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Oak Ridge National Laboratory

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From the Director

I am pleased to introduce *ornl 89*, the inaugural issue of an annual publication about the Oak Ridge National Laboratory. Here you will find a brief overview of ORNL, a sampling of our recent research achievements, and a glimpse of the directions we want to take over the next 15 years. A major purpose of *ornl 89* is to provide the staff with a sketch of the character and dynamics of the Laboratory. I find it an appealing sketch.

The past has brought us research achievements of truly impressive breadth and quality. The future holds unparalleled opportunities for service to our country and to our fellowman.

We are in an exciting place, in exciting times. Many areas of science and technology in which the Laboratory is involved are in revolution. Major developments in materials, separations sciences, robotics, genetics, the environmental sciences, protein engineering, and computations—to name a few—are occurring at unprecedented rates. Our challenge, and that of DOE's other national laboratories, will be to help American industry translate the new knowledge into commercially useful products and processes. We will meet this challenge if we don't underestimate it. In its way, this new challenge is more difficult than the Manhattan Project, which birthed the national laboratories nearly a half century ago. It is difficult because it requires fundamental changes in the relationships of industry, universities, and government. ORNL is a leader among government laboratories in taking the first steps towards change. But it is abundantly clear that we have many more steps to take.

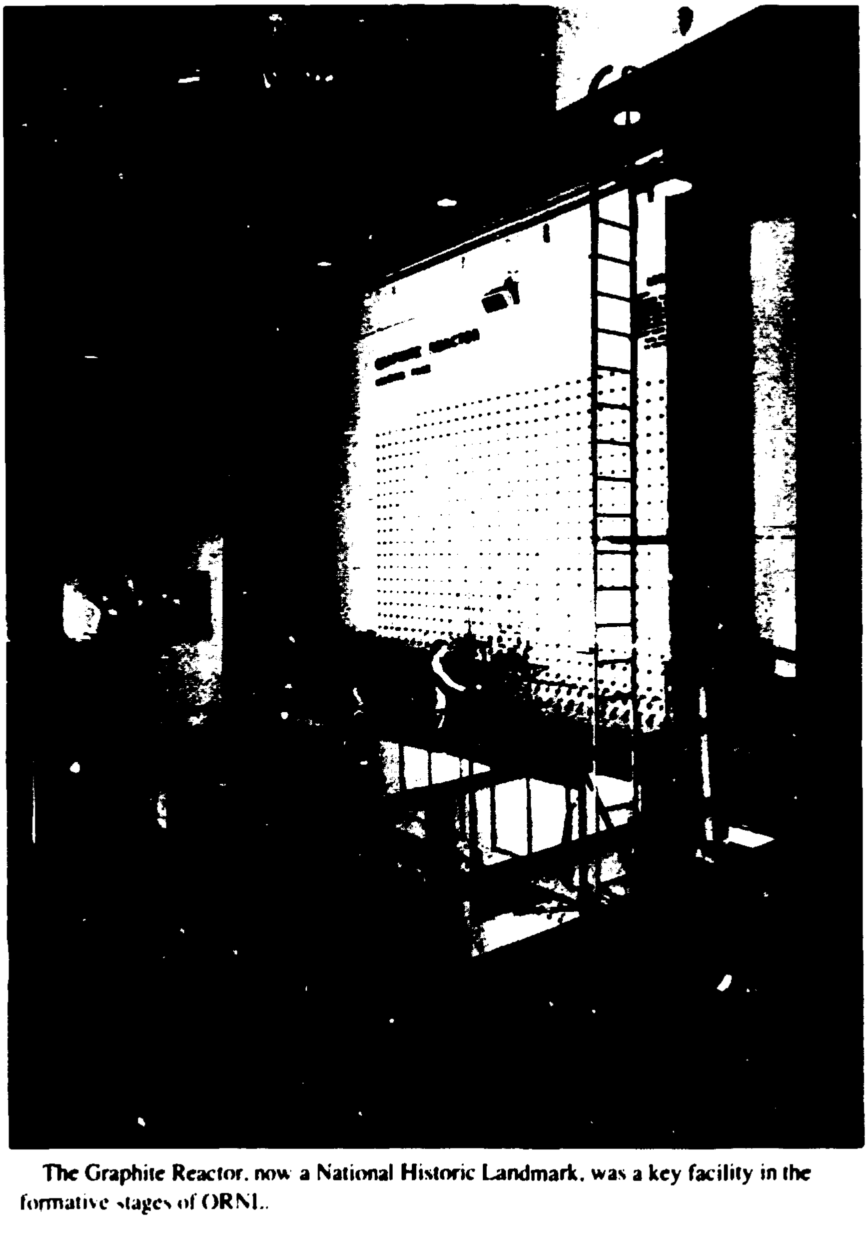
Alvin W. Trivelpiece
Director
Oak Ridge National Laboratory

Laboratory Overview

Genesis

The Oak Ridge National Laboratory had its beginnings in the World War II Manhattan Project. The major objective of the Laboratory's wartime activities was to develop the process for separating the man-made element plutonium from the uranium in which it was created. The technologies to produce and separate plutonium were developed in pilot scale at Oak Ridge, Tennessee, in preparation for large-scale production at Hanford, Washington.

Because plutonium was a new element and was not found in nature, it was necessary to produce small quantities for the research effort. To serve this need, the Graphite Reactor, now a National Historic Landmark, was built and put in operation in 11 months in 1943. It was the first reactor to operate at a power level sufficient to produce usable quantities of plutonium. In addition to the pioneering work in plutonium production and separations technologies, the wartime efforts yielded other new basic information, in particular, the initial characterizing of the identity and properties of many fission products and the biological effects of radiation.


The Graphite Reactor, now a National Historic Landmark, was a key facility in the formative stages of ORNL.

By June 1945, all the original objectives for which Oak Ridge was established were accomplished. After the war, the unique research facilities and the unusual talents of the Oak Ridge scientists and engineers were turned to peacetime missions. Building on the foundations established during the Manhattan Project, the Laboratory explored the new fields of nuclear science and technology.

ORNL Today

Roles and Missions

Born of the necessities of war, ORNL stands today as the nation's largest and most diverse energy research and development (R&D) institution. The Laboratory has two primary missions. One is to conduct applied research and engineering development in support of the U.S. Department of Energy (DOE) programs in energy conservation, fusion, fission, fossil, and other energy technologies. The other primary mission is to perform basic scientific research in selected areas of the physical and life sciences.

The Oak Ridge National Laboratory, X-10 site.

A secondary mission is to apply the Laboratory's resources to other nationally important tasks when such work is synergistic with the primary missions. Some of the issues addressed under the secondary mission include technologies related to international competitiveness, hazardous wastes, and selected areas of national defense. In addition to the R&D roles, ORNL performs some very important service functions for DOE. These functions include designing, building, and operating user facilities for the benefit of university and industrial researchers and supplying radioactive and stable isotopes that are not available from industry.

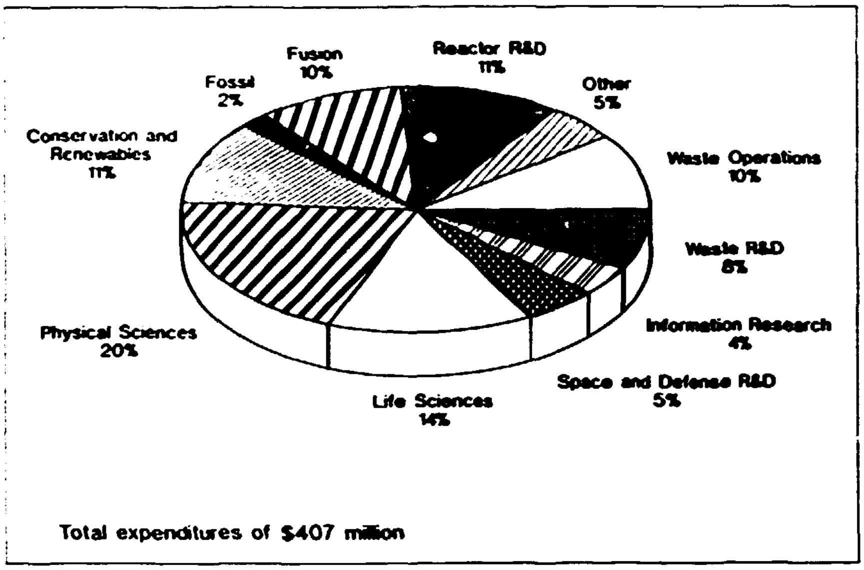
Research Programs

The research programs that support the Laboratory's missions cover a spectrum of scientific and technical activities.

