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Energy Technology Division

Research Summary — 1994

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Contents

Overview of the Energy Technology Division.....	1
Materials Technology	5
Ceramics.....	7
Corrosion.....	30
Mechanics of Materials.....	52
Tribology.....	68
Irradiation Performance.....	78
Components Technology.....	87
Superconductivity Applications.....	89
Analytical Thermal-Hydraulics.....	96
Thermal and Mechanical Sciences.....	108
Instrumentation and Nondestructive Evaluation.....	120
Transportation of Hazardous Materials	140
APPENDIX A: Regular ET Employees	155
APPENDIX B: Honors, Awards, and Professional Activities.....	159

Energy Technology Division

Overview of the Energy Technology Division

Energy Technology is the new name for the former Materials and Components Technology Division. In April 1993, Laboratory Director Dr. Alan Schriesheim announced a reorganization of Energy, Environmental and Biological Research and an expansion of the responsibilities of Dr. Harvey Drucker, the Associate Laboratory Director. The reorganized structure consists of three programmatic components: Energy and Industrial Technology, Environmental Sciences, and the Center for Mechanistic Biology and Biotechnology, as shown in the organization chart on the next page. The newly renamed Energy Technology Division was transferred to the Energy and Industrial Technology component, reporting to General Manager R. W. Weeks. "With the establishment of this new organization and the development of these key management positions," wrote Dr. Schriesheim, "I am confident that the Laboratory is well positioned to respond to high-priority Department of Energy research and development initiatives and to support the achievement of current national technological, economic competitiveness and environmental goals."

Inclusion of the phrase "economic competitiveness goals" reflects a major broadening of the mission of the Department of Energy. The current mission has been stated by the Department as follows:

"The Department of Energy, in partnership with our customers, is entrusted to contribute to the welfare of the Nation by providing the technical information and the scientific and educational foundation for the technology, policy, and institutional leadership necessary to achieve efficiency in energy use, diversity in energy sources, a more productive and competitive economy, improved environmental quality, and a secure national defense."

Within the Energy Technology Division, our challenge has been to identify our key strengths, i.e., our core competencies, and to apply them in support of the Laboratory in its efforts to help DOE accomplish its mission. The Energy Technology Division's competencies have developed over many years of research and development in materials, components, and instrumentation. The Division has capabilities in construction, fabrication, testing, and design. Internal organization of the Division, which was not changed at the time of the reorganization of Energy, Environmental and Biological Research, is shown in the organization chart on page iv.

With the Division reporting to the same General Manager (R. W. Weeks) as does the Industrial Technology Development Center (ITD), this organizational structure reflects the Division's role in reaching out to industry and places it in a key position to address the economic competitiveness goals of the

ET Funding Sources for FY 1994

Department of Energy. Through ITD, the Division develops collaborative research and development agreements (CRADAs) with the private sector. CRADAs are formal agreements between the Laboratory and private companies and/or groups of companies.

A major source of new funding has been the Office of Laboratory Technology Transfer in DOE's Office of Energy Research. This office provides funding specifically to support CRADAs. The purpose of CRADAs is to enhance the competitive advantage of U.S. companies by providing a mechanism under which intellectual property can be protected. The ET Division has enhanced its position for response to this new opportunity through representation on several Laboratory-wide working groups focusing on such areas as transportation, engineered materials, waste reduction and chemical processes, biotechnology, and manufacturing. Within the Division, we have streamlined the procedure by designating one person as our technology transfer representative and having him assist in the preparation of the voluminous CRADA paperwork.

While we have seen substantial growth in CRADA funding, the nuclear programs still account for a significant portion of our work. Research funded primarily by the Nuclear Regulatory Commission is directed toward assessing the roles of cyclic fatigue, intergranular stress corrosion cracking, and irradiation-assisted stress corrosion cracking on failures in light water reactor (LWR) piping systems, pressure vessels, and various core components. An important result of this work is information on the effect of strain rate on fatigue life. The Division supports the LWR industry in many other ways, including failure analysis of LWR components, assessing damage to the Three Mile Island reactor core, and reviewing proposed materials of construction for advanced LWR designs. Expected fluid flow and heat transfer under normal and off-normal operating conditions are calculated with the COMMIX codes. Flow-induced vibration is studied both analytically and experimentally.

In support of the fast reactor program, the Division has responsibility for fuel-performance modeling and irradiation testing.

The Division has major responsibilities in several design areas of the proposed International Thermonuclear Experimental Reactor (ITER). Most of this effort involves first wall, blanket, and coolant design. A major contribution has been to develop electrically insulating coatings to reduce magnetohydrodynamic forces in liquid-metal cooling systems. This has been accompanied by increased interest in the use of vanadium alloys. Breeding in and tritium release from solid breeder blanket material—mostly lithium-based ceramics—is both modeled and investigated experimentally.

The Division supports the Department of Energy in ensuring safe shipment of nuclear materials by providing extensive review of the Safety Analysis Reports for Packaging (SARPs). These reviews involve the selection of appropriate materials, a detailed structural analysis, a review of thermal characteristics, assessments of the containment and shielding, a criticality hazards analysis, and a verification that all applicable quality assurance requirements are included in the SARP. In addition, the Division provides education in the form of videos and workshops to promote the safe transport of hazardous materials.

Finally, in the nuclear area we are investigating the safe disposal of spent fuel and waste. A new phosphate-bonded waste form has been developed for the stabilization of mixed waste. Metal alloys are being studied for the containment of metallic fission products and fuel cladding. In the future, efforts to characterize DOE-owned spent nuclear fuel will be expanded. In work funded by DOE's Energy Efficiency and Renewable Energy (formerly Conservation and Renewable Energy), the high-temperature superconductivity program continues to be a major focal point for industrial interaction. More than 50 Superconductivity Partnership Initiative (SPI) agreements with private companies cover a range of work from powder synthesis to component manufacture. One near-term application is a flywheel for diurnal energy storage. Under an SPI agreement, an electric power utility is exploring this technology for peak shaving. Under other agreements, long lengths of wire capable of carrying electricity at a current density of $10,000 \text{ A/cm}^2$ and coils capable of generating magnetic fields of 2 Tesla have been developed. The Division assists DOE's Industrial Partnership Initiative: four separate efforts are being supported. The goals are to develop superconducting motors, generators, fault current limiters, and electric power transmission cables.

Coatings and lubricants developed in the division's Tribology Section are intended for use in transportation systems of the future. Through CRADAs with engine manufacturers, these are being developed for such diverse applications as protection of plastic fuel system components against the corrosive action of oxygenated fuels and as seals in gas turbine regenerators. With funding by DOE's Fossil Energy, continuous fiber ceramic composites are being developed for high-performance heat engines. In recent work, we have studied the degradation of fiber strength during composite manufacture and the beneficial effects of fiber coatings. Nondestructive testing techniques are being developed to evaluate fiber distribution and to detect flaws. A wide variety of coatings for corrosion protection of metal alloys are being studied. These can increase lifetimes significantly in a wide variety of coal combustion and gasification environments.

Materials Technology

Ceramics

Section Manager: U. Balachandran

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Murphy,¹² S. Olson,¹³ M. Pitz,³ G. Pollard,¹¹ B. C. Prorok,⁷ G. Risch,⁵ D. Trapp,¹⁴
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S. Zentack,¹⁶ W. Zhong³

Student Aides: E. Nicholson, J. Wesolowski

The Ceramics Section investigates the synthesis, fabrication, and characterization of ceramic materials and optimizes the properties of these materials for practical engineering applications. In most cases, the application is intended to facilitate the generation, storage, or distribution of energy. For example, the goal of the superconductor development program is to develop ceramic superconductors for more efficient generation, storage, and distribution of electrical energy. In a collaboration with Amoco, we utilize ceramics to convert methane to more valuable hydrocarbons, while in the structural ceramics program, we are improving the reliability of structural ceramics so that they might be used to fabricate more efficient gas turbine engines. In a new program, we will explore the fabrication of ceramic gas turbine blades directly from three-dimensional computer models. Other programs in the Ceramics Section focus on improving the structural reliability of ceramics for use as hot-gas filters, exploiting the cementitious properties of phosphate-based materials to isolate radioactive and chemical waste and serve as gas-tight sealants in solid oxide fuel cells, and developing a new generation of refractories in a continuing collaboration with Magneco-Metrel.

There have been several significant changes in personnel since the last review. Roger Poeppel, the previous manager of the Section, was promoted to Division Director and was replaced by U. Balachandran. Several new full-time staff members have been added.

¹Special Term Appointee.

²Serves two sections.

³Illinois Institute of Technology.

⁴Purdue University.

⁵University of Cincinnati.

⁶Alfred University.

⁷University of Chicago.

⁸Georgia Institute of Technology.

⁹SUNY Geneseo.

¹⁰Northwestern University.

¹¹University of Illinois at Urbana-Champaign.

¹²Memphis State University.

¹³Clemson University.

¹⁴Iowa State University.

¹⁵Case Western Reserve University.

¹⁶Virginia Polytechnic Institute.

They are Dileep Singh, who was promoted from postdoctoral appointee and is working in the areas of waste isolation and structural ceramics; Arun Wagh, a former special term appointee, who is applying his expertise in chemically bonded ceramics to radioactive and chemical waste isolation and development of sealants for the SOFC; and Jules Routbort, who brings a wealth of knowledge on point-defect chemistry and its relationship to diffusion and high-temperature mechanical properties. Subrata Banerjee, an expert in refractories from Magneco-Metrel, has joined the section on a one-year Laboratory Exchange appointment, and Rodney Mievile is a new special term appointee who is bringing his experience in catalysis to bear on the development of ceramic membranes for methane conversion.

Sample-characterization capabilities have been enhanced with the addition of a new optical microscope equipped with digital image analysis and hot stage for rapidly and accurately quantifying microstructural features at room and elevated temperatures, a surface-area analyzer for determining the total surface area of ceramic powders, and a helium pycnometer for accurately measuring sample density. A freeze-dryer has been added for preparing very homogeneous ceramic precursors.

Superconductor Development

The largest program in the Ceramics Section, superconductor development has as its goal the development of ceramic superconductors for practical applications in the area of generation, storage, and distribution of electrical energy. The general target is to produce long lengths (≈ 1000 m) of conductor capable of carrying $>10^4$ A/cm² in magnetic fields of >2 T at temperatures of >35 K. We focus primarily on the three systems that appear to hold the most promise as practical engineering materials: Y-Ba-Cu-O (YBCO), Bi-Sr-Ca-Cu-O (BSCCO), and Tl-Ba-Ca-Cu-O (TBCCO). However, the program also investigates promising new materials as they are developed, e.g., Hg-Ba-Ca-Cu-O (HBCCO), to maintain its position in the forefront of high-critical-temperature (high- T_c) superconductor research.

The performance of high- T_c materials is limited in two ways, by weak links and by flux creep. Weak links, the nonsuperconducting regions between superconducting grains, exist because impurity phases or cracks are present at grain boundaries or because the superconducting grains are poorly aligned. To eliminate weak links, nonsuperconducting phases and cracks must be eliminated by optimizing processing routes, and methods for aligning superconducting grains, e.g., powder-in-tube (PIT) processing, must be developed. Flux creep is the motion of quantized magnetic flux through the superconductor. The challenge here is to improve flux pinning by introducing so-called pinning sites that inhibit flux creep.

Because weak links dominate behavior of YBCO, its critical current density drops dramatically in weak magnetic fields (<0.01 T), so the use of YBCO for transporting high currents is not practical with present fabrication methods. However, YBCO is useful for magnetic levitation because it exhibits relatively high resistance to flux creep. Capitalizing on this, the Ceramics Section is fabricating YBCO levitators for flywheel energy storage in collaboration with the Superconductivity Applications Section and Commonwealth Edison.

High-performance superconducting downlinks (electrical leads designed for operation in a cryogenic temperature gradient) produced by ANL for 1500-A (peak) AC operation at power-line frequency. The 250-mm-long rectangular bars were made by sinter-forging material of the bismuth family of high-temperature superconductors.

Weak links are not so prevalent in BSCCO, primarily because good grain alignment can be achieved through appropriate mechanical deformation sequences. As a result, we have been able to fabricate monolithic BSCCO bars (see photo above) with critical current density (J_c) approximately one order of magnitude higher than that of monolithic YBCO. We have also collaborated with Intermagnetics General Corporation to fabricate high- T_c magnets, such as the one shown in the next photo. To date, we have assembled a magnet that utilized ≈ 780 m of BSCCO tape and generated a magnetic field of 2.6 T at 4.2 K, a world record for high- T_c materials. However, BSCCO is much more susceptible to flux creep than YBCO, so improved flux pinning will be required before it can be widely applied. We are also actively investigating PIT processing of TBCCO. This is of great interest because TBCCO has plate-like grains similar to those in BSCCO and so may be amenable to grain alignment, but it is less susceptible to flux creep than BSCCO and so should perform better in significant magnetic fields.

High- T_c superconductor coil made from Bi-2223 by the powder-in-tube process in collaboration with Intermagnetics General Corporation. The coil contains 780 m of Bi-2223 tape and has generated a magnetic field of 2.6 T at 4.2 K, a world record for high- T_c materials.

Methane Conversion and Utilization

As oil companies exploit more remote regions to maintain adequate oil supplies, they encounter ever-increasing amounts of natural gas. The upgrading of natural gas (containing mostly methane) to value-added products such as easily transportable fuels is driven by the abundance of natural gas in remote areas and by the disparity in prices of petroleum liquids versus gas on a Btu-cost basis. Over the past several years, extensive research has focused on converting methane to value-added products, especially easily transportable fuels and gasoline additives that minimize air pollution from automobile exhaust gases.

The first step in natural gas conversion is the generation of so-called "syngas" (short for synthesis gas). At present, syngas is generated by "steam reforming," which is highly energy- and capital-intensive. Another typical approach requires mixing of methane with air, but downstream processing conditions require cryogenic separation of the nitrogen, another costly process. Pure oxygen can be used, but its production is also expensive.

As a cost-effective alternative, we are working with AMOCO Corporation to develop ceramic membranes that allow air to be used in syngas generation reactions. In principle, air flows on one side of the membrane while methane flows on the other side. Because the membrane is permeable to oxygen, but not to nitrogen, the oxygen diffuses through the membrane and reacts with methane to generate the product gas. No external electrical source or circuitry is required, because the membrane is a mixed ionic/electronic conductor. To date, ceramic reactor tubes fabricated by the Ceramics Section have been

tested at AMOCO for >1000 h without failure and with >99% methane conversion efficiency. The next photo shows the membrane fabricated in a honeycomb configuration to provide multiple channels for passage of air and methane.

Structural Ceramics and Composites

For more than a decade, we have been developing and characterizing monolithic ceramics and composites with particulate, whisker, and fiber reinforcements for high-temperature structural applications. This work is funded by DOE and has involved interactions with Dow Corning Corporation on the development of improved ceramic composites and with Westinghouse Inc. for the development of hot-gas filters. Recent efforts have focused on continuous-fiber-reinforced ceramic matrix composites. Specifically, we have evaluated the effects of fiber strength and architecture and fiber/matrix interface characteristics on the mechanical properties of composites at ambient and elevated temperatures. The results are being used by the Instrumentation and Nondestructive Evaluation Section to guide their development of nondestructive testing methods.

The strength of fibers in composites is measured by fractographic techniques after processing and after exposure to service environments. These strength values are compared with the fiber strength in the as-fabricated condition to provide information on

*Honeycomb monolith
extruded from ceramic
membrane material*

the nature of flaw generation and fiber damage during processing and in service. Fiber/matrix interfacial properties are evaluated by fiber-pushout testing and electron microscopy on composites fabricated under different processing conditions. The flaw population and characteristics, fiber strength, and interfacial properties are then correlated with measured mechanical properties to gain critical information for processing composites with improved properties.

Waste Stabilization

Stabilization of chemical, radioactive, and mixed wastes by using phosphate ceramics is a new focus area in the Ceramics Section. Chemically bonded phosphate ceramics that set at room temperature are being synthesized to stabilize several DOE waste streams such as contaminated ashes, salt cakes, and cement sludges. Stabilization of these wastes will help in treating secondary waste streams that arise from present-day thermal stabilization processes (vitrification and plasma arc treatment). In addition, chemically bonded phosphate ceramics can stabilize wastes containing volatile species and pyrophorics, materials that cannot be treated by thermal stabilization.

Magnesium and zirconium phosphate have both shown excellent potential for stabilizing these waste streams. The mechanism of stabilization in these materials is both chemical solidification and physical encapsulation of wastes, resulting in superior waste forms. Optimization of the phase compositions, microstructure, and mechanical and physical properties has led to the development of dense and durable final waste forms. Because this process operates at low temperatures, its field implementation is expected to be cost-effective. Efforts are being made to scale up the technology for field applications. Demonstration of this technology will benefit not only the waste management efforts of DOE, but also those of the chemical, power, and defense industries.

Refractory Research

The Section is involved in a CRADA with Magneco-Metrel to develop pumpable refractory materials with high corrosion and erosion resistance for application in iron- and steelmaking processes. Under this program, refractory specimens of various compositions are formulated and fabricated by Magneco/Metrel, then evaluated for corrosion/erosion resistance at ANL. The microstructure and phase compositions are then characterized to gain an understanding of the corrosion/erosion degradation mechanism(s). Based on these evaluations, the refractory compositions and microstructures can be optimized for improved properties and performance.

Pumpable refractory materials developed to this point have proven to be among the best-performing materials in the world today for use in blast furnace trough runners. Currently, these materials are also being used in torpedo and iron-mixing ladles, reheat furnace hearths, and subhearths for steel processing in the United States, Canada, and Mexico. In cooperation with Magneco/Metrel, the Section is actively involved in preparing proposals to develop new and improved refractories and identify appropriate applications. This collaboration between Magneco/Metrel and ANL is an excellent example of a successful partnership between private industry and a national laboratory.

High-Temperature Mechanical Properties

We have concentrated our efforts on the steady-state deformation of a variety of important ceramics with the principal objectives of determining deformation mechanisms and kinetics and then relating the kinetics to self-diffusion. Tested materials include whisker-reinforced composites (Al_2O_3 containing SiC whiskers, Al_2O_3 toughened with ZrO_2 and containing SiC whiskers, and Si_3N_4 containing SiC whiskers), in-situ-reinforced Si_3N_4 , nonstoichiometric oxides, and most of the high-temperature superconductors. To illustrate some results, we have shown that the addition of SiC whiskers to Al_2O_3 inhibits grain-boundary sliding (gbs). The deformation mechanism changes from gbs to one of pure diffusion, with an activation energy close to that measured for cation grain-boundary diffusion. Most of the high-temperature superconductors deform by diffusional flow, and in the case of $\text{YBa}_2\text{Cu}_3\text{O}_x$ we have shown that deformation at the highest temperatures is controlled by the volume diffusion of Y, while at the lower temperatures, grain-boundary diffusion is the fastest path. These were the first measurements of diffusional kinetics in any of the high- T_c superconductors. In deformation, we have also demonstrated that dislocations introduced into Bi-Sr-Ca-Cu-O superconductors act as effective flux-pinning sites.

Oxygen Diffusion

This is a new program that will concentrate on oxygen diffusion in technologically important systems. Particular attention will be given to diffusion in potential perovskite-structured electrode materials for solid-oxide fuel cells in which ionic conductivity and oxygen diffusivity are critical parameters for efficient operation. Secondary ion mass spectrometry will be used to measure the ^{18}O diffusion profile after a diffusion annealing. The profile can be matched to the theoretical solution to the diffusion equation in order to extract an oxygen diffusivity. In addition, diffusion, electrical conductivity, and thermopower measurements will be used to construct a complete point-defect model for ZnO, an important material used for varistors.

Laboratory Exchange Program

The Ceramics Section continues to support ANL's laboratory exchange program, under which selected scientists from the research laboratories of U.S. corporations spend a year at ANL. At present, Dr. Subrata Banerjee, vice-president of product development at Magneco-Metrel, is working in the Ceramics Section to develop a new generation of refractory materials.

Recent Work by the Ceramics Section

Publications

Fabrication and Characterization of HTSC Coils Made from Bi-2223 Conductors

U. Balachandran, A. N. Iyer, P. Haldar (Intermagnetics General Corp.), J. G. Hoehn, Jr. (IGC), and L. R. Motowidlo (IGC Advanced Superconductors, Inc.)

INVITED Paper to be published in "Bismuth-based High Temperature Superconductors," May 1994.

Fabrication and Properties of Ag-Clad Bi-2223 Conductors and Magnets

U. Balachandran, A. N. Iyer, P. Haldar (Intermagnetics General Corp.), J. G. Hoehn, Jr. (IGC), and L. R. Motowidlo (IGC Advanced Superconductors, Inc.)

INVITED PAPER presented at 1994 Intl. Workshop on Superconductivity, Kyoto, Japan, June 6-9, 1994.

Melt-Processing of Y-Ba-Cu-O Superconductors for Improved Levitation

U. Balachandran, W. Zhong, J. E. Emerson, and R. L. McDaniel

Presented at 1994 Intl. Workshop on Superconductivity, Kyoto, Japan, June 6-9, 1994.

Recent Issues in the Fabrication of High- T_c Magnets and Long Length Multifilamentary Conductors

U. Balachandran, A. N. Iyer, P. Haldar (Intermagnetics General Corp.), J. G. Hoehn (IGC), L. R. Motowidlo (IGC Advanced Superconductors, Inc.), and G. Galinski (IGC Adv. Supercon.)

INVITED PAPER: Applied Superconductivity Vol. 2, No. 3/4, 1994, pp. 251-259.

Dense Ceramic Membranes for Partial Oxygenation of Methane to SYNGAS

U. Balachandran, J. T. Dusek, R. L. Mieville, R. B. Poeppel, M. S. Kleefisch (Amoco Research Center), S. Pei (Amoco Res. Ctr.), T. P. Kobylinski (Amoco Res. Ctr.), C. A. Udovich (Amoco Res. Ctr.), and A. C. Bose (Pittsburgh Energy Technology Center)

Submitted to Applied Catalysis A: General, Jan. 1994.

Processing and Properties of Ag-Clad Bi-2223 Tapes

U. Balachandran, A. N. Iyer, P. Haldar (Intermagnetics General Corp.), and L. R. Motowidlo (IGC Advanced Superconductors, Inc.)

INVITED PAPER to be published in Proc. 6th Ann. U.S.-Japan Joint Workshop on Superconductivity, Houston, TX, Dec. 6-7, 1993.

Recent Developments in Fabrication of Bi-2223 Conductors and Magnets

U. Balachandran, A. N. Iyer, P. Haldar (Intermagnetics General Corp.), J. G. Hoehn, Jr. (IGC), and L. R. Motowidlo (IGC Advanced Superconductors, Inc.)

INVITED PAPER to be published in Proc. 6th Ann. U.S.-Japan Joint Workshop on Superconductivity, Houston, TX, Dec. 6-7, 1993.

Grain Boundary Degradation of YBCO Superconductors Sintered in CO₂-Containing Atmospheres

U. Balachandran, K. L. Merkle, J. N. Mundy, Y. Gao (New Mexico Institute of Mining & Metallurgy), C. Zhang (San Jose State U.), D. Xu (SJSU), and G. Selvadurai (SJSU)

Submitted to Proc. Intl. Symp. on Grain Boundaries and Interfacial Phenomena in Electronic Ceramics, 1993 Pacific Rim Mtg., Nov. 7-10, 1993, Honolulu, HI.

Effect of Lead Content on the Formation of the 2223 Phase in the Bi-Sr-Ca-Cu-O System

M. Lelovic (U. of Pittsburgh), P. Krishnaraj (UP), N. G. Eror (UP), W. A. Soffa (UP), V. L. Richards (UP), and U. Balachandran

Submitted to Physica C, Sept. 1993.

Development of Ceramic Membranes for Partial Oxygenation of Hydrocarbon Fuels to High-Value-Added Products

U. Balachandran, S. L. Morissette, J. T. Dusek, R. L. Mieville, R. B. Poeppel, M. S. Kleefisch (Amoco Research Center), T. P. Kobylinski (Amoco Res. Ctr.), and C. A. Udovich (Amoco Res. Ctr.)

Proc. of Coal Liquefaction and Gas Conversion Contractors' Review Conf., Vol. 1, Sept. 1993, pp. 138-160.

Fabrication and Characterization of High-T_c Tapes and Coils Made from Ag-Clad Bi-2223 Superconductors

U. Balachandran, A. N. Iyer, C. A. Youngdahl, L. R. Motowidlo (IGC Advanced Superconductors, Inc.), J. G. Hoehn, Jr. (Intermagetics General Corp.) and P. Haldar (IGC)

INVITED PAPER submitted to Proc. of 3rd IUMRS-International Conf. on Advanced Materials, Toyko, Japan, Aug. 31-Sept. 4, 1993.

The Powder-in-Tube Processing and Properties of Bi-2223

U. Balachandran, A. N. Iyer, P. Haldar (Intermagetics General Corp.), and L. R. Motowidlo (IGC Advanced Superconductors, Inc.)

INVITED PAPER: J. of Metals, 45, 54-57 (Sept. 1993).

Fabrication, Properties, and Microstructures of High-T_c Tapes and Coils Made from Ag-Clad Bi-2223 Superconductors

U. Balachandran, A. N. Iyer, C. A. Youngdahl, L. R. Motowidlo (IGC Advanced Superconductors, Inc.), J. G. Hoehn, Jr. (Intermagetics General Corp.), and P. Haldar (IGC)

To be presented at Intl. Cryogenic Mater. Conf., Albuquerque, NM, July 12-16, 1993, and for publication in Advances in Cryogenic Engineering, Vol. 40, 1993.

Processing of YBCO Superconductors for Improved Levitation Force

U. Balachandran and W. Zhong

Proc. of 1st Intl. Conf. on Processing Materials for Properties, Nov. 7-10, 1993, Honolulu, HI, pp. 195-198.

Microstructure and Associated Properties of $\text{YBa}_2\text{Cu}_3\text{O}_x$ Superconductors Prepared by Melt-Processed Techniques

U. Balachandran, W. Zhong, C. A. Youngdahl, and R. B. Poeppel

INVITED PAPER: J. Electronic Materials, Vol. 22, No. 10, 1993.

Development of Commercially Viable High- T_c Bi-2223 Superconductor Tapes

U. Balachandran, C. A. Youngdahl, P. Haldar (Intermagetics General Corp.), and L. R. Motowidlo (IGC Advanced Superconductors, Inc.)

INVITED PAPER for Proc. of SC GLOBAL 93-Intl. Superconductor Applications Convention, San Jose, CA, Feb. 1-3, 1993.

Review of "Ceramic Transactions, Vol. 24: Point Defects and Related Properties of Ceramics," edited by T. O. Mason and J. L. Routbort

U. Balachandran

INVITED PAPER: Ceramics Abstracts, The Amer. Ceram. Soc., Nov. 1992.

Ceramic Membranes for Generation of Partial-Oxidation Products from Methane

U. Balachandran, J. T. Dusek, S. M. Sweeney, R. L. Mieville, P. S. Maiya, M. S. Kleefisch, S. Pei (Amoco Research Center), T. P. Kobylinski (Amoco Res. Ctr.), and A. C. Bose (Pittsburgh Energy Technology Center)

INVITED PAPER submitted to Proc. of Symp. on Alternative Routes for the Production of Fuels, Amer. Ceram. Soc. Natl. Mtg., Washington, DC, Aug. 21-16, 1994.

Fabrication of Ceramic-Membrane Tubes for Direct Conversion of Natural Gas

U. Balachandran, S. L. Morissette, J. J. Picciolo, J. T. Dusek, R. B. Poeppel, S. Pei (Amoco Research Center), M. S. Kleefisch (Amoco Res. Ctr.), R. L. Mieville (Amoco Res. Ctr.), T. P. Kobylinski (Amoco Res. Ctr.), and C. A. Udovich (Amoco Res. Ctr.)

Published in Proc. of 1992 Intl. Gas Research Conf. (IGRC 92), Orlando, FL, Nov. 16-19, 1992, pp. 565-573.

Recent Results in Characterization of Melt-Grown and Quench-Melt-Grown YBCO Superconductors

U. Balachandran, R. B. Poeppel, and A. K. Gangopadhyay (Northwestern U.)

INVITED PAPER: Proc. of T_c SUH Workshop on HTS Mater., Bulk Processing, and Bulk Applications, Feb. 27-28, 1992, Houston, TX, pp. 294-300.

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W. Wu, C.-Y. Chu, K. C. Goretti, and J. Routbort

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Programs of the Corrosion Section address specific concerns related to corrosion and the effects of various environments on mechanical behavior of materials used in several types of energy systems. The research is sponsored by various divisions of the Department of Energy (DOE), the Nuclear Regulatory Commission, and another DOE Laboratory. Research on aqueous, gaseous, and liquid-metal corrosion, thermodynamics and kinetics of gas/solid reactions, and high-temperature mechanical properties in three major program areas is summarized below.

Light Water Reactors

Fatigue and environmentally assisted cracking (EAC) of piping, pressure vessels, and core components in light water reactors (LWRs) are important concerns as extended reactor lifetimes are envisaged. Degradation in U.S. reactors includes fatigue of austenitic stainless steel (SS) in emergency core cooling systems and pressurizer surge-line piping in pressurized water reactors (PWRs), intergranular stress corrosion cracking (IGSCC) of austenitic SS piping in boiling water reactors (BWRs), and propagation of fatigue or stress corrosion cracks (which initiate in sensitized SS cladding) into low-alloy ferritic steels in BWR pressure vessels. Similar cracking has also occurred in upper-shell-to-transition-cone girth welds in PWR steam generator vessels, and cracks have been found in steam generator feedwater distribution piping. Occurrences of mechanical-vibration- and thermal-fluctuation-induced fatigue failures have been seen in LWR plants. Another concern is failure of reactor-core internal components after accumulation of relatively high fluence. The general pattern of the observed failures indicates that as nuclear plants age and the neutron fluence increases, many apparently nonsensitized austenitic materials

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become susceptible to intergranular failure by a degradation process commonly known as irradiation-assisted stress corrosion cracking (IASCC). Failures have been reported for components subjected to relatively low or negligible stress levels, e.g., control-blade sheaths and handles and instrument dry tubes of BWRs. Although most failed components can be replaced, some safety-significant structural components, such as the BWR top guide, shroud, and core plate, would be very difficult or impractical to replace. Our NRC-sponsored research has focused on (a) fatigue of ferritic steels used in piping, steam generators, and pressure vessels; (b) EAC of cast austenitic SSs; and (c) IASCC in high- and commercial-purity (HP and CP) Type 304 SS specimens from control-blade absorber tubes and a control-blade sheath used in operating BWRs. Work on thermal aging embrittlement of cast SSs has been completed.

