor power also increases—just the opposite of the power response in reactors in the West. If the increase in reactor power is not offset by other effects and if the increase leads to additional voiding, then the system is unstable and can progress to a runaway condition. The effect of the positive void coefficient is small at full power but becomes greater at low power. Because of this characteristic (and because of other thermal-hydraulic and control difficulties), the operating procedures for the RBMK reactors do not permit "continuous" operation of the reactor at power levels below 700 MW(th).

The Experiment and Operator Errors

Ironically, the accident occurred as the Soviets were attempting to conduct a safety-related experiment while the reactor was being shut down for routine maintenance. The experiment was designed to test a voltage-regulating scheme on the turbogenerator unit that would make use of the energy from the generator as the unit was coasting down. This source of power could be used in an emergency if off-site power were inadvertently lost (station blackout). This short-lived power was to be used to drive an emergency feedwater pump in one part of the emergency core-cooling system just long enough (45 to 50 s according to the Soviet report) for the emergency diesels to start up and supply the needed power. The test was to be conducted while the reactor operated at a power level just above its minimum permissible continuous-operation level [700 MW(th)] to allow the test to be repeated if the first attempt proved unsatisfactory.

As noted by the Soviet report, while cooling down the reactor to the test target level of 700 to 1000 MW(th), an "operator error" occurred—that is, the operators failed to make the necessary control adjustments that would have stopped and held the reactor at the target level. Soviet experts speculated that this error could have resulted because the operators were anxious to start the experiment after a 9-h delay at the 600-MW(th) level. The delay occurred because the electrical dispatcher ordered them to continue producing electricity. Consequently, after being given approval to continue with the experiment, the operators brought the power level down much faster than called for by the test procedure. Whether this faster "ramp" contributed to the operator error is unclear, but it is clear that after the power fell much lower



Schematic of a U.S. boiling-water reactor (Mark I) showing its containment systems.

than intended—down to 30 MW(th)—the fast ramp was instrumental in catching the reactor in the "xenon trap."

The fission and decay product, xenon, is a strong neutron absorber, or poison, which can have a strong effect on the neutron balance in the core. At any steady-state power, the xenon level is mostly kept in balance by the decay of the fission product iodine into xenon and the conversion ("burning out") of xenon into other isotopes by the absorption of neutrons. The reactor had been producing electricity for 9 h at 1600 MW(th), and the xenon had achieved equilibrium at that power. Because of the rapidity of the subsequent down ramp, not enough time and neutrons were available to burn out significant amounts of the xenon.

Consequently, when the reactor reached 30 MW(th), the xenon was initially at its 1600 MW(th) equilibrium value. The xenon content then rapidly increased because of the decay of iodine, which also was at its 1600-MW(th) equilibrium level. The buildup of xenon "poisoned" the reactor, dampening fission reactions. As a result, the operators were not able to return to the desired test level of 1000 MW(th). Even after all control rods were pulled out of the core, the reactor returned to only 200 MW(th).

Had the operators been able to set the power originally at the desired 1000 MW(th) level, in all likelihood the experiment would have been successfully conducted as it had been in a previous attempt. At the low power level, however, and because of the control rod configuration that resulted from actions to stabilize the power, system pressure, and steam drum water level, the positive void coefficient became the dominant influence over the reactivity. In addition, the high coolant flow (called for by the test procedure before coasting down the generator powering four of the eight operating main recirculating pumps) had rendered the reactor coolant almost uniformly saturated throughout the core. The system was operating on a steep part of the void-fraction vs steam quality curve—that is, a small increase in power would yield a relatively large increase in void, thus adding significant reactivity to the core.

Under this configuration, the accident was just waiting to happen. The instant the switch was thrown to start the coastdown experiment, the subsequent voiding and power excursion were inevitable. Once the power increase reached a level at which the operators were concerned enough to push the scram button, the rate of increase in power (and neutron flux) was too fast to be compensated for by the slow-moving emergency control rods.

Motives for Operator Action

Because of the conditions in which the operators had placed the reactor just prior to the experiment, continuing with reactor operation and with the experiment was a major violation of procedures. The question is, why did the operators do so? The Soviet delegation offered three explanations:

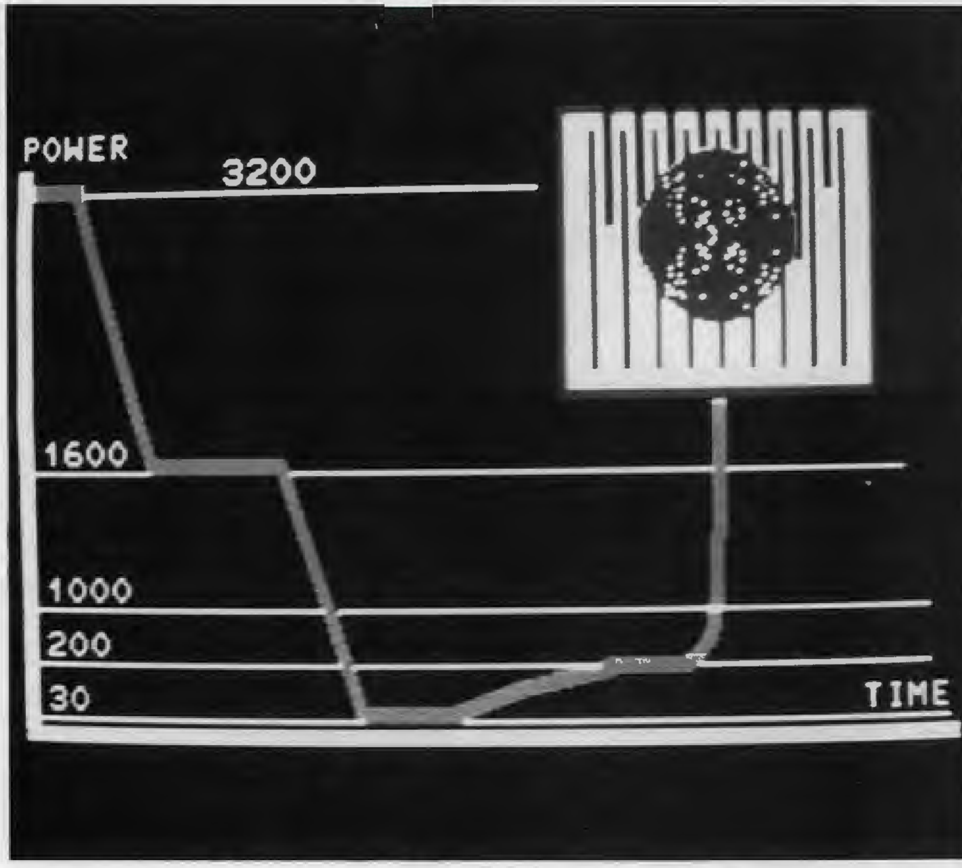
- The power level at which the operators found the reactor was prohibited by operating procedures. Because the operators had not been trained under these conditions, they may not have been aware of the extreme danger of their actions.
- The successful development of the voltage-regulating scheme was a high priority for the test personnel. If they did not complete the test during this scheduled shutdown for maintenance, they would have to wait a year for another opportunity for such a test. The operators were perhaps serving two masters. One chain of command was interested in completing the test expeditiously, while the other focused on reactor safety. At this time, the operators may not have given highest priority to safety because of the pressure they felt to make the experiment succeed.

