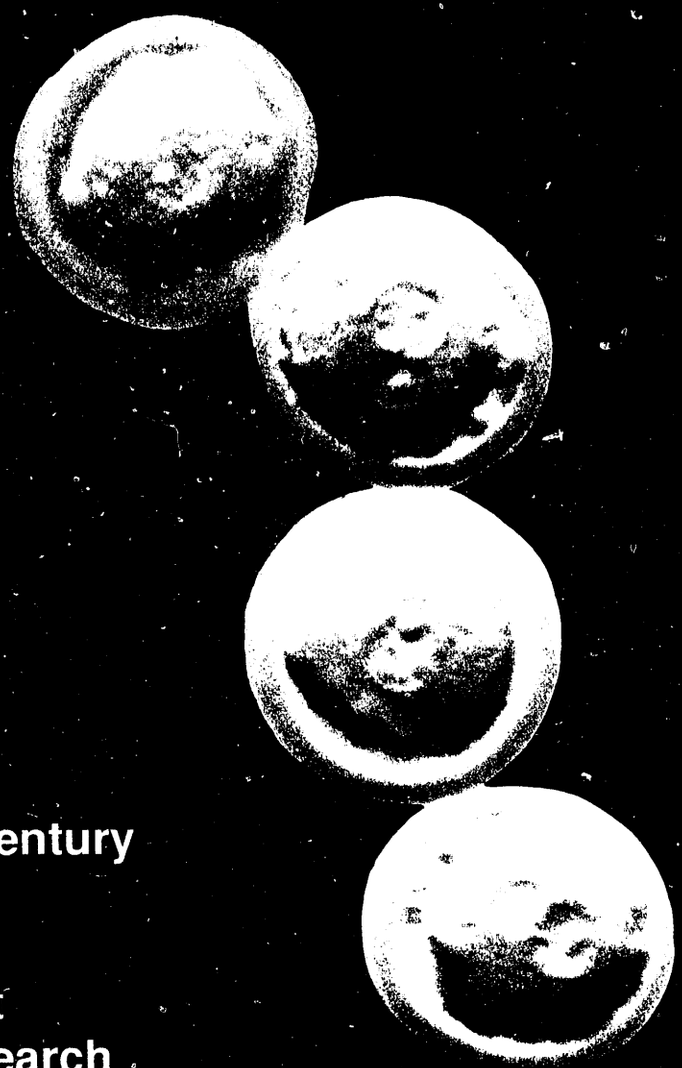
ORNL '90



Looking Ahead:
ORNL in the 21st Century

Greenhouse Effect
Heats Up CO_2 Research

Physicist Sticks 'Neck' Out
for New Heavy-Ion Fusion Theory

FROM THE DIRECTOR

What is it that moves a scientist to do the sort of work that's featured in the pages of ***ornl** '90*?

Inspiration? Dedication? Fascination?

In a word: yes!

Again and again at ORNL, I've seen a level of motivation and a commitment to scientific excellence that couldn't be bought at any price. Much of the work chronicled in this sampling, like much of the work at ORNL as a whole, takes place after normal working hours; outside the walls of the Laboratory; beyond the call of duty. A key insight may come in a flash—in the small hours of morning or between innings of a daughter's softball game. But such a flash has probably been preceded by days of preoccupation, weeks of pondering, months or even years of probing to tease out some thread of meaning from a mass of observations.

The creative instinct—surely one rightful name for what inspires a scientist to draw a new picture of the world, or some small corner of it—is a mysterious thing. Unlike nuclear fission or genetic mutation or submarine acoustics, creativity defies our best, most diligent efforts at quantification or manipulation or control. In fact, the harder we strive to pin creativity down, the more elusive it seems to become, whether the setting is a painter's loft in Manhattan or a chemist's lab in Oak Ridge. Impound even the purest mountain spring and eventually it will stagnate; but loose it to follow its instincts, and day by day it finds its way to the sea.

So when we're fortunate enough to find, make, or even stumble upon an environment that allows creativity to flourish, the least—and best—we can do is respect it ... and get out of the way while work and magic mingle.

Therein lies one of the hardest balancing acts required of a national laboratory: meeting a multitude of legal, financial, and environmental responsibilities while also preserving the freedom and flexibility that allow us to search for truth and light—sometimes in places we don't even know exist until we're *in* them.

When we succeed in that balancing act, when we provide the right mix of responsibility, resources, and freedom, we give scientists a rare opportunity to achieve things that are both deeply satisfying and highly useful. Things like revolutionary new ways to store computer data or pinpoint problems in motors. Keener listening systems to hear submarines whispering along beneath the ocean.

Technologies to save energy and clean up pollution and protect the atmosphere. Fundamental new ways to explain nuclear fusion and genetic disease.

***ornl** '90* tells just a few stories of what's possible in a setting that nurtures creative science.

We have more.

Many, many more.

Al Trivelpiece

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Cover: Mouse zygotes injected with foreign DNA fragments can yield mutations that shed new light on gene functioning. See article beginning on page 10.

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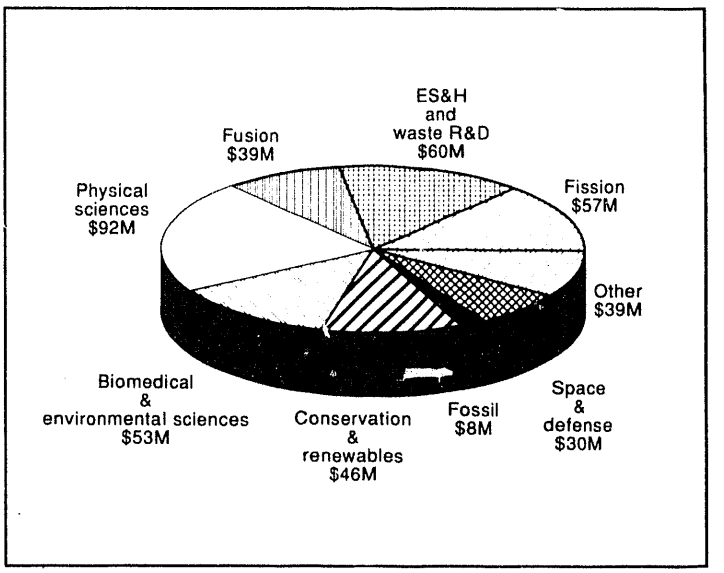
MASTER

ORNL took root in an isolated East Tennessee valley during the Manhattan Project, the World War II race to develop the atomic bomb. The wartime role of the Lab—"Clinton Laboratories," it was called then—was to find a way to produce and separate plutonium, one of two candidate materials for use in a fission weapon. The plutonium was produced in a pilot-scale reactor that was moderated, like its famous Chicago predecessor, by graphite. The Oak Ridge Graphite Reactor was the world's second nuclear reactor and the first isotope-production reactor. Its design, in turn, was the basis for large plutonium production reactors built at Hanford, Washington.

After World War II, the Laboratory's assignment broadened to include other isotope-separation techniques, as well as a growing role in reactor development and applications. During the 1950s, ORNL established the Oak Ridge School of Reactor Technology, or ORSORT. ORSORT and its graduates played a pivotal role in establishing nuclear energy as a peacetime source of electricity and as a dependable means of propulsion for the ships and submarines of the "Nuclear Navy."

As the nation's energy-related needs have diversified, so have the Laboratory's fields of R&D. Today ORNL remains a world leader in isotope development, especially isotopes for medical research and imaging, and in reactor technology and safety. But other important programs have evolved in additional fields of science and technology. As the largest of DOE's multiprogram energy laboratories, ORNL today brings its unique facilities and technical expertise to bear on a wide range of R&D challenges facing the nation and the world.

Energy technologies: The Laboratory conducts applied R&D in several key technologies. The **fission** program concentrates on improving nuclear power plants through better control systems, tougher materials, and inherently safe designs and fuels for a new generation of modular reactors. **Conservation** R&D seeks more efficient ways to use energy, through better building envelopes, advanced heating and cooling systems, more efficient electrical distribution equipment, strong new ceramics for high-temperature engines, and other energy-related developments. **Magnetic fusion** seeks to harness the power of the stars to supply clean, unlimited power for the future. **Renewable energy** sources under study here include fast-growing biomass, or energy crops, which can be converted to liquid or gaseous fuels. Finally, **fossil-energy** research explores ways to tap coal, our



ORNL's funding in fiscal year 1989 totaled $424 million.

Among schoolchildren: Thousands of students like these visit ORNL each year. In addition to brief programs designed simply to spark the interest of young minds, ORNL offers intense, multiyear research projects for some of the nation's brightest postdoctoral researchers.

most abundant fossil energy source, in ways that are clean, efficient, and environmentally sound.

Environmental and waste R&D: ORNL researchers are probing the processes, both microscopic and global in scale, that sustain the delicate balance of life on earth. They're also seeking better ways to manage the world's burgeoning wastes, which result from rapid population growth, accelerating Third World development, and rising material expectations around the globe.

Basic research: Underpinning the Laboratory's applied R&D in these and other fields is a strong tradition of fundamental science. Areas of experimental and theoretical research include physics (nuclear, atomic, and solid-state), chemistry, materials science, computing and mathematics, genetics and other biomedical research, and environmental sciences.

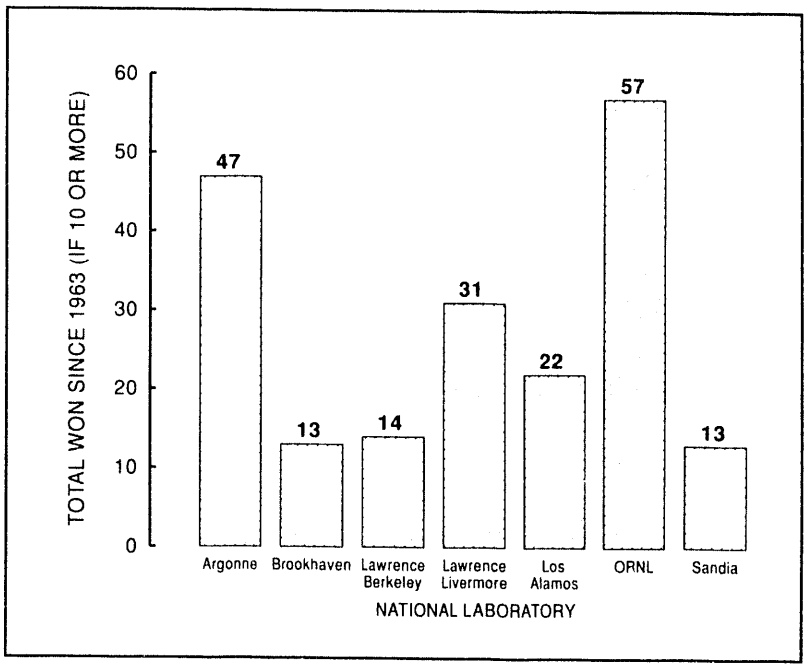
National R&D user facilities: ORNL operates a dozen unique research facilities for the benefit of scientists from universities, industry, and other research institutions, both domestic and international. These facilities range from nuclear research equipment to a state-of-the-art roofing-materials lab and a 13,000-acre environmental research park. Last year the facilities hosted well over 500 outside researchers. In addition, more than 2300 other researchers conducted research at ORNL last year through collaborative programs or other kinds of guest assignments.

Education: ORNL offers learning experiences for students at all levels, ranging from nature talks for preschoolers to two-year appointments for post-doctoral researchers. Last year more than 17,000 students and teachers participated in an ORNL-sponsored program, experiencing firsthand the Laboratory's commitment to preparing the scientific and technical workers of the future. To prepare for a predicted increase in the percentage of minority workers over the next decade, ORNL has initiated partnerships with a number of minority schools throughout the region.

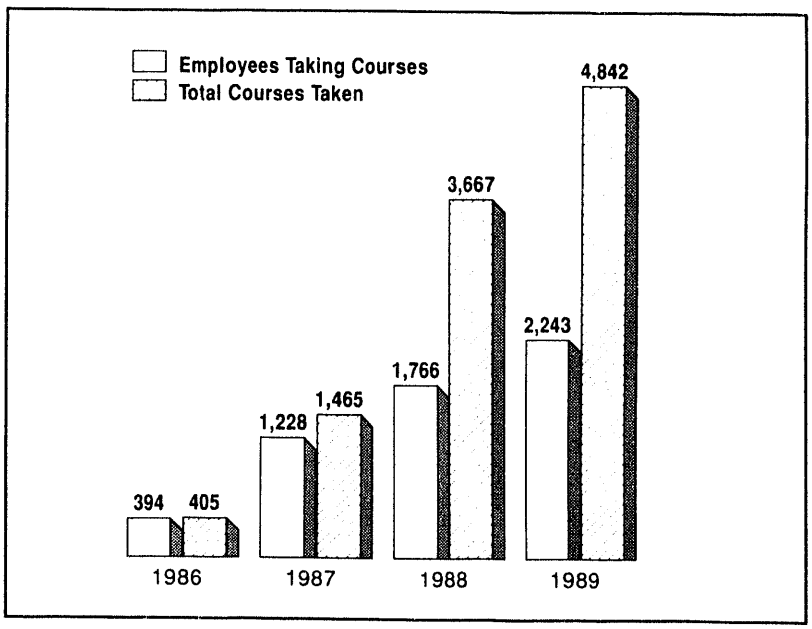
Knowledge transfer: ORNL is a leader among the national laboratories in transferring government-initiated science and technology to U.S. industry. In 1990, ORNL was the first DOE laboratory to sign a Cooperative Research

and Development Agreement (CRADA), a new form of collaboration authorized by Congress in 1989. By allowing cost-sharing and strong protection of proprietary data, CRADAs will foster new levels of teamwork between the federal and private sectors: technology transferred through elbows rubbing in the lab. Through CRADAs, licensing agreements, and other innovative forms of collaboration, industries can harness ORNL's scientific "reach" to solve problems or explore opportunities that would otherwise exceed their grasp.

The people of ORNL: ORNL's accomplishments are the work of some 4500 employees, divided nearly equally between professional staff and support staff. Of the Laboratory's professional scientists, engineers, and managers, nearly 900 (39%) hold Ph.D. degrees, and more than 500 others (23%) hold master's degrees. In 1990 nearly 500 employees, representing a wide spectrum of jobs and skills, participated in the Laboratory's Educational Assistance Program. The 1442 courses they took represented an investment by the Laboratory of more than $400,000 in their professional and career development.



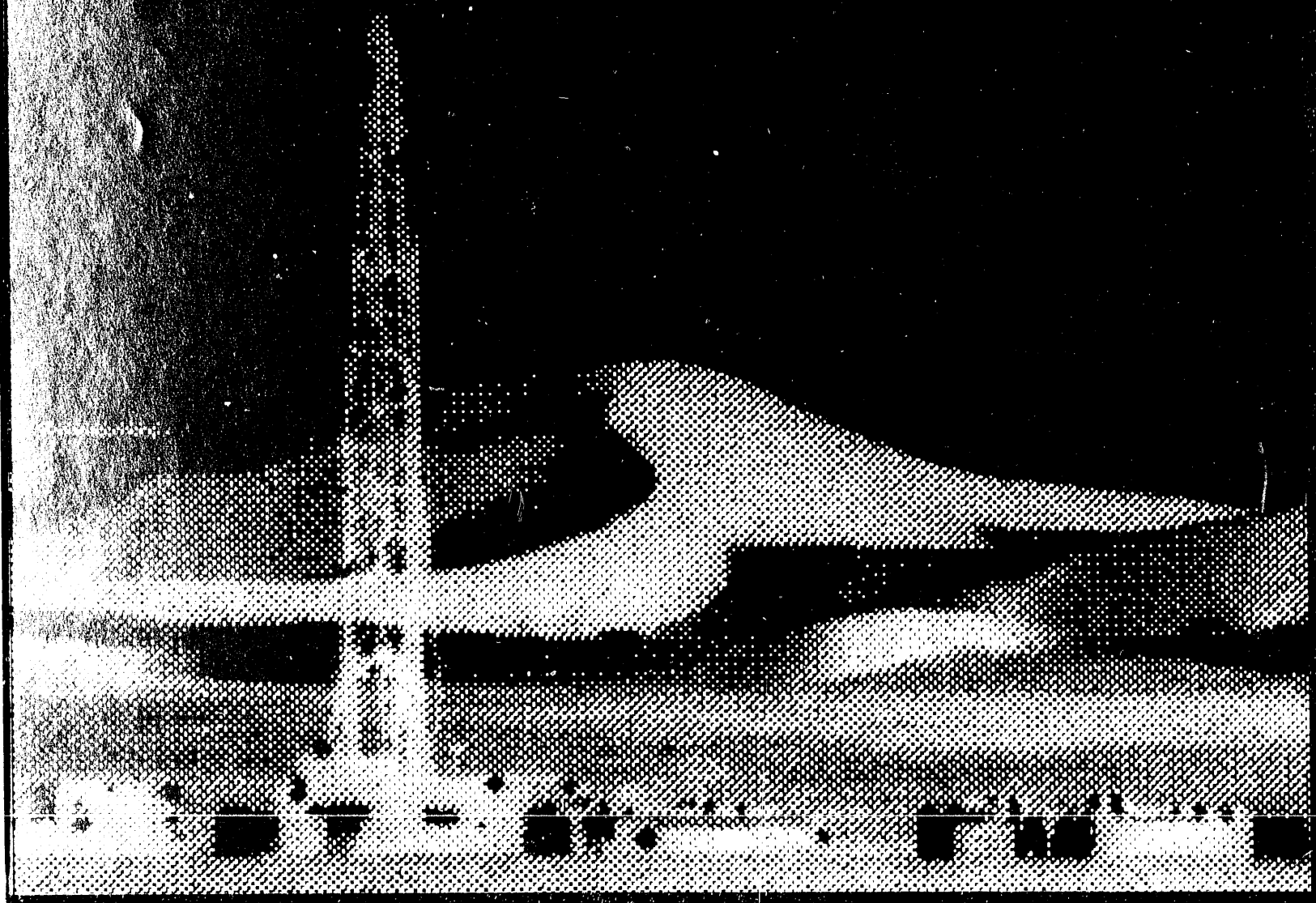
ORNL has won more R&D 100 Awards than any other DOE national laboratory.



In keeping with DOE's new emphasis, environment, safety, and health training has increased dramatically at ORNL over the last four years.

Looking ahead: ORNL in the 21st century

Emblem of uncertainty: Low-cost imported oil—now accounting for nearly half of America's petroleum needs—has its downside, suggests this photo negative of a well rising above the Saudi dunes.



DOE's laboratories contain the largest collection of scientific talent and research facilities in the nation, if not the world. This scientific power is essential to the United States in meeting the challenges we face in the years ahead—especially in the areas of ***energy****, the* ***environment****, and* ***global competitiveness****. As the largest of DOE's nonweapons laboratories, ORNL will be a major contributor in all three of these areas.*

Energy

War in the Middle East has made energy a grave national concern once again, and its prominence, both in the United States and worldwide, will increase through the remainder of this century and beyond. The world's largest reserves of oil lie in one of the world's most politically explosive regions, and—barring some political or geologic miracle—that fact will not change in the foreseeable future. In addition, global energy production and consumption will continue to rise, largely because of population growth and economic development in Third World countries. To offset the resulting energy-price increases and environmental strains, more emphasis must be placed on boosting efficiency and on developing non-fossil energy sources.

Even in the shorter run—within the next five years—here in the United States, we will face falling reserves of gas and oil, increased oil imports, higher energy prices, and a shortfall in electric generating capacity. These factors should spur increased emphasis on energy research and development by DOE and its national laboratories. As one of the world's largest energy research labs, we are in a good position to make major contributions to this effort.

Environmental and life sciences

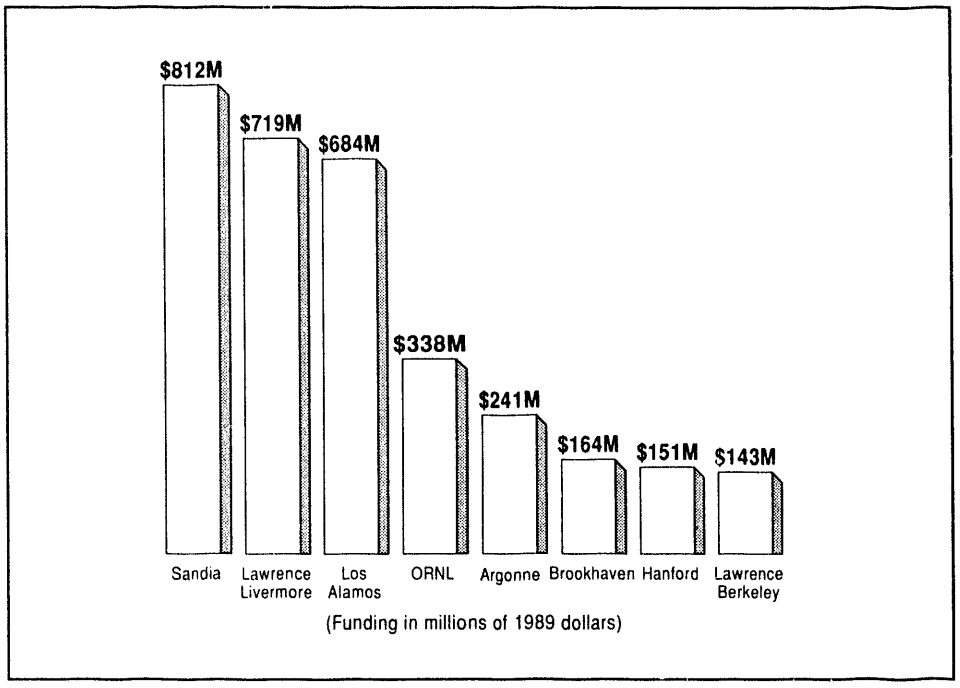
The world's population is currently increasing by some 85 million people each year: more than a quarter-million every day. As this population grows and as it becomes more affluent, the potential for global environmental change grows ever larger. Already, global warming and ozone depletion are threatening to redraw the world's land-use maps and increase skin-cancer rates. Yet these are only two early examples of the broader environmental implications of a burgeoning world economy.

NASA

Unless we improve our knowledge base about global environmental processes, we will be woefully ill-equipped to deal effectively with the environmental problems that loom ahead. Far more fundamental research is required before we will understand enough about global systems—atmospheric circulation, ocean dynamics, carbon cycling, geochemistry—to make intelligent responses. To explore these crucial issues in depth, ORNL has established the Center for Global Environmental Studies, a multidisciplinary center with an ambitious list of long-range research and analysis goals.

At the other end of the cosmic scale—the microscopic—a major revolution is

American Petroleum Institute



ORNL's 1989 DOE budget was larger than any other multiprogram laboratory's, but considerably smaller than the three weapons laboratories'.

occurring in molecular biology. During the next 15 years, the structure and workings of the human genome will be revealed as never before, allowing new understandings of the genetic bases of human disease. ORNL will continue its historic leadership in mammalian genetics and molecular biology. Our research in protein engineering will expand and assume increasing national importance with the construction of the Advanced Neutron Source, the world's most powerful research reactor, which will allow detailed neutron-scattering studies of the molecular structure of proteins.

With environmental research capabilities that are among the nation's best, we expect to make major contributions to humanity's understanding of the delicately balanced biosphere we call home.