Fatigue Testing of Carbon Steels and Low-Alloy Steels in Simulated Reactor Coolant Environments

Plain carbon steels are used extensively in PWR and BWR nuclear steam supply systems as piping and pressure vessel materials. The steels of interest for these applications include A106-Gr B and A333-Gr 6 for seamless pipe and A302-Gr B, A508-2, and A533-Gr B plate for pressure vessels. Fatigue tests have been conducted on A106-Gr B carbon steel and A533-Gr B low-alloy steel to evaluate the effects of oxygenated water on fatigue life of these steels. For both steels, environmental effects are modest in PWR water at all strain rates. The data in the two graphs below confirm the strong dependence of fatigue life on strain rate in oxygenated water. Fatigue life saturates at some low value, e.g., between 0.0004 and 0.001%/s in water containing ≈ 0.8 ppm dissolved oxygen (DO). Other data suggest that the saturation value of strain rate may vary with DO and sulfur content of the steel. Although the cyclic stress-strain and cyclic-hardening behavior of carbon and low-alloy steels is distinctly different, the degradation of fatigue life of these two steels with comparable sulfur levels is similar. The carbon steel exhibits pronounced dynamic strain

Total strain range vs. fatigue life for A106-Gr B and A533-Gr B steel at different strain rates in high-oxygen water at 288°C

aging, whereas strain-aging effects are modest in the low-alloy steels. Environmental effects on nucleation of fatigue cracks have also been investigated. The results suggest that high-temperature oxygenated water has little or no effect on crack nucleation.

Environmentally Assisted Cracking of Cast Austenitic Stainless Steels in Simulated BWR Coolant Environments

Cast-duplex SSs are used extensively in the nuclear industry in pump casings, valve bodies, piping, and other components in coolant systems of LWRs. The steels correspond to ASTM Specification A-351 grades CF-3, CF-3A, CF-8, CF-8A, and CF-8M, where the compositions of CF-3A and CF-8A fall within the composition limits of CF-3 and CF-8, but are further restricted to obtain ferrite/austenite ratios that result in higher ultimate and yield strengths. The molybdenum-free CF-3 and CF-8 grades contain low- and high-carbon concentrations (<0.03 and <0.08 wt.%, respectively) and are similar in composition to wrought Types 304L and 304 SS. The Mo-containing CF-3M and CF-8M grades with low- and high-C content are similar to Types 316L and 316 SS, respectively. After many years of service at reactor operating temperatures, these steels can undergo thermal aging embrittlement that is caused by precipitation and growth of a Cr-rich α' phase, an Ni- and Si-rich G phase, $M_{23}C_6$, γ (austenite) in the ferrite, and additional precipitation and/or growth of existing carbides at the ferrite/austenite phase boundaries. These compositional changes increase the tensile strength and decrease the impact energy and fracture toughness of the steels. Our work has shown that in general, the low-C CF-3 grade is most resistant to thermal embrittlement and the Mo-bearing high-C CF-8M grade is least resistant.

Cracking of cast SS components exposed to LWR coolants is rather infrequent compared to that of other pressure-boundary materials. However, through-wall cracks have occurred in manual gate valves made from CF-8M SS in the condensate return line in the emergency condenser system in a BWR. The purpose of our work is to (a) determine whether local compositional changes and concomitant increases in strength of the materials caused by thermal aging can influence EAC under cyclic loading in high-temperature water, and (b) establish whether CGR curves for wrought SS in high-temperature oxygenated water are applicable to cast grades of the steel in the as-received and thermally aged conditions.

Crack growth rate (CGR) tests have been conducted on fracture-mechanics specimens of CF-8M grade of cast SS in as-received and thermally aged conditions in air at 289°C to provide baseline information for comparison with results for wrought SSs in air in Section XI of the ASME Code and in oxygenated water. The results indicated that long-term thermal aging had no effect on CGRs of CF-8M SS in air. CGRs for as-received CF-3, CF-3M, CF-8, and CF-8M specimens and thermally aged CF-8 and CF-8M specimens are compared with predicted CGRs for wrought SSs in air and in water under the various loading conditions in the next figure. The lines denoted as $a_{\text{super}8.0}$ and $a_{\text{super}0.2}$ represent predictions from interim correlations that we developed for 289°C water containing ≈ 8 and ≈ 0.2 ppm DO. Predictions of the present correlation for wrought SS in air in Section XI of the ASME code are represented by the diagonal straight lines. Clearly,

Corrosion fatigue data for as-received CF-3, -3M, and -8M and aged CF-8M and -8 cast SS in water containing (A) 8 and (B) 0.2 ppm DO at 289°C. Diagonal lines correspond to crack growth in air in Section XI of the ASME Code. Dashed lines indicate predictions from a correlation for wrought SS.

the air curve is frequently nonconservative. The experimental CGRs for CF-8, -8M, and -3M specimens lie above the air line (solid curve), but for the most part are bounded by CGRs from the modified correlations for wrought SSs in water at 289°C. The CGRs of the CF-3M and CF-8M specimens (with carbon content of 0.018 and 0.065 wt.% and ferrite content of ≈ 5 and 27.8%, respectively) show the largest environmental enhancement in both the as-received and aged conditions. Metallographic evaluation of the specimens after the experiments indicated that the mode of cracking in CF-8M specimens in air was transgranular and that the crack path in all specimens in water favored the ferrite/austenite phase boundaries in the materials.

Irradiation-Induced Stress Corrosion Cracking of Austenitic Stainless Steels in Simulated BWR Water

Radiation-induced segregation (RIS) of alloying and impurity elements in austenitic steels irradiated to high-fluence in BWRs and PWRs is being investigated by scanning Auger microscopy to determine its role in IASCC of the steels. Although significant grain-boundary Cr depletion can play an important role in IASCC of thermally sensitized and irradiated components, we suspect that another primary process that involves trace impurity elements, which are not specified in the ASTM specifications, may contribute to IASCC of solution-annealed materials. These elements are typically associated with steelmaking processes and with fabrication of the actual components, i.e., elements associated with flux compounds, cutting agents, recycled scrap, and strengthening materials. Results of grain-boundary chemical analysis by Auger electron spectroscopy of specimens obtained from Type 304 SS components irradiated in operating BWRs were examined to determine the role of trace elements. Surprisingly, the susceptibility of slow-strain-rate-tensile (SSRT) specimens obtained from irradiated BWR components to

intergranular cracking correlates well with the grain-boundary concentrations of fluorine and vanadium shown in the next figure. Fluorine probably originates from welding electrodes or fluorspar, a compound frequently used as flux material by many producers of iron and steels (or from recycling of F-containing steel scrap), whereas V probably originates from ferrovanadium, a strengthening compound used extensively by most steelmakers. Fluorine seems to be trapped by certain types of precipitates, indicating an important role of precipitation in austenitic SSs.

Grain-boundary concentration of (A) F and (B) V vs. % IGSCC measured from SSRT tests of BWR neutron-absorber tubes and control-blade sheath irradiated to $\approx 2 \times 10^{21}$ n-cm⁻² ($E > 1$ MeV)

To further investigate the effects of alloy composition, fast-neutron dose rate, and fluence on IASCC of austenitic SS, numerous SSRT and miniaturized compact-tension fracture-toughness specimens were fabricated from 27 heats of steel (compositional variations of Types 304, 316, and 348 SS) and the specimens are being irradiated in the Halden, Norway, heavy boiling water reactor.

Fossil Energy

Studies of the high-temperature corrosion of metallic and ceramic materials are being conducted in simulated coal-gasification atmospheres and coal-combustion environments, typical of conventional pulverized coal-fired boilers, fluidized-bed systems, and low-NO_x boilers and High Performance Power Systems being developed by DOE under the Combustion 2000 program. The R&D effort is directed at establishing mechanisms of corrosion, predicting the onset of breakaway corrosion, and evaluating the role of stress and deformation in corrosion processes. Sulfidation resistance of structural alloys (namely, model Fe-Cr, Fe-Cr-Ni, and Fe-Cr-Al alloys with controlled additions of several refractory metals and rare earth elements) and oxide-dispersion-strengthened alloys (Fe-Al and Ni-Al intermetallic), is being evaluated by thermogravimetric tests, and postexposure microstructure of corrosion scales is being characterized by several electron/optical microscopy techniques. Alloy additions are made by bulk alloying, ion implantation, sputter deposit/ion beam mixing, and as coatings. Another major thrust of the program is to

evaluate the effects of corrosive environments on the tensile and creep properties of metallic alloys and fracture toughness properties of monolithic and ceramic/ceramic composite materials. Further, a collaborative program has been initiated between Fossil Energy and the Materials Division of Basic Energy Sciences in DOE to examine fundamental aspects of scaling in structural materials exposed to oxidizing environments.

Corrosion Behavior in Combustion Power Generation Systems

In support of the Combustion 2000 program, calculations were performed to evaluate the chemistry of gaseous and condensed products that arise in combustion of coal, and experiments are being conducted to evaluate corrosion performance and establish the role of corrosion in the degradation of mechanical properties of candidate materials. The chemistry calculations involve determination of the type and amount of combustion products over a wide temperature range (700-1700°C) at 1 atm pressure. In addition, nonequilibrium conditions due to kinetic factors are incorporated to assess their influence on the chemistry of condensed products in these environments.

A computer program, which is based on geometric programming and can be applied to a chemical system containing a large number of species, was used to calculate the chemistry of the products of coal conversion. Concentrations of all gaseous and condensed species were determined for a coal with two sulfur levels, temperatures, and air/fuel ratios. Of the 120 gaseous species considered, partial pressures of N_2 , CO_2 , H_2O , O_2 , SO_3 , HCl , NO , $NaCl$, Na_2SO_4 , $NaOH$, H_2 , H_2S , and S_2 were used to represent the chemistry of the coal-conversion products. The results showed that coal combustion forms a liquid phase that is essentially a silica-saturated silicate-sulfate condensate, with the components being largely $CaO \cdot SiO_2$, $Na_2O \cdot 2SiO_2$, $FeO \cdot SiO_2$, $MgO \cdot SiO_2$, Na_2SO_4 , and $NaCl$. At temperatures below 1177°C, partial pressures of $NaCl(g)$, $HCl(g)$, $NaOH(g)$, and $Na(g)$ change abruptly; a complex sodium aluminosilicate, $Na_2 \cdot Al_2O_3 \cdot 6SiO_2(s)$, tends to form; and the liquid silicate-sulfate condensate disappears. The $N_2(g)$, $H_2O(g)$, $CO_2(g)$, $O_2(g)$ species constitute ≥ 99 mol% of the total effluent in coal combustion. The partial pressure of $O_2(g)$ remains almost independent of temperature at 0.04 to 0.06 atm. The major sulfur-bearing species is SO_2 , which has partial pressures of 0.002-0.004 and 0.001-0.002 atm for high- and low-sulfur coals, respectively. At high temperatures, $NaOH(g)$ is the major sodium-containing species; below 1377°C, $NaCl(g)$ predominates. At temperatures above 1127°C, the partial pressures of $NaOH(g)$ and/or $NaCl(g)$ are $\approx 10^{-4}$ atm. Within the temperature range of 1127-1727°C, $HCl(g)$ and $NaCl(g)$ are the major chlorine-bearing species, the partial pressure of which varies within the relatively close range of 5×10^{-4} to 2×10^{-5} atm. Below 1127°C, the partial pressure of $NaCl(g)$ decreases with a decrease in temperature; however, partial pressure of HCl continues to stay at $\approx 10^{-4}$ atm. Partial pressures of $O_2(g)$, $CO_2(g)$, $H_2(g)$, $NaCl(g)$, $NaOH(g)$, and $HCl(g)$ appear to be independent of the amount of sulfur in the coal.

Experimental work involves procurement of materials such as highly alloyed metallic alloys, monolithic ceramic materials, metal-matrix ceramic composites and ceramic-matrix ceramic composites, and laboratory testing of these materials in air and in simulated combustion atmospheres. Salt and ash/slag mixtures are included in the study for evaluation of deposit effects on corrosion processes. The ultimate goal of the program is to

assess the materials from the standpoint of corrosion performance, mechanical integrity, microstructural stability, and long-term durability for application in heat transfer surfaces in High Performance Power Systems.

In support of fluidized-bed combustion (FBC) materials development, extensive testing of candidate materials has been conducted in simulated combustion environments in laboratory test facilities and in a 1.8 x 1.8 m advanced fluidized-bed combustion unit at the Rockwell International Energy Technology Engineering Center (ETEC) in El Segundo, CA. The laboratory tests examined the role of gas chemistry, sulfur sorbent, metal temperature, and cycling of gas chemistry on the corrosion of heat exchanger and tube support materials in FBC systems. The results showed that deposits of sulfated sorbent alone can lead to sulfidation of low-alloy steels. Austenitic alloys developed (Ca, Cr) oxide and/or chromia scales at steam temperatures but exhibited significant intergranular sulfidation at air-heater temperatures. Gas-cycling experiments showed that sulfidation can be triggered even in Type 310 SS (normally resistant to sulfidation attack) with a cycle time of 100 h and with gas chemistry varied between oxidizing and reducing environments. Application of reagent-grade CaSO_4 (simulating deposits in a bubbling FBC) and circulating fluid-bed (CFB) ash deposits showed acceptable corrosion behavior for a number of high-chromium austenitic alloys in CFB atmospheres, and to a limited extent in bubbling-bed conditions.

A test program was completed on the high-temperature corrosion performance of materials for application in coal-fired open-cycle magnetohydrodynamic (MHD) power generation. The R&D program showed that the corrosion mode of advanced alloys was predominantly oxidation, with some intergranular penetration of the alloy substrate. Corrosion occurred primarily as a solid-state reaction between the oxygen/sulfur in the environment and the alloy constituents. No liquid-phase corrosion product (similar to pyrosulfates or alkali-iron trisulfates in conventional coal-fired boilers) was observed in any of the tests conducted. Several advanced alloys exhibited corrosion rates of <0.5 mm/y at 760°C and will be suitable for intermediate-temperature air-heater service. The selection of an alloy for long-term application in MHD balance-of-plant components will be dictated by the extent of grain-boundary oxidation/sulfidation of the base alloy. Based on laboratory test data, a number of advanced alloys can give acceptable performance in an MHD steam bottoming plant.

Corrosion Behavior in Coal Conversion Systems

In coal-gasification and integrated gasification combined-cycle (IGCC) system environments, the gas chemistry is such that oxygen partial pressures are relatively low and sulfur partial pressures are moderate to high, depending on sulfur content of the coal feedstock. In such environments, structural materials are subjected to sulfidation attack and catastrophic corrosion, especially at elevated temperatures. Because the major objective in the development of corrosion-resistant alloys is to form a slow-growing scale that is well bonded to the substrate alloy, research is underway to modify the surface regions of the alloy for enhanced nucleation-growth of the oxide scale in the early stages of alloy exposure. Surfaces have been modified by implantation of Nb or Y so as to alter the chemical composition of the surface/subsurface regions and influence the scaling during early stages of exposures at elevated temperatures. Coatings have been developed via pack

cementation, low-pressure plasma spray, sputter deposition, and electrospark deposition (ESD) techniques and were examined for corrosion resistance in sulfur-containing atmospheres. Tests were conducted to evaluate the sulfur resistance of coatings, determine the influence of coating technique on corrosion, and compare the corrosion rates of coated and uncoated structural alloys in simulated gasification atmospheres. The results showed substantial improvement for pack cementation coatings and an ESD Cr carbide/Al coating in these reducing environments. Silicon or silicon-plus-oxygen sputter deposition resulted in substantial improvement in corrosion performance of an Fe-25%Cr alloy in simulated high-sulfur environments, typical of coal gasification systems (see the next figure). Research is in progress to develop oxide-dispersion-strengthened bulk alloys and to modify surfaces of several engineering alloys to improve their corrosion resistance in environments typical of coal-fired systems.

Weight change-exposure time data for Fe-25 wt.% Cr alloy in the uncoated condition and with Si or Si plus O sputter coatings exposed to a high-sulfur mixed-gas environment at 700°C

An extensive creep test program was conducted to evaluate the role of sulfur-containing environments on the creep properties of Alloy 800 and Type 310 stainless steel and to establish the role of sulfur in the scaling process, creep crack propagation, and rupture life. Tests were conducted in a temperature range of 650-927°C in air, low- pO_2 , and O/S mixed-gas environments. In addition, tests were conducted sequentially in a sulfur-free, low- pO_2 environment and then in an H_2/H_2S environment. The next figure shows creep-strain versus time curves for specimens tested at 843°C in several environments at an applied stress level of 55.2 MPa.

In the absence of sulfur in the test environment, the creep properties of Alloy 800 are improved in low- pO_2 atmospheres over those obtained in air. In O/S mixed-gas environments, the alloy exhibited minimal effect when pO_2 (test) > pO_2 (Cr oxide/Cr sulfide transition boundary). The alloy exhibited substantial reductions in creep life and creep-rupture ductility when pO_2 (test) < pO_2 (transition boundary). Average creep-rate values for accumulation of 5% strain calculated from creep-strain-versus-time data showed negligible effect due to variations in test-gas chemistry. Extensive microstructural analyses conducted

Creep-strain-versus-time curves for specimens tested at 843°C at an applied stress of 55.2 MPa in several gaseous environments. Letters and numbers in parentheses represent sample identification.

on several of the tested specimens indicated that creep performance of the materials is predominantly influenced by corrosion behavior of the alloy in different exposure environments.

Fusion Energy

Structural materials in a fusion reactor will be cooled by either a liquid-metal or aqueous coolant while undergoing displacement damage and transmutation reactions that produce hydrogen and helium atoms within the materials due to 14-MeV-neutron irradiation. Austenitic SSs, ferritic steels, and vanadium-base alloys are likely candidates for the first wall and divertor in the International Thermonuclear Experimental Reactor (ITER) and in subsequent power-producing fusion reactors. Current research is directed toward the acquisition of material-property data for design and construction of ITER and subsequent reactors. Studies include evaluations of the tensile, creep, fracture-toughness, and swelling properties of vanadium-base alloys after fast-neutron irradiation in Hanford Engineering Development Laboratory's Fast-Flux Test Facility at 420 and 600°C, and development of electrically insulating coatings on vanadium-base alloys in liquid lithium. Work on aqueous SCC of austenitic SSs in oxygenated water has been completed.

Effect of Dynamically Charged Helium on Mechanical Properties of V-4Cr-4Ti Alloy

Vanadium-base alloys are attractive for structural materials in fusion reactors because of their good mechanical, corrosion, and irradiation performance. However, some alloys exhibit high (>250°C) ductile-brittle transition temperatures (DBTTs), which would make them unacceptable. V-4Cr-4Ti has been reported to be virtually immune to irradiation embrittlement under conditions of negligible helium generation; the DBTTs determined from irradiated one-third-size Charpy-impact specimens were <-200°C. The effects of dynamically charged helium and tritium, and of neutron damage, on DBTT of the alloy were determined after irradiation in the Dynamic Helium Charging Experiment (DHCE).

Transmission electron microscopy (TEM) disks irradiated to 18–31 displacements per atom (dpa) at 425 and 600°C were fractured by repeated bending in a low-temperature bath. Miniature specimens were used because no Charpy-impact specimens were included in the DHCE experiment. Ductile-brittle transition behavior, shown in the next figure, was determined from quantitative scanning-electron-microscopy (SEM) fractography. Brittle fracture surface morphology was not observed at $>-120^{\circ}\text{C}$ regardless of the level of dpa damage or helium and tritium content in the alloy. Predominantly brittle-cleavage fracture morphologies were observed only at -196°C in some specimens irradiated to 31 dpa at 425°C and in which the estimated helium and tritium contents were highest. This indicates a DBTT between -175 and -200°C in specimens containing the highest levels of dpa damage, helium, and tritium in the DHCE experiment. No intergranular fracture was observed.

Swelling and Structure of Vanadium Alloys Irradiated in the Dynamic Helium Charging Experiment

The combined effects of dynamically charged He and neutron damage on density change, void distribution, and microstructural evolution of V-4Cr-4Ti have been determined after irradiation to 18–31 dpa at 425 and 600°C in the DHCE. For specimens irradiated to ≈ 18 dpa at 600°C with an estimated He/dpa ratio of 3–9 appm He/dpa (a range similar to the fusion-relevant ratio of ≈ 5 appm He/dpa), only a few microvoids were observed at the interface of the grain matrix and some Ti(O,N,C) precipitates. No microvoids were observed either in the grain matrix or near grain boundaries. It seems

Percent ductile-fracture morphology of DHCE specimens irradiated at 600 and 425°C vs. test temperature. Results from nonirradiated and non-DHCE specimens are shown for comparison.

that most of the dynamically produced He atoms are trapped in the grain matrix without significant void nucleation or growth. In this group of DHCE specimens, density changes were similar to those of non-DHCE (negligible He generation) specimens for a comparable fluence and irradiation temperature. Significant numbers of microvoids in the grain matrix and on localized grain boundaries were present only in specimens irradiated to ≈ 31 dpa at

425°C in high-tritium capsules, in which an excessive amount of helium was generated (estimated He/dpa ratio of 10–35 appm). Discontinuous regions of void segregation on grain boundaries were observed, and void number-density was significantly lower than in other alloys irradiated in tritium-trick experiments. The grain-boundary voids seem to have been produced by decay of tritium segregated to grain boundaries in the specimens at the onset of irradiation in high-tritium capsules (an artifact effect similar to tritium charging at 400°C in a tritium-trick experiment), rather than by segregation of He produced in the grain matrix. The next figure shows that density changes of the specimens were significantly higher than those from non-DHCE irradiations. Microstructural

Density changes of V-4Cr-4Ti from DHCE and non-DHCE specimens: (A) 600°C and (B) 425°C

evolution in V-4Cr-4Ti was similar for DHCE and non-DHCE irradiations, except for void number-density and distribution. As in non-DHCE specimens, irradiation-induced precipitation of ultrafine Ti_5Si_3 was observed for irradiation at 600°C but not at 425°C.

Development of Electrical Insulator Coatings for Liquid-Metal Blanket Applications

Corrosion resistance of structural materials and magnetohydrodynamic (MHD) force and its influence on thermal hydraulics are major concerns in the design of liquid-metal cooling systems for fusion first-wall/blanket applications. Vanadium-base alloys (e.g., V-5Cr-5Ti) are leading candidate materials for structural applications in a fusion reactor. The objective of this study is in-situ development of stable corrosion-resistant coatings, as well as insulator coatings at the liquid-metal/structural-material interface. The insulator coatings should be capable of forming on various shapes such as the inside of tubes or irregular shapes during operational conditions to prevent adverse currents generated by MHD forces from passing through the structural walls. The coatings could also improve general corrosion resistance and act as a diffusion barrier for hydrogen isotopes, i.e., deuterium and tritium.

AlN and CaO are prime candidates for electrically insulating the V-alloy first wall in the self-cooled concept for the International Thermonuclear Experimental Reactor. Several

methods are being evaluated for fabricating coatings that possesses adequate thickness and desirable physical, electrical, chemical, and mechanical properties.

The electrical resistance of a CaO coating produced on V-5Cr-5Ti by exposure of the alloy to liquid Li that contained 4 at.% dissolved Ca is shown in the next figure as a function of time at 698°C. The solute element, Ca in liquid Li, reacted with dissolved oxygen in the alloy substrate at 420°C to produce a CaO coating. The resistance of the coating layer was $\approx 0.4\text{--}1.3\ \Omega$ at 698°C. Thermal cycling between 267 and 698°C changed the resistance of the coating layer, which followed insulator behavior. These results suggest that thin homogeneous coatings can be produced on variously shaped surfaces by controlling the exposure time, temperature, and composition of the liquid metal. This coating method is

*In-situ electrical resistance of CaO coating
in liquid Li containing 4 at.% Ca, as a
function of time at 698°C*

applicable to reactor components of various shapes (e.g., inside/outside of tubes, complex geometrical shapes) because the coating is formed by liquid-phase reaction. The liquid metal can be used over and over because only the solutes are consumed within the liquid metal.

In ongoing work, aluminum nitride coatings on a V-base alloy were also prepared by a commercial physical deposition technique. The specimens exhibited $\approx 10\text{-}\mu\text{m}$ -thick coatings of pure AlN, which was found to be an electrical insulator. Procedures are presently being developed to characterize these coated samples and also to measure their electrical resistivity as a function of temperature and thermal cycling exposures.

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Patents

Iron-Based Alloys with Corrosion Resistance to Oxygen-Sulfur Mixed Gases

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J. H. Park

Patent application filed May 11, 1994; ANL-IN-94-022.

Surface Modification of High Temperature Iron Alloys

J. H. Park

Patent application filed Oct. 11, 1993; ANL-IN-91-95.

Mechanics of Materials

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The programs carried out by the Mechanics of Materials Section may be divided into three broad areas: (a) mechanical testing and component examination and analysis in support of light water reactor (LWR) and integral fast reactor (IFR) technology, (b) mathematical modeling and analysis of structures and systems in support of nuclear and nonnuclear energy development, and (c) fabrication and nuclear fuel reprocessing. Current work in the first area includes ongoing programs for the environmentally assisted cracking of LWR structural components, the review of aging issues for nuclear plant license renewal, the development of metallic waste forms for the integral fast reactor, and the analyses of failed components from operating nuclear power plants, together with a recently renewed program on the stress corrosion cracking (SCC) of candidate nuclear waste canister alloys. In addition, two recently completed programs are described briefly, namely the metallurgical examination and mechanical testing of material from the lower head of the Three Mile Island Unit 2 (TMI-2) nuclear reactor and the review of proposed materials of construction for safety system components in advanced LWRs.

In the second area, nuclear fuel behavior is being modeled for both LWRs and the IFR, as well as for the Advanced Neutron Source (ANS). Analytical research activities in support of fusion energy development include stress analysis and development of design criteria for the first wall of the International Thermonuclear Experimental Reactor (ITER), computer analysis of tritium breeding and transport in the ITER blanket, and analyses of plasma/first wall interactions in fusion reactors. Stress analysis studies are also being conducted in support of the advanced battery program. In the fabrication area, research is being conducted on fuel development and fabrication for the ANS, and support work for the Reduced Enrichment Research and Test Reactor (RERTR) is continuing. The fabrication of a series of dosimeters to demonstrate actinide burnup in EBR-2 while operating in the IFR mode has also been recently completed.

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LWR Mechanical Testing and Component Examination

Fatigue and Environmentally Assisted Cracking in LWRs

Experimental studies on the fatigue and environmentally assisted cracking of structural alloys in light water nuclear reactors are being conducted in conjunction with the Corrosion Section. These activities are described in detail in the chapter on the Corrosion Section.

Stress Corrosion Cracking Studies on Candidate Yucca Mountain Waste Container Alloys

The Yucca Mountain site in southern Nevada has been designated by Congress as the nation's first high-level nuclear waste repository, assuming further investigations confirm its suitability. In this repository, the metallic outer containers are intended to provide substantially complete containment of the nuclear waste for 300 to 1,000 years after emplacement. Limited groundwater containing dissolved Na^+ , Ca^{2+} , K^+ , Mg^{2+} , HCO_3^- , SiO_2 , SO_4^{2-} , and Cl^- may come in contact with the containers during that time, and stress corrosion cracking, corrosion, oxidation and embrittlement must be considered as possible degradation modes. The present program, sponsored by the U.S. Department of Energy under subcontract from Lawrence Livermore National Laboratory, focuses on the possible effects of the repository environment on crack growth rates in candidate container alloys.

Fracture-mechanics-type crack-growth-rate tests conducted to date on Types 304L and 316L SS and Incoloy 825 under high-load-ratio conditions (load ratio $R \geq 0.9$) at a stress intensity of $25 \text{ MPa}\cdot\text{in}^{1/2}$ revealed no measurable crack growth after 19,000 hours. Crack extension was observed for these three alloys in additional tests conducted in the same environment under the more severe conditions of greater stress intensities ($K_{\text{max}} = 27.4$ to $39.8 \text{ MPa}\cdot\text{m}^{1/2}$) and lower R values (0.2, 0.5 and 0.7). The observed growth rates are consistent with, but somewhat lower than, the 95% confidence limit upper-bound rates of austenitic stainless steel in air as published in the ASME Boiler and Pressure Vessel Code Section XI. More important, no environmental acceleration of crack growth under the test conditions is indicated. Crack-growth tests are continuing for Titanium Grade 12, Hastelloy C-4, Hastelloy C-22, and new heats of Incoloy 825.

Metallic Waste Forms for IFR Waste

Pyrochemical electrorefining to recover actinides from metal nuclear fuel is a key element of the Integral Fast Reactor (IFR) fuel cycle. The process separates radioactive fission products from the long-lived actinides and generates a lower waste volume with significantly less long-term toxicity as compared to spent nuclear fuels. The process waste forms include a mineral-based form that will contain fission products removed from an electrolyte salt, and a metal-based form that will contain metallic fission products, the fuel cladding, and process materials. Two candidate metal alloys, a stainless steel/zirconium alloy and a copper/aluminum alloy, are being considered for the IFR metal waste form, and ET is providing technical support to the Chemical Technology Division in the development and evaluation of these alloys.