• The Chernobyl staff and operating crew had the best operating and safety record of any of the RBMK reactor plants. This success might have made the operators complacent, overconfident, and a little too willing to take risks.

In summary, the accident itself can be technically classified as a "voiding-induced, super-prompt critical excursion," which drove a steam explosion that breached the primary system into a region of the confinement system that was so weak it could not rightly be called a containment. The subsequent ignition and burning of the graphite moderator served to extend and exacerbate the releases. The accident resulted from a combination of elements: an experiment conducted without authorization and without an adequate safety review, severe violations of operating and test procedures, and operator errors. All of these elements interacted with the particular design characteristics of the RBMK reactor—notably the positive void coefficient, the slow and ineffective (in this case) emergency control system, and the ineffectiveness of the containment—to a catastrophic end.

The Radioactivity Releases

From the standpoint of source terms (relative amounts and types of fission products available for escape to the environment from a reactor during a severe accident), the Chernobyl accident can be considered representative of the "worst" case. Yet only 31 people died and 203 persons were hospitalized. These numbers were lower than most experts anticipated, largely because of the competent, heroic, and effective accident management and emergency response measures taken by the Soviets to extinguish the various fires, limit the releases, stabilize the core debris, protect the surrounding populace, and treat those exposed.



Soviet photograph showing the reactor power vs time when the power level fell far below the intended level to 30 MW(th), the stabilization of the power at 200 MW, and the accident excursion.

The number of additional future cancers is uncertain and is the subject of much debate. An estimate from the Vienna meeting sets the increase at about 0.6% over the normal incidence rate in the 30-km area around Chernobyl and <0.15% in the rest of the European part of the Soviet Union. Epidemiological studies may never be able to detect these low levels of increase in the normal cancer incidence rate. Why were the consequences not as bad as would have been predicted for a release of this magnitude? With the exception of Kiev (1.6 million people located about 120 km southeast of Chernobyl), the reactor is situated in a region of low population density. Furthermore, the early lofting of the plume and the wind direction spared Kiev and the nearby town of Pripyat (population of 49,000) from the initial release.

What implications does the Chernobyl accident have for U.S. nuclear safety? Many obvious ones are related to human factors, human-machine interfaces, accident management, and emergency response. But I believe the Chernobyl accident shows the importance of designing new "forgiving" systems—reactors having inherent passive safety features that cannot be defeated by either unintentional or deliberate actions. ornl

SPECIAL SECTION:

Dynamic Analysis of the Chernobyl Accident

By LESTER C. OAKES

In July 1986, the Department of Energy asked Oak Ridge National Laboratory to assemble a team to model the various systems of the Chernobyl reactor. The purpose of constructing a detailed model was to better understand the causes, course, and consequences of the accident. DOE asked ORNL to select researchers from the various national laboratories who could perform dynamic analysis of reactor systems. The team, which was assembled in late July, had two short-term goals: (1) to assist in the preparation of the *Factual Report*, a source book for the U.S. delegation to the International Atomic Energy Agency (IAEA) meeting held in August 1986 in Vienna, Austria, and (2) to answer specific questions that might be raised by the delegates or their assistants before or during the Vienna meeting at which the Soviet report on the accident was made. The team is still working on meeting its long-term goal: to provide a better understanding of the Chernobyl accident, thus helping to assess the impact of the event.

Lester C. Oakes is associate director of ORNL's Instrumentation and Controls (I&C) Division and head of the division's Reactor Systems Section. A native of Knoxville, he has a master's degree in electrical engineering from the University of Tennessee at Knoxville. He joined ORNL in 1951 after working for Fairchild Engine & Aircraft Company. In 1979 he was assigned to the Electric Power Research Institute for about a year to assist in the evaluation of the Three Mile Island reactor accident. His research interests include automating large-scale reactor systems using state-of-the-art digital control technology and artificial intelligence. He is a Fellow of the Institute of Electrical and Electronics Engineers and, in 1987, was named Corporate Fellow of Martin Marietta Energy Systems, Inc.

Steam-Line Break Hypothesized

In July a team composed of staff members of ORNL, Argonne National Laboratory (ANL). Brookhaven National Laboratory (BNL), and Pacific Northwest Laboratory (PNL), met with the authors of the accident analysis chapter of the *Factual Report*. At this meeting (which occurred before the Soviet account of the accident was published), participants wanted to analyze hypothetical accident initiators. At that time, the most likely initiator was thought to be a break in the steam line leading from the main header to the steam drum. To analyze possible initiators of the accident quickly, ORNL researchers developed CRAS-1, a computer code that incorporated Chernobyl parameters. BNL used the same parameters in its existing MINET program. ANL assessed plausible core energetic events, and PNL supplied the parameters from which the analyses were performed. ORNL staff members doing the analysis were Mike Harrington, Syd Ball, and Ray Booth.

Translation difficulties and unavailability of information rendered some of the parameters more uncertain than we would have liked. In particular, the value of the positive void coefficient of reactivity was uncertain because it varies with coolant density and control rod positions as well as with the fractional burnup of the fuel (depletion of fissionable material). Another parameter for which slight uncertainties can make a large change in the understanding of the course of the accident is the effective fraction of delayed neutrons, which depends, among other things, on the fuel burnup.

The team members tried to understand the accident and the effect of these uncertainties by conducting sensitivity studies—that is, by varying those parameters and operating conditions that were not well known but could change the predicted accident severity. The analyses performed by the team show that a main steam line break could have initiated the accident.

Shortly after these analyses were completed, the Soviets released their report on the accident, and the U.S. modeling team was asked to duplicate the scenario using mathematical modeling techniques. Fortunately, the work previously carried out on the main steam-line break enabled the team to complete the analysis in time for the August IAEA meeting in Vienna. The CRAS-1 and MINET runs are shown in Figs. 1 and 2, respectively. The Soviets released the results of their analysis (Fig. 3) at the meeting. The CRAS-1 and MINET analyses yielded very similar results on all parameters analyzed in the

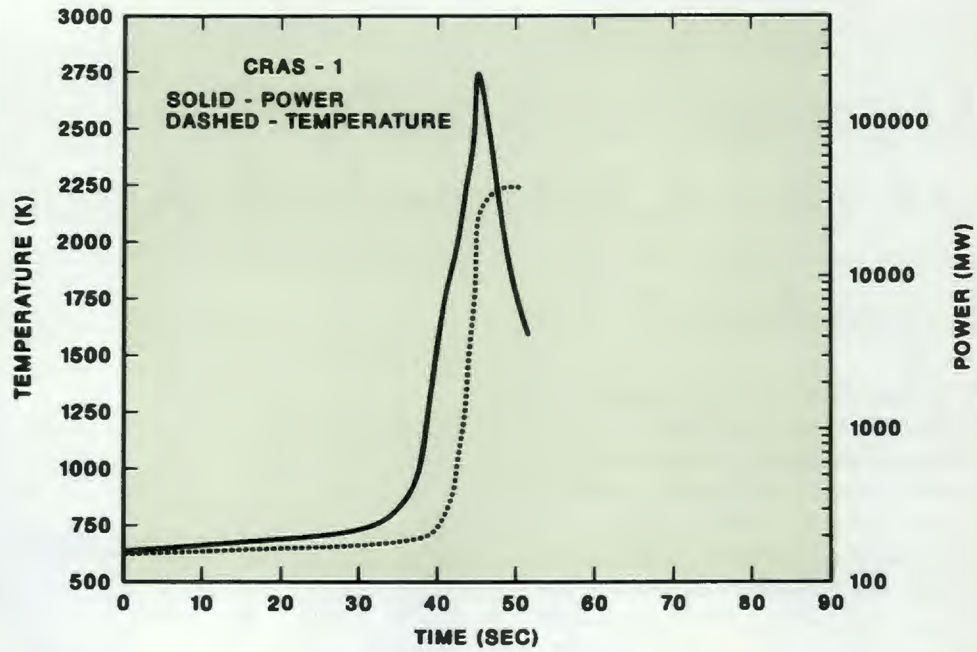


Fig. 1. Results of the ORNL analysis of the Chernobyl accident.

