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Oak Ridge National Laboratory review

Magnets for Fusion

Oak Ridge National Laboratory

review

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THE COVER: To artist Kip S. Thompson, son of Phil Thompson of the Engineering Division, the mythical superconductor can be found on certain trains that have refrigeration. To Larry Dresner of ORNL's Fusion Energy Division, superconductors include internally cooled superconducting magnets powerful enough to contain the elusive plasma fuel of fusion reactors. Recently, ORNL developed new design tools for such magnets. See article on page 12.

Editor

CAROLYN KRAUSE

Associate Editor

JON JEFFERSON

Consulting Editor

ALEX ZUCKER

Design

BILL CLARK

Publication Staff: Technical Editing/Ralph Sharpe; Typography/Cheryl Buford; Makeup/Ginger Ross; Proofreading/Renee Allmon, Martha Roberson; ORNL Photography and Reproduction departments.

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OAK RIDGE NATIONAL LABORATORY

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EDITORIAL

The Missing Link

By Herman Postma, ORNL Director

Over the last two years, several studies of the U.S. Department of Energy multiprogram laboratories have been performed. The studies were conducted by DOE's Energy Research Advisory Board (ERAB); the President's Private Sector Survey on Cost Control, which reports directly to the President; and the White House Office of Science and Technology Policy committee, headed by David Packard, which reviewed the laboratories at the request of George Keyworth, President Reagan's science advisor.

Initially, most of the members of these panels knew very little about national laboratories. Therefore, the panelists began to look into the nature and quality of the research and development activities at the national laboratories to decide if this work could be and should be done better elsewhere. By the end of their investigations, trips, and visits, the panelists found that the national laboratories are indeed strong, that they are carrying out pertinent activities, and that the quality of their performance is impressive. Of course, the studies also contained criticism—but not of the laboratories themselves. The government agencies that fund the laboratories were criticized for burdening the laboratories with paperwork, for not allowing them enough time and freedom for the kinds of investigations that lead to important discoveries, and for imposing overly constraining fiscal practices. Nevertheless, from our point of view, the studies turned out well, and the recommendations have been reassuring.

Even so, a serious deficiency remains in the reports from all three panels. The reports unfortunately take a fairly narrow view, focusing on the panelists' perceptions of what the precisely defined roles of national laboratories, industries, and universities should be. The studies try to carve out and define a distinct role for each type of institution and to spell out its job description with the intent to circumscribe and limit each institution's mission. Having been on the ERAB panel, I must share in my own criticism because I was not persuasive enough about the need for broader roles for all scientific institutions.

How is it possible to organize our scientific talent so neatly into simple, understandable niches when, in fact, the issues are complex, the science that needs to be done is complicated and interrelated, and the institutions themselves are intricate? As I see it, what this country needs is to find ways to remove the impediments that prevent cooperation among the scientists and engineers in these three broad research sectors. Combining the best scientific talent of our various institutions will increase the contributions of scientific research to the nation.

We need to identify the country's problems and bring to bear all our resources, all our scientific talent from all types of institutions. Incentives, such as the licensing of inventions, should be provided to motivate national laboratories to work more closely with industry. The nation needs more joint programs between universities and national laboratories to ensure that students receive the training in the work environment of national laboratory facilities that are not available at universities.

The studies do a disservice by attempting to remove the overlap that exists between institutions in the three research sectors. It is a mistake to eliminate competition when that competition is healthy and fosters the exchange of ideas and new applications. Perhaps now that the studies are done, the country will be ready to take a fresh look at how to remove the obstacles that prevent the cooperation necessary to make the best use of all types of scientific institutions. Rather than erect fences to separate researchers with similar interests who work in different types of scientific institutions, we need to open up more paths and smooth the way for greater laboratory-university cooperation and laboratory-industry interaction. Our nation can surely benefit from such cooperative ventures.

Paradox of the Striped Bass:

ORNL Fishes for Answers

By CHARLES C. COUTANT
and WEBSTER VAN WINKLE

One hundred pounds or more of glistening silver with striking black stripes running the length of each side. A sleek marvel of the coastal waters as long as a man is tall. A fish whose head alone " . . . contains a saucerfull of marrow sweet and good, pleasant to the palate and wholesome to the stomach which . . . will give a good eater a dinner," according to William Wood, whose discussion of striped bass appears in his 1634 book, *New England Prospects*. Captain John Smith of Virginia also loved the fish's taste, writing that "for daintinesse of diet they excell the Marybones of Beefe."

The striped bass, later known as rockfish to fishermen and *Morone saxatilis* to the scientific community, was "basse" to the early English of America. In the summer of 1623, a few fishermen in a single boat brought back enough of the "noble basse" to feed the Mayflower colonists for three months. So valued was this prize of the New World that the first resource conservation measure passed in the colonies called for preserving the fish for the highest of uses. Men were fined if caught using striped bass "for manuring the ground."

This ocean fish—so good that colonists baited it with chunks of lobster—peaked in commercial catches in the late 1800s. Today it faces the paradox of severe population declines in marine waters but unprecedented expansion in fresh waters—all as a result of

Chuck Coutant came to ORNL in 1970 to begin an aquatic thermal effects program in the Ecological Sciences Division, now called the Environmental Sciences Division. Earlier he had spent five years at the Atomic Energy Commission's facility at Hanford, Washington, where he studied the effects of reactor cooling water on fish and other aquatic life in the Columbia River. He first became interested in the ecological problems of power plant cooling in 1959 during cooling water studies of the Delaware River at Lehigh University in Pennsylvania, where he received his B.A., M.S., and Ph.D. degrees. His ORNL thermal studies led to extensive evaluation of the habitat requirements of the striped bass. He organized a symposium on "Striped Bass: Environmental Risks in Fresh and Salt Water" for the 1982 annual meeting of the American Fisheries Society and is now editing the proceedings. Webb Van Winkle came to the Environmental Sciences Division in 1972 from a two-year postdoctoral position in the Biomathematics Program at North Carolina State University and three years as assistant professor in the Biology Department at the College of William and Mary in Virginia. From 1975 to 1978 he led the Analysis and Modeling of Aquatic Populations and Ecosystems Group at ORNL, and from 1979 to 1983 he headed the Aquatic Ecology Section. A native of New Jersey, he holds a Ph.D. degree in zoology from Rutgers University. His research interests include fish population dynamics and modeling, striped bass biology, and analysis of environmental impacts, all of which were relevant for his involvement in the Hudson River Power Plant Case. Here Coutant, right, and Van Winkle examine a bass from a tank in the Aquatic Ecology Laboratory.

continuing human intervention. This paradox is now a subject of scientific investigation at Oak Ridge National Laboratory and elsewhere.

ORNL is emerging as a national center of expertise on striped bass because of many aquatic ecologists in ORNL's Environmental Sciences Division who have been studying the species' biological requirements and ecological interrelationships and management strategies that may protect and enhance this magnificent fish. The first ORNL studies on striped bass were conducted in 1972 to help the U.S. Atomic Energy Commission (AEC) fulfill its legal obligation of evaluating the total environmental impact of nuclear power plants. Subsequent studies were conducted for various government agencies in connection with the 10-year controversy over the extent to which the cooling systems of six power plants on the Hudson River killed striped bass and other fish (see box). The initial focal point of these ORNL studies was the Indian Point Unit 2 nuclear power plant.

Freshwater Surprises

In the summer of 1972, adult striped bass that had been stocked as juveniles began dying in conspicuous numbers in Cherokee Lake, a 12,000-ha (30,000-acre) reservoir of the Tennessee Valley Authority (TVA) on the Holston River about 70 km (45 miles) northeast of Oak Ridge. Thus began ORNL's involvement with freshwater studies of this prized game fish.

Breeding striped bass in freshwater was a revolutionary idea that began in 1956 when Bob Stevens, then with the South Carolina Department of Wildlife and Fisheries, recognized that landlocked striped bass could survive and, indeed, thrive in wholly freshwater impoundments. This was an interesting discovery because striped bass, a saltwater species found in U.S. coastal waters, behave like salmon in that they swim upstream into fresh waters to spawn and then normally return to the ocean.

Stevens made the discovery when the Santee and Cooper rivers in South Carolina were closed by dams, thus trapping a number of juvenile striped bass. This happy accident, in which ocean fish flourished in South Carolina's freshwater reservoirs, led to experimental and seemingly successful stockings of the estuarine species in other reservoirs. There is no doubt that Stevens's discovery has had a momentous impact on freshwater fisheries all across the United States.

In Tennessee, TVA's Cherokee Lake was the first impoundment to receive striped bass. Six years after the initial Cherokee stocking in 1966 and after the extraordinary fishery received national attention as the young fish matured, disaster struck. The biggest and most sought-after trophy fish were dying in the middle of summer. The heating of the Cherokee Reservoir by TVA's John Sevier coal-fired steam plant was suspected as a cause of the fish kill. Mercury contamination of the Holston River was another possible cause. Because of ORNL's work with mercury and because of our thermal effects pro-

Striped bass are collected in an electroshocking boat for tagging at Cherokee Lake. Dave Carroll, left, and Chuck Coutant catch the fish with nets and drop them in a live well to be electroshocked (far right). The stunned fish are then tagged and released to the lake.

gram, we were asked by the Tennessee Wildlife Resources Agency to search for the probable causes.

Fish History

To understand the paradox of the striped bass, which simultaneously faces severe population declines in marine waters yet unprecedented expansion in some fresh waters, one needs to know something of the history of the species on the western and eastern coasts of the United States. In the late 1800s, the striped bass was introduced to the west coast in San Francisco Bay. Although slow to leave the bay and populate coastal water and bays to the north, the species created a large and successful fishery in the bay and the Sacramento–San Joaquin Delta area. Natural spawning in the rivers was just as successful as ancestral east coast riverine spawning. The flourishing of the fish for over half a century began to slow in the mid-1970s, however, and the west coast population has been declining dramatically ever since. The decline is usually attributed to agricultural water diversions from the Sacramento and San Joaquin rivers, the pollution of San Francisco Bay, and the cooling systems of two power plants.

In the East, the Chesapeake Bay stock of striped bass has traditionally been the major contributor of fish up and down the Atlantic coast. Since 1970, however, this stock has failed to produce a major spawn, thus resulting in declining catches by commercial and sport fishermen. Similar declines were apparent in the Roanoke River stock to the south. Clear-cut causes of the eastern decline are less obvious; most likely a plethora of mechanisms are acting in this case, including declining water quality, increasing fishing pressure, and fluctuating freshwater flows and temperatures in the spring and summer. The absence of a similar decline in the Hudson River species (aided no doubt by restricted fishing, not by the presence of power plants) only complicates our attempts to discover causes of the overall declines in coastal stocks.

A mixed picture emerges in fresh water. The successful initial stockings in southeastern reservoirs led to a stampede of striped bass introductions as far away as Pennsylvania, Ohio, Kansas, Nebraska, and Oklahoma. Human interventions greatly extended the species' range, which is matched by few other species. Some populations became self-sustaining; however, most are maintained by programmed stocking by fisheries agencies. Nevertheless, a growing number of fishery managers of successful stocking programs throughout the country are now plagued by the summer die-offs that still affect TVA's Cherokee Lake.

Fantastic Voyage

While the fires of controversy raged over the construction of power plants on the Hudson, biological information on striped bass that was not available in the literature was obtained experimentally in ORNL's Aquatic Ecology Laboratory. For one thing, we needed data on actual mortalities induced by passage through power plant cooling systems (condensers). Toward this end, an experimental condenser loop was assembled by Bob Kedl and ORNL's Engineering Technology Division. Kedl and Chuck Coutant gave larval striped bass what they call the "fantastic voyage" through the mock condenser, where the bass received heat and physical stresses both alone and together.

Slightly more than half of the fish died from passage through the mock condenser. Most deaths could be accounted for by thermal shock alone because our data conformed with results of laboratory heat-shock bioassays. Glenn Cada has continued this research in the more sophisticated "power plant simulator," a bright blue, three-story plumbing structure adjacent to the Aquatic Ecology Laboratory.

Data were also lacking on the sublethal effects and indirect mortality of those striped bass larvae that survived passage through the

power plant condenser and that were returned to the river. Webb Van Winkle and Sig Christensen performed a series of experiments to test for sublethal effects of heat shock on the feeding of larvae. The researchers found that larvae may be less likely to feed after heat shock but that, once the larvae do start feeding again, they eat about as much as they did before the stress.

Because much of the public outcry against Indian Point concerned intake-screen losses of juveniles, we set about studying striped bass behavior by experimenting with various water flows through screens. We converted a large cylindrical tank in the Aquatic Ecology Laboratory to a circular "flume" in which segments of typical intake screening became barriers. Rebecca Bowles, a graduate student at the University of Tennessee, observed changes at certain flow velocities in the schooling and feeding behaviors of the fish that could account for the increased susceptibility of the fish to being caught and held against the screens. Interestingly, when the fish attempted to chase food particles, they were occasionally so distracted that they failed to make the normal responses of avoiding the screens. These lapses were sometimes fatal.

Van Winkle and Coutant prepare to inject a fish into the power plant cooling system simulator at the Aquatic Ecology Laboratory. The simulator subjects fish to the thermal and mechanical stresses that they might undergo if drawn into the pump and condenser of an actual power plant.

Temperature Selection

In the early 1970s, Coutant worked on a National Academy of Sciences panel on Water Quality Criteria to develop a rationale for using temperature-dependent growth rates of aquatic organisms as a criterion for establishing upper-limiting temperatures—the temperatures above which species growth is considerably reduced. He and Dave Cox then applied this rationale to striped bass by conducting a series of growth-temperature experiments in which the feeding level was also varied. The temperatures yielding maximal growth rate (24°C) and no growth (33.5°C) provided an estimated upper limiting temperature of 28.8°C that could be compared to water temperatures induced by power plant discharges on the Hudson and elsewhere. We were fascinated by the twisted spines created in fish raised at temperatures above 34.5°C, a defect that would certainly have brought on "ecological death" by predation even if it were not directly lethal.

In the National Academy review, Coutant advanced the hypothesis that temperatures preferred by fish in lakes and streams during summer months would generally match laboratory-measured temperatures at which fish growth rates were maximal. Field data on the fishes' own temperature selection could thus replace lengthy growth-temperature experiments as a means of establishing water temperature criteria. Temperature selection data would also provide insights into how different fish species separate and select different levels of a lake or stream as their aquatic habitats; this phenomenon, known as partitioning behavior, could be studied using water temperature gradients as a "structural" cue.

By employing the temperature-sensing ultrasonic fish tag developed at ORNL by Jim Rochelle of the Instrumentation and Controls Division, Dave Carroll and Coutant began tagging and tracking striped bass. Our first major success was in a small quarry lake on the Oak Ridge Reservation. Here, we followed two-year-old fish from shoreline recorders and found that they preferred a water temperature of 21-22°C during the summer season. This temperature range did not match the 24°C optimal growth temperature found in the laboratory for younger fish. This perplexing discrepancy was soon followed by more surprises that forced us to revise our view of striped bass in their environment.

The Hudson River Legacy

Why is ORNL, a laboratory nestled in the ridges and valleys of the Southern Appalachians, so concerned with this glistening aquatic wonder of coastal New England? Our paradoxical involvement with striped bass began in 1971 when a federal judge admonished the U.S. Atomic Energy Commission (AEC) for failing to fulfill its role of protecting the environment in licensing nuclear power plants, as called for by the National Environmental Policy Act (NEPA) of 1969. This decision demolished the AEC's position that thermal effects and other cooling-system-related issues fell outside its perceived mandate of evaluating only radiation-related effects.

After the ruling, one of the first nuclear power plants licensed on radiation grounds alone that was immediately subjected to thorough environmental review by the AEC was Indian Point Unit No. 2, which was built by the Consolidated Edison Company on the Hudson River in New York. The Hudson River is an important breeding habitat for the Atlantic Ocean striped bass. In the 1970s, this area became an infamous antinuclear battleground, partly because of widely circulated newspaper accounts of "truckloads" of dead fish being hauled to landfills to keep the cooling water intakes clear. In response to a public outcry against possible destruction of the striped bass in the Hudson River, the AEC turned toward ORNL, which had a thermal-effects research program, to determine the extent to which the striped bass population was endangered.

Our laboratory and field studies of the effects of hot water discharges from power plants on fish and of the ability of power plant cooling systems to kill fish by thermal and mechanical action became an important source of information for environmental impact assessments of power plants on the Hudson River. In the 1970s, these studies were sponsored by a succession of agencies—the AEC, U.S. Nuclear Regulatory Commission, U.S. Environmental Protection Agency, and U.S. Army Corps of Engineers. By the time the decade ended, striped bass had become a species of national importance.

In preparation for the Indian Point Unit 2 licensing hearing, ORNL ecologist Phil Goodyear spearheaded the development of biological models of the Hudson River that indicated what fraction of striped bass might be killed by being sucked in (entrained) or trapped (impinged) by power plant cooling systems. This approach was taken because it was thought that the size of power-plant-induced fish losses might best be determined by modeling the fish population. Goodyear, now with the U.S. Fish and Wildlife Service, began developing models based on data obtained in the 1960s on fish eggs and larvae in the Hudson. Although Consolidated Edison was initially critical of the ORNL modeling, the utility's consultants quickly followed with increasingly sophisticated models of their own.

ORNL's modeling tasks and data gathering became even more intensive in response to a series of hearings that tried to evaluate the effect on Hudson River fish of six power plants in the so-called Hudson River Power Case (see the ORNL *Review*, Winter 1979, p. 26). The stakes were high: if the utilities could not demonstrate that once-through cooling systems were not killing an intolerably high proportion of the fish, the power companies could have been forced to install costly cooling towers.

The more advanced models were increasingly relied upon by the decision makers in the Hudson River Power Case. Arsev Eraslan, an ORNL consultant from the University of Tennessee, spearheaded the development of a useful, detailed model based on hydrodynamic principles. Webb Van Winkle, Sig Christensen, Larry Barnthouse, Doug Vaughan, and Don DeAngelis of ORNL, in collaboration with Goodyear and John Boreman of the U.S. Fish and Wildlife Service, developed and applied life-cycle models and empirically based entrainment and impingement models. These empirical models proved to be even more useful and acceptable than the hydrodynamic models.

Summer Die-off Puzzle

Meanwhile, the summer die-offs in Cherokee Lake continued. Despite known mercury pollution of the main tributary river, analyses of bass tissues for mercury contamination by ORNL's Steve Hildebrand in 1975 yielded no unusual levels. Our attempts in 1974 and 1975 to tag large adult fish in Cherokee Lake to determine temperature preferences were frustrated by the poor survival of the captured fish. Many tagged fish died after a few hours of frantic, seemingly inexplicable diving for deep water, surfacing, and diving again. Finally, in 1976, one tagged fish survived for an extended period. Its behavior and temperature selection revolutionized our thinking.

This fish, which was captured in midsummer from a cool stream

A legal settlement of the ten-year Hudson River Power Case was reached in December 1980. No cooling towers had to be installed, but less costly fish-protection devices and operational procedures had to be implemented for the once-through cooling systems of the six power plants. The ORNL models substantially influenced the selection of these required mitigation measures.

The legacy of the large-scale Hudson River research effort has been a major advance of the field of fisheries impact evaluation and greatly enhanced understanding of the dynamics of striped bass populations in a large estuarine system. New findings were summarized in *Assessing the Effects of Power-Plant-Induced Mortality on Fish Populations*, a 1977 symposium book edited by Van Winkle.

The expertise of the ORNL team is still in demand as questions about population declines plague coastal fisheries and as the Hudson River settlement (with requirements for continued research) is implemented. Barnthouse, for example, was selected as a member of the Hudson River Panel for the Hudson River Foundation, which has responsibility for scientific policy and decisions on grant awards concerning all aspects of the Hudson River ecological system. Christensen and Van Winkle have served on several panels to review current studies and determine future research priorities involving compensation in fish populations, including those of the east and west coast striped bass. It is likely that ORNL will continue to benefit from its lengthy involvement in the Hudson River Power Case for many years to come.

Graduate student Terry Cheek releases a tagged striped bass into Watts Bar Lake in the winter of 1980. The temperature-sensing ultrasonic tag shown here was developed and built at ORNL by Jim Rochelle of the Instrumentation and Controls Division.

Cheek clutches a striped bass that he caught, tagged with a temperature-sensing ultrasonic device, and later released to Watts Bar Lake. The ultrasonic tag allows ecologists to determine the water temperature preferences of the tagged fish.

entering the reservoir, selected a water temperature of 20–22°C (closely matching the ORNL quarry fish). It spent its entire tracking period in the cool creek channel underlying the warm water (up to 32°C) of the tributary cove. Much of the time it lay in "holes," which we later determined to be submerged low waterfalls. It made only brief excursions to warmer water in the open reservoir and then quickly returned to the cool, submerged creek bed. This behavior helped us explain why the other tagged Cherokee fish had died so soon after being tagged.

Because we were attempting to tag fish in the summer, the fish we captured were already in a cool "thermal refuge"—a niche with water temperature that is within the limited range required for survival. As we tagged the fish, our boat would drift away from their preferred niches. When we released them to the water, they would frantically dive to find cooler water. If the cool water was not there or was deoxygenated, the fish would return to the surface for oxygen, where the water was too hot. Most fish died because they could not take the heat; like the fish that took the "fantastic voyage" in our mock condenser studies, the bass succumbed to thermal shock.