Laboratory-scale experiments have been performed to evaluate the two candidate alloy waste forms and to explore the trade-offs and operating parameters in the waste form production steps. This work included melting and casting of alloys, microstructural examination, general corrosion tests, and compatibility tests of alloy matrix to encapsulating components. In addition, calculations were also performed to evaluate the ability of the waste form to tolerate radiogenic heating. These calculations indicate that both the steel/zirconium and copper/aluminum waste form matrices should have adequate tolerance to radiogenic heating. However, the laboratory-scale experiments indicate that the stainless steel/zirconium alloys offer a number of advantages in terms of mechanical strength and ductility, metallurgical characteristics, and simplicity of the overall waste form process. Based on the test results and the process designs, the steel/zirconium alloy has been selected as the preferred waste form matrix, and current work is focused on development of this matrix.

Review of Aging Issues for License Renewal

A substantial number of older nuclear power plants will reach the end of their initial 30-year licensing periods in the next 10-15 years, and the NRC is developing criteria for license renewal. One of the more important considerations in developing these criteria is properly accounting for component aging and time-dependent degradation processes. Accordingly, the NRC has initiated a program at ANL to review the technical literature with respect to generic aging effects and to critically evaluate the potential materials- and component-related aging issues.

Under the first phase of this program, ANL has been asked to conduct a comprehensive review of the technical literature generated under the NRC's Nuclear Plant Aging Research (NPAR) Program. A total of 99 NPAR reports, along with ≈ 180 NRC information notices and generic letters to nuclear plant license holders on materials and component reliability issues, have been identified for review. A review team made up of personnel from ANL's Energy Technology and Reactor Engineering Divisions has been assembled, the review procedure and format have been defined, and the review process is underway. Under Phases 2 and 3 of this program, the aging processes and mechanisms identified in this first phase will be critically evaluated for relevance and significance to license renewal, and a technical report documenting the findings of the review will be prepared.

TMI-2 Vessel Integrity Program

A program to determine the extent of damage suffered by the TMI-2 nuclear reactor as a result of the 1979 loss-of-coolant accident has been completed. The objectives were to determine a scenario for, and deduce the temperatures of, the steel in the lower vessel head during the accident; determine the mechanical properties of the steel from the lower head under the accident conditions; and assess the integrity of the TMI-2 vessel during the accident. This program was sponsored by the NRC and the Organisation for Economic Co-operation and Development (OECD), and the research was conducted by ANL, the Idaho National Engineering Laboratory (INEL), and participating member countries of the OECD.

Microstructural examinations of 15 samples recovered from the TMI-2 lower head by ANL, INEL, and participating OECD laboratories determined that a roughly circular "hot spot" approximately 0.9 m in diameter developed in one quadrant of the lower head during the accident, and that the maximum temperature at the center of the hot spot was $\approx 1100^{\circ}\text{C}$. Creep, tensile, and impact properties were determined for the lower head material by ANL and the OECD laboratories over a range of temperatures, and these properties were used by INEL to model the thermal and mechanical response of the lower head during the accident.

Materials for Advanced-Reactor Safety Systems

The materials of construction for two proposed advanced, passively safe light water reactor (LWR) concepts, namely the General Electric Simplified Boiling Water Reactor (SBWR) and the Westinghouse Advanced Passive 600 MWe Reactor (AP600), were reviewed in detail. This work was sponsored by the NRC as a part of possible licensing considerations. The objectives of these reviews were to (a) evaluate proposed advanced-reactor designs and the materials of construction for the safety systems, (b) identify all aging and environmentally related degradation mechanisms for the materials of construction, and (c) evaluate from the safety standpoint the suitability of the proposed materials for the design application. The safety-related systems selected for review for these two LWRs included (a) reactor pressure vessel, (b) control rod drive system and reactor internals, (c) coolant pressure boundary, (d) engineered safety systems, (e) steam generators (AP600 only), (f) turbines, and (g) fuel storage and handling system. In addition, the use of cobalt-based alloys in these plants was reviewed.

The selected materials for both reactors were generally sound, and no major selection errors were found. It was apparent that considerable thought had been given to the materials selection process, making use of lessons learned from previous LWR experience. The review resulted in the suggestion of alternate and possibly better materials choices in a number of cases, and several potential problem areas were cited.

Analysis of Failed Components from Nuclear Power Plants

This activity, which has been carried in the Mechanics of Materials Section for several years, is sponsored primarily by Commonwealth Edison Company, although analyses were also performed for Long Island Lighting Company and Northern States Power in the past two years. The objectives of the analyses are typically to determine the root cause(s) of failure and to suggest remedial action to avoid similar failures. Analyses performed in the past two years include several examinations of failed cemented WC seals from BWR coolant pumps and core shroud cracking from the Quad Cities and Dresden nuclear stations.

Mathematical Modeling and Analysis

Fuel Behavior in the Integral Fast Reactor: Fundamental Studies

Bias-driven growth of voids has been identified as a major swelling mechanism in the α -uranium phase of irradiated U-Pu-Zr metal fuels being developed at ANL for the Integral Fast Reactor (IFR). The trends in U-Pu-Zr swelling data prior to fuel/cladding contact can be interpreted in terms of unrestrained void swelling. It is theorized that the swelling mechanisms at work in the α -uranium phase can be modeled by single-vacancy and single-interstitial kinetics, thus avoiding the use of complicated defect-interaction terms required for the calculation of void nucleation. A mechanistic model has been developed wherein gas bubbles that are formed on α/δ phase boundaries during the incubation period act as potential nuclei for cavities. The model can predict both gas-bubble-driven swelling (overpressurized cavities) and bias-driven void swelling (underpressurized cavities), as well as the transition from one swelling mechanism to the other. Results of this study demonstrate that the relatively long incubation times characteristic of IFR swelling and gas release can be understood in terms of a reduced gas-bubble nucleation rate on the α/δ phase boundaries, i.e., the α/δ phase boundary lamellae are less efficient gas-bubble incubators than normal high-angle grain-boundaries. Results obtained with the model have been compared with U-10Zr and U-19Pu-10Zr deformation data, and with high-purity uranium swelling data.

Fuel Behavior in the Integral Fast Reactor: Fuel Element Modeling

The LIFE-METAL code has been developed to assess the steady-state thermal, mechanical, chemical/metallurgical, and irradiation performance of metallic (U-xPu-yZr) fuel elements with steel (316SS, D9, HT9) cladding. Emphasis over the past several years has been on validating and ensuring the quality of LIFE-METAL calculations in support of the efforts to develop a safety case for the conversion of EBR-II driver fuel to various U-Pu-Zr alloy fuels. Fuel data (e.g., axial strain, fuel gas release, and swelling) and cladding data (e.g., diametral strain and wastage depth profiles, as well as failure frequency) from >100 fuel element irradiations have been used to validate LIFE-METAL. In particular, fuel/cladding chemical/metallurgical interaction during normal operation and transients has been highlighted as a possible design-life-limiting mechanism. Under the direction of the modeling effort, the steady-state interaction data for cladding embrittlement have increased from several points to >80 points. Concurrently, the higher-temperature data base for fuel/cladding liquefaction has increased significantly. This has allowed substantial improvement in LIFE-METAL modeling, code validation, and design applications. Both best-fit materials model parameters and upper-bound design parameters have been determined for cladding penetration (by embrittling lanthanides) and fuel/cladding liquefaction. This reflects the dual purpose of LIFE-METAL as a materials modeling code and a design-analysis code. Other efforts have included development of first-principles fundamental models for solid/gaseous fission-product swelling and improved fuel and cladding models to allow better predictions of fuel/cladding mechanical interaction.

Advanced Neutron Source

Development of the design for the Advanced Neutron Source, a new high-flux research and test reactor, is underway at Oak Ridge National Laboratory. This reactor concept will require nuclear fuel to operate satisfactorily at temperatures and neutron flux levels never before encountered. The Section is modeling the behavior of fuels proposed for this reactor. A leading candidate is U_3Si_2 dispersed in a suitable matrix material. Recent modeling activities have focused primarily on an irradiation-induced crystalline/amorphous transition in U_3Si and U_3Si_2 .

A rate-theory model has been formulated wherein amorphous clusters are formed by the damage event. These clusters are considered centers of expansion (CE), or excess-free-volume zones. Simultaneously, centers of compression (CC) are created in the material. The CCs are local regions of increased density that travel through the material as an elastic (e.g., acoustic) shock wave. The CEs can be annihilated upon contact with CCs, forming either a crystallized region indistinguishable from the host material, or a region with a slight disorientation (recrystallized grain). The recrystallized grains grow by accumulating additional CCs.

Amorphization of a recrystallized grain is hindered by the presence of the grain boundary. Preirradiation of U_3Si above the critical temperature for amorphization results in the observed formation of nanometer-size grains. In addition, the subsequent reirradiation of these samples at temperatures below the critical level shows that the material has developed a resistance to radiation-induced amorphization. In the model, it is assumed that grain boundaries act as effective defect sinks, and that enhanced defect annihilation is responsible for retarding amorphization at low temperature. The calculations have been validated against data from ion-irradiation experiments with U_3Si and Si.

ITER Stress Analysis and Design Criteria

Anticipated thermal and internal pressure loadings on the proposed International Thermonuclear Engineering Reactor (ITER) blanket, particularly its first wall, are such that the material is likely to undergo cyclic plastic strain, raising concerns about possible fatigue and ratcheting failures. The Engineering Design Analysis phase of the ITER, which follows the Conceptual Design Analysis phase, is presently underway. In this phase, detailed designs for a reference shielding blanket (water-cooled Type 316 stainless steel) and a backup advanced breeding blanket (Li self-cooled V-alloy) are being prepared by the four home teams, together with the Joint Central Team (JCT) at Garching, Germany. A member of ET has been designated as Project Leader for the U.S. home team on ITER structural design criteria, and the ET Division is involved in conducting stress analysis in support of ITER blanket design.

Early in 1994, preliminary structural design criteria were developed and submitted to the ITER JCT at Garching for use in their analyses. In addition, an interim structural design criteria is being developed by an international committee that includes ET participation. A first draft of this interim structural design criteria is to be released in October 1994.

Preliminary stress analysis of the advanced blanket design has been conducted to show that transient thermal analyses of the pulse cycle will be needed to correctly predict the greatest stress range and thus the fatigue life of the first wall. During preliminary design, steady-state thermal analyses are usually conducted for plasma-on and plasma-off conditions; these analyses are adequate for designs that do not use a strongback. However, in blanket designs with a strongback, the large difference in thermal response times between the thin first wall and the thick strongback requires transient thermal and structural analyses to correctly estimate blanket fatigue life.

Analysis of Plasma/Material Interactions in Fusion Reactors

Modeling and analyses are being performed to study the effects of high thermal loadings from the plasma on the plasma-facing materials (PFMs) such as the divertor plate and first wall. The high thermal loads occur due to plasma instabilities (disruptions) that cause loss of plasma confinement during off-normal operations. Disruptions in tokamak reactors are of serious concern and present a potential obstacle for successful operation and reliable design. Erosion of plasma-facing materials due to thermal energy dump during a disruption can severely limit the lifetime of these components, thereby diminishing the economic feasibility of the reactor.

Three major areas must be investigated to correctly evaluate material response during a plasma disruption. These are target material thermodynamic response, vapor cloud hydrodynamics, and radiation transport. The figure on the next page is a schematic illustration of the various interaction zones and processes that occur during the plasma/material interaction following a disruption. This problem involves three moving boundaries: the vapor front, the receding surface, and the solid/liquid interface. These three moving boundaries are interdependent, and a complete solution should link them dynamically and simultaneously. A comprehensive model is developed in which the interplay of the major physical processes during the plasma/material interaction are taken into account. Models for thermal evolution of a material, plasma/vapor interaction physics, vapor hydrodynamics, and radiation transport have been developed, integrated, and perfected in a self-consistent way in sufficient detail to realistically simulate the effect of a disruption on plasma-facing components. Candidate PFMs such as beryllium and carbon were considered in the analysis. The dependence of the net erosion rate on the characteristics of the plasma/vapor interaction zone for both plasma ions and electrons is being analyzed. The effect of uncertainties in reactor disruption conditions on the net erosion rate is also being analyzed.

Results of disruption simulation indicate that plasma electrons will cause higher erosion rates than plasma ions having the same initial kinetic energy. Carbon ablation thickness is usually higher than that of beryllium under similar conditions. However, if the beryllium melt layer is lost during the disruption, beryllium erosion will be much higher than that of carbon-based materials. Higher disruption energy densities usually expend most of the energy in heating the front of the ablated vapor, causing more forward radiation away from the PFM and less backward radiation towards the divertor. This scenario will generally result in a modest increase in erosion rate compared to an increase in energy density.

*Schematic diagram of interaction zones and processes
during fusion reactor plasma/material interaction
after a disruption*

Models and Properties for Beryllium and Tritium-Breeding Ceramics

This task has expanded over the past several years from modeling tritium transport and retention in lithium-bearing ceramics to critically assessing the data base and developing models and correlations for use in design analysis for the thermal, mechanical, chemical compatibility, and tritium and helium performance of beryllium and lithium-based ceramics. This work has been guided by the needs of the TER program. Development and validation of the TIARA code for the prediction of tritium inventory in, and tritiated gas species released from, Li_2O has recently been completed and documented. TIARA is based on the mechanisms of bulk diffusion, surface desorption, solubility, and second-phase (LIOT) precipitation and has been validated to 20 data points for tritium inventory following in-reactor purge-flow tests. Also completed and documented recently under this task is the lithium-based ceramic and beryllium data base with input from the Russian Federation, the European Community, the United States, and Japan. This work was coordinated by this Section and is an ongoing task.

Because of the successful integration of data base and design-analysis needs in the solid breeder data base work, this task was expanded last year to include liquids that serve as both coolants and breeders (e.g., Li and Li-Pb). It is anticipated that the task will be expanded next fiscal year to focus primarily on coordinating the critical assessment and data-base documentation for all of the materials under consideration for the ITER first wall (i.e., austenitic and ferritic steels, vanadium-based alloys, beryllium, and copper-based alloys).

Stress Analysis for the Advanced Battery System

Together with SAFT (France), ANL is currently involved in a project funded by the U.S. Advanced Battery Consortium to develop an Li/FeS₂ battery for use in the automobile industry. In all of the various designs being considered for this battery, a critical component is the ceramic seal that acts as an insulator between adjacent cells. For the battery to operate efficiently, seal integrity must be maintained throughout the life of the battery. The ET Division is helping in this effort by conducting stress analyses for all the designs and ensuring that adequate safety margins are maintained against cracking of the seal due to fabrication and service stress. A second objective is to help analyze various mechanical loading tests being conducted by the ANL's Chemical Technology Division to measure the structural strength of the batteries and to use these tests to derive mechanical properties of various components and their interfaces.

Fabrication and Nuclear Fuel Development

Reduced-Enrichment Research and Test Reactor

The Reduced-Enrichment Research and Test Reactor (RERTR) program provides technical support for the nuclear nonproliferation policies of the federal government. The fundamental objective of this program is to develop and demonstrate technology for the conversion of nuclear facilities that use high-enriched uranium to low-enriched ($\approx 19.7 \pm 0.2\%$) uranium that cannot be readily diverted for weapons use. Test U₃Si₂ plates fabricated in the program have demonstrated very good irradiation performance at high fuel burnups, and these plates have been used in the conversion of numerous international research reactors to low-enriched fuel.

At present, the major priorities of the program are (a) fabrication of proof-of-concept ⁹⁹Mo irradiation targets to demonstrate low-enriched uranium (LEU) technology for the production of the medical radioisotope ⁹⁹Tc, (b) development of techniques and new fuel alloys to increase fuel loadings beyond the current levels and to demonstrate that all research reactors can be converted to LEU, (c) interaction with the Russian RERTR program to assist with the conversion of their research reactors to LEU fuel, and (d) continuation of technology transfer with domestic and foreign fabricators to improve the quality of plate-type elements.

Advanced Neutron Source Reactor

In addition to the fuel modeling work for the ANS described above, the Section is also involved in development and fabrication of fuels for this reactor concept. A third set of 18 "fuel holders" has been fabricated and is being prepared for shipment to ORNL for irradiation in the High Flux Isotope Reactor. The fuels under consideration include low-enriched U₃Si₂, medium-enriched U₃Si₂, and high-enriched U₃Si, U₃Si₂, UAl₂, and U₃O₈.

A cooperative effort with Babcock & Wilcox has focused on the development of fabrication techniques to produce fuel plates with state-of-the-art homogeneity.

Fundamental studies of fuel powder loading and rolling characteristics and their relationship to uniformity of fuel distribution have led to production of fuel plates with significantly improved homogeneity.

Fabrication of Actinide Burnup Dosimeters

Dosimeter capsules have been fabricated for EBR-II experiments to determine the fission and neutron capture rates in four minor actinides (Np^{237} , Pu^{240} , Am^{241} , and Am^{243}) that are responsible for the long-term radiological hazards of spent nuclear fuel. The EBR-II experiments will demonstrate that an IFR-type fast reactor can fission these nuclides at a rate sufficient to convert the radiological hazard of the nuclear waste to a short-term problem.

The dosimeters were fabricated for a ten-day run and three one-year runs at full power. Three nuclides (U^{238} , U^{235} , and Pu^{239}) are being inserted along with the four actinides as controls to compare their fission cross sections and yields with published data. Dosimeters with Co, Cu, Fe, Ni, and Ti ("light metals") are also included to further characterize EBR-II neutronics during the experiment.

A total of 212 vanadium metal dosimeters, with loadings of ≈ 7 to 9 mg of one of the above materials, were fabricated. Of these, the 95 light-metal dosimeters were fabricated by ANL Central Shops; 45 U^{238} , U^{235} , and Pu^{240} dosimeters prepared by ORNL for a previous experiment were inspected and passed; and the remaining 72 dosimeters, including the high-irradiation actinides Np^{237} , Am^{241} , and Am^{243} were assembled, welded, and inspected in ET's glovebox fabrication facility. The very high radiation fields associated with these latter actinides, their alpha activity, and the extremely small size of the dosimeters (2.79-mm diameter x 3.05 mm length), posed numerous experimental handling problems during assembly. Nonetheless, the dosimeters were completed in time to meet the required EBR-II insertion deadline.

Removal of Contaminants from Copper and Aluminum Alloys

Two experimental activities are being conducted in conjunction with the Energy Systems Division to develop practical methods for removing or substantially reducing contaminant levels in commercial copper and aluminum alloys. The first of these activities involves the removal of lead from copper-based scrap and is being conducted under a Cooperative R&D Agreement (CRADA) between ANL and the Brass and Bronze Environmental Research Corporation. Lead is introduced unintentionally in the remelting of scrap or is added intentionally to improve machinability. In either case, its presence is objectionable when the alloy is to be used for plumbing fixtures and other components that have contact with drinking water. A number of slagging systems have been explored with unsatisfactory results, and present activities are focusing on the use of molten salt treatments of fabricated components to chemically remove lead exposed at the surface.

In the second activity, a process is being developed to remove antimony impurities from remelted aluminum scrap. Antimony is intentionally added to certain aluminum

casting alloys by some European manufacturers for microstructural refinement, but its introduction into other alloys through scrap remelting can adversely affect mechanical properties. Calcium metal additions have been found to be effective in reacting with and removing antimony, and melting experiments are being conducted to determine the kinetics of and optimize the process.

Support for Other Programs

The unique fabrication capabilities within the Section also support other ANL programs in such areas as casting, metalworking, and heat treatment. Recent examples include the development of techniques for the production of duplex HT-9 tubing lined with vanadium and the rolling of amorphous metal foils to 5 μm .

Recent Work by the Mechanics of Materials Section

Publications

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T. C. Wiencek, J. E. Matos (EP), and G. L. Hofman (FE-AW)

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Tribology

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The Tribology Section conducts research and development on low-friction and wear-resistant surface coatings and treatments applied to ceramic and high-temperature metal substrates, for use under high load and high temperatures in aggressive chemical atmospheres. These coatings are primarily intended to protect engine-component surfaces undergoing sliding and rolling contact in advanced transportation systems, including low-heat-rejection diesels, automotive gas turbines, and other new-generation engine systems being developed under the sponsorship of the DOE Office of Transportation Technologies, and U.S. industry. The overall goal of the Tribology Section is to promote industrial competitiveness by developing new tribological technologies and solving problems associated with friction, wear, and lubrication. The Section has established and maintained close contact with transportation-related industries to determine their critical tribological needs and to facilitate the transfer of technologies developed at ANL.

Engineered Tribological Interfaces

This project is aimed at exploring the factors that control the tribological properties of surfaces by the application of coatings and/or the use of surface-modifying treatments such as ion implantation. The major emphasis is on developing low-friction, highly wear-resistant surfaces that can endure extreme tribological conditions due to high loads, speeds, and temperatures. In recent months, Tribology staff have developed a variety of low-friction, high-wear-resistant coatings on ceramics and other engineering materials (such as superalloys, plastics, and composites) intended for utilization in components for low-heat-rejection diesels and other high-temperature advanced engines and engine power trains. Specific examples include the development and testing of soft metallic coatings on ceramic parts and piston ring/liner assemblies under conditions that simulate actual engine operation; development of diamond and diamondlike carbon (DLC) films on ceramic and metallic materials for friction and wear control under severe tribological conditions; development of solid/liquid lubrication concepts that have been demonstrated as effective

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in achieving very low friction and wear in ceramic components over wide ranges of temperatures and loads; development of ion-beam-mixed MoS₂ films on ceramic surfaces for ceramic bearings and space applications; development of wear-resistant nitride, carbide, and boride layers on steels and other alloys; and development of naturally occurring lubricious-oxide layers on superalloys for gas-turbine applications.

Our research focuses on three major areas: (a) development of low-friction and low-wear surfaces by a variety of surface-modification methods, including physical-vapor-deposition techniques (ion-beam-assisted-deposition, plasma sputtering, and thermal evaporation); (b) development of ultrahard, low-friction diamond, diamondlike, and other similar coatings by plasma-assisted chemical vapor deposition; and (c) tribological testing and characterization of surfaces before and after modification and coating.

Coating by Physical Vapor Deposition

A major effort in the Tribology Section has focused on the design and construction of a sophisticated and versatile facility for the ion-beam-assisted deposition of low-friction, low-wear coatings (see photo below). This facility consists of a large, ultrahigh-vacuum chamber with two individually controlled electron-beam evaporation sources and simultaneous or sequential ion sources that produce ions with energies from a few eV up to 1500 eV. A six-degree-of-freedom specimen manipulator, including rotational motion, ensures uniformity in the coating of irregularly shaped substrates and provides support and manipulation for complex engine components such as piston rings and liners. In addition, the Section has a large commercial sputtering apparatus for the deposition of multilayer metallic and lubricious coatings and recently has developed an ultrahigh-vacuum apparatus for depositing fullerene compounds as tribological coatings.

We have developed silver coatings on alumina, zirconia, and silicon nitride ceramic substrates, which reduced wear rates by factors of 10 to 3500, depending on load, temperature, velocity, and substrate. We also developed and tested soft metallic coatings on

Automotive parts being loaded into the ion-beam-assisted deposition chamber for coating with diamondlike carbon (Photo © R. A. Erck, 1993)

ceramics and piston ring/liner assemblies under conditions that simulate actual engine operation. Recent tests with synthetic liquid lubricants show a synergistic effect on both wear and friction, with improvements in both properties when a liquid lubricant is used in conjunction with a silver-coated ceramic. With the simultaneous use of silver and synthetic oil, the friction coefficients were reduced by factors of 3 to 10 from that with oil alone, depending on test temperature (e.g., from 0.15 to 0.05 at room temperature, and from 0.13 to 0.015 at 300°C). Furthermore, in most cases, wear was reduced to unmeasurable levels even during tests at high temperatures and loads.

Deposition of boron, boron oxide, Re, Ce, and Ni coatings on Ni-base superalloys dramatically reduces wear and provides low coefficients of friction (<0.3) at high temperatures. This study aims to develop new surface alloys that will result in the formation of lubricious oxides through the selective and/or collective oxidation of elemental species at high temperatures. The low-friction mechanisms of these coatings are due mainly to the formation of a soft oxide layer in open air. Some oxides can form a low-melting point eutectic that acts as a grease at high temperatures. This research will have significant impacts on the development of advanced turbine engines. Currently, collaborative work is underway with GM-Allison to implement the research findings for automotive gas turbine applications.

To prevent absorption of fuel (and the resulting degradation of engine efficiency) by thick thermal barrier coatings (TTBCs) used in advanced diesel engines, we have developed dense metallic seal coatings. With IBAD processing, we found that a thin, dense metallic coating (Ag or an Nb/Cr alloy) could be deposited on porous zirconia TTBCs, with the coating filling or covering large open pores that intersect the surface.

Diamondlike carbon films reduce friction and provide wear resistance on ceramic and metallic engine parts (fuel injection components, valve stems, etc.) under severe tribological conditions. Our laboratory tests indicate that DLC coatings dramatically reduce friction and afford excellent wear resistance to sliding surfaces of ceramic and steel components. These coatings ensure excellent durability and wear performance at temperatures up to about 300°C.

Plasma-Assisted Chemical Vapor Deposition of Diamond and Diamondlike Coatings

The Tribology Section's microwave plasma deposition source allows production of diamond, DLC, and similar ultrahard coatings on ceramics and other high-temperature materials. The main thrust of this effort is production of smooth, adherent diamond films that serve as lubricious, wear-resistant coatings without causing severe wear of mating components. Initial efforts were directed at forming smooth, thick diamond films at high deposition rates of up to 1 $\mu\text{m/hr}$. A multistep microwave-plasma-deposition process was recently developed to deposit relatively smooth diamond films on rough-surfaced films. Gas-phase chemistry and deposition parameters were effectively controlled in order to improve adhesion and tribological properties of diamond films deposited on pure elements (e.g., Si) and advanced ceramics (such as SiC and Si₃N₄). Preliminary evaluation of these coatings indicates that very low friction coefficients (0.2-0.3) can be achieved with these

High-temperature pin-on-disk apparatus used for evaluating tribological properties of lubricious oxides

coatings and that wear of underlying substrates can virtually be eliminated. Unlike DLC coatings, diamond coatings appear to have much better temperature durability; tests at up to 400°C revealed no problems.

Tribological Testing and Surface Characterization

In support of our coating and surface-modification research, we have developed extensive state-of-the-art facilities for tribological evaluation and surface characterization. These facilities include two high-temperature pin-on-disk tribometers; an oscillating-slider wear-test machine for dry and lubricated testing at temperatures up to 900°C; a pin-on-disk machine for dry and lubricated testing at room temperature; a high-resolution surface profilometer, and an adhesion-force tester. Computerized control and digitized data acquisition systems are used extensively with these test machines for better data management and accuracy.

Our surface-characterization equipment includes a JEOL 840A scanning electron microscope with built-in energy- and wavelength-dispersive X-ray analysis, and an ultramicrohardness tester for in-situ measurements of the hardness of extremely thin films. Furthermore, a number of other surface and structure characterization systems available throughout ANL are often used to elucidate friction and wear mechanisms of coatings and other tribomaterials.

Program Direction

Over the years, the Tribology Section has established close contact with transportation-related industries to determine their critical tribological needs and to facilitate the transfer of technologies developed at ANL. Currently, the Section is teamed with several large and small companies through contract agreements to develop new tribological technologies that can reduce overall emissions and improve fuel efficiency in advanced transportation systems. Specifically, surface engineering of lightweight materials such as plastics, ceramics, and aluminum alloys is underway to explore the potential of these materials for new-generation vehicle applications. Research on diamond and DLC coatings is gaining strength and becoming oriented toward such demanding engine applications as fuel-injection plungers, valve stems, and seals. Work on lubricious oxides is also continuing, with the focus turning toward automotive gas turbine applications. In addition, we have participated in extensive technology-transfer activities that included several visits and meetings with the representatives of major industrial companies (some of these interactions resulted in a number of CRADA proposals), on-site technical assistance, and the organization of several technical sessions for the annual ASME/STLE Tribology conference, the annual STLE conference, and the ICMC conference.

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U.S. Department of Energy Tribology Program Seeks Application for Diamond Films in Transportation Industry

F. A. Nichols and J. M. Perez (DOE)

INVITED PAPER: in *Finer Points*, 4, No. 3 (1992) pp. 8-25.

Polycrystalline Diamond Films

X. Z. Pan, G. R. Fenske, and R. H. Lee

DOE-OTM Tribology Program Semiannual Progress Report, April-September 1992, Feb. 1993.

Irradiation Performance

Section Manager: L. A. Neimark

Principal Investigators: A. G. Hins, H. Tsai

Support Staff: A. B. Cohen, D. A. Donahue, J. E. Sanecki

Salaried Staff and Technicians: L. F. Essenmacher, D. J. Evans, W. C. Kettman,
F. Pausche, Jr., D. O. Pushis, F. E. Savoie

Secretary: E. L. Hartig

Visiting Scientist: K. Yamamoto¹

The principal objective of the programs in this Section is to determine and assess the behavior of materials, principally fuels and claddings, in the core environment of nuclear reactors, and to identify research and development areas as necessary. This environment results in neutron damage and chemical, metallurgical, and mechanical processes that occur at high temperatures. The Section's activities have focused on fuel development for liquid-metal-cooled reactors and the Advanced Neutron Source reactor at Oak Ridge National Laboratory. New initiatives include the investigation of first-wall materials for fusion reactors, and the characterization of DOE-owned spent nuclear fuel. The Section operates the Alpha-Gamma Hot Cell Facility (AGHCF) and the Irradiated Materials Laboratory (IML), in which it conducts postirradiation examinations and investigations.

Fuel Development

Integral Fast Reactor

The Integral Fast Reactor (IFR) program is ANL's initiative for developing an inherently safe liquid-metal-cooled reactor (LMR) in combination with an integral fuel-reprocessing facility. The fuel cycle is based on U-Pu-Zr alloy fuel, a system first explored at ANL in the 1960s. The Section's current activities include lead responsibilities for prototype fuel-rod irradiation tests completed in the Fast Flux Test Facility (FFTF); a fuel-design variables test, and a series of transient overpower tests in EBR-II; and investigation of irradiated and unirradiated fuel/cladding compatibility under off-normal conditions. The Section also performs destructive examination of EBR-II fuel rod experiments for the ANL Fuels and Engineering Division. Also, a joint effort with the Reactor Engineering Division is investigating the behavior of whole irradiated fuel pins under simulated off-normal conditions in the AGHCF. The Section is also assisting the Chemical Technology Division in evaluating the lithium-salt reduction of LWR fuel as part of the Actinide Recycle Program. The IFR has accounted for a significant fraction of the Section's activities.