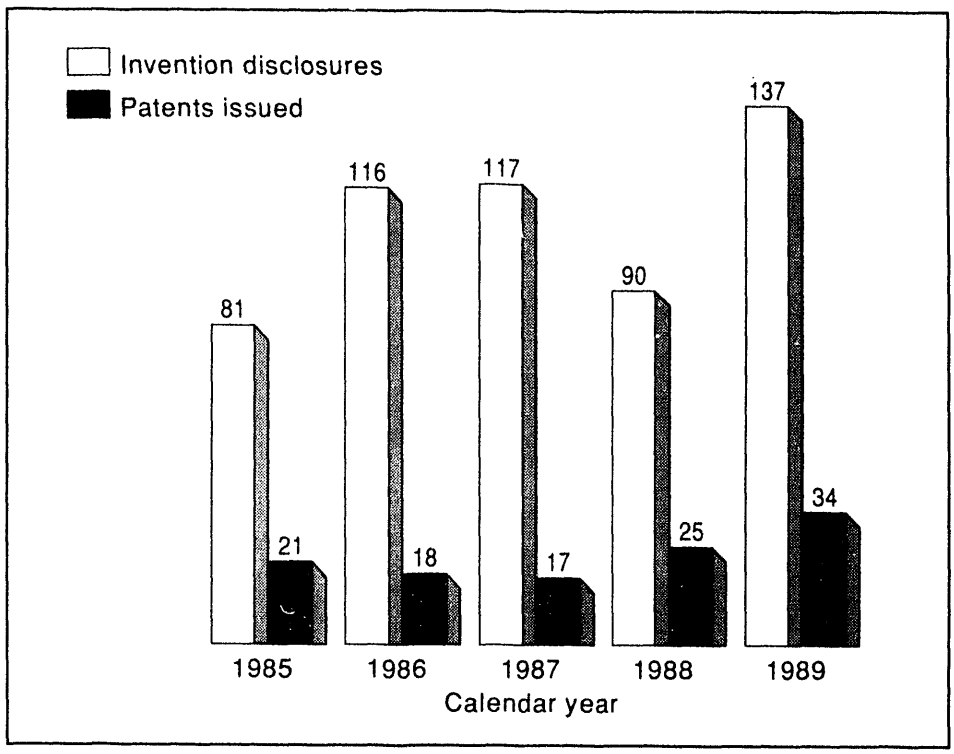
Competitiveness

The issue of international competitiveness is one of our nation's most pressing problems. It is not just a passing, faddish concern; it is a complex structural problem with difficult scientific and technical dimensions—and no quick fixes. As a nation, we must do many things to begin addressing it: Strengthen our education system, putting special emphasis on scientific and technical education. Continue to replenish our reservoir of basic scientific knowledge. Help American industry translate this new knowledge into commercially useful products and processes.

DOE Secretary Watkins has challenged the national laboratories to help restore U.S. competitiveness through improved technology transfer and better scientific and technical

education. In some ways, this challenge is more difficult than the Manhattan Project, the urgent wartime program that spawned the national labs nearly half a century ago. It is difficult because it requires fundamental changes in the relationships among industry, universities, and government; in particular, it requires an easing of the borders that keep these groups apart, so the nation can apply all its intellectual resources to a common goal.

Research and development can address many of the important issues facing the nation, but there will be signficant funding constraints. The federal deficit will continue to constrain new government initiatives. Competition for research funds will increase. Cutbacks in defense spending will turn many defense labs into strong competitors for the civilian R&D dollar. DOE's environmental and waste problems will continue for a decade or more, and funding to address them will divert resources from science. The budget constraints will prompt efforts to improve the efficiency and effectiveness of DOE's laboratory system. For the same reason, big science projects—the Superconducting Super Collider and ORNL's Advanced Neutron Source, for example—will receive sharper scrutiny from Congress and the White House. Attempts to cut spending may lead to pressures on DOE to consolidate facilities. In such a climate, any facility or program that is not producing significant scientific or technological advances will be at risk.



Invention disclosures and patents issued reached a five-year high at ORNL in 1989.

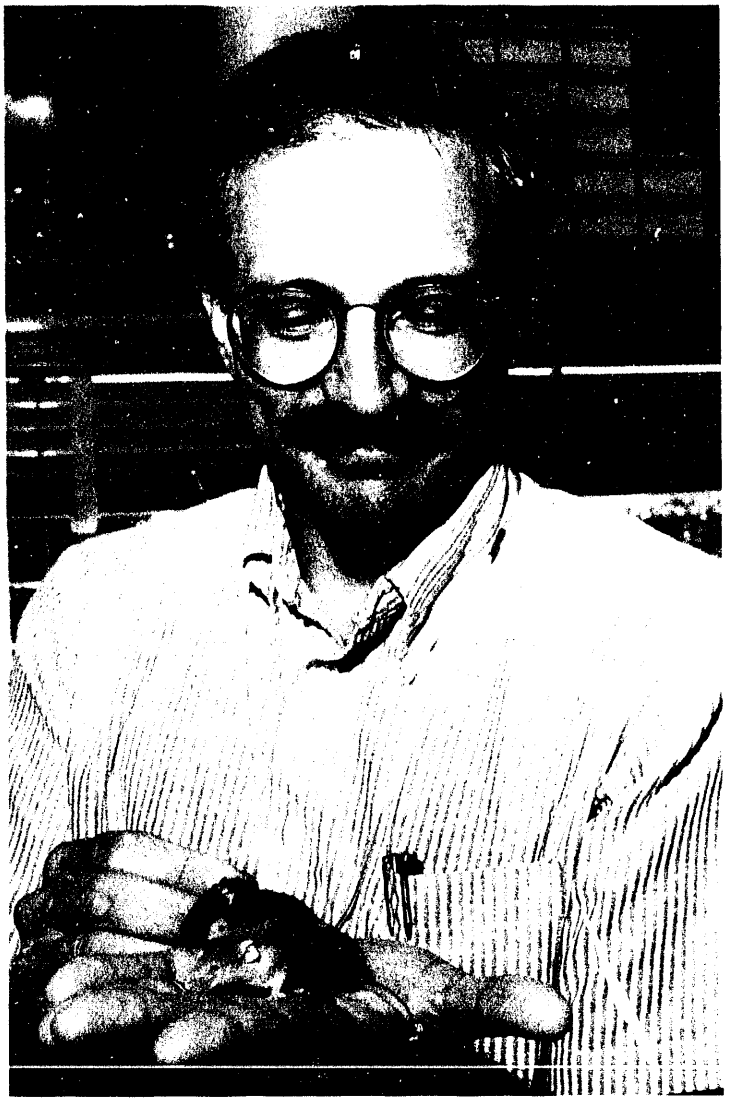
The next decade and beyond at ORNL will, in short, be a time of great pressure.

It will also be a time of equally great promise.❖

RESEARCH HIGHLIGHTS

Insertional mutations shed new light on gene function

Mutation made manifest: Rick Woychik holds two mice from ORNL's "mouse house." One has the normal dark "agouti" coat; the other wears a golden coat that results from insertional mutation.



Cystic fibrosis. Kidney disease. Sickle cell anemia. Mental retardation. Muscular dystrophy. Manic depression. Emphysema.

These and some 4000 other human diseases are known or thought to be caused by genetic defects—flaws in the intricate biochemical code transmitted by the three billion signals of human DNA.

The causes—and potentially the cures—of these diseases may eventually be deciphered with the help of insertional mutagenesis, one of the newest biological research tools in use at ORNL. The technique may also help illuminate even more fundamental mysteries, including cell-to-cell communication and the intricate orchestration of mammalian development.

Insertional mutagenesis is the technique of shooting extra DNA into mouse chromosomes to cause genetic changes. So far it is in large-scale use at only a handful of the world's research centers, including ORNL. According to ORNL biologist Rick Woychik, the technique could reveal a wealth of information about how genes function—and malfunction—not just in mice, but in humans.

It's difficult to study gene malfunctions in people. Human mutations, for instance, tend to be isolated, individual tragedies—a birth defect here, a miscarriage there—not controlled, repeatable experiments. But since mouse genes are similar to human genes, says Woychik, researchers can learn much by forcing changes in mouse genes, then applying the findings to human biology.

Deciphering the biological *Britannica*

The human genome—the encyclopedic set of 24 double-helix chromosomes—contains a mind-boggling three billion pairs of chemical bases, which encode the instructions for general development and individual differences. A 15-year, $3-billion U.S. effort, the Human Genome Project, has begun to analyze those three billion base pairs to determine their chemical sequences. However, one key to interpreting the findings will come from studies of mutations in mice.

"Simply looking at DNA sequences—analyzing them chemically—doesn't tell you much about where genes are and what they do," explains Woychik. "Think of, say, *Encyclopaedia Brittanica* with all the letters in it—but without any periods or spaces between the words." (Abithardtofigu reoutisntit?) "All the information is there, but it's pretty meaningless if you can't make out the words and sentences. A chemical map of the genome is kind of like that.

"But when something goes wrong—when a mutagenic structural change happens in the DNA at certain parts of the genome and causes an obvious defect in the animal—that tells you what the gene does when it's working right. In other words, the mutation has disrupted the

expression of the gene that normally prevents the defect"—and, by doing so, has unmasked the gene's identity.

"These mutational clues help us begin to make out the individual words of the genetic encyclopedia, in effect," Woychik continues, "so we can put them into sentences, into pieces of information we can read and understand." (A bit easier to figure out, isn't it?)

ORNL's Biology Division has decades of expertise in using mutagenesis to probe the intricacies of development. Woychik's project is one of many descendants, to use the obvious metaphor, of the mouse mutagenesis studies pioneered here by Liane and Bill Russell to explore the biological effects of radiation and chemicals. Insertional mutagenesis is, then, simply a sophisticated new version of a proven research methodology.

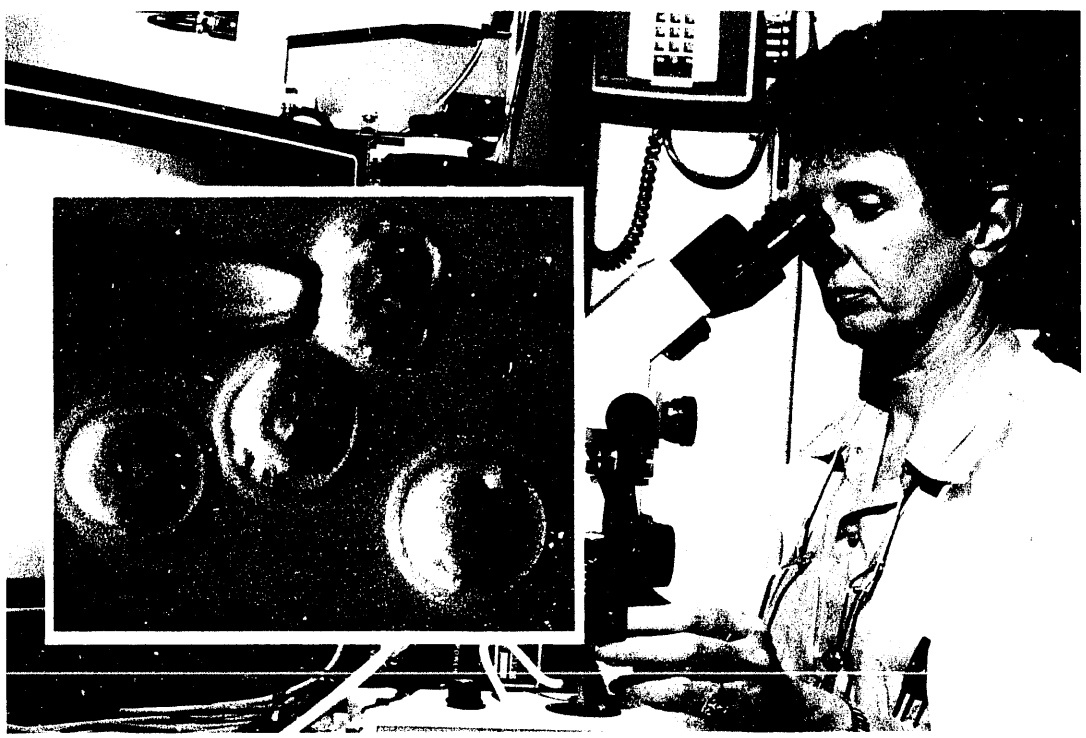
"The role of mutagenesis in identifying gene function is key," Woychik continues. "In every biological system we've looked at over the past thirty or forty years, mutations have been one of the best ways of identifying where particular genes on the DNA are located and what they do."

By way of example, Woychik cites an insertional mutation descriptively called "kink tail," which points to a gene responsible for normal development of the lower spine. Other insertional mutations are helping with the analysis of genes responsible for normal—and abnormal—kidneys and limbs, and even those in charge of the mysterious cell-to-cell communication process that tells some cells how to make a heart and others how to form skin (see "Closing in on kidney disease," below).

Ab ovum: how it begins

Three mornings a week, peering through a binocular microscope, lab technician Gene Barker sifts through tissue from mouse oviducts. He's harvesting zygotes, or fertilized eggs—a hundred at a sitting—each about half the diameter of the period at the end of this sentence. Then, with practiced hands, micromanipulators, and a glass pipette with a tip too fine to be seen by the naked eye, technician Barbara Beatty punctures each of the zygotes and injects a micro-droplet containing about 500 identical fragments of foreign DNA—harmless, inert pieces cloned in a bacterium. She puts the zygotes in an incubator overnight and hopes that the DNA will worm its way, by a mechanism nobody yet

Using micromanipulators and a glass syringe finer than a human hair, lab technician Barbara Beatty injects foreign DNA fragments into fertilized mouse eggs (inset).



Closing in on kidney disease and other human health problems

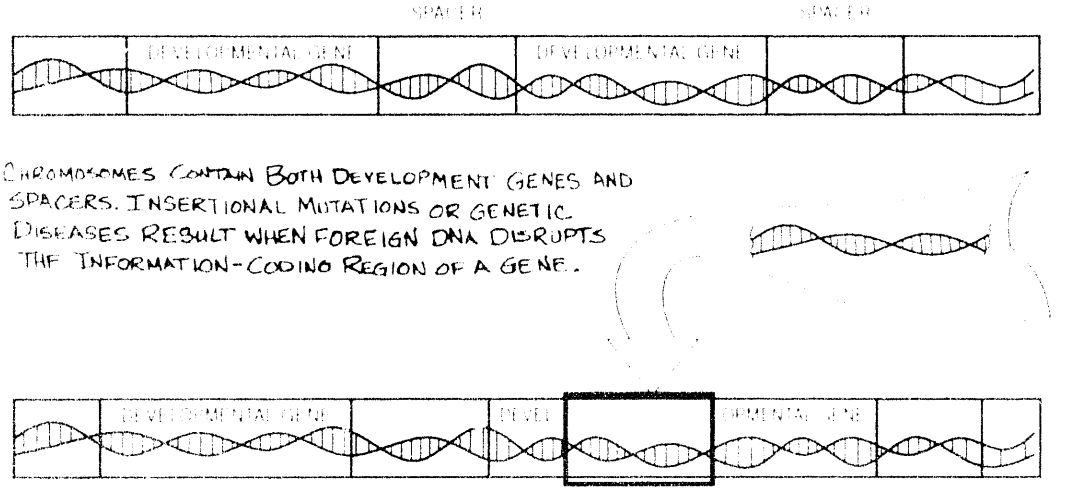
One of the estimated 4000 genetic diseases that may eventually be understood and overcome through insertional mutagenesis is polycystic kidney disease, which can cause hypertension, urine poisoning, infections, and even premature death. "Polycystic kidney disease is a tremendous human health problem," says Woychik. "Unfortunately, nobody's been able to get a molecular handle on the defective genes that are responsible for it." Until now. An insertional mutation located on mouse chromosome 14 has been found to cause polycystic kidneys in mice; postodoctoral follow Monica Lee-Tischler and graduate student Judy Moyer are now analyzing the altered gene to learn more about how it functions. "By cloning this mouse mutation, we may now have molecular access to the genes that normally prevent this condition," says Woychik. "The animals that develop polycystic kidneys could be good models for developing drugs to treat the problem in humans.

Other puzzling health problems that may be illuminated by insertional mutagenesis are sterility and fetal death, or miscarriage. Among people of childbearing age, about one couple in six is sterile. And each year more than a half-million U.S. women have miscarriages, most of them unexplained. Genetic defects are likely culprits in both cases, says Woychik, pointing to mutations that trigger high rates of embryonic death in mice. Identifying the causes of these problems is a long way from solving them . . . but it is a step.

Insertional mutations will also help unravel an even more fundamental biochemical process—what Woychik calls "the miracle of development." Consider the process that led to . . . well, to *you*. A single cell, the fertilized ovum, divided to form two cells, then four, then eight—initially all alike, undifferentiated in appearance. Soon, though, in response to biochemical signals encoded somewhere in the three-billion-rung ladder of your DNA, cells began grouping and evolving into the specialized clusters of tissues, organs, and systems: heart, lungs, skeleton, brain. "Many, many different genes have to fire in a very specific sequence to orchestrate this," notes Woychik. "The molecular circuitry involved is very complex—and it's fascinating to study."

Understanding this developmental orchestration requires understanding the biochemical signals that allow cells to communicate with one another. Using DNA probes originally derived from an insertional mutation, graduate student Scott Bultman is characterizing the genes responsible for the agouti coat color in mice—fur that is black at the base and tip, golden in between. "There are many variations within the agouti region," says Woychik, "most of them generated by exposure to radiation or chemicals." These genes are intriguing because they appear to help regulate the communication that occurs between the cells of the hair follicle and the pigment-producing cells located around the growing hair shaft. What's more, the gene also seems to play a role in even more basic cell-to-cell communications: one variation, or "allele," of the coat-color mutation produces embryos that stop developing and die.

In this case, as in others produced by insertional mutagenesis, a look at the developmental process-gone-wrong may give molecular geneticists a far better picture of what normally makes it go so right. ❖



understands, into the midst of one of the mouse chromosomes.

Only a third of the eggs will survive and develop to term. Most of the offspring will be, to all intents and purposes, ordinary lab mice.

But once a week, on the average—once for every 300 eggs injected with DNA—the result is an important new genetic line. With systematic breeding—allowing maternal recessive gene to meet paternal recessive gene—that new genetic line will yield a mutation that could unlock some of the secrets of human diseases and death.

By the end of the five-year project—after tens of thousands of DNA injections—the result will be some 100 new breeding lines of mice that carry insertional mutations. And because of the potential for breakthrough findings, says Woychik, every one of the 100 may represent "a lifetime career for an investigator."

Molecular homing signals

Each of the mutant lines produced by this painstaking work is a beginning, not an end in itself, Woychik stresses.

Here's why: Once inserted into the mouse chromosomes, the microinjected DNA, or "transgene," changes the structure of the mouse's "host" DNA. An insertional mutation arises when this structural change in the DNA alters or switches off the expression of that region's normal gene. The key feature of insertional mutagenesis is that the integrated transgene—the one causing the mutation—can also be used as a molecular "marker" to locate the altered region. With two billion pairs of chemical bases in the mouse genome—two billion rungs on the twisted ladder of its DNA—a marker comes in handy if you're trying to locate a particular spot. Otherwise, says Woychik, "it's like looking for a microscopic needle in a very large haystack."

In short, it's that dual nature—disruptor *cum* homing signal—that lets insertional mutagenesis shine a powerful light on the structure and function of genes.

Taking aim at genetic mysteries and human diseases

Despite the research value of insertional mutagenesis, the way it works isn't clear. "Nobody knows how or why or where the DNA will incorporate into the mouse genome," says Beatty. "It's still something of a mystery."

Other researchers, including ORNL's Gene Rinchik, are probing the secrets of genetic breaks and repairs. But the insertional mutagenesis team focuses single-mindedly on pumping in the microdoses of foreign DNA and watching what happens. The results reflect both scientific precision . . . and random luck.

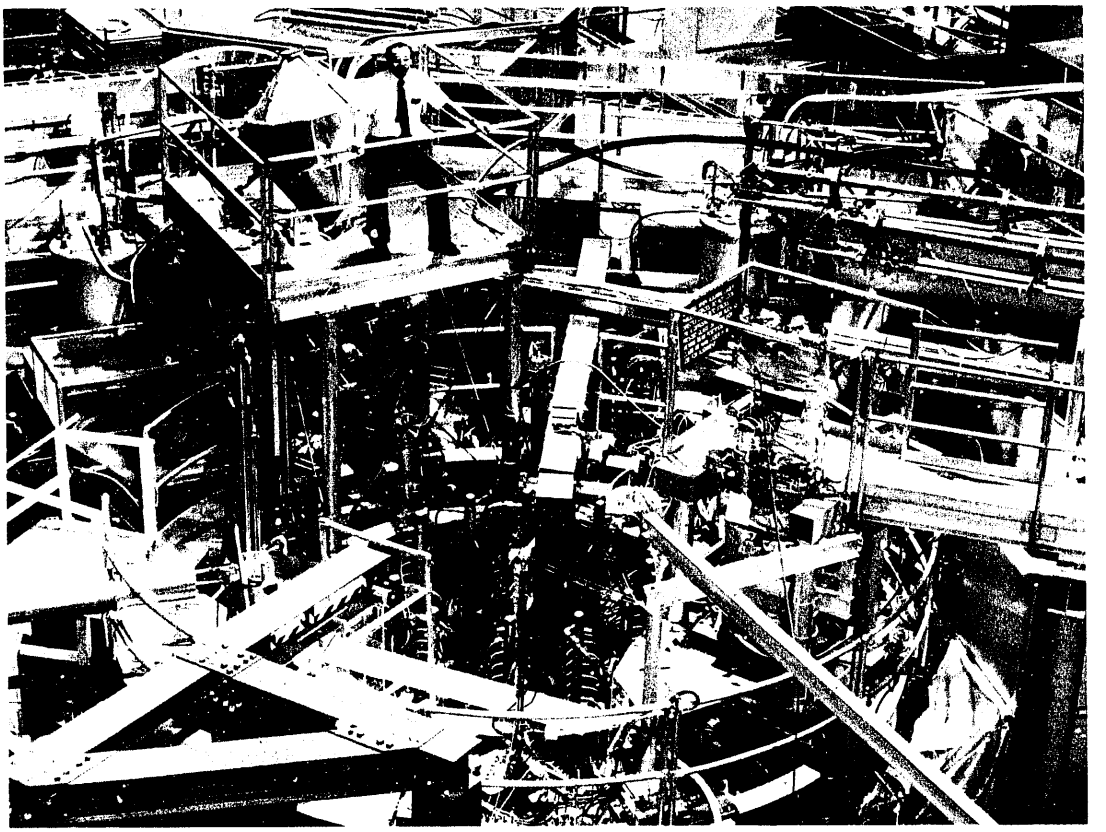
"In each new line of transgenic mice, the microinjected DNA integrates at a different site somewhere in the host chromosome, presumably at random," explains Woychik. "Over the course of the project, we hope to discover many genes whose position and function haven't been characterized by conventional techniques. There are lots of important developmental genes lurking in the depths of the mouse genome that can't be efficiently identified any other way."

As each new genetic line is characterized, a payoff important to human disease could begin to emerge. "We can do controlled mutagenesis experiments in the mouse that obviously can't be done in humans," says Woychik. "We can characterize the genes associated with the mutant conditions. Most importantly, the DNA probes from the mouse may help us identify the homologous genes on the human genome, telling us their location and function."

"We're not doing these experiments in mice as an academic exercise. We hope—we expect—that the work that we're doing will have important biological

Graduate students Scott Bultman (left) and Jeff Schrick study the locus on mouse chromosome 2 that is responsible for normal coat color and mutations of it. The picture is an autoradiograph, made by exposing X-ray film to radioisotope-tagged DNA probes that locate the inserted DNA, or transgene.

ATF: Plugging holes in leaky fusion buckets



The Advanced Toroidal Facility, overseen by John Glowienka.

Fusion reactors are like leaky buckets, says physicist John Glowienka. In today's experimental devices, energy dribbles out faster than it can be pumped in; soon, he predicts, science will plug enough of the leaks to stay ahead.

Fusion is the power of the stars—and of the hydrogen bomb. For more than forty years—ever since the first thermonuclear explosion—scientists have been trying to tame fusion, harness it, so that instead of a cataclysm it produces controlled heat. Heat that can boil water that can spin a turbine that can generate electricity.

The prospect is tantalizing: a clean, unlimited source of energy, fueled by that wholesome, all-natural heavy-hydrogen source we call water.

But slow-motion fusion hasn't proved easy. For fusion to work as an energy "engine," say Glowienka and other physicists, an ionized mix of hydrogen fuel particles—called a plasma—must be heated to a hundred million degrees or better and tightly compressed. The plasma must be held together—in a fire bucket, of sorts, one made of magnetic fields rather than steel or concrete—long enough to yield more energy than it takes to start and sustain the reaction. Passing this milestone—called breakeven—requires overcoming large, naturally occurring energy losses. Big leaks.

When fusion research began in the late 1940s, the bucket leaked woefully: energy losses were millions of times greater than breakeven. Although much still remains to be understood,

today's best fusion experiments are less than a factor of two away from breakeven.

The progress has come from hard-won understanding of what causes the energy losses. Insights gained on one machine lead to better performance—smaller leaks—with the next, and so on.