accident, giving us confidence that our models were reasonably accurate. These U.S. results were also very close to the Soviet results. The next short-range goal of the team is to assess the safety improvements that the Soviets announced they would make at reactors of the same type as the disabled one at Chernobyl.

Scenario of the Accident

On the basis of the analyses, the team developed the following scenario to explain the course of the Chernobyl reactor accident. Although this amounts to second-guessing the Soviets, they too are probably having difficulty in reconstructing the accident. Similarly, eight years after the 1979 reactor accident at Three Mile Island, details of the events are not all that well understood.

The Chernobyl accident followed the course shown in Figs. 1 through 3 for about the first 40 s into the accident. When the operators saw the power beginning to increase, they attempted to shut down the

In July 1986, ORNL assembled a team from several DOE laboratories to model the various systems of the Chernobyl reactor to better understand the causes, course, and consequences of the April 26, 1986, accident there. Comparisons of the U.S. national laboratory results with the actual accident results reported by the Soviets indicate that the best way to obtain a thorough understanding of a reactor system is by extensive dynamic analyses on a verified model. Had the Soviet designers run the analysis before April 26 and informed the operators of potential problems before the proposed turbine test, the author believes that the reactor operators would have approached the experiment more cautiously.

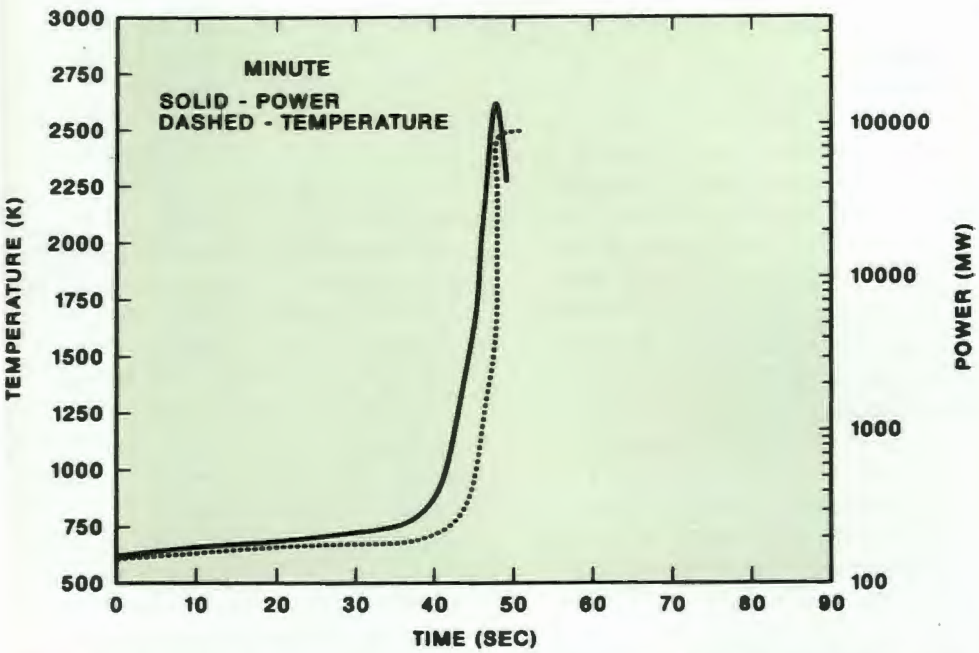


Fig. 2. Results of the Brookhaven National Laboratory analysis of the Chernobyl accident.

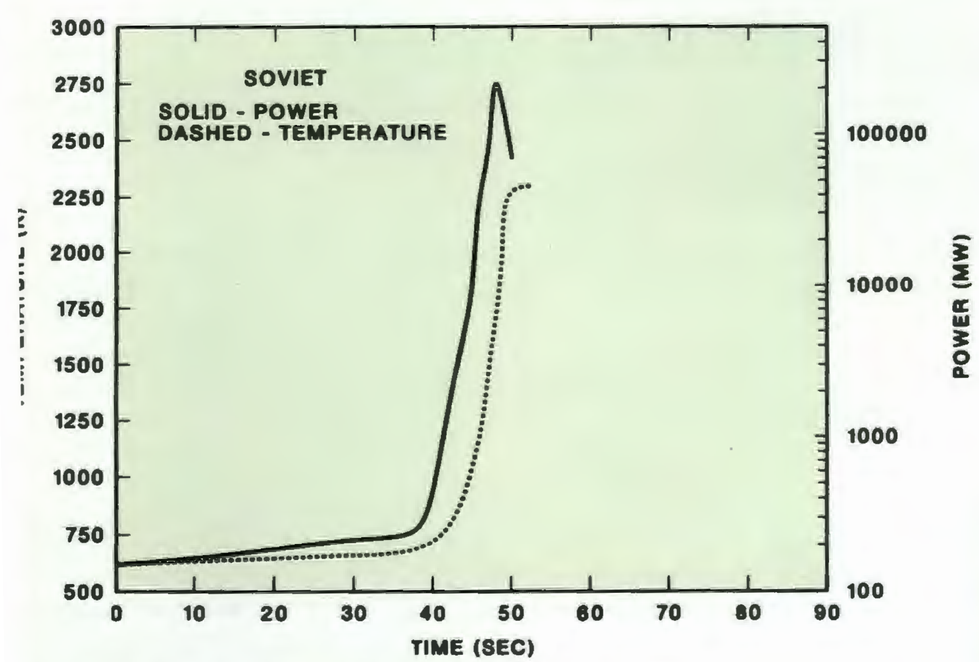
reactor by inserting the control rods. Incredibly, the design of the rods was such that the initial effect of inserting them was to increase reactivity rather than decrease it as intended. Because of the positive void coefficient of reactivity, the power then became very high, possibly reaching several hundred times full power before it was turned downward by the fuel Doppler coefficient, a fast negative temperature coefficient of reactivity in the oxide fuel. However, by the time the power began to decrease, so much energy—about 300 cal/gm—had been deposited in the fuel that the uranium oxide pellets either melted, if they were heated slowly, or shattered, if they were heated rapidly. As a result, fission gases were liberated, thus raising the pressure in the fuel pins high enough to rupture them.