¹Japanese Power Reactor and Nuclear Fuel Development Corporation.

Advanced Oxide Transient Performance

The purpose of this LMR program is to investigate the transient overpower performance of advanced oxide fuel pin designs at slow ramp rates. This is a cooperative program between DOE and the Japanese Power Reactor and Nuclear Fuel Development Corporation. The program uses the unique capability of the EBR-II reactor for whole-core overpower events at slow ramp rates of 0.01 to 10%/s. Phase II of the program, begun in 1987, highlights advanced alloys for oxide fuels and is expected to be a seven-year effort. The Section's role is to conduct three transient overpower tests in EBR-II, conduct a series of whole-pin transient heating tests in the AGHCF, and perform all postirradiation examinations for the program's three experimenters in the AGHCF. The first of the overpower tests was conducted in early 1992, and the transient heating tests began in early 1994 after a series of preliminary check-out tests.

Uranium-Silicide Development

Lastly, the Irradiation Performance Section continues to support the development of U_3Si_2 fuel for the Advanced Neutron Source Reactor at Oak Ridge National Laboratory. The capabilities of the AGHCF in characterizing irradiated materials are being used in this program.

Fusion Materials

The Section has the responsibility for the design, fabrication, and irradiation of an experiment in EBR-II to investigate the irradiation behavior of vanadium-base alloys for first-wall application in fusion reactors. Should EBR-II not be available for this entire experiment, irradiation will take place in another suitable reactor. This experiment is part of the U.S. contribution to the ITER Program. In addition, the Section had the responsibility for designing the remotely operated equipment for the hot-cell disassembly of tritium-containing irradiation capsules, which contained a group of vanadium alloy specimens. This effort provided information that will assist in the design of any future irradiation experiments that require predoping with tritium.

Ancillary Activities

The Section is continuing its involvement with the Corrosion Section in the NRC's Irradiation-Assisted Stress Corrosion Cracking Program for LWR stainless steel components. Our efforts provide the investigators with the necessary fractographic (SEM) and microchemical (Auger microprobe) data for evaluating the phenomenon.

The Section's hot-cell facility, the AGHCF, has become the focal point for handling irradiated materials from other programs at the Laboratory. One such activity was the examination and failure analysis of a target from the Intense Pulsed Neutron Source. Another such activity was identifying and characterizing a number of irradiated units that had been stored for about 25 years in Argonne's below-ground vaults, which are now being decommissioned.

The Section continues to provide its services and unique hot-cell capabilities to other national laboratories and industrial organizations. One such interlaboratory relationship is with the Knolls Atomic Power Laboratory. Commonwealth Edison Company, a large electric utility, has availed itself of our hot-cell capabilities for failure analysis of highly irradiated structural materials.

Future Direction

With DOE's recognition of the urgent need to remedy vulnerabilities in its storage of DOE-owned spent nuclear fuel (SNF) has come the need to characterize the current state of the SNF in order to establish a clear path forward for its eventual entombment in a geologic repository. The Section has been participating in DOE task groups to identify characterization needs and facilities where the work could be done. The AGHCF has many of the required capabilities, and it is envisioned that the Section and the AGHCF will play a significant role in this new and emerging DOE program.

Recent Work by the Irradiation Performance Section

Publications

Experience with IPNS Targets

J. M. Carpenter and A. G. Hins

Proc. of the ICANS XII Conf., Abingdon, England, May 24-28, 1993, Vol. 2,
Rutherford Appleton Lab. Report No. 94-025, pp. T-1 thru T-11.

Environmentally Assisted Cracking in Light Water Reactors Semiannual Report - April 1993-September 1993

O. Chopra, H. M. Chung, T. Karlsen, T. F. Kassner, W. F. Michaud, W. E. Ruther, J. E. Sanecki, W. J. Shack, and W. K. Soppet

NUREG/CR-4667, Vol. 17, ANL-94/16, May 1994.

Swelling and Structure of Vanadium Alloys Irradiated in the Dynamic Helium Charging Experiment

H. M. Chung, B. A. Loomis, H. C. Tsai, L. Nowicki, J. Gazda, and D. Smith

Contribution to the Fusion Reactor Materials Semiannual Progress Report,
DOE/ER-0313/16, for the Period Ending March 31, 1994.

Effect of Dynamically Charged Helium on Mechanical Properties of V-4Cr-4Ti

H. M. Chung, B. A. Loomis, H. C. Tsai, L. Nowicki, D. Busch, and D. L. Smith

Contribution to the Fusion Reactor Materials Semiannual Progress Report,
DOE/ER-0313/16, for the Period Ending March 31, 1994.

Irradiation-Assisted Stress Corrosion Cracking of Materials from Commercial BWRs: Role of Grain-Boundary Microchemistry

H. M. Chung, W. E. Ruther, J. E. Sanecki, A. G. Hins, and T. F. Kassner

To be published in Proc. of 21st Water Reactor Safety Information Mtg.,
Oct. 25-28, 1993, Bethesda, MD.

Effects of Fabrication Variables on Impact Properties and Microstructure of V-Cr-Ti Alloys

H. M. Chung, L. J. Nowicki, J. E. Sanecki, J. Gazda, and D. L. Smith

Presented at 6th Intl. Conf. on Fusion Reactor Materials, Sept. 27-Oct. 1, 1993,
Stresa, Italy; Fusion Reactor Materials Semiannual Progress Report for the Period
Ending Sept. 30, 1993, DOE/ER-03137/15.

Grain-Boundary Microchemistry and Intergranular Cracking of Irradiated Austenitic Stainless Steels

H. M. Chung, W. E. Ruther, J. E. Sanecki, and T. F. Kassner

To be published in Proc. of 6th Intl. Symp. on Environmental Degradation of
Materials in Nuclear Power Systems - Water Reactors, San Diego, CA,
Aug. 1-5, 1993.

Environmentally Assisted Cracking in Light Water Reactors Semiannual Report - October 1992-March 1993

H. M. Chung, O. K. Chopra, W. E. Ruther, T. F. Kassner, W. F. Michaud, J. Y. Park, J. E. Sanecki, and W. J. Shack

NUREG/CR-4667, VOL. 16, ANL-93/27, Sept. 1993.

Stress Corrosion Cracking Susceptibility of Irradiated Type 304 Stainless Steels

H. M. Chung, W. E. Ruther, J. E. Sanecki, and T. F. Kassner

Proc. 16th Intl. Symp. on Effects of Radiation on Materials, June 21-25, 1992, Denver, CO; STP 1175, pp. 851-869.

Stress Corrosion Cracking Susceptibility of Irradiated Type 304 Stainless Steels

H. M. Chung, W. E. Ruther, J. E. Sanecki, and T. F. Kassner

To be presented at 16th Intl. Symp. on Effects of Radiation on Materials, Denver, CO, June 21-25, 1992.

Environmentally Assisted Cracking in Light Water Reactors: Semiannual Report

H. M. Chung, T. F. Kassner, S. Majumdar, J. Y. Park, A. Purohit, W. E. Ruther, J. E. Sanecki, and W. J. Shack

NUREG/CR-4667, ANL-92/30, Aug. 1992.

Vanadium-Lined HT9 Cladding Tubes

A. B. Cohen, T. C. Wiencek, and H. Tsai

INVITED PAPER: Proc. 15th Conf. on Emerging Methods for the Production of Tubes, Bars and Shapes, ASM Intl., Clearwater, FL, May 2-3, 1994.

Fuel/Cladding Compatibility in U-19Pu-10Zr/HT9-Clad Fuel at Elevated Temperatures

A. B. Cohen, H. Tsai, and L. A. Neimark

J. Nucl. Mater., 204 (1993), 244-251 (Proc. Intl. Symposium on Reliable Fuels for Liquid Metal Reactors, ANS/ENS Winter Mtg., Nov. 15-20, 1992, Chicago, IL).

Results of Mechanical Tests and Supplementary Microstructural Examinations of the TMI-2 Lower Head Samples

D. R. Diercks and L. A. Neimark

NUREG/CR-6187, ANL-94/8, May 1994.

Mechanical Properties and Examination of Cracking in TMI-2 Pressure Vessel Lower Head Material

D. R. Diercks and L. A. Neimark

Presented at Mtg. on Achievements of the OECD Three Mile Island Vessel Investigation Project, Boston, MA, Oct. 20-22, 1993; to be published in Proc. of Mtg.

Results of Mechanical Tests and Supplementary Microstructural Examinations of the TMI-2 Lower Head Samples

D. R. Diercks and L. A. Neimark

OECD-NEA-TMI-2 Vessel Investigation Project, TMIV(93)AL02, June 1993.

Behavior of Mark-22 Fuel during In-Cell Overheating Experiments

J. W. Holland, E. E. Gruber, L. A. Neimark, A. E. Wright, and T. H. Bauer
ANL/NPR-93/1, Jan. 1993.

Metallurgical Examinations and Mechanical Properties

G. E. Korth, D. R. Diercks, and L. A. Neimark
TMI-2 Vessel Investigation Project Integration Report, TMI V(93)EG10, Oct.
1993, pp. 4/1-4/23.

Results of Examinations of Pressure Vessel Samples and Instrument Nozzles from the TMI-2 Lower Head

G. E. Korth (EG&G Idaho, Inc.), D. R. Diercks, and L. A. Neimark
Proc. of NRC 21st Water Reactor Safety Information Mtg., Oct. 25-27, 1993;
NUREG/CP-0133, Vol. 2 (1993).

Modeling the Behavior of Metallic Fast Reactor Fuels during Extended Transients

J. M. Kramer (RE), Y. Y. Liu, M. C. Billone, and H. C. Tsai
J. of Nucl. Materials 204, 203-211 (1993).

Behavior of EBR-II Metallic MK-V-Type Elements in Simulated Loss-of-Flow Tests

Y. Y. Liu, H. Tsai, M. C. Billone, J. W. Holland, and J. M. Kramer
Proc. Intl. Symposium on Reliable Fuels for Liquid Metal Reactors, Nov. 15-20,
1992, Chicago, IL, J. of Nucl. Materials 204 (1993) pp. 194-202.

The Foaming of A-Al Fuel under Simulated Reactor Accident Conditions

L. A. Neimark and Y. Y. Liu
Proc. of 1990 Intl. Mtg. on Reduced Enrichment for Research and Test Reactors,
Newport, RI, Sept. 23-27, 1990, ANL/RERTR/TM-18, CONF-9009108,
pp. 138-144.

Examinations of Nozzles and Guide Tubes

L. A. Neimark, T. L. Shearer, and D. W. Akers
TMI-2 Vessel Investigation Project Integration Report, TMI V(93)EG10,
Oct. 1993, pp. 6/1-6/20.

TMI-2 Instrument Nozzle Examinations at Argonne National Laboratory

L. A. Neimark, T. L. Shearer, A. Purohit, and A. G. Hins
In Three Mile Island Reactor Pressure Vessel Investigation Project, Achievements
and Significant Results, Organisation for Economic Co-operation and Development,
Paris (1994), pp. 225-237.

TMI-2 Instrument Nozzle Examinations at Argonne National Laboratory

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TMIV(93)AL01, Feb. 1993.

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L. A. Neimark and Y. Y. Liu
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Uranium-Plutonium Interdiffusion at 750°C

M. C. Petri (FE), A. G. Hins, J. E. Sanecki, and M. A. Dayananda (Purdue U.)

Submitted to J. of Nuclear Materials, Jan. 1994.

Mechanistic Interpretation of an Observed Rate Dependence of Low-Temperature Swelling of Irradiated Uranium Silicide Dispersion Fuels

J. Rest and G. L. Hofman

Proc. 15th Intl. Symp. on Effects of Radiation on Materials, Nashville, TN, June 17-21, 1990, eds. R. Stoller, A. S. Kumar, and D. S. Gelles, Amer. Soc. for Testing and Materials, Philadelphia, 1992, pp. 797-809.

The Effect of Crystal Structure Stability on Swelling in Intermetallic Uranium Compounds

J. Rest, G. L. Hofman, and R. C. Birtcher

Proc. 14th Intl. Symp. on *Effects of Radiation on Materials*, Andover, MA, June 27-29, 1988, eds. H. Packan, R. E. Stoller, and A. S. Kumar, Vol. II, ASTM STP 1046, American Society for Testing and Materials, Philadelphia, PA, 1990, pp. 789-811; also, Proc. of 1988 Intl. Mtg on Reduced Enrichment for Research and Test Reactors, ANL/RERTR/TM-13, July 1993..

Environmentally Assisted Cracking in Light Water Reactors Semiannual Report, April-Sept. 1992

W. E. Ruther, H. M. Chung, O. K. Chopra, T. F. Kassner, S. Majumdar, J. Y. Park, J. E. Sanecki, A. G. Hins, and W. J. Shack

NUREG/CR-4667, Vol. 15, ANL-93/2 (June 1993).

Final Report on the TOPI-2 Test: Effects of a Fifteen Percent Overpower Transient on a Breached Mixed-Oxide Fuel Pin

R. V. Strain and L. A. Neimark

ANL-ORT/OT-23, Feb. 1994.

Casting of Metallic Fuel Containing Minor Actinide Additions

C. L. Trybus, J. E. Sanecki, and S. P. Henslee

J. of Nucl. Materials (1993) pp. 1-6, Proc. ANS/ENS Intl. Conf., Chicago, IL, Nov. 15-20, 1992.

The COBRA-1B Irradiation Experiment in EBR-II

H. Tsai, A. G. Hins, R. V. Strain, and D. L. Smith

Contribution to the Fusion Reactor Materials Semiannual Progress Report for the Period Ending March 31, 1994.

Final Report on Operational Transient Test TOPI-1D

H. Tsai, L. A. Neimark, and A. Boltax

ANL-ORT/OT-26, Feb. 1994.

Behavior of Mixed-Oxide Fuel Elements during the TOPI-1E Transient Overpower Test

H. Tsai, L. A. Neimark, K. Hirai (Japanese Power Reactor and Nuclear Fuel Development Corp. [PNC]), K. Yamamoto (PNC), and S. Shikakura (PNC)

To be presented at 1994 ARS Intl. Mtg., Advanced Reactor Safety, April 17-21, 1994, Pittsburgh, PA.

Behavior of Mixed-Oxide Fuel Elements during an Overpower Transient

H. Tsai, L. A. Neimark, T. Asaga, and S. Shikakura (Japanese Power Reactor and Nuclear Fuel Development Corp.)

To be presented to 1992 Intl. Symposium on Reliable Fuels for Liquid Metal Reactors, Nov. 15-20, 1992, Chicago, IL.

Final Report on Operational Transient Test TOPI-1C

H. Tsai and L. A. Neimark

ANL-ORT/OT-25, Oct. 1992.

Irradiation Performance of Full-Length Metallic IFR Fuels

H. C. Tsai and L. A. Neimark

To be presented to Intl. Conf. on Design and Safety of Advanced Nuclear Power Plants (ANP '92), Oct. 25-29, 1992, Tokyo, Japan.

Debris Relocation Scenario

J. R. Wolf, L. A. Neimark, and D. W. Akers

TMI-2 Vessel Investigation Project Integration Report, TMI V(93)EG10, Oct. 1993, pp. 8/1-8/15.

Components Technology

Superconductivity Applications

Section Manager: J. R. Hull

Principal Investigators: Y. S. Cha, R. A. Erck, T. M. Mulcahy,
R. C. Niemann, K. L. Uherka

Technicians: D. J. Evans, A. S. Wantroba

Secretary: J. A. Stephens

Postdoctoral Fellow: Z. J. Yang

Visiting Scientists: P. E. Phelan,¹ T. D. Rossing²

Students: E. F. Hilton,³ C. T. Mancione,⁴ J. L. Passmore,⁵ G. J. St. Pierre⁶

The special properties of superconducting materials allow many unique applications whose importance has increased significantly with the discovery several years ago of materials that superconduct at temperatures above the boiling point of nitrogen. The Superconductivity Applications Section conducts research and development on new applications of superconductivity and its support technologies. The work is both experimental and analytical.

Many of the Section's projects are funded by the Superconductivity Technology Center at ANL; such projects are conducted with industrial collaborators, typically with each institution funding its own work but with staff from each institution working on the same project. In addition, the Section is presently receiving substantial funding from Commonwealth Research Corporation (CRC) for the development of a flywheel energy storage device that uses superconducting bearings. Section members are thus frequently involved with industrial scientists and engineers in these collaborative programs. The Section collaborates closely with the ET Ceramics Section in fabricating experimental superconducting devices, and with members of the ANL Energy Systems Division in developing magnetically levitated ground transport (maglev) systems.

Cryostat Current Leads

A cryostat current lead provides power from room-temperature sources to devices operating at liquid helium temperatures. Early experimental work in collaboration with the Westinghouse Science and Technology Center resulted in a high-temperature superconductor (HTS) lead that superconducted 2 kA. Experiments with this lead demonstrated, for the first time that helium boil-off from such a lead could be lower than that of the minimum obtained by the best theoretical lead made entirely of a normal conductor. Since then, we have constructed a lead-test apparatus with the very low

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background heat leakage of about 10 mW. This apparatus has allowed testing of a pair of HTS leads with a 100-A current and with less than one-tenth the boil-off of a conventional lead.

Based on experimental results from our test apparatus and on analyses of lead performance, we have discovered that the ratio of helium vapor density to liquid density significantly modifies the relationship between heat input and vapor mass flow. We have also shown theoretically that a minimal boil-off exists for self-cooled leads and that an intermediate-temperature heat sink is needed to reduce boil-off below this limit. We have examined the stability of HTS leads and found a relationship for the temperature dependence of thermal conductivity that enables us to design leads that display absolute stability and whose helium boil-off is almost one order of magnitude lower than that of a conventional lead. In addition, we have applied for a patent on a unique design for an HTS lead, and this invention has been licensed to Illinois Superconductor Corporation.

We are presently collaborating with two companies in work on HTS leads. Superconductivity, Inc., is interested in HTS leads of ≈ 1500 A for the 1-MW superconducting magnetic energy storage (SMES) devices that it markets commercially. Babcock and Wilcox is interested in 16-kA HTS leads for its 0.5-MWh prototype SMES device. Work in these projects has focused on improving the robustness of HTS leads in real-world operating conditions.

Magnetic Bearings

For several years, the Section has explored the use of HTSs in magnetic bearing applications. Most of the present effort involves collaboration with CRC. We have demonstrated an HTS bearing with a rotational drag that is more than two orders of magnitude lower than that of a conventional magnetic bearing and several orders of magnitude lower than that of mechanical bearings. With this bearing, an energy-efficient flywheel could be constructed with a bearing loss of $<2\%$ /day. Such a flywheel has the potential for use in diurnal utility energy storage or as a replacement for batteries in an electric vehicle. Several patents on this bearing/flywheel concept are in process.

Two vacuum-chamber apparatuses have been developed at ANL to test the rotational losses of HTS bearings. One is a glass bell-jar test chamber with an oil-diffusion pump. This apparatus is capable of testing bearings with rotating mass up to ≈ 1 kg. The second apparatus is a stainless steel chamber with a turbomolecular vacuum pump capable of testing rotating masses of >100 kg. We have identified several design improvements to further reduce loss, and we expect to test these designs in rotors of increasing size.

We have recently initiated a cooperative R&D agreement (CRADA) with the Association of American Railroads to study the use of flywheel energy storage in locomotives.

Fault-Current Limiter

We have invented an HTS fault-current limiter (FCL) that operates as a nonlinear resistor. A patent application has been filed and we have licensed the invention to Illinois Superconductor Corporation. A small model of this FCL has been built and successfully operated at ANL.

Stabilization of HTS Magnets

We have applied for a patent on a new type of stabilization for HTS magnets. When operated at a temperature above 20 K, HTSs are expected to have difficulties if a perturbation results in a normal zone, because the propagation velocity of the normal zone is several orders of magnitude lower than that in low-temperature superconductors. All of the heat will be dissipated locally and the magnet may then burn out. Thus, in a conventional superconductor magnet design (even one using an HTS with high current density), the magnets would be unreliable. We have used microchannel heat exchanger techniques to design HTS magnet concepts that are cryostable when using subcooled liquid cryogenes. Once HTS conductors with useful current density become available, HTS magnets of this design should be stable and reliable. We are testing this design concept experimentally with a 5-kA power supply.

Maglev

The Section is collaborating with members of ANL's Energy Systems Division in the development of maglev systems, as part of the U.S. program to evaluate this technology. One project utilizes a rotating-wheel test facility on which experimental models of maglev vehicles are levitated over guideways mounted on the wheel to test levitation properties and vehicle dynamics. We have also used a new finite-element computer code (ELEKTRA from Vector Fields Ltd.) that analyzes three-dimensional eddy currents with moving conductors. A number of experiments have been conducted on the wheel and used to verify the results of the code. ELEKTRA is part of a general three-dimensional electromagnetics code that the Section uses to design and evaluate magnets.

Electromagnetic Casting

We have recently initiated a CRADA with Inland Steel Corporation to model the use of electromagnetic (EM) edge dams in twin-roll casting of molten metals. The basic idea of the EM edge dam is the use of an EM field to support a wall of liquid metal at the ends of the rolls. Conventional mechanical dams have significant problems that have prevented the use of twin-roll technology for some time. Using patented technology originally developed at ANL, Inland has developed the EM edge dams to near-commercialization. The Section will use ELEKTRA to calculate the eddy currents induced in the molten metal and then use the results as input to another ANL computer code (CaPS) that predicts fluid flow with free surfaces.

Recent Work by the Superconductivity Applications Section

Publications

Dynamic Stability of Maglev Systems

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ANL-92/21, April 1992.

Dynamic Stability of Maglev Systems

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Transverse Temperature Distribution and Heat Generation Rate in Composite Conductors Subjected to Constant Thermal Disturbance

Y. S. Cha
Submitted to Cryogenics, April 1994.

Thermal Characteristics of a Low-Loss Liquid-Helium Dewar

Y. S. Cha, R. C. Niemann, and J. R. Hull
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Y. S. Cha, J. R. Hull, and R. C. Niemann
Proc. of 1993 ASME Winter Ann. Mtg., New Orleans, LA, Nov. 28-Dec. 3, 1993.

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Y. S. Cha, M. T. Lanagan, K. E. Gray, V. Z. Jankus, and Y. Fang (U. of Illinois at Chicago)
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Dynamics of Liquid Helium Boil-off of Experiments with a Step Change in Pressure

Y. S. Cha, R. C. Niemann, and J. R. Hull
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Y. S. Cha
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Thermodynamic Analysis of Helium Boil-off Experiments with Pressure Variations

Y. S. Cha, R. C. Nieman, and J. R. Hull

Cryogenics 1993, Vol. 33, No. 7, pp. 675-679.

Effects of Hot-Rolling on Powder-in-Tube BSCCO Tapes

J. Guo, J. Schwartz, Y. S. Cha, C. T. Wu, and K. C. Goretta

For presentation at Intl. Cryogenic Materials Conf., Albuquerque, NM, July 12-16, 1993, and for publication in Advances in Cryogenic Engineering, Vol. 40, 1993.

Current Leads and Magnetic Bearings

J. R. Hull

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Stable Levitation of Steel Rotors Using Permanent Magnets and High-Temperature Superconductors

J. R. Hull, J. L. Passmore, T. M. Mulcahy, and T. D. Rossing

Submitted to J. of Applied Physics, 11/27/93.

Advances in Superconductivity: Applications Emerge From New Materials

J. R. Hull

Submitted to Mechanical Engineering, June 1, 1993.

High-Temperature Superconducting Current Leads

J. R. Hull

INVITED PAPER: presented at 1992 Applied Superconductivity Conf., Chicago, IL, Aug. 23-28, 1992; IEEE Trans. on Appl. Superconductivity, Vol. 3, (March 1993) pp. 869-875.

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J. R. Hull and K. L. Uherka

Proc. 27th Intersociety Energy Conversion Engineering Conf., San Diego, CA, Aug. 3-7, 1992, Vol. 4, pp. 155-160.

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J. R. Hull and R. B. Poeppel

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J. R. Hull, A. Unal (Texas Tech. U.), and M.-C. Chyu (TTU)

Cryogenics, 1992, Vol. 32, No. 9, pp. 822-828.

Potential for Use of High-Temperature Superconductors in Fusion Reactors

J. R. Hull

Proc. 5th Intl. Conf. on Fusion Reactor Materials, Clearwater, FL, Nov. 17-22, 1991;
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Magnetic Levitation and Stiffness in Melt-Textured Y-Ba-Cu-O

J. R. Hull, T. M. Mulcahy, K. Salama (U. of Houston), B. R. Weinberger (United Technologies Res. Ctr.), and L. Lynds (UTRC)

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Forces on a Magnet Moving Past Figure-Eight Coils

T. M. Mulcahy, J. He, D. M. Rote, and T. D. Rossing

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Edge Effects on Forces and Magnetic Fields Produced by a Conductor Moving Past a Magnet

T. M. Mulcahy, J. R. Hull, J. D. Almer, and T. D. Rossing (Northern Illinois U.)

Presented at Intl. Magnetics Conf. (Intermag '92) St. Louis, MO, April 13-16, 1992;
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Engineering Design of a High-Temperature Superconductor Current Lead

R. C. Nieman, Y. S. Cha, J. R. Hull, W. E. Buckles (Superconductivity, Inc.), and
M. A. Daugherty (Superconductivity, Inc.)

Submitted to 5th Ann. Intl. Industrial Symp. on the Supercollider (IISCC) and
Exhibition, San Francisco, CA, May 6-8, 1993.

Performance Evaluations of Demountable Electrical Connections

R. C. Niemann, Y. S. Cha, J. R. Hull, W. E. Buckles (Superconductivity, Inc.), and
M. A. Daugherty (Superconductivity, Inc.)

Presented to Cryogenic Engineering Conf. and Intl. Cryogenic Materials Conf.
(CEC/ICMC), Albuquerque, NM, July 12-16, 1993; accepted for publication in Vol.
39, Advances in Cryogenic Engineering.

High-Temperature Superconducting Current Leads for Micro-SMES Application

R. C. Niemann, Y. S. Cha, J. R. Hull, W. E. Buckles (Superconductivity, Inc.), B. R. Weber
(Supercond., Inc.), and M. A. Daugherty (Los Alamos National Laboratory)

Presented at 13th Intl. Conf. on Magnet Techn., Sept. 20-24, 1993, Victoria, B.C.

Performance Measurements of Superconducting Current Leads Having Low Helium Boil-off Rates

R. C. Niemann, Y. S. Cha, and J. R. Hull

Presented to 1992 Applied Superconductivity Conf., Chicago, IL, Aug. 23-28, 1992;
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Practical Superconductor Development for Electrical Power Applications - Annual Report for FY 1993

R. B. Poeppel, K. C. Goretti, T. R. Askew, U. Balachandran, Y. S. Cha, J. A. DeLuca (General Electric), S. E. Dorris, J. T. Dusek, W. A. Ellingson, J. E. Emerson, K. Goretti, K. E. Gray (MSD), J. D. Hettinger (MSD), J. Hu, J. R. Hull, R. T. Kampwirth (MSD), D. S. Kupperman, M. T. Lanagan, V. A. Maroni, R. L. McDaniel, D. J. Miller (MSD), R. C. Niemann, J. J. Picciolo, J. L. Routbort (MSD), J. P. Singh, K. L. Uherka, and C. A. Youngdahl

ANL-93/33, Oct. 1993.

Practical Superconductor Development for Electrical Power Applications - Annual Report for FY 1992

R. B. Poeppel, K. C. Goretti, U. Balachandran, I. Bloom, Y. S. Cha, N. Chen, S. E. Dorris, E. D. Doss, J. T. Dusek, J. E. Emerson, K. E. Gray, M. C. Hash, J. D. Hettinger, J. R. Hull, R. T. Kampwirth, M. A. Kirk, D. S. Kupperman, M. T. Lanagan, V. A. Maroni, R. L. McDaniel, D. J. Miller, R. C. Niemann, J. J. Picciolo, J. L. Routbort, J. P. Singh, K. L. Uherka, R. Wheeler, and C. A. Youngdahl

ANL-92/38, Oct. 1992.

Design Aspects of Mid-Size SMES Using High-Temperature Superconductors

S. M. Schoenung (W. J. Schafer Associates, Inc.), W. R. Meier (W. J. Schafer Assoc.), R. A. Fagaly (General Atomics), M. Heiberger (GA), R. B. Stephens (GA), J. A. Leuer (GA), R. A. Guzman (GA), and J. R. Hull

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Diffusion and Cooling Rate during Annealing of Sintered Bulk $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$

S. Y. Seol and Y. S. Cha

Applied Superconductivity, Vol. 2, No. 1 (1994) pp. 7-16.

Transient Analysis and Burnout of High-Temperature Superconducting Current Leads

S. Y. Seol and J. R. Hull

Cryogenics 1993 Vol. 33, No. 10, pp. 966-975.

Analytical Thermal-Hydraulics

Section Manager: R. A. Valentin (Acting)

Staff: M. Bottoni, T. H. Chien, H. M. Domanus, R. C. Schmitt, W. T. Sha, J. G. Sun

Postdoctoral Appointees: F. C. Chang, J. Ding

Secretary: S. A. Moll

The main research discipline of the Analytical Thermal-Hydraulics Section is numerical simulation of complex fluid flow phenomena, with particular emphasis on the development and implementation of mathematical and phenomenological models of single-phase and multiphase fluids. Research activities emphasize numerical simulations for reactor transients, development of codes to model the flow and solidification of metals, and applications related to fossil energy systems.