Energy technology R&D covers all the major energy areas. In fusion, the emphasis is on stellarator confinement configurations, plasma heating, fueling systems, superconducting magnets, first-wall and blanket materials, and applied plasma physics. The ORNL nuclear fission activities support DOE's commercial nuclear power program through R&D on nuclear fuel reprocessing, high-temperature gas-cooled reactors, instrumentation and controls, nuclear wastes, and materials. The Laboratory's program on conservation and renewable energy emphasizes research on high-temperature materials, electric power distribution systems, conservation technologies for buildings and industry, biomass production, and energy storage. ORNL's fossil energy work concentrates primarily on materials and on innovative approaches to coal conversion and utilization.

Basic and applied research in the physical, social, informational, and life sciences provides the foundation for technology development work. Biological and environmental research emphasizes the interaction of energy-related physical and chemical agents with the environment and with living organisms. Research in information includes work on expert systems and simulations. In the physical sciences, research areas include high-temperature materials; neutron scattering; surface physics; aqueous, analytical, and environmental chemistry; robotics; parallel computing; and heavy-ion physics.

The Laboratory's programs, which total over $400 million per

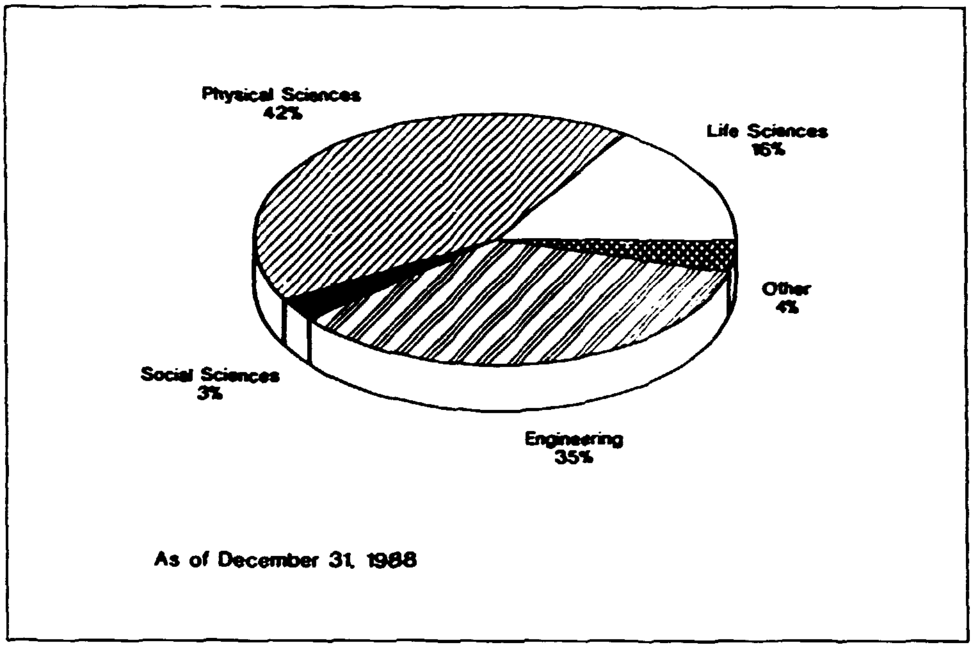


The Laboratory's total operating budget of about $400 million is distributed over several major program areas.

DOE's Office of Energy Research is ORNL's single largest sponsor

Sponsor	Percent of operating expenditures in FY 1988
DOE	
Office of Energy Research	40.2
Conservation and Renewables	10.5
Nuclear Energy	9.1
Defense Programs	7.6
Fossil Energy	1.9
Other DOE	9.3
NRC	3.6
Other non-DOE	17.8

year, are funded by a number of sponsors. DOE, the owner of the Laboratory, is ORNL's largest sponsor, providing nearly 80% of total funding. But there are a number of other important sponsors including the U.S. Nuclear Regulatory Commission, the U.S. Department of Defense, the U.S. Department of Health and Human Services, the U.S. Environmental Protection Agency, the National Science Foundation, and the Electric Power Research Institute.



As of December 31, 1988

The research capabilities of ORNL span a range of disciplines (1552 professionals in R&D divisions).

Staff

Traditionally, the strength of ORNL has been its people, and that is true today. The staff of about 4400 is unsurpassed in its balance of multidisciplinary skills and talents. The professional staff is made up of a diversity of complementary disciplines in engineering; mathematics; and the physical, social, and life sciences. The researchers are supported by a variety of skilled craftsmen, including glassblowers, machinists, welders, electricians, pipefitters, electronics technicians, and many more. This variety of talent gives ORNL the capability to take a technology from concept to prototype. Although skills are important, the characteristics that make ORNL effective in multidisciplinary research are the cooperative spirit and the dedication to teamwork by the people at the Laboratory.

Collaboration, Cooperation, and Technology Transfer

For many years, ORNL has been the steward of many highly sophisticated experimental facilities. Thirteen of these facilities have been designated as user facilities. Therefore, they are available to researchers from universities, industry, and other government laboratories. The user facilities jointly serve the R&D community and DOE's programs. Sharing these resources minimizes unnecessary duplication, promotes beneficial scientific interactions, and makes efficient use of the nation's investment in costly and, in many cases, unique equipment.

Because of the user facilities and the nature of the Laboratory's programs, the number of guest researchers coming to ORNL to do collaborative research has been increasing rapidly. Guest researchers now number about 2300 per year. Approximately 60% of the guests are from universities. However, the number from industry has been increasing, and this segment now constitutes about 30% of all guests.

Another facet of collaboration is R&D subcontracting with universities and industry. Over $86 million was spent by ORNL in FY 1988 to obtain outside assistance through subcontracts. About 60% of these expenditures were with industry. Universities received nearly $20 million, or about 23%.

The technology transfer policy of the federal government, as stated in the April 10, 1988, executive order, is ". . . to ensure that federal agencies and laboratories assist universities and the private sector in broadening our technology base by moving new knowledge from the research laboratory into the development of new products and processes . . . ." ORNL has responded to this need through a vigorous technology transfer program. By the end of FY 1988, ORNL had negotiated 28 technology licenses with private industry. In addition, the Laboratory has formed four industrial consortia or research centers and is now doing work for industry at a rate of $12 million per year.

The ORNL staff and management are deeply committed to the translation of the Laboratory's scientific and technical developments into agents of positive influence on the economy of the United States. Our success will ultimately determine whether we are a national laboratory in fact as well as in name.

User Facilities

The Laboratory has 13 user facilities:

- **Atomic Physics EN Tandem Accelerator**
- **[illegible]**
- **Health Physics Research Reactor**
- **High Temperature Materials Laboratory**
- **Holifield Heavy Ion Research Facility**
- **Low-Temperature Neutron Irradiation Facility**
- **National Center for Small-Angle Scattering Research**
- **Neutron Scattering Facility**
- **Oak Ridge Electron Linear Accelerator**
- **Oak Ridge National Environmental Research Park**
- **Roof Test Facility**
- **Shared Research Equipment Collaborative Research Program**
- **Surface Modification and Characterization Collaborative Research Center**

Research Highlights

Introduction

With the thousands of ongoing R&D projects at a diversified national laboratory such as ORNL, it is difficult to select just a few of those projects that exemplify the institution. ORNL serves as an example in contributing to fundamental scientific knowledge, advancing technology's capabilities, and improving the quality of life. All of these qualities characterize the R&D projects discussed in this document. The projects encompass many disciplines, and a variety of problems and needs are addressed including the following:

- producing advanced new semiconductors through experimental laser techniques,
- developing better ways of separating and purifying chemicals,
- toughening ceramics so that they can withstand ever-higher stresses,
- finding unexpected and valuable products while unraveling basic chemical riddles,
- creating intelligent robots for the future,
- arriving at new understandings of genetic damage and how it can lead to miscarriages and birth defects, and
- strengthening the nation's security against nuclear attack.

If this collection of R&D projects seems a bit inhomogeneous, it is intentional. The discussions are meant to be as diverse as the projects and the people involved in them—projects and people who exemplify the best of ORNL.

Laser-Deposited Crystalline Films: Key to Tomorrow's Electronics

"One of the biggest revolutions in materials science"

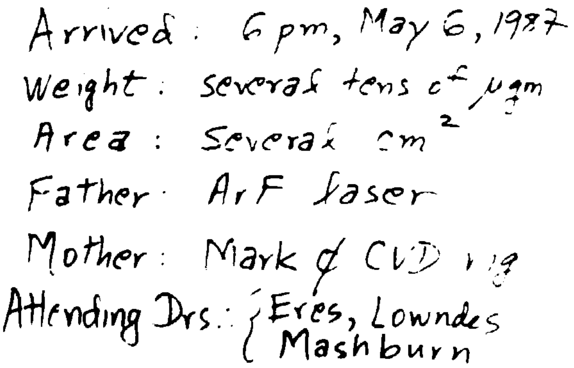
When Doug Lowndes came to ORNL's Solid State Division nine years ago for research on processing materials with pulsed lasers, what he had to work with was a ruby rod laser.