The ensuing mix of very hot fuel particles, molten fuel, and water generated large quantities of steam that expanded upward, driving the column of water above it at a high velocity. Because this column of water could not negotiate a right angle turn at the top of the coolant tubes, it continued upward, shattering the reloading ports and venting under the biological shield. Because the accident moved rapidly through the core, enough escaping steam accumulated under the 1000-ton shield to drive it upward into the reloading gallery, and at the same time, tear the roof from the building. This "explosion" cleared a pathway for fuel and other pieces of core components that were hurled into the air by the expanding steam and other possible energy-producing events occurring in the core.

The conclusions of the U.S. analysis are consistent with the Soviet report that hot fuel particles ignited nearby building roofs and that large graphite pieces were found on some roofs, as shown in the videotapes presented in Vienna.

Lessons from the Accident

From the brief work done thus far, what lessons have been learned (or should I say relearned) from the Chernobyl accident? First, safety systems should not be bypassed. Although some of the functions bypassed in this instance did not contribute to the severity of the accident, disabling the reactor trip circuit that shuts down the reactor when the last of the two turbines



ig. 3. Results of the Soviet analysis of the Chernobyl accident.

stops operating was perhaps a fatal mistake. Had this trip been operational, the reactor would likely have been safely shut down before serious trouble began. Second, shutdown safety rods should be positioned where they can be effective immediately upon a scram (shutdown). The Soviet operators knew that they had entered an area of low differential rod worth, a condition in which too few rods are in position to effect a rapid reactor shutdown; however, for some reason, they chose to ignore it. Third, gross alterations in experimental procedures, done under the stress of an experiment going wrong, are unacceptable. The series of mistakes made by the operators showed a lack of understanding of the unstable nature of Chernobyl-type reactors.

Finally, and perhaps most important, the operators seemed to lack understanding of the fundamental behavior of their reactor. Chernobyl-type reactors exhibit unstable behavior because of the large positive void coefficient of reactivity—the tendency for an increase in power to increase the voids, thus bringing about a further increase in power and more voids. Figures 1, 2, and 3 all show the insidious nature of the power instability. They all show a very slow departure from the steady value (nothing to really alarm an operator) up to the point where the excursion was triggered. At that point, the power suddenly started rising so fast that it was impossible to take effective corrective action because of the positive void coefficient coupled with the long scram delay times and low (or positive) differential rod worth.

Comparisons of the U.S. national laboratory results with the actual accident results reported by the Soviets indicate that the best way to obtain a thorough understanding of a reactor system is by extensive dynamic analyses on a verified model. Had the Soviet designers run the analysis (from which Fig. 3 was derived) before April 26, 1986, and informed the operators of potential problems before the turbine test, the reactor operators surely would have approached this particular experiment with considerably more caution, and the world would not again be experiencing such an adverse reaction prompted by an accident that could have been avoided. ornl

SPECIAL SECTION:

Environmental Aspects of the Chernobyl Accident

By F. OWEN HOFFMAN

During the early afternoon of April 28, 1986, Sweden reported the possibility of a nuclear accident in the Soviet Union. U.S. news reporters immediately contacted the Environmental Sciences Division (ESD) office at Oak Ridge National Laboratory seeking information about the potential significance of the accident. The news media considered ESD a potential source of information because of publications by John Trabalka and Stanley Auerbach on the 1957–1958 nuclear disaster at Kishtym in the Ural Mountains of the Soviet Union.

Like the rest of the U.S. scientific community, we at ORNL were surprised by requests for information concerning an event about which we knew nothing. However, because we have a research contract with the Swedish National Institute for Radiation Protection, we quickly placed a call to Stockholm to find out what was happening. That call was the beginning of what became a major effort to obtain data from colleagues in Sweden, the Federal Republic of Germany (FRG), the United Kingdom, Holland, and Switzerland, and contacts within the Commission of the European Communities, the International Union of Radioecologists, and the International Atomic Energy Agency (IAEA).

That evening, while additional data were being gathered from Sweden, my co-workers Zell Combs and Gordon Blaylock met with

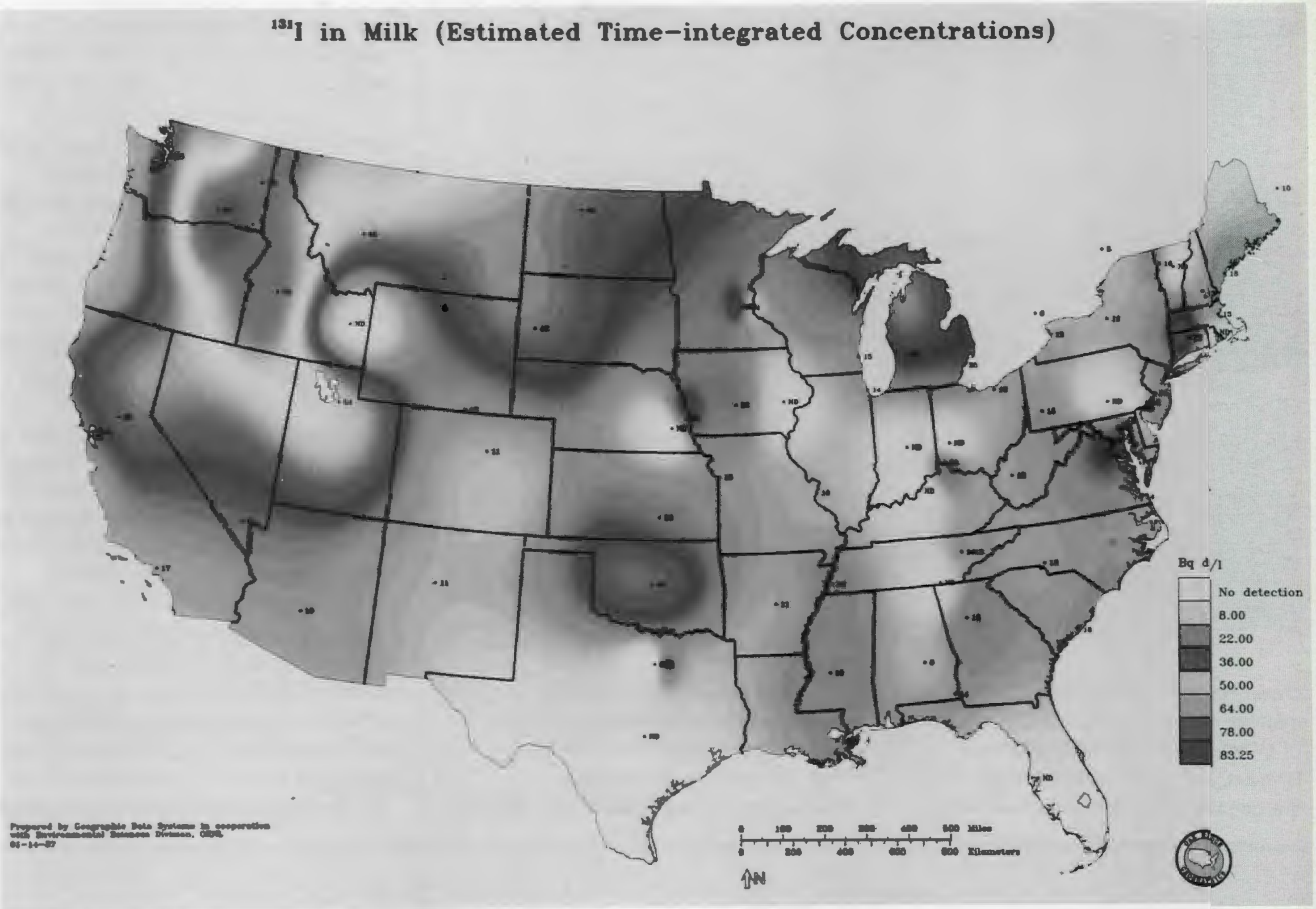
Owen Hoffman is a research staff member in the Aquatic Ecology Section of ORNL's Environmental Sciences Division. He has conducted research on the behavior and fate of radionuclides in the environment. As a scientific consultant to the International Atomic Energy Agency and the Swedish National Institute for Radiation Protection, he has worked on validating and evaluating the reliability of environmental radiological assessment models. In 1986 he was elected to the board of directors of the International Union of Radioecologists. Hoffman came to ORNL in 1976 from the Federal Republic of Germany, where he worked from 1971 through 1975 as a staff ecologist for the Institute for Reactor Safety in Cologne. In Germany he also served on the Advisory Committee on Radioecology for the Federal Ministry of the Interior. He has a Ph.D. degree in ecology from the University of Tennessee at Knoxville. Here, he and Marilyn Frank watch as Lauren Larsen inserts a sample of hay from Kingston, Tennessee, in a gamma spectrometer to determine its radionuclide content shortly after the Chernobyl reactor accident. The instrument had been used before the fallout reached the United States to determine the background count on equivalent samples. Information provided by the gamma spectrometer and multichannel analyzer indicates the amount of cesium-137, iodine-131, and other radionuclides present in the sample.