One important sign that the prospects for continued leak-plugging are good has recently emerged from the Advanced Toroidal Facility, ORNL's "stellarator" fusion machine (a cousin of the better-known tokamak). According to Glowienka, ATF's operations manager, experimental results there during 1990 help confirm the basic soundness of the theory on which ATF and other fusion machines are based.

Once you get past the most basic of analogies and explanations—buckets and stars and water—things get tough to explain. Much of fusion research is a complex and multidisciplinary specialty. Its practitioners sometimes struggle to translate concepts and principles from the language of fusion—complex math and physics formulas—into everyday prose. It may take an hour of background explanation to set the stage for a five-minute anecdote.

The key point, though, is this: Experiments on ATF confirm the existence of "bootstrap current," a self-propelling current (hence the name) within the plasma. Bootstrap current has long been predicted by the theory that attempts to explain the behavior of fusion plasmas and has even been indirectly observed. But it hasn't been controlled and directly observed.

Not until now. Not until ATF.

An only slightly lesser point is this: ATF's experimental values for bootstrap current differ from theoretically predicted values by a factor of two. By *only* a factor of two.

In many disciplines, that discrepancy would be considered large. But in the elusive quest for fusion—where the gap between theory and practice may be factors of tens, or even hundreds—a factor of two is near surgical precision, and may reflect merely uncertainties in measurements.

Sketching plasma behavior

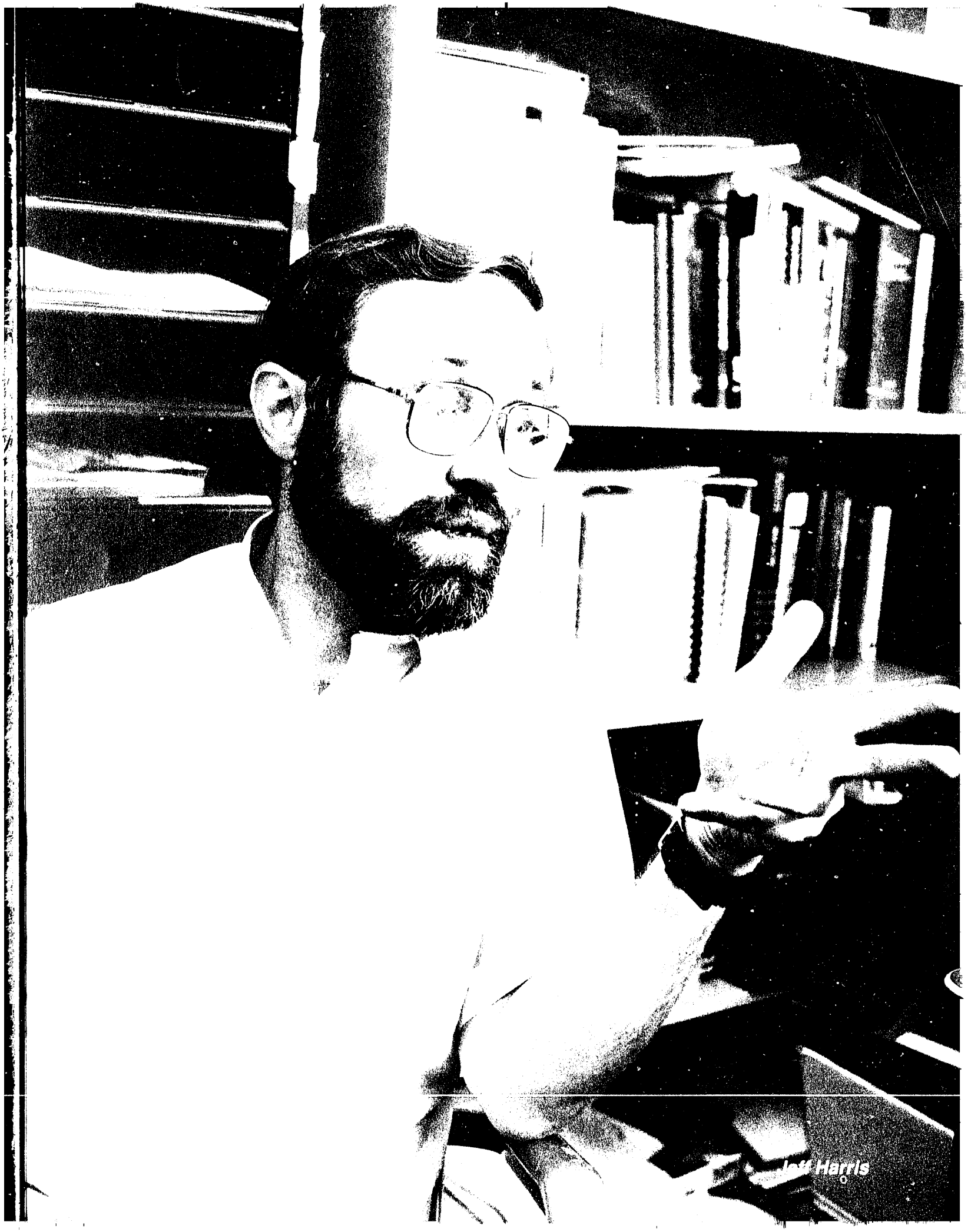
To piece together what happens in fusion experiments, researchers draw on many disciplines: atomic and plasma physics, material sciences, electrical and mechanical engineering, and others. The composite picture is a sketchy one, concedes physicist Ben Carreras: Researchers don't yet have a complete theory explaining the behavior of a magnetically confined plasma, so they rely on assumptions and simplifications to make sense of experimental observations. "For some calculations, it's enough to assume that the plasma is an electrically charged fluid that flows along the machine's magnetic field," notes Carreras. "That's a big simplification."

Other simplifications are necessary to allow computer modeling, another key tool for understanding plasma behavior, adds Glowienka. "If you can model a single particle, you can—with a big enough computer—model an entire plasma," he says. "Right now, we can model the motion of tens of millions of particles. But an actual, real-life plasma may be ten billion times bigger than that.

"In simplifying," Glowienka continues, "sometimes you make the wrong assumptions, or eliminate factors that are important. Or sometimes you can model what's happening but can't solve the equations. We can't quantify a plasma nearly as well as we can, say, interplanetary motion or a slingshot trajectory for the Space Shuttle."

Checking the soundness of the theoretical model is a key mission of ATF; ultimately, of course, experimenters hope both to refine the model and to demonstrate economically

(continued on p. 19)


Jeff Harris

"Wit from woe" : ATF finds shortcut to second stability

It was the fall of 1988. ORNL's newest fusion research reactor, the Advanced Toroidal Facility, was complete—more or less—and beginning its experimental life—sort of.

One of the machine's missions was to explore the "second stability regime," a stable state which the high-strung, gaseous fusion plasma would reach—in hopeful theory, at least—as its temperature and pressure rose above a turbulent barrier zone.

What happened as the $20-million machine began operation is a classic example of the twists and turns—the outtakes and insights—by which real-world science proceeds, says Jeff Harris, a physicist in ORNL's Fusion Energy Division.

Here is the story in Harris's words:

"We were trying to get the machine up and running. We'd had budget problems, and everything was really bare-bones: We had very little in the way of diagnostics [instrumentation] and only about half as much plasma heating power as we'd hoped to.

Then disaster struck.

We were mapping the magnetic flux surfaces in the plasma—those are the contours of the magnetic field which are followed by the plasma's ions and electrons. To map the surfaces, we launch a beam from an electron gun and follow the beam around the magnetic field lines. The electrons follow the field lines like beads on a string; some of them hit a fluorescent screen, giving us a picture of the surfaces.

We expected to see a series of smooth, nested surfaces. Instead, the surfaces were broken up into lots of eddies and bumps and warbles—"magnetic islands," they're called.

Magnetic island are caused by field errors—nonsymmetric distortions in the magnetic field. It doesn't take much of a distortion—about one part in a thousand—to make a significant island.

These islands cause a loss of plasma particles and heat—sort of like a big short circuit. In our case, instead of a nice, smooth pressure profile all the way out to the edge—a gradual drop in pressure from the dense central zone—it was chopped off at the first big magnetic island.

We had worried a lot about this problem, and had gone to great lengths to prevent it. We did hundreds of computer calculations to simulate possible field errors and their effects. We developed special construction and testing techniques to assemble the main magnetic coils within a tolerance of a few millimeters—no small feat, since the coil system weighs about twenty tons and measures almost twenty feet [five meters] across. We even tried out some of our new alignment testing techniques on a Soviet stellarator that had a field error and were able to help find the source of its problem.

So after all this preparation, we were pretty disappointed when the electron beam measurements showed that we had magnetic islands in ATF anyway. Right away we started re-examining our work; we also began a new series of measurements to pinpoint the problem. Eventually somebody did a quick back-of-the-envelope calculation and showed that there was an error in the way the large electrical cables were connected to the helical field coils.

There was a lot of pressure to fix it, this $20-million machine that wasn't working right. It was sort of like the Hubble [Telescope]. It was *very* like the Hubble.

(more)

. . . wit from woe

"We quickly came up with a way to compensate for the field error, but the engineering and hardware for the fix were going to take a few months. In the meantime, we kept the machine running to get some experience and basic data, and to bring the various plasma heating systems and diagnostic instruments into operation.

While we were doing this we took a lot of magnetic fluctuation data, just to see what the plasma's stability looked like. We really didn't expect to see anything special at the modest plasma pressures we were getting. But late one night—it was about midnight—we loaded the results into a Macintosh PC to plot trends in the data.

Originally, we'd thought that at about 3% beta [beta is the ratio of plasma pressure to magnetic pressure—a measure of the energy density of the plasma], second stability could be significant. With the field errors, though, we could get up to only a half-percent, so we weren't expecting much. But the fluctuations increased until the betas got to about 0.3%, then—heavens to murgatroyd!—they started to go down, just as you'd expect with second stability. We looked at each other and said, 'Wait a minute . . .'

It turns out, we discovered, that the bizarre pressure profile we had was an advantage for us because it shifted the center of the plasma outward into a deeper, more stable magnetic 'well.' And the betas—the measly, lousy, crummy betas we had—were enough to get second stability; they were, in fact the easiest way to get it; and if we hadn't had the field error, the best thing to do would have been to create it. We had accidentally done exactly the right thing; we had stumbled into it; to reverse a saying from a Russian writer, we got 'wit from woe.'

But 'chance favors the prepared mind' [Pasteur]. The reason we were able to make the right conclusion is that we were primed for it. To our credit, we jumped on it; we *pounced* on it.

After nearly two years the analysis still holds up. We're happy about that—usually if something's going to turn into a turkey, you know it in a few months.

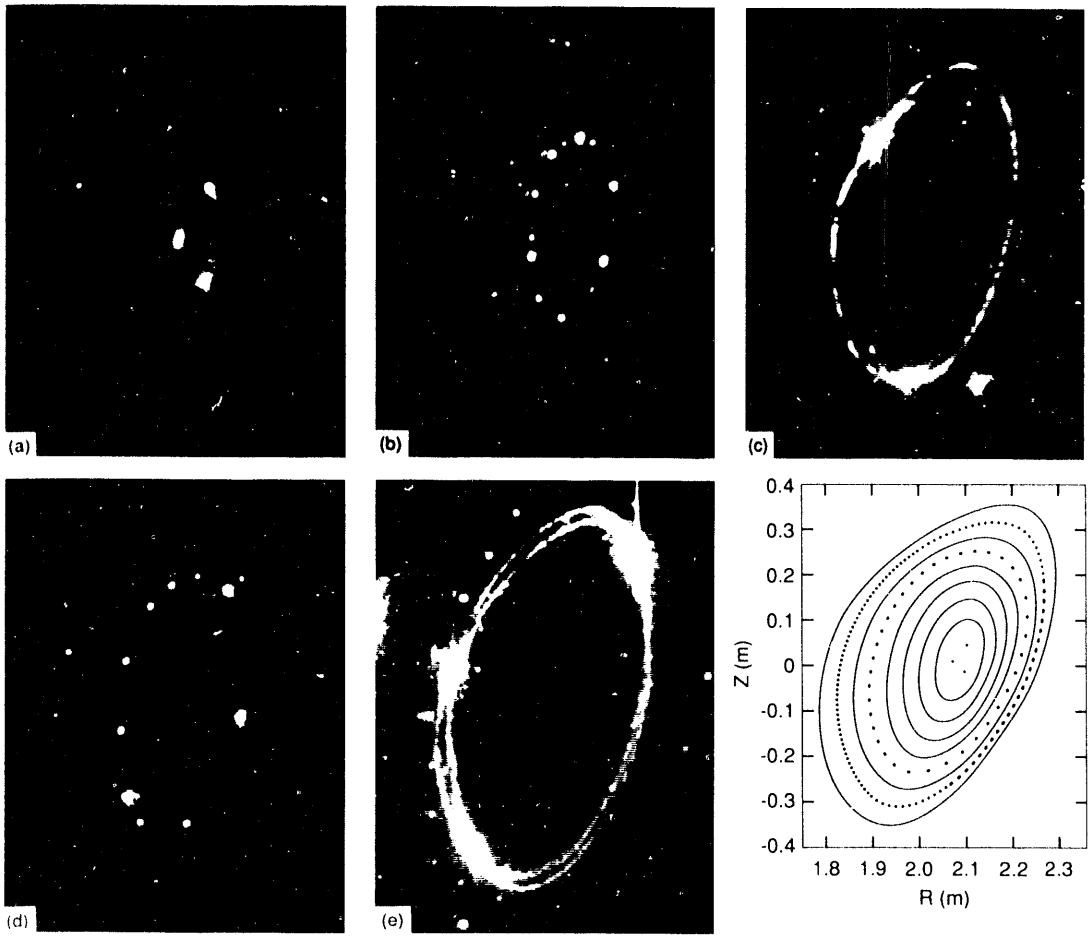
Eventually, history may view second stability the way we view the sound barrier today. People used to think that you couldn't fly faster than sound; that the plane would just break apart. What they finally found was that the plane actually flew better once it got through the turbulence. But even if second stability doesn't prove to be very helpful in a practical way, it's an important validation of fusion theory.

Anyway, that's the story—because of a field error, we were able to lower the required performance for entrance into the second stability regime by a factor of five of six. As a result, we were able to make the world's first direct observations of second stability.

In our scholarly writings, we describe these findings as if we understood them all along. It makes for clearer scientific explanation—but it isn't the way it happened. It never is, in my experience.

It makes a pretty good yarn—but it's only half a story. We didn't get enough data to prove that the plasma confinement had actually improved—that second stability is actually good for something, as we hope it is. Now we hope to go back and reintroduce the sharp plasma profile in a different way, and at higher beats, to see if we're onto something really important.

Then the second half of the story can be told. ❖"

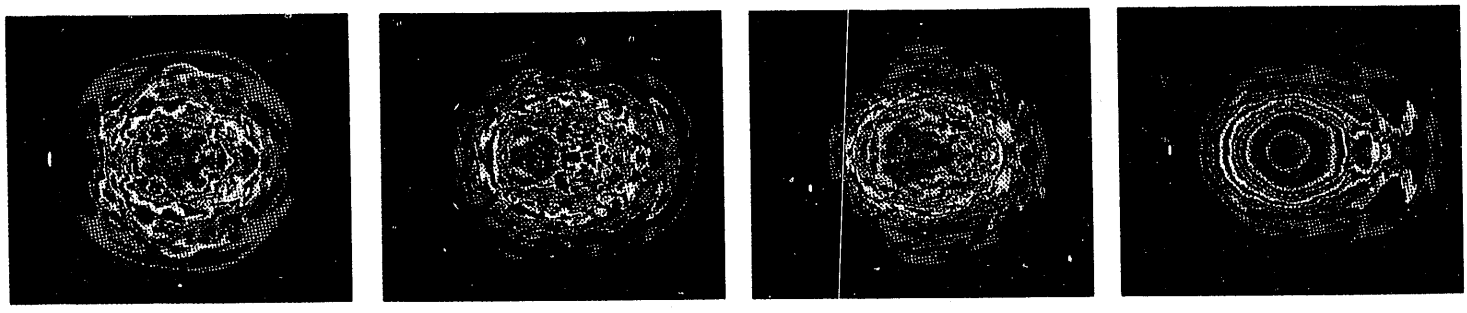


Star light, star bright? These starlike images are actually photos of electrons within ATF. The path traced by the electrons as they spiral outward reveals the magnetic surfaces within the experimental device. The bright spots in (c) and (e) are magnetic "islands," which disrupt the smooth, concentric surfaces researchers seek.

viable fusion. "I'd hate to jump on an airplane designed solely by a theoretician," notes Glowienka. "I'd like to see something experimental showing that at least its predecessor flew."

In addition to the bootstrap-current studies, ATF is also exploring another predicted phenomenon, the second stability regime (see "Wit from woe," above). Second stability, sometimes called "the calm *after* the storm," offers hope that plasma-disrupting turbulence will decline once temperatures and pressures rise above a critical barrier zone.

ATF's ability to explore bootstrap current, second stability, and other plasma behaviors is the result of its designed-in experimental flexibility, which lets researchers vary its magnetic field conditions and watch the effect on the plasma. ATF is a stellarator—similar to the tokamak, fusion's front-runner for commercial viability, but with some key differences that account for its flexibility. Instead of pulsed operation, ATF is designed for steady-state running. Instead of using a combination of external magnets and internal (plasma-generated) currents to confine and control the flow of particles, ATF relies solely on external coils to control and vary plasma conditions.



$\langle\beta\rangle = 0.07\%$ $\langle\beta\rangle = 0.20\%$ $\langle\beta\rangle = 0.38\%$ $\langle\beta\rangle = 0.58\%$

Steps to second stability: These computer simulations show self-stabilization of ATF's plasma. At lower density, or beta (the ratio of plasma pressure to magnetic pressure), the plasma is highly turbulent. At the highest beta (far right), the plasma has stabilized.

And—most striking in sketches of its magnetic field lines—in contrast to the tokamak's smooth doughnut-shaped plasma, ATF's plasma is twisted and convoluted into the form of a bumpy cruller.

These magnetic "bumps," created by ATF's corkscrew magnetic coils, are an important feature in studying bootstrap current, notes Carreras. "The bumps create a viscosity in the plasma, slowing down the flow of particles and creating a charge imbalance," he explains. "By changing the bumpiness, we can change the particle flows and the current. We can make the current large, or we can make it zero."

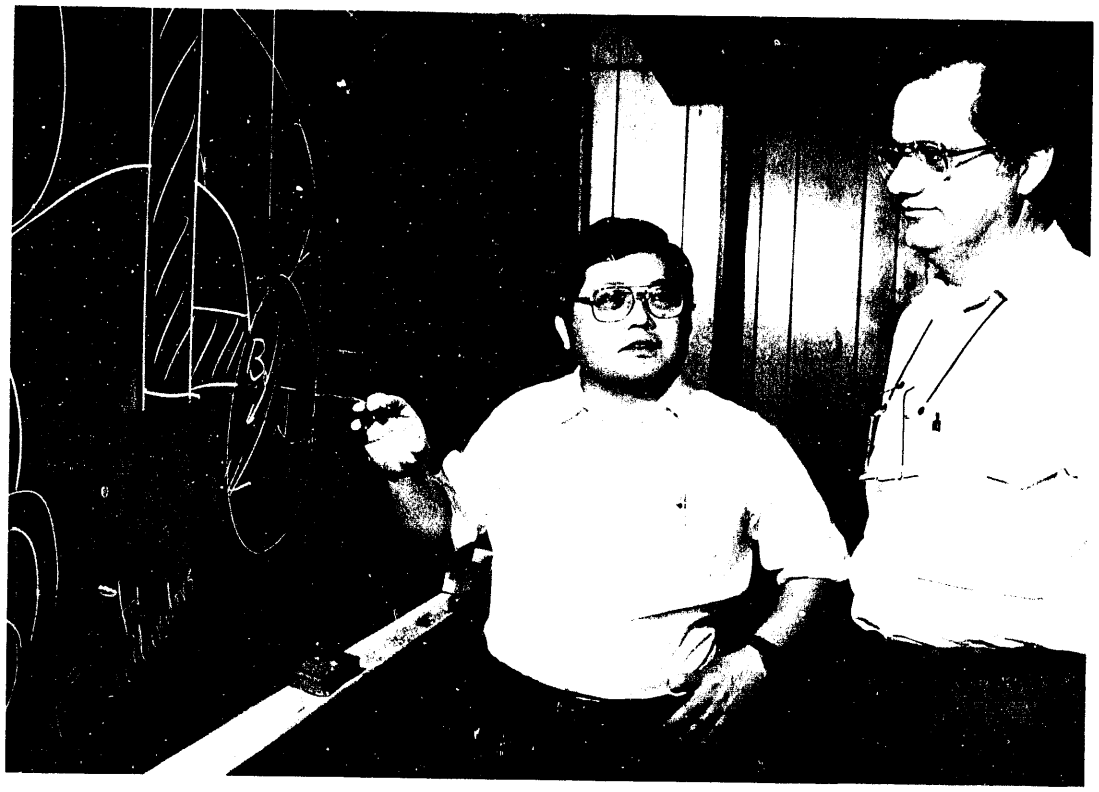
Today's tokamaks, by contrast, require large magnetic currents within their plasmas to create the magnetic bottle that confines the particles and to force the particles to move (and, ideally, to fuse). "In a tokamak, the large current in the plasma generates the fields that confine that plasma," explains Carreras. "That is both the advantage and the limitation of the tokamak. The plasma generates the magnetic field which confines the particles—that makes it simpler in some ways—but you don't have much control over it."

The tokamak's strong plasma current also gets in the way of studying bootstrap current. "In a tokamak, the current that provides the main confining field is thousands of kiloamps," says Glowienka. "The predicted bootstrap current for experiments on today's scale is only about ten kiloamps"—a relative whisper of current, one drowned out by the tokamak's confining current. "The beauty of ATF is that the plasma can be current-free," he adds. "There's no 'shouting,' so you can hear the whisper."

The bootstrap current findings have potential benefits for both ATF and tokamaks, points out physicist Masanori Murakami. "In a tokamak, you want to maximize the bootstrap current, to provide the 'drive' that moves the particles. In ATF you want to minimize it, to make it zero. So it's important for us not only to verify the theory, but also to demonstrate the ability to control the bootstrap current."

What lies ahead on ATF's 'bumpy' road

Exploring bootstrap current further—refining both theoretical understanding and experimental control—is just one of the items on ATF's experiment agenda over the next seven years, says Glowienka. Other goals include a boost in plasma heating power (to allow higher temperatures and pressures) and an increase in



Physicists Masanori Murikami, left, and Ben Carreras help interpret the experimental observations of bootstrap current in ATF.

running time from 20 seconds (the current limit) to an hour or, eventually, continuous (steady-state) operation.

A more general goal for the entire U.S. and international fusion program is to pinpoint the cause of energy leaks and to find ways to plug them. This goal will require fusion-reactor components that can achieve and sustain the high-temperature, high-pressure conditions for fusion . . . and more precise models of other facets of plasma behavior, such as those provided by ORNL's success with bootstrap current and second stability. The goal isn't perfection; just higher confidence.

"We could go out today and build a reactor that might work," speculates Glowienka, putting the present odds of success at perhaps 50-50. "But it's hard to ask the taxpayers for $5 billion for something that has a 50-50 chance of working. Also, it would have to be really big—two to five times bigger than utilities would want. And because of the pulsed current drive, you'd have to start it, shut it off, start it, shut it off . . . the kind of cyclic stress that causes things to break."

Still, Glowienka is optimistic. "In contrast to the forties and fifties, when we were a factor of a million away from scientific breakeven, now we're within a factor of two.

"We'll always have a leaky bucket," he concludes. "Right now, we think it's leaking faster than we can afford. We just gotta be smart enough to know which holes we can plug."❖

Editor's note: Because of reductions in the national fusion budget, ATF may have to be placed on standby in October 1991.

ORNL researcher probes "cold fusion"

It sounded too good to be true—and it was. That, at least, has been one judgment widely pronounced on "cold fusion."

But not everyone is giving up on the phenomenon, even if they aren't quite sure that it's fusion. So says ORNL chemical engineer Chuck Scott, who continues to see intriguing results form a series of experiments he began a year-and-a-half ago.