Applications of COMMIX in Analysis of the AP-600 Passive Containment Cooling System

Code Development and the COMMIX Code

Since 1976, the Section has been engaged in developing three-dimensional, steady-state/transient, single-phase/multiphase computer codes for predicting temperature, velocity, pressure, and phasic concentration distributions in reactor component and multiple-component energy systems under normal and off-normal operating conditions. The codes in the COMMIX series allow global analyses of heat transfer and fluid flow phenomena in a single component (such as a rod bundle, reactor plenum, piping system, or heat exchanger) or in a multicomponent system, i.e., a combination of these components. The COMMIX codes use a porous-media formulation in which volume porosity, directional surface porosity, distributed resistance, and distributed heat sources or sinks are employed to analyze continuum/quasicontinuum flow domains. The concept of directional surface porosity greatly facilitates modeling of velocity and temperature fields in anisotropic media and improves resolution and accuracy. The full three-dimensional, transient, conservation equations of mass, momentum, and energy are solved as a boundary-value problem in space and as an initial-value problem in time.

Applications to AP-600

During the past two years, the major application of COMMIX has been in the simulation of the passive containment system of the AP-600, an advanced-concept pressurized water reactor being developed by Westinghouse. To ensure satisfactory performance of the AP-600 Passive Containment Cooling System (PCCS), shown in the first figure, it is necessary to predict both the evaporation rate at the outside surface of the steel containment vessel and the condensation rate at its inside surface because the two are intimately related to vessel pressure and temperature. To this end, a simplified liquid-film

AP-600 passive containment cooling system

tracking model for time-dependent flows has been developed and implemented in the COMMIX code. Filmwise condensation was assumed in the model and the film flow was laminar-based for the range of Reynolds number encountered in the Westinghouse PCCS small-scale tests. The liquid-film tracking model computes film thickness and its local mean velocity and temperature along the streamwise direction as time progresses. Because currently available PCCS small-scale experimental data are available only for steady-state conditions, a steady-state liquid-film tracking model should be adequate. However, in COMMIX, the conservation equations are solved as a boundary value problem in space and as an initial value problem in time. For this reason, a time-dependent model is more appropriate for COMMIX simulations. More important, the future analysis of design basis accidents (DBA) will require a time-dependent formulation. Coupled with the liquid-film tracking model, pertinent heat and mass transfer models for flows inside the vessel and in the outside annulus are being developed and implemented.

An assessment of the heat and mass transfer models used in CONTAIN, a code developed by Sandia National Laboratories, was made by incorporating these models in COMMIX and comparing code results with the six experimental data sets currently available. Compared were the various performance parameters of the PCCS, namely average wall heat flux, temperature rise of air flowing through the outside annulus, evaporation rates, wall temperature distributions, and vessel pressure. These data were obtained from Westinghouse AP-600 PCCS small-scale tests made available to us by the Westinghouse

Electric Corporation via the U.S. Nuclear Regulatory Commission. In the present study, the steam inflow rate, which was also the overall condensate flow rate, was used as an input for the calculation.

Based on the COMMIX results obtained to date, the following observations can be made:

- Air flow in the annulus outside the steel containment vessel of the Westinghouse small-scale test facility, which was induced by a fan at the top of the vessel, was highly turbulent. Average velocity in the annulus was 2 to 5 m/sec and the Reynolds number based on the equivalent diameter of the annulus was 1 to 3×10^5 . This is clearly a case of turbulent forced convection, and the heat and mass transfer analogy is applicable. However, annular air flow in the real AP-600 system is by natural convection; validation of heat and mass transfer models for natural convection is lacking, and comparison with experimental data is needed.
- The steam/air mixture flow inside the containment vessel produced mixed convection. Velocity along the wall was downward and was about 1 m/sec. In the central region, the flow was upward due to steam fed in at the bottom of the vessel to simulate the result of a main steam line break (MSLB) or loss-of-coolant accident (LOCA). The flow field was complex and resembled natural circulation in an enclosed cylinder having cooled walls and a large height-to-diameter ratio with ellipsoidal domes at the top and the bottom. There were two distinct flow fields: one in the dome region, and the other in the cylinder region. The COMMIX calculations also predicted flow stratification (more steam in the upper portion of the vessel and more air in its lower portion). This agrees with experimental observations.
- To separately assess the heat and mass transfer models used in the CONTAIN code for the outside annulus and for the interior of the vessel, the measured streamwise wall temperature distribution of the vessel was used as a boundary condition in a COMMIX calculation. It was found that the Dittus-Boelter correlation for turbulent heat transfer in the annulus produced satisfactory results when the correlation's numerical constant 0.023 was raised to 0.037, as was done in CONTAIN. This modification can be justified on the basis of the wavy interface between the falling water film and the rising air flow. The use of a simple correlation, $Nu = 0.14 (GrPr)^{1/3}$ for heat transfer and $Sh = 0.14(GrSc)^{1/3}$ for mass transfer, for the complex flow inside the containment vessel was also investigated. These correlations, based on data for turbulent free convection outside of vertical plates or cylinders in still media, were developed for a very different environment from that of the AP-600 PCCS. Their use in the safety analysis of AP-600 PCCS certainly needs careful investigation. The results from COMMIX using these models showed that the calculated and measured pressures inside the vessel differed considerably when the wall heat flux was high. For this reason, a *turbulent mixed convection* (TMC) model, based on a heat transfer correlation proposed in 1987 by Chen et al., was tentatively selected to replace the turbulence-free convection model used in CONTAIN. Significant improvement in the predicted vessel pressure was achieved this way.

- Having established the usefulness of the TMC model, we conducted COMMIX calculations for the various performance parameters without using the measured wall temperature information as a boundary condition. The heat transfer correlations used in CONTAIN and the TMC model were examined. At low heat fluxes, reasonable agreement was obtained between the measured and calculated data for the performance parameters by using either CONTAIN's heat transfer correlation or the TMC model. However, at the highest heat flux (Westinghouse Test 18), the predicted vessel pressure exceeded the measured by 16.4% when CONTAIN's correlation was used. The discrepancy was reduced to 6.4% when the TMC model was employed. The ability to accurately predict vessel pressure is of paramount importance in reactor safety analysis. Additional validation of the TMC model with Westinghouse PCCS large-scale tests is underway.
- The measured wall temperature distributions in the streamwise direction for Tests 17 and 18 exhibited a characteristic dip in the region $0 < x < 0.5$ m, where x is the distance measured from the stagnation point of the upper elliptical dome. The phenomenon was also revealed by the calculated data using the TMC model. In contrast, the calculated wall temperature distributions using CONTAIN's heat transfer correlation failed to show the characteristic dip.
- In addition to the COMMIX study, a rigorous procedure was developed for calculating the mixed convection heat transfer coefficient in the laminar regime. Also, the momentum, heat, and mass transfer analogy has been examined in a fundamental way. This used the governing conservation equations for both laminar and turbulent boundary layer flows with the proper associated boundary conditions. Conditions under which the analogies are valid were investigated, as were those conditions leading to their failure. The existence of universal or near universal velocity profiles in turbulent boundary layers was found to be conducive to applying heat and mass analogies.

Multiphase Flow Research for Fossil Energy Applications

The general objective of the multiphase flow research activity is to develop general purpose gas/liquid/solid flow models applicable to a variety of fossil energy system evaluations. Numerical studies have concentrated on liquid/solid slurry flows in piping systems with empirical rheological models for shear lift and virtual mass. For turbulent two-phase flow, model extensions have been developed for bubbly and particulate simulations. Two areas of current work are summarized in following sections; these cover development of solid-phase constituent relations using kinetic theory, and gas-phase turbulence modulation due to the presence of particulate matter.

Kinetic Theory Models

In the kinetic theory formulation for solids flow, a detail model is needed for particle-particle collisions. Transport equations for solids flow can then be obtained, via the Boltzman equation, from the velocity distribution function of the particles. The process becomes somewhat more complex when an interstitial fluid is introduced. Based on a model first developed by Ding and Gidaspow for bubbling fluidization, a COMMIX implementation is being developed that will apply to gas-particle systems and will be free of arbitrary model parameters.

To test the initial COMMIX version of this model, a specific class of granular flow problems was considered because validation data were available for such granular models. An additional partial differential equation for the fluctuating energy (granular temperature) must be solved to obtain shear viscosity, bulk viscosity, and pressure of the solid phase.

For simple shear flow, nondimensional forms of the shear stress and normal stress were obtained and compared with available experimental data for glass beads in an annular shear cell. The results of this evaluation are shown in the graphs on the next page; shear and normal stresses are plotted in the graphs as a function of solids volume fraction for various values of the particle-to-particle coefficient of restitution. This model eliminates arbitrary assumptions for viscosities and pressures in the solid phase, as well as the need for adjustable parameters in a constitutive equation. It does, however, require that one determine the coefficient of restitution between particles by experiment.

Simulation of Particulate Flows

Our primary effort has been on improving the general multiphase capabilities of COMMIX, verification of the code through comparison with experiment, and identification of further needed code improvements.

To improve the multiphase modeling capabilities of COMMIX, the $k-\epsilon$ turbulence model available for single-phase flow has been extended to particulate flow. This extension has been made by applying the standard model for single-phase flow to the domains occupied by each phase in a multicomponent flow and by simulating the additional sources of turbulence arising from the interaction between the different phases. Following this development, quantitative evaluation of the terms simulating the additional sources of turbulence has been made for the case of solid particles transported by a lighter fluid and for gas bubbles transported by a denser fluid.

Calculations made for both particle and bubbly flows have shown the correct qualitative tendencies, i.e., an increase of turbulent kinetic energy for high Reynolds numbers. When a particle Reynolds number is lower than about 100, there is no increase of turbulent kinetic energy, due to vortex shedding by the particles. Rather, there is a suppression of turbulent kinetic energy due to oscillatory motions of the particle and to viscous dissipation. The latter effect, which had not been considered earlier, has now been simulated.

Upper: Nondimensional shear stress vs. solids volume fraction; Lower: Nondimensional normal stress vs. solids volume fraction

Suppression of turbulent kinetic energy by particles with low Reynolds numbers has been made in the following way: (1) Assuming fully developed turbulence, a power spectrum, i.e., a distribution of turbulent kinetic energy as a function of wave number, is postulated. It is assumed that the distribution is the same as in single-phase flow. (2) An attenuated spectrum of turbulence is computed, based on the method by Al Taweel and Landau. (3) The attenuated spectrum is integrated over all wavelengths to obtain the global reduction of turbulence intensity. The main feature of this approach consists of applying a method developed for a spectral distribution of turbulence to a code such as COMMIX, where only integral values averaged over the full turbulence spectrum are computed.

Verification of the current version of the turbulence models used in COMMIX has been made on the basis of data from three experimental series, as summarized below.

- Experiments of Simonin and Viollet, performed at Electricité de France (EDF): These experiments were run in a vertical axisymmetric pipe of 50

mm diameter with turbulent water flow. At the inlet, a uniform distribution of air bubbles was injected. When the turbulent-flow profile develops, the bubble concentration changes along the pipe radius. The first graph below gives a comparison between computed and experimental void fraction distributions along the normalized pipe radius. The second graph shows computed and experimental velocity distributions.

Upper: Radial distribution of void fraction at inlet, and comparison of Simonin-Viollet data (EXP) with COMMIX computation (COM). Lower: Radial distribution of water axial velocity, and comparison of Simonin-Viollet data (EXP) with COMMIX computation (COM).

- Experiments from the NOVA series, run at the Kernforschungszentrum Karlsruhe: These experiments were run in a vertical pipe of 70 mm diameter with turbulent water flow and injection of air bubbles at the inlet. This experimental series is continuing and aims at recording detailed three-dimensional measurements of turbulent velocity fluctuations. As of now, only preliminary calculations have used this data set.
- Experiments of Tsuji et al. performed at the Osaka University: measurements of air and solid particle velocities in a vertical pipe of 30.5 mm diameter were run with spherical particles of 0.2 to 3 mm diameter. The particle density varied between 970 and 1030 kg/m³. It was confirmed both experimentally and computationally that the presence of large particles enhances the turbulent kinetic energy of the carrying fluid, while small particles damp the turbulence.

The numerical simulations of the experimental series noted above have correctly predicted turbulent flow far from the walls; however, substantial deficiencies in the numerical calculation of particle concentration close to the walls have been found. To cope with this problem, several code improvements have been considered. These include:

- Simulation of compressibility (nonzero divergence of the flow) in the source terms of turbulent kinetic energy.
- Eventual replacement of the k- ϵ turbulence model with the k-w model (w is defined as the mean value of the variance of vorticity fluctuations). Following a literature review, it was concluded that the k-w model performs generally better than the k- ϵ model.
- Simulation of interparticle forces when particle concentration become high.
- Dropping the limiting assumption of isotropic turbulence. This would imply replacing the two-equation model of turbulence with a Reynolds stress model.

Generic Casting Modeling

Fluid Flow and Heat Transfer Phenomena in the Casting Process

Casting is one of the most direct methods of producing industrial parts or components in desired shapes. Although the casting process has been in existence for thousands of years, it involves a host of complex phenomena that are still not thoroughly understood. The principal phenomena are fluid flow and heat transfer, because they control grain size and shape, porosity, and segregation of the alloying elements in the final cast product. The flows in casting molds typically have both free surfaces and moving solidification boundaries. Air and other gases may be trapped within the molten material, forming a two-component

mixture. Nonuniform heat transfer, coupled with large temperature gradients and buoyancy forces, produces natural convection currents in the molten metal. In certain circumstances, the flow may exhibit turbulence.

Casting Modeling is a research and development program that formally started in March 1990 as a consortium that originally comprised ANL, Caterpillar, and Teledyne Corporation. Early in 1992, Teledyne Corporation withdrew from the consortium for financial reasons. The program continued as a cooperative between ANL and Caterpillar and most of the original objectives were achieved.

The overall program objective is to develop state-of-the-art software for simulating the casting process. This software is to be applicable as an industrial tool and not restricted to research applications. Expected benefits include superior castings produced with significantly reduced capital and operating costs. Furthermore, the program should benefit new product development, when first-run rejects are excessive and often cost-prohibitive. The importance of this program has been confirmed by industry's participation, which provided a 50% cost share for Phase I over a three-year period that ended in May 1993 and with Caterpillar fully funding a two-month Phase II effort in 1994.

Phase I of the program has been successfully completed and has produced the Casting Processes Simulator (CaPS-2D) software package. In anticipation of the dissemination of CaPS, permission to copyright has been requested and granted by DOE. The copyright has been registered and the Laboratory is actively seeking avenues for subsequent CaPS licensing and distribution. A package is being prepared for submittal to the Energy Science and Technology Software center.

Recently, Phase II has been completed; it involved extension of CaPS capabilities to three dimensions. CaPS-3D is currently being tested on industrial problems at Caterpillar.

The Casting Process Simulator (CaPS) software comprises several modules that are used to set up, simulate, and analyze detailed results of transient, multidimensional mold filling and solidification. Commercial software is used in CaPS for some pre- and post-processing aspects. Currently, PATRAN is used to construct the geometry. The CaPS mesh generator module automatically determines a structured mesh approximation to the geometry described by PATRAN. Other CaPS modules aid the user in graphically assessing the mesh and the assignment of initial and boundary conditions to the geometry. It has become clear that alternative descriptions of geometry are needed to be interfaced with CaPS to enhance marketability and widen the potential user base. While the consensus in 1990 of Caterpillar and Teledyne was to interface with PATRAN for specifying geometry and generating postprocessing graphics, Proengineer appears to be the current choice for describing the geometry.

Currently, PATRAN is also used in CaPS to graphically display postprocessed simulation results. Again, the current choice has shifted to another commercial package called AVS. Development of CaPS interfaces to alternative postprocessing graphics software are being considered.

Recent Work by the Analytical Thermal-Hydraulics Section

Publications

Solidification Modeling of a Spiral Casting to Determine Material Fluidity

S. Ahuja, H. M. Domanus, R. C. Schmitt, L. Chuzhoy (Caterpillar Inc.), and J. V. Grabel (Caterpillar Inc.)

Submitted to Concurrent Engineering Approach to Materials Processing II, 1993 Materials Week, Pittsburgh, PA, Oct. 17-21, 1993.

Modelling of Bubbly and Annular Two-Phase Flow in Subchannel Geometries with BACCHUS-3D/TP

M. Bottoni and R. W. Lyczkowski

Submitted to Nucl. Techn., May 1994.

A Variant of the ADI Method for Two-Phase Flow Calculations

M. Bottoni

Computers Fluids Vol. 23, No. 2 (1994), pp. 305-321.

Theoretical and Pragmatic Modeling of Governing Equations for a Two-Phase Flow in Bubbly and Annular Flow Regimes

M. Bottoni and W. Sengpiel (KfK, Karlsruhe, Germany)

To be presented to 4th Brazilian Thermal Science Mtg. (ENCIT-92), Dec. 1-4, 1992, Rio de Janeiro.

Implementation of an Anisotropic Turbulence Model in the COMMIX-1C/ATM Computer Code

M. Bottoni and F. C. Chang

Flow-Induced Vibration and Fluid-Structure Interaction, PVP Vol. 258, 1993.

Capabilities of Reynolds Stress Turbulence Model in Applications to Thermal Stratification

F. C. Chang and M. Bottoni

Transient Thermal Hydraulics, Heat Transfer, Fluid-Structure Interaction, and Structural Dynamics, PVP Vol. 270, 1994.

Potential Capabilities of Reynolds Stress Turbulence Model in the COMMIX-RSM Code

F. C. Chang and M. Bottoni

Presented at 1993 TECHNOLOGY 2003, Anaheim, CA, Dec. 7-9, 1993.

COMMIX Analysis of AP-600 Passive Containment Cooling System

F. C. Chang, T. H. Chien, J. Ding, J. G. Sun, and W. T. Sha

Proc. 20th Water Reactor Safety Mtg., Bethesda, MD, Oct. 21-23, 1992, pp. 163-168.

COMMIX-PPC: A Three-Dimensional Transient Multicomponent Computer Program for Analyzing Performance of Power Plant Condensers, Volume II: User's Guide and Manual

T. H. Chien, H. M. Domanus, and W. T. Sha

ANL-92/2, Vol. II, Feb. 1993.

COMMIX-PPC: A Three-Dimensional Transient Multicomponent Computer Program for Analyzing Performance of Power Plant Condensers, Volume I: Equations and Numerics

T. H. Chien, H. M. Domanus, and W. T. Sha

ANL-92/2, Vol. I, Feb. 1993.

Two-Phase Power-Law Modeling of Pipe Flows Displaying Shear-Thinning Phenomena

J. Ding, W. Lyczkowski, and W. T. Sha

Proc. 5th Joint DOE/NSF Workshop, Ithaca, NY, Sept. 29-Oct. 1, 1993,

pp. 375-385.

Numerical Analysis of Liquid-Solids Suspension Velocities and Concentrations Obtained by NMR Imaging

J. Ding, R. W. Lyczkowski, W. T. Sha, S. A. Altobelli (Lovelace Medical Foundation), and E. Fukushima (Lovelace Med. Found.)

Powder Technology, 77 (1993) pp. 301-312.

Modeling of Concentrated Liquid-Solids Flow in Pipes Displaying Shear-Thinning Phenomena

J. Ding, R. W. Lyczkowski (ES), and W. T. Sha

Submitted to Chemical Engineering Communications, 1994.

Asymptotic Power Spectrum Analysis of Chaotic Behavior in Fluidized Beds

J. Ding and S.-W. Tam (CMT)

International Journal of Bifurcation and Chaos, Vol. 4, No. 2 (1994) pp. 3727-341.

User's Guide for the Casting Process Simulator Software, CaPS-2D, Version 1.0

H. M. Domanus, R. C. Schmitt and S. Ahuja

ANL-93/14, July 1993.

Instability of Flow of Liquid Film over a Heated Surface

W. T. Sha and S. L. Soo (U. of Illinois at Urbana-Champaign)

To be presented at 3rd Intl. Symp. on Multiphase Flow, Xian, China, Sept. 19-21, 1994.

Development of Steady Flow of Liquid Film over a Domed Cylinder

W. T. Sha and S. L. Soo (U. of Illinois at Urbana-Champaign)

Submitted to Intl. J. of Heat and Fluid Flow, Oct. 1992.

Modeling of Solids Global Fluctuations in Bubbling Fluidized Beds by Standing Surface Waves

J. G. Sun, M. M. Chen (U. of Illinois at Urbana-Champaign), and B. T. Chao (UIUC)

Int. J. Multiphase Flow, Vol. 20, (1994) pp. 315-338.

Validation of COMMIX with Westinghouse AP-600 PCCS Test Data

J. G. Sun, H. T. Chien, J. Ding, and W. T. Sha

Presented at 21st Water Reactor Safety Information Mtg., Bethesda, MD, Oct. 25-27, 1993.

Analysis of Thermal Mixing and Boron Dilution in a PWR

J. G. Sun and W. T. Sha

NUREG/CR-5822, ANL-91/43, July 1992.

Development of Liquid-Film Tracking Models for Analysis of AP-600 Passive Containment Cooling System

J. G. Sun, W. T. Sha, and Y. S. Chen

Presented at ASME Winter Ann. Mtg., New Orleans, LA, Nov. 28-Dec. 3, 1993.

Transient Flows and Pressure Waves in Pipes

X. Q. Wang (Nuclear Industry Management Institute), J. G. Sun, and W. T. Sha

Transient Thermal Hydraulics, Heat Transfer, Fluid-Structure Interaction, and Structural Dynamics, PVP Vol. 270, pp. 39-44, ed. Y. W. Shin, ASME, New York, 1994.

Thermal and Mechanical Sciences

Section Manager: M. W. Wambsganss

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Support Staff/Visiting Scientists: Y. Cai, D. M. France,¹ S. Zhu

Technician: R. K. Smith

Secretary: J. A. Stephens

Students: B. Knodel,² T. N. Tran²

Staff backgrounds and program activities in the Thermal and Mechanical Sciences Section represent many diverse areas, including structural dynamics, thermal-hydraulics, heat transfer, fluid flow, and vibration. Staff expertise and experience is primarily in experimentation and testing, but also extends to modeling. A particular strength of the Section is the array of test facilities that it operates. These include the Flow-Induced Vibration Test Facility (an 8,000-gpm water flow loop), the Flow and Heat Transfer Test Facility (a computer-controlled, thermal-hydraulic, transient, nonisothermal, 2,200-gpm water loop), a low-velocity water channel, an ice-slurry test facility, an adiabatic two-phase flow apparatus, small-channel heat transfer test apparatuses for flow boiling and condensing, and a 500-gpm water loop; under construction is a small-channel apparatus for flow boiling visualization.

The Section performs applied research, component development and performance testing, and consultation. Current activities include research in the areas of flow-induced vibration, multiphase flow and heat transfer in small channels, ice slurries for district cooling, and vehicle/guideway interaction dynamics for high-speed trains using magnetic levitation. Activities in support of the Advanced Photon Source (APS) project at ANL include ongoing vibration studies with emphasis on the storage ring magnet/girder support assemblies. Consulting is being carried out for the Taiwan Power Company (Taipower).

Flow-Induced Vibration

Crossflow-induced vibration and instability continue to receive extensive attention in several countries, most notably Japan, Canada, and France. Experts in this subject area consider this to be an important topic of academic interest that has practical applications; see recent reviews published in *Technology for the '90s*, ASME, July 1993, by Price (Canada), Zdravkovich (U.K.), Axisa (France), and Blevins (USA). The Thermal and Mechanical Sciences Section conducts three programs in this area: (a) DOE Office of Basic Energy Sciences (BES) program to develop and apply methods to identify and characterize nonlinear and chaotic vibration in fluidelastic systems, (b) a multiyear program funded by Taipower to develop methods for predicting tube vibration in heat exchangers, and (c) a two-year program funded by the Electric Power Research Institute (EPRI) to measure motion-dependent fluid forces acting on tube arrays.

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Chaos in Fluid/Structure Systems

Integrated theoretical and experimental studies are performed to enhance the understanding of stability phenomena involving both fluids and solid structures and their coupling. The objectives are to improve our physical understanding and provide mathematical modeling of the nonlinear dynamic interactions of fluid/structure systems and to seek reduced-dimension mathematical models for complicated fluid/structure systems. A class of important and practical problems, including fluidelastic instability of loosely supported tube arrays, is being studied analytically and experimentally. In addition, coupled stack/wire dynamics due to wind excitation are being investigated analytically to compare with observations. The work is performed as a cooperative research program with Cornell University. Results from this project include (a) unsteady-flow theory for fluidelastic instability of tube arrays in crossflow, (b) characterization of chaotic vibration of tubes in tube arrays, (c) identification of excitation mechanisms and nonlinear response of a coupled stack/wire system, and (d) measurement of motion-dependent fluid forces for wake-induced flutter of tubes in crossflow.

Flow-Induced Vibration

This program, funded by Taipower since 1988, includes diagnosis and resolution of flow-induced vibration problems at Taipower, such as excessive oscillation of valves, pumps, and piping systems; training of Taipower staff, as well as professional staff from research organizations and universities in Taiwan, through seminars, short courses, and staff visits; assistance in the development of computer programs and design guides for predicting flow and vibrations in steam generators and heat exchangers; and development of an unsteady-flow theory for vortex-induced vibration of tubes in crossflow.

Fluid Forces Acting on Tube Arrays in Crossflow

The purpose of the program is to evaluate existing fluid-force data, measure motion-dependent fluid forces, and complete the unsteady-flow theory for fluidelastic instability of tube arrays in crossflow. Knowledge of fluid excitation forces is essential for predicting forced vibration due to turbulent flow. Motion-dependent fluid forces, including fluid damping and stiffness, are the key elements in the development of a dynamic stability theory. Without an understanding of these fluid forces, development of a reliable method for predicting flow-induced vibration in heat exchangers and steam generators will be very difficult. Because of the existing test facilities and extensive experience at ANL, EPRI is sponsoring a two-year program to measure the motion-dependent fluid forces for several tube arrays for application in the evaluation of the potential for flow-induced vibration in steam generator. Specifically, the program objectives are to (a) measure the fluid forces that act on tube arrays in crossflow due to the motion of a tube within a tube array and, from the measured fluid forces, calculate fluid damping and fluid stiffness associated with coupled tube motion; (b) analyze the stability of tube arrays based on the unsteady-flow theory and using the measured motion-dependent fluid-forces coefficients; and (c) evaluate the existing fluid-force data developed by EPRI and its contractors, as well as other data in the literature. This is a new program, initiated in March 1994.

Multiphase Flow and Heat Transfer

Our research in the area of multiphase flow and heat transfer is focused on compact heat exchangers for phase-change (boiling and condensing) applications. We are engaged in two DOE-funded research programs, one funded by the Office of Industrial Processes (OIP), under the Advanced Industrial Concepts Division, and the second by the Office of Energy Research (ER), under the Laboratory Technology Transfer Program, as a CRADA with Modine Manufacturing Company of Racine, WI.

Compact Evaporators for Process Industries

The objective of the DOE/OIP-funded research task is to perform fundamental studies that will contribute directly to the development of the technology base required for designing compact heat exchangers for the process industries. In particular, we are investigating multiphase flow and heat transfer issues associated with the boiling/condensing of pure fluids and multicomponent mixtures in small noncircular channels that are representative of the flow passages in compact heat evaporators. The resulting data are used to develop (a) an understanding and characterization of the basic multiphase flow and heat transfer mechanisms and (b) validated correlations and predictive methods that will form the basis for developing a design methodology and industry standards for multiphase flow applications of compact heat exchangers.

Current research activities are focused on small circular and noncircular channels (hydraulic diameter < 3 mm) and evaluation of the effects of channel geometry and size on boiling heat transfer coefficients and associated heat transfer mechanism(s). The test channels are heated to produce a constant heat flux. Local heat transfer coefficients, as a function of mass quality, are determined from measurements of wall-surface temperatures, in-stream bulk fluid temperatures, and inlet/outlet pressure. Geometry and size are test parameters. Experiments have been completed on a rectangular channel (4.06 x 1.70 mm) and a circular tube (2.46-mm diameter). The most significant finding is that a nucleate boiling mechanism dominates to low values of wall superheat ($\approx 3^\circ\text{C}$), and the convective-to-nucleate boiling transition is expected to be a function of channel size and fluid. Mechanistic studies that include flow visualization of the boiling process (bubble growth and departure) in small channels are also being performed. Flow will be visualized by ultra-high-speed video. The results of these studies will lead to the development of mechanistic-based correlations.

Flow patterns are important to the understanding of phase-change heat transfer mechanisms and are used to guide the development and application of mechanistic-based correlations. Two-phase dynamic pressure data have been analyzed by the techniques of chaotic dynamics with the objective of developing a methodology to identify two-phase flow patterns and transitions. Techniques that were applied include power spectral densities, autocorrelation functions, Lyapunov exponents, and fractal dimensions.

High-Performance Compact Condensers

A cooperative R&D agreement (CRADA) with Modine Manufacturing Company began in October 1992. The objective of this project is to develop the technology base required by Modine to further develop and optimize the design of Modine's high-performance, parallel-flow condenser for vehicular air-conditioning applications. Modine's condenser uses flattened tubes, each containing a number of small, typically noncircular flow passages. The objectives are to (a) identify the flow-passage size and geometry that yield the highest-performance heat transfer surface for condensation, (b) develop validated correlations for condensation and two-phase pressure drop, (c) apply these correlations in the optimal design of heat transfer surfaces for condensers used in vehicular applications, and (d) design, fabricate, and performance-test a prototype condenser.

Experimental design considerations led to a test section consisting of a multipassage condensing tube sandwiched between two multipassage coolant tubes, thus forming a counterflow heat exchanger. A small-channel condensing test apparatus has been designed to accommodate the test sections and test parameters, as specified by Modine, and fabrication has been completed (see photograph). Total condensation takes place within the test section. Data analysis requires a correlation for the single-phase heat transfer

Small-channel apparatus for study of condensation heat transfer

coefficient on the coolant side and knowledge of the end of condensation (initiation of subcooling). With regard to the coolant-side heat transfer coefficient, we developed and applied unique methods for generating the required data and developing the correlation, as well as for determining the end of condensation. The latter method uses a strip, instrumented along its length with thermocouples, that is in contact with the cooling tube. An abrupt change in the temperature profile measured by the strip thermocouples has been shown to be a reliable indication of the end of condensation. We have developed and validated computer-based programs for data acquisition and reduction. An initial set of condensation test data has been obtained from a tube with circular flow passages.