meteorologist Frank Kornegay and began plotting meteorological information on a map of Europe—the first attempt at ORNL to speculate on the possible extent and severity of the accident. By simply estimating a wind trajectory distance of 1600 to 2400 km (1000 to 1500 miles) and assuming an average wind velocity of the transporting air layer of from 24 to 32 km (15 to 20 miles) per hour, we calculated that the travel time of radioactivity was about three days. Given what we knew about the time of arrival of radioactivity in Sweden, we estimated that the accident probably occurred on April 25. (The accident actually occurred early in the morning of April 26.) The next morning I received a similar estimate from colleagues at Studsvik, Sweden.

Measurements of the fallout of Chernobyl radionuclides offer a unique opportunity to test the accuracy of predictive models and to trace the movement of submicron materials from the atmosphere to various parts of the environment. Examples of such environmental processes that can be studied this way are wet and dry deposition, surface interception and retention of deposited material, and food chain bioaccumulation of elements chemically related to the Chernobyl radionuclides.

Chimney Effect

On May 1, ORNL held its first Laboratory briefing on Chernobyl. At that briefing, most of the discussion was based on speculation, much of which was later proven false. For example, Sweden reported that satellite photographs indicated that a second reactor had been involved. We had estimated that dose rates at the site might be as high as several thousand rads per hour; however, our calculations did not take into account the great height to which the radioactivity was initially thrust into the atmosphere (now known to have exceeded



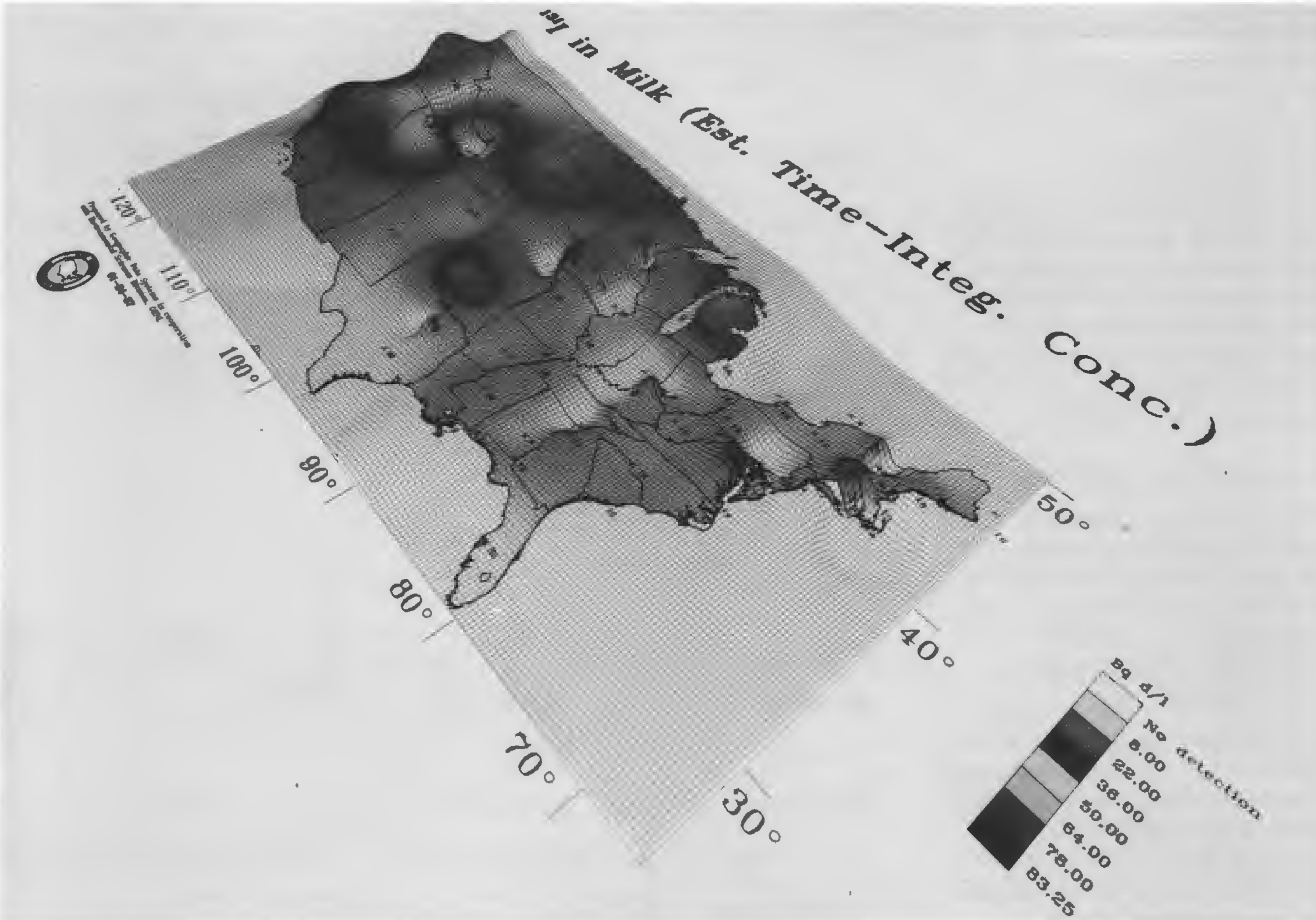
Estimated time-integrated concentrations of iodine-131 in milk in the United States two weeks after the Chernobyl accident are shown on this map. Concentrations are highest in the Northwest.

1.6 km, or 1 mile). This "chimney effect," created by the energy emitted by the explosion and fire, prevented extreme lethal levels of contamination from occurring near the reactor, but it also contributed to the global dispersion of radioactivity.