Cold fusion, or "fusion in a jar," was announced with great fanfare at a Utah press conference in March 1989 by researchers Stanley Pons and Martin Fleischmann. The pair said that they had achieved fusion, a potentially limitless source of power for the future, in a simple electrolytic cell at room temperature—far below the millions of degrees required for conventional "hot" fusion. The reaction was fueled by heavy (deuterated) water and catalyzed by a palladium electrode; the proof, they said, was twofold: the unusual heat produced by the reaction, plus the presence of many tritium atoms, explainable only by the fusion of deuterium.

But quickly overshadowing any chemical or physical reaction in the laboratory was the emotional reaction in the fusion-research community. Many scientists lined up on either side of a heated "is it or isn't it?" battle. After several months of initial support from other labs, Pons and

Fleischmann's methods and conclusions began to draw increasing fire. Perhaps most damaging, the June 1990 issue of *Science* magazine published a news/comment article suggesting that the tritium findings at Texas A&M University—an important independent corroboration for Pons and Fleischmann—were tainted by sloppiness or, worse, outright fraud.

Within a month after the initial announcement of cold fusion, Scott and some of his ORNL colleagues set up a series of electrolytic cells based on the Pons and Fleischmann announcement. Using somewhat more sophisticated instrumentation, the ORNL experimenters searched for tritium, excess heat and neutrons produced by the cells—evidence that could help or hurt the claims for cold fusion, or point to some other reaction.

In hundreds of hours of operation with a half-dozen test cell, Scott has seen results that are both erratic and intriguing: Some of his test cells have done nothing noteworthy; others have produced "small but significant" quantities of neutrons and excess heat for more than 200 hours at a time, says Scott—sometimes continuing for a while even after a cell's electric current has been switched off.

Scott is confident he's seeing something real—he just isn't quite sure what it is. "The concensus of the people still involved is that there is an effect of unknown genesis—excess energy or excess power. It can't be consistently reproduced . . . but it also can't just be discarded," he asserts. "The excess energy is pretty well accepted by people who are involved in the field, but nobody has any idea what the mechanism is, so to call it cold fusion is certainly premature."

Like many other researchers, Scott thinks Pons and Fleischmann should have sought more peer review before announcing their theories in the mass media. He also takes a more conciliatory view, though, noting, "All of us get involved in things that lead us down blind paths.

"We certainly don't want to claim something that isn't there, but it also seems appropriate to investigate it," he concludes. "After all, it is the essence of science to investigate the unknown." ❖

Echoes of Red October

ORNL technology aids sub-hunting, stealth

Deep beneath the waters of the world's oceans, submarines play a ghostly quiet game of cat-and-mouse. Perhaps the key players are the "boomers," the strategic (missile-carrying) subs that carry enough nuclear-tipped missiles to destroy dozens of inland targets. But each side's boomers are targets, too, stalked by the other side's smaller, nimbler attack subs.

This high-stakes game is the stuff of which spy thrillers are made, as the success of *The Hunt for Red October* attests. Two projects within ORNL's Instrumentation and Controls Division are playing a part in the game.

The projects, sponsored by the Navy's David Taylor Research Center in Bethesda, Maryland, and the Naval Sea Systems Command, focus on submarine acoustics. For a submarine it is sound, measured on the scale of whispers, that can spell the difference between stealth and detection, between success and failure, maybe between life and death.

According to Jim Jansen, leader of the Real-Time Computing Systems Group, ORNL's submarine work involves both "theirs" and "ours": listening for theirs; shrouding ours in silence. Since 1985, the group has developed and delivered systems representing an $11 million investment by the Navy in ORNL's instrumentation and computing expertise; another $9 million worth of work is still under way.

Rig for silent running

Aboard a floating acoustics laboratory somewhere at sea, technicians listen to every new U.S. submarine. The Navy hopes they don't hear much.

"Before a submarine is delivered to the Navy, the ship has to pass a series of rigorous tests to make sure it's not generating too much noise," explains Randall Wetherington, project manager for a new ship-based analysis system ORNL has developed for the testing facility. In addition to initial tests, all U.S. subs have periodic checks to make sure they're still running quietly.

The complete noise-testing process can take anywhere from two days to a week. Acoustic data are acquired as the sub performs different maneuvers, with different pieces of equipment operating. "They turn on pumps, run the periscope up and down—all the things they would do on a mission," says Wetherington. The arrays of hydrophones pick up the sub's faint sounds on each pass; these sounds are then converted to digital data and analyzed with a data-processing system developed by the ORNL group.

The ORNL-developed system must handle large amounts of data in small amounts of time: over two million data samples per second from the array elements. The system must analyze the data in real time—the five minutes the test run takes—because as soon as the sub completes one test run, it turns around and makes another. To keep up with the flood of data, the system uses eight computers operating in parallel; together, they can perform 400 million calculations a second. The data from each run, which totals four gigabytes, is temporarily stored on computer disks; then it is compressed to a final size of about four megabytes by the data-analysis system as the sub prepares for a new run.

The system has been installed on a research vessel, the *MONOB* (for MObile NOise Barge), a converted World War II-vintage water tender. With the installation of the data-analysis system aboard the *MONOB*, one phase of ORNL's contribution to the sub-testing program was completed. Now the Laboratory is helping with a second, more challenging phase, which may take up to five years: the development of supersensitive systems—new hydrophone arrays and new

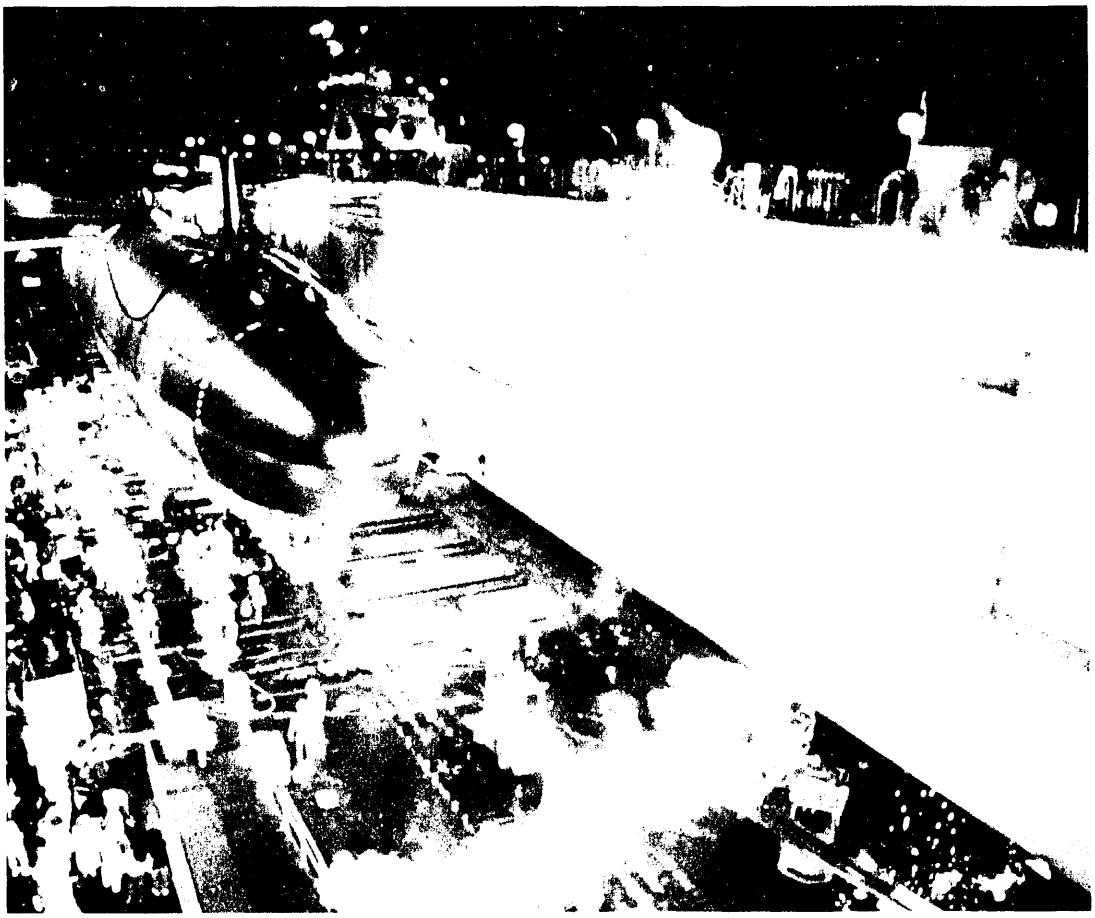
Techno-thriller stars sub-chasing technology

As this and the following excerpts show, Tom Clancy's fictional novel *The Hunt for Red October* (Naval Institute Press, 1984) vividly dramatizes the undersea game in which ORNL's submarine-acoustics projects play a vital part.

"Throughout the oceans of the world, and especially astride the passages that Soviet submarines had to cross to reach the open sea, the United States and other NATO countries had deployed gangs of highly sensitive sonar receptors . . . . Very little could cross a barrier without being detected. Even the ultraquiet American and British attack submarines were generally picked up."

U. S. Navy

"During her last overhaul, the ***Dallas*** *had received . . . the most powerful computer yet installed aboard a submarine. . . . Its purpose . . . was to process and analyze sonar signals; [it] stripped away ambient noise and other naturally produced sea sounds to classify and identify man-made noise. It could identify ships by name from their individual acoustical signatures, much as one could indentify the finger or voice prints of a human."*



Paramount Pictures Corp.

Big fish out of water: a scene from the Paramount thriller *The Hunt for Red October.*

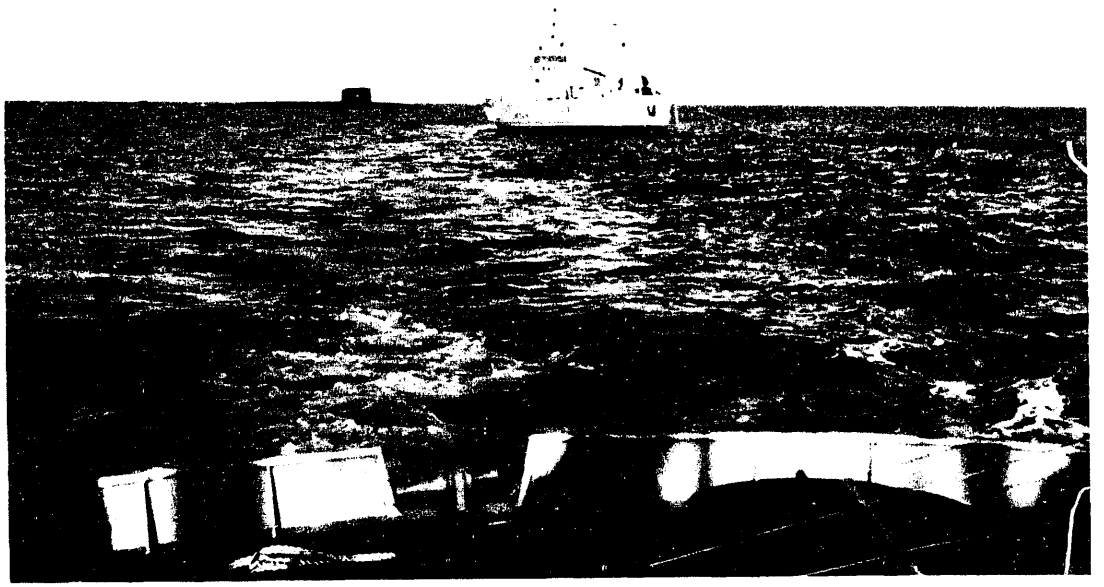
data processing capabilities—to test the even quieter submarines of the future.

Building a slice of ocean

President's Island, Memphis, Tennessee—At a long-idle ironworks on a Mississippi River peninsula—a facility that once made reactor pressure vessels, until the nuclear industry ran aground—the Navy is now completing the world's largest pressurized water tunnel.

The tunnel—the length of a football field, and pressurized to simulate conditions deep underwater—will serve submarine designers the way wind tunnels serve aerospace engineers: as a tool for systematically studying the flow of water around models of hulls, propellers, and other components of submarines and ships.

The tunnel is called the Large Cavitational Channel, a reference to the problem it's designed to fix. "Cavitation is the bubbling effect made by propellers, hulls, et cetera, under adverse pressure and velocity conditions, or when actual flow properties don't



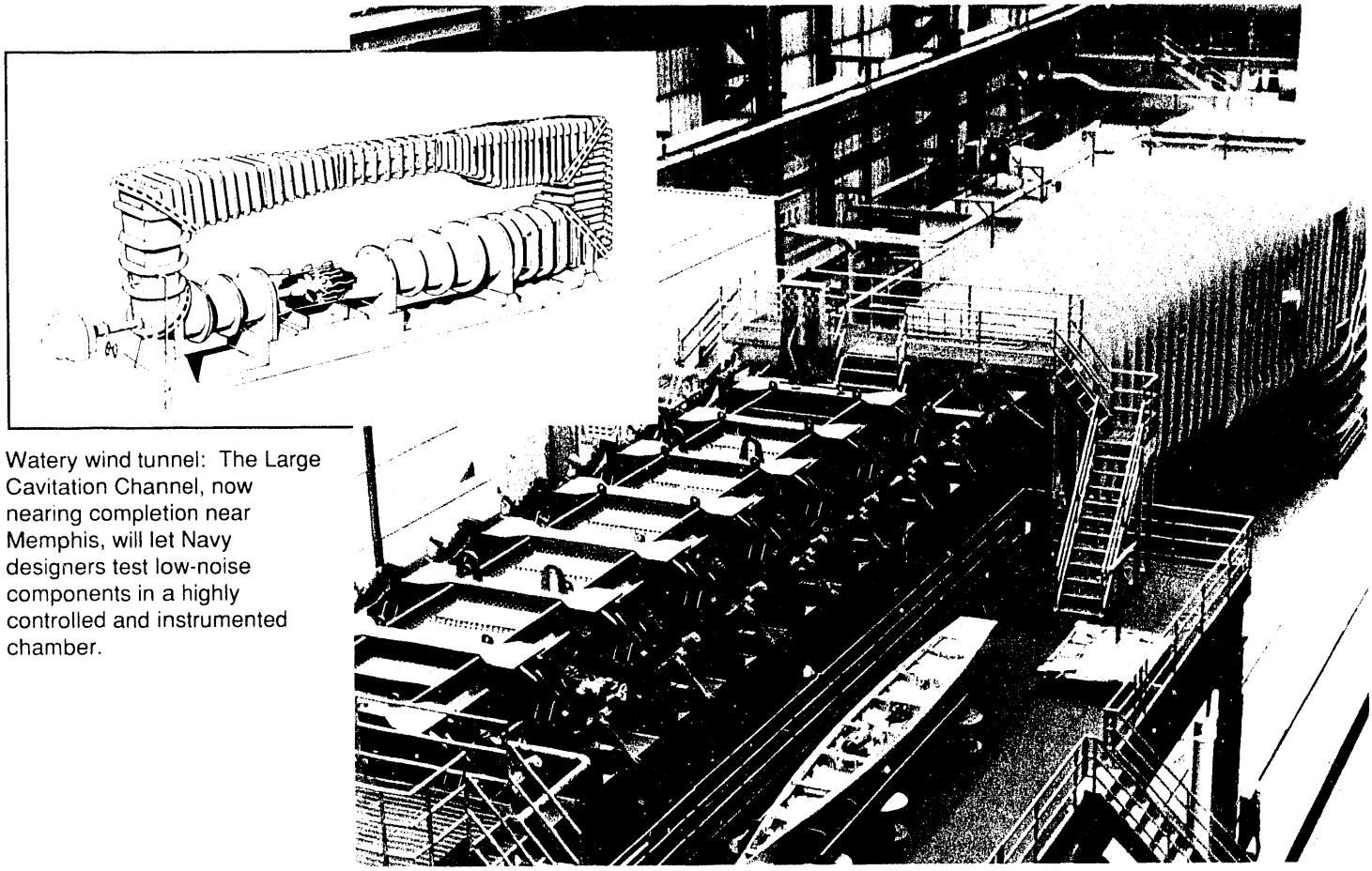
The *MONOB*, a floating acoustic lab, includes an ORNL data-analysis system. Silhouetted against the horizon is a submarine undergoing acoustic tests.

"The operating pattern of an attack submarine was much like that of a combat infantryman. With a rifleman it was called dash-and-cover; with a sub, sprint-and-drift. After detecting a target, a sub would race to a more advantageous position, stop to reacquire her prey, then dash again until a firing position had been achieved. The sub's quarry would be moving too, and if the submarine could gain position in front of it, she had then only to lie in wait like a great hunting cat to strike."

match the assumed design conditions," explains Wayne Manges. To stealth-prizing submariners, cavitation is an especially unwelcome phenomenon because it creates telltale noise.

Manges is project manager for ORNL's development of systems to record and analyze all the data from the tunnel: acoustic signals from the models and components tested, as well as data about conditions such as water temperature and pressure, flow rate, and air content. Because the tunnel is highly instrumented, the data systems must process large volumes of data (9.5 megabytes per second), and do it very quickly (200 million operations per second).

The Memphis facility, scheduled to begin operation in the fall of 1991, is not the only place for large-scale testing of ship and submarine designs: At the David Taylor Research Center, there's a longer (but unpressurized) tank through which models are towed, and at a deep lake in northern Idaho, a 33-meter (110-foot) unmanned submarine serves as a realistic testbed for new



Watery wind tunnel: The Large Cavitation Channel, now nearing completion near Memphis, will let Navy designers test low-noise components in a highly controlled and instrumented chamber.

U. S. Navy /David Taylor Research Center

*"The **Dallas** was quartering an area east of the Grand Banks. . . . They were moving at five knots, trailing out the BQR-15 towed-array sonar. They'd had all kinds of contacts. First, half the submarines in the Russian Navy had whipped by at high speed, many trailed by American boats. An **Alfa** had burned past them at over forty knots, not three thousand yards away. It would have been so easy, Jones had thought at the time. . . . That **Alfa** had been meat on the table."*

Members of I&C's submarine-acoustics team, some sporting Navy submarine caps.

equipment and operating procedures. But the Memphis tunnel will allow far more precise control of hydrodynamic test conditions and will yield data that are far more detailed than the other big test facilities yield. The eventual payoff: U.S. subs that are ever quieter, ever more elusive.

The Navy is understandably tight-lipped about many of the details of its submarine and sub-hunting technology, even with the ORNL experts it has turned to. "We tell the Navy that we've found out more from *The Hunt for Red October* than we have from them," Jansen says, only half-jokingly.

Finally, after a string of unanswerable questions, Jansen smiles. "Go read the book." ❖

'FOOTBALL' THEORY: TIME TO PUNT?

Physicist sticks 'neck' out for new heavy-ion fusion theory

Physicist Paul Stelson builds his case for a new theory of heavy-ion fusion with experiments at ORNL's Holifield Heavy Ion Research Facility.

Advances in scientific thinking sometimes run a challenging obstacle course before winning broad acceptance. Consider the theories of Einstein or Copernicus.

Scientific controversies no longer get quite so heated now, of course, as when Copernicus got burned for positing the heliocentric solar system. Still, in science theory as in politics, an incumbent has a natural advantage over a challenger.

Just ask Paul Stelson.

Stelson, a researcher in ORNL's Physics Division, has spent the past few years backing a theoretical challenger. So far the incumbent theory still holds sway. But Stelson thinks the new theory is gaining ground.

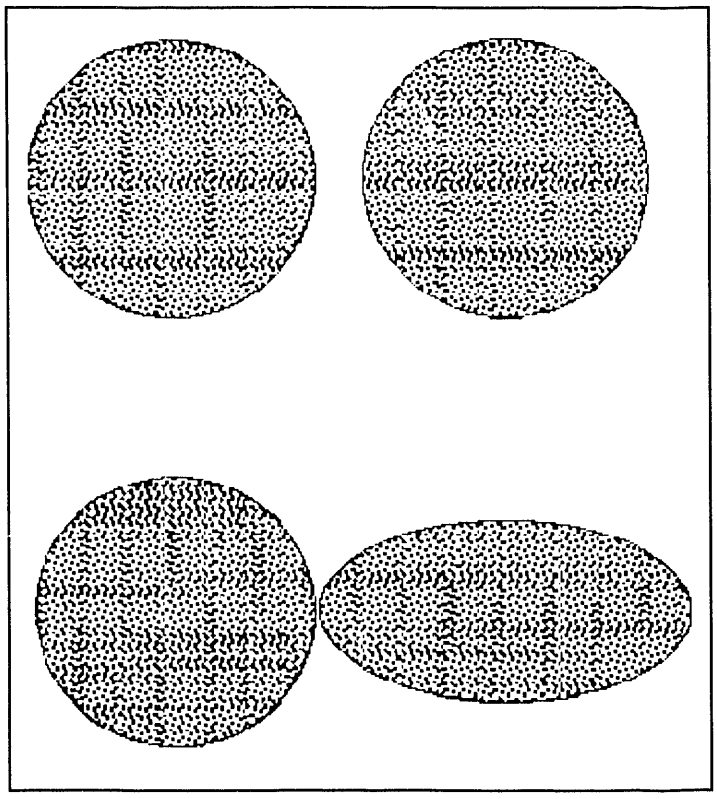
Stelson's dark-horse theory would change the accepted view of what causes higher-than-predicted rates of fusion among nuclei of heavy ions, such as calcium and nickel, when one is hurled at another by an accelerator. The current view is something Stelson calls the "football theory." Stelson wants to supplant it—or at least supplement it—with what he calls the "neck theory."

Curiously, one of the original goals of research on heavy-ion fusion was a better understanding of the reverse process, fission. Stelson explains: "Even though we've known about fission for more than fifty years, there are a lot of things, from a nuclear physics point of view, that we haven't fully understood, such as why a nucleus splits into unequal fragments. The idea behind heavy-ion fusion is that if we can bring nuclei together, we can better understand what happens when they split."

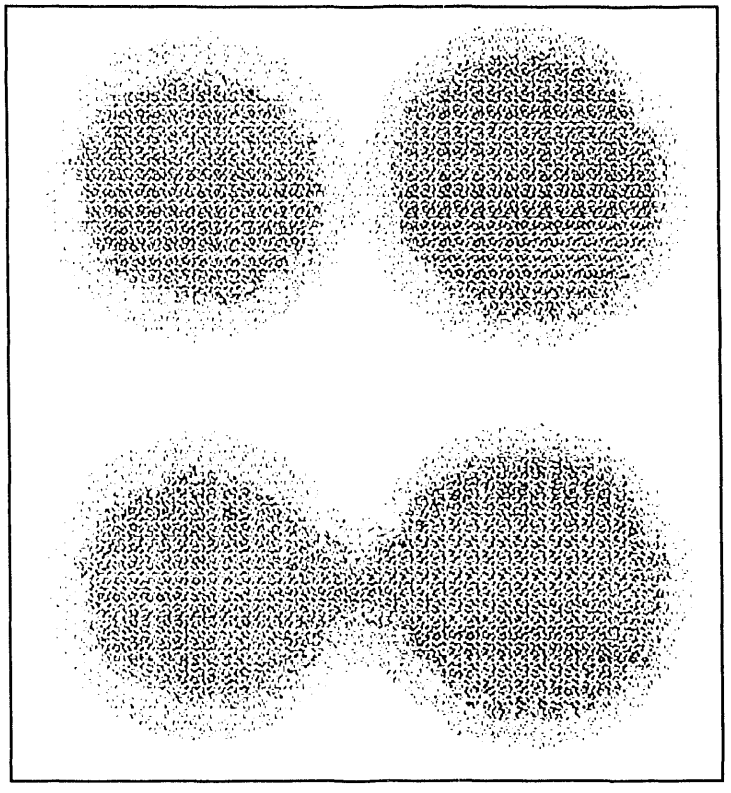
This back-door approach to understanding fission occurs at ORNL's Holifield Heavy Ion Research Facility, where nuclei from tin, nickel, lead, and other heavy elements are forced together, typically at energies of several hundred million electron volts (eV). It's a bit like targeting one subatomic billiard ball with another one moving at millions of kilometers an hour.