Looking ahead to the commercialization of experimental processing techniques, Lowndes had a good idea of the quality of performance industry would require of lasers. He also believed that ruby lasers could not provide this performance because they could fire only one pulse a minute. The ruby rods were brittle and easy to break, the optical coatings on the ends of the rods were soft and easy to scratch, and the cooling systems were plagued by leaks.

"It was clear that the ruby laser would never have the ruggedness and reliability that a production line would need," recalls Lowndes. "Besides, the light beam was actually too good, too coherent; it set up diffraction patterns we didn't want on the surfaces we were modifying.

"So all along, we were working on the assumption that lasers themselves would change in some rather fundamental ways."

They have. What Lowndes has to work with now is the excimer laser, a pulsed gas laser that's fast, rugged, and reliable. Equally valuable, the light beam isn't too good—it's just good enough; the waves of ultraviolet light are sufficiently out of synch to produce a smooth, homogenous distribution of energy over a surface, so there are no diffraction patterns.



Arrived: 6 pm, May 6, 1987
Weight: several tens of μgm
Area: Several cm^2
Father: ArF laser
Mother: Mark ∅ CVD rig
Attending Drs.: Eres, Lowndes, Mashburn

This jubilant announcement heralded ORNL's first successful effort at laser-controlled growth of a thin silicon film.

As lasers have advanced dramatically, so have the materials-processing techniques they allow. When Lowndes came to Oak Ridge, his ORNL colleague, Dick Wood, was using lasers to anneal high-efficiency solar cells. At the time, high efficiency meant a sunlight-to-electricity conversion rate of about 15%, even with Wood's experimental techniques. Today, his relatively simple photovoltaic cells made from single-crystal films of silicon can achieve efficiencies near 20%. Further gains will be hard to come by; the theoretical limit on efficiency—the best this type of silicon cell can ever do—is 24%. Silicon cells are limited because they absorb and convert only a narrow band of energy from the sun's spectrum, mainly the near-infrared wavelengths.

But efficiencies of 30 to 40% may become possible through the use of pulsed excimer lasers, which control the growth of thin crystalline films. It's a technique Lowndes and research staff members Djula Eres, Dave Geohegan, and Doug Mashburn are now studying. "The key to achieving these dramatically higher efficiencies," Lowndes says, "will be making 'multicolor' cells that absorb a wide range of solar wavelengths."

Picture sunlight streaming into a prism and a rainbow flowing out. Each piece of the rainbow can be aimed at a solar cell that is tuned specifically to that color: silicon for near-infrared, gallium arsenide for red, perhaps cadmium sulfide for yellow, and zinc selenide for blue-green.

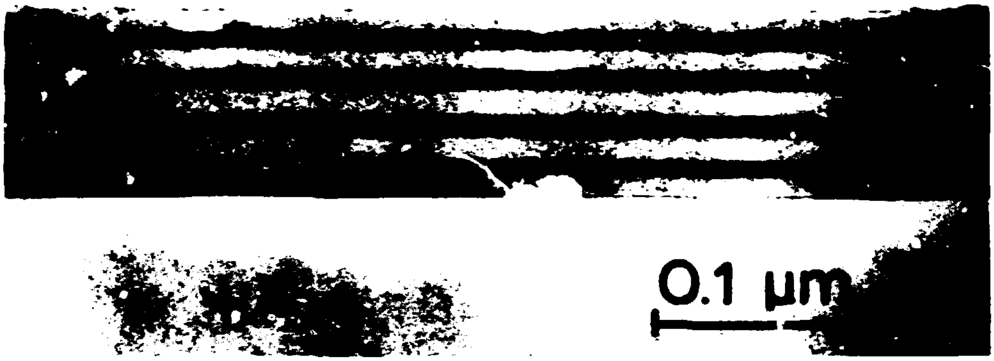
Now, instead of a prism and an array of different cells, picture a single cell incorporating several ultrathin layers or films, each absorbing a different band of the spectrum. That's a multicolor or spectrum-splitting solar cell.

The excimer laser beam enters this reaction chamber from lower right. The laser's energy breaks chemical bonds in a source gas, allowing controlled deposition of a thin film on a substrate. The chamber's top window allows measurement of film growth. Valves control the flow of source gases.

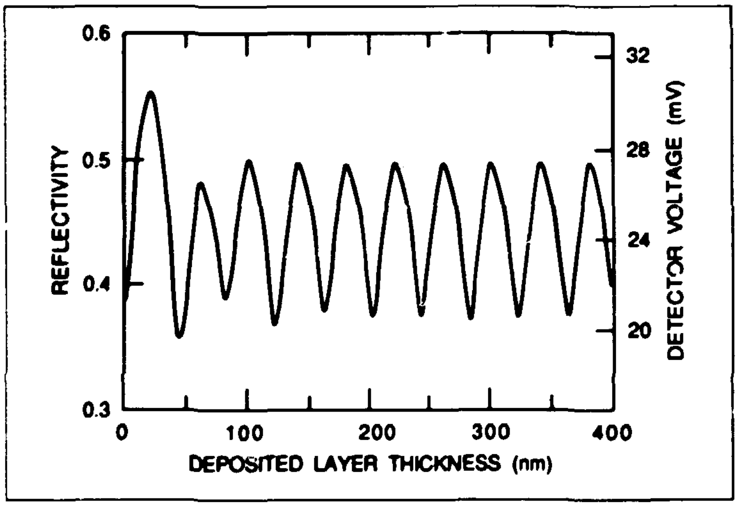
It's simple to picture but, with conventional processing techniques, impossible to make. Here's why: Each layer must be only a micrometer thin. Its crystalline structure must be near-perfect to allow electrons to flow freely through the latticework of atoms. The atoms must line up with those in adjoining layers. In precisely the right places, it must contain precise amounts of dopants, which are the deliberate impurities that impart electrical properties. The boundaries between layers must be sharp, with no diffusion of crystal or dopant molecules from one layer to another.

Now comes the really tricky part. Heat, which is used to trigger the chemical reactions conventionally used to grow crystalline films, has damaging side effects. In crystal lattices, it produces defects such as vacancies or gaps; it promotes diffusion of dopants from one layer to another; and it blurs the boundaries between layers. In short, heat is the enemy of precision-engineered semiconductors.

According to Lowndes, what's needed is a new, low-temperature way to control the crystal-growing reactions. He believes he's found it in the ultraviolet light of the excimer laser, which can trigger and



Alternating layers of silicon (light) and germanium (dark) demonstrate the precise control possible with laser-grown films. The silicon layers are 107-angstroms thick, and the germanium layers are 58-angstroms thick. The crystalline structures of the layers are aligned in an ordered "superlattice."



The graph shows the changes that occur in reflectivity as alternating layers of silicon and germanium are deposited.

precisely control the film-growing reactions.

The thin films used in semiconductors are grown by chemically splitting parent molecules that contain the needed elements or compounds. Breaking the molecules' chemical bonds releases reactive fragments such as atoms, ions, or radicals. Lowndes calls these chemical fragments the "precursors" of film growth; a nonspecialist might call them "ingredients." When a gas carrying the precursors is passed over a substrate material or foundation, the film begins to crystallize.

With thermal processing, the temperature required to break the chemical bonds is high; usually 300 to 900°C. "Unfortunately," explains Lowndes, "the best temperature for growing high-quality crystalline films is almost always lower." But with laser processing, the bonds are broken by the energy in photons of light, rather than by heat. As a result, the substrate can remain much cooler.

"The beauty of using laser light instead of heat to drive the chemical reaction is that it frees you to choose the substrate temperature that gives the best-quality crystalline film," says Lowndes.

Lowndes' technique relies on the ultraviolet light of the excimer laser. "For processing on an industrial production line, excimer lasers have a number of advantages over other kinds of lasers," he explains. "One advantage is their reliability, their ruggedness: they're gas lasers, so they're less prone to damage than crystalline-rod lasers. Another advantage is that they produce ultraviolet light. Ultraviolet photons have much higher energy than visible-light photons, so they can break molecular bonds without heat. Finally, because the laser emits pulses of ultraviolet light, you have 'digital' control over the film growth, even at the level of single layers of atoms."

Safety Benefits Could Save Industry Millions

The advantages of switching from heat to light are not just technological. According to Lowndes, the biggest payoff may be in reducing environmental and safety problems connected with toxic source gases for semiconductors. "The industry spends millions of dollars a year worldwide on safety equipment and environmental cleanup," he explains.

Doug Lowndes checks the helium-neon laser and detector (center) used to measure film growth in the reaction chamber (below).

Consider silane, the source gas for growing silicon films: it burns on contact with air. Even more hazardous are the gases needed to "dope" the semiconductor with elements that give it electrical properties. "The three most common dopants are boron, arsenic, and phosphorus," notes Lowndes. "The source gases for these dopants, diborane, arsine, and phosphine, are all deadly poisons.