During this briefing we reported that the levels of radioactivity in the air had dropped in Sweden and that the plume had begun to return to the Soviet Union. However, Kornegay speculated that high levels of fallout might occur over the Alps because of a shift in wind trajectories and the probability of heavy rain in that region of Europe. To our surprise, a call received the next morning from Munich, FRG, confirmed that thunderstorms during the evening of April 30 had deposited large amounts of radioactivity in southern Bavaria. Some areas were contaminated with levels as high as 35 kBq/m^2 of cesium-137, or ^{137}Cs (this concentration is about ten times the maximum levels that accumulated downwind from the Nevada Test Site during the period of atmospheric weapons testing and about one-third the maximum values reported from Sweden). This information was the first indication that Chernobyl fallout was going to occur over most of the European continent.

Checking Local Fallout

In the absence of information from the Soviet Union, we continued to monitor reports from Europe and intensify personal contacts with European colleagues. Within ESD, interest began to grow concerning the possibility that Chernobyl fallout could be detected in Tennessee. Many of us did not expect Chernobyl fallout to reach the United States, but Lauren Larsen insisted that it would. He began to take samples of rain and vegetation and analyze them using a germanium detector for gamma-emitting radionuclides. During the



Estimated time-integrated concentrations of iodine-131 in milk in the United States two weeks after the Chernobyl accident are shown in this computer plot. Concentrations are highest in the Northwest. The map was originally produced in color; the key in this black-and-white version is misleading because the darkest tone does not represent the highest iodine-131 concentrations (shown in red at the top of peaks).

second week of May, Chernobyl fallout arrived in Oak Ridge. Rainwater samples showed measurable amounts of iodine-131 (^{131}I), ruthenium-103 (^{103}Ru), ^{134}Cs, and ^{137}Cs. Larsen organized a group of ORNL volunteers to bring him additional samples of rain, vegetation, and milk to measure radiation. Nelson Edwards of ESD supplied milk from his own cow, and Leroy West of the Plant and Equipment Division obtained milk from his neighbors' cows. Robert Cook of ESD brought in rainwater and vegetation from the Great Smoky Mountains National Park, and Marilyn Frank made up sample collection kits and helped Larsen prepare samples for counting. Additional milk was purchased from local dairies, and vegetation was sampled from representative pastures in the region around Oak Ridge. Meanwhile, data on Chernobyl fallout concentrations in the atmosphere were being obtained by Jim Eldridge of the Analytical Chemistry Division and ESD's Ernest Bondietti and Jerry Brantley. Bondietti and Brantley have already published their findings in *Nature*.

A summary of the levels of radioactivity found in environmental samples collected near ORNL are presented in Table 1. These concentrations are about 100 to 1000 times lower than those reported in western Europe and are more than a million times lower than levels reported in the northwest region of Byelorussia in the Soviet Union. A comparison of time-integrated concentrations of iodine-131 (^{131}I) in Oak Ridge milk samples and samples taken in Europe clearly depicts these relationships (see Fig. 1).

Table 2 lists the concentrations of ^{137}Cs in foods produced in Finland, Sweden, Bavaria, and the United Kingdom. The high concentrations reported for freshwater fish may be due to rapid runoff of ^{137}Cs from watersheds and accumulation of this radionuclide in lakes. In some areas of these countries, the highest exposures received by population subgroups resulted from the consumption of freshwater fish. These findings are surprising because the aquatic environment is believed to be of minor importance in assessing the health impacts of radioactivity releases to the atmosphere.

Some Surprising Findings

The Chernobyl fallout data obtained from this volunteer effort are now being used together with data from other locations in the United States and abroad to investigate a number of global scientific issues.

The fallout data are being used to test, or validate, the predictions of mathematical models used in radiological assessments. The results of these tests will improve our understanding of the strengths and weaknesses of models as predictive tools. So far, we have found that models overestimate the concentrations of ^{131}I in milk by a factor of 10 to almost 100. This overprediction occurs even when the time-integrated concentration of ^{131}I in air at a specific site is given as the starting point of the calculation. This result is surprising given the abundant data base upon which these models have been developed.

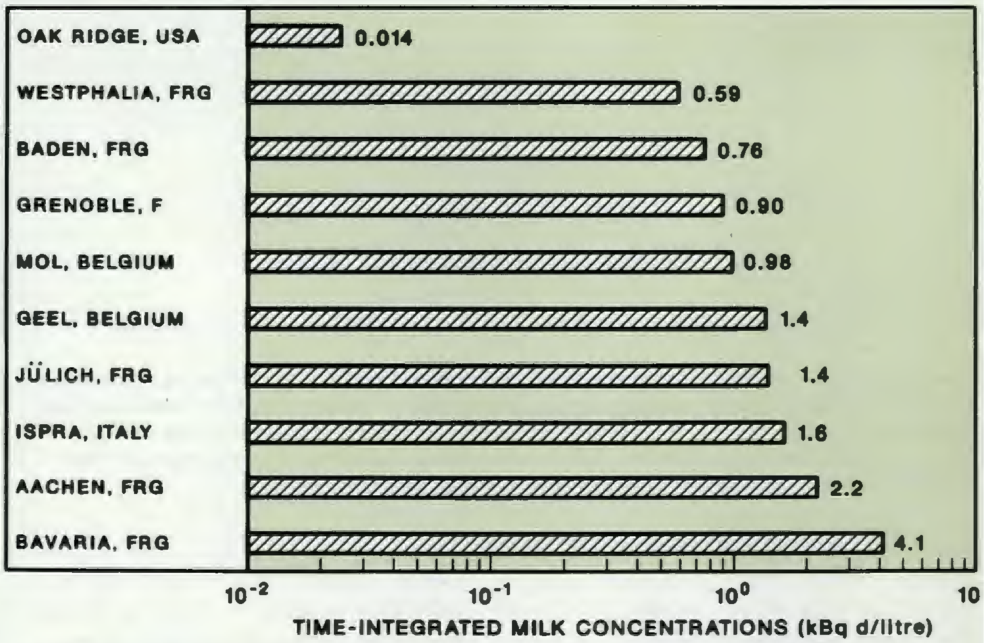
The bulk of this discrepancy appears to be related to the processes governing the transfer of ^{131}I from the atmosphere to vegetation (e.g., pasture grass eaten by cows). Most likely, the values assumed in the models for estimating the wet and dry deposition of ^{131}I are too high. In addition, the amount of ^{131}I in air present as the highly reactive elemental iodine vapor may have been overestimated and the amount present as the relatively unreactive methyl iodide may have been underestimated. Methyl iodide is not readily deposited from the atmosphere by either rain or dry deposition processes and, therefore, does not contribute effectively to the contamination of milk.