In 1977-78, after changing our working hypothesis to fit our observations of the Oak Ridge quarry and Cherokee Lake fish, we restructured our fish-tagging studies at Cherokee Lake. We began to test our new theory that adult striped bass need cool water near 20–22°C to survive. About 80 fish and two years later, we had solid evidence that large, adult striped bass in the Cherokee Lake select temperatures near 20°C and that springs or spring streams are the niches where adult bass prefer to concentrate during June through September.

Impounded reservoirs tend to stratify in the summer into warmer, oxygen-rich levels and cooler, oxygen-poor levels. What we found is that the adult bass go to cooler levels, but that only a few places with cool water are sufficiently oxygenated. The large bass avoid the rest of the reservoir because the surface waters are too warm and the cool, main channels, although cool, are too low in dissolved oxygen to support the fish. Tagged fish that left the cool, oxygenated water died, as did hundreds of other fish weighing more than 4–5 kg.

Other factors besides thermal shock apparently caused the fish die-offs. Starvation seemed to play a role, because we found skinny bass and fish with empty stomachs or swollen gall bladders, thus indicating that bile secretions had not been used for digestion. Most importantly, we noticed that the warm surface water teemed with gizzard and threadfin shad—the striped bass's favorite spring and fall food. This observation suggested that the adult fish have such an aversion to warm water that they elect to starve rather than leave their preferred thermal niche. Another possible cause of death may be suffocation; in seeking cool water not already overcrowded with fish, some bass may end up in a deoxygenated channel.

We further tested the temperature preferences of adult striped bass in 1979–80. Terry Cheek, a graduate student working with us from Tennessee Technological University, tracked more than 80 fish that swam more than 100 km (up to 70 miles) to escape the warm waters of lower Watts Bar Reservoir in summer for the cool water (17–19°C) of the Clinch River. We also found that striped bass thrive in deep, cool Norris Lake, where fish that weigh more than 23 kg (5 lb) have been caught.

A distinct conclusion began to emerge: the temperature requirements of striped bass change with increasing age. We found that one-year-olds in the laboratory grow best near 24°C, two-year-olds select water temperatures near 21–22°C in the field, and large adults select even cooler temperatures (near 20°C). The habitat of

Cheek, left, and Kelly Roy, technician at the Environmental Sciences Division, weigh and measure a striped bass prior to tagging at Watts Bar Lake.

adult striped bass appears to be strongly limited in the rich, productive Cherokee Lake, where they survive only in the small, cool refuge areas formed by small springs and spring-fed creeks. Juveniles up to about 5 kg, however, thrive in the warm surface waters that teem with their prey—the shad. In Watts Bar Lake, the abundant cool water flowing from the Clinch River in summer helps support a large population.

We filled a data gap by conducting temperature preference tests on small juveniles using several methods in the Aquatic Ecology Laboratory. We found that the young fish selected temperatures near 26°C. Clearly, no single upper temperature limit applies to striped bass. It is a species with a complex, shifting relationship to temperature, with a kind of generation gap of its own. While the small juveniles require the warm surface waters of reservoirs and estuaries to grow, the adults seek out cooler waters elsewhere to survive.

Hence, a logical explanation for the increasingly reported summer die-offs of large fish may well be the lack of sufficiently cool, oxygenated water in southern reservoirs during summer to support the growing hordes of young fish stocked or spawned in these warm, organically rich reservoirs. This evolutionary strategy of "resource partitioning," or difference in thermal preference which separates juveniles and adults, would seem to help this voracious predatory fish survive in saltwater environments by greatly reducing the feeding of the adults on their young. Cannibalism seems most prevalent where no strong thermal stratification exists to separate the ages. Such a strategy of shifting thermal niche with increasing age apparently can prove detrimental to the species in the sometimes marginal environments of freshwater reservoirs.

What do these findings mean for management of freshwater fisheries? Our results suggest that fishery biologists should encourage fishing and control stocking programs so that the cool water refuges of reservoirs are not overcrowded with adult stripers in the summer. In other words, the waters selected for introduction of stock should have the proper amount of food and oxygen and sufficient thermal refuges.

Coastal Population Declines

We are now interpreting our laboratory and field study results in fresh water to try to understand and thus reverse the population declines seen in estuaries. On the West Coast, the reluctance of San Francisco Bay striped bass to populate coastal waters outside the bay seems linked to their tendency to avoid temperatures cooler than about 18.5°C wherever choices are available. In the Chesapeake Bay, high temperatures in surface waters during summer and increasing oxygen depletion in cooler, deeper waters (identified in recent studies by the U.S. Environmental Protection Agency) may cause conditions that are similar to those in Cherokee Lake and that may make survival difficult for adults that remain in the bay. In both the Chesapeake and San Francisco bays, toxic materials from human sources such as industry may have accumulated in thermal refuges where adults congregate, thus exposing breeding stocks to especially high toxicant concentrations. These factors could be partly responsible for the decline in the striped bass population in coastal waters.

On the bright side, evidence obtained by ORNL researchers and others indicates that the striped bass that spawn in the Hudson River are contributing a greater proportion of stock to the Atlantic Ocean than was previously believed. This spawning success may be

Coutant, right, and Michael Vandenavyle of Tennessee Technological University use "gill nets" to catch striped bass for fish tagging studies in Watts Bar Lake.

attributable to the Hudson River's deep channel that remains cool and oxygenated throughout the summer.

Last year, Webb Van Winkle and Deva Kumar reevaluated data obtained by Texas Instruments (TI) that supported the 40-year-old belief that most striped bass from Maine to North Carolina are spawned in the tributaries of Chesapeake Bay. The TI study indicated that in 1975 about 90% of adult stripers of all ages combined were spawned in the Chesapeake, 7% were spawned in the Hudson River, and 3% were spawned in the Roanoke River. In contrast, the ORNL evaluation showed that the Hudson contributed a much higher proportion of striped bass of certain ages, including 40–50% of the 10-year-old fish. These findings suggest that fish management efforts, now concentrated on the Chesapeake, should be directed also to the Hudson River to help reverse the decline of the coastal stocks of striped bass.

It is exciting to think that research and analysis conducted in the hills of Tennessee may be keys to the survival and success of the noble "basse." Our understanding of the biological and ecological requirements of the species has been greatly enhanced by our laboratory and field studies in stressful environments. The impetus of environmental impact assessments for power stations on the Hudson River has vastly extended the state of the art of evaluating the dynamics of fish populations in general and of striped bass in particular. Perhaps, most of all, we recognize that the interplay of ORNL's regulatory roles, national environmental research responsibilities, and local interests and research sites has led to exciting and productive avenues of research.

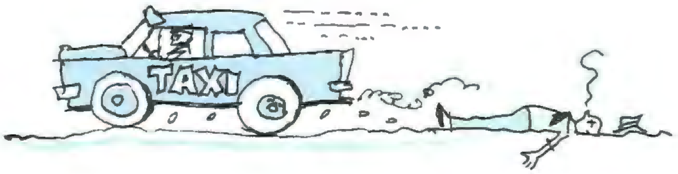
Although the expanding research perspectives of our individual projects have necessaril led to divergence of goals and methods, we continue to share common interest in and appreciation o the fish extolled in these remarks by William Wood:

> *The Basse is one of the best fishes i the Countrey, and though men are soon wearied with other fish, yet are they never with Basse.*

Almost 350 years after Wood penned this praise, aquatic ecologists and fishermen alike still find his observation to be true.

take a number

By V. R. R. Uppuluri



Base-Rate Fallacy in Probability Assessment

Recently, the "cab problem" has been discussed in psychological literature. In this problem, a cab is involved in a hit-and-run accident at night in a town that has two cab companies—the green and the blue. The following data are given:

1. Of the cabs in the town, 85% are green and 15% are blue.
2. A witness identified the cab involved in the accident as a blue cab. The court tests his ability to identify cabs under appropriate visibility conditions. When presented with a sample of green and blue cabs, the witness correctly identifies the color of 80% of the cabs and errs in 20% of the color identifications.

Question: What is the probability that the cab involved in the accident was blue rather than green?

Surveys have shown that most judges think that the probability that the cab involved in the accident is blue is 0.8. However, the use of Bayes' theorem indicates that the real probability of a correct response is not 80% but only 41%.

The first answer of 0.8 does not take into account the so-called "base-rate information" that 85% of the cabs are green and 15% are blue. This "base-rate fallacy" is said to occur because people tend to ignore base rates and to individuate information instead when it is available. If the base-rate information and the probability that a witness can correctly identify colors at night are integrated using Bayes' theorem, an accurate probability assessment would be obtained in the case of the cab.

Some Unusual Integers

The four-digit number 1233 has an unusual property. If you break it down into two two-digit numbers, 12 and 33, and then sum up the squares of both these numbers, you will find that $12^2 + 33^2 = 1233$. The only other four-digit number with this unusual property is 8833 ($8833 = 88^2 + 33^2$).

It can be shown that no two-digit number exists that is equal to the sum of the squares of its digits.

Larry Dresner, who came to ORNL in 1954, was trained as a theoretical physicist at Princeton University, from which he received his Ph.D. degree in 1959. He has pursued a wide range of research interests: reactor and neutron physics, water desalination by reverse osmosis, the interaction of shock waves with structures, and the stability of superconducting magnets. Because of these diverse interests, he has worked for several divisions: the Reactor Division (forerunner of the Engineering Technology Division), the Neutron Physics Division (forerunner of the Engineering Physics Division), the Chemistry Division, and the Fusion Energy Division. In 1960–61 he was a guest scientist at Kernforschungszentrum Karlsruhe in West Germany; in 1973–74 he was a Fulbright Scholar at the Weizmann Institute in Rehovot, Israel; and in 1981–82, he was an exchange scientist at the Japan Atomic Energy Research Institute in Tokai-mura, Japan. In 1960 he wrote a book entitled *Resonance Absorption in Nuclear Reactors*. Several years later he translated from German to English Karl Wirtz and Karl-Heinz Beckurts's book *Neutron Physics* and Thomas Jaeger's book *Principles of Radiation Protection Engineering*. He is a coauthor with ORNL's J.S. Johnson of the chapter on reverse osmosis in K.S. Spiegler and A.D.K. Laird's book *Principles of Desalination*. His newest book, which will soon be published, is *Similarity Solutions of Nonlinear Partial Differential Equations*. Here, he works out some theory in the presence of his esteemed experimental colleagues, John Miller (center) and Winston Lue.

Cable-in-Conduit Superconductors:

A Story of Science in the Making

By LAWRENCE DRESNER

In Joel Hildebrand's book *Science in the Making*, the celebrated chemist reflects that "the way we write up our results, in papers and books, in the passive voice, giving the impression that we start with precise measurements and proceed by strict logical steps to incontrovertible conclusions" is different from what we really do—that is, "starting with hunches, making guesses (most of which prove to be wild), making many mistakes, going off on blind roads before hitting on one that seems to be going in the right direction." The latter he calls "science in the making."

Citing his own work as an example of this homely process, Hildebrand writes, "Because I am trying to give, not an objective, analytical description of science, but a subjective impression, as felt by a scientist, of 'inside science,' . . . it seems appropriate to draw heavily on my own experience, where I best know the successive steps of speculation and experiment . . . telling the story of the gradual development of a theory."

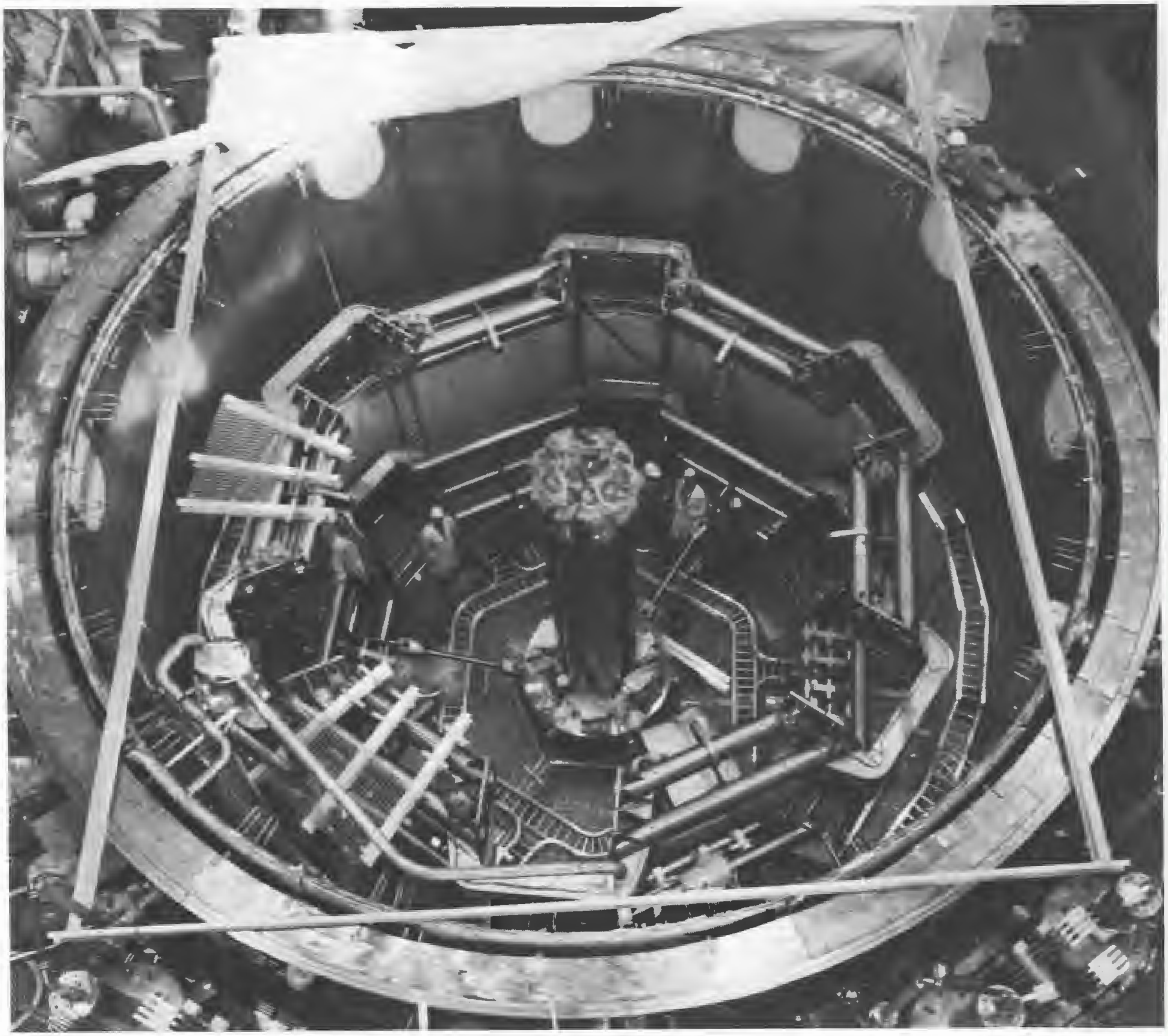
I shall do the same here—telling from the inside the story of the development of a kind of supercon-

ORNL researchers in the Fusion Energy Division admire the Japanese superconducting magnetic coil, which arrived in Oak Ridge in November 1982. The Japanese coil and a coil made by the General Dynamics-Convair Division of San Diego and shipped to ORNL in June will be tested this fall in the Large Coil Test Facility.

ducting magnet that may someday confine the plasma fuel of fusion reactors.

Because the plasma fuel of fusion reactors reaches temperatures several times hotter than the center of the sun, it cannot be confined by a material wall. This superhot gas of charged particles, however, can be confined by a suitably shaped magnetic field. The magnets that make this field are massive—they are several meters in diameter and weigh about 40 tonnes. If they were wound with copper wire, the magnets themselves would consume much of the electrical power produced by the reactor because of their electrical resistance. Fortunately, certain materials exist that completely lose their electrical resistance when cooled to very low temperatures (~ 20 K or −253°C). These materials are appropriately called superconductors. A great many are known, but presently the niobium-tin compound Nb_3Sn and some alloys of niobium and titanium are the most widely used. If a magnet is wound with superconducting wire, only a little electrical power is needed for refrigeration to keep the magnet cold. Thus, the huge magnets that will be employed in fusion reactors must be wound with superconductors if these reactors are to produce more energy than they consume. Consequently, for economics and energy efficiency, supercold magnets will be called upon to contain superhot fusion fuel.

Because helium is the only material that remains fluid at the low temperatures needed to make superconductors work, it alone can serve as the refrigerant. When the helium refrigerant has sufficiently cooled the magnet, the magnet loses its resistance and can be charged with current. As the current and magnetic field increase, powerful mechanical forces come into play that make the magnet expand somewhat like a tire being inflated. While a magnet is being charged, it creaks and groans as different parts of its winding slip and slide over one another. Each time the winding slips, friction converts a little magnetic energy to heat. These localized heat pulses are really very small and could be ignored at room temperature. But in the strange world of cryogenics, such thermal perturbations must be taken into account.



The vacuum tank of the Large Coil Test Facility has a bucking post at the center, a torque ring to support the coils, and a liquid-nitrogen-cooled cold wall around the tank periphery.

At these extremely low temperatures, the specific heats of materials are very low; thus, even tiny additions of heat can cause large rises in temperature—large enough, in fact, to make the superconductors lose their wonderful property of having no electrical resistance. When superconducting magnets lose this property, they do so with a vengeance, suddenly becoming thousands of times more resistive than copper. Because the magnets have been carrying very large currents, they begin to produce copious heat, which may eventually cause a runaway loss of superconductivity throughout the magnet. When this happens, we say that the magnet quenches.

Magnets that quench can destroy themselves as the energy stored in their magnetic fields is converted to heat. To prevent this destruction, we combine the superconductor with copper or aluminum so that if the superconductor becomes resistive, the copper or aluminum can serve as a low-resistance parallel path. Then, when a quench starts, we have time to connect an external resistance

The Japanese coil was installed in the Large Coil Test Facility vacuum tank in January 1983. In the foreground at right is the bucking post around which the six magnets will be arranged. Unlike the Westinghouse coil, which is internally cooled, this coil is a bath-cooled magnet.

across the magnet terminals to permit most of the stored magnetic energy to be safely dissipated as heat in the external resistance rather than in the magnet. In this way, we can protect superconducting magnets from destruction if they quench.

Preventing Quenches

Because commercial fusion reactors should be reliable sources of electricity, it is desirable to prevent magnets from quenching to avoid interruptions in reactor operation. To keep magnets from quenching, we must prevent a localized resistive zone from spreading over the whole magnet by overwhelming the resistive heat it produces with helium cooling. If we can provide enough cooling (and keep the resistive heat low enough by providing enough copper to make a low-resistance parallel path), we may be able to abort a quench and maintain continuous operation.

Two methods exist for bringing the helium refrigerant into contact with the superconductor. One is to immerse the whole magnet in a bath of boiling helium (which boils at -269°C). The other is to flow the helium through hollow superconductors just as one passes water through hollow copper conductors in resistive magnets. Both bath-cooled and internally cooled superconductors are currently in use. In Oak Ridge National Laboratory's Large Coil Program, both types enjoy equal favor: of the six magnets to be tested in a toroidal array at ORNL's Large Coil Test Facility next year, three will be bath-cooled and three will be internally cooled.

To ensure adequate transfer of heat to the helium in the hollow space, we must pump the helium in turbulent flow at speeds of several meters per second. Because we do not know when or where the conductor might slip and create a resistive zone, we must maintain a continuous flow. Speeds of a few meters per second are relatively modest, and the cost of maintaining a turbulent flow at room temperature is correspondingly modest. However, in the strange world of cryogenics, this is not the case. The work of the pump is dissipated in an environment where the temperature must be kept at 4 K. To prevent this cryogenic temperature from rising, a refrigerator is required to remove the pump-generated heat, which is ultimately rejected at room temperature. Even in the ideal world of thermodynamics, the refrigerator must expend 75 units of work to remove one unit of heat from the cold magnet. In the real world of inefficient machines, the factor is more nearly 500. Thus, refrigeration power has become a significant factor in the power budget of fusion plants.

Helium Flow Speed

One way to decrease the need for refrigeration is to reduce the

Dresner, Miller, and Lue (from left to right) plan an experiment using the Fusion Energy Division's 8-T facility magnet. Facility magnets supplied the adjustable background fields in which the experiments on short samples of cable-in-conduit conductors were carried out.

pump work by lowering the helium flow speed. Of course, by lowering the helium flow speed, heat transfer is lost, but the loss can be made up by increasing the surface area of the superconducting material. Because the surface may be increased by finely dividing the metal into thin wires, there arose the concept of a cable of superconducting wires inside a hollow pipe in intimate contact with the helium.

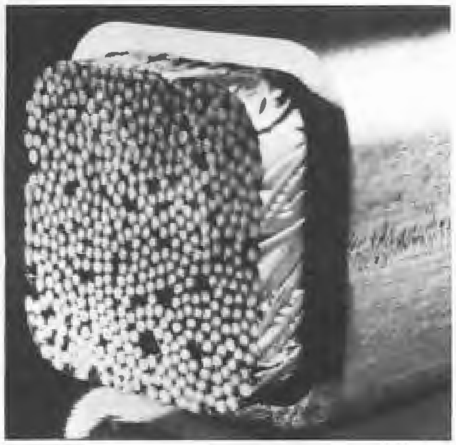
Such internally cooled cable-in-conduit superconductors were originally proposed in 1975 by Bob Brown of ORNL's Fusion Energy Division and Mitch Hoenig, Yuki Iwasa, and Bruce Montgomery of the Massachusetts Institute of Technology (MIT). At that time, the MIT group was working under contract to ORNL. Their invention reduced the need for refrigeration power—but not enough to please some scientists in the superconducting-magnet community.