The subatomic billiard games at the Holifield have had some surprising outcomes. "When we first started looking at this process about ten years ago, one of the early findings was that these heavy nuclei fused together much more often than we thought they would—orders of magnitude more often," recalls Stelson. "We've always known that they'll fuse if you bring them close enough together, where the attractive nuclear force is strong enough to overcome the Coulomb barrier. But what people began to find in experiments at the Holifield is that you don't have to bring the nuclei as close together as we thought."

The Coulomb barrier—named for Charles A. de Coulomb, the eighteenth-century French physicist who first measured electrostatic forces precisely—is the inherent repulsion



The "football" theory relies on nuclear deformations to explain the penchant of nuclei to fuse.



According to the "neck" theory, the outermost nucleons pull nuclei together, much like two drops of water.

between two positively charged particles. The Coulomb barrier poses a hurdle that must be cleared—physicists speak of its "height"—before the stronger but shorter-range nuclear force kicks in to draw subatomic particles together. "When a nucleus splits, the nuclear force that's broken to release the fragments can be as much as a ton," notes Stelson. From a heavy-ion fusion perspective, then, nuclei find one another powerfully attractive, but only after they've gotten past the outlying Coulomb barrier.

The puzzling thing—the thing current theory has difficulty explaining, says Stelson—is why fusion so often occurs between particles that don't quite have the energy needed to clear the top of the Coulomb barrier. On the miniscule scale of the Coulomb barrier—typically 1 to 2 fermis (that's 1 to 2 millionths-of-a-millionth of a millimeter)—the force drawing nuclei together is only a hundredth as strong as the Coulomb force driving them apart. Despite the apparent lopsidedness of the forces, says Stelson, some nuclei with energies 5 to 10% below the threshold fuse up to 1000 times more often than traditional physics calculates it should.

The effort to explain the higher-than-expected rates of subbarrier fusion has given rise to some theoretical contortions, explains Stelson. "Nuclei are not really spherical; they're deformed by the nuclear forces between the individual protons and neutrons. Uranium nuclei, for example, are football-shaped. If you bring together two permanently deformed nuclei in the right orientation, it's kind of like throwing two footballs at each other: The pointed ends collide first, and sooner than if you threw two round balls together. Technically, this deformation—its contribution to fusion—is known as the 'collective effect.' I call it the football theory."

In the effort to make experimental results fit the theory, says Stelson, some physicists have assigned "extremely generous or even unrealistic amounts of collectivity" to the colliding nuclei. In simpler terms, they've assumed *very* long footballs—about twice as long as other measurements and calculations suggest is the case.

"My own view, though," Stelson continues, "is that when you bring two nuclei together, they form a 'neck' of material—the way two drops of water do when they suddenly join—through which neutrons can flow. I think it's this neck of material that causes the nuclei to fuse: As the nuclei come together, the outer nucleons probe each other, start to interact, and pull the two together."

To test the theory, Stelson is methodically bringing nuclei together at subbarrier energies—energies at which the Coulomb force would normally cause them to just bounce off one another. With some kinds of nuclei, especially light isotopes, that's exactly what happens. But with others—especially heavier nuclei, and particularly *their* heaviest, neutron-laden isotopes—the odds of fusion are clearly higher.

This "enhanced fusion" is not, Stelson stresses, related

to "cold fusion"—a fact he also pointed out to a physicist who came calling from Utah, the birthplace of the cold fusion theory.

The key to higher fusion among heavier isotopes seems to be their larger number of valence neutrons—the outermost, loosest-bound ones. "In those isotopes, the valence neutrons—which make up a neutron 'skin'—tend to stick out," explains Stelson. "For example, calcium-48 has eight more neutrons than calcium-40, and it's more likely to fuse. So is nickel-64, which has more valence neutrons than nickel-58."

Although experimental results in Oak Ridge and elsewhere are lending support to the newer theory, resistance to it remains strong, partly because the calculations it entails are far more complex than those for the football theory and must be worked out individually for each kind of nucleus. As a result, says Stelson, some physicists dismiss it simply because they hope it isn't true.

"I favor the neck approach; I think 90% of physicists . . . don't," he calculates. "There is something [in the football theory], but I don't think it adequately explains the phenomenon. In lighter systems, like oxygen bombarded onto nickel, collective effects could be the main factor. But when you go to heavier systems, like tin on nickel, the collective effects get harder to invoke."

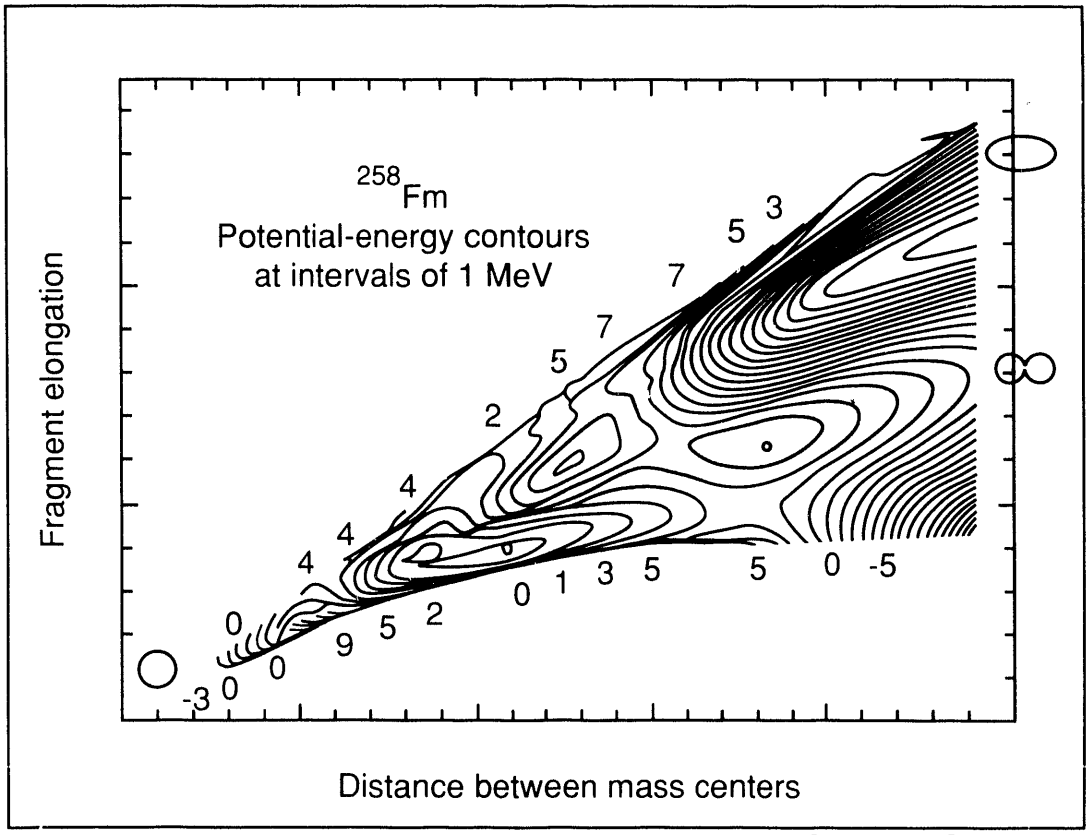
Could a combination of the two theories explain the experimental results? "It could, but . . . ," Stelson trails off. "The collective effects seem to modulate where the neck formation occurs. Where the neck starts forming can depend on whether the nuclei are deformed, but the deformation is not the primary factor in many of these enhanced fusion reactions."

"I wouldn't want to bet $10,000 that I'm right, but my thinking is that the primary factor is the neck formation—which can be *modulated* by the collective effect."

"You can't get in there and take a picture. If you could, you could convince everybody, but it isn't possible."

"You also can't legislate these theories. All you can do is keep trying to gather more information and hope people will be convinced." ❖

Mapping nuclear fragmentation: This "contour map" shows different paths a fermium-258 nucleus may take—depending on how it deforms—as it splits into fragments. The changing energy potential follows the course of the upper "valley" if the nucleus elongates football-style before splitting; it follows the lower valley if the fission involves the more compact shapes posited by the neck-formation theory.



(Source: Lawrence Berkley Laboratory)

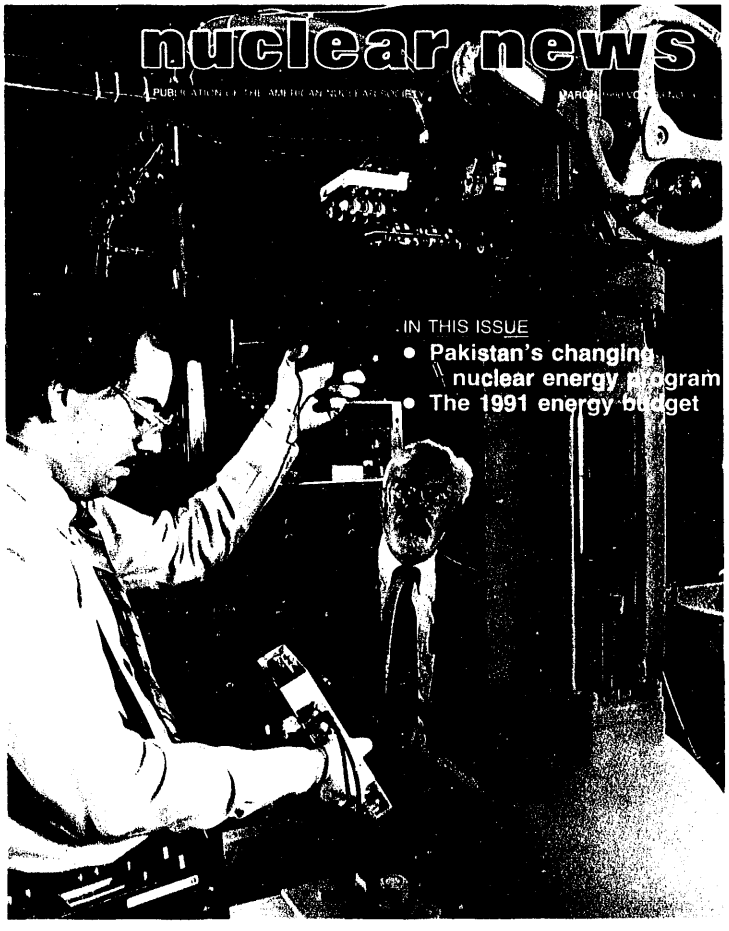
EKGs FOR MACHINES

Diagnosing equipment from electrical "signatures"

Chances are you've already been hooked up to this technology's medical first cousin.

Motor current signatures—written not in ink, but in amperes and cycles per second—are close kin to electrocardiograms, or EKGs. Just as the heart, healthy or otherwise, produces characteristic electrical fluctuations (the heart is, after all, a bioelectric pump), so does any electric motor. An EKG can give a doctor early warning of arterial blockages, arrhythmia, heart enlargement, and other cardiac problems. In much the same way, a motor current signature analysis (MCSA) can give an equipment operator or engineer advance warning of poorly seating valves, failing bearings, flow obstructions, and other troubles.

Howard Haynes (left), Dave Eissenberg, and their valve-testing system made the cover of *Nuclear News* in March 1990.



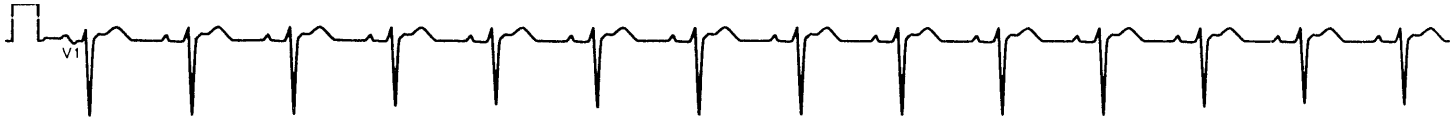
According to its ORNL developers, this new diagnostic technique reveals a wealth of previously hidden detail about the motor itself . . . and about whatever the motor is pushing/pulling/turning/driving/pumping/compressing.

In pedigree, the technique is purebred nuclear. ORNL engineers Dave Eissenberg and Howard Haynes initially developed MCSA for the Nuclear Regulatory Commission as a way to monitor the toll which aging and wear take on motor-operated valves in nuclear power plants. ORNL instrumentation expert Bob Kryter helped translate Haynes's signal-processing techniques, including demodulation, filtration, and amplification, into a portable, battery-powered system for field use. Taking the same idea down a somewhat different electronic path, Steve Smith of ORNL and Don Hendrix of the Oak Ridge Gaseous Diffusion Plant developed a signal-processing technique to monitor the large compressors used in uranium enrichment.

Now, with both MCSA technologies receiving patents, the developers and marketers of this nuclear-bred monitoring technique are looking toward other applications, including coal-fired power plants, steelmaking machinery, chemical process equipment, and even consumer appliances.

The China Syndrome and other preventable nightmares

Remember *The China Syndrome*, the Jack Lemmon/Jane Fonda thriller about a near-meltdown at a nuclear power plant? The plant's problem—well, one of its problems—was a mysterious "shudder," which Lemmon's engineer character finally traced to a faulty feedwater pump. Okay, okay, it's all make-believe, but play along: Suppose Wilford Brimley, who played the reactor operator, could have simply glanced at a computer screen 10 minutes into the film and drawled, "Well, Jack, looks like we got ourselves a burnt bearing in that auxiliary feedwater pump there." End of



Normal EKG

mystery. End of problem. End of film. (Not much of a movie, true, but that's a different dilemma.)

The focus of the technique developed by Eissenberg, Haynes, and Kryter is a reminder of how closely life sometimes parallels art. The motorized valves that control the flow of feedwater and steam are crucial elements of a reactor's safety systems. In a 1985 event at an Ohio nuclear plant, for example, two balky valves turned a minor incident into a potentially crippling accident. The closed valves, which failed to open on command, cut off all feedwater to the reactor's steam generators. Both generators boiled nearly dry, and the temperature and pressure of the reactor's coolant rose sharply. It was more than 15 minutes before the valves could be opened by hand and the reactor stabilized.

The basis for the signature-analysis system is this: While a motor is doing the work it's designed to do, it also acts as a continuous "transducer," turning variations in its mechanical load into corresponding variations in the electric current it draws. If, for example, damaged gear teeth cause a momentary increase in friction each time they grind together, the motor instantly compensates each time by working harder—and drawing more current. "An electric motor is self-compensating; it naturally tries to maintain a constant speed," explains Kryter. "The harder you try to restrain it, the harder it pulls." Sort of like kids.

To find a way to use this phenomenon in a workable monitoring system, one that could diagnose problems in valves (and in the motors powering them), Haynes used a laboratory test rig equipped with a valve like those used in many nuclear plants. "Once I came up with the signal-processing techniques to read the valve motor's normal signature," Haynes explains, "I introduced some common defects—damaged gear teeth, overtight valve-stem seals, and so on—to help me interpret abnormal signatures." Haynes and Kryter then gathered signatures from more than 20 valves at various nuclear plants as a way to gauge the similarities and differences in signatures from individual motor-operated valves.

An on-line system developed by Haynes, Kryter, and others was used in late 1989 and early 1990 to monitor eight motor-operated valves at Philadelphia Electric Company's Eddystone power plant, a coal-fired plant that houses a utility-industry research center. The valves they monitored route steam to heat the boiler's feedwater—and block it if a significant leak should occur in a heater tube. During the four-month test, the on-line system was used to record and analyze electrical signals from "well over a thousand" openings and closings of the valves, says Haynes. In addition, the researchers used portable MCSA equipment to gather signatures from pumps, fans, compressors, and other equipment.

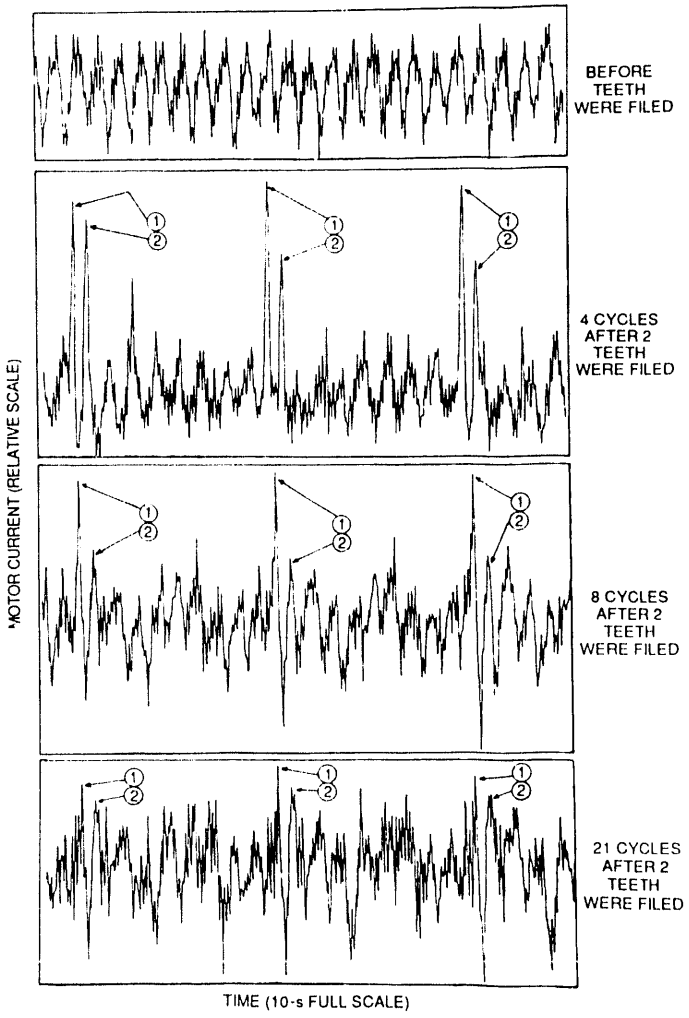
The on-line system discovered several potentially serious

Instrumentation engineer Bob Kryter helped shrink the diagnostic components into a portable system for field use.

Abnormal EKG

EKG courtesy of University of Tennessee Memorial Hospital

Motor current signature before and after introduction of a gear defect. Gradually the defect "wears in" and becomes less distinct.



problems that are now being corrected at Eddystone, says Haynes. The data showed that MCSA can give early warning of a variety of problems, including poor lubrication, rough gears, and incomplete seating of valves. In addition, the experiment demonstrated that demodulated motor-current signals can detect broken rotor bars in motors—a capability that makes it useful for nearly any kind of electric motor.

The Electric Power Research Institute, a nationwide utility consortium, has closely followed the development of MCSA and other preventive monitoring techniques. EPRI's Monitoring and Diagnostics Center, the research facility located at Eddystone, is now being equipped for routine use of MCSA. At ORNL, meanwhile, the technique is being considered—not surprisingly—for use at the High Flux Isotope Reactor, as well as in advanced heating and cooling equipment now under development.

Elsewhere, the technique has sparked the interest of other government agencies. "The Navy is considering it for monitoring shipboard equipment," says Eissenberg, "and NASA's Goddard Space Flight Center is interested in using it for life-testing equipment that will be going into space."

Tuning in signals broadcast by motors

One of the key selling points of MCSA is that it offers a way to extract and interpret detailed information that is already carried by a motor's power lead—information that, until now, has remained largely unknown and inaccessible. It's there for the taking, without the need for expensive, specialized equipment such as vibration accelerometers. Once you figure out how, tapping the information is a bit like using a radio to tune in free broadcasts, instead of hiring a band to custom-make music.

The concept is elegantly simple, explains Steve Smith: "Anything that varies a motor's load—shaft wobble, bearing drag, process variations in the equipment that the motor is driving—causes instantaneous variations in the shaft torque." Those variations, in turn, change or modulate the motor's "slip frequency," the rate at which the spinning armature continuously lags behind the rotating electric field (generated by the motor's field windings) that pulls it along. If you're confused, try this: Picture a donkey being coaxed along by a carrot. If he's straining under a heavy load, he has trouble keeping up with the carrot; if his load suddenly lightens, he gains on it. If the donkey worked as precisely as an electric motor, you could read variations in his "slip distance" as a measure of his changing load.

With ac motors, the challenge is how to spot the small variations, which are normally overshadowed by the strong peaks that occur 60 times each second, when the powerline's current reverses direction. "If

you think of the 60-Hz component as a carrier wave, the modulations appear as sidebands above and below it," explains Smith. "But they're very small—so small that often a standard spectrum analyzer can't pick them up because they're below its noise floor." Smith designed his own version of a demodulation circuit to extract the useful information from the signature. The circuit works much like a Sony Walkman extracting music from a radio wave: It cancels out the carrier wave; boosts the weaker, diagnostically useful signals; and plots them either by amplitude (relative strength) or by phase (related to the change in slip frequency).

Smith's system can greatly boost the sensitivity of standard signal-spectrum analyzers—"by a factor of a hundred," he says—and at very little cost. "These spectrum analyzers may cost 25 grand," Smith notes. "The demodulator can be mass-produced for maybe 25 bucks."

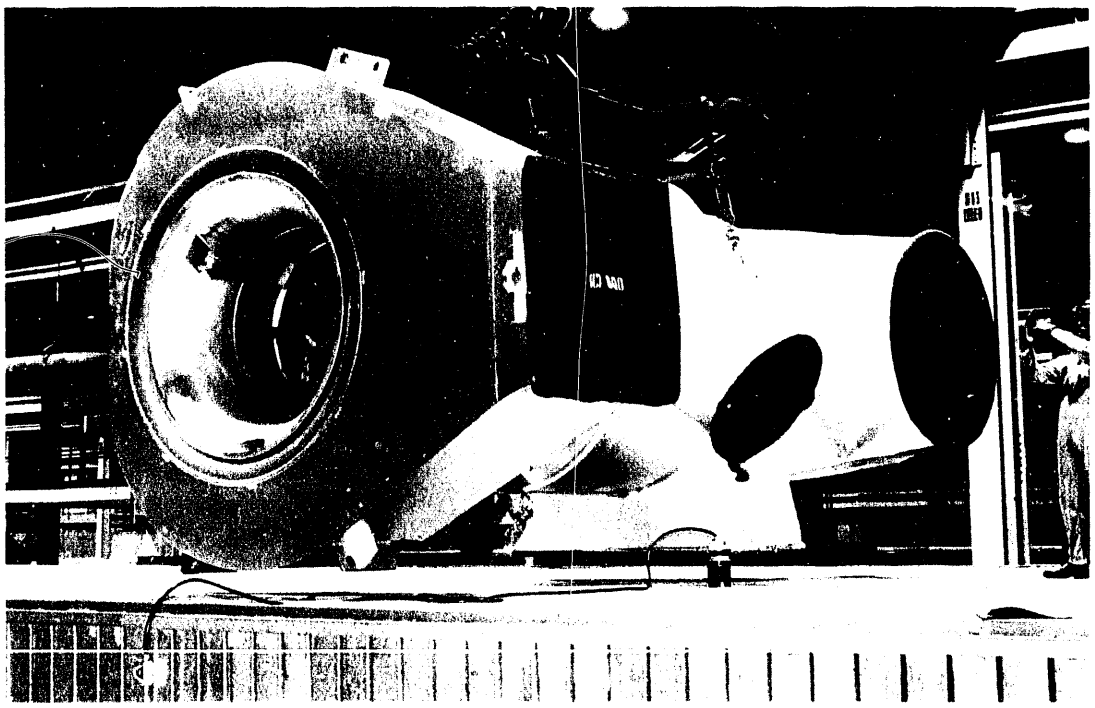
Smith is about to put the technique to a two-year test on some 100 compressor motors at DOE's Portsmouth uranium enrichment plant. Early warnings of problems in the process can offer big savings: If turbulence in the gas flow goes undetected and uncorrected, for instance, the powerful compressors (rated up to 3300 horsepower) can quickly destroy their turbine-blade assemblies, necessitating a $25,000 repair.

Besides preparing for the enrichment-plant test, Smith and several ORNL colleagues are adapting the technique to other kinds of motors. They're also designing a microchip that could squeeze the sophisticated signal-analysis circuitry into an inexpensive, hand-held analyzer.

From nuclear plant to home refrigerator?