Ice Slurries for District Cooling

Demonstration Programs

Efforts continue in the promotion and transfer of technology involving ice-slurry district cooling. This technology was conceived and pioneered by ANL over the last seven years. Attention is focused on fostering first-of-their-kind demonstrations of this technology. A small-scale demonstration organized and designed by ANL, Northern States Power, and EPRI is currently underway in Minneapolis. Ice slurry generated at a utility service center with an 84-ton ice maker is pumped through 2-in.-diameter pipes to cool the service center and two local businesses. Efforts this year have centered on a large commercial-scale demonstration at ANL in a collaborative effort between ANL research and plant facilities groups, and potentially with the collaboration of Commonwealth Research Corporation, under the DOE IHEM/FEMP program for demonstrating new emerging technologies at federal labs. As planned, this program will be of two- to three-year duration and will be funded at about \$4 million by both government and private-sector contributions. If funded, the program will involve 1-ft-diameter piping delivering ice slurry to several site buildings from a central plant having an 800-ton ice-slush maker. Initial response from DOE is favorable. With successful completion of these efforts, the program will have accomplished the following:

- Demonstrated workability of ice-slurry generation, transport, and storage in a field environment involving multiple loads and storage tanks at large commercial scale.
- Developed control and operation philosophy relative to space cooling, district cooling, and potential for load shifting.
- Accelerated the transfer of advanced cooling technology developed by DOE by bringing together, in a sharply focused effort, research and development groups, equipment manufacturers, and the end user in a collaborative program.
- Developed an engineering design data base to enable the application of ice-slurry cooling in a wide range of situations.

Fundamental Studies

In a supplemental effort, the fundamentals of ice-slurry flows are being investigated in a Ph.D. research project with the University of Illinois at Chicago. A laboratory-scale ice-slurry flow facility, featuring 1-in.-diameter piping, has been designed and fabricated at ANL. The facility uses the direct-freeze method to manufacture ice. Project objectives are to measure the flow and heat transfer characteristics of various ice slurries as a function of ice fraction and ice-particle size. The flow facility has been debugged, and preliminary data have been obtained.

Advanced Photon Source

The Advanced Photon Source (APS) currently under construction at ANL is a user facility for synchrotron radiation research. In the facility, positrons circulate in a 1040-ft-diameter storage ring and emit photons (X-rays) of high intensity. Successful operation of the APS requires a very stable closed orbit for the positrons. A contributor to beam instability is vibration of the storage ring quadrupole magnets. Such vibration can lead to distortion of the positron closed orbit and to potentially unacceptable beam emittance growth. The vibration criteria are very stringent. With the objective of ensuring that vibrations will not degrade the performance of the machine, Section staff have conducted an ongoing program of vibration studies that support APS design, development, and operation.

As construction proceeds, our emphasis is on solving more specific vibration problems. This contrasts with our previous activity involving general site measurements of ground motion and structural response.

A vibration problem of particular importance is the dynamic response of the storage ring magnet/girder assemblies. The girder supports the quadrupole magnets, and the girder, in turn, is supported by three sliding-wedge-type alignment jacks; the jacks rest on pedestals that are securely anchored to the storage ring basemat. Although the response of the quadrupole magnets to ambient ground excitation was essentially within the original design specifications, a large amplification of ground motion was observed at the quadrupole magnets; this could lead to potential operational problems. Therefore, a major program was initiated to reduce this amplification factor. In particular, a large number of viscoelastic damping materials, configured in various ways, were studied. Several applications were successful in reducing the amplification by a factor of approximately 10. The program is continuing, with the objective of optimizing the design of the damping treatment and minimizing the cost of retrofitting the magnet/girder assemblies in the storage ring tunnel.

Another problem area under investigation is flow-induced vibration of critical APS components. Many APS operational systems are water-cooled, including the storage ring quadrupole magnets. A large vibration response of the quadrupole magnets was observed when cooling water was flowing. A program is being developed to address this and other flow-induced vibration problems.

Maglev Studies

The dynamic response of a magnetically levitated transportation system is very important for the safety, ride quality, guideway design, and cost of these high-speed systems. The key elements in the study of maglev system dynamics are magnetic forces. In the past, many studies have been performed to help us understand and predict magnetic forces for differing cases. It appears that most maglev-system designs are based on magnetic forces calculated or measured by the quasi-steady-motion theory. At this time, only limited studies have been published and many stability issues remain unresolved. A general approach to the calculation of motion-dependent magnetic forces and an experiment to measure magnetic forces have been developed. This study presents for the first time a direct method, based on the unsteady-motion theory, of measuring motion-dependent magnetic forces.

The experimental setup includes a rotating drum, a shaker, force transducer, and displacement transducer. The rotating drum is covered with aluminum sheet rolled to a diameter of 27 cm, and drum surface speed can be varied from 0 to 50 m/s. Three series of tests have been performed: magnet only, magnet and aluminum plate, and magnet and copper plate. Magnetic forces are measured as a function of gap and speed. An additional investigation has also been performed with conducting plates inserted between the magnet and drum to study the role of passive damping. The effects of conductivity, gap, excitation amplitude, and excitation frequency were investigated. Once magnetic damping and stiffness are known, the dynamic response of maglev systems can be predicted. In addition, a passive damping plate can be introduced to improve ride quality and control stability. Other control techniques that are based on the characteristics of magnetic forces can also be applied. The described technique will be very useful for measuring magnetic damping and stiffness coefficients of prototypes and will provide the necessary elements for predicting maglev response and controlling maglev systems.

To study vehicle dynamics and stability, tests of a small model have been performed on a flywheel. The test was run from low to high speed, and vertical and lateral accelerations were measured with accelerometers. Different instability regions were identified. A new vehicle model will be designed and fabricated to study the effect of various system parameters and to compare analytical and experimental results on vehicle stability.

Consulting

Consulting efforts are valuable because they provide Section staff with early indications of real-life problems and concerns faced by utilities and industry. Additionally, consulting provides an opportunity to apply the expertise developed in the course of conducting fundamental and applied research.

At present, the Section provides consultation to Taipower on flow-induced vibration and related areas. Completed efforts included the presentation of seminars and short courses at Taipower, and evaluation of flow-induced vibration of heat exchangers and large control valves.

Recent Work by the Thermal and Mechanical Sciences Section

Publications

Application of Chaos Theory in Identification of Two-Phase Flow Patterns and Transitions in a Small, Horizontal, Rectangular Channel

Y. Cai, M. W. Wambsganss, and J. A. Jendrzejczyk

Submitted to Int. J. of Multiphase Flow, March 1994.

Numerical Analysis for Dynamic Instability of Electrodynamic Maglev Systems

Y. Cai and S. S. Chen

Submitted to Shock and Vibration Journal, Feb. 1994.

Vehicle/Guideway Interaction and Ride Comfort of Maglev Systems

Y. Cai, S. S. Chen, D. M. Rote, and H. T. Coffey

Submitted to ASME J. Dynamic System, Measurement, and Control, Aug. 1993.

Vehicle/Guideway Interaction and Ride Comfort of Maglev Systems

Y. Cai, S. S. Chen, D. M. Rote, and H. T. Coffey

Proc. Intl. Conf. on Speedup Technology for Railway and Maglev Vehicles, Nov. 22-26, 1993, Yokohama, Japan, pp. 109-.

Instability of Electrodynamic Maglev Systems

Y. Cai and S. S. Chen

Presented at 64th Shock & Vibration Symp., Fort Walton Beach, FL, Oct. 25-28, 1993; submitted to ASME J. Dynamic Systems, Measurement, and Control.

Dynamics, Stability, and Control of Maglev Systems

Y. Cai, S. S. Chen, S. Zhu, T. M. Mulcahy, D. M. Rote, and H. T. Coffey

Proc. Maglev '93, 13th Ann. Conf. on Magnetically Levitated Systems and Line Drives, Argonne Natl. Lab., May 19-21, 1993, 265-.

Nonlinear Dynamics of an Elastic Cable under Parametric and External Resonances

Y. Cai and S. S. Chen

Accepted for publication in ASCE J. of Engineering Mechanics.

Dynamics and Controls in Maglev Systems

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Dynamic Stability of Maglev Systems

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Vol. 1, pp. 533-543.

Nonlinear Dynamics of Loosely Supported Tubes in Crossflow

Y. Cai and S. S. Chen

J. of Sound and Vibration 168(3), (1993) pp. 449-468.

Chaotic Vibrations of Tubes with Nonlinearly Supported Tubes in Crossflow

Y. Cai and S. S. Chen

J. of Pressure Vessel Technology, Vol. 115 (1993), pp. 128-134.

Nonlinear Fluid-Stiffness-Controlled Instability of a Tube Row in Crossflow

S. H. Chen and S. S. Chen

Presented at Asian-Pacific Vibration Conf. '93, Nov. 14-18, 1993, Kitakyushu,
Japan; Proc. Symp. on Flow-Induced Vibration in Engineering Systems, pp. 8-13.

Chaotic Vibration in Fluidelastic Instability of a Tube Row in Crossflow

S. H. Chen and S. S. Chen

ASME Publication, PVP Vol. 258, pp. 11-19, 1993.

Fluid-Structure Interaction

S.S. Chen, Editor

In Technology for the 90's - A Decade of Progress, ASME Publication,
pp. 543-972, 1993.

Flow-Induced Vibration and Fluid-Structure Interaction

S. S. Chen, Contributing Editor

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S. S. Chen

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S. S. Chen, S. Zhu, and Y. Cai

To be published in J. of Sound and Vibration, Feb. 1994.

Fluid Damping and Fluid Stiffness of Tube Arrays in Crossflow

S. S. Chen, S. Zhu, and J. A. Jendrzejczyk

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Experiment on Fluidelastic Instability of Loosely Supported Tube Arrays in Crossflow

S. S. Chen, S. Zhu, and Y. Cai

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Motion-Dependent Fluid Forces Acting on Tube Arrays in Crossflow

S. S. Chen, S. Zhu, and J. A. Jendrzejczyk

ANL-93/15, June 1993.

High-Performance Microchannel Heat Exchanger for Cooling High-Heat-Load X-ray Optical Elements

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Micromechanical Systems, The Amer. Soc. of Mechanical Engineers, New York,
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General Vibration Monitoring, Coupling between a Storage Ring Tunnel I-Beam Support Structure and Tunnel/Basemat

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General Vibration Monitoring: Coupling between Experimental Hall Structure and Storage Ring Tunnel and Basemat

J. A. Jendrzejczyk, M. W. Wambsganss, and R. K. Smith

ANL/APS/IN/VIB-93/4, March 1993.

General Vibration Monitoring, Experimental Hall

J. A. Jendrzejczyk, M. W. Wambsganss, and R. K. Smith

ANL/APS/IN/VIB-93/3, Jan. 1993.

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J. A. Jendrzejczyk, M. W. Wambsganss, and R. K. Smith
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Boiling Heat Transfer in a Small, Horizontal, Rectangular Channel

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Determination and Characteristics of the Transition to Two-Phase Slug Flow in Small Channels

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The Instrumentation and Nondestructive Evaluation (INDE) Section conducts research and development in a broad range of energy-related technologies. Major areas of responsibility are the development of instruments and NDE techniques for fossil energy, conservation, and nuclear technologies. Another strong area for the Section has been the development of sensors and technologies for arms control and treaty verification. We have been actively involved in a number of initiatives such as AMTEX, AUTO, Manufacturing, and others related to the general competitiveness of American industry. The projects described below give a clear indication of the breadth of our work.

Arms Control

Millimeter-Wave Detector

This program is funded by the DOE Office of Nonproliferation and National Security, Office of Research and Development. The goal is to develop a millimeter-wave (mm-wave) sensor for standoff detection of chemicals associated with weapons production. Millimeter-wave detection of chemical species is based on rotational energy transitions of molecules. Two approaches are being pursued: one is an active technique that uses the

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swept-frequency radar technique and the other is a passive technique that uses the multispectral radiometer technique. (An environmental monitoring version of this technology is discussed later in this chapter.)

The two most critical parameters for a chemical sensor are the detection sensitivity and chemical selectivity. Because the mm-wave absorption of a molecule equals emission under local thermodynamic equilibrium, these parameters are the same for both the active and the passive techniques. To determine these parameters, an active mm-wave spectrometer was designed and built in the frequency range of 225-315 GHz. The main features of the system are that it uses a backward-wave oscillator and a frequency tripler for the source, a gas cell with feed lines for controlled measurement of gas/vapor mixtures, and a hot electron bolometer for the detector. The frequency can be swept over a wide bandwidth (≈ 45 GHz) in fractions of a second, and the mm-wave absorption lines of the desired gases can be determined at different partial pressures in a nitrogen medium.

The mm-wave sensitivities of several chemicals related to weapons production were measured in the laboratory at two pressure regimes: (a) low pressure and (b) atmospheric pressure. The measurements were compared with simulation for several molecules. The simulation used a Lorentzian pressure-broadening equation to predict the pressure-broadened spectra from low-pressure spectral data that are available in the literature. Good agreement was obtained between simulation and measurements.

To determine the chemical selectivity of the technique, both synthetic and real chemical mixtures were tested and analyzed. The synthetic mixture consisted of 11 chemicals and the real mixture consisted of 9 chemicals. Two different signal processing approaches were evaluated: (a) the conventional multivariate technique and (b) a new deconvolution technique specially developed for this application. The multivariate technique requires knowledge of the constituents of the plume mixture to be characterized, and it works well if the calibration samples are representative of the mixture. The deconvolution technique in principle does not require prior knowledge of the mixture constituents and is aimed at detecting the presence and amount of a target chemical in an unknown plume. Test results have shown a dramatic improvement in chemical resolvability with this new technique.

Micro-Mass Spectrometer

This program is funded by the DOE Office of National Security and Nonproliferation. The goal of this work is to develop a miniature mass spectrometer for the detection of materials associated with nuclear production/enrichment and proliferation activities. This sensor system is based on a miniaturized linear or reflectron time-of-flight (TOF) mass spectrometer. The system will ultimately be highly portable, weighing 15-18 lb and having a volume no larger than a notebook ($\approx 4 \times 9 \times 11$ in.) with all components. The spectrometer will be capable of performing multiphoton ionization (MPI), resonance-enhanced multi-photon ionization (REMPI), and resonance ionization mass spectroscopy (RIMS) of selected species.

The unique features of this system include a highly miniaturized (≈ 20 -cm-long) linear reflectron ion flight tube and advanced ion detector technologies. Ionization uses an N_2

laser system for MPI and an N₂ dye laser system for REMPI and RIMS. Despite the radical departures from conventional mass spectrometer technologies (which may incorporate 1-m flight tube designs), the feasibility study has concluded that the new designs will be capable of operating with performance specifications that are similar to their much larger laboratory counterparts. These specifications include excellent mass resolutions (i.e., on the order of 200 for a linear system and 600-800 for the reflectron systems at a mass/z of 100 atomic mass units), and sensitivities (i.e., generally ppm to ppb, but possibly lower for RIMS analysis).

Current tasks include development of laboratory models for the reflectron and linear TOF systems. These models will be used to evaluate the sensitivity of the miniature designs to materials of interest. Additionally, miniature hand-portable designs are being finalized. These systems will be employed for on-site inspection or placed on-site for remote automated monitoring.

Smart-Material Seal

This program is funded under the ANL advanced-concept project for arms control and treaty verification. The goal is to develop a "smart seal" that provides seal authentication and also contains a memory that records the history of operation. Two types of seal configuration, strip and blanket, have been evaluated. A strip seal was fabricated from a stainless steel strip of 0.003-in. thickness, on which three piezoelectric films were attached. Similarly, a blanket seal was made from a thin metal sheet on which a number of piezoelectric films of irregular shapes were attached. Seal authentication was demonstrated by either active TOF measurement or signal-matching. Both seals were tested for various operations, including opening and closing of the seal's lock. A neural-network technique is being developed for signal analysis.

Proliferation Detection

Civilian reactors could be used to generate weapons-grade fissile material and for deceptive practices in the dismantling of weapons in order to conceal fissile material. Detecting such clandestine activities is very difficult, and DOE is playing an important role in developing methods for checking compliance with the Nuclear Non-Proliferation Treaty. The INDE section is addressing this issue in an advanced-concepts project that uses pulsed neutrons to experimentally validate models for identifying reactor operation history through isotopic analysis of tags or effluent. The project will apply the use of pulsed neutrons to isotopic analysis by monitoring neutron-energy-dependent prompt gammas during irradiation. In this study, Argonne's Intense Pulsed Neutron Source (IPNS) is being used as a test bed.

Tracking Treaty-Limited Components with Commercial Technology

This project is developing a system to monitor the movements of treaty-limited items and transportation vehicles by determining and transmitting the locations of treaty-

limited-item movements throughout eastern Europe and the former USSR. The commercial aspect of this technology provides an openness that will contribute to acceptance of this system for movement surveillance by the treaty participants. Analysis of the surveillance is used to verify treaty compliance. Supporting systems are being utilized to complete the technology. Secure tags for treaty-limited components have been developed by Lawrence Livermore National Laboratory and the tag technology is being adapted for use in the project through a cooperative effort. When a tag attached to an item is tampered with, information about the item and its location is sent to the system operators. This tracking and security information is transmitted to DOE TRANSCOM headquarters in Washington, DC, via established commercial service for satellite communication.

Fossil Energy

On-Line Nuclear Magnetic Resonance Monitor

This is a joint Cooperative R&D Agreement (CRADA) funded by DOE Fossil Energy, Bartlesville Program Office, between Amoco Corporation, Bio-Imaging Research, Inc. (BIR), and ANL. The purpose is to develop, demonstrate, and transfer technology associated with on-line nuclear magnetic resonance (NMR) sensing and control technology for application to light oil residuum and heavy oil upgrading. Goals include (a) development of on-line NMR sensor technology (NMR pulse techniques and prototype), (b) implementation of the NMR sensing and control system prototype in the plant environment, (c) implementation of this technology for a variety of upgrading processes and characterization needs (for both residuum and heavy oil) over the lifetime of the proposal, and (d) transfer of the technology to BIR for commercialization.

The NMR sensing technology provides genuinely enabling near-term technology with the ability to perform on-line characterization of residuum and heavy oil properties, as required for the prediction of processability and of upgraded products yields, as well as for efficient process control. Unlike other process-control sensing systems (such as gas chromatography, laser chromatography, Fourier transform infrared, near-infrared, and mass spectroscopy), NMR technology can be used to monitor the chemical and physical properties of optically diffuse liquids, semisolids, and solids. This technology is directly applicable to many of Amoco's heavy oil upgrading needs. For example, in residuum and heavy oils, NMR measurements can be quantitatively correlated with a variety of properties such as viscosity, molecular weight distributions, aliphatic/aromatic ratio, and presence of impurities.

The feasibility of applying NMR spectroscopic techniques to process sensing and control is being evaluated via laboratory experiments. Experiments to date have shown excellent sensitivity to impurities (e.g., water) and to specific gravity variations of the residuum. Additionally, the studies have indicated that sufficient signal-to-noise ratio will be available for both on-line ^1H and ^{13}C NMR spectroscopic monitoring in the plant environment. In the next two tasks, a prototype instrument will be developed or modified as required and its operation verified in a series of laboratory experiments. In the final task, system efficacy will be evaluated through on-line operation in a pilot or production

facility. In each task, emphasis is on developing the most robust techniques and instrumentation for the in-situ process-control environment.

NDE of Continuous Fiber Ceramic Matrix Composites

This work is part of the ceramic technology base support being developed as part of the Fossil Energy materials program. Fracture toughness of ceramics can be improved significantly with the use of newly developed continuous fiber ceramic matrix composites (CFCCs). However, the reliability of mechanical properties depends on many factors, including fiber/matrix interfacial shear strength, type of chemical bond at the fiber/matrix interface, density uniformity, direction of the fibers, type of fiber, and use of either multifiber tows or single large individual filaments ($>50\text{ }\mu\text{m}$ in diameter). Of current technological interest are applications to hot-gas filters for hot-gas clean-up and for high-temperature sections of coal-gas fired gas turbines.

In cooperation with Oak Ridge National Laboratory and industrial partners (also funded by DOE/Fossil Energy), CFCCs made of SiC/SiC are being produced by a number of processes, including chemical vapor infiltration (CVI). SiC two-dimensional and three-dimensional weave structures are being produced by changes in the CVI process. At ANL, we are developing nondestructive characterization methods to measure various characteristics of these materials. Specifically, we are developing 3-D microfocus X-ray computed tomographic (MXCT) imaging methods to detect and measure (a) axial and radial density variation and (b) fiber orientation by coupling image processing with X-ray image data. In this case, a 3-D MXCT system has been totally designed and built in-house at ANL. Results so far have shown that fiber orientation can be determined to $\pm 2^\circ$ with image data (1024×1024 by 14 bits) from our new current detector system. We have also made extensive software modifications for scatter corrections, geometrical distortions, and ring artifacts to obtain higher-quality data for analysis.

To begin understanding the effects of fiber/matrix-bond chemical interactions, we continue to use NMR spectroscopy to study fiber-surface chemistry; ^{29}Si , ^{13}C , and ^{17}O were examined. Magic angle spinning was employed in several magnetic-field-strength NMR systems at ANL to study these effects. No correlations have yet been established relative to interfacial shear strength.

Ultrasonic Viscometer

This program is funded by the DOE Fossil Energy AR&TD program, with the objective of developing advanced instrumentation for fossil-energy processes. In FY 1994, we re-examined ultrasonic methods for liquid viscosity measurement. A novel approach was developed, combining both ultrasonic longitudinal-wave and shear-wave impedance measurements. The longitudinal-wave measurement allows one to determine liquid density and sound velocity in the liquid. Liquid viscosity can then be derived from the shear-impedance measurement. The technique was tested for highly viscous liquids such as honey and epoxy; results agree with reported values. An ultrasonic viscometer has been designed and patented: it is the only nonintrusive viscometer known to exist.

Energy Efficiency And Renewable Energy

Development of Nondestructive Characterization for Monolithic Ceramics

Heat Engine Project

This work is part of the large DOE transportation system effort on development of ceramics for advanced heat engines. Several near-term advanced heat engine components are being developed from monolithic structural ceramics. These include turbine blades, nozzles, and combustor liners. Because these materials are susceptible to fracture by flaws (e.g., voids, inclusions), as well as by subcritical crack growth, the detection of flaws for high reliability in ceramic production is imperative. In a joint activity with the Allied-Signal Aerospace/Ceramic Components Division, we are playing an integral role in helping to improve reliability in Si_3N_4 ceramic processing. We are engaged in two NDC methods this year: (a) X-ray computed tomography for mapping density distributions in pressure-slip-cast rotors as part of the DOE Advanced Turbine Technology Applications program (ATTAP) and (b) nuclear magnetic spectroscopy for characterizing gel-cast components.

We have demonstrated that radial and axial density variations in as-cast or presintered ceramics can be mapped by X-ray CT. This study utilized cylindrical specimens processed under various pressure-slip-cast conditions (see figure below). We are now extending this technology to the measurement of density gradients in actual ceramic rotors for the ATTAP project.

NMR Spectroscopy and Imaging of Advanced Ceramics and Ceramic Composites

The objective of this work is to develop and evaluate advanced NDE technology for characterization of the chemical and physical properties of advanced ceramics and ceramic composites. Working in conjunction with Dr. Ogbemi O. Omatete of the Materials and Ceramics Division, Oak Ridge National Laboratory, we will evaluate the utility for NMR to aid the process development and on-line production of gel-cast composites. Nondestructive NMR imaging and spectroscopic studies will enable visualization of the polymerization process, calculation of polymerization rates, and measurement of viscosity within the component. Additionally, imaging methods will be employed for flaw determination and the results will be correlated with results obtained through destructive analysis and fracture mechanics.

Advanced Turbine System

As part of the DOE Office of Industrial Technologies project on Advanced Turbine Systems (ATS), we are developing and applying NDE methods to turbine engine components in a joint activity with Solar Turbines, Inc. (a wholly owned subsidiary of Caterpillar Inc.). Specifically, we are studying Si_3N_4 and SiC , which will be used to produce turbine blades, nozzles, and combustor liner tiles. The NDE methods under development are X-ray radiographic imaging, dye penetrant, laser scatter (utilizing information obtained from the ARPA project described later in this section), and a new method utilizing measurement of specific damping capacity of the material. We have established initial theoretical detection limits of the components using X-ray imaging technology and we have developed laser scatter methods for surface and near-subsurface characterization (see photograph).

Low-Cost Ceramic Initiative: Ceramic Machining

As part of the DOE Office of Transportation Systems/Heat-Engines/Materials Program, a new program was initiated in 1993 to develop lower-cost ceramics. A key aspect is reduction of machining costs. Based on the results of the ARPA-funded laser scatter project, this technology was selected to establish whether the laser scatter information could be used to assess machining-induced damage, with a preference for an on-line detection mechanism. The work is a joint project with the Caterpillar Technical Center in Peoria. Si_3N_4 and SiAlON are being examined. Fast, aggressive machining methods are being studied, and the ANL-based laser scatter system is being studied as a method for detecting machining-induced damage.

Development of Nondestructive Characterization Methods for Continuous Fiber Ceramic Matrix Composites

This work is part of the DOE Office of Industrial Technologies (OIT) project addressing process-reliability issues relative to production and eventual industrial application of continuous fiber ceramic matrix composites (CFCCs). As part of this large program,

Using laser scattering to evaluate the surface and near-subsurface of a ceramic turbine blade

development of nondestructive characterization methods was identified as a necessary and critical step. The Division was identified as the technical lead in this task. The total CFCC program involves 10 industrial teams consisting of CFCC producers, independent test facilities, and end users. The project involves both oxide-based (Al_2O_3 , ZrO_2) materials and nonoxide (SiC , Si_3N_4) materials. Work at ANL has focused on development of infrared imaging systems to detect thermal shock damage, fiber/matrix interface oxidation, delamination, and poor fiber distribution.

Superconductivity Partnership Initiative

Development of X-Ray Imaging for High-Temperature Ceramic Superconductor Process Control

We have continued to explore X-ray imaging technology, specifically dual-energy methods, to study power-in-tube-processed BSCCO superconductor wires. A problem in processing has been the development of a phenomenon called "sausaging." This is a nonuniform axial cross section of the superconductor powder in the tube; severe sausaging can cause total discontinuity in the superconductor. Dual-energy X-ray through-transmission imaging was shown to be capable of detecting this phenomenon and was used to determine onset as a function of rolling conditions. Work continues on this and other related NDE for superconductors.

NDE of High-Temperature Ceramic Superconducting Tapes

Under a joint program between ANL and American Superconductor Corporation, ultrasonic and neutron diffraction techniques have been applied to the evaluation of high-temperature ceramic superconductor composites made by the powder-in-tube (PIT) method. The primary application for these superconductors is wire for motors. Ultrasonic velocity measurements have been used to monitor the PIT processing of silver-clad superconducting tapes. The velocity measurements indicate the presence of a liquid phase during sintering, as well as changes in crystal structure during fabrication. Knowledge of the liquid phase is very important for optimizing the fabrication process so the tapes will conduct the highest possible critical current. Results indicate that the ultrasonic technique can be used to monitor the processing of this type of ceramic superconductor. The system has been automated and is being used routinely for characterizing superconducting tapes. Neutron diffraction measurements have been made to determine the residual strain in the silver sheath and the superconducting ceramic. These strains are the result of differences in the thermal expansion of the constituents and can affect the mechanical and electrical properties of the superconducting tapes.

Energy Research

Development of Rapid Prototyping Technology for Ceramics: Reverse Engineering

This is a new CRADA joint project with the Division's Ceramics Section. Focus is on development of the new materials processing technology known as rapid prototyping (also called toolless or desktop manufacturing). At present, the state of development of this technology is that polymer, wax, and nylon parts have been produced but ceramic components have not yet been produced. If ceramic parts could be produced by this technology, significant manufacturing savings could be realized in one-of-a-kind situations, as well as in limited production runs that would allow testing to verify mechanical integrity and "fit and function." For complex-shaped parts, including parts with complex internal geometry, e.g., internally cooled turbine blades, attachment designs, etc., the precision of internal dimensions must be confirmed. Reverse engineering using the Division's high-spatial-resolution X-ray CT scanner allows the direct digitization of complex geometry components. The resulting image files can then be used to obtain dimensional data sets to allow comparison to the desired dimensions. The critical issue in the image data is edge detection. Many image-processing approaches are being taken to clarify this issue, including gradient methods and neural net approaches. The CRADA partners are Scientific Measurement Systems of Austin, Texas (X-ray imaging technology), and Spectra Group Limited of Maumee, Ohio (rapid prototyping technology).

Rapid Prototyping for Heat-Engine Components

This is the second new rapid prototyping project. Again, this is a CRADA and is joint with ET's Ceramics Section and with the Metals and Ceramics Division of Oak Ridge

National Laboratory. Although funded, the project is still being finalized in terms of CRADA details. The planned CRADA partners are Allied-Signal Aerospace Corporation/Ceramic Components Division and Solar Turbines, Inc./Caterpillar.

The purpose of this project is to advance rapid prototyping of ceramics to the stage that engine components can be produced for engine testing. Currently, the manufacturing of newly designed ceramic components for initial testing is extremely expensive and incurs long time delays. This technology may allow fast prototype testing. Attendant is the need to verify density uniformity by NDE methods, dimensional verification via NDE, and reliability of mechanical properties. All are to be addressed in this project.

National Sensor and Control Technologies Data Base

This a new program funded by DOE Energy Research, Laboratory Technology Transfer program. The purpose is to develop a national data base on sensor and control technologies. This resource will provide U.S. industry with a dial-up data base that catalogs the existing sensor and control technologies and describes their applications. In FY 1994, we established the format and selected the software for the data base. For demonstration purposes, we are establishing the ANL sensor data base.

Details of work for this program are protected under a CRADA and are the property of AMTEX.