It is at this point that I became involved with cable-in-conduit superconductors. Soon after leaving ORNL's Chemistry Division to join the Magnetics and Superconductivity Section of the Fusion Energy Division in May 1975, I read about the MIT cable-in-conduit superconductor. I remember thinking how ironic it was that, in the midst of all the unusual technical problems posed by the construction of large superconducting magnets, a mundane problem like pump work was the technical shoal on which we would founder. Because I could hardly believe it, I made some calculations to see if the allegations were true.

The problem was to determine how fast the helium had to flow to ensure the magnet's recovery from a heat pulse of a certain size. The largest heat pulse from which a conductor recovers—returns to the superconducting state—is what is called the "stability margin." I sought to calculate the stability margin as a function of helium flow speed.

To do this, I wrote a program for the time-share computer of the Fusion Energy Division. At first, I did what researchers at MIT, Westinghouse, and General Electric were doing—that is, I followed the temperatures of the metal and helium by integrating forward in time, waiting to see if the metal temperature increased. If it did, I reduced the initial heat pulse and tried again. This procedure involved much trial and error and proved extremely inconvenient. I quickly grew bored and frustrated as I sat at an unresponsive keyboard and waited for my infrequent turn at the busy computer.

Then, I got an idea that helped speed up the process. Instead of integrating forward in time, I started at the desired end point and integrated backwards in time. The initial condition, which was revealed after one integration, gave the stability margin directly without trial and error. Now, I had a program that was not only ten times faster than my first program



The cable-in-conduit conductor of ORNL's Large Coil Program, to which the research results described in Larry Dresner's article apply, will be used in this coil being built for ORNL by the Westinghouse Electric Corporation.

but also could be automated because it required no human intervention between cases. I could therefore do extensive parameter surveys that others could not perform.

One of the first things I did was to determine the stability margin (for a given helium flow speed) as a function of the proportions of superconducting material, copper, and helium inside the conduit. Because these composition variables often seemed to be arbitrarily chosen, I wanted to know if some values are better than others. The very first calculations that I performed with my improved program showed that there is an optimum conductor composition—that is, a composition that is best because it has the maximum stability margin. This conductor, which I dubbed the "stability-optimized conductor," solves both the problem of finding the maximum stability margin for fixed pumping power and the related problem of finding the minimum pumping power for a fixed stability margin. Thus, by correctly selecting the material proportions, we can reduce the pumping power without causing a loss of stability.

Following this observation, my colleague Winston Lue and I began designing superconducting magnets based on stability-optimized conductors for possible use in tokamak fusion devices. We found that we could reduce the pumping power requirements to about one-tenth of what had been deemed necessary in earlier studies. We hoped this finding would change the minds of the doubters in the superconductor community.

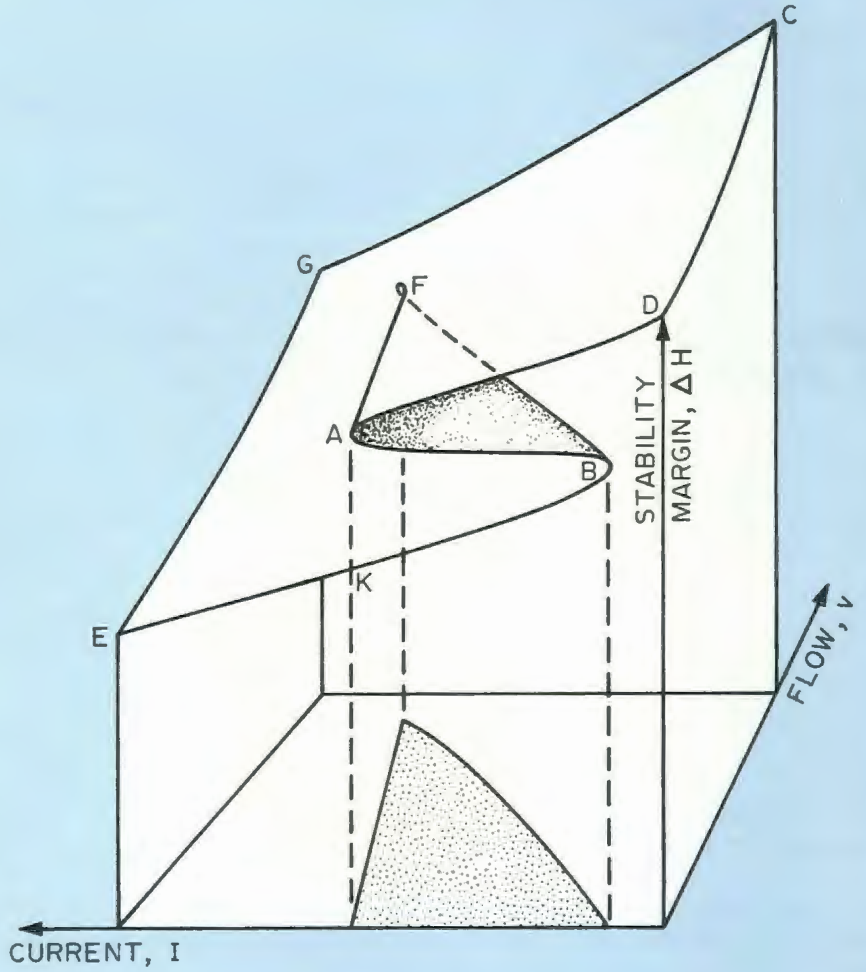
A Turn of Events

Albert Einstein once remarked that "God is subtle but not malicious." My colleagues and I would soon see how true this assertion is. While we were putting the finishing touches on our calculations, the MIT group had performed some experiments to measure stability margins. They reported that the stability margin is nearly independent of helium flow speed right down to zero flow. In other words, the conductors recovered from substantial heat pulses—that is, returned to the superconducting state—even when the helium permeating the cable was stagnant.

This finding was quite contrary to expectation, for the calculations suggested that as helium flow rate (and therefore heat transfer) approached zero, so would the stability margin. How then was the heat transferred so as to prevent loss of superconductivity? The MIT group's answer was that an early transient stage of heat conduction in the helium is responsible. By making allowances for it in their computer program, they brought their calculations into agreement with their measurements. But the agreement obtained at MIT turned out to be fortuitous, and a vital scrap of experimental information from an entirely different source indicated the correct solution.

John Miller, Winston Lue, and I had been studying the problem of vapor locking in small channels, a problem that affects only bath-cooled magnets. As an experimental object, John and Winston had used a triplet of superconducting wires twisted around a heater wire and sheathed in a stainless steel tube filled with stagnant helium. They found that the stability margin was high when the ends of the tube were open, but the margin fell by more than an order of magnitude when the ends of the tube were sealed. Such a precipitous drop in the stability margin is incomprehensible if recovery in stagnant helium is caused by transient heat conduction as the MIT group proposed. John and Winston's findings suggest, instead, that recovery from heat pulses in stagnant helium occurs because of momentary flow induced by early conductive heating of the helium. The momentary flow is caused by the thermal expansion of the helium. Plugging the ends of the tube suppresses induced flow and sharply decreases the stability margin.

Even though I wholeheartedly accepted the correctness of this new explanation, I thought it was important to perform calculations to demonstrate that the heating rates used in John and Winston's experiments would, in fact, induce high flow speeds in initially stagnant helium. The calculations require some knowledge of compressible flow—knowledge that I had fortunately acquired ten years before in ORNL's Civil Defense Project. In a few days, I had completed the calculations—finding induced speeds of more than 10 m/s, high enough to explain our observations. John and Winston found it too difficult to measure the induced flow speeds, but they could easily measure the helium pressure rise



Schematic representation of the stability margin as a function of imposed helium flow and steady current (not to scale). The fold in the stability surface is connected with the occasional multivalued nature of the stability margin. Points under the surface correspond to recovery; points above it correspond to a quench. In the region of multiple stability (shaded triangle), the margin of safety is the lower stability margin (sheet GEKB) simply because it is not known how large the thermal perturbations will be. Because the margin of safety is larger under the sheet FDC (upper stability margin), it is advisable to operate at steady currents smaller than that at point B, the so-called limiting current.

associated with the induced flows. Because they found good agreement with my predictions, we concluded that induced flow, not transient heat conduction, explained MIT's high stability margins with stagnant helium.

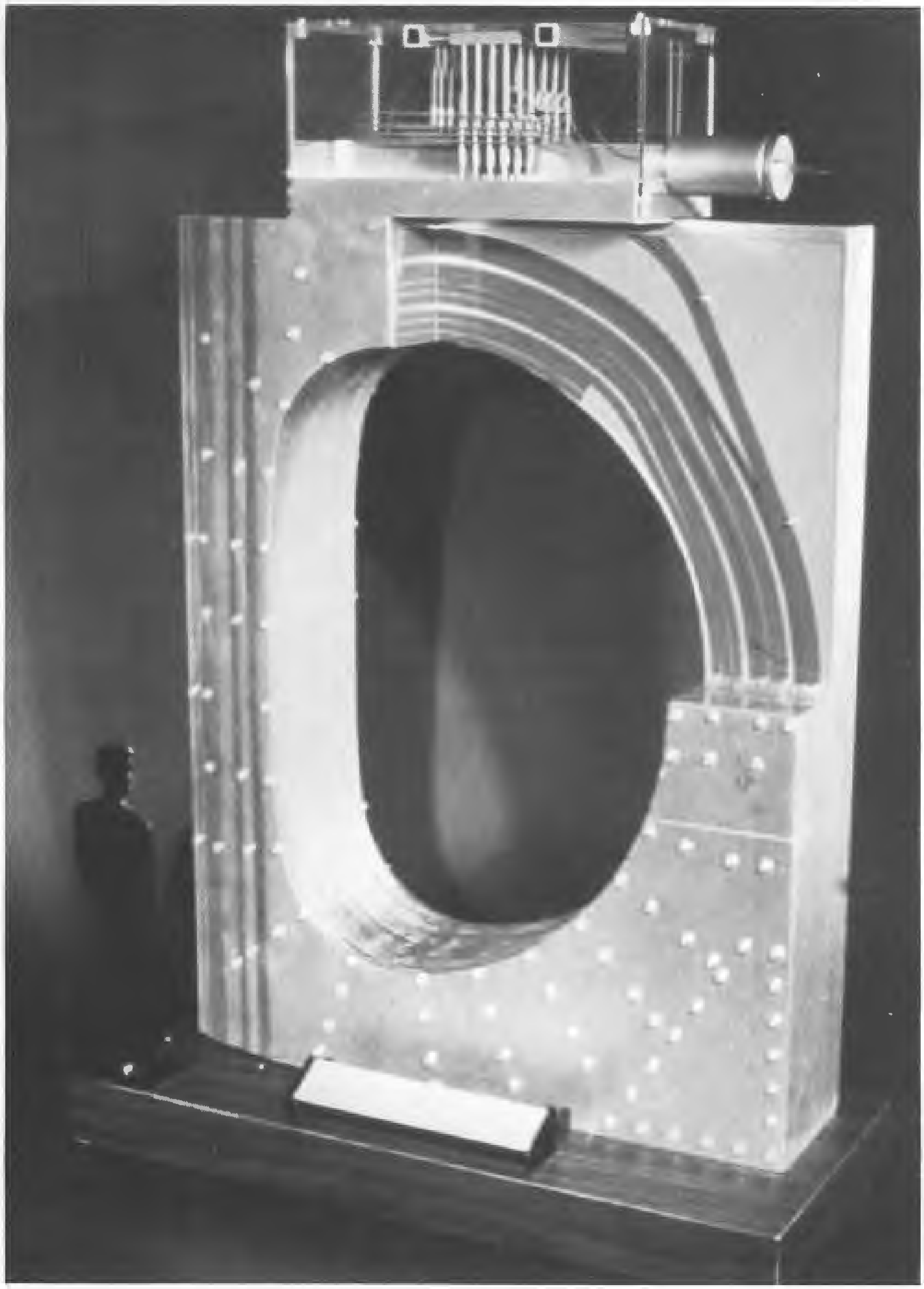
If helium flow is induced by natural causes, then pumping is not needed to impose the flow to prevent loss of superconductivity. The practical impact of high stability without imposed flow is profound because such a finding scotches completely the pumping-power objection to cable-in-conduit conductors. Eliminating strenuous pumping reduces the need for refrigeration power, thus making cable-in-conduit conductors more economical.

The fortunate existence of powerful induced flow, of course, cast doubt on the validity of my previous numerical work, in which I, along with everyone else, had treated helium as an incompressible liquid. Glad as I was that we here at ORNL had advanced our understanding, I could not escape some melancholy as I saw my idea of integrating backwards in time consigned to the trash can with yesterday's newspaper.

Recovery-Quench Regions

We at ORNL not only had a good idea of what was going on in cable-in-conduit conductors, we also had a convenient object of experimental study. Because the triplet of wires twisted around a central heater proved versatile and allowed easy control and measurement of the heat input to the conductor, John and Winston launched a program of measuring stability margins with this device. It was not long before they encountered another example of God's subtlety.

Using triplets cooled by stagnant helium, they observed that the



This cutaway model of the Westinghouse coil for the Large Coil Test Facility shows the cable-in-conduit conductor wound in the aluminum support plates.

conductor would sometimes recover for small heat inputs, quench for larger heat inputs, recover again for even larger heat inputs, and finally quench for the largest heat inputs. This sequence of recovery-quench-recovery-quench with increasing heat input did not always happen; sometimes the expected sequence of recovery-quench occurred. Which behavior they observed apparently depended partially on the steady current in the triplet.

When John and Winston first told me about this multivalued stability, I had some doubts, but because I knew they were careful and clever experimenters, I soon accepted the possibility that multiple stability is real, even though I had no idea how it came about. That was a fortunate decision for me, because what happened next proved Louis Pasteur's dictum that "chance favors the prepared mind."

In the early days of stability-optimized conductors, when I imagined the flow to be externally imposed by a pump, I had already calculated the stability margin as a function of the helium flow speed. Later, when I calculated the flow speed induced by an imposed heat input, I was effectively calculating the helium flow speed as a function of stability margin. The rub was that while I knew how flow speed and stability margin determined each other, I did not know either one at the start. What I had was the solutions to two half-problems but no way to put them together.

Then one day in Winston's office, in the midst of a conversation, I saw the way. Each half-problem could be considered as a curve plotted on axes labeled "stability margin" and "helium flow speed." In one graph, stability margin was the independent variable, and flow speed was the dependent variable. In the other graph, the reverse was true. Because I knew the shapes of these curves from my earlier solutions of the two half-problems, I saw that if we plotted them both on the same piece of paper, the two curves would have either one or three intersections. It was a simple matter to interpret one intersection as separating two regions of behavior (recovery-quench) and three intersections as separating four regions (recovery-quench-recovery-quench).

The whole realization came to me in a rather bewildering flash.

Somewhat shaken by my brainstorm, I said to Winston, "I know how it can happen," turned on my heel, went to my office, and wrote out my explanation without the slightest hesitation. The text I wrote that day in December 1978 appeared later in the published paper in which John, Winston, and I announced our discovery.

John and Winston thoroughly surveyed the stability margin of their wire triplets as a function of the steady current in the superconductor and the externally imposed helium flow. From their data, we determined that the upper stability margin is often ten times as great as the lower stability margin, thus suggesting that we should operate at steady currents smaller than a certain value, which we call the "limiting current."

My intersecting-curves theory of multiple stability gave me a way to calculate the limiting current. I plunged ahead with this calculation, determined to press my original conception as far forward as I could. The theory was not good enough to yield an accurate value of the limiting current, but it showed how the limiting current depends on important parameters such as the temperature of the helium and the proportions of helium, copper, and superconducting material in the conductor. Applied even to scant data, my rule could specify, by scaling, the limiting current in any configuration.

John and Winston immediately seized on this scaling rule as a target for experimental investigation. That tale is not yet fully told, but so far they have found the scaling rule for the limiting current to be accurate. It has become the cornerstone of ORNL's design procedure, the crux of which is avoidance of the region of multiple stability.

With this picture of stability in mind, I resurrected an old idea—the stability-optimized conductor. By avoiding the region of multiple stability through application of the scaling rule, it was now possible to determine the best composition—that is, the one whose upper stability margin is the highest. I suggested this idea as the basis for the design of a cable-in-conduit conductor at the Japan Atomic Energy Research Institute, where I spent 1981 and part of 1982.

Internal Pressure Problems

Knowledge of the stability margin, which had so long concerned John, Winston, and me, helps us to design magnets that are not likely to quench. But if the magnets do lose their superconductivity because of some unforeseen circumstance, we must be sure that they are not destroyed. One potential hazard faced by quenching cable-in-conduit conductors is the extremely high internal pressure they may undergo because of the heating of the helium inside them. This problem worried another member of our team, H. T. Yeh, who was concerned with protecting magnets. He mentioned it to me often, and eventually I turned my attention to his concern.

Again, the key to the problem was calculating the heating-induced flow of the helium. In earlier stability computations, I found that the response of the helium (after milliseconds of heating) was determined by its inertia and that its friction with the superconducting wires could be neglected. But in this case, the response of the helium (after seconds) was determined solely by its friction with the wires; therefore, its inertia could be neglected. Once I realized that the inertia of the helium could be neglected, I simplified the problem and arrived at an easily evaluated formula for the highest pressure that would be reached during the quench. My estimates for the coil built by the Westinghouse Electric Corporation and scheduled to be tested at the Large Coil Test Facility (LCTF) next year were high and excited some controversy; therefore, I asked John and Winston to conduct experiments to check my formula. Collaborating on an experiment with Stewart Shen, they verified its accuracy. Accordingly, this formula took its place among ORNL's tools for designing magnets.

While manipulating the equations of compressible flow to solve the problem of the peak quench pressure, I noticed that they had a similarity solution (a special kind of solution that is easy to calculate) that described the response of the helium during, roughly, the first second of heating. This observation, too, could be traced to my work in the Civil Defense Project, in which I first encountered similarity solutions in the shape of G. I. Taylor's solution to the problem of a point explosion in air.

The similarity solution I discovered gave a simple analytic formula, valid during the first second or so, for the velocity with which the helium is expelled from the ends of the cable-in-conduit conductor. According to my computations, this velocity can reach 20-40 meters per second after one second. I was concerned that such vigorous thermal expulsion of helium from a quenching cable-in-conduit magnet might well damage the delicate refrigerator that supplies cold helium to the magnet. I again turned ideas over to John and Winston and, once again, they skillfully performed an experiment that corroborated my formula. It, too, took its place among ORNL's design tools. As a postscript, let me add that the engineers in charge of the LCTF have taken note of this problem of thermal expulsion. According to them, some rather expensive turbines may be at risk, and tests are planned to verify whether a problem exists and, if so, to correct it.

Lue, Dresner, and Miller also work on other magnet programs in the Fusion Energy Division. Here, they discuss the stability of the bath-cooled ELMO Bumpy Torus (EBT) magnet shown in the background. The EBT approach to fusion is the leading alternative to tokamak and mirror machines.

Some Lessons

Our research has provided us with the tools for designing internally cooled magnets that have advantages over bath-cooled superconductors. We have found that heating-augmented heat transfer reduces the need for refrigeration power and, more importantly, permits cable-in-conduit superconductors to operate stably with much higher current densities than do conventional bath-cooled superconductors. Operation at high current density allows reduction in magnet size, weight, and cost—important advantages in the design of economical fusion reactors. We found also that the same level of stability can be maintained at a higher field by reducing the temperature of the helium, an advantage that reveals an important flexibility of internally cooled magnets.

Our research results were applied to the design of the cable-in-conduit conductor used in the coil being built by the Westinghouse Electric Corporation for ORNL's Large Coil Program.

What else can be learned from all this history? One lesson is that the old-fashioned method of paper-and-pencil calculation leapfrogging bench-scale experiment is sometimes a better road to understanding than resorting to large electronic computers. All my computations, except the earliest ones on stability-optimized conductors, were done with paper and pencil. The explanation of multiple stability, the scaling rule for the limiting current, and the formulas for the quench pressure and the expulsion velocity are all the products of "brute thought" and computations that involved nothing more elaborate than a hand-held calculator. The experiments, which were carried out with care and imagination, focused mainly on single triplets of wire, the smallest possible module of a cable-in-conduit conductor. And, yet, we at ORNL discovered what others, preoccupied with computers, missed.

Perhaps the sincerest praise of our way of proceeding is to be found in the lament of a foreign colleague who attempted to study cable-in-conduit conductors by means of a computer. "Such elaborate procedures," he wrote, " . . . require an appreciable amount of computing time, [and] extensive parametric studies of stability margins are thus beyond [the] present-day's scope." The most telling point against the brute force of giant programs is that none of them has been able so far to model the phenomenon of multiple stability.

The second lesson is the advantage of wide, general knowledge over deep but narrowly specialized knowledge. This advantage is somewhat akin to the evolutionary advantage of the unspecialized and unprepossessing early mammals over the highly specialized and vastly more imposing dinosaurs. In the current instance, a smattering of compressible flow gained from several years in ORNL's Civil Defense Program and a little knowledge of heat and mass transfer gained from several years of studying water desalination in ORNL's Water Research Program helped me to solve problems that would have remained baffling had my training been more narrowly specialized. All this seems to me to plead for a mildly peripatetic style of professional life, marked by occasional changes in one's field that revive one's enthusiasm and enlarge one's repertoire of skills.