"These gases are thermally unstable; they have to be so the necessary bond-breaking can occur. But they're highly volatile, and if you have a gas leak, it can spread very quickly."

Because of the toxicity and volatility of the source gases, semiconductor plants require sophisticated, expensive pollution-control and safety equipment. In Lowndes' laboratory, as a small-scale case in point, cylinders of silane and disilane are locked in sealed cabinets that are continuously vented into a collection and incineration system. A computer-controlled shutdown system, designed by Mashburn, continuously monitors about 40 different process sensors. An abnormal reading on one of the sensors, or manually pushing one of the "panic buttons" located throughout the laboratory, will automatically close the gas valves in a fraction of a second. Semiconductor manufacturing plants, which operate with personnel less skilled than laboratory scientists, require even more complex safety equipment.

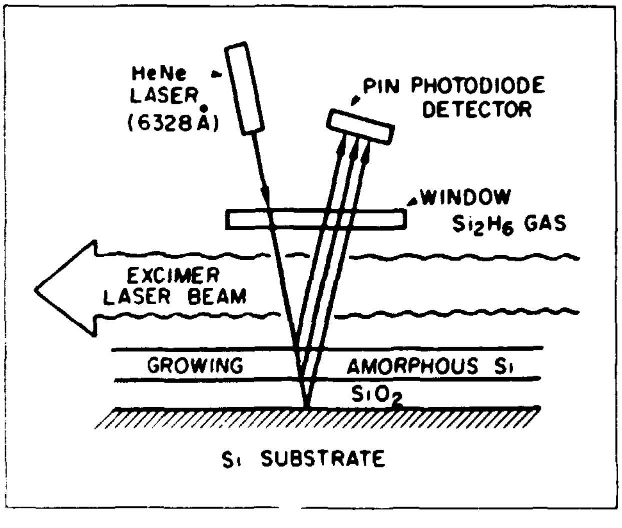
Tightening restrictions on air and groundwater pollution are already threatening to curtail semiconductor manufacturing in California's Silicon Valley. "Soon," says Lowndes, "industries may not be allowed to use some of these materials at any price.

"Technical benefits aside, it may make economic sense to go to another, nonthermal process," he continues. "With lasers, the photon energies available are much greater than typical chemical-bond strengths, so there's no reason to continue using dangerous, thermally unstable gases. An alternative is to use less-volatile liquid sources instead. These are inherently safer and easier to handle."

Applications Include Computers and Superconducting Circuits

The first commercial use of the photon-controlled film growth technique may be only a few years away. "One eventual goal," says Lowndes, "would be for semiconductor firms to mass-produce multicolor solar cells with efficiencies of 30 to 40%."

Another possible application is materials for multilayer computer memory chips. "There are two ways you can improve computer chips," says



Film growth is measured, in the form of changing reflectivity, by a helium-neon laser as the excimer laser passes through a source gas above the substrate and the growing film.

Lowndes. "One way is by shrinking devices laterally, making them smaller and smaller and putting them closer and closer together This allows faster computing; it also allows more memory for a given chip size. The other way is through vertical integration—stacking layers of circuitry one on top of another. If there's a limit to how much you can shrink things laterally, the only way to go is up, layer upon layer."

The key to vertical integration is epitaxial crystal growth of layers of different atoms in alignment. It is not necessary that the layers have the same crystalline structure but that they are oriented at an angle that produces the same spacing between atoms in different layers. One of the goals of Lowndes, Eres, and Geohegan is to grow such epitaxial multilayers.

Another goal is to study combining pulsed ultraviolet lasers with projection masks to deposit fine-line metallic patterns over large areas. Essentially, this is one-step, batch-processed printed circuitry, but with finer features than current techniques allow.

One unexpected benefit of the research was the recent development (by Mashburn and Geohegan) of a way to deposit films of superconducting alloys. "Eventually," says Lowndes, "superconducting films could make it possible to build high-frequency and electrical-circuit systems that are free of electrical resistivity and, therefore, free of energy-robbing waste heat."

Conclusion

The advanced materials needed for superconducting devices, high-efficiency solar cells and circuitry-packed computer chips, don't come naturally; they come only artificially. By using relatively simple "parent" molecules to form multilayer structures, Lowndes and other materials scientists are engineering artificial new materials with specialized properties that are radically different from those of their parents. At the heart of the advances in artificially structured materials are increasingly sophisticated processing techniques and tools such as the excimer laser.

The National Research Council, in a 1986 report, designated artificially structured materials as one of the nation's most important research topics in physics throughout the decade of the 1990s.

Lowndes calls it simply "one of the biggest revolutions in materials science."

The cover of the March 1988 *MRS Bulletin*, published by the Materials Research Society, featured an ORNL photo of laser deposition of a thin superconductor film—an application that could produce advanced circuitry and, eventually, highly efficient motors.

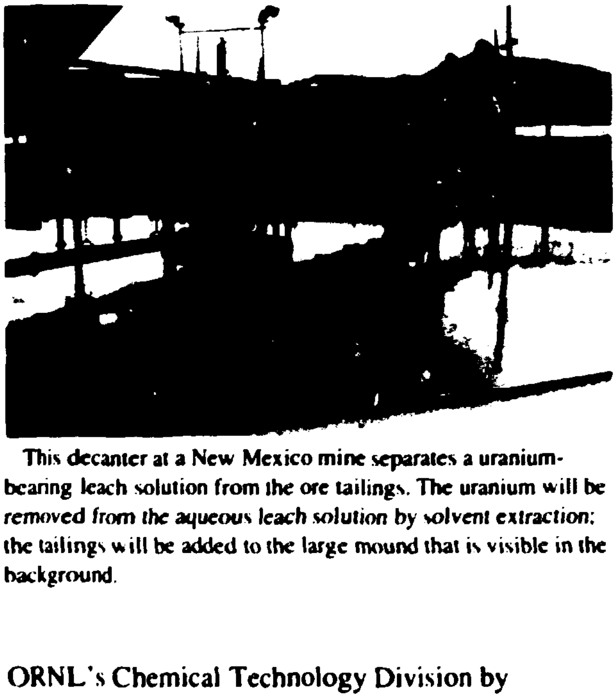
ORNL Brings Solvent Extraction into the "Electronic Age"

Setting: A metal refinery in the Arizona desert, June 1988. Road scrapers are pushing low-grade ore into flat-topped heaps as big as football fields and as high as two-story buildings. A latticework of pipes, laid atop a dozen of these heaps, drizzles out an acid solution at about 9000 liters a minute. The acid perks down through the ore, leaching out the metal as a sulfate. Next, the "pregnant" leach solution is piped into a tank, along with an organic solvent designed to latch onto much of the sulfate. Like oil and vinegar, the organic solvent and the metal-bearing aqueous solution prefer not to mingle. So at one end of the tank, a turbine-type impeller—in effect, a giant blender—churns the two liquids into intimate contact so the solvent can remove as much of the metal sulfate as possible. This step will be repeated, with fresh solvent, in two other downstream tanks to complete the extraction.

Meanwhile, in a nondescript laboratory in Oak Ridge, Tennessee, water drizzles through a nozzle into a funnel-shaped, glass vessel that is filled with solvent. The vessel is linked to a few pieces of tubing, two small pumps, and a couple of wires and electrodes. It is also linked, at least conceptually, to the massive Arizona refinery. It is a development that could revolutionize the way some metals, isotopes, and drugs are purified. The vessel is further linked to the history of ORNL, which began 45 years ago primarily as a radioisotope-extraction laboratory and which "grew up on solvent extraction," in the words of former Director Herman Postma.

The simple laboratory apparatus represents a profoundly new approach to the process of liquid-liquid solvent extraction. It's a patented way of mixing two liquids far more efficiently by using an electric field instead of the usual mechanical equipment. The technique is being developed in ORNL's Chemical Technology Division by chemical engineers Bob Wham; Tim Scott; and, recently joining the project, Osman Basaran.

". . . we can do things you can't even do mechanically, and we can do them with much less energy."



This decanter at a New Mexico mine separates a uranium-bearing leach solution from the ore tailings. The uranium will be removed from the aqueous leach solution by solvent extraction; the tailings will be added to the large mound that is visible in the background.