Computer-Aided Fabric Inspection

Work has begun in the INDE Section to help the textile industry improve the quality of its products. AMTEX is a national collaborative effort between many textile companies and several national laboratories to improve the competitiveness of the textile industry. The Section will bring the expertise and technology developed through other programs to AMTEX to help increase the industry's technology base.

Sensors for Agile Manufacturing

The purpose of this project is to develop sensors for automation of the servicing processes associated with garment assembly; the results will be improved product quality and process productivity. The major deliverable will be demonstrations of the sensor technologies and controls as they apply to identified industry needs. Demonstrations will be carried out in both the laboratory and the production environment.

Advanced In-Car Sensing and Control

Micro-Mass Spectrometer Sensing System

This work is directed toward development and demonstration of a miniaturized multiport mass spectrometer (MPMS) for real-time, in-situ exhaust emission sensing and control. The MPMS prototype will be based on a highly miniaturized (i.e., 4-to-10-cm-long flight path) time-of-flight mass spectrometer. Emphasis is on the development of MS technology that can be mass-produced by technologies such as micromachining and very-large-scale integration.

Surface Acoustic Wave Sensor

This program will develop a surface acoustic wave (SAW) chemical sensor that can measure tailpipe-out emissions and thus monitor the performance of the catalytic converter system. A SAW sensor uses a piezoelectric substrate with patterned electrodes for signal transduction. A thin film that can selectively absorb gas molecules covers the surface, and the gas is detected with high sensitivity by measuring the SAW frequency shift.

Work for Others

Application of Neutron Diffraction to Determination of Residual Strains in Engineering Materials

Neutron diffraction techniques using ANL's Intense Pulsed Neutron Source, together with the General Purpose Powder Diffractometer, have been employed to measure residual strains in crystalline particles embedded in otherwise amorphous materials, including fiber reinforced composites, with an accuracy sufficient to validate analytical models used to predict mechanical properties. The particles act as "strain gauges" for these materials. The stress-free temperature has also been measured with neutron diffraction by determining bulk strain as a function of temperature. The stress-free temperature is needed to predict mechanical properties, and the only practical way to obtain this experimental value is by neutron diffraction. In addition, the coefficient of thermal expansion as a function of crystallographic direction has been measured in composites by neutron diffraction to characterize anisotropic effects.

Acoustic Leak Detection and Location for DHC Systems

A collaborative effort continues between DOE, Consolidated Edison of New York, and NRG Energy (a subsidiary of Northern States Power) to develop an acoustic system for locating leaks in underground piping. Results of field testing with acoustic sensors placed on bare pipe indicate that information is present in the acoustic signal that could help locate leaks. However, the use of in-stream sensors appears to have more potential for leak location. Laboratory experiments have been completed in the program to develop an

in-stream acoustic microphone. Placing the sensors directly in steam significantly improves the chances of accurately locating leaks in buried pipes. A valve and sensor system for inserting microphones into the underground piping has been developed. Valve and sensor systems have been delivered to both Consolidated Edison and NRG Energy for insertion in their district heating systems. Divisional staff will analyze acoustic signals after these systems have been installed.

ASME Task Group on Digital Imaging Applications for the Nuclear Industry

In cooperation with the Nuclear Regulatory Commission, the American Society of Mechanical Engineers (ASME) has organized a task group to develop a code for digitizing industrial radiographic film. Storing on computer the hundreds of thousands of radiographs associated with the construction of a nuclear power plant will save the utilities a considerable amount of money and time, and preserve the aging films. The INDE section is participating in this effort to develop the specifications and standards necessary to faithfully reproduce the indications on ASME-code-acceptable radiographs.

State of Illinois Grant: Infrared Imaging Development for Thick Thermal Barrier Coatings

The development of high-efficiency diesel engines with acceptable exhaust emissions requires higher operating temperatures in the combustion zone. One method under development to allow components to withstand these temperatures is the use of ceramic coatings. Plasma-sprayed ZrO_2 coatings are being developed by Caterpillar Inc. This project, cofunded by the State of Illinois and Caterpillar, is the second award received by the Section for development of time-resolved-infrared imaging (TRIR) methods to detect defects in plasma-sprayed coatings.

In this joint project, Caterpillar produces specimens of different coating types and thicknesses (up to 3.5 mm), with and without known disbond regions, on various substrates. To conduct nondestructive analysis for correlation with Caterpillar's destructive analysis, ANL uses the recently developed TRIR laboratory that includes a state-of-the-art infrared camera coupled to a personal computer, specially developed software, and several systems to apply known-input heat pulses. Software developed at ANL has been used to study differences in thermal transients, which have been related to regions of nonbonding. Analytical models have been shown to correlate very well with experiment data. Destructive analysis completed by Caterpillar has provided necessary input data on flaw thicknesses. Also, Caterpillar has made the necessary thermal property measurements on each component in the layered structure for input to the model.

The results of this project have been successful enough that Caterpillar has duplicated the ANL infrared laboratory and has made important upgrades to the system. Results to date show that defects of significance can be detected.

ARPA: Development of Laser Scatter Methods for Ceramic Bearings

This project is part of a large multiyear ARPA effort to develop ceramic bearings. As part of a ARPA project to apply ceramic bearings to engines, ANL has been developing laser-based methods to characterize the surfaces and near-subsurfaces of Si_3N_4 bearing components.

To address surface characterization and near-surface measurements, we established a laser scattering laboratory that uses an He-Ne laser (35 mW), together with many optical components for both laser beam insertion and subsequent detection of the scattered light. A CCD array camera is coupled to an IBM 486/33 MHz computer to handle data acquisition, image processing, and image display. This is coupled to a SUN SPARC II/GS for additional signal analysis. A granite table is used to support the optical system workstation. By using optical Fourier transform detection coupled with cross-polarization, we have demonstrated a detection sensitivity to subsurface microstructure and cracking.

Further, we have developed initial automated signal analysis methods, using neural networks, as a means to automatically interpret the laser data and discriminate microstructural variations.

Laboratory Directed Research and Development

Millimeter-Wave Sensor for Environmental Monitoring

This program is funded by ANL's Laboratory Directed Research and Development program. The objective is to investigate the potential of the millimeter-wave technique for continuous emissions monitoring (CEM) of industrial effluents. With the enactment of the Clean Air Act amendments in 1990, the need for CEM devices has taken on added importance for a variety of manufacturing industries and waste treatment facilities. Emphasis is on commonly occurring pollutants such as combustion products, volatile organic chemicals, and auto exhaust emissions.

A theoretical analysis was made to compare the mm/sub-mm-wave technique with optical techniques. Using a data base called HITRAN, we calculated detection sensitivities in the mm/sub-mm and infrared (IR) ranges for several environmentally hazardous molecules. For molecules with strong dipole moments, mm-wave detection sensitivity is comparable to or better than that of the IR technique, but for weak-dipole-moment molecules, it can be lower than the IR technique by two to three orders of magnitude. The main advantages of the mm/sub-mm-wave technique, however, are wide-area monitoring, simultaneous measurement of several target chemicals in real time, ease of spectral interpretation, and operability under hostile environments and all weather conditions.

The proof of principle of the active mm-wave technique was tested in air. Using a sweeper in the 75-110 GHz range and a frequency tripler, we generated mm waves at 225-330 GHz. A plume was created by heating D_2O in a beaker and releasing the vapor into the path of the mm-wave beam. A corner reflector on the far side of the plume returned

the radiation to a hot-electron-bolometer receiver. Lenses were used to collimate and focus the mm-wave beam. The measurement results showed the D₂O absorption lines clearly, and the line height decreased as the release rate of vapor decreased with time, thus confirming the detection.

Recent Work by the Instrumentation and NDE Section

Publications

Ultrasonic Wave Propagation in Multilayered Piezoelectric Substrates

H. T. Chien, S. H. Sheen, and A. C. Raptis

Submitted to Special Issue on Thin Films for Acoustoelectronics of IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, April 1994.

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X-Ray Computed Tomographic Imaging

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Detection of Subsurface Defects in Machining Silicon Nitride Ceramics by Optical Scattering Methods

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Application of Neutron Diffraction to Determination of Residual Stresses in Advanced Composites

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The Use of Local Computerized Tomographic Inspection for Nondestructive Evaluation of Ceramic Components

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Predicting the Performance of 3-D X-Ray Computerized Tomography Systems

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Laser Scatter Methods for Detection of Subsurface Machining Damage in Ceramics

J. S. Steckenrider, W. A. Ellingson, G. A. Forster, M. H. Haselkorn (Caterpillar Inc.), and
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Quantification of Volume Flaw Sizes in Ceramics by Image Processing of 3-D X-Ray Tomographic Data Sets

M. C. Stinson (Central Michigan U.), D. A. Holloway, and W. A. Ellingson

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Recognition of Subsurface Defects in Machined Ceramics by Application of Neural Networks to Laser Scatter Patterns

M. C. Stinson (Central Michigan U.), O. W. Lee (UCLA), J. S. Steckenrider, and W. A. Ellingson

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Patents

Solid-State NMR Imaging System

N. Gopalsami, S. L. Dieckman, and W. A. Ellingson

U.S. Patent No. 5,153,516 issued Oct. 6, 1992.

Ceramic Tamper-Revealing Seals

D. S. Kupperman, A. C. Raptis, and S. H. Sheen

U.S. Patent No. 5,169,188 issued Dec. 8, 1992.

Millimeter-Wave Sensor for Monitoring Effluents

N. Gopalsami, S. Bakhtiari, A. C. Raptis, and S. L. Dieckman

Patent application filed June 20, 1994. ANL-IN-94-046.

Transportation of Hazardous Materials

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The Transportation of Hazardous Materials Section primarily provides direct technical support to DOE in reviewing Safety Analysis Reports for Packaging (SARP) of radioactive material shipping packages for compliance with DOE Orders and with NRC and DOT regulations. In addition, the Section provides technical assistance to DOE on a variety of generic waste management and transportation issues, including the production and distribution of training and public information videos.

SARP Review Group

This Group operates independently of other Section programs and comprises a multidivisional, dedicated staff that includes the disciplines necessary to review the entire range of information provided in a SARP. On the average, more than 10 SARPs are under consideration by ANL at any one time. The SARP is a voluminous document that describes the package technically and justifies why the package meets all applicable regulations.

Each SARP consists of nine Chapters: General Information and Drawings, Structural, Thermal, Containment, Shielding, Criticality, Operating Procedures, Acceptance Tests and Maintenance Program, and Quality Assurance. Selected review activities are described below.

Materials (D. T. Raske)

The objective of the materials review is verification that materials of construction will maintain the package integrity under the mechanical and thermal loadings expected during both normal and hypothetical accident conditions of transport. Although no specific acceptance criteria exist for packaging materials, all materials used for construction must be documented so that the package can be evaluated.

The general requirements for containment vessel structural materials for Category I high-level radioactive material Type B packages designed to Section III, Subsection NB of the ASME Code are described in Article NB-2000. The Code allowable structural materials are listed in Section II, Part D, Subpart 1. Non-Code materials may be acceptable for

¹Special Term Appointee.

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containment vessels and containment vessel bolting if they are qualified by criteria equivalent to those applied to Code materials. These criteria are:

- Procurement according to an authoritative material specification such as ASTM, AMS, MIL, or SAE.
- Quantitative proof of the material's suitability for both the maximum and minimum service temperature.
- Certification of materials and fabrication equivalent to the requirements given in Section III, Subsection NB, paragraph NB-4120 of the ASME Code.
- Nondestructive examination (NDE) equivalent to the requirements given in Section III, Subsection NB, paragraph NB-2580 of the ASME Code.

In addition, both Code and non-Code bolting materials should satisfy the following requisites to ensure quality:

- Procurement of material or finished bolts from a vendor that is qualified in accordance with a quality assurance plan.
- Quantitative proof that the bolts are not counterfeit, including confirmation of chemical and mechanical properties.

Structural (P. Turula, Y. Y. Liu, D. T. Raske, and A. Stojimirovic)

The objective of the structural review of a SARP is to verify that the packaging satisfies all structural design and test requirements, and that the packaging will perform as intended under both the normal conditions expected in transport and the hypothetical accident conditions. The requirements and the transport conditions are detailed in the regulations contained in Title 10 of the Code of Federal Regulations, Part 71 (10 CFR 71). Depending on the level of radioactivity of the content in a packaging and the required margin of safety, different criteria are used for design, manufacture, use, and maintenance of structural components for containment, subcriticality, and shielding (See table below). Category I, II, and III components are determined on the basis of the diagram in the first figure, where A_1 and A_2 are the maximum activities of the special form and other-than-special-form radioactive materials, respectively, that are permitted in Type A packagings. (The values of A_1 and A_2 for various radionuclides are listed in Appendix A of 10 CFR 71.) Notice that a higher level of radioactivity in a packaging generally requires a greater margin of safety, which is often obtained with more stringent design and fabrication criteria, especially for the structural components used for containment.

The structural review of a SARP typically follows the standard format given in the NRC Regulatory Guide 7.6, which covers topics such as design criteria, weights and center of gravity, mechanical properties of materials, general standards for all packages, lifting and tiedown standards, conditions and tests under normal conditions of transport, specific

Category I, II, and III components based on radioactivity levels of contents (adapted from NRC Regulatory Guide 7.11, Table 1)

Component Safety Group	Container Contents		
	Category I	Category II	Category III
Containment	Section III Subsection NB	Section III Subsection ND	Section VIII Division 1
Subcriticality	Section III, Subsection NG		
Shielding and Other	Section VIII, Division 1 or Section III, Subsection NF		

Sections of the ASME B&PV codes applicable as design, manufacture, use, and maintenance criteria for Category I, II, and III components for containment, subcriticality, and shielding.

sequence of tests under hypothetical accident conditions, special-form materials, fuel rods, and appendix. Interdisciplinary cooperation is often required between the structural reviewer and other reviewers on materials, thermal, containment, shielding, criticality, and quality assurance. Close interaction with DOE EH-332, which coordinates the overall SARP review with the SARP applicant's engineering staff, is also required to resolve any technical issues before DOE can issue a Certificate of Compliance for the packaging.

The formal process to resolve technical issues identified in the structural review, as in other areas of review, is facilitated by DOE EH-332 through written questions and responses between the reviewer and the SARP applicant. This formal process continues until all technical issues in a SARP are satisfactorily resolved. For the structural analyses performed in the SARP, the structural reviewer invariably conducts his own independent confirmatory analysis, either by bounding calculations or by sophisticated computer analysis, using finite-element structural analysis codes such as ANSYS and ALGOR. Structural reviews have been performed for five SARPs during the past year: (1) the Transuranic Package Transporter-I (TRUPACT-I) for contact-handled transuranic waste, (2) the

Beneficial Uses Shipping System (BUSS) for CsCl and SrF₂ irradiation capsules, (3) the ATR Fresh Fuel Shipping Container, (4) the Paducah Tiger Overpack for Model 48X 10-ton UF₆ Cylinders, and (5) the Model UC-609 Shipping Package for tritium.

The following paragraphs present a specific example of the type of analysis performed in a structural review for a package that carries highly enriched fresh fuel for a test reactor. This analysis considers the hypothetical puncture test, and investigates possible package orientations for the prototype puncture test to establish the one that would induce maximum damage. Prior to consideration of a complex finite-element model, the analytical approach described here was attempted.

A package consisting of an outer and an inner container is dropped flat on the puncture bar from a height of 1 m (40 in.), as shown in Part [a] of the next figure. Just before impact, Part [b], the package will have attained a certain velocity from the free fall. Part [c] of the figure depicts what happens at one instant during the impact. At the exact instant that the inner container is hit and halted by the puncture bar, the inner container begins to act as the puncture bar's extension, effectively stopping the upper cover of the outer container. This instant corresponds to the one depicted in Part [c]. In the next instant, the outer container's lower cover will be decelerated by the already halted upper cover. The two halves of the outer container are attached to each other by hinges, and these hinges and their connection to the package would have to sustain the impulse load that corresponds to halting of the outer container's lower cover after the instant depicted in [c]. Failure of either hinge (meaning hinges and pin) or their connection to the container (weld) could cause the outer container to open, thus creating a very unfavorable condition for the fire test, which can follow a puncture drop test.

However, prior to impact, the inner container is not in direct contact with the outer container, but rests on 2.5-cm (1-in.)-thick plywood spacers that center and support the inner container, and that also provide air space for thermal insulation of the inner container. Upon impact with the puncture bar, this gap will provide room for deformation of the 2.5-cm-thick wall of the outer container, which is made of plywood and steel sheeting. The strain energy absorbed by the package during deformation is computed by considering the deformation of the plywood and the steel. However, there are large uncertainties in computing the energy for the steel because the deformation restraints are not well defined. Fortunately, the steel energy can be conservatively shown to be only a fraction of the plywood energy.

The calculations reveal that the strain energy stemming from deformation of plywood and steel alone will not suffice to stop the package; it is only about 25% of the initial kinetic energy. The container as a whole will therefore continue to fall, allowing the energy of the puncture-bar impact to be transferred to the inner container. The remaining energy will be converted into an irreversibly lost part, through indentation of the impact volumes, as well as into strain energy of the package that is converted back into kinetic energy of the package as it bounces off the puncture bar.

At this point, "classical" analytical modeling without finite-element methods becomes quite complex. A higher level of model complexity must be used to arrive at an adequate determination of the behavior of the structure. A classical model can be formulated by con-

ATR package drop configuration

sidering a larger number of independent deformation or displacement mechanisms, e.g., considering the three degrees of freedom corresponding to separate deformations of the two halves of the outer box and deformations of the inner box. The modeling must represent the stiffness relationship relative to the gap along the two halves of the outer box and the restraining force in the hinges connecting them. This stiffness is highly dependent on the specific details of the hinges and their connection to the package as well as on how the force from the hinges is further distributed to the rest of the package. All this can be considered in classical modeling, but the more conventional choice is to model these factors using a finite-element code that can handle inelastic material properties and dynamic response. However, in using a robust general-purpose finite-element code, a seemingly adequate model can be constructed without understanding the subtleties of the stiffnesses or flexibilities between the various interconnecting parts of the structure; thus, these values are likely to be misrepresented in the model. The approach described above forces the analyst to investigate the structure until he or she understands its behavior well enough to represent its connections and components with reasonable geometries, connectivities, and material properties, ensuring results that are more likely to approximate the real structural behavior.

Thermal (V. L. Shah)

The thermal review evaluates the thermal operating characteristics and performance of the package under normal transport and hypothetical accident conditions, taking into account the extreme environmental conditions, minimum and maximum decay heat loads, and damage caused by the drop and puncture tests as specified in 10 CFR 71. The review also includes confirmatory analyses; comparison of the analytical results with allowable limits of temperature, pressure, and thermal stresses for the package components; and determination of the effect of thermal performance on the structural, containment, and shielding areas of the package.

To determine that a package complies with the CFR requirements under all transport conditions, the confirmatory analyses are focused on modeling and evaluating package performance under worst-case conditions. An example of a review performed recently of the UC-609 package is described below. The HEATING6 module of the SCALE Computer Code was used for the analysis. The SARP Review Group selected HEATING6 because this module is designed specifically for thermal analysis of nuclear shipping casks. Furthermore, this module has been thoroughly tested on a set of casklike problems; has been compared with other thermal analysis codes such as TRUMP, TEMPEST, Q/TRAN, CINDA-3G, etc., and is well documented.

The UC-609 package, shown in the next figure, is designed for shipping a storage vessel containing tritium in any of its forms. The outer container is a right circular cylindrical drum fabricated from 14-gauge Type 304 stainless steel. The stainless steel flat cover is secured to the top lip of the drum with eight brackets. Celotex fiberboard disks and annular pieces of varying thickness fill the space between the drum and containment vessel. The containment vessel consists of two parts, the body and the cover. The body of the vessel is a stainless steel right circular cylinder with a semielliptic bottom and a machined flange, welded to a semielliptic head, at the top. The cover consists of a flange welded to the dished part of a semielliptic head. A copper gasket between the body and cover forms the primary seal for the containment boundary. The interior of the containment vessel contains an aluminum tube liner. The space between the containment vessel and liner is filled with aluminum honeycomb. A stainless steel cap over the top layer of Celotex, and a Cerafelt disk between the Celotex and drum cover, provide thermal protection to the Celotex.

The containment review staff must know if the drum and Celotex structure will provide sufficient protection so that during the hypothetical accident thermal event, the containment vessel temperatures and pressures will stay below the allowable limits for the package to meet the containment requirements. Confirmatory analysis of the hypothetical accident thermal event used a two-dimensional axisymmetric model of the package (next figure). To evaluate the performance under the worst-case condition, the package was assumed damaged from the hypothetical accident drop and puncture tests. The structural review and the test results presented in the SARP had concluded that the maximum damage from the side drop, end drop, and puncture events will be flattening of the drum to a depth of 2.5 cm (1 in.), crushing of the end to a depth of 2.5 cm, and indenting of the drum to a depth of 2.5 cm, respectively. The model therefore assumed the package as being compressed by 2.5 cm at the top and bottom from the end-drop tests and by 2.5 cm at the sides (equivalent reduction in outer radii of Celotex and drum being 0.25 cm [0.1 in.]) from the side-drop and puncture tests. The model of the package is shown in the next figure.

Temperatures of the gasket and containment vessel, predicted in the analysis, are shown in the next figure. The maximum temperatures and maximum containment vessel pressure, together with the allowable limits, are presented in the table. The maximum internal pressure for the containment vessel was calculated with the following assumptions: tritium in the storage vessel has leaked into the containment vessel; the gas mixture in the containment vessel obeys perfect gas laws; some of the tritium has decayed into helium-3; and the transit and wait period for the decay of tritium is one year or less.

UC-609 package

The maximum allowable limits of 145°C (293°F) and 760 kPa gauge (110 psig) at the containment boundary are shown by the test results presented in the SARP to meet the containment requirements of 10 CFR 71.51(a)(2). The analysis shows that the peak temperature and pressure are below the allowable limits and therefore the UC-609 package will comply with the performance requirements of 10 CFR 71.51(a)(2) under the hypothetical accident test conditions specified in 10 CFR 71.73.

Containment (J. J. Oras, Jr.)

The containment review evaluates the (a) integrity of the containment boundary, (b) radioactive-leak-rate requirements for normal and hypothetical accident conditions, and (c) special double-containment requirements for plutonium shipments. The containment review is intimately connected with the structural and thermal analyses for impact on the environment and integrity of the containment boundary. On occasion, the reviewer finds that the Code of Federal Regulations (CFR) or the American National Standard for

Model of UC-609 package

Radioactive Materials - Leakage Tests on Packages for Shipment (ANSI N14.5-1987) are unclear in an area of concern. The reviewer then proposes a position or interpretation to the certifying office in Washington so that the containment review can proceed. The following is a proposed ANL position on package leakage tests after a change of gasket or O-ring.

*Component temperatures in UC-609 package
(hypothetical accident thermal event)*

Condition	Analysis	Allowable Limit
Peak Gasket Temperature	103°C (217°F)	145°C (293°F)
Peak Containment Vessel Temperature	131°C (268°F)	145°C (293°F)
Peak Containment Vessel Pressure	648 kPa gauge (94 psig)	760 kPa gauge (110 psig)

*Peak temperatures and pressures during hypothetical
accident thermal event*

Background

10 CFR 71.51(a)(1) requires that for a Type B package under the test conditions specified in 10 CFR 71.71 (Normal Conditions of Transport), "there would be no loss or dispersal of radioactive contents, as demonstrated to a sensitivity of 10^{-6} A₂ per hour." The ANSI N14.5 standard specifies methods for demonstrating that Type B packages comply .

with the package containment requirements of 10 CFR 71 for design, fabrication, assembly and periodic verification. 10 CFR 71 is the legal requirement, while ANSI N14.5-1987 is only a guide that is a consensus opinion of experts in the packaging and transportation of radioactive materials.

Position

Section 6 of ANSI N14.5-1987 requires an acceptance leakage test before shipment of a loaded package in which the old O-rings or gaskets forming part of the containment boundary are replaced with new O-rings or gaskets of the same type. This acceptance leakage test should be an integrated test of the entire package rather than an individual component test. The acceptance leakage test requirement for new O-rings or gaskets is consistent with the acceptance leakage test requirement for a modification or change of any component of the containment boundary, i.e., the lid. The applicant must show by testing that the O-rings or gaskets can safely be reused a specified number of times without exceeding the package release rates required in 10 CFR 71. If O-rings or gaskets are reused within the proven range of safe usage, the postloading leakage test need not be more sensitive than 10^{-3} std cm³/s and need not be an integrated leakage test of the entire package. Because the package with these particular individual O-rings or gaskets has passed an acceptance or periodic leakage rate test, the package would satisfy the package release rates required in 10 CFR 71, providing the package was reassembled properly. The postloading leakage test to much less stringent leakage rate criteria verifies that the package was reassembled properly. If O-rings or gaskets are replaced (not reused), the postloading, acceptance and periodic-leakage tests become the same integrated leakage test that must show compliance with the package release rates required in 10 CFR 71.

Justification

The basis for the preceding position is found in Section 6.3.2 of ANSI N14.5-1987: "When components of reusable Type B package containment systems are modified, or when replacement is made of components not routinely replaced, the affected portion of the containment system shall be tested according to 6.3.1." The words "not routinely replaced" refer to items such as metallic O-rings and gaskets that are used only once. Section 6.3.1 of ANSI N14.5-1987 states that each reusable containment system shall be assembled for shipment and tested to show that the maximum permissible leakage rate corresponding to the maximum permissible release rate from the package containment, the only legal requirement, is satisfied. Thus, Section 6.3.1 of ANSI N14.5-1987 refers to an integrated leakage test. The words "the affected portion of the containment system" refer to either the inner or outer containment, whichever is affected. When items routinely replaced (reused) such as elastomeric O-rings/gaskets are changed, these items should be tested according to Section 6.3.1 of ANSI N14.5-1987 because the containment boundary has been modified by replacement of a component that has not been tested. When O-rings/gaskets are reused, these items should be tested according to Section 6.5 of ANSI N14.5-1987 where the postloading leakage test need not be more sensitive than 10^{-3} std cm³/s and need not be an integrated leakage test of the entire package.

The ANL position satisfies ANSI N14.5-1987, guarantees compliance with the release requirements of 10 CFR 71, and can be applied universally to any packaging.

Shielding (F. G. Prohammer and E. M. Pennington)

The objective of the shielding review of a SARP is to verify that the packaging design satisfies all shielding requirements and that the packaging will perform as intended under normal conditions of transport and under hypothetical accident conditions of transport. The shielding requirements for both conditions of transport are given in 10 CFR 71. Under normal conditions, the radiation levels external to the package must not exceed 200 mrem/hr at the accessible external surface of the package or at any point on the outer surface of a closed vehicle in which the package may be shipped. If the package is shipped in an open vehicle, then the radiation levels apply to any point on the vertical planes projected from the outer edges of the vehicle, on the upper surface of the load, and on the lower external surface of the vehicle. In addition, the radiation levels must not exceed 10 mrem/hr at any point 2 m from the above surfaces, and also must not exceed 2 mrem/hr in any normally occupied positions in the vehicle. Under hypothetical accident conditions, the radiation levels must not exceed 1000 mrem/hr at 1 m from the package surface.

The shielding review is carried out by independent analyses to confirm the assertions in the SARP that the packaging design meets the regulatory requirements. The principal tools used in the analyses are the ORIGEN, NITAWL, XSDRNPM, and XSDOSE modules of the SCALE computer code system. Gamma ray and neutron sources are obtained by running the ORIGEN module. Cross sections are processed by NITAWL for use in XSDRNPM, which is an S_n transport code, to yield gamma and neutron fluxes. These fluxes are used in turn by XSDOSE to produce gamma and neutron dose rates. When discrepancies arise between the claims in the SARP and the finds of the reviewer, or if the SARP contains insufficient information to perform the confirmatory analyses, written exchanges take place between the applicants and the reviewers until all outstanding issues are resolved. In addition to written exchanges, either teleconferences or face-to-face meetings between applicants and reviewers are sometimes held. When all issues are resolved, the reviewer contributes a Shielding Evaluation Section for a Technical Review Report that is submitted to the Department of Energy confirming that packaging design represented in the SARP satisfies the regulatory requirements. Shielding reviews were carried out for the Paducah Tiger Overpack for Model 48X 10-ton UF₆ cylinders and for the TRUPACT-I shipping container during the last year.

Criticality (F. G. Prohammer and E. M. Pennington)

The objective of the criticality review of a SARP is to verify that the packaging design satisfies all of the criticality requirements and that the packaging will perform as intended under normal conditions of transport and under hypothetical accident conditions of transport. The criticality requirements for both conditions of transport are given in 10 CFR 71. Under normal conditions a package used for the shipment of fissile material must be so designed and constructed and its contents so limited that it would be subcritical if water were to leak into the containment system or its liquid contents were to leak out. In addition, the maximum reactivity of the fissile material is to be attained with the most

reactive credible configuration, with moderation by water to the most reactive credible extent, and with close reflection by water on all sides. Under hypothetical accident conditions, the package must remain subcritical with the fissile material in the most reactive credible configuration consistent with the damaged condition, with water moderation to the most reactive credible extent, and with reflection by water on all sides as close as is consistent with the damaged condition.

Further restrictions on the packaging design and contents are based on the number of packages that must remain subcritical under normal and hypothetical accident conditions. Three categories of packages are recognized: Fissile Class I, Fissile Class II, and Fissile Class III. In all three classes, it is assumed that there is optimal interspersed hydrogenous moderation between the packages, that the most reactive configuration of packages is considered, and that the group of packages is closely reflected by water on all sides for both normal and hypothetical accident conditions. For Fissile Class I, any number of packages must remain subcritical for normal conditions and 250 damaged packages must remain subcritical for hypothetical accident conditions. For Fissile Class II, the allowable number of packages that can be shipped is determined such that five times that number remain subcritical under normal conditions and twice that number remain subcritical under hypothetical accident conditions. For Fissile Class III, the allowable number of shippable packages is determined such that twice that number of packages remain subcritical under normal conditions and that number of packages remain subcritical under hypothetical accident conditions.