The last lesson and the simplest is best summarized by Nobelist Peter Medawar, who said that "there is no knowing in advance where a research enterprise may lead." Certainly an excellent case in point is our research in cable-in-conduit superconductors. ornl

lab anecdote

Changing of the Contractor

Changing contractors at Oak Ridge National Laboratory has happened before—although it has been 35 years since a change was made. ORNL has experienced two contractor changes so far in its 40-year history. Because ORNL will have a new contractor in 1984, it seems appropriate to review how the Laboratory was affected by its earlier contract changes. In a recent interview, Alvin Weinberg, former ORNL director and now head of the Institute for Energy Analysis at Oak Ridge Associated Universities, recalled the effects of the contract changes on the Laboratory and on his own career in the 1940s.

During World War II, ORNL was operated by the University of Chicago as an offspring of the school's Metallurgical Laboratory. Shortly before the war ended, the university decided to leave Oak Ridge; in 1946, the Monsanto Company of St. Louis came in as the Laboratory's contractor.

After only a little more than a year, Monsanto also decided to leave as contractor. "What happened," says Weinberg, "is that Monsanto wanted the Laboratory to be incorporated much more strongly into its framework—that is, Monsanto wanted the Laboratory staff and equipment moved to St. Louis. The Atomic Energy Commission was unwilling to agree to this proposal. So, Monsanto announced that it would pull out but would continue to operate the Laboratory until a new contractor was found."

Once again the Laboratory faced the problem of finding a new contractor. At the same time it also was confronted with the problem of finding a new Laboratory director. Monsanto had arranged for Eugene Wigner to be the Laboratory's research director, but Wigner stayed at the Laboratory for only a year and then decided to return to Princeton University. After he left, the Laboratory operated without a director for about a year.

During this period the AEC decided to invite the University of Chicago to take over the contract again at the end of 1947 when Monsanto was to leave. Thus, the University of Chicago began to seek candidates for a Laboratory director.

About this time, the Laboratory was intent on building what was called the High Flux Reactor. At Christmas 1947, Jim Fisk, AEC research director, came to the Laboratory to announce that the Commission had decided not to build the High Flux Reactor in Oak Ridge. "Many people at the Laboratory were unhappy about that decision," says Weinberg, "because they felt that the High Flux Reactor was to be the central nuclear facility that would have given the Laboratory a renewed sense of purpose during the postwar period."

At this point the prospects for the Laboratory were so dim that nobody wanted the job of director. Says Weinberg, "It was the most extraordinary thing—I think the University of Chicago asked a dozen or more people to become director. Even when the deadline for Monsanto's leaving approached, the University still had not found a Laboratory director."

Then Union Carbide, which already operated the gaseous diffusion plant, informed the AEC of its interest in taking over the Laboratory. "So far as we could tell," Weinberg says, "one of the main reasons for this expression of interest was that Union Carbide was uncomfortable in a town that had competing companies; Carbide felt that this would complicate labor relations. Thus, they wanted to operate the Laboratory as well as the gaseous diffusion plant in Oak Ridge."

In January 1948, Carbide's people took over operation of ORNL. "They continued the search for a Laboratory director, but like the University of Chicago, they had no luck at first," says Weinberg. "They must have asked a dozen-and-a-half people, 'Here's this nice laboratory; don't you want it?' Nobody wanted it.

"Finally they chose me—to some degree out of desperation, I think. They asked me if I wanted to be director, associate director, or research director. I was only 32 years old at the time, and I said, 'Well, I think I would prefer to be the associate director; let somebody else be the director.' Nelson Rucker, who had been the head of the Y-12 Plant, came in as the director, and I was the associate director. Then, two years later, Clarence Larson became the director and I became research director. So, that's how I got to be associate director, then research director and, later, director of the Laboratory. (Weinberg was the director of ORNL from 1955 to 1973.)

"The decision to choose Carbide came as quite a surprise to all of us. We didn't know that the negotiations with Carbide were going on. Of course, in retrospect, it seemed like a natural thing; Carbide was already well ensconced at the gaseous diffusion plant and later took over the Y-12 Plant.

"When the announcement was made that Carbide was coming in, many of the scientific people were appalled. Our people were concerned about the implications of throwing all these sensitive, head-in-the-sky scientists, most of whom had university backgrounds, into

ORNL director Alvin Weinberg (second from left) and Union Carbide Nuclear Division president Clark Center (center) accompany King Hussein of Jordan on a tour of ORNL in the 1950s. They are flanked on the left by John Swartout, ORNL deputy director, and on the right by Sam Sapirie, manager of Oak Ridge Operations of the U.S. Atomic Energy Commission.

the hands of this industrial ogre called Carbide. But some of us argued that, after all, we had already been operated by another industrial company—Monsanto—and that had been okay. And after a while people realized that Carbide wasn't such an ogre and that the relationship could be quite successful."

Weinberg attributes the success of the Carbide-ORNL relationship to the extraordinary understanding on the part of Clark Center, Carbide's chief representative at that time. "He was anxious to maintain the research atmosphere around the Laboratory, and he understood that the research staff had certain sensitivities to be reckoned with, so he was careful not to move in and change everything."

In looking back, Weinberg says that it probably would not have made a difference whether the contractor was the University of Chicago or Monsanto or Union Carbide. "In comparing the contract change then with the contract change today, I see only two real differences," he adds. "At that time, Carbide seemed like a great big unknown to the people at the Laboratory, and most of them felt somewhat antagonistic about being taken over by an industrial company. I suspect that this time the situation will be quite different because people have had a successful experience working under Carbide's management. I think that now they would be likely to view a new industrial contractor as not so different from Carbide.

"Also, at the time of the previous transition," Weinberg continues, "there was no Laboratory director. So Carbide had to both take over as contractor and find somebody to run the place. This does not appear to be the case today because a director is already there."

A contract change obviously can be expected to have an effect on some people's careers. This was certainly true in Weinberg's case. "As I said, I think to some degree they chose me out of desperation to help manage the Laboratory. Carbide had run out of candidates. Had there not been a contract change, I probably would never have become director of the Laboratory."

—*Jon Jefferson.*

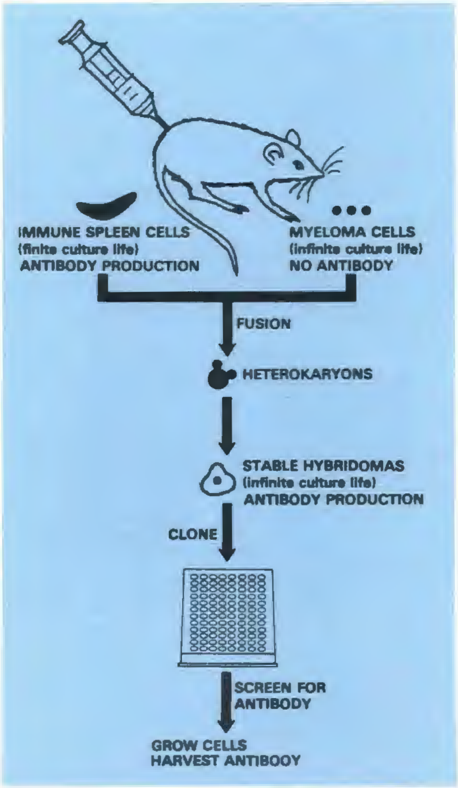
Monoclonal Antibodies and Cancer

By STEPHEN KENNEL

Cancer—the unregulated, autonomous growth of cells—has been killing humans for centuries. Only in the last 100 years have there existed certain therapies, including drug and radiation treatments, that show promise in retarding the spread of human cancers. However, a cure for the disease has yet to be found, and no new approaches to the treatment of cancer have been made in the last 20 years. What is new in the past five years, however, is the ability to make traditional cancer therapies more effective through the application of the new biotechnology.

The term "biotechnology" traditionally refers to the controlled use of living systems or their active fractions to bring about chemical and physical change. The ancient practice of making wine by fermenting grapes is an example of biotechnology. Also, for example, Oak Ridge National Laboratory has harnessed special microorganisms in its bioreactors for cleaning up liquid wastes and producing useful fuels and chemicals. Nowadays, however, biotechnology has taken on another meaning in the light of revolutionary techniques in molecu-

Steve Kennel, a native of Morton, Illinois, received his B.S. degree in chemistry from the University of Illinois and his M.S. and Ph.D. degrees in biochemistry from the University of California, San Diego. After two years as a postdoctoral fellow and three years as an associate at Scripps Clinic and Research Foundation in San Diego, he came to ORNL's Biology Division in 1976. Since then, he has developed strong ties with the University of Tennessee's Microbiology and Biochemistry Departments and has taught immunology and virology at the University of Tennessee–Oak Ridge Graduate School of Biomedical Sciences. Currently, he is studying the effectiveness of monoclonal antibodies in treatment of cancers in mice and the use of these antibodies in lung toxicology. His previous research has embraced the basic biochemistry of bacterial photosynthesis and various aspects of immunology and cancer virology. His research is supported by the U.S. Department of Energy and the National Institute of Environmental and Health Sciences. Kennel is a member of the Health Effects Research Study Section of the Environmental Protection Agency. Here, Trish Lankford watches as Kennel injects a mouse with monoclonal antibody.



A monoclonal antibody is the product of the fusion of immune spleen cells, which produce antibodies, and myeloma cells, which have infinite culture life. The antibody-making cells can be produced in a mouse's spleen by injecting the mouse with an antigen.

lar biology which were developed in the 1970s.

The new biotechnology permits scientists to isolate specific fractions of living matter, such as genes and proteins, and produce them in large quantities. Two major advances in molecular biology have been made. First, recombinant deoxyribonucleic acid (DNA), or gene splicing, techniques have been used to transplant genes into bacteria, thus forcing the host to produce large amounts of desired products such as insulin, human growth hormone, and interferon. Second, new hybrid cell techniques have been used to produce monoclonal antibodies, which can be produced from fused cells that are grown from single cells (clones). Monoclonal antibodies bind to individual tumor cells and, therefore, show promise for combating cancer. In ORNL's Biology Division, part of our effort in cancer research is devoted to studying how monoclonal antibodies can be used to eradicate cancers in experimental animals.

What Are Monoclonal Antibodies?

When foreign materials such as proteins, microorganisms, and cancer cells are present in the body, complex sets of white blood cells called lymphocytes are mobilized by the immune system to help eliminate these materials. Some lymphocytes produce serum proteins, termed immunoglobulins, that can bind to specific sites on foreign molecules. These immunoglobulins are called antibodies when the specific sites at which they bind (antigens) are known. An antiserum contains a mixture of all of the different immunoglobulins that the host has produced both before and after encounter with the foreign material in question.

In the early 1970s in London, England, Georges Köhler and Cesar Milstein developed a technique for producing monoclonal antibodies to help answer their questions about the immune system. Köhler and Milstein used the new biotechnology to generate large amounts of a single (monoclonal) antibody from descendants of hybrid cells, each of which is composed of a cancerous lymphocyte cell and an antibody-producing lymphocyte cell of the immune system. These hybrid cells are called hybridomas.

Since 1975, when Köhler and Milstein reported their hybridoma technique for selecting and propagating individual lymphocyte cell lines in tissue culture to produce a single, unique, homogeneous antibody population, scientists have used these special antibodies to purify valuable molecules; to tag cells for identifying them; and to "zip code" drugs, radioactive agents, and other toxic packages so that they are delivered only to specific tumor cells. What is most exciting is that these pure-binding reagents have revolutionized cancer research.

How They Are Made

Hybridomas, which are used to produce monoclonal antibodies, are generated by a simple procedure that combines the useful properties of two different cell types—namely, myelomas and spleen cells. Myelomas are cancerous lymphocytes that can be propagated in tissue culture. Myelomas can produce monoclonal immunoglobulins, but these immunoglobulins usually lack the desired ability to bind to a specific target cell. On the other hand, splenic lymphocytes from an immunized animal are actively producing antibodies to the foreign material of interest; however, when these cells are removed from the body, they slowly die and cannot be routinely established as continuous, long-lasting cell cultures.

Köhler and Milstein demonstrated that cell fusion can be used to join the desired property of the immune spleen cell (i.e., antibody production) to the attribute of the cultured parent myeloma (i.e., infinite culture life). The resulting fused cells (heterokaryons) can be selected for growth in a special growth medium and then tested for production of specific monoclonal antibodies. Resultant cell lines, or hybridomas, that produce the desired antibodies can then be grown in cell cultures indefinitely.

Why Are They Special?

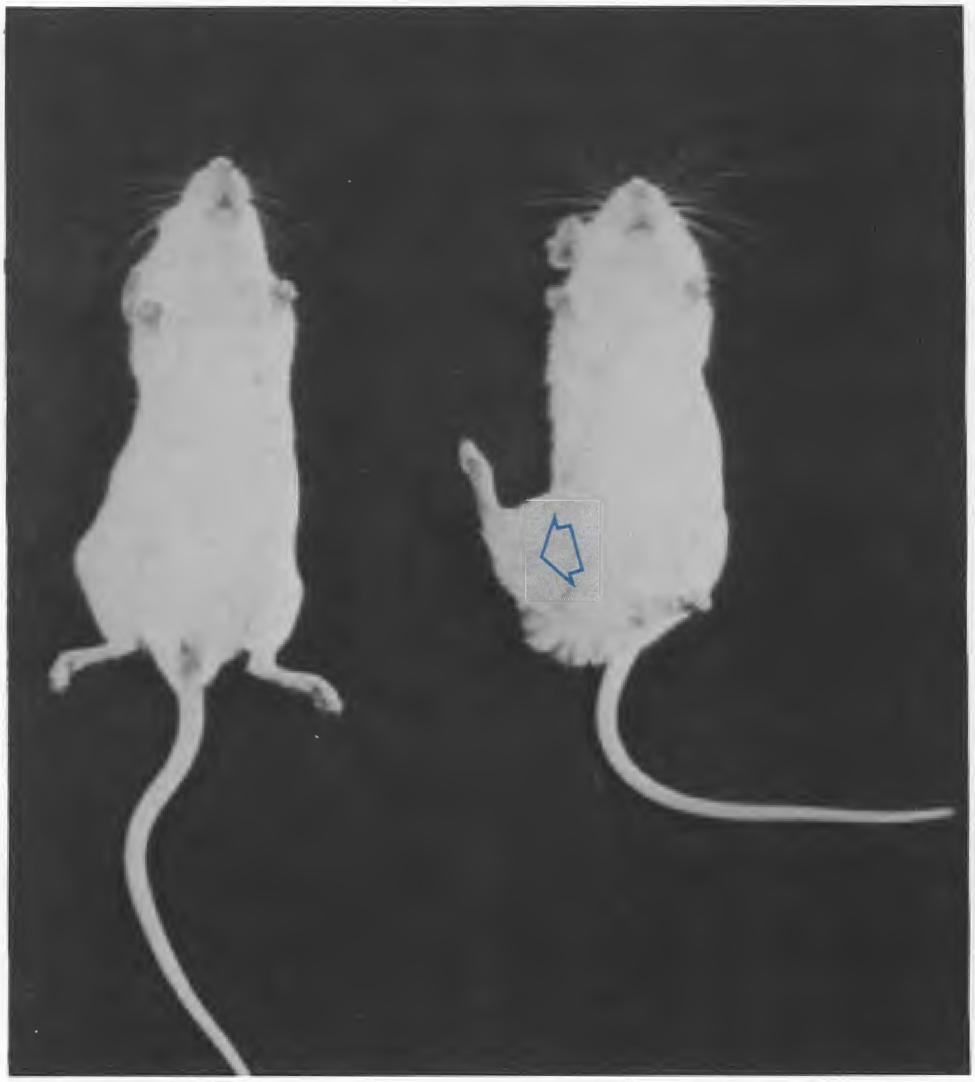
Monoclonal antibodies have three major advantages over mixtures of antibodies known as antiserums. First, like a key that fits into only one lock, a monoclonal antibody binds to one, and only one, molecular site (epitope). This absolute binding specificity ensures that the determinant site (epitope) is present wherever specific binding is demonstrated. Based on this principle, monoclonal antibodies can be made for use in detecting specific molecules, such as those that indicate the presence of cancer.

Second, because monoclonal antibodies are homogeneous, they can be purified with relative ease. On the other hand, antibodies from antiserums are invariably contaminated with immunoglobulin molecules that have undefined binding properties.

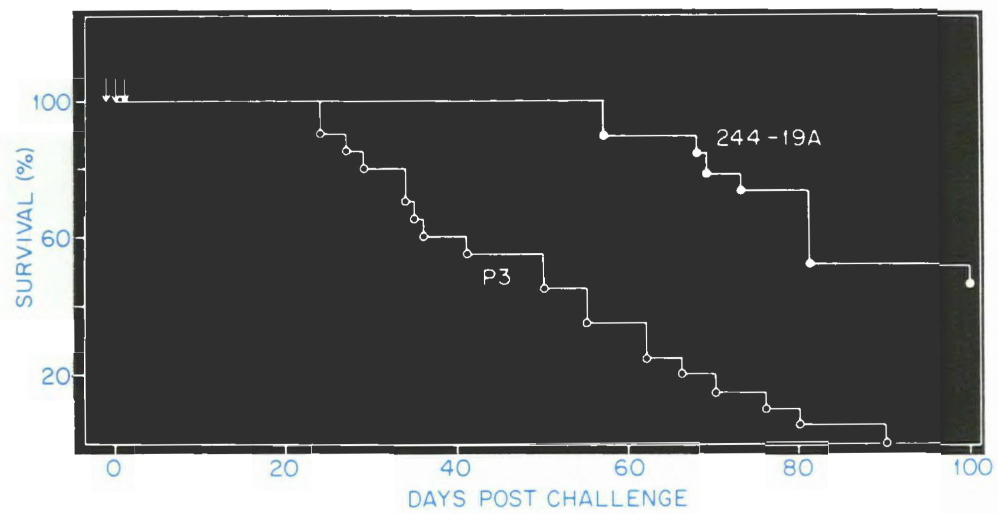
The third and most important advantage of monoclonal antibodies over antiserums is that their properties are reproducible—that is, a particular hybridoma cell line can be preserved by freezing and later thawed for use, or it can be transferred between laboratories without causing changes in binding specificity. Thus, the proper characterization of the binding properties of a monoclonal antibody will be as valid in the twenty-first century as it is today.

Uses in Cancer Therapy

Many types of cancer cells are recognized as foreign by the host's



These mice with potentially lethal tumors were treated with monoclonal antibodies. Both mice had solid tumors under the rear legs. The tumor has regressed in the mouse at left, but the leg tumors are still present in the mouse at right (see arrow). Some mice that are treated with monoclonal antibodies, as well as all control animals, have progressively growing tumors in their legs that ultimately cause the mice to die.



Mice with potentially lethal tumors were treated with monoclonal antibodies on the days indicated with arrows. In the days that followed, the percentage of mice that survived was higher in the treated mice (closed circles) than in the control animals (open circles).

immune system. In the case of progressive disease, however, the immune system has obviously failed to eliminate or control the abnormal cells. It is hoped that administration of a monoclonal antibody can augment the host defenses enough to allow the immune system to prevail.

Over the past three years, scientists have discovered that certain monoclonal antibodies can join forces with host lymphoid cells to eradicate experimental leukemias (cancer of the white blood cells) and sarcomas (solid tumors) in mice. These results have been so promising that treatment of human tumors with monoclonal antibodies made in mice but directed to sites on human tumors is in progress. At least one patient with lymphoma (a solid tumor of lymphocytes) apparently has been cured, and significant remissions have been noted in clinical trials with human melanoma (a fatal skin cancer) as well as colon and prostatic carcinomas. It is not yet known if monoclonal antibodies will have to be made for each individual tumor or if an antibody specific for a particular cancer type (i.e., melanoma) can be used to treat all patients afflicted with this disease. It is likely that the answer lies somewhere between these two extremes.

A major consideration in treatment with monoclonal antibodies is the choice of the species in which the antibodies are made. Even though mouse monoclonal antibodies have proved moderately effective in therapy of human tumors, the treatments are difficult to repeat in the same patient. The reason for this difficulty is that the mouse antibody is also perceived as foreign by the human host; as a result, human antibody is produced against the mouse antibody a few days after the first treatment. If human monoclonal antibodies were available, this side reaction would be minimized and multiple treatments would be possible.

Mouse Sarcoma Model

In my work on viral carcinogenesis at Scripps Clinic and Research Foundation in San Diego, it became clear that virus-induced tumors could be models for immunotherapy. I tried making antiserums that were "tumor specific," but I was always frustrated because of the mixture of antibodies I had to work with. Soon after I came to ORNL in 1976, hybridoma technology became available; consequently, the obvious solution to my problems was at hand. My colleagues and I now use the hybridoma approach for several purposes.

We have addressed the problem of cancer therapy in a model system using sarcomas in mice. In this work, we are following up on our recent success in preparing monoclonal antibodies that react specifically with several mouse lung carcinomas. Our progress in the area of solid tumors results largely from the excellent work by Trish Lankford and Linda Foote in my laboratory. By tricks of immunization, we can cause mice to become immune to normally lethal tumors (sarcomas). We have isolated monoclonal antibodies to the tumor cells from these immune mice. The hybridoma cells that produce the best antibody have been grown in mass culture to produce large amounts of the antibody. By using various doses of the antibody to treat mice having growing tumors, we have cured 20–30% of the animals at risk; the cure rate depends on the antibody dose delivered and the size of the tumor at the time of treatment. To date, this is the only model system in which therapy of a solid tumor has been effective and in which the antibody used was from the same species (strain of mice) in which the tumor grows.