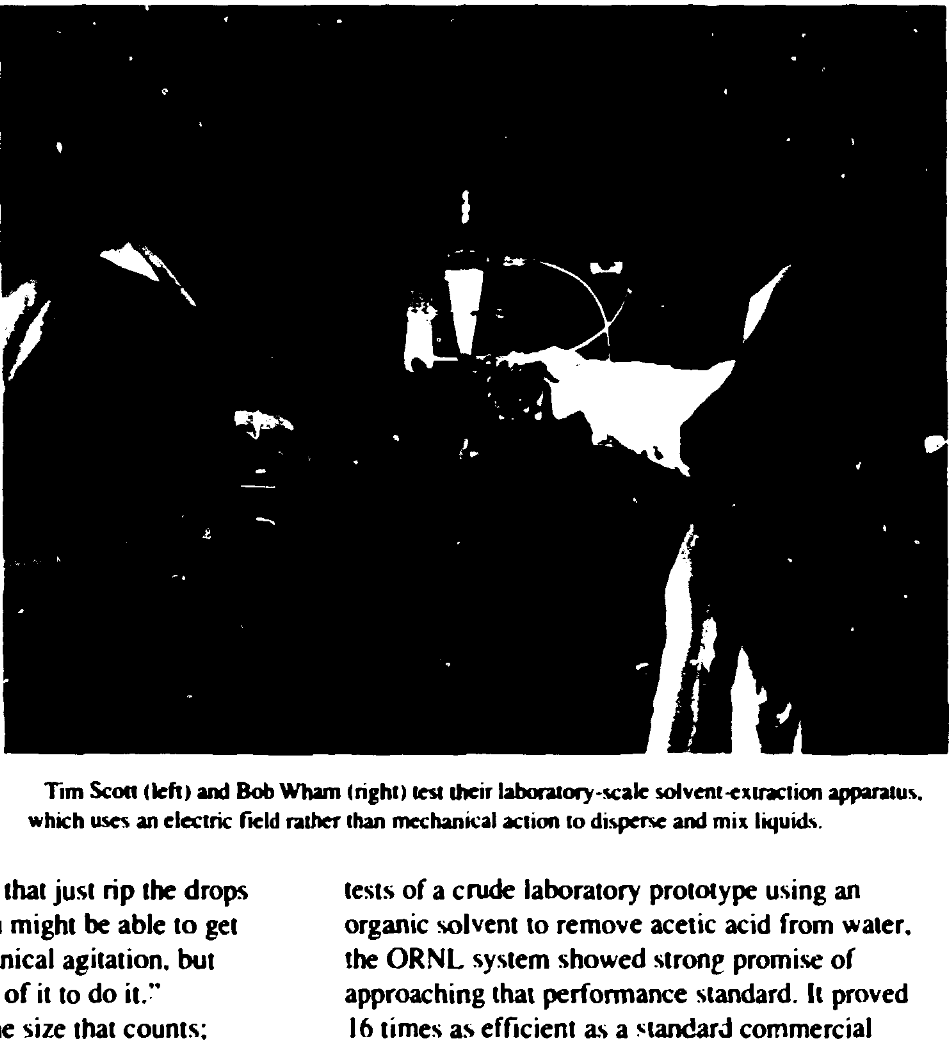
Separating or purifying materials such as precious metals, pharmaceuticals, and radioisotopes can be some of the most difficult and expensive chemical separation processes. Final costs for pure substances range as high as hundreds; thousands; or, for rare isotopes, even millions of dollars per gram. These "high-value chemicals," say the researchers, are the prime near-term candidates for commercializing the new solvent extraction technique they are now refining.

The technique uses a high-strength electric field to break the pregnant aqueous solution, or phase, into minute droplets. Most of the droplets produced by the field measure only 1 to 5 microns in diameter, hundreds of times smaller than the droplets in a typical mechanical-agitation extractor.

"We use electrodes to generate a high-strength electric field right at the tip of the aqueous-phase nozzle," explains Wham. "The field creates shear forces that just rip the drops apart. Actually," he adds, "you might be able to get droplets this small with mechanical agitation, but you'd have to beat the hell out of it to do it."

Adds Scott, "It's not only the size that counts; uniformity is just as important. Even if you manage to get very small droplets with mechanical mixing, you get big variations in droplet size, and that hurts your efficiency."

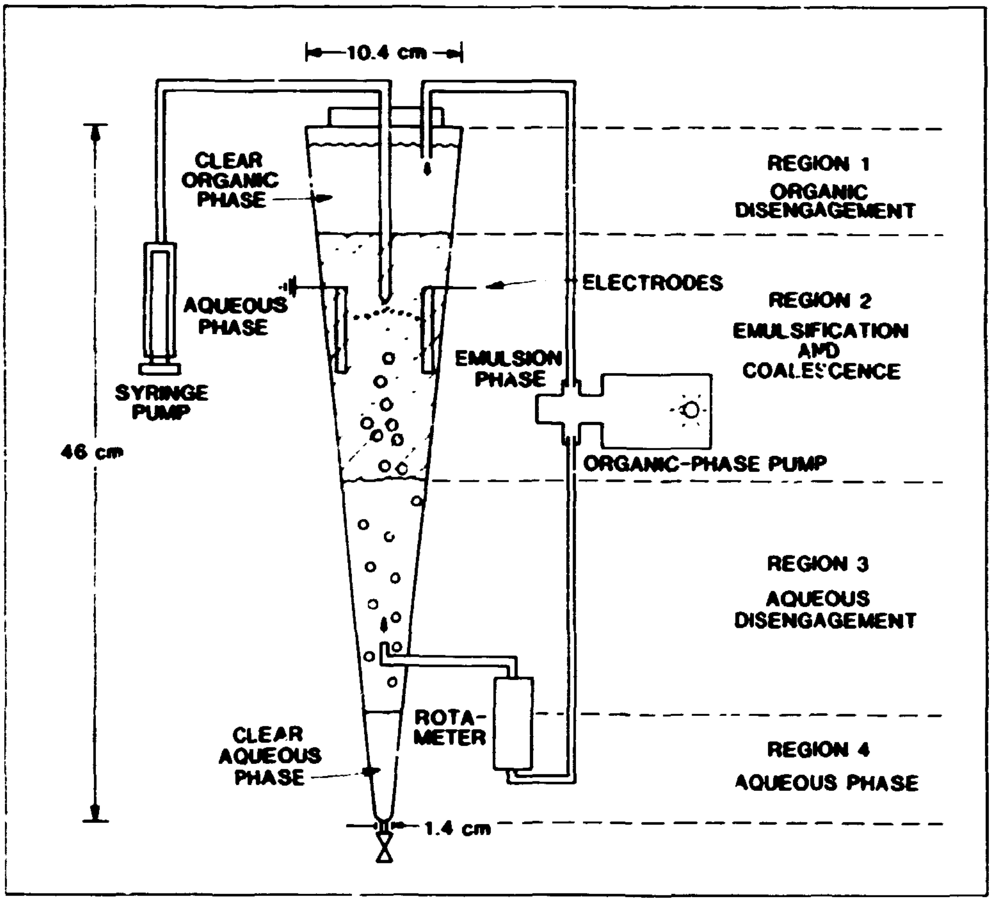
The fine, uniform droplets are one key to the promise of the new technique: For a given volume of liquid, a 100-fold reduction in droplet size translates into a 100-fold increase in surface area, and, therefore, a 100-fold increase in the efficiency with which the solvent can contact the aqueous-phase droplets and perform the extraction. In actual tests of a crude laboratory prototype using an organic solvent to remove acetic acid from water, the ORNL system showed strong promise of approaching that performance standard. It proved 16 times as efficient as a standard commercial solvent-extraction column and 10 times as efficient as the best commercial system now available. Predicts Scott, "With a more refined system, we think we can go significantly higher than that."



Tim Scott (left) and Bob Wham (right) test their laboratory-scale solvent-extraction apparatus, which uses an electric field rather than mechanical action to disperse and mix liquids.

Efficiency, Simplicity, and Safety

The electric field does more than just break up the droplets into an extremely fine emulsion. It also sets them in motion around the electrodes, providing



This drawing shows the simplicity of the system. The "loaded" aqueous phase flows out of the nozzle between electrodes where a high-strength electric field breaks it into minute droplets and sets up circulation of the droplets through organic solvent. After circulation, droplets of aqueous phase, minus the extract, coalesce and settle to the bottom of the vessel.

constant contact with fresh solvent that is flowing up through the circulation zone.

The high-surface area of the droplets, coupled with continuous contact with fresh solvent, allows the equivalent of many separation stages to be packed into one compact vessel. And because the circulation and liquid-liquid contact are concentrated in the zone right around the electrodes, an "interface layer" only a few centimeters high, the process is far more energy efficient than conventional equipment in which virtually a vesselful of liquid is stirred. "In fact," says Scott, "our system cuts energy requirements by 99%, if you figure that mechanical mixing can match our system's uniform, micron-size droplets. But mechanical mixing can't really do that, so the comparison isn't even fair. The important point is, we can do things you can't even do mechanically, and we can do them with much less energy."

Another strong commercial selling point is the simplicity of the system. With no impellers, gears, or other moving parts within the separation vessel, the chances of costly, time-consuming equipment failure are almost zero. That's a particular advantage in hazardous-chemical processing plants where opening a vessel to replace an impeller or shaft can expose workers to danger. "Often there's a 'bone pile' of broken parts inside radiochemical process equipment," notes Wham. "It's sometimes safer just to leave them lying there than to go in and retrieve them."