The criticality review is carried out by performing independent analyses to confirm the assertions in the SARP that the packaging design meets the regulatory requirements. The principal tools used in the analyses are the BONAMI, NITAWL, XSDRNPM, and KENO V.a modules of the SCALE computer code system. The first three modules process cross sections that are used by the KENO V.a module, which performs a Monte Carlo calculation to determine the criticality of a fissile material configuration. When discrepancies arise between the claims in the SARP and the findings of the reviewer, or if the SARP contains insufficient information to perform the confirmatory analyses, written exchanges take place between the applicants and the reviewers until all outstanding issues are resolved. In addition to written exchanges, either teleconferences or face-to-face meetings between applicants and reviewers are sometimes held. When all issues are resolved, the reviewer contributes a Criticality Evaluation Section for a Technical Review Report that is submitted to the Department of Energy confirming that packaging design represented in the SARP satisfies the regulatory requirements. Criticality reviews were carried out during the last year for the Paducah Tiger Overpack for Model 48X 10-ton UF₆ cylinders, for the TRUPACT-I shipping container, for the ATR Fresh Fuel shipping container, and the Unirradiated Fuel shipping container.

Quality Assurance (R. R. Fabian)

The objective of the quality assurance (QA) review is verification that all applicable QA requirements for Type B and fissile material packaging are included in the SARP. The QA Chapter includes provisions for control of design, procurement, fabrication, handling, cleaning, assembly, inspection, testing, operation, maintenance, repair, and modification activities. The QA requirements are specified in DOE Orders 1540.2 (Hazardous Material

Packaging for Transport-Administrative Procedures) and 5480.3 (Safety Requirements for the Packaging and Transportation of Hazardous Materials, Hazardous Substances, and Hazardous Wastes) and the Code of Federal Regulations 10 CFR 71 (Packaging and Transportation of Radioactive Material) and 49 CFR 173 (Shippers - General Requirements for Shipments and Packagings). Guidance for implementation of QA requirements from the DOE Orders and federal regulations is contained in NRC Regulatory Guide 7.10 (Establishing Quality Assurance Programs for Packaging Used in the Transport of Radioactive Material) and ASME NQA-1 (Quality Assurance Program Requirements for Nuclear Facilities). Additional QA requirements are specified in the procurement section of the QA Chapter for important-to-safety parts to ensure material compliance with the packaging design due to an increase in counterfeit parts in the nuclear, transportation, and aerospace industries. To prevent the use of counterfeit parts, independent verification of material properties of critical parts must be included in the QA Chapter.

In addition to reviewing SARPs, select members of the ANL SARP Review Group, along with two members of the ANL-West Quality Assurance Department, conduct a three-day "QA Training Course for Radioactive Material Packaging" at DOE field office sites to train DOE contractors in techniques for developing a QA Plan at the onset of a project. The Plan includes QA requirements for the design, procurement, fabrication, assembly, inspection, testing, operation, maintenance, repair, and modification of the packaging. The training course demonstrates which QA requirements are packaging-specific for inclusion into the QA Chapter. Because a number of DOE contractors may use a packaging, only packaging-specific QA requirements are included in the QA Chapter of the SARP. The QA training course provides valuable information for developing, establishing, and implementing an effective QA Plan and a QA Chapter for a specific packaging. During the past seven years, ANL has conducted 25 QA training courses for DOE and its contractors.

Recent Work by the Transportation of Hazardous Materials Section

Publications

Evaluation of Photothermal Imaging for Treaty Verification

N. Gopalsami, K. Gopalan, A. C. Raptis, and V. L. Shah

ANL/ACT V-93/1, May 1993.

The Case for Endurance Testing of Sodium-Heated Steam Generators

A. Onesto (Rockwell International Corp.), H. R. Zweigh (Rockwell Intl. Corp.), D. C.

Gibbs (Rockwell Intl. Corp.), R. D. Carlson, E. Rodwell (EPRI), and C. R. Kakarala

(Babcock & Wilcox)

J. of Nucl. Techn., 103, 168-186, Aug. 1993.

Regulatory Compliance in the Design of Packages Used to Transport Radioactive Materials

D. T. Raske

INVITED PAPER: At ASME Pressure Vessel & Piping Conf., Denver, CO, July 25-29, 1993.

Appendix A: Regular ET Employees

Administration

Staff R. B. Poeppel, Division Director
 W. J. Shack, Associate Division Director
 R. A. Valentin, Associate Division Director
 W. E. Brewer, Building Manager, 300 Area
 A. C. Smith, Building Manager, 212
 B. H. Malak, Financial Administrator
 C. A. Malefyt, Managing Technical Editor
 D. L. Telfer, Staff Assistant

Salaried B. K. Baudino
 J. L. Toenies

Materials Technology

	Ceramics	Corrosion	Mechanics of Materials
<i>Staff</i>	U. Balachandran S. E. Dorris K. C. Goretta M. T. Lanagan P. S. Maiya J. J. Picciolo J. L. Routbort D. Singh J. P. Singh A. Wagh C. A. Youngdahl	T. F. Kassner O. K. Chopra H. M. Chung A. B. Hull K. Natesan J. H. Park W. E. Ruther W. K. Soppet	D. R. Diercks M. C. Billone A. M. Hassanein S. Majumdar J. Y. Park J. Rest T. C. Wiencek
<i>Salarted</i>			W. F. Burke C. F. Konicek
<i>Technicians</i>	J. E. Emerson R. L. McDaniel	R. W. Clark G. M. Dragel L. J. Nowicki D. L. Rink	T. M. Galvin D. R. Perkins
<i>Secretary</i>	S. M. Hagamann*	S. M. Hagamann*	P. J. Peterson
	Tribology	Irradiation Performance	
<i>Staff</i>	F. A. Nichols D. E. Busch R. A. Erck* A. Erdemir G. R. Fenske	L. A. Neimark A. B. Cohen D. A. Donahue A. G. Hins J. E. Sanecki H. Tsai	
<i>Salarted</i>		W. Kettman F. Pausche F. E. Savoie	
<i>Technicians</i>	R. H. Lee	L. F. Essenmacher D. J. Evans* D. O. Pushis K. E. Stair	
<i>Secretary</i>	D. K. Moores	E. L. Hartig	

*Assigned to more than one section.

Components Technology

	Superconductivity Applications	Analytical Thermal- Hydraulics	Thermal and Mechanical Sciences
<i>Staff</i>	J. R. Hull Y. S. Cha R. A. Erck* T. M. Mulcahy R. C. Niemann K. L. Uherka	R. A. Valentin (acting manager) M. Bottoni T. H. Chien H. M. Domanus R. C. Schmitt W. T. Sha J. G. Sun	M. W. Wambsganss S. S. Chen S. U. Choi J. A. Jendrzeczyk K. E. Kasza
<i>Technicians</i>	D. J. Evans* A. Wantroba*		R. K. Smith A. Wantroba*
<i>Secretary</i>	J. A. Stephens*	S. A. Moll	J. A. Stephens*
	Instrumentation and NDE	Transportation of Hazardous Materials	
<i>Staff</i>	A. C. Raptis H. T. Chien S. L. Dieckman W. A. Ellingson N. Gopalsami E. R. Koehl D. S. Kupperman W. P. Lawrence S. H. Sheen	G. F. Popper R. D. Carlson Y. Y. Liu J. J. Oras, Jr. F. G. Prohammer D. T. Raske V. L. Shah P. Turula	
<i>Salaried</i>	W. E. Brewer		
<i>Technicians</i>	R. N. Lanham		
<i>Secretary</i>	N. M. Heeg	J. L. Fisher	

*Assigned to more than one section.

Appendix B: Honors, Awards, and Professional Activities

Honors and Awards

U. Balachandran, Recipient of 1992 Award of Merit for Outstanding Work in the Field of Technology Transfer, from Federal Laboratory Consortium for Technology Transfer, May 1992.

U. Balachandran, Recipient of 1994 Award of Merit for Outstanding Work in the Field of Technology Transfer, from Federal Laboratory Consortium for Technology Transfer, April 1994.

U. Balachandran, Recipient of Sir C. V. Raman Visiting Professor Award, for service to Dept. of Nuclear Physics, presented by U. of Madras, India, Oct. 1992.

U. Balachandran and V. Maroni, Recipient ANL Pacesetter Award, for accomplishments in the categories of Wire Development, System Development, and Technology Transfer, Feb. 1993.

U. Balachandran, R. B. Poeppel, J. E. Emerson, and S. Johnson, Recipients of 1993 R&D 100 Award, An Efficient New Process for Commercial Production of Phase-Pure Superconductors, June 1993.

U. Balachandran, Awarded certificate of recognition and appreciation from the Minerals, Metals & Materials Soc. for organizing a symposium titled "Processing of Long Lengths of Superconductors, held Oct. 17-21, 1993, Pittsburgh, PA.

W. Brewer, Pacesetter Award for efforts in providing leadership, conducting research, developing the concept, conducting analyses and decision-making in the development of a cathode processor for the Integral Fast Reactor, 1994.

Y. S. Cha, Recipient Argonne National Laboratory Pacesetter Award, Nov. 1993.

E. Koehl, Pacesetter Award for engineering support, fabrication engineering, design, drafting, word processing, assembly wiring, modification and checkout in development of a cathode processor for the Integral Fast Reactor, 1993.

D. S. Kupperman, Recipient of 1992 Award of Merit for Outstanding Work in the Field of Technology Transfer, from Federal Laboratory Consortium for Technology Transfer, May 1992.

M. T. Lanagan, Recipient of 1992 Award of Merit for Outstanding Work in the Field of Technology Transfer, from Federal Laboratory Consortium for Technology Transfer, May 1992.

R. Lanham, Pacesetter Award for efforts in providing leadership, conducting research, developing the concept, conducting analyses and decision-making in the development of a cathode processor for the Integral Fast Reactor, 1993.

R. H. Lee, Chromium Carbide Crystals Growing on Chromium in Microwave Plasma CVD, First-place photomicrograph in 1992 Intl. Metallographic Contest, Oct. 1992.

R. H. Lee, Recipient of Honorable Mention Award for "Zebra Tails" in the 1992 Nikon Intl. Small World Competition, New York, Aug. 1992.

R. L. Lee, First Place, Class 8 photomicrography contest sponsored by AMS/IMS (Intl. Metallography Soc.), Charleston, SC, Aug. 1993.

R. H. Lee, First Place, Artistic Black and White Microscopy, Intl. Metallography Contest, Charleston, SC, Aug. 1993

R. H. Lee, Argonne Open House exhibit with Arts at Argonne: 25 framed photomicrographs in lobby of Bldg. 201, funded by U. of C. Board of Governors for ANL, May 1994.

R. H. Lee, Cover photo of fullerene crystals 1993-94 Argonne annual report, "Research Highlights"; also four background photos inside report.

Y. Y. Liu, Recipient of 1992 Significant Contribution Award, Materials and Technology Division of Amer. Nuclear Soc., presented at 1993 ANS Winter Mtg., San Francisco, Nov. 1993.

R. C. Niemann, Recipient Fermilab Technology Award, 1993.

Professional Society Activities

U. Balachandran, Member Amer. Ceram. Soc., Electronics Div. Program Committee, April 1993.

S. S. Chen, ASME Fellow, 1984 to present.

S. S. Chen, Honors Chairman (1990-94) and Executive Committee member (1990-96) of PVPD, ASME.

S. S. Chen, Member, Task Force on Flow-Induced Vibration of Welding Res. Council, 1990 to present).

S. U. Choi, Chairman, Intl. Energy Agency District Heating and Cooling Advanced Fluids Experts Group, 1990 to present.

W. A. Ellingson, Member Neutron Scattering Society of America (NSSA), July 1992 to present.

W. A. Ellingson, Named Fellow of Amer. Ceram. Soc., Dec. 1993.

A. Erdemir, Secretary, Solid Lubricants Technical Committee, Soc. of Tribologists and Lubrication Engineers, May 1990-April 1993.

A. Erdemir, Vice-Chairman, Solid Lubricants Tech. Committee, Soc. of Tribologists and Lubrication Engineers, 1993 to present.

A. Erdemir, Member Ann. Mtg. Program Committee of Society of Tribologists and Lubrication Engineers, 1992 to present.

A. Erdemir, Member Soc. of Tribologists and Lubrication Engineers, 1988 to present.

A. Erdemir, Member ASM-International, 1983 to present.

A. Erdemir, Member American Ceramics Society, 1990 to present.

A. Erdemir, Member The Metallurgical Society, 1983 to present.

A. Erdemir, Member American Society of Mechanical Engineers, 1992 to present.

A. Erdemir, Member Sigma-Xi Honor Society, 1988 to present.

J. R. Hull, Elected Senior Member of Institute of Electrical and Electronics Engineers, Inc., Nov. 1993.

K. E. Kasza, Paper Reviewer for American Nuclear Society.

K. E. Kasza, Paper Reviewer for International Journal of Heat and Mass Transfer.

D. S. Kupperman, Member Amer. Physical Soc., 1970 to present.

D. S. Kupperman, Fellow Amer. Soc. for Nondestructive Testing, 1987 to present.

D. S. Kupperman, Member Amer. Soc. of Mech. Engineers, 1975 to present.

D. S. Kupperman, Co-Chair of Tech. Transfer Session of 1992 ASME Winter Ann. Mtg., Anaheim, CA, Nov. 9, 1992.

R. H. Lee, Treasurer, 1992-1993; Vice President for Education, 1992-1993; President, 1994 to present, Argonne Toastmasters Club.

R. H. Lee, Vice-President, State Microscopical Society of Illinois, July 1994 to present.

R. H. Lee, Produced videotape, "Argonne Explorers Program Microscopy Laboratory," Feb.-April 1992, used in Argonne Open House DEP display, May 21, 1994.

R. H. Lee, Produced videotape: "Argonne Explorers Microscopy Laboratory, Dec. 1993-April 1994," for DEP and Microscopical Soc. of America.

K. Natesan, Member of Board of Directors of Symposia for Engineering Aspects of Magnetohydrodynamics, Inc. (SEAM, Inc.), June 1993-1997.

J. P. Singh, Named Fellow of Amer. Ceram. Soc., Dec. 1993.

K. L. Uherka, Member American Soc. of Mechanical Engineers, 1960 to present.

K. L. Uherka, Member Sigma Xi, Scientific Res. Soc., 1966 to present.

R. A. Valentin, Member ASME Advanced Reactor Com., 1986 to present.

R. A. Valentin, American Power Conf., Chair of Nuclear Div. and Member, Planning Committee, 1990 to present.

Other Committee Participation

U. Balachandran, Superconductivity Demonstration, INVITED TALK presented at Blue & Gold Dinner, Glenview, IL, Feb. 5, 1993.

U. Balachandran, Session Chairman SC Global '93 Conf., San Jose, CA, Feb. 1-3, 1993.

U. Balachandran, INVITED to serve on committee to examine Ph.D. dissertation at Anna U. (Madras, India), Mar. 1993.

U. Balachandran, INVITED to serve on committee to examine Ph.D. dissertation at U. of Madras (India), Feb. 1993.

U. Balachandran, Organizer for Symposium F, "Superconducting Ceramics," at Pacific Coast Regional Mtg. (PCRM) of Amer. Ceram. Soc., Los Angeles, Oct. 19-22, 1994.

U. Balachandran, INVITED EXAMINER of Ph.D. thesis for U. of Kerala, India, July 1993.

U. Balachandran, Examiner of Ph.D. thesis at U. of Madras (India), Aug. 1993.

U. Balachandran, Science Fair Judge at Lincoln Park H.S., Chicago, Jan. 14, 1994.

U. Balachandran, Science Fair Judge for The Avery Coonley School, Downers Grove, IL, Jan. 27, 1994.

U. Balachandran, Scientific host to Chicago Science Explorer class from Daniel Webster Elementary School, Argonne Natl. Lab., Jan. 11, 1994.

U. Balachandran, Chairman, Session on High Temperature Materials, at the 1st Intl. Conf. on Processing Materials for Properties, Honolulu, Nov. 7-10, 1993.

U. Balachandran, Co-Chair of Session S4: High Temperature Superconductor Bulk Research, 1994 Spring Mtg. Materials Res. Soc., San Francisco, April 4-8, 1994.

U. Balachandran, Chair of Session on High-Temperature Superconducting III: Issues in Processing and Properties of High-T_c Superconductors, at 123rd TMS Ann. Mtg., San Francisco, Feb. 27-Mar. 3, 1994.

Y. S. Cha, Member, ET 300-Area Safety Committee, 1989 to present.

S. S. Chen, Member, Intl. Steering Committee, Intl. Conf. on Aero-Hydroelasticity, Oct. 18-21, 1993, Beijing, China.

S. S. Chen, Member, Intl. Steering Committee and Coordinator of Symp. on Flow-Induced Vibration in Engineering Systems, Asia-Pacific Conf., Nov. 14-18, 1993, Kitakyushu, Japan.

S. U. Choi, Member, ET Division Social Committee, Oct. 1990 to present.

W. A. Ellingson, Member Interagency Coordinating Committee on Structural Ceramics, 1986 to present.

W. A. Ellingson, Chair of Session at 2nd Ann. Res. Symposium for The Amer. Soc. for Nondestructive Testing, Nashville, TN, Mar. 29-April 2, 1993.

W. A. Ellingson, Chair of Session on Ceramic Processing at ASNT 1993 Spring Conf. and 2nd Ann. Res. Symp., Nashville, TN, Mar. 31, 1993.

W. A. Ellingson, Member RCMS RC Special Meetings Committee, Amer. Soc. for Nondestructive Testing, 1993 to present.

R. A. Erck, Chair of committee for review of author's guidelines at STLE '93, Calgary, Alberta, May 17-20, 1993.

A. Erdemir, U.S. Natl. Coordinator for VAMAS-TWA-I (Versaille Project on Advanced Materials and Standards), Wear Test Methods Technical Working Area-I, June 1992 to present.

A. Erdemir, Member NSF Panels on Young Investigator Award and Res. Initiation Grants, April 1992.

G. R. Fenske, Member Transportation Working Group Subcommittee, Sensor Subcommittee, May 1993 to present.

K. C. Goretta, Seminar Coordinator for ET Division, Aug. 1993 to present.

K. C. Goretta, Member ET Division Social Committee; Treasurer, Sept. 1993 to present.

K. C. Goretta, Member Ph.D. Defense Committee, U. of Illinois at Urbana-Champaign, April 11, 1994.

K. C. Goretta, Member Management Negotiating Committee for Technician's Union Contract, May 9, 1994 to present.

K. C. Goretta, Member Ph.D. Comprehensive Examination Committee — A. C. Biondo, Illinois Institute of Technology, Chicago, Nov. 21, 1991.

K. C. Goretta, Member Ph.D. Qualifying Examination Committee, U. of Illinois at Urbana-Champaign, Oct. 23, 1992.

K. C. Goretta, Member Ph.D. Defense Committee, Illinois Institute of Technology, Chicago, Nov. 21, 1992.

K. E. Kasza, Member Argonne Working Group for On-Site Demonstration of Developing Conservation Technologies, April 1993 to present.

D. S. Kupperman, Member, Board of Directors of Oak Park (Illinois) Children's Museum, 1992 to present.

D. S. Kupperman, Resident Scientist for District 97 Global Village Scientist Program, 1991 to present.

M. T. Lanagan, Co-organizer of Poster Session for Chicago-Milwaukee Section of the Amer. Ceram. Soc., Mar. 19, 1993.

M. T. Lanagan, Judge, Science Fair, Jefferson Jr. High School, Naperville, IL, Mar. 9, 1994.

M. T. Lanagan, Member M.S. Thesis Committee for candidate at University of Illinois, May 27, 1994.

M. T. Lanagan, Member, Ph.D. Thesis Committee, Georgia Institute of Technology, for candidate, April 8, 1994,

R. H. Lee, Conducted nine-week course on Microscopy for the Argonne Explorer Post, Dec. 1993, with Mary Buckett and Steve Rozeveld.

S. Majumdar, Member, Sub-Group on Elevated Temperature Design of the ASME Boiler and Pressure Vessel Code, 1978 to present.

C. A. Malefyt, Volunteer Editor, Publications Committee, Society for Technical Communication, 1990 to present.

C. A. Malefyt, ET Division Technology Transfer Representative, 1990 to present.

C. A. Malefyt, ET Division Coordinator, Open House activities, 1994.

C. A. Malefyt, ET Division ES&H Training Coordinator, 1991 to present.

C. A. Malefyt, ET Division Alternate Records Coordinator, 1993 to present.

C. A. Malefyt, Appointed Authorized Derivative Classifier by DOE-Ch, Oct. 1993.

F. A. Nichols, Member of ANL Transportation Working Group (1993).

J. J. Oras, Member ET 300-Area Safety Committee to present.

J. J. Oras, ET Quality Assurance Representative to present.

J. J. Oras, Technical Reviewer for Nuclear Technology, a journal of the Amer. Nuclear Soc., 1991 to present.

J. J. Oras, Alternate member of N14 Standards Comm., Packaging and Transportation of Radioactive Materials, for Amer. Natl. Standards Institute (ANSI).

J. J. Oras, Member ANSI N14.5 Comm., for Leakage Tests on Packages for Shipment, 1994 to 1996.

J. H. Park, Organizer of symposium for 186th Meeting of The Electrochemical Soc., Miami Beach, Oct. 2-7, 1994.

J. Y. Park, Member Subcommittee G1.08 on Corrosion of Nuclear Materials, Amer. Soc. for Testing and Materials, 1983 to present.

J. Y. Park, Member Committee E08 on Fracture & Fatigue of Materials, Amer. Soc. for Testing and Materials, 1979 to present.

J. Y. Park, Member Committee F04 on Medical Surgical Materials and Devices, Amer. Soc. for Testing and Materials, 1981 to present.

D. Singh, Member Final Waste Forms Working Group, DOE-Mixed Waste Integrated Program.

J. P. Singh, Organizer of Symposium on Ceramic Matrix Composites at 96th Ann. Mtg. & Expo. of Amer. Ceram. Soc., Indianapolis, April 24-28, 1994.

J. P. Singh, K. C. Goretta, and G. Lewis (Memphis State U.), Member, M.S. Thesis Defense Committee, Memphis State U., Oct. 9, 1992.

J. P. Singh, Organizer of Processing and Microstructure-Property Relations in Novel Materials Symp., 95th Ann. Mtg. and Exposition, Am. Ceram. Soc., Cincinnati, April 18-22, 1993, also Session Chair: "Nanophase Materials I."

K. L. Uherka, Member DOE/HQ Technical Evaluation Committee for reviewing Small Business Res. Initiative (SBRI) proposals, 1989 to present.

K. L. Uherka, Member DOE/CH Technical Review Board for reviewing Industrial Heat Pump proposals, 1988 to present.

K. L. Uherka, Member IEEE Superconductivity Review Group for evaluating submittals to the Applied Superconductivity Conf., 1992 to present.

R. A. Valentin Member, DOE Steering Committee for University Awards in Nuclear Engineering, 1987 to present.

R. A. Valentin, Chair of ANL Outstanding Service Awards Committee, 1984 to present.

R. A. Valentin, Chair of ANL Director's Special Colloquium Committee, 1984 to present.

R. A. Valentin, Member ANL Fellows Committee, 1988 to present.

R. A. Valentin, Member ANL Reactor Safety Review Committee, 1992 to present.

R. A. Valentin, Chair of EEST POC-HP, March 1, 1994 to present.

Invited Teaching and Research at Other Institutions

S. U. Choi, Visiting Professor, Dept. of Engineering, Purdue U. Calumet, Hammond, IN, Aug. 1990 to present.

A. Erdemir, Boric Acid as a Solid Lubricant, INVITED lecture, presented to The Lubrication Workshop for Railroad Industry, the Assn. of Amer. Railroads, Mar. 16, 1993, Chicago.

A. Erdemir, Boric Acid Based Lubricants, INVITED lecture, the Lube School of the STLE Chicago Section, covering areas of "Metalworking Fluids and Industrial Lubricants," Argonne Natl. Lab, Mar. 17-18, 1993.

Invited Conference Participation

U. Balachandran, INVITED Chair of Sessions on Magnetic Levitations and Propulsion I and II at INTERMAG '93 Conf., Stockholm, April 13-16, 1993.

U. Balachandran, INVITED TALK: Hinsdale Central High School, Hinsdale, IL, Mar. 4, 1993.

U. Balachandran, INVITED: Chair of Session on HTSC-Composition/Characterization at 1993 Amer. Ceram. Soc. Ann. Mtg., Cincinnati, April 18-22, 1993.

U. Balachandran and T. Sato, Chairs of Session on Particle-Shape Control at 3rd IUMRS Intl. Conf. on Advanced Materials, Tokyo, Aug. 31-Sept. 4, 1993.

U. Balachandran and K. Togano, Chairs of Session on Bulk Processing at 3rd IUMRS Intl. Conf. on Advanced Materials, Tokyo, Aug. 31-Sept. 4, 1993.

U. Balachandran, Chair of Session on Mixed Conductors, 96th Ann. Mtg. and Expo., Indianapolis, April 24-27, 1994.

U. Balachandran, Chair of Session on High-Temperature Superconductors III: Issues in Processing and Properties of High- T_c Superconductors, San Francisco, Mar. 1, 1994.

S. S. Chen, INVITED Chair for Awards Luncheon, ASME Pressure Vessels and Piping Conf., New Orleans, June 21-25, 1992.

S. S. Chen, INVITED Session Chair and Session Developer for the 1992 Intl. Symp. on Flow-Induced Vibration and Noise, ASME Winter Ann. Mtg., Anaheim, CA, Nov. 8-13, 1992.

S. S. Chen, INVITED Member of Conference Committee and Poster Session Co-chair, Maglev '93, Argonne Natl. Lab., May 19-21, 1993.

S. S. Chen, INVITED Technical Program Chair, ASME Pressure Vessel and Piping Conf., June 19-23, 1994, Minneapolis.

W. A. Ellingson, Session Chair of 6th Intl. Symp. on Nondestructive Characterization of Materials, Honolulu, June 7-11, 1993.

A. Erdemir, Session Chair and Organizer of Solid Lubricants Session at 1992 STLE Ann. Mtg., May 4-7, 1992, Philadelphia.

A. Erdemir, Session Chair and Organizer, Wear Resistance of Ceramic, Metallic, and Composite Coatings, at 19th Intl. Conf. on Metallurgical Coatings and Thin Films, San Diego, CA, April 6-10, 1992.

A. Erdemir, Session Chair and Organizer, Wear Resistance of Ceramic, Metallic, and Composite Coatings at 20th Intl. Conf. on Metallurgical Coatings and Thin Films, San Diego, CA, April 18-23, 1993.

A. Erdemir, ANL coordinator of Lubrication School of STLE Chicago Section, "Metalworking Fluids and Industrial Lubricants," Argonne Natl. Lab., Mar. 1-18, 1993.

K. C. Goretta, Session Organizer: Fabrication Methodology, 3rd World Congress on Superconductivity, Munich, Germany, Sept. 1992.

K. C. Goretta, Chair of Finance Committee, 1992 Applied Superconductivity Conf., Chicago, Aug. 1992.

K. C. Goretta, Organizer of Poster Session, Chicago-Milwaukee Chapter of Amer. Ceram. Soc., Mar. 30, 1993.

K. C. Goretta, Supervisor of Judges: Student Poster Night, Chicago-Milwaukee Chapter of Amer. Ceram. Soc., April 19, 1994.

K. C. Goretta, Session Chair: Symposium on Structural Ceramics Composites, Ann. Mtg. of Amer. Ceram. Soc., Indianapolis, April 24-27, 1994.

K. C. Goretta, Chair: Materials Res. Soc. Technical Organizing Comm. for Joint ISTEC/MRS Superconductivity Workshop, Maui, HI, June 1995.

K. C. Goretta, Session Organizer: Fabrication Methodology, 4th World Congress on Superconductivity, Orlando, FL, June 27-July 1, 1994, Aug. 1993-present.

K. E. Kasza, INVITED Organizer of DOE/EPRI-sponsored Workshop on Ice Slurry Cooling for Utility Companies and Engineers, Minneapolis, May 11-12, 1992.

K. L. Uherka, Chair and Organizer, Session on Role of Superconductivity for Storage and Transmission, 55th Ann. Amer. Power Conf., Chicago, April 13-15, 1993.

R. A. Valentin, Organizer of All Nuclear Power Session, American Power Conf., Chicago, April 13-15, 1993.

R. A. Valentin, Organizer and ANL Host, Nuclear Engineering Education Research Grant Program Review, Argonne Natl. Lab., Feb. 24-26, 1993.

T. C. Wiencek, INVITED TALK given at Wheaton-Warrenville South High School, Wheaton, IL, Feb. 9, 1993.

Editorial Activities

U. Balachandran, E. W. Collings (Battelle Columbus Div.), and A. Goyal (Oak Ridge Natl. Lab.), edited Processing of Long Lengths of Superconductors, as published by The Minerals, Metals and Materials Soc., Warrendale, PA, 1994.

S. S. Chen, Member Intl. Advisory Editorial Board of ACTA Mechanica Solida Sinica, 1990 to present.

S. S. Chen, Member Advisory Board of Japan Soc. of Mechanical Engineers Intl. J., 1993-1995.

S. S. Chen, Editor, Fluid-Structure Interaction, in Tech. for the 90's, - A Decade of Progress, ASME publication (1993), pp. 543-972.

D. S. Kupperman, Associate Editor of Applied Physics Ltrs., 1992 to present.

D. S. Kupperman, Associate Technical Editor of Materials Evaluation, 1984 to present.

R. H. Lee, Editor, Micronotes 2, a monthly meeting notice and informal newsletter for the State Microscopical Soc. of IL, Jan. 1994 to present.

K. Natesan, Member of Editorial Committee, J. of Material Engineering and Performance ASM, 1991-1995.

R. B. Poeppel, Editor-in-Chief: Applied Superconductivity, Vol. 1, Pergamon Press, 1993 to present.

J. P. Singh and S. Banerjee, Editors, Microstructure and Properties of Refractories, Key Engineering Materials, Vol. 88 (1993), Trans Tech Publications.