This model system will help to answer two important questions: What is the mechanism by which the antibody helps to eliminate the tumor cells? What dose and treatment schedule are best when this type of antibody is used? A general conclusion is emerging from our studies and those of others: an antibody must interact with the host immune cell system to be effective. Even though monoclonal antibodies should be capable of killing tumor cells by themselves, they are not efficient in this function unless they are coupled with certain lymphoid cells from the host. Work is under way to identify the particular cell type involved and the exact mechanism of the interaction so that effective treatments can be designed predictably.

Although it is important to use basic information in designing treatment schedules, it is also useful to take an empirical approach. We have set up experiments to determine the optimal dose and schedule of monoclonal antibody therapy. It is already clear that trace amounts (micrograms) of an antibody are not effective against large tumors. On the other hand, doses as small as one milligram may be adequate. Our initial studies also indicate that dividing the total dosage into three or six individual treatments results in a more successful therapy. We have not yet tried continuous infusion of an antibody into the animals, although this approach should be feasible because of the availability of cheap, implanted "minipumps" for continuous release.

All of the dose rate studies described above are possible only because we have an antibody made in the same species of animal in which the tumor is growing. Current rapid progress in production of human monoclonal antibodies should promote treatment of this sort for cancer patients in the next few years. We hope that our model studies using animals will aid in the design of these treatment schedules for humans.

In the Future

As previously mentioned, the future of cancer treatment with monoclonal antibodies is extremely bright. Many new methods of diagnosis are also being developed. Several biotechnology companies are now devoting considerable effort to developing monoclonal antibody assays for detection of cancer. Three major companies that deal exclusively with monoclonal antibodies either have marketed or will market "cancer tests" this year.

Another major advance has been made in the field of tumor imaging. Antibodies can be tagged with different isotopes of radioactive iodine, or they can be covalently modified with metal chelates. These adaptations allow the investigator to incorporate the isotope of choice, that is, the one with the appropriate energy, path length, and half-life to give the desired result. Labeled antibodies that bind to tumor cells in the body can be detected easily by radiation counters. Thus, the sites of the tumor are determined and the extent of the disease is known. The antibody-imaging technique can help physicians to decide which therapy to use and to assess whether the therapy tried was successful.

Realistically, we cannot assume that monoclonal antibodies will cure all cancers. Interaction of the antibodies with the host immune system is so complex that our approaches will continue to be largely empirical. In cases where monoclonal antibody therapy is not successful, a combination therapy may work.

Monoclonal antibodies are proteins that contain many potentially reactive sites. Without destroying their binding properties, molecules can be covalently attached to antibodies. Because monoclonal antibodies bind specifically to tumor cells, they should be able to deliver attached molecules to these cells. If the molecules are cytotoxic (poisonous to cells), so-called "targeted chemotherapy," or the "magic bullet" approach, should be possible. Toxic agents such as diphtheria and cholera toxins, radioisotopes (alpha, beta, and gamma emitters), and standard chemotherapeutic drugs have been attached to monoclonal antibodies, which then direct their toxic effects to tumor cells. A benefit of such targeting is the reduction of the side effects of chemotherapy on normal body cells. We at ORNL and others are investigating this approach in "test tube" experiments; however, much work will have to be done before toxic congregates can be used in humans.

Certainly, treating of cancer with therapeutic agents such as drugs and radioisotopes as well as prepared antibodies to tumor cells is not a new idea. However, the recent development of techniques for making monoclonal antibodies promises to provide cancer patients with safer, less painful, and more effective treatments based on conventional approaches. Most importantly, monoclonal antibodies provide the basic science tools for designing even better treatments of the diseases collectively known as cancer.

BOOKS

Fusion: Science, Politics, and the Invention of a New Energy Source, *by Joan Lisa Bromberg, MIT Press, Cambridge, Mass., 1982, 256 pp + notes and index. Reviewed by Arthur H. Snell, consultant to ORNL's Physics Division and former director of ORNL's Thermonuclear (now Fusion Energy) Division.*

This book is the officially commissioned history of magnetic confinement plasma research in the United States. It is excellent.

The story starts in the early 1950s with the stellarator concept of Lyman Spitzer at Princeton, with Jim Tuck's work on the pinch effect at Los Alamos, and with Herbert York's sponsorship of magnetic mirror confinement at Livermore. The history, which covers a 25-year span through 1978, encompasses an enormous realm of theoretical and technological development. This work has led to an increased understanding of the elusive, slippery, delicate fourth state of matter, in this case a hydrogen plasma that must be suspended at a temperature of 100 million degrees in a vacuum by magnetic forces arranged so as to forestall its many modes of escape. [Inertial confinement by such techniques as laser compression of deuterium-tritium (D-T) pellets is designedly not covered in detail.]

Bromberg engagingly examines the many aspects of progress in fusion energy development, including technical achievements, problems of interlaboratory and international rivalries, instances of mutual assistance, and the fiscal and administrative implications of increasing budgets. She traces the overall shift of policy from independent laboratories to central coordination in Washington under the scrutiny of the inevitable review committees, and she examines the growing involvement of universities and industry. She gives less emphasis to the burst of activity in atomic physics; the increased skill in measuring plasma densities, temperatures, distributions, lifetimes, and impurities; and the developments in applied theory and modeling. Although substantial, these accomplishments would involve technical detail and would detract from the central story.

As an example of the international aspect of fusion research, consider the 1958 Atoms for Peace Conference in Geneva, Switzerland, to which Bromberg devotes two chapters. This was the occasion of the removal of secrecy from fusion research. Scientists at the U.S. Atomic Energy Commission (AEC) laboratories were acquainted with the British research, including their toroidal Zeta experiment, and we knew a little about other Western European efforts, but we were completely ignorant about Soviet accomplishments, although we knew the Russians to be active and expert in the field. Hence, a strong atmosphere of suspense prevailed among those technically involved.

Although the Americans did not know what the Russians were up to in fusion research, they were eager to outdo them at Geneva. Because the Russians had launched Sputnik during the previous autumn, the AEC Commissioners in Washington felt an acute need for the United States to regain some technological prestige, or at the very least not to take another licking if the Russians appeared with a new surprise. Thus, Geneva became the stage for a major U.S. exhibit.

The temporary building erected for exhibits was expanded into a "Geneva Spectacular" with 2,800 m^2 (30,000 ft^2) allotted for the U.S. program. Special power lines were run in, heavy exhibits were flown over the Atlantic Ocean, and teams of technical experts were sent to Geneva weeks ahead of the conference to get everything operating.

The hope of the AEC commissioners was to produce the neutrons of an actual fusing plasma on the floor of the exhibit, but that did not happen because it was indeed not that easy. Princeton exhibited a figure-8 stellarator; Los Alamos showed some working pinch devices; Livermore displayed magnetic mirror machines; and Oak Ridge had two operating models of the Direct Current Experiment (DCX), a device that used John Luce's concept of a hydrogen molecular ion beam injected transversely between two mirror coils so as to intersect a carbon or hydrogen arc running in the vacuum from one mirror to the other. Some of the molecular ions were dissociated in the arc, and the resulting atomic ions remained trapped in the magnetic field. The models were designed and operated by Ed Shipley and his colleagues, and the circle of trapped H^+ ions was beautifully displayed when tungsten dust was sprinkled from above to make a starry wreath visible through windows in the vacuum tank.

Against all of this activity, the Russians merely displayed some modest tabletop models, some made of wood. Thus, to the scientists, the exhibit appeared to be a vast overkill on the part of the United States, although this was by no means the case in the formal conference presentations. However, the AEC commissioners were pleased with the exhibit, which drew 100,000 visitors. Nevertheless, the lasting value of the conference lay in the acquaintances made and the information exchanged; controlling fusion became an international effort.

For the nonspecialist, Bromberg's book is quite readable. The topics inevitably involve jargon in the names of devices, in confinement and heating methods, and in the many types of instabilities that must be considered. However, Bromberg explains the concepts, sometimes with simple diagrams; therefore, if you don't know a magnetic well from a picket fence, don't be deterred. The book also contains many references to reports, minutes, and interviews that add to an unusually scholarly record.

Some concepts fade out, such as Astron and DCX, while others persist through the years in modified versions, and the most advanced move toward higher power, larger size, and greater expense. Always, the administration in Washington has to decide which of the major approaches to support at the expense of nascent schemes that might eventually be superior. The administration must also defend the program before Congress, which sometimes wants to see a path to commercial power that is more clearly defined than scientists can provide.

As plasma physics comes increasingly under control, engineering problems demand attention. Superconducting coils, radiation damage by the 14-MeV neutrons from the D-T reaction, confinement and removal of tritium from the lithium blanket, remote handling for maintenance and repair all require consideration. As a result, other laboratories enter the field, the budget increases from $2 million in 1954 to about $400 million in 1978, and the Washington staff expands from 3 in 1952 to 50 in 1975. Meanwhile, the growth in understanding plasmas is tremendous; the approach to "breakeven"—fusion power out equals heating power in—results in a 100,000-fold increase in the product of the ion density and the confinement time of the plasma. That critical but preliminary goal now seems to be in reach.

In Bromberg's book, the Oak Ridge story is related along with the stories of the other laboratories involved in fusion research. Several years after the start, ORNL entered the field in 1957-58. This was the time of Arthur Ruark, Ed Shipley, and others whose efforts centered on Luce's DCX. The hope was that the population of trapped atomic ions would build up, burn out the background gas, become random in particle directions and energy, and become sufficiently dense to allow one to turn off the original arc. With the discovery and increased understanding of microinstabilities, however, the scheme had to be abandoned in the 1960s, and ORNL lost its main program.

At this acutely critical time, Ray Dandl, Norm Lazar, and Gareth Guest suggested the injection-into-microwave-plasma (IMP) experiment in which Luce's vacuum arc was replaced by a hot-electron plasma of the kind later developed in Dandl's ELMO program. Because of the hot electrons, loss mechanisms of DCX would not be expected.

In 1969, however, national interest was aroused by the confirmed success of the Russian "tokamak"—a toroidal device in which the plasma is formed as the secondary current of an iron-core transformer. Having the power facilities for a tokamak experiment, ORNL scientists proposed ORMAK. We were scooped, though, by Princeton scientists who converted their Model C stellarator into a tokamak in a quick four months. Thus, although ORMAK was operating in 1971, Princeton became the nation's leading tokamak laboratory.

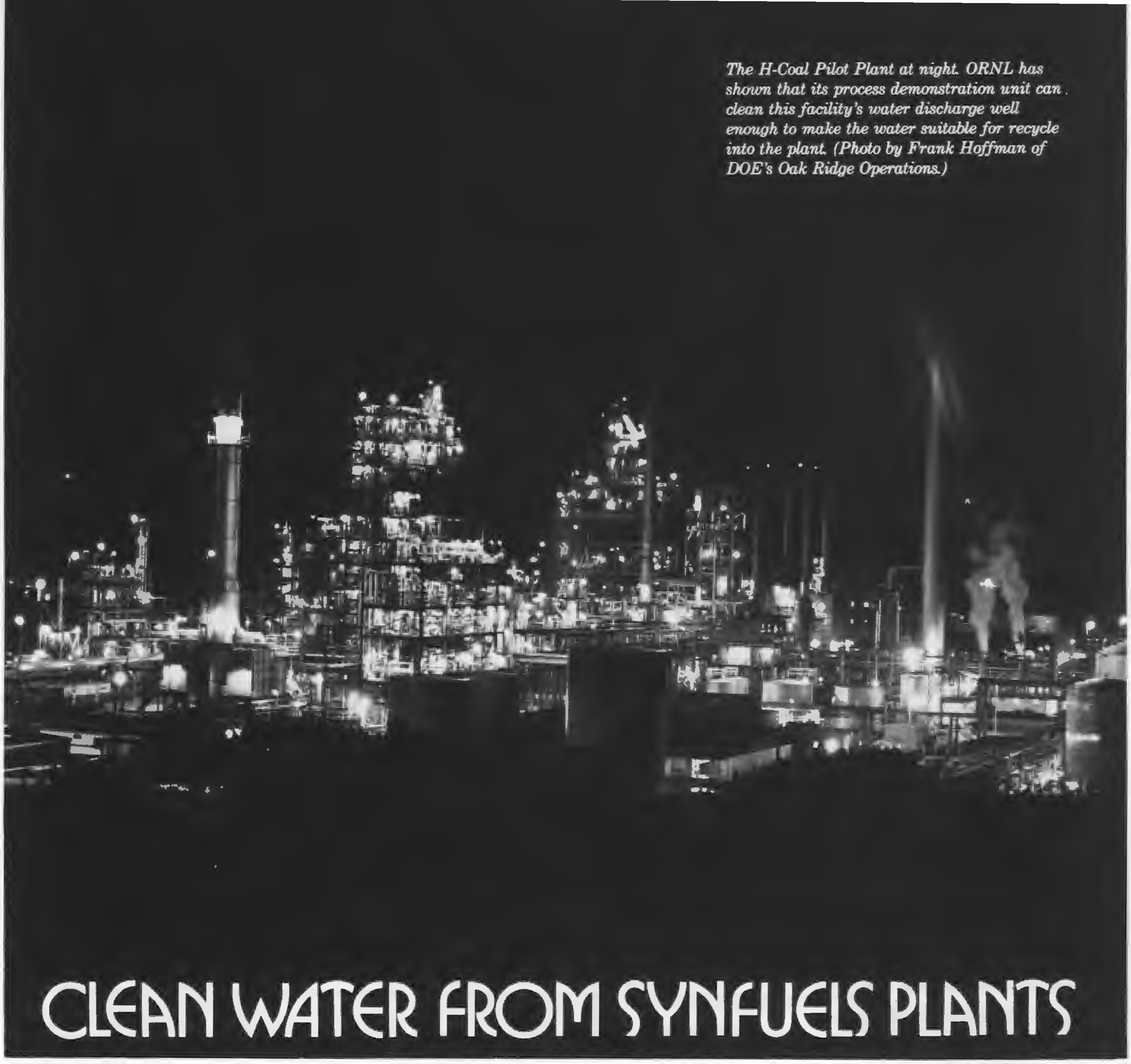
In 1978, ORNL made a substantial contribution to the task of heating the plasma in Princeton's next tokamak—the Princeton Large Torus (PLT). Bill Morgan and his colleagues developed four beams of 40-keV neutral deuterium atoms, which injected 2 MW of heating power into the PLT and (aided by Princeton's suppression of impurities) raised the plasma temperature from 10 million to 80 million degrees. Bromberg characterizes this feat as a "stunning success" because the hot plasma behaved much better than expected.

ORNL's first tokamak (ORMAK) graces the cover of Joan Lisa Bromberg's history of fusion energy, which is reviewed by Art Snell.

Meanwhile, Ray Dandl, Bill Ard, and their colleagues had been developing the ELMO concept. This first involved heating the electrons in a plasma between simple mirror coils and using electron cyclotron resonance with microwave power in the vacuum. Though modest, these experiments showed plasma stability. Dandl and Odell Eason contracted with the Hughes Aircraft Company for development of microwave tubes of increasing power and frequency so that the ELMO magnetic field could be raised into an appropriate range. Then came a crucial experiment in which they canted the mirror coils so that the coils were not parallel. Confinement was still adequate, thus indicating that additional canted coils could be installed so as to complete the doughnut and thereby avoid end losses through the mirror coils—hence, the ELMO Bumpy Torus. Valuable theoretical help was provided by Lew Hedrick and Gareth Guest, and the program became a recognized backup to Princeton's tokamak program and Livermore's tandem mirror program. Also, incidentally, the microwave power tubes found good use in other laboratories.

In the mirror program, ORNL made a major contribution that unfortunately is not specifically recognized by Bromberg. This advancement concerns the loss of plasma energy that moves axially through the mirror coils—a problem recognized when mirrors were first conceived. At one stage, the Livermore scientists had planned to make the best of the situation by collecting the associated electric power and putting it to use, a process that they called "direct conversion." In 1967, however, ORNL's George Kelley saw that the end loss could be much reduced if a subsidiary pair of mirrors were placed outside of each of the main mirror coils. This "tandem mirror" concept works through control of the plasma potentials in the outer regions that reduces the plasma loss from the main, central region. The Livermore researchers enlarged upon and refined Kelley's concept so that it reduced the end loss a hundredfold; it is now an essential feature of their current large tandem mirror experiment.

At the end of this history, Princeton's Tokamak Fusion Test Reactor and Livermore's Tandem Mirror Experiment are the big, leading experiments and the ELMO Bumpy Torus (EBT) is a close runnerup. Bromberg appropriately makes us aware of the unsolved engineering concerns and the economic uncertainties of the various schemes. Since the time of her writing, of course, there have been further developments: the EBT Proof of Principle Experiment has been apparently shelved; the reversed-field pinch has shown success at Los Alamos; the U.S. Department of Energy has approved major funds for the "torsatron" (a stellarator variant called the Advanced Toroidal Facility to be built at ORNL); and "spheromaks" (compact tori with attractive features) are under study at Princeton, Los Alamos, and the University of Maryland. Thus, the field remains dynamic, and the next two decades may be exciting indeed. When their history is written, let us hope that it is done with the same scholarship, thoroughness, and sensitivity shown in this book.



The H-Coal Pilot Plant at night. ORNL has shown that its process demonstration unit can clean this facility's water discharge well enough to make the water suitable for recycle into the plant. (Photo by Frank Hoffman of DOE's Oak Ridge Operations.)

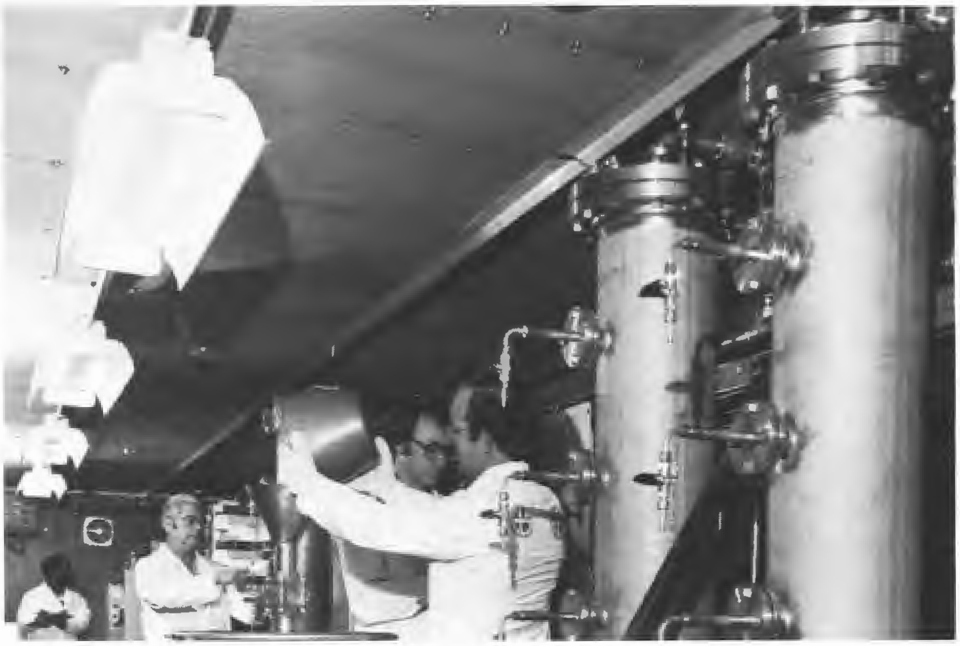
CLEAN WATER FROM SYNFUELS PLANTS

By CAROLYN KRAUSE

In coal conversion plants that operate on the principle of direct liquefaction by solvent dissolution, the feed coal is converted to liquid and gaseous products that can be used for chemical feedstocks and fuels. This conversion proceeds by contact of the coal with a process-derived solvent at high temperature and pressure in the presence of hydrogen gas. A by-product of the liquefaction process is water.

Hydrotreating coal in this manner generates wastewater, some of which comes from water present in the incoming coal (the water content of coal ranges from 1 to 45% as mined). In addition, oxygen present in the feed coal reacts with the process hydrogen to form water. A third source of wastewater in some processing schemes is water that is injected downstream of the liquefaction reactor to prevent the deposition of solids on heat-exchange surfaces.

As envisioned, commercial coal-conversion plants will also require large amounts of water to operate. Water is needed in the boilers that provide steam for the conversion process and in cooling water circuits that remove process heat. If suitably cleaned, the water produced in the conversion process could be used to replace the clean



Checking out the equipment in the process demonstration unit assembled at ORNL are, front to back, Cliff Brown, Joe Walker, Jack Rose, and Mike Harris.

water lost by evaporation in cooling towers. Complete recycle of the process-derived water—a condition known as "zero discharge"—could be particularly attractive in the arid western United States, where sources of water are becoming increasingly scarce.

However, there is a problem: water produced from coal is highly contaminated. It contains dissolved salts that can clog boiler tubes and decrease the efficiency of heat exchangers in cooling water circuits. It also has a high concentration of organic chemical contaminants. Unless treated, this water is unfit for process recycle or for legal discharge to streams.

At the H-Coal Plant in Catlettsburg, Kentucky, where Ashland Synthetic Fuels, Inc., has demonstrated one method for converting 181,000 kg (200 tons) of coal daily to synthetic crude oil, the water discharged from the coal-conversion process undergoes conventional secondary treatment. This water is clean enough to be discharged according to current U.S. Environmental Protection Agency standards. However, the water is not suitable for reuse in the plant and would not meet the stringent regulations for zero discharge or controlled release that are anticipated for synthetic fuel facilities in the 1990s.