Phenomenon Is Puzzling—but It Works

The researchers have found that the electric field has still another benefit. Once the droplets have been dispersed, set into motion, and unloaded by the solvent, the field also promotes their coalescence; they clump together and settle to the bottom of the vessel for removal. A simple demonstration dramatically proved the dual effect. The researchers used a single jolt of electric current to create a fine emulsion. It remained suspended for days, until they restored the electric field, and then coalesced almost at once.

The phenomenon of simultaneous dispersion and coalescence is a complex one, which varies with the type of field and the dielectric properties of the aqueous solution. "There's a lot we don't know yet," says Scott, "but one thing that we are fairly sure of is that transient fields, ac or pulsed dc, seem to work better at causing coalescence; if the field is constant as the charged droplets approach each other, they're less likely to coalesce. Also, with a more 'leaky' dielectric—one that allows more current flow between the electrodes—we see higher charges on the droplets, and that affects coalescence. At this point it's still impossible to predict exactly how everything's working.

"We've raised a bunch of questions about what goes on in emulsion materials in an electric field," adds Wham. "They're things that are important to us, as fundamentalists, to understand." His comment is both apt and ironic because it was basic research that uncovered the puzzling phenomenon in the first place.

Despite the unanswered scientific questions, the applied technology offers immediate promise to the chemical industry. "We don't quite know why it works or how it works, but we do know it works," Wham summarizes. The developers have filed two patent applications on their system, and they've asked ORNL's Office of Technology Applications to fund production of a more advanced prototype that can be demonstrated to potential industrial users.

"We've now developed it to the point where an industry could invest about a year's work and find out if it's going to work in a particular separation process," says Wham. Adds Scott, "Again, we think that specialty chemicals—isotopes, precious metals, pharmaceuticals—are the best bets for commercializing this in the next few years."

While Scott and Wham talk of near-term commercial applications, scientific fundamentalism creeps in again. Despite "fantastic" extraction efficiencies, they say, the technique is limited to low flow rates. A better understanding of the basics of coalescence might lead to higher flow rates.

As the talk shifts from commercialization to fundamentalism and back again, the sharp boundary between basic research and applied technology begins to blur once more. A nearby analogy is irresistible: A switch is thrown somewhere, and two ordinarily separate phases of science begin to break apart, to intermingle, to interact. Something passes from one phase to the other, and both are altered by the transfer. Eventually, out of seeming turbulence and turmoil, something new and valuable coalesces; perhaps something that could not have been obtained any other way except by this process, which is somewhat puzzling—but which works.

Microwave-Fired Ceramics: Denser, Stronger, Cheaper

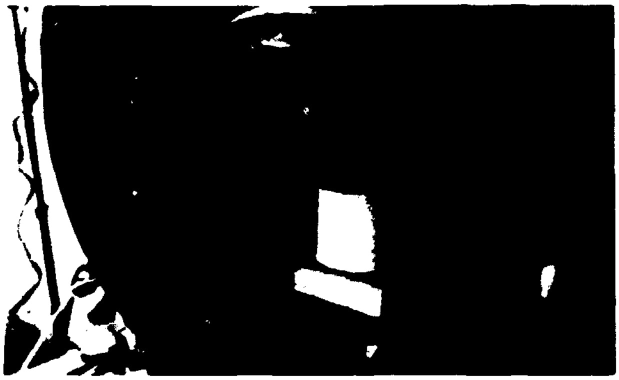
Microwave-fired ceramics is a sophisticated new ceramics-processing technique that almost any amateur chef who uses a microwave oven can understand, at least on an elementary level.

The technology that lets you bake a potato to steaming fluffiness in minutes instead of an hour may soon allow companies to make stronger and tougher ceramic parts more quickly and economically than with conventional heating and at temperatures hundreds of degrees lower.

"The method being studied at ORNL relies on the same principle as home cooking," says microwave engineer Hal Kimrey of Fusion Energy Division. Microwave-length energy "couples" with molecules in the material, causing them to vibrate; this produces heat directly rather than by the indirect (and therefore slower, less efficient) routes of radiation to the surface and then conduction into the material. There are differences in the equipment, of course, mainly in frequency and power. Home microwave ovens operate at a frequency of 2.45 gigahertz and power levels of less than a kilowatt; the gyrotron microwave source being used at ORNL produces waves at a frequency of 28 gigahertz and can reach power levels of 200 kilowatts, about 300 times higher.

Microwave heating has the potential to revolutionize sintering, the firing process that turns finer-than-dust powders into harder-than-steel components. Sintering predates written history. Perhaps it originated when some long-ago Mediterranean shepherd chanced to notice that old potsherds fished from the ashes of a campfire were stronger than new pots dried in the sun. The technology has advanced considerably since then, of course, but the principle remains the same.

> *". . . we think we're onto something totally new."*



A silicon carbide sample, nestled within a cylinder of alumina fiberboard insulation, awaits sintering in the microwave cavity. The insulation prevents surface heat loss that would cause uneven sintering and thermal stresses.

An unsintered "green body," the shaped and pressed compact of powder of alumina, for example, is softer than chalk. White powder rubs off onto your hands; if you drop it on the floor, you need a broom and a dustpan to scoop it up. But when the green body is sintered at high temperature, usually well above 1000°C, the millions of individual powder grains fuse into a dense, tightly bound solid that can withstand temperatures and stresses beyond the limits of many metals.

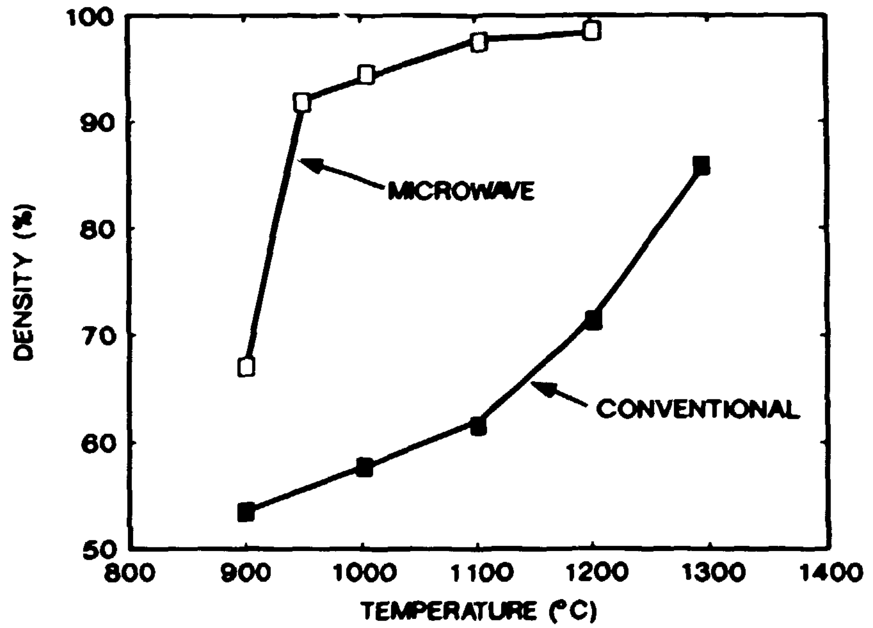
Precisely controlled sintering is crucial to producing many of the key properties of today's ultrastrong high-temperature ceramics such as those used in turbine rotors of jet engines and cylinder sleeves of diesel engines. The more even the heating rate throughout a green body, for example, the more uniform the ceramic's microstructure will be; therefore, it will be less subject to weakening voids or flaws. Other critical factors in achieving dense, fine-grained ceramics include the rate of heating (the faster the rate, the finer the grain) and the sintering temperature itself (the higher the temperature, the denser the ceramic).

One vexing problem with conventional heating, however, is the inevitable trade-off between speed and uniformity. If you fire a part fast, the uneven distribution of heat can create internal stresses and flaws that weaken it; if you slow the heating to match the material's conduction rate, the grain size increases.

That trade-off isn't required with microwave sintering, according to ceramist Mark Janney of the Metals and Ceramics Division. "With microwave sintering, we can get both fine grain sizes and extremely high densities—better than 99% of the theoretical maximum," says Janney. "With conventional heating, you normally have to settle for coarser grain sizes to get such high densities."

Janney, a powder-processing specialist who joined the project in late 1986, has found that microwave-sintered ceramics can apparently surpass conventionally fired ceramics in density, fineness of grain, and fracture strength. Microwave-sintered samples even compare well with ceramics subjected to hot-pressing, an expensive and time-consuming technique in which high-sintering temperatures are coupled with high pressure to eliminate large pores during densification.

"Even for fairly complex parts, near-net-shape green bodies might be possible, with microstructures as good as those of hot-pressing," says Janney. "The cost ramifications of that—the savings from minimizing machining of the finished parts—are amazing."



Microwave sintering of alumina yields higher densities, and therefore greater strength, at far lower temperatures than conventional firing.