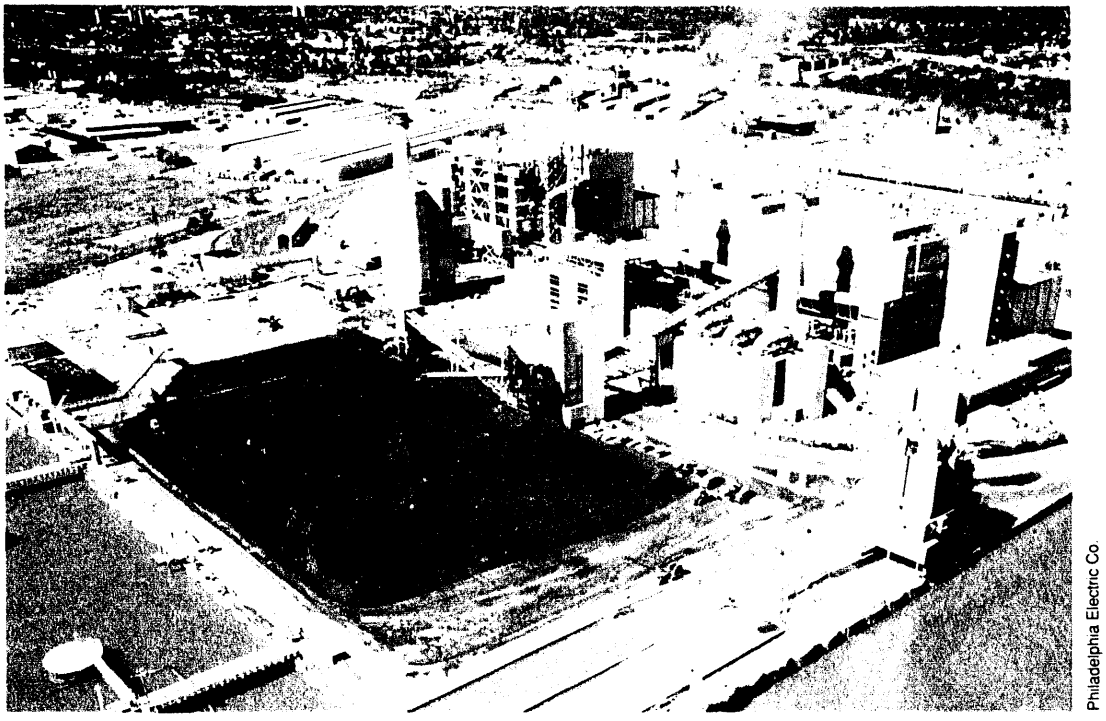
Now that MCSA has shown what it can do, the work of invention has begun to give way to the business of marketing.

So far, four companies have bought nonexclusive rights to



A ton of prevention: Equipment such as this mammoth compressor at DOE's Portsmouth uranium-enrichment plant can avoid costly breakdowns and repairs if motor current signature analysis detects problems in time.

Philadelphia Electric Company's Eddystone steam plant is a long-term test site for the new diagnostic technique.



Philadelphia Electric Co.

MCSA; the licensing agreements include both versions of the technology. According to Tom Berg of the Energy Systems Office of Technology Applications, who negotiates licensing agreements for ORNL technologies, three of the four companies focus mainly on nuclear-plant monitoring. But Berg says the newest licensee, Spectrum Technologies USA, Inc., is aiming at broader applications. Spectrum, a New York firm, markets predictive maintenance hardware and software for a variety of electrical equipment.

Berg hopes this latest license—or another one soon—will create inroads for MCSA into large chemical-process and manufacturing facilities. "This technique could be really valuable in places like steel mills, chemical plants, durable-goods factories, and other heavy industries," explains Berg. "If they can predict and prevent a breakdown, they can save tens of thousands of dollars a minute in downtime costs."

Berg also foresees eventual applications in consumer goods such as appliances and cars, where a built-in microchip could compare the electrical signature of key components with a library of normal and abnormal signatures. "If you had this built into your refrigerator, it could light a red indicator light if, say, the compressor motor were losing a bearing, or a yellow light if your Freon started getting a little low," notes Berg. "As this technology evolves, we're finding the applications and market are really expanding."

Motor current signature analysis isn't likely to replace all other forms of monitoring for electric motors and motor-driven equipment, any more than the EKG is the be-all and end-all in heart diagnosis. But for many kinds of equipment, says Kryter, "This technique looks good as a first line of defense. It's quick, it's cheap, and it's easy."

A TRILLION BYTES OF LIGHT:

New optical technique may revolutionize data storage

Ask Tuan Vo-Dinh what inspired his latest invention and sooner or later he'll probably mention Plato. Or Kant. Or Kierkegaard.

The newest development by inventor Vo-Dinh—no, scrap journalistic convention; call him Tuan—is a radical new technique for optically storing computer data.

Lots of computer data. A trillion bytes or so of computer data.

The technique—which *High Fidelity* magazine has called "awe-inspiring"—could offer the potential for data-storage densities over a million times greater than magnetic floppy disks allow and more than 1500 times greater than today's optical disks permit.

As Archimedes might comment, if he were around to see the latest in data storage, "Eureka!" Or, as Tuan himself might say, "Geez!"

Archimedes isn't on Tuan's list of inspirational thinkers—Tuan prefers a more theoretical orientation in his philosopher-scientists. But no matter.

Molecules in resonance

Tuan's new technique is called Surface-Enhanced Raman Optical Data Storage, or SERODS. The technique relies on the optical "fingerprints" of molecules: When excited by a laser or other intense light source, molecules emit (or scatter) a characteristic light, determined by the molecule's vibration frequencies. The phenomenon—the Raman effect—is named for Indian physicist C.V. Raman, who discovered it in the 1920s.

A half-century later, optical physicists developed a technique for amplifying, or enhancing, the normally weak Raman effect by factors of a million or more. The enhanced effect occurs when molecules are surrounded by a specially prepared metal matrix or substrate which resonates in sync with them. Since the mid-1980s, Tuan's research group has devised numerous applications of the phenomenon, mainly for monitors to detect potentially cancer-causing pollutants. The data-storage technique is actually a by-product, a digression from those biological applications.

Simply put, SERODS uses a laser to "write" on a surface-enhanced disk. The laser selectively destroys the amplifying molecule/matrix structure in some microscopic regions, leaving it intact in others.

The different signal strengths—enhanced and unenhanced—are as different as night and day. More to the point, they're as different as "0" and "1"—the building blocks of binary computer data.

It doesn't take much computer savvy to grasp, at least on a simplistic level, the data-storage potential of a disk with trillions of zones of enhanced and unenhanced molecules. Just add a laser scanning head, plus

Tuan Vo-Dinh explains how his new optical system offers unprecedented data-storage density. In the background is one of Tuan's cubist paintings.

software that reads a strong signal as, say, a "1" and a weak signal as a "0."

In hindsight, the concept is one of those elegantly simple, "Why didn't *I* think of that?" ideas. Ironically, Tuan says, that very response is the main obstacle his invention must clear to gain acceptance. "New concepts always have that problem," he notes philosophically, especially within large companies. "People have built their careers on a certain technology, and their company has spent billions of dollars on it. They say, 'Geez, we have a multi-hundred-million dollar research program. If this were such a good idea, wouldn't we have come up with it ourselves?'" Also, he notes, "The enhanced Raman technology is new, so people in the computer field may not be aware of it. Here, we are at the forefront of the technology."

As a result of the inertia which any new concept must overcome—inertia that is often deeply rooted in large corporations—Tuan expects that it will take a smaller, more risk-oriented company to get SERODS to market.

Most of the needed technology already exists. "We estimate about two or three years, with some minumum R&D, to engineer all these things together in a black-box prototype for a feasibility demonstration," he predicts. If the demonstration is successful, he sees "no major hurdles" to keep the technology from being harnessed—not even financial hurdles. "The marketing research people say it will take about $5 million for the prototype; when they give me that number, I say, 'Geez, it's so expensive.' They say, 'No, it's very cheap—for high-tech things, this amount of money is nothing'."

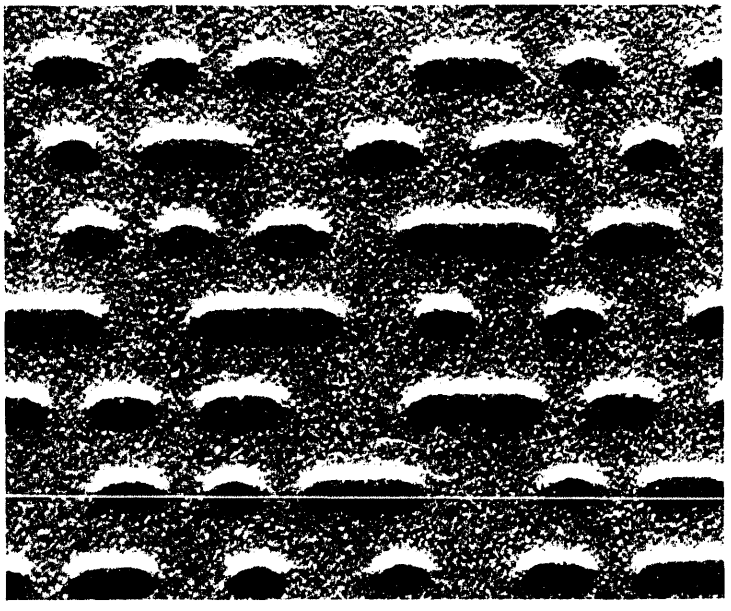
Adding a third dimension . . . and a molecular lock

In its likeliest initial version, SERODS will store each bit on a microregion of about a thousand molecules; eventually, says Tuan, there's the potential to store a bit on a single molecule. By contrast, current optical-disk storage requires physical pits on the surface of a disk to alter its reflectivity; a single pit measures about half a micron across (roughly 0.000025 in.)—and may encompass millions of molecules. "At the current state of technology, we can achieve two orders of magnitude—a hundred times—better than conventional optical data storage," says Tuan. "And that is about a thousand times less sensitive than the theoretical limit."

Perhaps equally significant, from the standpoint of storage potential, is that SERODS is not limited to two-dimensional surfaces, the way current storage techniques are. As a first step toward three-dimensional storage (and the higher densities it would allow), Tuan is developing a multilayer version. "I think first it will be a disk with five to ten layers," he explains. "Of course, it's simpler to say than to do, but I think we've already shown the conceptual possibility of 3-D." Eventually, he foresees SERODS systems reading cubes or other superdense 3-D formats that other storage techniques just can't offer.

Another key advantage of the technique is its data-protection potential. A SERODS disk could be read only by a laser/detector tuned to the exact frequencies of that disk's

The surface of a conventional compact disk is marked by microscopic pits and "lands," physical features which scatter light differently. This photo, taken by a scanning electron microscope, magnifies the disk by over 7000 times.



IOP Publishing, Ltd.

Raman-emitting molecules. That property could provide, in effect, a molecular "lock" on the data, making the technique especially attractive to potential customers in the military or other security-conscious fields.

Computers, cubism, and communism

After explanations, after analogies, a nagging question remains. To recast it slightly: If nobody else thought of it, why Tuan? What switched on the light bulb in his head? He gropes for an answer: "I'm involved in optical spectroscopy; I use computers; I'd been interested in optical ways to store data. I just happened to link these; I just happened to be at the place where I said [here he snaps his fingers], 'Geez, why don't we try this?' You can call it luck; you can call it whatever."

But as Tuan talks—a soft, rapid English with Vietnamese topspin and a twist of French—it clearly sounds like more than luck.

For Tuan, science—like philosophy and art—is one pathway in the ultimate quest to understand the elusive reality of human existence. Leaving computer data storage behind, he veers off on a dizzying tangent that somehow, in the space of five minutes, swoops from relativity ("to put a man on the moon and bring him back safely—or to unveil the boundaries of our universe—we had to account for the different speeds of time") to the rise of cubist art in the 1950s ("it has a lot to do with our changing, multidimensional perception of the universe") to the role of the transistor—the proletarian of the information revolution—in the democratization of eastern Europe ("Marxism has been conquered by a machine, and that machine's called TV").

The digression also takes him back to his student days at the Swiss Institute of Technology in Zurich, where late-night discussions of Kant and Kierkegaard and Hegel illuminated the interconnections between science and philosophy. Heisenberg and Einstein—that legendary Zurich alumnus—were never far from mind. "We would come out after our dinner at the student house—it was very cheap—and say, 'Geez, have you read Kierkegaard lately?' or 'As scientists, are we Hegelists?' "

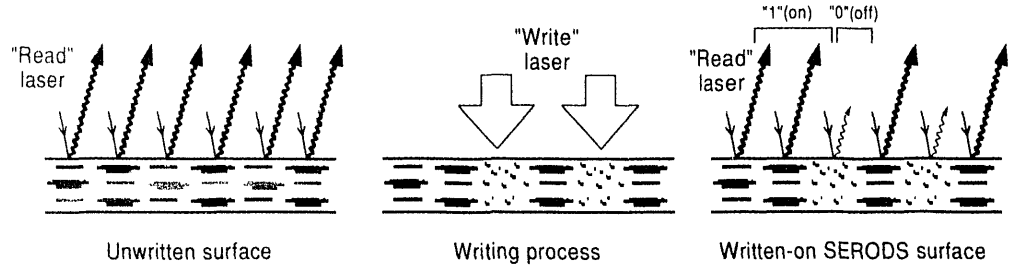
To grasp the genius of those legendary thinkers is to grasp the kinship between science and philosophy, the unity of space and time, the interplay of technology and history, says Tuan. "That's how they made discoveries," he exclaims.

"Those are the visions that make breakthroughs."

Indeed.

Eureka.

Geez. ❖



A Raman-enhanced medium, left, scatters uniformly strong SERS signals from its entire area. After modification, center, a SERODS medium has microregions with distinctly different signal strengths, right.

The SERODS system is based on a spectrographic signal-boosting ("enhanced") medium which is subsequently laser-treated to destroy the enhancement in selected microregions. The vastly different signal strengths are the basis for binary bits of data.

THREAT TO ATMOSPHERE BREATHES URGENCY INTO RESEARCH

Researchers seek ozone-safe refrigerants and insulation

Putting roofing technology to the test: An assortment of new roofing and insulating materials will face the elements at this new ORNL facility. Highly sensitive instruments will measure the long-term energy performance of the building materials.

Not far from ORNL's historic Graphite Reactor sits a tin-roofed, tin-walled barn of a building. It's only a few years old, but once the beige paint fades, it will be hard to tell from the dingy sheds nearby, which hark back almost half a century.

Inside, it looks like a building-supply store: Stacks of rigid insulating foamboard—hundreds of panels of it—the stuff that goes on a house before the siding is nailed or the roof is laid. Rolls of "Attic Blanket," shiny fiberglass quilts that rest atop batts or loose-fill insulation. A small shingled roof—complete with attic—propped a few feet off the floor, looking oddly amiss without a building beneath it. The only thing missing is a ROOF RESEARCH CENTER cap on Jeff Christian's head as he leads a visitor through the place.

Tacked onto one side of the building is a smaller, lower addition. The interior of the addition suggests a used-appliance warehouse: Refrigerators, air conditioners, and heat pumps sitting around in various states of disassembly, many with wires and gauges dangling from them. Here and there, a few control consoles and computer terminals. A couple of big meat-locker-looking rooms, one containing a lone Amana refrigerator, the other housing a window air conditioner that looks as if it's being ingested by predatory ductwork. All the place needs is a sign: "ORNL Heating and Cooling, Inc."

Don't let the low-tech appearance fool you. The work in this tin barn is sophisticated science: research that can boost the energy efficiency of U.S. buildings—and help protect the globe's protective ozone layer in the bargain. Researchers here are working to find energy-efficient substitutes for CFCs. Chlorofluorocarbons—CFCs—are a class of compounds widely used both as refrigerants and as "blowing agents" to put the bubbles in foam insulation. They're also the largest source of ozone destroying chlorine in the stratosphere; the greatest single threat to the globe's protective ozone layer, which

screens out hazardous ultraviolet radiation from sunlight. (See "CFCs: From White Knights to Black Hats," below.)

Over the next eight years, CFC use will be cut sharply in the U.S. and many other countries. The cuts are the result of an international agreement forged in Montreal in 1987 and now adopted by more than 50 nations. The agreement is officially titled the "Protocol on Substances That Deplete the Ozone Layer," but generally it's called simply the "Montreal Protocol." As the cuts specified by the Montreal Protocol take effect, the research in this ORNL barn will help ensure a smooth, energy-efficient transition from CFCs to ozone-safe replacements.

Helping builders not to "blow" it with CFCs

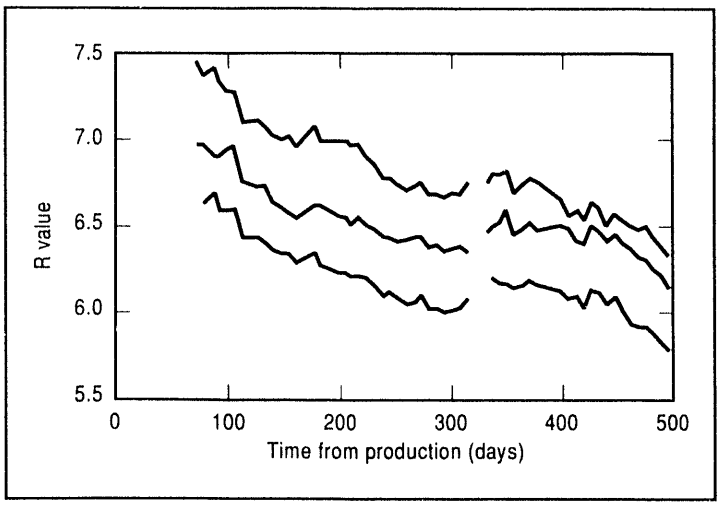
When the mandate to cut CFCs came from Montreal, Energy Division's Jeff Christian thought, "Oh, no. All this good progress on saving energy is going to be sideswiped by the CFC issue." Christian, like other buildings-efficiency researchers here and elsewhere, had spent years making the case for the value of well-insulated buildings.

In the era of cheap fuels, heating and cooling costs were a minor consideration in building design. But when energy prices soared in the 1970s, those costs became a key factor. The sudden demand for energy efficiency led to many new construction practices and products—among them, rigid foam panels for insulating exterior walls, roofs, and foundations. The panels—typically made of polystyrene, polyurethane, or polyisocyanurate—are often blown, or made bubbly, with CFCs, usually CFC-11 or CFC-12.

Today's panels offer insulating values of about R-6 per inch, says Christian. That's twice the value of traditional "blackboard" sheathing, plus good structural rigidity, without added weight. Foam building insulation has become the nation's second-largest use of CFCs (after auto air-conditioning), accounting for some 100 million pounds of CFCs per year.

But the CFCs gradually diffuse out of the foam and into the atmosphere. CFCs are also released during the foaming process itself, as "fugitive" emissions. So the CFCs in building insulation were a natural target for the Montreal cuts.

The hundreds of foamboard panels inside ORNL's Roof Research Center each measure 4 feet by 8 feet by a nominal 2 inches in thickness (people say "nominal" a lot when talking about building materials, because nothing ever



The insulating ability, or R value, of blown foamboard declines gradually as the insulating gas diffuses out. In this long-term comparison, a foamboard sample blown with ozone-destroying CFC-11 shows why CFCs have proven so useful: It outperforms samples blown with more benign alternatives. (The apparent increase in resistivity around days 200 and 350 actually reflects only a recalibration of instruments.) Continued breakdown of the planet's ozone layer will make CFC alternatives increasingly attractive from an environmental standpoint, though.

CFCs: From White Knights to Black Hats

CFCs, developed some 60 years ago by a Frigidaire research chemist, ushered in a new era of safe, efficient refrigerators (and, later, home and auto air-conditioning). They were hailed as wonder chemicals for their relative inertness and low toxicity. In the ensuing decades, industry found more and more uses for CFCs: to make insulated coffee cups, to push hairspray and deodorant out of cans, even to fluff up whipped toppings.

The sterling image of CFCs was tarnished in the mid-1970s, when research first implicated aerosol sprays and other CFCs in the breakdown of the stratosphere's ultraviolet-absorbing ozone layer—a phenomenon that threatened to damage crops, attack the phytoplankton base of the marine food chain, and cause human health problems ranging from cataracts and corneal tumors to sharply higher rates of skin cancer.

Consumers heeded the alarms and stopped buying CFC aerosols; manufacturers scrambled to devise pumps, roll-ons and glide-ons. By 1977, when the government announced plans for strict aerosol controls, CFC aerosol use in the U.S. had already dropped by half; by the end of the decade, it had plummeted by 95%.

A Hole in the Atmosphere

To most consumers and legislators, the phase-out of CFC aerosols—and the scuttling of plans for a U.S. fleet of ozone-damaging supersonic transport jets—had "solved" the ozone problem.

Then, in 1985, ozone took center stage again. A British research team in Antarctica reported that it had found sharply dropping ozone concentrations, a seasonal trend that began in the mid-1970s and worsened every year since. Over the course of a single decade, they reported, the autumn ozone level had dropped 40% below Antarctica's historical average. Satellite data confirmed the British team's finding; in the fall of 1985, atmospheric scientists mapped a five-mile-deep "hole" in the Antarctic ozone layer that had grown to the size of the United States.

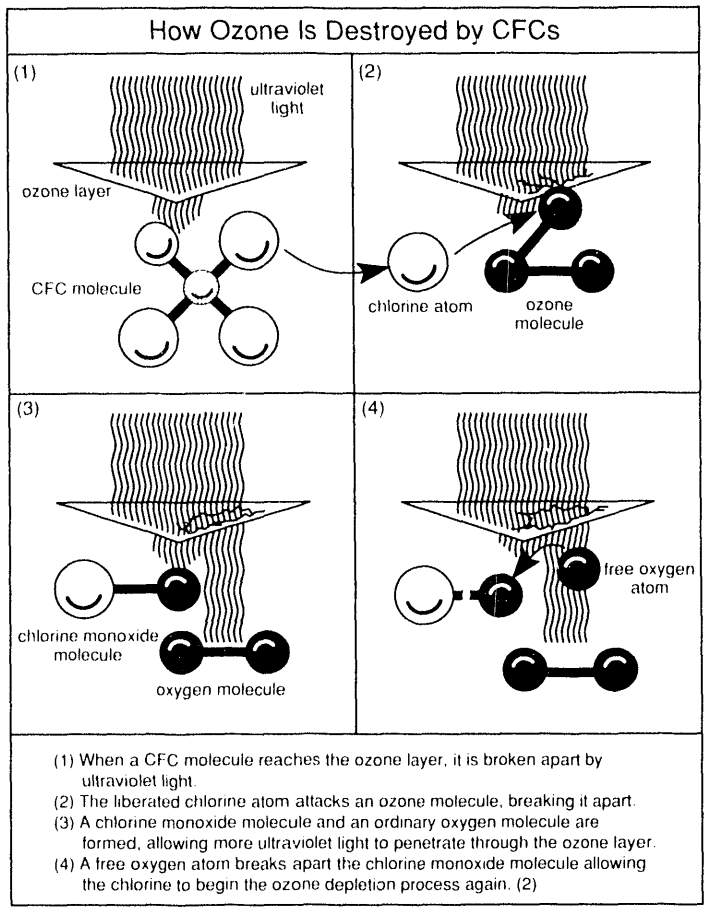
Large scientific expeditions to Antarctica were mounted in the fall of 1986 and 1987; the research tools for the latter expedition boasted two sophisticated high-altitude aircraft, including a U-2 "spy plane" modified to map the seasonal ozone hole.

At the same time as the 1987 expedition—but a hemisphere away, in Montreal—the United States and 23 other nations agreed to cut production of most CFCs by 50% by 1998; the preamble to the agreement called for the ultimate elimination of ozone-depleting compounds.

The CFC industry, which had long resisted further curbs on CFCs, began facing the inevitable. In March 1988, DuPont—the largest U.S. producer of CFCs, accounting for half the market—announced that it would end production of most fully halogenated CFCs by early in the next century.

measures quite what it's said to). The panels are made of polyisocyanurate, a urethane foam used mainly in roofing.

"Normally these are blown with CFC-11, which is tough to find substitutes for," says Christian. "For the short-term, people are doing things like mixing in carbon dioxide as a CFC extender—using a larger fraction of air, in essence." Some products, in fact, such as panels of expanded polystyrene, are already being blown entirely with air. "But their insulating value is down in the R-4 range," notes Christian, "so to get the same degree of insulation, you have to use 50% more. Weight is a big issue; so are durability and fire ratings—a whole gamut of things have contributed to the market penetration of the current products. These are things we were happy with until the CFC restrictions hit."