ORNL's Cleanup Methods

Researchers in Oak Ridge National Laboratory's Chemical Technology Division have designed and built a mobile process development unit (PDU) to test three processes for cleaning up the H-Coal wastewater so that the water meets recycle and expected discharge criteria. The ORNL equipment also has been successfully tested on wastewater generated at the Advanced Coal Liquefaction Research and Development Facility (ACLF), formerly known as the Solvent Refined Coal (SRC-1) pilot plant, in Wilsonville, Alabama. This work has been done in support of ORNL's Life Sciences Synthetic Fuels Program and ORNL's Fossil Energy Program.

"The wastewater PDU that we developed," says Richard Genung, head of biotechnology and environmental programs in the Chemical Technology Division, "was designed to be mobile and to treat four liters (1 gallon) of real wastewater a minute under actual operating and process conditions."

The PDU was designed in late 1980 by former ORNL chemical engineer George Oswald as a transportable unit that is contained in two tractor-trailer vans. The PDU was installed at the H-Coal Plant in December 1981, and tests were run from February through September of 1982. "A two-week field test completed in June 1982," says Oswald, "showed that the processes in our PDU can provide effluents of desired quality."

In October 1982, the PDU was moved to the ACLF in Wilsonville. In February of this year, Cliff Brown headed a group that ran tests with the PDU during a three-week experimental campaign at the ACLF. The ORNL staff researchers who participated in operating the PDU and analyzing the results were Steve DeCicco (now with the U.S. Synthetic Fuels Corporation), Mike Harris, Jim Hewitt, Dick Roop, Jack Rose, and Joe Walker.

"The processes are not new," says Brown. "What is new is that we showed that these wastewater treatment processes could be applied to water discharged from coal-conversion facilities to make the water suitable for recycle or for discharge to meet the anticipated stringent regulations."

The PDU Processes

Secondary treatment of process-derived water removes most of the phenolic compounds, leaving only about 1–5 parts per million (ppm) of these toxic chemicals. The water, however, still contains 100–500 ppm of total organic carbon, including polycyclic aromatic hydrocarbons (PAHs). Dissolved

H-Coal Pilot Plant in Catlettsburg, Kentucky.

salts of calcium, magnesium, potassium, silica, and sodium are also left behind in the treated water. Also, the water still has trace metals such as aluminum, barium, iron, manganese, potassium, strontium, and zinc.

ORNL's three-pronged scheme for tertiary treatment of coal-contaminated water embraces various combinations of three processes: ozonation, adsorption onto activated carbon, and reverse osmosis.

Ozonation is used to remove total organic carbon, including PAHs, from contaminated water. The process employs ozone gas, a strong oxidant, which has been extensively used in Europe in the same manner that chlorine is used in the United States to disinfect drinking water. High concentrations of ozone can ultimately break down all organic compounds into water and carbon dioxide. Ozone, however, is expensive because the process of producing it requires a large amount of energy; the gas is produced by exposing oxygen to an electric discharge. Therefore, the ORNL researchers use just enough ozone to break down the ring structure of the aromatic compounds and decrease the chain length of nonaromatics, thus converting the compounds to simpler compounds. One scenario for incorporation of the ozonation process into wastewater treatment schemes is to recycle the ozonated wastewater to a biological treatment unit, such as an activated sludge unit, where the organic compounds (which previously resisted being digested by bacteria) can now be successfully degraded.

Like the ozonation system, the activated carbon unit in the PDU can be used to remove organic contaminants in the water. Activated carbon is produced by partial gasification of a substrate, such as coal, under carefully controlled conditions. The activation process produces particles that are very porous and thus have an extremely high surface area. Certain classes of organic molecules adhere to, or are adsorbed by, sites on the particles.

Water treated by reverse osmosis in ORNL's process demonstration unit (jar at right) is clearer than the untreated water (jar at left) from the coal conversion pilot plant at Wilsonville.

The combination of ozonation and activated carbon adsorption has raised at least two questions that the ORNL researchers would like to be able to answer. First, does ozonation prior to carbon adsorption improve the efficiency of the adsorption process in cleaning wastewater? Says Brown, "Ozonation may enhance the overall efficiency of the adsorption process. This is probably because of the presence of bacteria on the activated carbon particles rather than because of an actual increase in adsorption efficiency. The activity of the bacteria is increased by the presence of high levels of dissolved oxygen in the water as a result of the ozonation process. The rate of biological degradation of wastewater should in turn be increased by the presence of simpler molecules that result from ozonation of the wastewater."

The second question concerns the advantages and drawbacks of using carbon adsorption or ozonation for removal of residual organics. Because both processes can, in theory, reach the same end, the economics of the two competitive processes must be compared before it is clear which process is more

Advanced Coal Liquefaction R&D Facility (formerly SRC plant) in Wilsonville, Alabama.

desirable. The ORNL data will be helpful in making an economic comparison.

Reverse osmosis, the third process in the PDU, is used to remove dissolved solids, including trace metals, from the wastewater. In this process, a permeable membrane made of cellulose acetate or polyamide permits water, but not dissolved solids, to pass through to the other side. Pressure is used to overcome the natural osmotic pressure, which makes water "want" to go toward the dissolved solids side; thus, the water direction is reversed. Up to 80% of the water is recovered on the water-rich side, and a solution of highly concentrated salts is left on the other side. In this way, reverse osmosis filters out the salts and other ionic constituents, including more than 90% of many of the trace metals. In one mode of operation, the concentrated salts are then dried and disposed of as a solid waste.

Brown thinks that the three-process scheme could be particularly useful in the arid western United States, because large deposits of lignite, which is 45% water, are present in the West. "Plants built there for making synthetic fuels from lignite and even oil shale," he says, "could benefit from treatment schemes that would permit the recycling of process-derived water."

Results at Wilsonville

During the experimental campaign earlier this year at the ACLF in Wilsonville, ORNL researchers found that carbon adsorption was effective for removal of total organic carbon, about 65% of which was removed from the feed water. The color of the water was reduced substantially. After the ORNL chemical engineers passed the effluent treated by carbon adsorption through reverse osmosis, which was operated to recover 80% of the water fed to it, it was found that the reverse osmosis process had rejected 90% of the dissolved solids. This water treated by carbon adsorption and reverse osmosis contained only 5% of the total organic carbon and 7% of the dissolved solids originally present in the feed water.

The researchers ran a parallel series of experiments in which the ozonation unit was operated on the same feed water that was treated by the activated carbon unit. Under the given operating conditions, the main treatment effect noted was a significant reduction of the color-causing species in the wastewater.

Looking Ahead

ORNL would like to evaluate the cost-effectiveness of its wastewater treatment scheme but because of funding limitations, it has no plans to do so. However, sooner or later, it will become desirable to look at the economics of this combination of treatment processes. "Site-specific economic evaluations of this approach are needed," says Brown. "As engineers, we provide data that economists can use to figure out costs and benefits."

In the meantime, ORNL is planning to return the PDU to Oak Ridge, where it will be used with other ongoing waste treatment projects. One such project is the fluidized-bed bioreactor, which has been developed and improved over the past few years. Also, ORNL is seeking funding from the U.S. Department of Energy to build a portable unit that employs solvent extraction and wet-air oxidation, a process of burning organic material in water at high temperature and pressure in the presence of a catalyst. In the latter combination of techniques, the phenols extracted could be sold, thus making this approach more economical.

ORNL's goal in this work is to simultaneously meet synthetic fuel plants' requirements for large volumes of water and the public's need for a clean, safe environment. In essence, ORNL is looking for the best combinations of processes to "polish" treated wastewater so it is clean enough for use in or discharge from the synthetic fuels facilities of the future.

Home Sweet Home: How Clean Is Indoor Air?

People spend at least three-fourths of their time living and working indoors. Because of recent measures taken in buildings to save energy and money, concern has arisen about whether breathing indoor air is potentially hazardous to our health. Wood, kerosene, and gas stoves and other low-cost heating devices may spew out toxic fumes that can be trapped in well-insulated, weatherized buildings, which permit little exchange of indoor with outdoor air. Other pollutants that may be confined in tightened buildings are formaldehyde and radon.

The problem of indoor air pollution only now is being given some attention by scientists and governmental regulatory agencies. Previously, except for occupational protection, most of the regulations concerning air quality have focused on outdoor air. Recently, the Consumer Product Safety Commission and the U.S. Department of Energy asked Oak Ridge National Laboratory and others to collect data to determine whether pollutant levels in homes are exceeding the recommended maximum levels in the workplace.

Members of Dick Gammage's Instrumentation and Measurements Group in ORNL's Health and Safety Research Division have just completed a year-long study of indoor air pollutants in 40 homes in Oak Ridge and West Knoxville. This study represents an attempt to monitor the levels and fluctuations, over time, of a wide range of chemical pollutants in several different types of homes and to look for interrelationships between the levels of indoor pollutants and the types of housing, heating fuels used, geographical locations, consumer products in the homes, lifestyles of the occupants, and weather conditions. Field monitoring was conducted by University of Tennessee (UT) staff and students under a subcontract with the UT Chemistry Department. The final phase of the study was completed this past spring under the direction of ORNL researchers Alan Hawthorne and Charles Dudney, who analyzed the data.

The levels of nitrogen oxides, carbon monoxide, and other toxic gases emitted by combustion sources such as unvented space heaters, gas ranges, wood stoves, and fireplaces were monitored in 40 homes. These levels were compared with those in another group of homes without combustion sources. Also, during the winter months, integrating passive detectors were used in all 40 homes to measure the levels of radon—a radioactive gas that percolates into homes from underlying soil, water, and building stone. In addition, the project participants measured levels of formaldehyde, a carbon-hydrogen-oxygen (HCHO) compound, which emanates from urea-formaldehyde foam insulation and pressed-wood products such as particleboard in flooring and furniture, wood paneling, fiberboard, and plywood.

Based on the new data obtained during the winter—the heating months—and the results from the earlier studies, Hawthorne and his colleagues have found that the indoor air quality ceiling guideline for formaldehyde (0.1 parts per million) and the guideline for the average annual concentration for radon (3 picocuries/liter) in homes on reclaimed uranium-processing sites were exceeded on numerous occasions. Nitrogen oxide and carbon monoxide levels also rose above recommended levels for a short time in homes having certain types of combustion sources such as gas and wood stoves.

In houses fewer than five years old, the average level of formaldehyde was found to be 0.08 ppm—twice as high as the mean formaldehyde level of 0.04 ppm in older houses. The highest concentrations of formaldehyde tended to occur during hot and humid summer weather. The generation and release of formaldehyde from resins in structural materials, insulation, and furnishings are known to rise with increased temperature and humidity. In more than half of the houses measured monthly, on at least one occasion the concentration of formaldehyde in one or more rooms exceeded the indoor-air guideline of 0.1 ppm recommended by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers. In contrast, the mean monthly concentrations of formaldehyde outdoors were always less than 0.03 ppm. The highest concentrations of formaldehyde (up to 0.4 ppm) were observed in an energy-efficient house with a polyethylene vapor barrier in the floors and walls.

Tom Matthews uses a surface emission monitor that he developed to measure formaldehyde emissions from a specific source (such as decorative wall paneling) in a home.

Long-term measurements of radon during the winter season showed that the 3-pCi/L guideline was exceeded in one-third of the houses. The highest radon levels were found in houses built on permeable limestone ridges. Houses located on less permeable clay sediment in the valleys generally showed levels of radon close to the national average of 1 pCi/L. Hawthorne speculates that the porous limestone serves as a conduit for radon gas produced in underlying uranium-rich shale deposits.

Volatile hydrocarbons were measured routinely in the indoor air of all the houses and in several samples of outdoor air. The indoor levels of these organic compounds were frequently ten times as high as the outdoor levels or even higher. The ORNL measurements revealed that gasoline fumes were present in every room in the 40 houses and increased with approach to an attached garage or any other room having storage vessels containing gasoline or motor oil. Whenever a car was run in the garage, gasoline-containing exhaust fumes were usually drawn quickly into adjoining rooms. Cleaning, polishing, and painting introduced additional volatile organic compounds into room air. The identification, concentration, and persistence of most of these latter compounds have yet to be determined; however, ORNL researchers are conducting an investigation of organic compound concentrations and sources in homes to obtain this needed information.

The concentrations of gases emitted by combustion were generally low during the warm seasons of the year. Carbon monoxide and NO_x were less than 2 and 0.02 ppm, respectively, except at a few houses located near busy thoroughfares or where automobiles were operated inside attached garages. In winter the operation of unvented combustion devices (gas cooking stoves and kerosene space heaters) caused marked and transient increases in the levels of CO_x, NO_x, and particulates.

The rate of exchange between outdoor and indoor air in houses made tight as a result of energy conservation measures was found to be generally quite low. The mean value was 0.38 air changes per hour (ach). When the duct fan was operating in houses with central heating, ventilation and air-conditioning systems, the mean air exchange rate nearly doubled to 0.72 ach. Leaks in the duct system exterior to the living space are most likely responsible for this effect, but more research is needed to determine if operating duct fans reduces potential health effects.

According to Dudney, "This large study of indoor air quality in 40 Oak Ridge homes is merely an early effort to understand a complex phenomenon. The air quality inside our homes depends strongly on what we do to our homes and how we live inside them. Studies such as this one provide technical data concerning the relationships between occupants' activities and indoor air quality. As data are developed and evaluated, information will become available to guide building occupants who are concerned about indoor air pollution in selecting the safest indoor combustion devices, techniques of weatherization, ventilation systems, furniture, and building materials." Such enlightened choices should reduce potential health effects and make "home sweet home" sweet again.

Stephanie Morris samples formaldehyde vapor with a passive monitor to determine one facet of indoor air quality over a 24-h period.

Neutron Dosimeters: Which Type Works Best

Neutrons are a relatively common type of radiation to which people can be exposed. The determination of how much radiation is absorbed by people is called dosimetry. Neutron dosimetry is needed in facilities involved with certain types of accelerators, fusion experiments, medical radiotherapy, nuclear medicine, nuclear energy research, nuclear power generation, and radiation instrument calibration.

In these facilities the energy of the neutrons varies by a factor of more than 10^9. Because neutrons of different energies interact with materials in different ways, this large energy range makes neutron dosimetry particularly difficult. This difficulty is further compounded because very low and very high doses and dose rates must be measured. Also, regulatory agencies—such as the Nuclear Regulatory Commission—say that each neutron dosimeter should be accurate to within 50% to provide information adequate to ensure the health and safety of the wearer. The problem, then, is to find and use the neutron dosimeter that can determine the wearer's exposure to within 50% of the actual dose.

Many types of neutron dosimeters are commercially available, and many others are in-house designs made especially for use at particular institutions. These include film, thermoluminescent, and track etch dosimeters. Which types of dosimeters are best suited for the various applications? To help dosimeter users find out, Steve Sims, Dick Swaja, and Rick Greene of ORNL's Health and Safety Research Division are conducting two annual neutron dosimetry intercomparison studies. Routine low-dose occupational exposures are simulated in one study, and high-dose accident exposures are simulated in the other one.

Both studies are conducted using ORNL's Health Physics Research Reactor (HPRR). This unique research tool is perfectly suited for this application because its neutron fields are well known, it can deliver neutrons at dose rates that differ by a factor of 10^{15}, and it permits the positioning of a variety of shield types near it to allow simulation of different environments encountered throughout the nuclear industry.

In general, these intercomparison studies have shown that about one-half of the 4500 neutron dosimeters tested meet the existing regulatory requirements. The ORNL studies have also demonstrated that no single type of neutron dosimeter is adequate for the variety of applications found in the nuclear industry. To obtain accurate measurements, the user must select a type of neutron dosimeter that performs adequately for the neutron energy distribution and the dose rates expected to be encountered in the user's particular application. The results of these studies allow the participants to select the neutron dosimeter most appropriate for their use.

Over the years, these studies have attracted more than 100 different organizations including about three dozen from outside the United States. Several organizations participate in at least one of the two studies every year. More than 60 organizations were involved with the intercomparison studies performed in 1982.

The studies at ORNL not only allow the dosimeter users to test and compare their dosimeters with those of other users under a variety of conditions but also give the users an opportunity to attend lectures and demonstrations by dosimetry experts and to participate in group discussions concerning their dosimetry problems and the latest solutions offered by researchers. In short, the dosimeter user can learn how his or her dosimeter performs, how other types perform, and how experts view his or her dosimeter.

"These studies," says Sims, "are important technology-transfer activities and are expected to continue annually as long as interest in them remains high."

Surfaces and Defects

The size and shape of two types of atomic rearrangements on an artificially stepped tungsten surface have been ascertained for the first time at ORNL using low-energy electron diffraction (LEED). Successful use of the LEED technique in deriving quantitative information on surface structure has applications to measuring and characterizing surface changes in semiconductor materials in electronic devices.

The LEED study was done by Gwo-Ching Wang, an experimentalist in ORNL's Solid State Division, in collaboration with her husband, T. -M. Lu, a theorist at the University of Wisconsin. She set out to determine the validity of the prevalent belief about the effect of artificial defects on a surface atomic structure during a phase transition—as when the temperature is altered.

Surface atoms in tungsten, chromium, and molybdenum rearrange themselves when the crystal is cooled below room temperature. As a result, the surface structure differs from the atomic structure in the crystal's bulk. It has been thought, however, that the rearrangement would be generally inhibited if defects were introduced by polishing or etching the surface or slicing the surface at a very small angle.

To test this predictive model, Wang prepared a tungsten surface by cutting it at an angle of 3.5°. This process created steps, each of which had a depth of only one atomic layer. The distance between one step edge and the next—called the terrace width—was about 28 Å. According to the model, the surface layers of atoms over a width of 20 Å would not be rearranged because of the presence of the artificial steps. Thus, the steps would have a long-range inhibition effect on atomic rearrangement on the crystal face.

Wang's LEED studies showed that the long-range inhibition effect does not hold true for a stepped tungsten surface that is cooled below room temperature. To get a LEED pattern, Wang used an electron gun which bombarded the crystalline tungsten with a well-collimated beam of electrons. Some of the electrons striking the surface atoms are elastically backscattered to a phosphorescent screen where they trigger the emission of a symmetrical pattern of light when diffraction has occurred. This pattern is a direct indication of the geometrical arrangement of atoms in a unit mesh in the surface layer of the material.

The LEED pattern obtained on a stepped tungsten surface by Wang revealed that a rearrangement of surface atoms had occurred. The pattern had extra spots, thus indicating that one of every four atoms at the top corners of a cubical atomic structure had moved sideways; consequently, all the surface atoms that exhibit lateral and diagonal movement formed a zigzag pattern, a model developed by British scientists M. K. Debe and D. A. King. Because the extra spots in the LEED pattern had different intensities as well as shapes as determined by a detector, Wang was able to measure the size and shape of regions on the crystal face in which either of two types of rearranged atomic structure predominated.

Both atomic structures had zigzag patterns formed by the displaced atoms, but the zigzag chain of atoms in one type was perpendicular to the step edges, whereas the chain of displaced surface atoms in the other dominant type was parallel to the step edges (90° rotational difference). Focusing on a step with a terrace width of 28 Å, Wang measured the region, or domain, of one type of rearranged atomic structure to be a rectangular 22 by 50 Å, while the other type covered an area 22 by 22 Å. Thus, the presence of steps inhibited atomic rearrangement only over the short range (6 to 8 Å rather than 20 Å as had been predicted). Furthermore, reconstruction occurred within a distance much closer to the step edges than was previously observed on some stepped semiconductor surfaces.

In another experiment, Wang studied a molybdenum-rhenium alloy in which rhenium atoms randomly substitute for 5% of the molybdenum atoms in the crystal. She cooled the crystal and examined LEED patterns to determine the effects on the surface atoms. She found no evidence of surface reconstruction, indicating that rhenium inhibits atomic rearrangement.

"Our studies," says Wang, "show that the zigzag model is valid, that the model predicting that defects such as steps should have a long-range inhibition effect on surface atomic rearrangement is invalid, that artificially introduced point impurities do have an inhibiting effect, and that LEED can be used not only to obtain qualitative information but also to quantitatively pin down the range of inhibition and preferred atomic movement on surfaces in phase transitions." ornl

Paul Kasten has been director of ORNL's Gas-Cooled Reactor Programs since 1970. He has been an ORNL staff member since 1950 when he received his Ph.D. degree in chemical engineering from the University of Minnesota. In his first 15 years at ORNL, he worked in the fields of reactor physics, analysis, and evaluation. In 1963–1964 he served as guest director of the Institute for Reactor Development at the Nuclear Research Center in Jülich, Federal Republic of Germany (FRG). In 1964 he was an FRG delegate to the Third International Conference on the Peaceful Uses of Atomic Energy held at Geneva, Switzerland. In 1967 he visited India as a member of a U.S. Reactor Evaluation Team. In 1968 he was a U.S. delegate to the International Atomic Energy Agency thorium conference in Vienna, Austria. From 1965 to 1970 he was associate director of ORNL's Molten-Salt Reactor Program. For 17 years he taught graduate courses in chemical and nuclear engineering at the University of Tennessee, where he was a Ford Foundation Professor of Nuclear Engineering from 1965 to 1970. This is Kasten's second article for the *Review*. His first article, "The Interesting Fuel for the HTGR," appeared in the Fall 1973 issue. In that article he summarized ORNL's development of techniques for reprocessing spent HTGR fuel elements and fabricating new fuel elements for recycle. In this article he examines why the HTGR concept has stayed alive even though it has not been commercialized. Here, Kasten, left, and Phil Rittenhouse discuss the technology development plan that ORNL has worked on with GA Technologies, Inc.