Uniformity and "Transparency" Are Keys

Because it heats materials directly at the molecular level, microwaving is faster and possibly more energy-efficient than firing in a conventional furnace. And because the high-frequency 28-gigahertz wavelengths are short, their energy is distributed far more evenly throughout the heating cavity. As a result, Kimrey and Janney don't suffer the ceramic equivalent of the problem that sometimes plagues home microwave cooks: entrees that are steamy in some spots but stone-cold in others.

"This process works best with materials that are relatively transparent to the electromagnetic radiation, so that it passes through them over and over again as it bounces around," says Kimrey. "We call this degree of transparency the 'skin depth.' Alumina has a skin depth of tens of feet—much greater than the part size—so the microwaves heat it uniformly throughout. On the other hand, if the skin depth is shallow, the microwaves would just be heating the surface, and we'd have the same problems as with conventional heating." The uniformity of microwave heating is especially valuable with complex shapes (e.g., turbine rotors) that are difficult to heat uniformly in conventional furnaces.

Two medallions of microwave-sintered zirconia are shown here. The medallion on the left was sintered with low-frequency (home-frequency) microwaves in which energy is dispersed unevenly into "hot" and "cool" spots; the one on the right was sintered with uniformly distributed high-frequency microwaves. The low-frequency microwaves caused internal thermal stresses, radiating from the hot spot at lower left, that shattered the medallion.

Besides uniformly distributing the energy, the shorter, higher-frequency microwaves have another advantage, explains Kimrey. "As the frequency goes up, the dielectric absorption increases because you get closer to the molecular resonances. For example, alumina absorbs 25 times more power per unit volume at 28 gigahertz than at 2.45 gigahertz."

Gyrotrons capable of higher frequencies are on the horizon: A 140-gigahertz gyrotron is now available from one manufacturer, and a

280-gigahertz design is under development. Eventually, however, higher frequencies may entail a disadvantage. At extremely high frequencies a material's skin depth decreases, so the increased absorption might be offset by uneven heating.

Much research remains to be done. "It's difficult, in this frequency range, to find literature on the dielectric properties of these materials," says Kimrey, "partly because the hardware necessary to make that kind of study is only now becoming available."

Adds Program Manager Bill Snyder, "You more or less have to start with a series of Edisonian experiments—throw it in there and see what happens." Snyder, a materials specialist in Engineering Technology Division, recently took on the responsibility for seeking industrial involvement and coordinating the research efforts.

Commercial Applications Are Numerous

"You might be able to do some things with microwave sintering that you just can't do otherwise," says Janney. For example, one promising application of microwave sintering is in firing computer "chip carriers," metal-ceramic composites that pack hundreds of meters of conductor wire into a pad smaller than a slice of sandwich bread. "Normally these chip carriers are built up of 30 to 50 layers of alumina, each screen-printed with conductor wire," says Janney. "Because this multilayer composite has to be sintered at a temperature of around 1550°C—above the melting point of copper—the conductor has to be molybdenum. Molybdenum isn't as good as copper, though, because its resistivity is higher and it heats up more. We've demonstrated that we can sinter alumina at a temperature of 950°C, which is below copper's melting point. This opens the door to developing a multilayer chip carrier using copper instead."

Sintering with microwave energy could prove a boon in processing other difficult-to-make ceramics such as boron carbide. Boron carbide is one of the hardest known substances, yet it weighs about the same as aluminum; consequently, it is being developed as lightweight armor for military vehicles such as helicopters and tanks. Conventional processing of boron carbide requires hot-pressing at a temperature of 2200°C. However, using 2.45-gigahertz microwaves, colleague Cress Holcombe of the Oak Ridge Y-12 Plant's Development Division has successfully sintered boron carbide in a total cycle time of less than 3 hours—less than one-half the time required with hot-pressing.

Eventually, microwave sintering may offer energy savings for the ceramics industry, both because of reduced processing times and temperatures and because most of the microwave energy is converted into heat within the ceramic itself rather than dispersed in massive oven walls and elements. But far more economically important than energy savings, according to Janney and Kimrey, are the better quality and higher "yield" (the proportion of undamaged sintered parts) made possible by uniform, low-stress heating with microwaves.

Kimrey foresees commercial use of the technique fairly soon, possibly within a few years. "A lot depends on how well we can work with industry, though," he adds. "Every company is naturally interested in its own particular application; however, whether you're talking about turbine rotors or electronic substrates for computers, much of the processing is the same. We'd like to find a way to work with industry on a generic basis rather than one-on-one. Within a year or two, we envision building and staffing a facility that companies could share with us."

International competition is fierce in ceramic technology, especially the race with Japan to develop engines that rely on ceramic components for more efficient, high-temperature operation. "The Japanese have demonstrated over and over again their ability to take a good idea and run with it," observes Kimrey. "We'd like to see U.S. industry have first crack at this technology."

Recycled Equipment Is Key to New Processing Technique

Recycled equipment from a defunct fusion project is the key to ORNL's exploration of microwave sintering of ceramics. Microwave engineer Hal Kimrey has adapted the gyrotron oscillators built to heat plasmas in the old ELMO Bumpy Torus (EBT) project, turning them into heat sources for a sintering furnace.

Kimrey began thinking about the technique in 1984, when the EBT, a project he was working on, began to wind down. The EBT used gyrotron tubes to produce high-frequency microwaves for plasma heating. Kimrey wondered whether there could be life for the gyrotrons after EBT.

"When I started looking at other kinds of things to do with microwave energy," Kimrey recalls, "I went back and talked with folks I had already worked with in M&C on the gyrotron window problem." The problem: the ceramic windows at the ends of gyrotron tubes absorb a fraction of the high-frequency energy emitted by the tubes, so they heat up; at high-power levels, the resulting thermal stresses can break the windows. But now, with no fusion plasma waiting on the other side, the problematic window appeared in a new light. It became a window of opportunity.

By 1986, with some ORNL exploratory funding to build a microwave furnace and with some materials expertise from M&C ceramist Paul Becher, Kimrey demonstrated that microwave energy could be used to sinter aluminum oxide. That accomplishment won the project enough funding from the ORNL Director's R&D Fund to continue through FY 1987, with the participation of powder-processing specialist Mark Janney of M&C.

Although the ORNL gyrotron is capable of 200 kilowatts of power, Kimrey usually operates it at far less—about the same as [illegible] microwave ovens use. "Once, while we were experimenting, I turned on the generator at 20 kilowatts," recalls Kimrey, "and this big piece of ceramic just went boom." Since then, Kimrey has developed a finer touch on the controls. "Generally we use more power for the control electronics than for the microwave energy," he notes.

The project has evolved considerably beyond a way to make use of some unemployed fusion equipment. Project Manager Bill Snyder hopes to secure enough funding—about $[illegible] million—to support a full-time staff. To that end, Snyder is negotiating with a half-dozen sponsors, ranging from DOE's Basic Energy Sciences and Conservation and Renewable Energy Programs to DARPA, the Defense Advanced Research Project Agency.

Still, the project's origins are not forgotten. "This is good PR for the fusion program because it shows that fusion is spinning off valuable technologies," says Kimrey. "That's always been an important benefit of the space program, and we think that it can be an important benefit of the fusion program too."

Decades-Old Error Leads—Eventually—to "Whiskers" for Reinforced Ceramics

Carlos Bamberger set out to synthesize a reported new compound. He didn't succeed.

In the course of his efforts, however, he did manage to find several other new compounds. He also found new ways of making powders of titanium nitride and boron nitride. Best of all, or at least most patently useful, he found a way to make titanium nitride "whiskers," which may prove valuable for reinforcing advanced ceramic composites.

It was a classic story of following a trail of basic research that somehow strayed into applications, of taking scientific detour upon detour, and of coming out both far afield and far ahead of where he had expected.

Bamberger's odyssey began more than five years ago when he tried to duplicate a high-temperature reaction of sodium cyanide with titanium oxide. In 1950 a Polish chemist reported that this reaction had synthesized a new compound composed of sodium, titanium, and nitrogen (dubbed "sodium tianide").

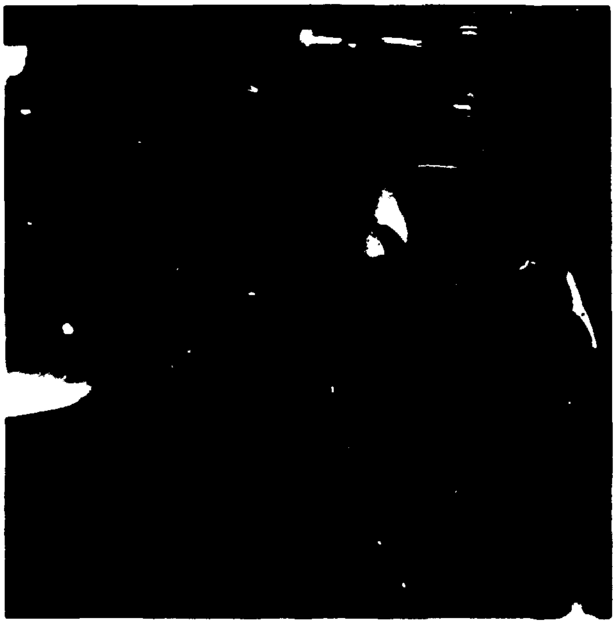
Thus begins a story that Bamberger enjoys telling.