(1) When a CFC molecule reaches the ozone layer, it is broken apart by ultraviolet light.
(2) The liberated chlorine atom attacks an ozone molecule, breaking it apart.
(3) A chlorine monoxide molecule and an ordinary oxygen molecule are formed, allowing more ultraviolet light to penetrate through the ozone layer.
(4) A free oxygen atom breaks apart the chlorine monoxide molecule allowing the chlorine to begin the ozone depletion process again. (2)

(Source: *Glass Houses*, Investor Responsibility Research Council)

Each CFC molecule emitted has the same greenhouse effect as 15,000 CO_2 molecules entering the atmosphere... and can destroy up to 100,000 ozone molecules.

One promising alternative is foams blown with HCFCs—hydrogenated CFCs that are lower in chlorine and only one-twentieth as reactive with ozone. The test panels at ORNL have been blown with five different blowing agents: CFC-11 and four potential HCFC substitutes, which yield initial R values only 5-8% lower than the conventional CFC-blown foam, according to tests at the Roof Research Center.

Even HCFCs may be only an interim solution, though. "The word from EPA," says Christian, "is that there will be a push to get rid of all of them eventually."

A key focus of ORNL's foam research is aging—the gradual decline in R values. "Right off the assembly line, this polyisocyanurate panel may give you an R value of, say, 9," explains Christian, tapping a sheet of foamboard, "but then it degrades, as oxygen and nitrogen diffuse into the foam cells and CFCs diffuse out."

One way of studying aging is long-term outdoor exposure at the Roof Test Research Apparatus, a small shed located a hammer's throw from the main building. There, a half-dozen different combinations of foam panels and protective membranes are midway

through a two-year exposure. The field measurements of the samples' changing R values are checked periodically against precisely controlled tests in ORNL's Thermal Properties Laboratory by Ron Graves and Dave McElroy of the Metals and Ceramics Division.

Graves and McElroy have also developed a promising new method for predicting the long-term effects of aging. By slicing the insulating panels into thinner wafers to allow faster diffusion of the CFCs, Graves and McElroy can simulate 15 years' worth of aging in a single year. Their technique, which closely tracks the field performance of the panels so far, will give the building-supply industry, contractors, and building owners a reliable standard for predicting the lifetime performance of new, environmentally safer insulating boards.

In roof research, as in other parts of life, one thing leads to another, says Christian—"another" being, in this case, a giant hole in the ground nearby. "After we started doing these tests, the National Roofing Contractors Association said to us, 'Hey, wait a minute. When you give us these new roofing products, we're going to put them on buildings, we're going to put hot tar on them, we're going to run our gravel buggies over them. Are you sure these things are going to stand up?' A roofing contractor has a lot on the line: He guarantees his work for *x* number of years, so he wants some assurance that these substances are going to perform as expected.

"So now we've built a 30- by 70-foot [10- by 20-meter] flat roof, and we've put various samples into it and put hot tar on them and run gravel buggies over them, and we're watching what happens. Also, underneath the roof, we've built a series of basements to test foundation insulating materials and techniques."

The partnership evolving between the Laboratory, materials suppliers, and builders works well, says Christian. "Industry has the chemists and capabilities to modify these formulations, as well as the contractors actually using these materials; we have the understanding of thermal measurements and the facilities to test these materials— rapidly, accurately, systematically.

"We hear all this rhetoric about the Laboratory working

Jeff Christian and foamboard blown with CFC-11 and ozone-safer alternatives.

with private industry. But this is really close to what it ought to be."

Keeping cool with ozone-safe substitutes

ORNL's search for new refrigeration technologies predates the Montreal Protocol, says Energy Division chemist Jim Sand, speaking amid an assortment of air conditioners, heat pumps, and refrigerators. "A lot of this work got started back in the seventies, when oil went up," Sand explains. The initial focus was simply efficiency; now, the need to find ozone-safe CFC replacements adds both complexity and urgency.

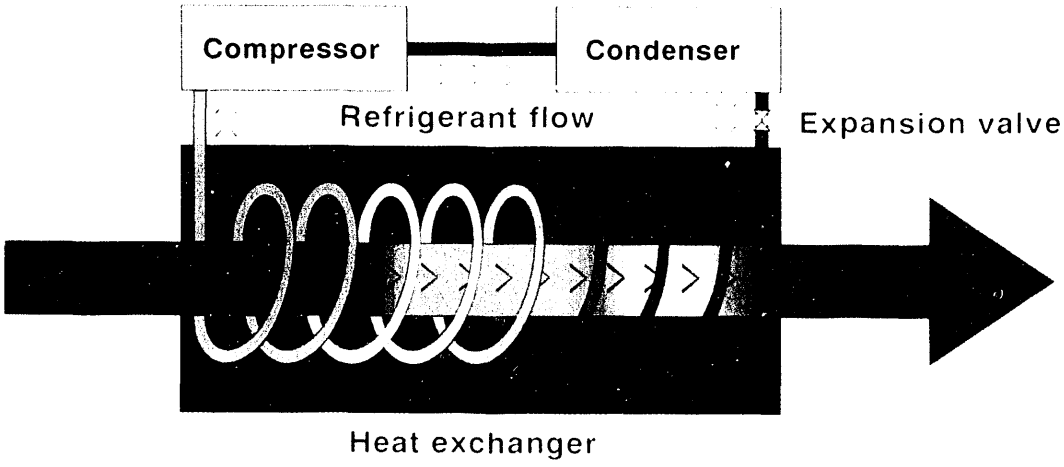
The chief target is CFC-12, also called refrigerant 12, R12, and the generic tradename "Freon." R12 is used in home refrigerator-freezers and—in far greater quantities in the U.S. (some 54 million kilograms, or 120 million pounds, per year)—in automobile air conditioners.

The work in ORNL's Advanced Refrigeration Group, where Sand works, focuses partly on "drop-in" replacements for CFC refrigerants, alternatives that can be used in existing equipment with only minor modifications. Two currently available drop-ins tested by Ed Vineyard, Sand, and Bill Miller are made by mixing R12 with ozone-safe refrigerants. Although R12 remains the primary ingredient in both mixtures, they do pose one-third less threat to ozone than R12 alone. They also allow modest gains in energy efficiency. Other potential replacements are mixtures of R22, R152a, R134a, R124, R143a, R134, and R142B—hydrogen-containing refrigerants that contain little or no chlorine. Although not entirely ozone-safe either, the mixtures are at least 95% less ozone-damaging than R12; unfortunately, notes Sand, some of them are not as energy efficient in current equipment designs.

A less immediate drop-in replacement is R134a, a chlorine-free refrigerant that poses no threat to ozone. Because R134a closely mimics R12 in boiling point and vapor pressure, Sand says it has been considered "the default replacement" until recently. However, the switch wouldn't be a simple swap—and wouldn't be cost-free: Studies of toxicity and materials compatibility are far from complete; a new type of compressor oil would have to be developed; and one ORNL

Ed Vineyard, left, and Jim Sand with test refrigerator.

In a heat exchanger that takes advantage of a refrigerant mixture's "temperature glide," or changing boiling point, incoming air passes through progressively colder coils; because there's always a substantial air/coil temperature difference, efficiency is higher.

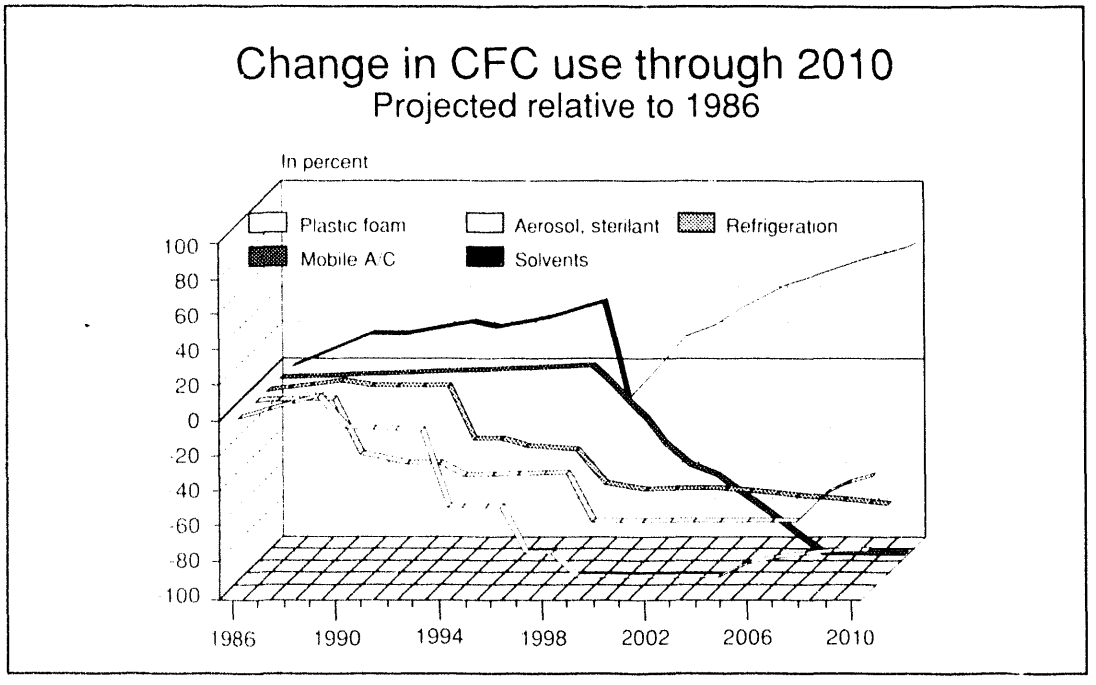


test of R134a in a conventional refrigerator-freezer found energy consumption to be nearly 8% higher than with R12.

In the quest for kinder, gentler refrigerants, Vineyard and Sand recently surveyed the available information on the properties of more than 200 refrigerants. Using a small "breadboard" heat-pump system—actually a leftover heat-pump water heater, souped up with a maze of thermocouples and pressure transducers—the researchers narrowed the list to a dozen relatively unstudied refrigerants that merit a closer look as safe alternatives to ozone-destroying CFCs.

Besides testing drop-in substitutes, which mimic pure refrigerants like R12, the Advanced Refrigeration Group is experimenting with more innovative refrigerants, mixtures that take advantage of the different boiling points of their component fluids to yield efficiency gains. With such mixtures—nonazeotropic mixtures—the boiling temperature creeps upward as the more volatile components begin to vaporize. This change in a nonazeotrope's boiling point is called its "temperature glide." A heat exchanger tailored to the temperature glide can operate more efficiently than one using a refrigerant of uniform temperature—in sort of the way a compact car with a five-speed can outperform a pickup stuck in second gear.

As efficiency researchers work to help the chemical and heating-and-cooling industries adapt to swift changes in CFC use, Sand—like Christian—praises the complementary relationship between



The Montreal Protocol is expected to cut CFC use sharply in many sectors, but the growing need for solvents to clean electronics will pose problems.

Glass Houses, IRRC

government lab and private industry. "We tend to be very poor equipment designers," he observes. "We're more concept explorers—does it work, or doesn't it? Once we show industry something that looks good, they'll design the bejabbers out of it to get the optimal design." Although refrigerant makers such as DuPont and Atochem aren't funding the ORNL work directly, they are—in exchange for test data—supplying test batches of refrigerants (such as the custom-synthesized R32, which costs a hefty $1600 per pound to make in a lab). Notes Sand, "If they supply us with twenty or thirty pounds of, say, R32, that's worth a lot."

By now, Sand doesn't expect easy answers to the hard questions raised by CFCs and ozone damage. "People didn't just stop doing their homework on refrigerants for fifty years," he observes. "If there were something clearly better out there, they probably would have come up with it already. The real question is, what are we willing to live with now, in the interest of environmental acceptability?" ❖

[illegible] A researcher samples [illegible] in the ocean, the [illegible] main "sink" for the gas.

MODELING GLOBAL CHANGE

Greenhouse effect heats up CO_2 research at ORNL

"Are these the shadows of the things that Will be, or are they shadows of things that May be, only?"
Ebenezer Scrooge, A Christmas Carol

One afternoon not long ago, model-maker Bill Emanuel got curious.

Emanuel, a researcher in ORNL's Environmental Sciences Division, has spent the past decade working on a computer model of how carbon shuffles back and forth between Earth's air and the land and water. The model is based on data stretching back to the mid-1700s, just before the industrial revolution—fired by coal and driven by steam—began to pick up speed. It was then, two-and-a-half centuries ago, that concentrations of carbon dioxide in the atmosphere began to climb. If you graph the concentration of atmospheric CO_2 between 1750 and now, the line rises slowly at first, like a coastal plain edging above sea level, then—especially in the past century—swings upward, like the slope of a mountain aspiring toward vertical.

The rise worries both scientists and nonscientists, many of whom now shake their heads gravely over the "greenhouse effect," the steady buildup of infrared-trapping CO_2 that threatens to heat the planet, melt the polar ice caps, flood coastal cities, and redraw the world's land-use maps.

As concern rises, so does funding for research—on a curve even steeper than the increase in CO_2 emissions. One measure of ORNL's increasing focus on climate-change research is the creation a year ago of a Center for Global Environmental Studies. The new Center focuses on the greenhouse effect and other big-picture problems, including ozone depletion, deforestation, desertification, and worldwide pollution, says acting director Mike Farrell.

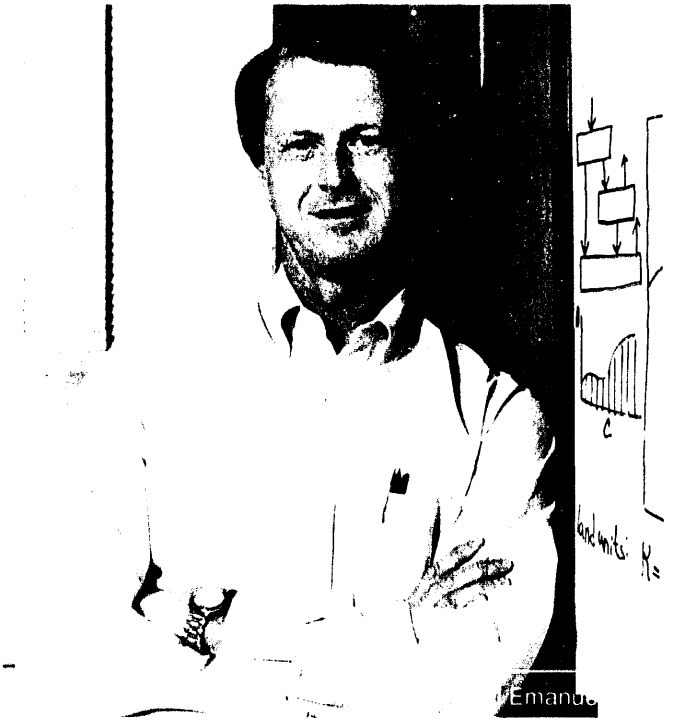
Anyway, on that afternoon, Emanuel was thinking about the rising chorus of voices calling for a 50% cut in CO_2 emissions from fossil-fuel burning. A swift cut of that magnitude could halt the buildup of atmospheric CO_2 and avert the greenhouse effect, suggested some scientists; the cut would allow the oceans, the main "sink" for carbon, to begin absorbing the accumulating gas. The 50% cut was endorsed by scientific and diplomatic representatives of some two dozen nations at a 1987 meeting in Montreal.

His curiosity aroused, Emanuel turned to the computational tools of his trade and modeled the effect of such a cut. Starting with the estimated 6 billion metric tons (6×10^{15} grams) of carbon pumped into the atmosphere in 1988 by fossil-fuel burning, he assumed an instant 50% reduction in fossil-fuel CO_2 emissions.

Emanuel worked for a couple of hours to program the model. Then he waited a couple more for the results.

They surprised him: Despite a 50% cut in fossil-fuel emissions, said the model, the concentration of CO_2 in the

(Continued on p. 54)



"If you can't stop it, you can try to slow it down."

In the face of mounting evidence that CO_2 and other greenhouse gases will raise the globe's temperature, [illegible] are the policy choices facing us—stop burning coal? build bigger air conditioners? throw in the towel?

[illegible]'s Center for Global Environmental Studies [illegible] knotty issues such as these.

Dan Jones, an Energy Division economist working with the Center, sees three main options. "First," he says, "you can try to stop it altogether. But Bill's [Bill Emmett's] number says you can't do that—an 80% reduction is out of the picture, given current technology or even anything we can foresee within the next twenty years."

Option 2? "If you can't stop it, you can try to slow it down," says Jones. "Lessen the total temperature rise, or delay the time when any given rise will occur." One of the most effective (and most costly) strategies, he argues, would be U.S. support for cleaner energy technologies overseas—for example, in China and India, where population growth, increasing energy demands, and plentiful coal will combine to produce much of the likely increase in CO_2 emissions in the coming decades.

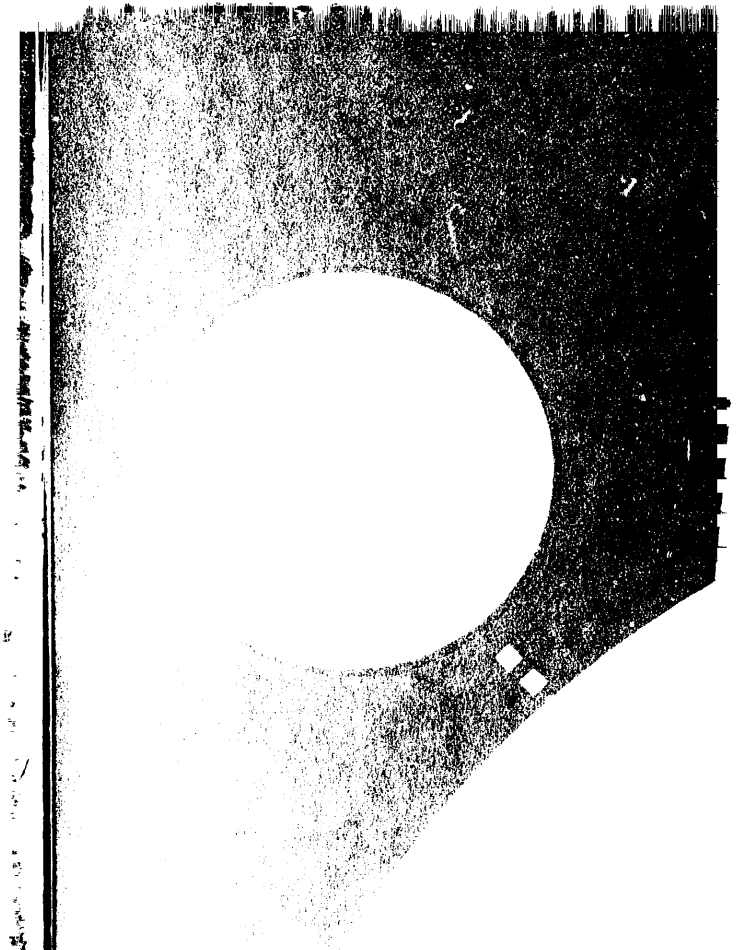
Finally—realistically—says Jones, "You can find ways to help society adapt to climate changes, if you can predict what those changes are going to be. For example, if you can estimate how much the oceans will rise or how rainfall and temperature regimes will change, you might discourage condo-building on the coast or develop new seed types designed to do well under different temperature or rainfall conditions."

Jones casts a slightly jaundiced eye on the current revival of environmental chic (*People* magazine, the epitome of fadism, now has a regular "EcoWatch" feature). "It's cheaper to read about it than to do something about it," Jones says. "We hear a lot of talk about saving the environment, but if people want to keep the price of gas low, and have a lot of money left over to buy VCRs and go to Disney World, they're not going to vote for changes that cost much."

One factor that could change that pattern, though, is rising concern over health problems caused by pollution. "If more and more people get skin cancer," says Jones, "they may get mad enough to do something about it. Another key factor will be economics. "Rising prices for commodities like food and gasoline will motivate a lot of people to find differ[illegible] ways of doing things," [illegible] Jones. "But whether w[illegible] can impose a carbon ta[illegible] encourage conservatio[illegible] and fund R&D—that's another question."

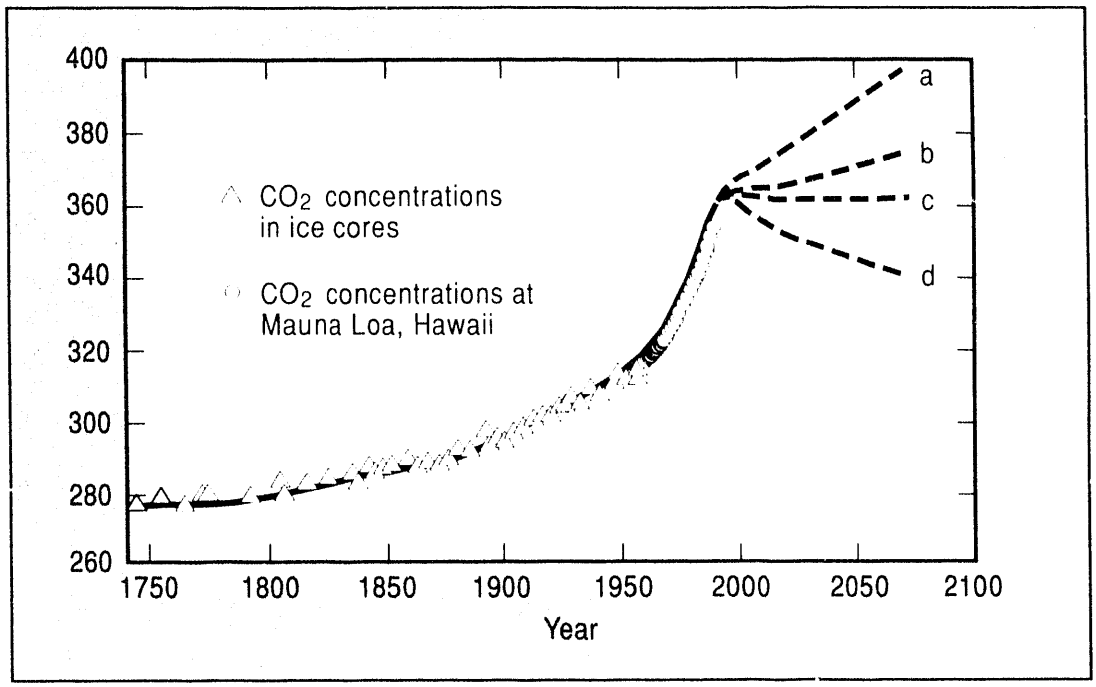
The saving grace in glo[illegible] warming, Jones notes, [illegible] that it will be gradual, [illegible] spread over decades [illegible] maybe a century or mo[illegible] "Over a hundred years [illegible] people have time to adj[illegible] to just about anything," [illegible] observes. "But within [illegible] hundred years, we're a[illegible] going to have some pr[illegible] bad 'hiccups'—for example, some remark[illegible] severe famines. The United States is big en[illegible] and rich enough to weather that. But lots [illegible] countries aren't." Th[illegible] result could be escalati[illegible] tensions between competing Third Worl[illegible] countries, and more conflicts between th[illegible] Haves and the Have N[illegible]

Despite the magnitud[illegible] the problem, Jones isn't ready to give in and tu[illegible] up the air conditione[illegible] "Think about the magnitude of the changeover from the h[illegible] to the automobile and [illegible] rapidly that happened," [illegible] urges. "We certainly d[illegible] have to throw up ou[illegible] hands just because w[illegible] can't keep the climate [illegible] way it is in 1990." ❖



heat

Measurements of carbon dioxide in Antarctic ice cores show steady increases, traceable to the beginning of the Industrial Revolution. Measurements high atop Hawaii's Mauna Loa peak show sharper increases in the past three decades. Projections show future levels of atmospheric CO_2, assuming fossil-fuel emission cuts of (a), 58%; (b), 75%; (c), 83%; and (d), 100%.



atmosphere would continue to rise. Not as sharply, mind you, but unmistakably—a slope less like the Matterhorn, more like Mt. LeConte.

Emanuel went further: He plugged in other reductions to see what would halt the buildup. A 60% cut didn't do it. Even a 75% cut didn't do it. According to the model, a cut of more than **80%** would be required.

Why so drastic? To explain, Emanuel draws an analogy he's obviously used before. "Think about your bathtub," he directs. "Imagine that the tap is open, so water's going into the tub, but the drain's open, too, so water's also going out. How far can you open the tap before the water level starts to rise?