The Staying Power of the High Temperature Gas-Cooled Reactor

By PAUL KASTEN

For the past five years, the U.S. Department of Energy's high-temperature gas-cooled reactor (HTGR) has faced extinction. Each year the president has not budgeted any money for the program, but fortunately, Congress has provided funds annually to keep the program alive. The president's budget for fiscal year 1984 again contains a zero for the HTGR program, which sponsors the work of about 40 technical staff members at Oak Ridge National Laboratory. Nevertheless, based on past experience, we remain confident that Congress will again save the endangered HTGR program.

Although the HTGR program lacks the support of the administration and only one commercial HTGR is operating in the United States, the HTGR program has nevertheless survived primarily because, despite the problems plaguing nuclear energy, interest in the concept continues to be strong. Because of the 1979 loss-of-coolant accident at Three Mile Island, rising capital costs, and excess power generation capacity, the nuclear industry is in the doldrums. Even so, developing and commercializing the HTGR appears worth pursuing because it is a very safe, high-efficiency reactor with attractive siting features that permit broader applications of nuclear energy.

HTGR Features

The HTGR is a versatile power reactor with a variety of attractive features that make it particularly efficient and safe. It is a thermal reactor that uses graphite as a moderator and helium gas as the coolant. Because graphite has the unusual property of becoming stronger with increasing temperature and because helium is chemically inert, the HTGR may be operated at very high temperatures. Thus, because superheated steam can be produced to spin turbines to generate electrical power, the power generation efficiency of an HTGR is 38–39%—in other words, up to 39% of the nuclear energy is converted to electricity. By contrast, the power generation efficiency of a light-water reactor (LWR) is about 34–35%. Because of the HTGR's capability of attaining high temperatures, it can be applied to fossil fuel conversion processes for producing chemicals such as hydrogen, ammonia, and methanol and for converting coal to liquid and gaseous fuels.

Another feature of the HTGR is that the high-temperature helium leaving the reactor core can be used to power a gas turbine. The gas turbine-HTGR system is particularly attractive for generating electricity in arid regions, such as certain portions of the western United States where water is so scarce that dry cooling towers are needed.

Because of the special properties of graphite, helium, and the fuel used and because of the low power density of the core, the HTGR is inherently a very safe reactor. In particular, it has a high heat capacity—that is, a capacity to absorb excess heat in a loss-of-coolant accident, thus preventing a rapid rise in the fuel temperature and allowing several hours in which to take corrective action without core damage. In addition to its large inertia in system response under accident conditions, the HTGR's other safety features result because helium does not change phase, react with reactor material, or decompose under irradiation. All these features are particularly important if new markets for nuclear power are to be achieved.

Because of its physics characteristics, the HTGR economically employs a thorium-uranium cycle—that is, the neutrons produced by the fissioning fuel (initially uranium-235) can be efficiently used to convert thorium-232 to fissionable uranium-233. This fuel cycle is more economical for the HTGR than is the uranium-plutonium cycle used in LWRs. The higher fuel conversion ratio that results is one reason for the early interest in the HTGR. Also, because it produces uranium-233, which is not found in nature, the HTGR can extend our nation's supply of fissionable uranium fuel.

ORNL and HTGRs

The commercial high-temperature gas-cooled reactor (HTGR) that is operating near Denver, Colorado, is a product of years of development by GA Technologies, Inc. (formerly General Atomic), with important contributions from ORNL. The Fort St. Vrain Reactor uses a coated particle fuel that is designed to retain fission products; the fuel kernels are coated with layers of pyrolytic carbon and silicon carbide and then dispersed in a carbonaceous matrix to form fuel rods. ORNL played a key role in the development and testing of that fuel. ORNL also contributed to the design of the prestressed concrete vessel for the FSVR and has worked in many other technical areas with GA to develop the HTGR into a safe, efficient power reactor.

The HTGR program at ORNL began in 1959 as part of ORNL's Gas-Cooled Reactor Program, which at that time emphasized development of the Experimental Gas-Cooled Reactor, a project that was terminated in 1966. The early HTGR work emphasized development of coated particle fuels, reactor physics evaluations, and assessment of a pebble-bed reactor design developed by the Sanderson and Porter Company.

During the early 1960s, international exchanges in HTGR technology were instituted and have continued. In 1966 the reactor physics efforts were reoriented to participation with GA in the Peach Bottom HTGR startup program. After the Peach Bottom reactor started power operation in 1967, ORNL researchers participated in surveillance and analysis of the circulating radioactivity in the coolant circuit. In the mid-1960s, ORNL's work included evaluation of the design and fuel cycle performance of large HTGRs, the development of prestressed-concrete reactor vessels (PCRVs), the development of fueled graphite, studies of fission product behavior, and materials

The Early Years

Considering the nation's need for energy efficiency and fuel conservation and concerns about reactor safety, the HTGR appears to be an attractive concept. Why, then, isn't it commercialized? The answer lies in the effects of economic and political events on nuclear power growth in the past ten years. Before then, the HTGR studies (graphite and metals). In the 1970s HTGR research at ORNL expanded to include experimental studies in fuel recycle which involved reprocessing of spent fuel and fabrication of new fuel using the uranium-233 separated from irradiated thorium. In addition, HTGR safety studies were initiated.

Currently, ORNL is testing fuel behavior for the next generation of HTGRs; the reference fuel is a fuel kernel that differs from that in the Fort St. Vrain Reactor in that the reference fuel has improved high-temperature properties. We are providing detailed statistical information on the fission-product-retention performance of irradiated fuel. ORNL studies also are providing basic data on the mechanical, physical, and chemical behavior of HTGR materials, including metals, ceramics, graphite, and concrete. ORNL has an important role in the development of improved HTGR graphites and in the specification of criteria that need to be met by commercial products. We are also developing improved reactor physics design methods.

ORNL's work in component development and testing centers upon the Component Flow Test Loop (CFTL), which is being used to evaluate the performance of the HTGR core support structure. Other work includes experimental evaluation of the shielding effectiveness of the lower portions of an HTGR core; this evaluation is being done at ORNL's Tower Shielding Facility. ORNL researchers are developing welding techniques for cladding steam generator tubesheets and for attaching tubing to the tube sheets and are testing ceramic pads on which the core posts rest. In addition, ORNL researchers are performing extensive testing of concrete materials obtained from potential HTGR site areas that could be used in PCRVs.

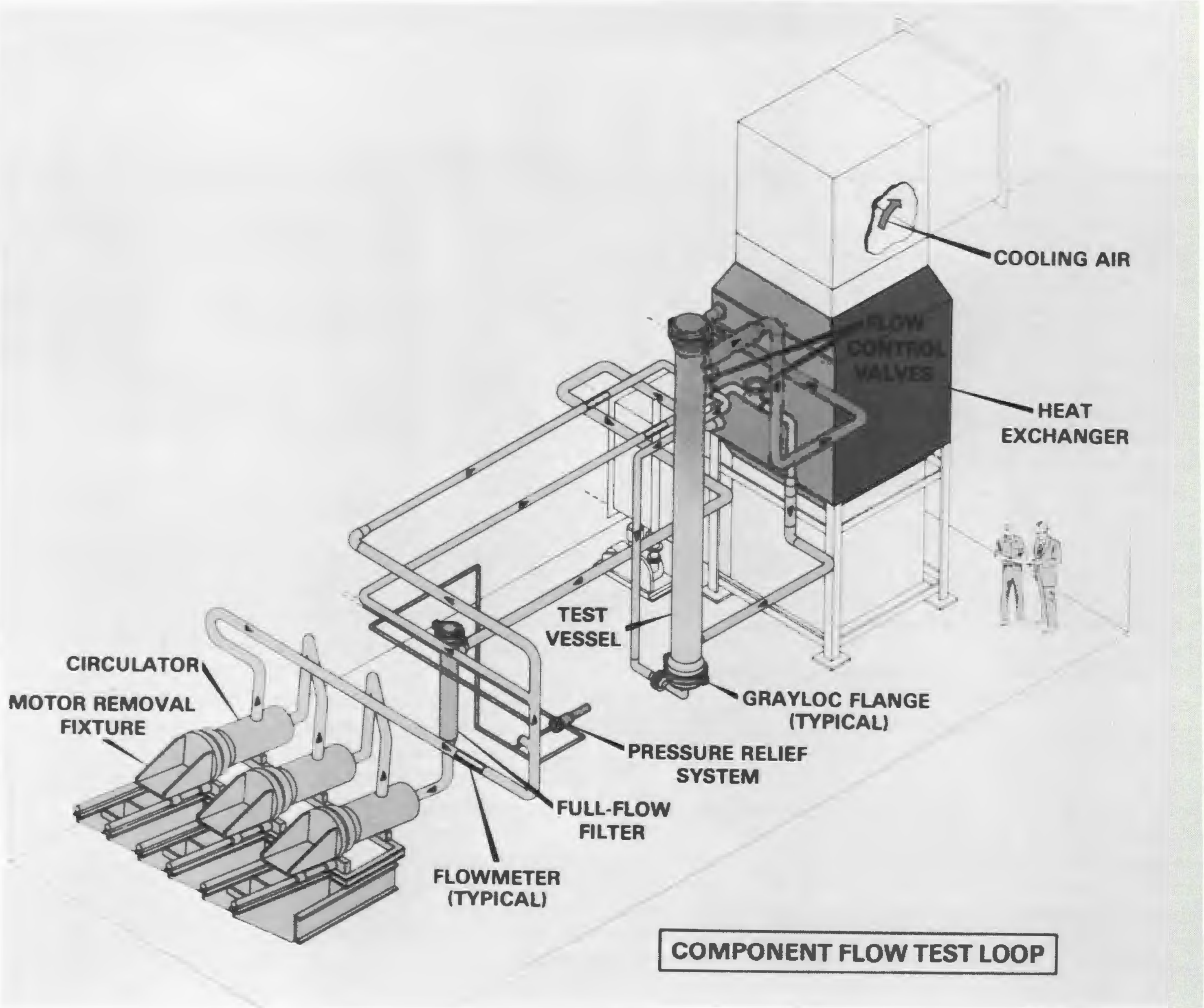
Tom Wynn at the Component Flow Test Loop.

ORNL is serving as a peer reviewer of small, modular reactor designs being developed by GA and General Electric Company. We are evaluating the national need for developing HTGRs, with emphasis on the longer-term applications to fossil conversion processes. The ORNL program continues to provide technical expertise to the national program.

The HTGR program remains alive at ORNL because the reactor is a safe, efficient source of nuclear process heat and electricity. Even though the U.S. nuclear power industry currently faces political and economic problems, few political leaders are willing to give up a potentially important source of energy such as the HTGR.—P.K.

concept appeared to have an especially promising future.

A crude version of the HTGR was first conceived by Farrington Daniels at ORNL in 1947. However, the present version of the HTGR was conceived by Peter Fortesque in 1954 and subsequently developed by General Atomic (GA) in the United States and by the United Kingdom Atomic Energy Authority in Great Britain. (GA, which is located in La Jolla, California, is now called GA Technologies, Inc.) In the 1950s and 1960s, work on thermal reactor alternatives to LWRs focused on systems with improved fuel conversion ratios; these systems are known as "advanced converters." Efficient electricity production was emphasized; nuclear reactor safety, proliferation concerns, and actual commercial risks were concerns—but not issues—at that time. Being an advanced converter having a high thermal efficiency, the HTGR appeared economically feasible based on the evaluations carried out in the 1960s. The original motivation for developing an advanced converter reactor stemmed from a rapid growth in LWR use, limited availability of low-cost uranium, and inability to rapidly introduce fast-breeder reactors (FBRs)



Schematic of the Component Flow Test Loop, which tests how well HTGR components perform under normal and emergency operating conditions.

into the economy. This scenario suggested that the efficient use of uranium provided by advanced converters would be needed in the 1980s and 1990s prior to the anticipated commercialization of FBRs. Advanced converters, including HTGRs, were expected to fill this time gap, or "window."

However, by the end of the 1960s, the U.S. Atomic Energy Commission (AEC) shifted its emphasis almost exclusively to the development of FBRs because of the perception that the window between excessive buildup of LWRs and commercial introduction of FBRs would close. Thus, the advanced converter was no longer needed, and this new perception prompted the AEC to deemphasize development of advanced converters.

Nevertheless, the HTGR concept remained alive because GA continued to support it strongly and because electric utilities showed strong interest in the future use of HTGRs, both as steam-cycle and gas-turbine systems. As a result, the AEC continued to support the HTGR concept—although at a relatively low level.

Several experimental HTGRs built and operated in the 1960s showed that the concept is technically feasible. The first experimental HTGR was the DRAGON reactor, which was built in England under the European

Herb McCoy of the Metals and Ceramics Division examines a printout that states the impurity levels in helium and the thermal and mechanical loads on various metal specimens located in test frames along the wall. Specimens of nickel-based and other alloys of steel are subjected to mechanical stresses in a helium environment and to high temperatures. Researchers also measure the extent of corrosion and carburization (formation of metal carbides) that results from interaction of helium impurities with the metal specimens. These impurities include carbon monoxide, carbon dioxide, methane, water vapor, and hydrogen.

Organization for Economic Cooperation and Development (OECD). The DRAGON reactor, which operated from 1964 to 1976, generated 20 MW(t) (no electrical generator was installed). The Arbeitsgemeinschaft Versuchs-Reaktor (AVR), which was built in the Federal Republic of Germany (FRG), has been operating since 1967. The 15-MW(e) AVR has operated with an outlet coolant temperature of 950°C, which is higher than the 700°C outlet temperature needed for conventional steam cycle HTGRs. In the United States, the 40-MW(e) Peach Bottom HTGR was built near Philadelphia, Pennsylvania, and was operated from 1967 to 1974. All these reactor experiments demonstrated that HTGR technology is practical, but the experimental reactors lacked the large-scale components needed to demonstrate commercial viability.

By 1974 GA had built the first commercial HTGR—the 330-MW(e) Fort St. Vrain Reactor (FSVR) near Denver, Colorado. The FSVR, which was built for a utility, the Public Service Company of Colorado, has operated since then with various degrees of success. The problems that have arisen have not been attributed to any defects in the HTGR concept. Most of the problems have been resolved, and the FSVR is now licensed to operate at 100% power. The FSVR has demonstrated several important features, such as extremely low radiation exposure to maintenance workers, excellent fuel performance, good steam-generator experience, very low levels of circulating radioactivity, and excellent safety characteristics.

Another HTGR power station is under construction in the FRG. This reactor is patterned after the AVR and uses pebble-bed fuel. Initial operation of this 300-MW(e) reactor is expected in 1984.

Events of the 1970s

Economic events of the 1970s had an adverse impact on the HTGR's potential for commercialization in the United States. The series of cost increases in oil that began in 1973 combined with other events to produce runaway inflation and high interest rates, thus eventually causing a worldwide economic recession. Consequently, the capital costs for power plants increased as did energy costs in general, thereby resulting in increased energy conservation and less growth in demand for electricity than the utilities expected. Because of the decrease in projected growth in electrical generation requirements, utilities quickly stopped ordering new power plants; in fact, since 1975 there have been virtually no new orders for nuclear power stations (there was one order in 1978). Thus, it is not surprising that the HTGR was never commercialized.

In the early 1970s, GA offered HTGRs commercially and signed contracts with several utilities for a total of ten units ranging in power level from 770 to 1170 MW(e). However, during 1974–1975, after the initial large increase in the cost of imported oil and the slowdown in the U.S. economy, six of the ten HTGR orders were cancelled. As a result of these events, compounded by the uncertainty in licensing requirements, GA concluded that the front-end costs for completing the remaining orders involved too large a financial risk and withdrew from the commercial HTGR market.

Other events in the late 1970s influenced nuclear energy. In 1977 the federal government responded to proliferation concerns by delaying the use of fuel reprocessing and construction of FBRs—mainly the Clinch River Breeder Reactor, which was originally scheduled to begin operating by 1980 but which still has not been built. The government also placed more emphasis on "once-through" fuel cycles in the LWRs and the storage of spent fuel. Both increases in the estimated reserves of economically recoverable uranium ore and lowered expectations of nuclear power growth suggested that reprocessing and FBRs were not needed in the near future. The increases in estimated capital costs of FBRs as well as LWRs delayed the time at which FBRs could be commercialized.

The Tower Shielding Facility, where a radiation shielding experiment will be conducted for the DOE program to develop high-temperature gas-cooled reactors.

Given the previous factors, it might have been expected that development of an advanced converter such as the HTGR would gain more support because, after all, these circumstances once again created a window. However, advanced converters were not aggressively supported because of the following factors: (1) efficient fuel use requires the recycling of fuel produced in advanced converters, an impossibility because fuel reprocessing was forbidden at the time; (2) the stoppage in LWR orders spawned the philosophy that "if we can't sell LWRs, why do we need to develop anything else?"; and (3) the expectation of a reduced market for nuclear power plants and larger estimates of natural uranium resources combined to suggest that the best decision was to stick with the status quo.

However, studies performed in the late 1970s suggested a possible new role for advanced converters. If operated in tandem with FBRs designed to breed uranium-233 in blanket regions for use in fueling thermal converter reactors ("symbiosis" fueling), advanced converters could significantly reduce the number of FBRs that are needed in the long term. This new role gives long-term importance to the advanced converters, thereby extending their use beyond the window time frame. Such tandem use of reactors has two advantages: it gives more flexibility in reactor choice, and it improves reactor economics if the long-term capital costs of FBRs are indeed higher than those of thermal reactors, as is currently estimated. These advantages of tandem use of the HTGR and FBR have not yet had an impact on reactor development. The reasons for this delay include the uncertainty in the outlook for the FBR and the events at Three Mile Island. The TMI-2 reactor accident evoked a new recognition of commercial risks, raised concerns about reactor safety and licensing requirements, and forced utilities to backfit LWR plants with expensive equipment to make the plants safer. The resulting increased costs of LWRs, concerns about changing licensing requirements, and the expectations of much lower demand for power led to additional cancellations of LWRs previously ordered by utilities. Currently, all commercial reactor development in the United States is at a standstill.

New HTGR Perspective

The large increase in the cost of imported oil over the past ten years has given a new perspective on the importance of HTGRs. The high cost of oil, followed by increases in the costs of natural gas and coal, has highlighted the need to save our limited fossil fuels for essential uses such as transportation and production of chemicals. Nuclear energy to date has been used primarily to generate electricity, thus conserving some fossil fuels that could have been consumed for this purpose. Nevertheless, the savings are small compared to the total amount of fossil fuels used to generate energy.

Only about one-third of the energy consumed in the United States last year was used to generate electricity. Furthermore, while the potential to displace oil and gas in the electrical sector with nuclear energy is still significant and important to accomplish, a greater potential exists for oil and gas displacement in the industrial and commercial sectors. (The ability for nuclear energy to displace conventional transportation fuels is not anticipated for many decades, although it could have a major impact if electrical automobiles were to become commonplace or if methanol were predominantly used as fuel.) Because of its high core-exit coolant temperature, the HTGR has the ability to supply nuclear process heat, although LWRs can also supply process steam in certain locations and applications. The nuclear process heat capability of the HTGR is particularly suitable for those applications where high-pressure steam is needed either for the industrial process or for steam transport and for application to fossil fuel conversion processes. These latter applications are anticipated to be needed extensively starting in 2000–2010. Some of these processes can use steam from a steam-cycle HTGR, while others will need a special type of HTGR called a very high temperature reactor (VHTR), which has exit coolant temperatures of up to 950°C, as in the AVR. The VHTR is of interest for the steam reforming of natural gas for production of methanol, hydrogen, or ammonia and for selected processes used in the conversion of oil shale and coal to fuel oils and gases.

While the recent glut of oil has eased oil-import problems, oil shortages are anticipated for the 1990s. Efforts are needed now to develop the HTGR for process heat applications in a timely fashion. Such applications will require new developmental work and an expanding economy—that is, new industry. Because of the excellent safety features of the HTGR, this type of reactor is well suited for siting close to industries, which are usually located in populous areas. The long-term benefits of using HTGRs for generating industrial process heat will be to reduce the environmental impact of producing industrial energy, to reduce oil and gas consumption, and to significantly improve our long-term economic well-being by diverting fossil fuels from process heat generation to the production of transportation fuels and chemicals.

Although not given much emphasis now, utilities have long been intrigued with the gas turbine-HTGR

Jim Hull, Dan Ingersoll, and F. J. (Buzz) Muckenthaler (left to right) check out the construction of the upper boron pin layer of the mock-up of a lower reactor core assembly. The mock-up will be used for a radiation shielding experiment to test the shielding effectiveness of this configuration and to collect data on neutron streaming in coolant holes.

system, which incorporates a helium turbine within the coolant circuit for the generation of electricity. Because the gas turbine discharges helium at relatively high temperature and because the recycled helium coolant requires little cooling, the gas turbine-HTGR system is particularly suited for dry cooling towers, an attractive idea in arid locations. Alternatively, the relatively high-temperature coolant discharge could be a heat source for district heating or desalination of salt water. In locations having adequate cooling water, gas turbine-HTGR systems can achieve very high thermal efficiencies (45-50%) by using both vapor and gas cycles. For high efficiencies, outlet coolant temperatures of up to 950°C would be appropriate; therefore, gas turbine-HTGR applications would logically follow development of VHTRs.