Some of the discrepancy between model predictions and measurements may be explained by an apparent lower secretion of ^{131}I into cow's milk in spring than during other times of the year. This effect has been reported by investigators in Europe and the United States, but it is not accounted for in current

Table 1. Range of radionuclide concentrations in environmental samples from Chernobyl fallout near Oak Ridge, Tennessee

Date	Sample	Units	^{131}I	^{106}Ru	^{137}Cs	^{134}Cs
5/13–6/13	Pasture vegetation	Bq/kg, dry	0.96–18.3	0.60–13.2	1.35–15.4	0.19–10.7
5/15–6/4	Milk (from farms)	Bq/L	0.23–1.59	ND[a]	0.02–0.39	ND–0.17
5/26–6/16	Milk (from stores)	Bq/L	0.06–0.30	ND–0.03	0.01–0.27	ND–0.14
5/13–6/27	Rain	Bq/L	0.04–5.07	0.14–0.98	0.04–0.67	ND–0.31
5/9–6/2	Air	Bq/m^3	0.007–0.011			
5/16–6/4	Deer (thyroid)	Bq/kg, fresh	1.85–20.4			

[a]ND = not detected.



Time-integrated concentrations of ^{131}I in cow's milk for various locations in the northern hemisphere shortly after the Chernobyl reactor accident. The time-integrated iodine levels in Byelorussia, U.S.S.R., were estimated at 1.8×10^4 kBq d/litre.

Table 2. Concentration of ^{137}Cs in foods produced in countries that received Chernobyl fallout radionuclides, in Bq/kg

Food	Finland	Sweden	Bavaria	United Kingdom
Milk and milk products	20	8–80	300	360
Grains	10	>10	17–194	
Leafy vegetables	10	>10	5–12	
Fruits and berries	30		47–300	
Mushrooms	20–6,700		30–2,200	
Beef	100	10–500	20–147	
Elk		20–1,600		
Venison		150–1,200		
Reindeer	500–8,000			
Aquatic birds				
Duck	10–6,900			
Canada goose		3,840		
Mallard duck		1,290		
Marine fish				660
Baltic herring	30	23		
Atlantic codfish		2		170
Other fish	50			
Freshwater fish				
Brown trout		18,700		660
Rainbow trout		6,280		82
Perch	30–15,900	14,240		445
Pike	30–1,300	4,690		42
Crucian carp		1,870		
Other fish	50–9,300		13–1,100	
Shellfish				
Signal crayfish		2,280		
Winkles				800
Mussels				150
Shrimp			48	

Source: B. Gordon Blaylock, ORNL, Environmental Sciences Division.

radiological assessment models.

Using Chernobyl data to test models has suggested that the average human exposure from the ingestion of ^{131}I-contaminated milk may not be substantially more important than direct inhalation of ^{131}I in air. This result is contrary to the generally accepted notion that the ingestion of ^{131}I-contaminated milk presents the dominant route of exposure to the human thyroid. Because most adults do not consume large quantities of fresh milk, the thyroid exposures received from breathing ^{131}I in air may have been just as great, if not greater, than exposures received from ingesting ^{131}I in milk.

Chernobyl fallout data are also helping us assess the usefulness of naturally occurring radionuclides as quantitative tracers of the transfer of submicron aerosols from the atmosphere to vegetation. For example, beryllium-7 (^{7}Be) is continuously formed in the stratosphere through cosmic ray bombardment of atoms of nitrogen and oxygen. This natural gamma-emitting radionuclide is always present in measurable amounts in air, rain, and vegetation and, thus, has potential for use as a tracer.

The results we have obtained thus far indicate that measurements of natural ^{7}Be might be useful for quantifying the rain-to-vegetation transfer for a variety of pollutants potentially dispersed in the atmosphere as submicron particulates. Analyses of samples collected in the Oak Ridge vicinity have shown strong correlations between naturally occurring ^{7}Be and the Chernobyl radionuclides in rain and vegetation (see Fig. 2). These results indicate that it may be possible to use ^{7}Be to quantify the transfer to vegetation of contaminants in rain for a variety of storm events at different times of year.

Perspective on the Chernobyl Accident

Currently, analysis of data on concentrations of Chernobyl radionuclides is continuing, and information is being collected from all over the world. The first reports we received were primarily concerned with documenting the extent of contamination and estimating the potential hazard to human health. This information indicates that radiation exposures received by people outside the Soviet Union is a small fraction of the exposure received from natural sources. Inside the Soviet Union, the highest radiation exposures were limited to the Chernobyl power plant personnel and firemen exposed on the Chernobyl reactor site shortly after the first phase of the accident.

Of about 300 persons admitted to hospitals in the Soviet Union for radiation exposure, 203 had symptoms of acute radiation syndrome from gamma irradiation. A number of these received extensive radiation burns to the

Hoffman and Frank watch as Larsen clips grass from a 1 m² plot (measured out by a string on four nails) to be weighed and processed for a radioactivity count. These measurements are used to estimate the amounts of iodine-131 and other radionuclides that end up in cows' milk as a result of grazing on contaminated pastures.

Larsen places a sample of clipped grass into the bag held by Frank as Hoffman watches. Larsen played an active role last May in obtaining grass and milk samples to determine the Oak Ridge fallout resulting from the Chernobyl reactor accident.

skin from beta-emitting radionuclides. Extensive beta radiation burns of the skin is thought to have contributed substantially to 29 of the 31 known fatalities. From the information available, it appears that over the next 70 years, the spontaneous incidence of all cancers among the 135,000 people evacuated from the region near the reactor site will not likely increase by more than about 0.6%. The corresponding figure for the remaining population in most regions of the European part of the Soviet Union is not expected to exceed 0.15%; however, a more likely figure (according to the IAEA's International Nuclear Safety Advisory Group) is about 0.03%.

Despite the comparatively low doses received by populations outside the Soviet Union, political problems abound. Many of these problems have been brought about by extremely restrictive and inconsistent radiation limits placed on maximum permissible levels of radioactivity in imported foods. Much of the well-publicized burying of moose and reindeer carcasses in Scandinavia are related directly to the adoption of such restrictive standards. For example, a limit of 300 Bq/kg for ^{137}Cs has been established by the European Communities for imported foods. Under most circumstances, this limit would produce a dose to an individual that is much less than 1% of the lifetime dose resulting from exposure to natural background radioactivity.

Radiation protection standards for imported foods has become a major concern, and a review of these standards is being conducted by the IAEA and the World Health Organization.

Currently, we have noticed a shifting emphasis in the information that we are receiving