"If we add carbon to the atmosphere faster than the oceans can absorb it—if we continue to increase the rate of release at about the same rate as the last four or five years—it's like that bathtub: If the faucet's open wide enough, the water rises even though the drain's open."

Emanuel and his colleagues spent a year working through the math and physics and—with the help of the group's resident oceanographer, Tsung-Hung Peng—the ocean dynamics of their finding.

"We now understand why the models behave this way," Emanuel notes. "Mathematically, it all makes good sense, but it's a little bit counterintuitive.

"The intuitive logic goes like this," he elaborates: "The transfer of CO_2 from the atmosphere to the ocean is driven by the difference in CO_2 pressure between the two. By burning fossil fuels all this time, we've built up the pressure in the atmosphere; if we immediately cut the emissions, we might expect to see a rapid decrease because of the pressure difference."

PLANT A BILLION TREES?

To fight the greenhouse effect, President Bush has called on Americans to "plant a billion trees."

The reason? Trees take CO_2 from the air during photosynthesis and incorporate the carbon into their tissue—as cellulose—as they grow. If enough trees do that, logic would seem to suggest, the CO_2 problem is history. A simple, wholesome, all-natural solution.

Unfortunately, it's not quite that simple, explains Greg Marland of ORNL's Environmental Sciences Division. Trees eventually die and decay; when they do, the above-ground vegetation—branches and trunks—releases CO_2 back into the air. So there's little scientific evidence that a billion trees would make much of a dent in the CO_2 problem. "We did some calculations a while back," notes Marland. "They showed that to get much impact from planting trees, you'd have to cover Australia with pines."

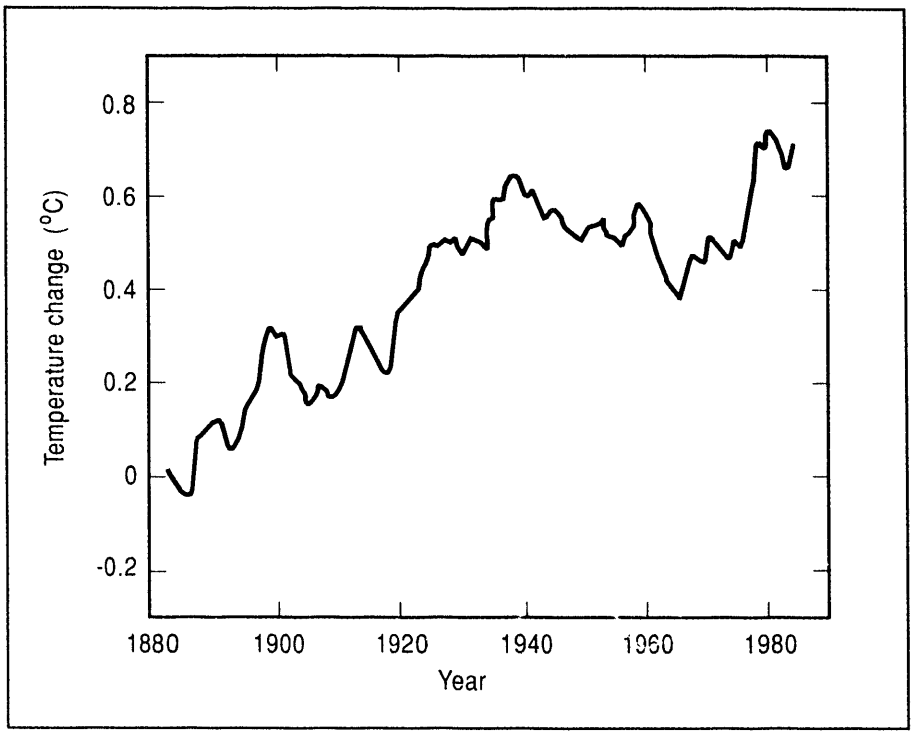
The "plant a billion" concept isn't without potential, but it may need a new twist, says Marland. "If you were really trying to pack away carbon on land, you might not even think in terms of trees," he explains, "because what you really want to do is get it below ground. For example, grasses are actually more efficient below-ground carbon producers than trees are, so you might want to plant grass. You might want to plant a lot of undergrowth, try to stimulate undergrowth in existing forests."

In fact, the CO_2 buildup has added a new focus to DOE's biomass program, which ORNL manages. Besides their promise as an alternative to fossil fuels, some forms of biomass now offer added potential as a natural "carbon scrubber."

Instead of simply planting trees, then, says Marland, "You might want to think more broadly."

In other words, see the forest instead of the trees.

Earth's temperature (averaged over five-year periods) has increased by about 0.7°C (1.3°F) over the past century.



Adapted from Hansen and Lebedeff, *Geophysical Research Letters*, April 1988.

But as the model shows, it's not that simple. Because of the small "drain"—the limited diffusion rate—between the air and the surface waters of the oceans, even a substantial decrease in emissions isn't likely to stop the rise in atmospheric concentrations.

Emanuel's model offers a sobering preview of the atmosphere's possible future—one he isn't overly optimistic we can change. "The U.S. is a leading contributer to the world's total fossil-fuel release—about one-fifth, I think," explains Emanuel. "But long-term, the biggest problem is Chinese coal. The Chinese are sitting on an enormous coal resource, and at their current rate of population increase, it's hard to see how they can do anything but burn it. If I understand it right, even if everybody else quit burning fossil fuels and only the Chinese went ahead, it would be enough to cause significant climate changes."

Viewed from that vantage, atmospheric CO_2 is more symptom than disease—and there's no easy cure to be found in tree-planting programs or emission controls. "To me, anyway," muses Emanuel, "it's not so important to plant a billion trees as to start asking some really fundamental questions about population and things of that sort."

Those fundamental questions will, in fact, set much of the agenda for ORNL's Center for Global Environmental Studies, which will branch out to explore a host of other issues besides CO_2 emissions: population growth, energy demand, deforestation, and the myriad other "things of that sort" that combine to alter the climate—even the very destiny—of the planet.

A destiny that we humans may become increasingly effective at modeling, if not molding.

The shadows of things that Will be, or of things that May be, only? ❖

Climate change: a "minor perturbation" in a planet's lifetime?

Life on Earth is an increasingly delicate balance. One neoclassical view of the balancing act, a view gaining New Age respectability, is the "Gaia (or Gaea) hypothesis"—a reference to Greek mythology's Earth-goddess. The Gaia hypothesis holds the planet itself to be a living system, one that creates and maintains a life-sustaining environment. It's an instinctively comforting view ("not to worry—the Earth will 'fix' the CO_2 problem"), but because of the rapid changes introduced by humans, the planet's regulatory systems can't keep up: It's as if centuries of natural change are being compressed into every year.

From a Gaia-type perspective, even disastrous greenhouse effects would be "a minor perturbation," says Emanuel. "We're worrying about something in the thousands of years; the Gaia theory refers more to things that happen over hundreds of thousands or millions of years," he explains. "The climate may go through a change, but after we burn the world's fossil fuels completely and all the carbon redistributes, the climate will recover."

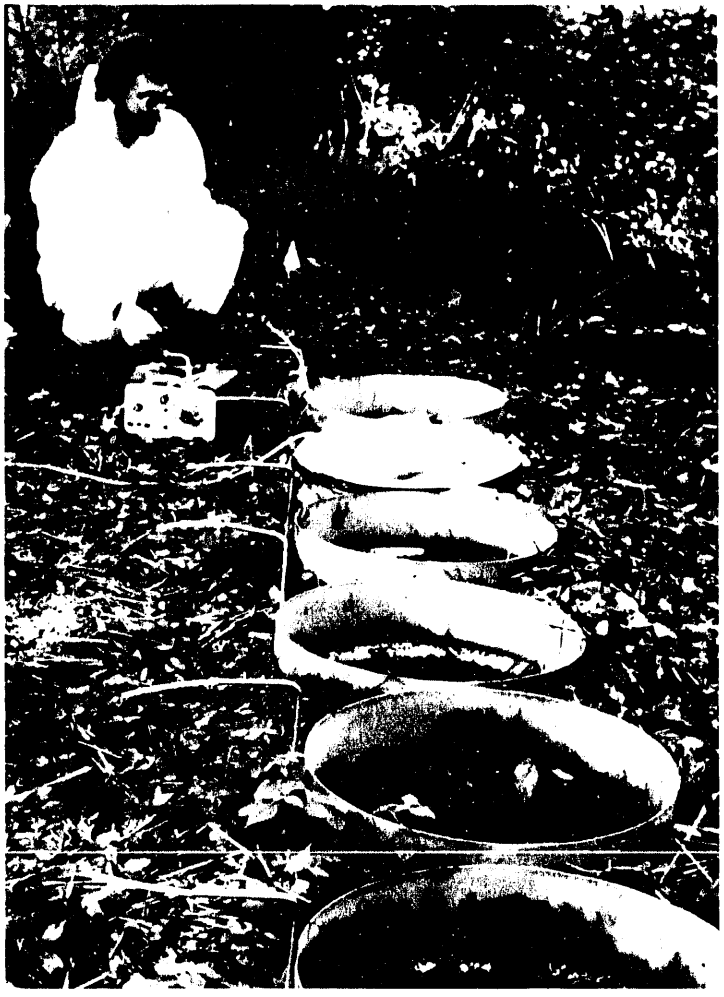
That's good news.

Somebody be sure to tell the dinosaurs.

Battle of the bugs

Microbes to mitigate messes

A researcher monitors the effectiveness of bacteria that digest pollutants—in this case, PCBs (polychlorinated biphenyls), cancer-linked oils widely used until recently to insulate electrical equipment. PCB pollution is a problem at thousands of sites nationwide.



For 40 years the government's sprawling K-25 plant enriched uranium—originally, for the Manhattan Project's early atomic weapons; later, for nuclear power reactors. Today the Oak Ridge plant's mammoth enrichment "cascades" are stilled . . . but their legacy remains active. On a small hilltop above K-25, for example, is a waste-burial ground where thousands of gallons of cleaning solvents were disposed of in the late 1970s.

The contaminants here—mainly petroleum distillates and other volatile organic compounds—are the leavings of the government's uranium business. But they represent a far, far broader problem: Similar pollutants taint the soil and groundwater at thousands of industrial sites nationwide—many of them abandoned, many others still active.

Now, in the search for better ways to clean up their own backyard, Oak Ridge biotechnologists are enlisting tiny new allies: naturally occurring microbes that break down pollutants into far safer components, such as carbon dioxide and water. The potential long-term payoff from the work: effective, affordable ways to reclaim contaminated sites—not just in Oak Ridge, but all over the nation.

Cleaning agent needs a clean-up

Among the EPA-regulated pollutants in the K-25 burial-ground seeps, the most serious is trichloroethylene, or TCE. Now banned as a suspected carcinogen, TCE is a powerful solvent that was widely used to degrease metal, "dry-clean" clothes, and decontaminate electronics. As a result, it's one of the most common organic pollutants in U.S. groundwater, says Steve Herbes of ORNL's Environmental Sciences Division. Herbes is project manager for the effort to develop "bioremediation" techniques for breaking down TCE and other volatile organic pollutants, including DCE (dichloroethyene, a decay product of TCE), methylene chloride, and other organics.

The traditional way of treating TCE-contaminated water—called "air stripping"—does little more than move the pollutant from one medium to another. Air is bubbled through the tainted water, and the TCE diffuses into the air. That method raises an obvious question, says Tony Palumbo, a microbiologist who is the project's chief investigator: "Do you really want to take your groundwater pollution and put it into the air?" Other pump-and-treat options, ranging from carbon fixation and burial to incineration, are more effective—but also more expensive. Bioremediation, by contrast, could mean a simple, inexpensive way to break down the pollutants into far safer compounds: water, carbon dioxide, and trace amounts of harmless chloride ion.

Dueling microbes

The TCE project will feature a one-on-one competition between two different microbes.

To the winner go . . . well, the *spoils*.

One of the microbial competitors is a naturally occurring (but uncommon) methanotroph, or "methane eater," first identified in groundwater from Oak Ridge. The enzyme that allows the bacterium to feed on methane also happens to oxidize TCE. The reaction is called "co-metabolism" because the TCE breakdown is simply a by-process, what Herbes calls a "fortuitous accompaniment" to the methane digestion.

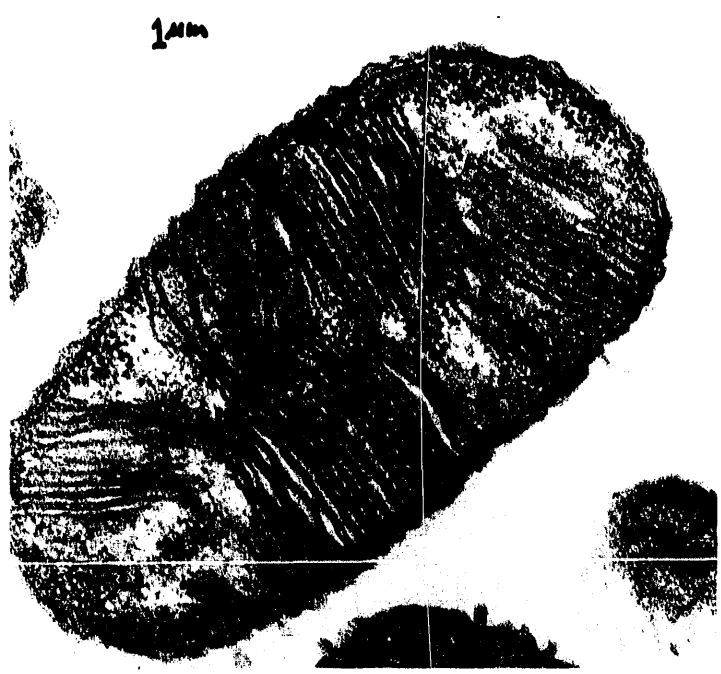
One variety of methanotroph has already shown its stuff in lab tests, says chemical engineering researcher John Cosgrove: It removed half the TCE from contaminated groundwater on a single pass through a laboratory-scale reactor, and up to 95% during a second pass. The reduced TCE levels, 50–100 parts per billion, are not low enough to pass EPA standards of 5 ppb—"there's the rub," concedes Cosgrove—but the outlook is good. "We've seen evidence in shake-flask experiments that our cultures are capable of getting the contamination below our detection limits—about 5 ppb—but we haven't been able to do that in the bioreactor yet," explains Cosgrove. "We're hoping that by varying the cultures or adjusting the levels of copper or manganese—elements that influence the effectiveness of the reaction—we can reach the lower concentrations."

The other microbe in the competition is a bacterium of the genus *Pseudomonas*, which feeds on the organic solvent toluene (commonly used as an octane booster and paint solvent). Like the methane eaters, the pseudomonads contain enzymes that co-metabolize TCE.

A pair of field demonstrations, scheduled to begin in the summer of 1991, will determine the competition's winner. The demonstrations will employ four larger bioreactors on loan from the U.S. Air Force, which is experimenting with biodegradation to clean up airbases, where fuel spills and heavy solvent use contribute to widespread contamination of soil and groundwater.

PCBs and other wastes

Four other bioremediation projects under way at ORNL focus on breaking down other kinds of pollutants in groundwater and soil: carcinogenic PCBs (polychlorinated biphenyls, once widely used in electrical transformers, and now a nationwide waste-disposal problem); petroleum-based contaminants; mercury; and organic waste mixtures that also contain radioactive contamination.



The numerous parallel membranes in this "methane eater" hold the methane-digesting enzyme and greatly increase the surface area for breaking down both methane and the pollutant TCE.

GREAT MOMENTS IN BIOTECHNOLOGY

Waste-busting bugs are just one chapter in biotech's history

Many nonscientists' introduction to bioremediation came in June 1990, when microbes helped digest an oil spill from the supertanker *Mega Borg* off the coast of Texas. According to cleanup officials, the microbes—a bacterium of the genus *Pseudomonas*—digested up to a third of the 300,000-gallon spill, reducing the oil to an emulsion of fatty acids that sank beneath the surface and entered the marine food chain.

But bioremediation isn't as recent as the high-tech name implies. Loosely defined, it's been around for many centuries—often in the form of applied food-chain politics. (Bioremediation, like most of life, is relative: One creature's remediation may be another creature's dinner—and another critter's death.)

In ancient Egypt, cats enjoyed sacred status—and kept Pharaoh's granaries free of mice and rats. In India, Riki Tiki Tavi made a name for mongooses, those experts at "remediating" cobra-infested gardens. Millenia of crocodiles have said "aahh" while birds picked their teeth. In more- or less-sophisticated processes harking all the way back to prehistory's waste pits, unsung bacteria have shown their moral fiber by uncomplainingly digesting human sewage. And before the days of smallpox vaccine and breadmold-turned-antiobiotic, "modern medicine" meant using maggots to cleanse wounds of dead tissue.

Other forms of biotechnology have long helped make civilization more civil: Yeast to make bread rise and beer bubble. Bacteria to turn milk into yogurt and cheese. Walking barnyard "bioreactors" to convert plants into other forms of fuel—corn into drumsticks, grass into sirloins.

Today's specialized waste-busting bugs are, then, simply a recent addition to the biotechnology work force. Another new addition: viruses as "research assistants," helping neuroscientists trace the highways and byways of the nervous system. Yet another new job, in a more blue-collar vein: microscopic miners. Mining companies are already using bacteria to extract more copper from low-grade ore. Now, researchers at Idaho National Engineering Laboratory (INEL) are experimenting with a similar technique to leach cobalt and gold from normally unprofitable ores. Seems the INEL researchers have been bitten by the "gold bug."

The five projects, funded through DOE's Office of Technology Development, were budgeted at about $25 million for fiscal-year 1990, says program manager Phil McGinnis. McGinnis hopes for additional funding to allow larger field demonstrations over the next several years.

Ironically, regardless of how successful the experimental techniques prove to be, they may never be harnessed in Oak Ridge on more than a demonstration scale. That's because the environmental cleanup timetable set by DOE and EPA can't wait for the results of the field demonstrations. But with thousands of other contamination "hot spots" nationwide, there will be ample opportunity for ORNL's waste-busting bugs to show their stuff elsewhere.

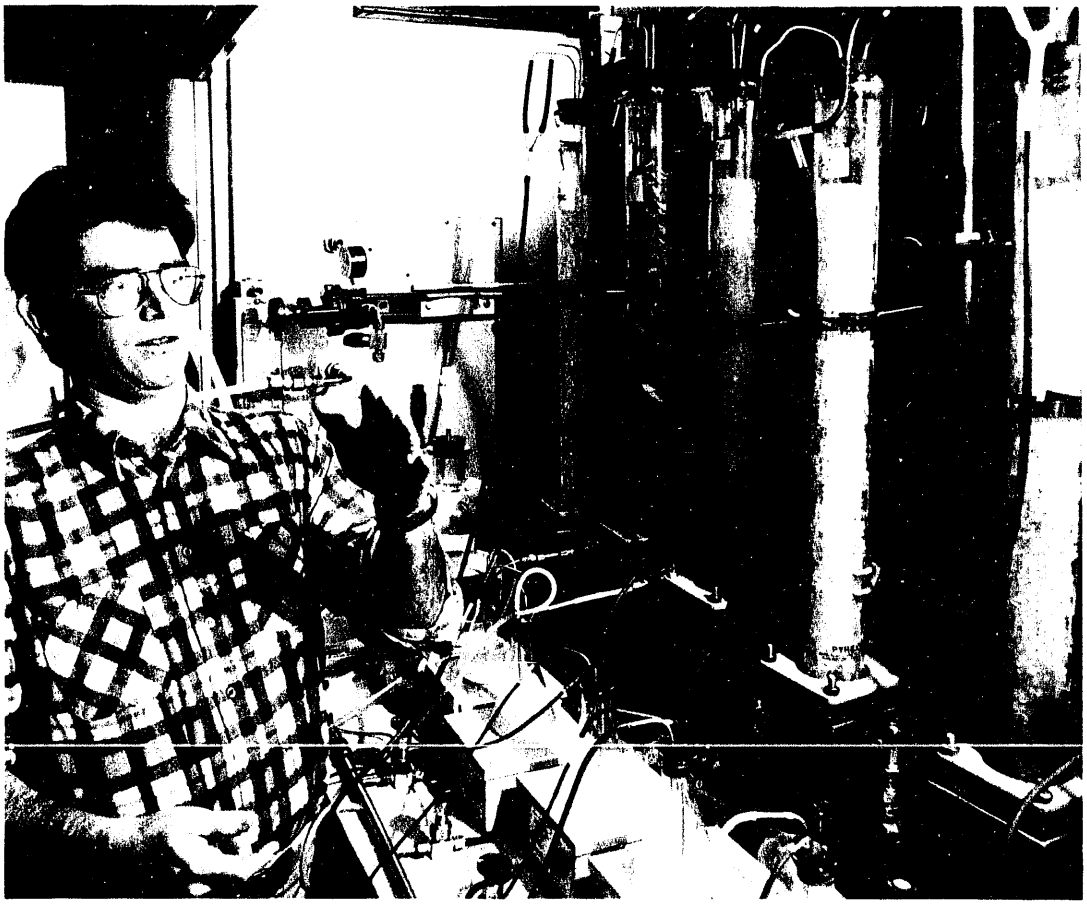
A method with a future

Someday bioremediation of contaminated sites will become "the method of choice—once it's developed." So predicts Tony Malinauskas, director of the waste R&D program that encompasses the five biotechnology projects. But societal hurdles may slow the pace of development and acceptance, he concedes.

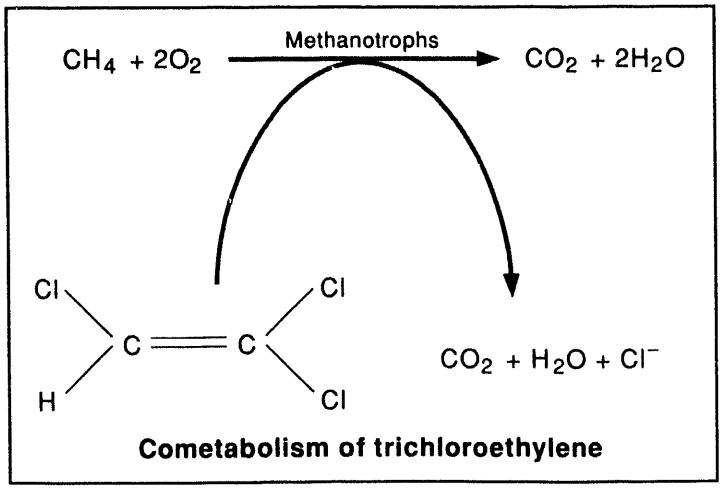
"Using microbes is environmentally safest," says Malinauskas. "It eliminates the personnel exposures connected with excavation and external treatment of contamination." Another advantage is that the microbes provide their own "delivery system," giving them an edge over pumped-in chemicals. "The contamination can be hard to hit with chemicals," he explains, "especially if it has a ten- or fifteen-year head start. With microbes, though, the contamination is the attractant; it's their food."

Despite that advantage—and the cost savings it can offer—the technology faces an uphill battle for public acceptance. "Bio should be farther along—and I don't know why it isn't," Malinauskas ponders. "But there are social hurdles you've got to clear. We could probably make great strides if we could use genetically engineered microbes, but I don't think that will be acceptable for a long time—if ever. We would have to unambiguously demonstrate total control over the microorganism. Visions of the 'Andromeda strain' [a fictional

Lab technician John Cosgrove compares the effectiveness of TCE-metabolizing microbes under different bioreactor conditions.



As a methane eater feeds on methane, top, its digesting enzyme (methane monoxygenase) "fortuitously" breaks down TCE into carbon dioxide, water, and chloride ions.



Cometabolism of trichloroethylene

microorganism that escapes from a lab and wreaks havoc] are strong."

Meanwhile, as other waste-management options such as landfills and incinerators run afoul of mounting public opposition, the nation is "treading water" with respect to environmental quality, says Malinauska. "It's sad that it's cheaper to throw away a tin can and make a new one than to recycle. But when we can no longer throw something away, we're going to have to recycle it."

"A lot of our options are awaiting public approval," muses Malinauskas, whose career includes years in nuclear-energy research ... and nuclear-accident cleanup. "But sometimes the public is smarter than we think." ❖

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