Outlook for the HTGR

The HTGR has come into favor at different times for different reasons, thus showing the versatility of the reactor. All reasons for supporting the concept are still valid—(1) an advanced converter is needed both before and immediately after FBR introduction, (2) nuclear process heat is a needed application of national importance for both cogeneration and fossil conversion processes after the 1990s, and (3) gas turbine-HTGR systems with dry cooling towers will be needed when power plants are sited in arid regions.

One overriding question mark is the capital cost of HTGRs. Insufficient experience exists today to determine the costs accurately. Detailed estimates made through the years indicate that HTGRs are competitive with LWRs, although concern still exists about what the actual costs will be. Because recent licensing changes resulting from the TMI-2 accident have not had any significant impact on the FSVR, HTGRs might be gaining on LWRs. However, capital costs will have to decrease for all nuclear plants if nuclear reactors are to compete economically with each other and with other types of power plants. It is important to decrease construction time for all nuclear plants.

Recently, studies have been performed on modular HTGRs. These systems would have power levels in the range of 200-300 MW(t) and would consist of several units, or modules, built at a given site. Because of their smaller sizes and their low core-power densities, modular HTGRs promise to retain fission products within the fuel coatings even under complete loss of coolant pressure and flow—an additional safety feature. Furthermore, the use of several units at a site would improve plant availability and possibly ease cash-flow requirements. It is not clear whether such modular HTGRs could compete economically with large HTGRs. However, studies of modular HTGRs and their economic feasibility are continuing.

Who Is Involved?

The national HTGR program has been supported by DOE at about $40 million per year for the last several years; continuation of this level of support is anticipated for next year. The major participants in the program are GA, which performs the major share of the design and technology development and still intends to be the HTGR vendor; Gas-Cooled Reactor Associates (GCRA), an organization sponsored by more than 30 utilities, which gives utility focus to the program and serves as the program coordinator; ORNL, which provides strong support to the technology development effort and serves as a technical reviewer; General Electric Company, which provides design and engineering support in selected HTGR areas and emphasizes VHTR applications; Combustion Engineering, which provides component expertise with emphasis on steam generator design and development; and United Engineers and Constructors, which serves as architect-engineer. In addition, Bechtel Group, Inc., and Idaho National Engineering Laboratory are involved in special design studies, analyses, and evaluations.

Both GCRA and GA are actively seeking a customer for a lead HTGR plant. Currently, Gulf States Utilities and Gulf Oil Corporation are evaluating the use of a cogeneration HTGR to provide steam and electricity in the Texas-Louisiana region, where several large refineries are being operated by natural gas. Because low-cost gas contracts will expire in a few years, a cogeneration HTGR might be economically attractive for this region. Florida Power and Light Company continues to evaluate the HTGR for possible use in meeting the expanding power needs and satisfying environmental requirements in the Miami area.

The work is also carried out in cooperation with FRG under the U.S./FRG Umbrella Agreement in Gas-Cooled Reactor Technology. The areas of cooperation primarily concern fuels, materials, graphite, fission product behavior, and spent-fuel treatment. A cooperative program with Japan on VHTR development could be established within the next year.

It is clear that development and commercialization of the HTGR have a strong constituency who help to keep the American program alive. Many at ORNL are still convinced that development of the HTGR is worthwhile, and we are continuing to make technical contributions to the program (see box). The enthusiasm of program participants has undoubtedly been an important source of the staying power of the HTGR. To those who have asked me the question (and there have been a few), "Is the HTGR still alive?" my response is to quote an old German proverb, which, loosely translated, says, "Projects that are declared dead never die." ornl

Elizabeth Etnier and Curtis Travis, editors of Health Risks of Energy Technologies, *review a draft for another book they are editing—this time on groundwater contamination.*

Health Risks of Energy Technologies:

The Experts' Views

Reasons for the difference between expert and public viewpoints concerning the risks of nuclear power were addressed at a symposium held January 3–8, 1981, when a group of experts convened in Toronto, Ontario, to discuss a subject of public interest: Which of the energy-producing technologies are most likely—and which are least likely—to cause workers and the public injury, disease, and death. Curtis Travis and Elizabeth Etnier of ORNL's Health and Safety Research Division chaired the symposium, which was sponsored by the Committee on Science, Engineering, and Public Policy of the American Association for the Advancement of Science (AAAS).

Since then, Travis and Etnier have compiled, edited, and published the symposium papers in their 1983 book, *Health Risks of Energy Technologies.* This AAAS Selected Symposium book is the first of its kind to compare the health risks of different energy technologies as viewed by experts from a variety of disciplines—mathematics, physics, economics, engineering, radiobiology, risk assessment, and public policy analysis. The only other book on comparative risk assessment in the energy field was that published in 1982 by Herb Inhaber, also of ORNL's Health and Safety Research Division.

The chapters of the book are titled "Judging the Health Risks of Energy Systems," "Health Risks from the Nuclear Fuel Cycle," "Health Risks from Coal Energy Technology," "Health and Safety Impacts of Renewable, Geothermal, and Fusion Energy," "Global Risks from Energy Consumption," and

"Economic Valuation of the Risks and Impacts of Energy Development." None of the authors are from ORNL.

The experts, some of whom cited ORNL research results, have concluded that the risk of occupational death and injury is highest for workers at power plants fueled by coal and lowest for those at nuclear power plants. Between the two extremes is the occupational risk for the unconventional technologies, including solar power, biomass, and geothermal energy. The public health risk from nuclear power generation is also lower than that of coal power generation. The risk of total cancers from routine and catastrophic radiation releases from nuclear facilities is much less than is the risk of cancer and fatal respiratory diseases caused by air pollution from coal-fired power plants.

The Nuclear Dilemma

Although the experts' numbers suggest that nuclear energy is quite safe, nevertheless, the public's perception of the risk of nuclear power suggests that this technology is less acceptable to most Americans. Public apprehension about nuclear power has contributed to the virtual halt in licensing and construction of nuclear reactors. The book seems to break new ground in explaining the public's lack of confidence in nuclear technology.

Travis and Etnier suggest in their introduction to the book that society will accept health and safety risks posed by a technology if the technology is familiar, if the public is given the choice of whether to assume the risk, and if the risk is not catastrophic—that is, that the technology can be harmful or fatal to no more than a few individuals at any one time. To back up these points, Travis and Etnier present examples.

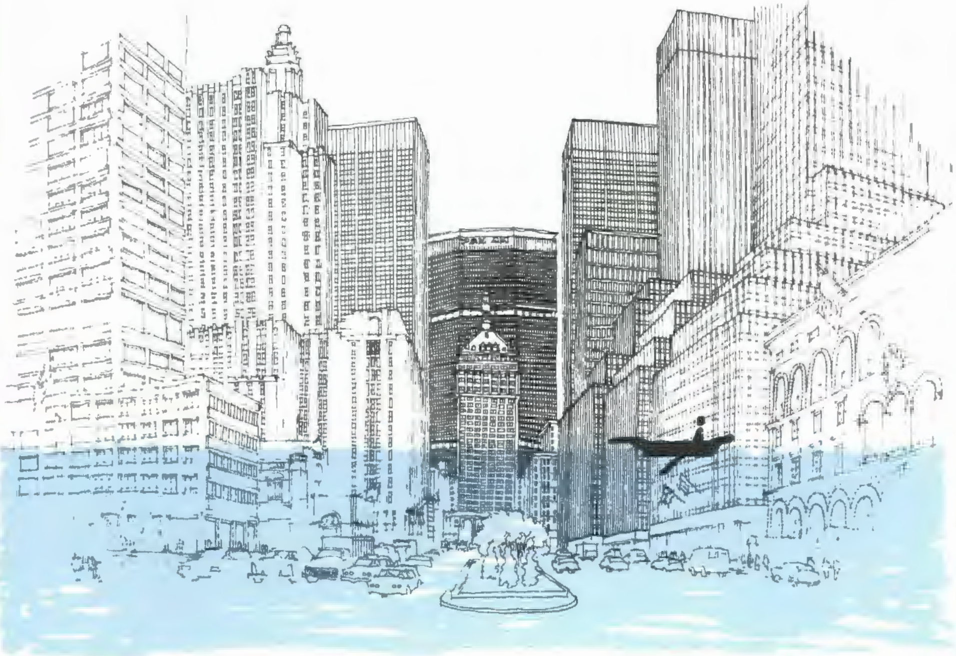
"Rail travel," says Travis, "was greatly feared 150 years ago but now is quite acceptable even though the risk is virtually the same. About 330,000 people die each year from cigarette smoking; yet smokers continue to voluntarily accept the risk of lung cancer caused by inhalation of cigarette smoke. Auto accidents kill more than 57,000 Americans a year, but we still drive our cars, thinking of them as necessary hazards that injure or kill only a few people at a time, although admittedly at a high frequency."

Considering these factors of societal risk acceptance, Travis and Etnier provide insights concerning the public's reluctance to accept nuclear power, which has not yet killed a member of the public. Says Etnier, "People are afraid of the technology because it is new. They are unwilling to take on the involuntary risk of exposure to radiation, which is widely regarded as an invisible menace. Finally, they are frightened of the possibility of a catastrophic nuclear accident even though the probability of such an accident is quite low."

From Start to Finish

This state-of-the-art compilation of occupational and public health risks of different energy technologies examines all aspects of the fuel cycle. It considers the health and safety risks of mining; processing; transportation; power plant construction, operation, and maintenance; and waste disposal.

"Examination of the risks of energy technologies from start to finish is quite new," says Etnier. "This approach has not been done for other sources of risk such as automobile manufacture and use. When we think of the health risks of cars, we tend to think of highway accidents. Few people consider the risks to the miners who produced the coal to make the steel for cars or the risks to workers in the steel and automobile industries.



This drawing of a city threatened by coastal flooding as a result of the carbon dioxide greenhouse effect depicts one of the health effects of increased fossil combustion.

These people have accidents and may die from them. All such risks are considered in current evaluations of energy technologies."

One of the most interesting chapters in this book is the examination of the health risks of emerging technologies such as solar, geothermal, low-head hydroelectric, biomass, and fusion energy. Solar energy is preferred by many because it seems so safe and environmentally benign compared to coal and nuclear technologies. In reality, it has its problems. The construction of solar thermal plants requires large amounts of materials such as steel, aluminum, copper, and glass. Acquiring these materials and manufacturing solar components from them offers not only the potential for accidents and deaths but also the release of hazardous pollutants. For example, solar power towers increase the possibility of worker falls and aircraft collisions, and photovoltaic cells that convert sunlight to electricity are manufactured from toxic materials such as silicon, gallium arsenide, and cadmium sulfide.

Because energy supply technologies have health risks, one approach to reducing these risks is to reduce the need for energy by increasing the efficiency of its use. Frank von Hippel, a theoretical physicist who contributed to the book, suggests that instead of building synthetic fuel plants, it would be wiser to invest money in retooling automobile production plants to manufacture cars that are highly fuel efficient.

Risk Analysis Problems

Risk assessment of energy technologies is based on hard data whenever such data are available. For emerging technologies such as solar power, synthetic fuels, and fusion energy, such data do not exist. Therefore, the experts look at data from comparable industries that provide a clue as to what the risks would be.

"To assess the risk of manufacturing photovoltaic plates for solar electric technology," says Etnier, "we have to examine the data now available on accident rates in the steel manufacturing industry. Because no data exist on accidents associated with the maintenance of rooftop solar collectors, we have to look at the known rate of accidental falls among professional roofers. (There have been 2.8×10^{-7} deaths and 8.5×10^{-4} mandays lost per manhour worked for roofing and sheet metal workers.) The current occupational figures help experts predict the risks of manufacturing and maintaining solar collectors."

assessment experts must face other difficulties. In the case of nuclear and coal technologies, for example, the possible adverse effects on people's health may not be confined to the local risks from pollution or accidents. In their introduction, Travis and Etnier note that "several technologies have consequences which are global in nature. Examples are the possibility of nuclear war due to the proliferation of nuclear materials, and the production of acid rain from sulfates and nitrates formed in the atmosphere after coal combustion. Another problem associated with coal combustion is the possibility of global climate modification caused by atmospheric accumulations of carbon dioxide given off during combustion of fossil fuels."

The carbon-dioxide-induced "greenhouse effect" has caused concern that the earth's surface temperature may rise significantly, an impact whose health risks presently defy quantification. Reginald Gotchy, an author associated with the Nuclear Regulatory Commission, speculates that a climatic warming might cause millions to die of starvation as a result of crop

This solar power tower in New Mexico is not risk-free as an energy source. Worker falls and aircraft collisions with the tower are possible, and accidents have occurred in the industries that produce the materials used in the power tower.

failures and severe losses of productive land because of lack of rain or because of coastal flooding that would result from the melting of polar ice caps. Under these conditions, millions more might die from territorial wars as nations battle for control over the remaining productive land.

The question of risk also has ethical considerations that complicate risk analysis. "An ethical system is needed to assign relative weights to different categories of risk," says Travis. "We may choose to cut back on nuclear energy and burn more fossil fuels, accepting the increased occupational and public health risks of doing so. But as a result, the climate may be modified and cause problems for future generations. Is it morally acceptable to export risks into the future to individuals who will receive no benefit?

"Burning fossil fuels produces acid rain that has potential health and environmental impacts in other states or countries. Is it morally acceptable to export risks to people in another place? If we could rank or weight risks from an ethical point of view, then we would be more able to make decisions about which energy technologies to use. Because no consensus on a proper weighting exists, experts cannot provide an absolute ranking of energy technologies."

In summary, the book and its editors make clear the difficulties and complexities of risk assessment. The March 1979 accident at Three Mile Island (TMI) is perhaps one of the best examples of the problems faced by risk analysts. In general, the probability of a nuclear accident is considered quite low, suggesting that nuclear power is reasonably safe. "But," says Travis, "if we take TMI as an example, then we have to say that a serious accident occurred after 396 reactor years, suggesting that a nuclear accident might occur every 8 or 10 years. If this were the case, nuclear power might seem very hazardous in spite of the fact that no deaths resulted from the TMI accident."

In the book, Baruch Fischhoff, Paul Slovic, and Sarah Lichtenstein, research associates at Decision Research in Eugene, Oregon, write on the TMI dilemma. "Examples of information being interpreted so as to enhance the polarization of views, rather than bring about their convergence, are easy to find in risk debates. Three Mile Island 'proved' the possibility of a catastrophic meltdown to some, while to others it demonstrated the reliability of multiple containment systems. The existence of those containment systems shows the safety consciousness of the industry to some, the inherent hazardousness of nuclear power to others."

If one person's idea of a hazard may be seen by another as a sign of safety, then risk analysis must be a risky business. —*Carolyn Krause.*

BOOKS IN PRINT

The following books in print are authored or edited primarily by ORNL staff members:

Indoor Air Quality, by P. J. Walsh, C. S. Dudney, and E. D. Copenhaver, CRC Press, Inc., Boca Raton, Florida (1983).

The Modern Theory of Alloys, by J. S. Faulkner, *Progress in Materials Science,* Vol. 27, Pergamon Press, Oxford, England (1982).

Dynamics of Lotic Ecosystems, by T. D. Fontaine III and S. M. Bartell, Ann Arbor Science Publishers, Ann Arbor, Michigan (1983).

Advanced Techniques for Characterizing Microstructures, ed. F. W. Wiffen and J. A. Spitznagel (Westinghouse Research Center, Pittsburgh, Pennsylvania), the Metallurgical Society of the American Institute of Mining, Metallurgical, and Petroleum Engineers, Warrendale, Pennsylvania (1982).

The Science of Photomedicine, ed. James D. Regan and John A. Parrish (Harvard University Medical School), Plenum Publishing Corporation, New York (1982).

Water Chlorination: Environmental Impact and Health Effects, Vol. IV, Book 1 Chemistry and Water Treatment; Book 2 Environment, Health, and Risk, by R. L. Jolley, W. A. Brungs, J. A. Cotruvo, R. B. Cumming, J. S. Mattice, and V. A. Jacobs, Ann Arbor Science Publishers, Ann Arbor, Michigan (1983).

Tracers in the Sea, by W. S. Broecher and T. H. Peng, Eldigio Press, Palisades, New York (1982).

Energy Risk Assessment, by Herbert Inhaber, Gordon and Breach, New York (1982).

awards and appointments

Charles D. Scott and **Graydon D. Whitman** have been designated Corporate Fellows of Union Carbide Corporation.

James B. Ball has been appointed director of the Physics Division. He succeeds **Paul Stelson**, who has returned to full-time research after serving as director for ten years.

Martin S. Lubell has been named a member of the Task Group on Materials for Utilization at Cryogenic Temperatures of the Metal Properties Council, Inc.

Karl Erb has been appointed technical assistant to Alex Zucker, ORNL's Associate Director for Physical Sciences.

James D. Regan has been appointed to the Editorial Board of the journal *Cell Biology and Toxicology*.

Robert N. Compton has been elected to a three-year term as a member of the Executive Committee of the Division of Electron and Atomic Physics of the American Physical Society.

Richard L. Hahn recently was a Visiting Scholar at the Chemistry and Physics departments of Southwestern University.

G. Daniel Robbins has been named a member of the Board of Visitors of the Graduate School of Library and Information Science at the University of Tennessee.

Cornelius E. Klots has been elected a member of the Board of Editors of the *International Journal of Mass Spectrometry and Ion Physics*.

O. Lewin Keller was appointed a member of the Steering Committee for the Workshop on Future Directions in Transplutonium Elements Research sponsored by the Committee on Chemical Sciences of the National Academy of Sciences. He also has been named chairman of the Board of Visitors of the Department of Chemistry at the University of Tennessee.

J. R. Peterson was selected as a Rapporteur for the Panel on Chemical Properties at the Workshop on Future Directions in Transplutonium Element Research sponsored by the National Academy of Sciences. He also was chosen as one of five plenary lecturers at the First International Conference on the Chemistry and Technology of the Lanthanides and Actinides in Venice, Italy.

G. P. Smith has been named a member of the Program Committee for the Fourth International Symposium on Molten Salts.

M. Guven Yalcintas has been elected chairman of the Technical Group for Biology and Medicine of the American Nuclear Society.

John Hogan, **James Rome**, and **John Sheffield** have been elected Fellows of the American Physical Society.

Three members of the Fusion Energy Division have been named editors of international journals. They are **John Hogan**, *Physical Review A*; **Julian Dunlap**, *Physics of Fluids*; and **Dieter Sigmar**, *Nuclear Fusion*.

D. L. Selby has been named the Outstanding Member of the Year of the Oak Ridge/Knoxville Section of the American Nuclear Society.

The American Society for Testing and Materials has bestowed its Longevity Award on **Robert W. McClung** for 25 years of continuous service in ASTM standardization.

Jack Cunningham was asked to serve as a member of the Advisory Technical Awareness Council of the American Society for Metals.

F. W. Wiffen was appointed organizer for the Workshop on Copper and Copper Alloys for Fusion Reactor Applications sponsored by the Office of Fusion Energy of the U.S. Department of Energy.

James L. Scott received a Certificate of Appreciation from the American Nuclear Society for serving as general chairman of the Fifth Topical Meeting on the Technology of Fusion Energy held in Knoxville this year.

L. L. Horton and **P. F. Tortorelli** served as session chairmen for the Symposium on Advances in Materials Analysis sponsored by the Oak Ridge Chapter of the American Society for Metals.

Russell Robinson has been appointed scientific director, **Charles Jones** has been named technical director, and **James L. C. Ford** has been named users liaison officer of the Holifield Heavy Ion Research Facility.

William S. Lyon has received an Honorary Member Award from the E-10 Committee on Nuclear Technology and Applications of the American Society for Testing and Materials.

Jack Harvey has been elected secretary-treasurer of the Executive Committee of the Division of Nuclear Physics of the American Physical Society.

L. C. Oakes has been elected a Fellow and **M. J. Roberts** has been elected a senior member of the Institute of Electrical and Electronics Engineers.

R. L. Shepard has been elected chairman of Committee E-20 on Temperature Measurements of the American Society for Testing and Materials.

Annetta Watson was named a member of the Rural Abandoned Mine Program Reclamation Committee, which is administered by the Soil Conservation Service of the U.S. Department of Agriculture and the Office of Surface Mining of the U.S. Department of Interior. She also has been named a member of the Surface Mine Bonding Task Force, which was appointed by the Tennessee Commissioner of Public Health to advise the Division of Surface Mining on bond-setting criteria.

R. Julian Preston has been elected councilor of the Environmental Mutagen Society.

Joe McGrory and **Frank Plasil** have been appointed to the Program Committee of the Division of Nuclear Physics of the American Physical Society.

Carolyn T. Hunsaker was elected president and **Patricia D. Parr** was elected treasurer of the East Tennessee Chapter of the Association for Women in Science.

Virginia R. Tolbert was listed in 1982 Outstanding Young Women in America.

Sam Hurst received an honorary D.Sc. degree from Berea College and was named a member of the National Research Council Evaluation Panel for Radiation Research, a panel of the National Bureau of Standards.

Thomas H. Row has been elected chairman of the Power Division of the American Nuclear Society.

The Environmental Sciences Division has bestowed its Scientific Achievement Award for 1983 on **Donald D. DeAngelis**.

OAK RIDGE NATIONAL LABORATORY *REVIEW*
P.O. Box X, Oak Ridge, Tennessee 37830

The Tower Shielding Facility is the site of a radiation shielding experiment to be performed in support of the program to develop high-temperature gas-cooled reactors. See the article on page 39.