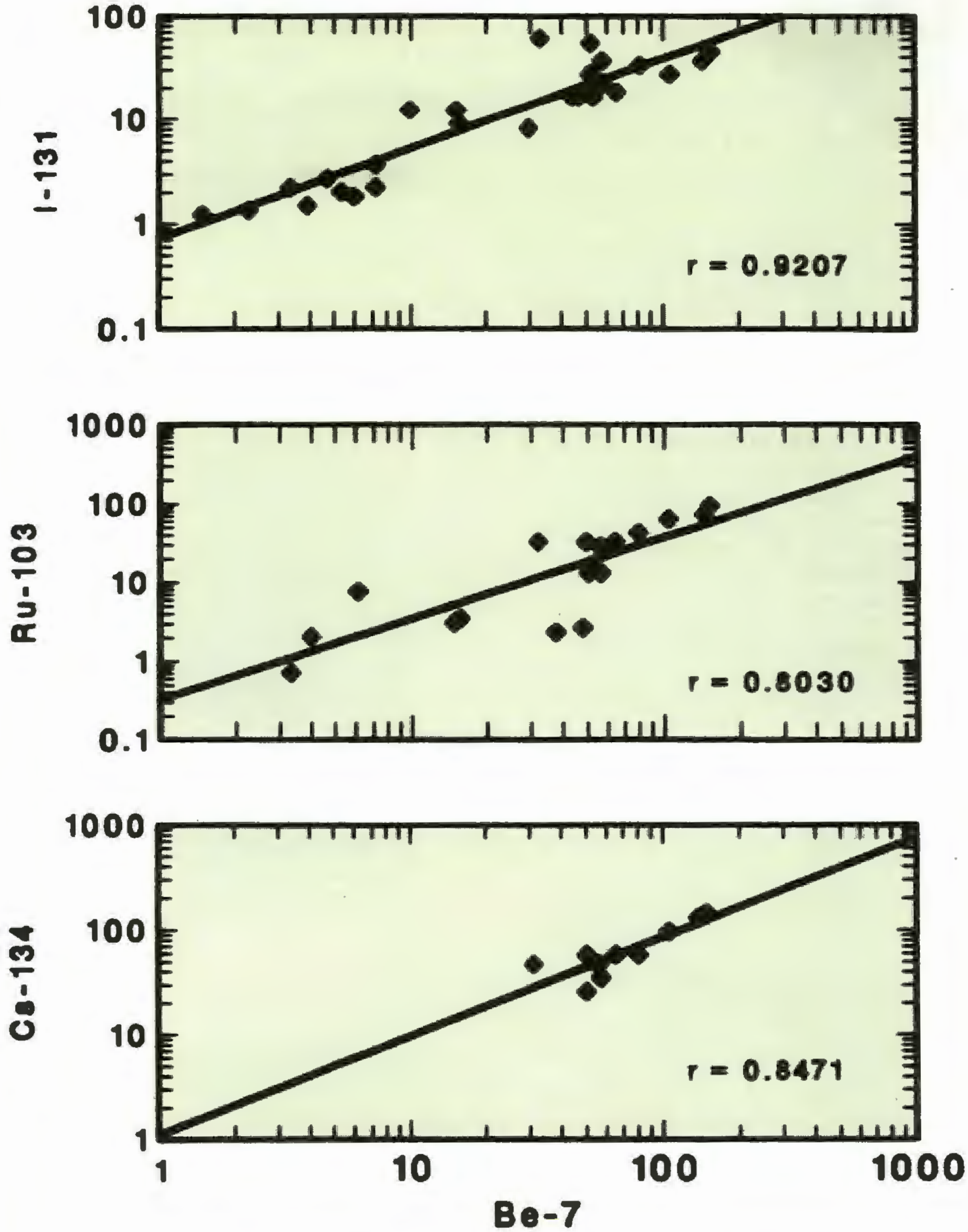


Fig. 2. Rain-to-vegetation transfer factors for Chernobyl radionuclides plotted against those for naturally occurring beryllium-7. The transfer factors are expressed as concentration ratios (pCi per kg wt veg/pCi per L rain).

from colleagues in Europe. Much less is being said about the estimation of doses and potential health effects. Instead, an increasing number of researchers are dealing with the scientific investigation of the processes governing the dispersion, deposition, retention, redistribution, and bioaccumulation of the radionuclides released during the accident. Much of our own research has proceeded in this direction as we continue to analyze measurements made globally on concentrations of Chernobyl radionuclides in environmental samples.

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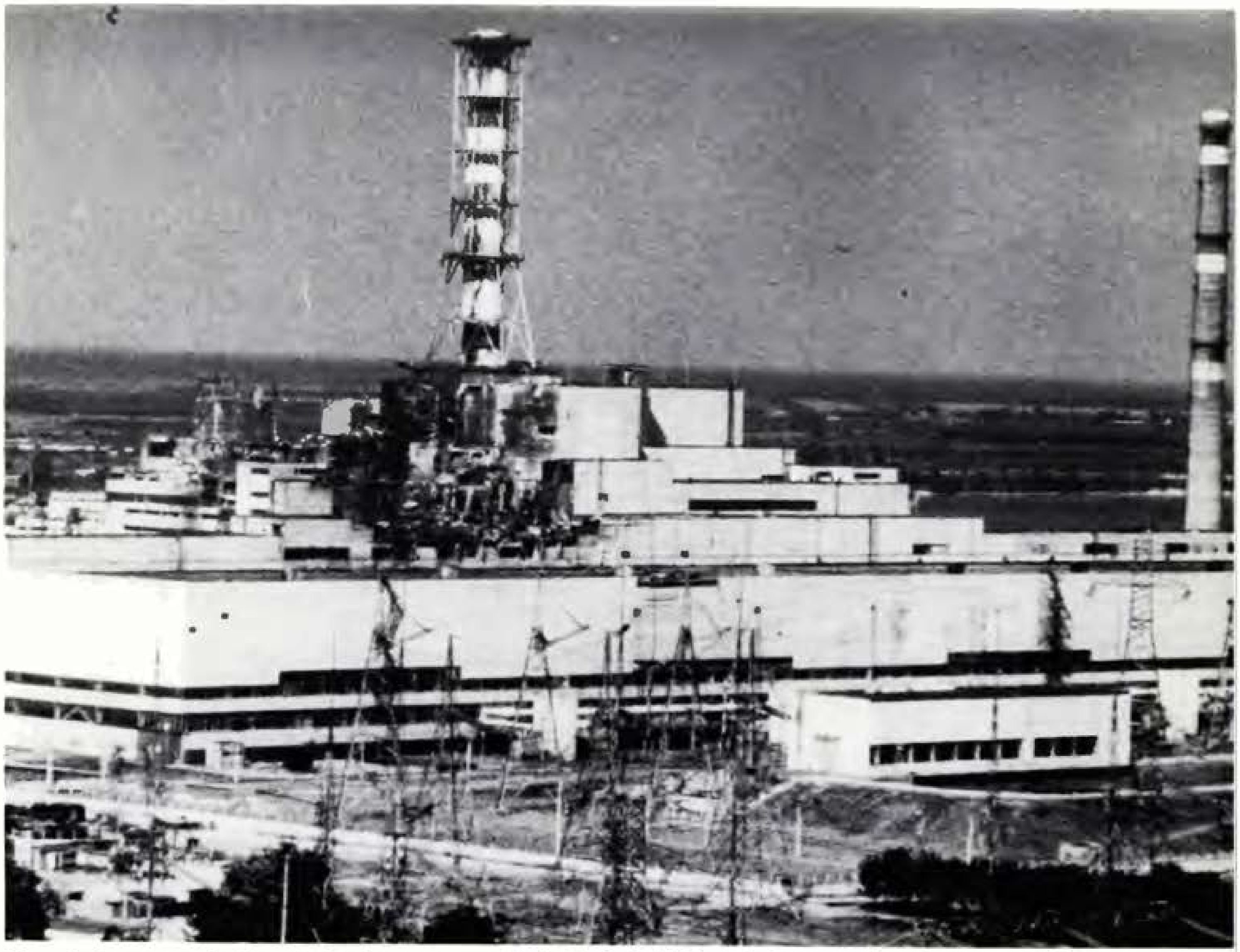

The ruined reactor at the Chernobyl nuclear-power complex in the Soviet Union raised new questions about reactor safety and stimulated international scientific studies. Some of these studies were performed at ORNL. They are discussed in a special section on the Chernobyl reactor accident and its impacts, starting on page 28.