"The compound was reported in 1950, but nobody followed up on it," relates Bamberger. "The chemistry of cyanide at high temperatures has been neglected; the cyanide is so poisonous, I think people have been afraid of it.

"I figured either this compound, 'sodium tianide,' existed and might have interesting properties, or it didn't exist. My gut feeling was that it didn't exist; the reaction didn't look right to me. I'd never seen anything similar. After so many years, you get a feel for things like this, you develop instincts. My instincts told me the report was wrong.

"When I did the reaction, I got a lot of products I couldn't identify, either by Raman spectroscopy or by X-ray powder diffraction. I had an inkling what some of the products were, but I also found in the literature that knowledge of this family of compounds, sodium titanates, was a mess. So I decided to synthesize the whole family and identify them unequivocally so I could study the original

"If I hadn't had the freedom to pursue this research, . . . I would never have found these things."



Carlos Bamberger checks the reaction that produces titanium nitride whiskers. The whiskers are formed in a crucible inside cylinder (right); liquid in flask (left) traps noxious gases resulting from removal of volatile species from reaction.

A sample of Bamberger's titanium nitride whiskers, magnified about 10 times. The longest of the whiskers shown are about 2.5 mm (0.1 in.) in length.

reaction. When I finally did that, I was able to conclude that the compound 'sodium tianide' didn't exist. The earlier chemist had evidently made an analytical error."

The trail had come to a dead end. But a new trail branched off in another direction.

"Still, I was interested in the products of the reaction—a mixture of titanium nitride with sodium titanates. Titanium nitride is something of technological importance: it's very hard, it has a high melting point (2950°C), and it has a high electrical conductivity. It could be used to make high-temperature crucibles for melting metals. It's also used in cheap jewelry to simulate gold plating. This gold finish on my wristwatch, for example, might be titanium nitride.

"But I had a problem with the reaction products; I couldn't separate the sodium titanate from the titanium nitride. Then it occurred to me that instead of using titanium oxide as a starting material, perhaps I could use a salt such as titanium phosphate. If I did that, maybe I could convert all the titanium into nitride and all the phosphate into sodium phosphate, which would be easy to remove because it's water soluble.

"In making a phosphate to use as a starting material, using a reaction I had patented some years ago, I ended up with two phosphates instead—the one I wanted plus a new one. I started reacting both of them with different proportions of cyanide, a standard procedure.

"When I used small ratios of cyanide to titanium, I didn't get what I expected; instead, I got a bunch of other things I had to identify, including two new phosphates containing sodium and titanium.

"I also got a sodium-titanium 'bronze,' a material in the form of bluish-black crystals. The name is misleading: it really has nothing to do with bronze. It's old nomenclature for certain kinds of compounds that usually have dark colors and behave almost like metals. Maybe the earliest ones looked like bronze.

"Anyway, I had all these new compounds to study, so I systematically began reacting each with large excesses of cyanide. As I expected, all of the reactions gave titanium nitride powder except for the titanium bronze, which produced titanium nitride 'whiskers.' This turned out to be a new reaction and possibly a new way to make titanium nitride whiskers."

The whiskers are tiny, needle-like structures made of a single crystal. They measure up to several microns in diameter and up to 2 centimeters long.

Ceramic composites reinforced with other kinds of whiskers are proving to be remarkably strong and fracture-resistant. For example, ceramists in ORNL's M&C Division have developed ceramic composites reinforced with silicon carbide whiskers. Cutting tools made of whisker-reinforced alumina can be operated at 3 to 10 times the speed of ordinary tungsten carbide tools. The whiskers, dispersed evenly throughout the composite's matrix, help to distribute stresses that can fracture ordinary monolithic ceramics.

Bamberger and a few samples of his collection of titanium nitride whiskers. The microscope is used to check the size, uniformity, and "cleanness" of the whiskers.

But applications for Bamberger's titanium nitride whiskers lie farther down the path. For now, we will go back to our story. "Finding this reaction that produced titanium nitride whiskers was totally unexpected but very important. There are not many good candidate materials for whiskers. Ever since, I have worked to improve the reaction."

A drawer in Bamberger's laboratory is filled with hundreds of sample vials attesting to his work to improve the reaction. Each vial represents one experimental run. A cardboard tray with dozens of pigeonholes, like a half-scale Coke-bottle crate, contains still more of the vials. Lining one side of the tray are the successes—vials containing titanium nitride whiskers; on the other side are the failures—brownish and blackish powders. "The brown ones are titanium nitride powder," explains Bamberger. "The black ones? I don't know."

Several rows of empty pigeonholes separate the two groups of vials; success and failure have not yet met in the middle.

Bamberger pulls out one of the successes. Within the vial, tiny slivers sparkle a warm gold beneath the laboratory's fluorescent light. "I think this one is my best," beams Bamberger. "Some of the whiskers are very large; you can see them easily with your naked eye."

Bamberger answers a question, Do different experimental conditions explain the variable results? "Not always. I can't control the reaction that well yet. Usually I don't get just whiskers; I may also get a lot of junk. So far I don't even know the process by which the whiskers are formed. But I'm working on it.

"It will take a lot of work to know how much we can control the process and how to tailor it for ceramic applications," he continues. "For example, the ceramics people don't yet know the optimum size for titanium nitride whiskers for composites; they do for silicon carbide, but this is completely different. It will take a very broad research effort, and we're just starting."

Bamberger ends his story with a moral: the importance of scientific freedom. "If I hadn't had the freedom to pursue this research, which some people thought was a waste of time, I would never have found these things."

More steps lie ahead; more scientific detours, which are paths worth following. Bamberger is continuing this research that began as an inadvertent detour, many twists and turns and years ago, when a Polish chemist, through an analytical error, reported synthesizing a compound that has apparently never existed.

HERMIES: Evolution on the Fast Track

Movement: one of the traits of animal life. Intelligent movement: one of the distinguishing traits of higher animals, including humans.

A one-celled paramecium seeks light. It can move toward a patch of sunlight on the surface of its pond; if it bumps into something on the way, it can back up and try again.

A human being seeks light. It, too, can move toward sunlight. But it can also find—even invent—artificial sources of light. The difference in capabilities is almost infinite.

Evolving the intelligence that makes that difference took millions of years—no, hundreds of millions of years.

But in just six years, ORNL's HERMIES (Hostile Environment Robotic Machine Intelligence Experiment Series) will have "evolved" the capability to make these intelligent movements:

- scan and "map" a room containing both stationary and moving objects,
- figure out the most direct way to avoid or remove obstacles and reach the other side of the room,
- locate its goal: an instrument panel,
- read a meter on the panel,
- adjust a lever as needed to change the meter's reading to a desired value, and
- go back to its starting point, navigating mainly by memory of what it has learned about the room.

HERMIES will never be able to match human capabilities. But it's well on the way to becoming a robot that ultimately could do some things a human couldn't. For example, it could enter a lethally contaminated radiation zone, find a trouble spot, diagnose and repair malfunctioning equipment, and adjust dials and levers to restore normal operating conditions—not through remote control by human operators but through its own base of programmed knowledge plus on-the-spot "learning" about which actions produce the right results.

> *"This will probably be the most exciting accomplishment of the next few decades."*

Advances in the HERMIES III generation include improved manipulator arms, sensory fusion (combining sonar, video, and laser input), and an eightfold increase in on-board parallel computing power.

HERMIES I, circa 1984, shown here with a University of Tennessee graduate student, Tom Swift. The robot's vision at this stage consisted of two sonar sensors (top). Computing power was limited, and motor control proved to be a problem.

The evolution of HERMIES began in 1984 with HERMIES I, a simple machine that consisted of an IBM-clone microcomputer, a single microchip for high-level planning, and two sonar sensors, all mounted on a crudely motorized platform. Later HERMIES I evolved arms, Heathkit "Hero" arms, the kind that have been available to home tinkerers for years.

HERMIES I had to be spoon-fed its knowledge of the world. The dimensions of the experiment room and the locations of objects in it were preprogrammed into the computer along with the path HERMIES was to navigate.

Building HERMIES I cost a total of $12,000 including labor, recalls Chuck Weisbin, director of the Robotics and Intelligent Systems Program (RISP) within the Engineering Physics and Mathematics Division. "One of the things we learned with HERMIES I was that for $12,000 we could build a mobile robot that didn't work," laughs Weisbin, who has overseen all of HERMIES' evolutionary stages.

"HERMIES I was built mostly by students using off-the-shelf parts. It just didn't have the fine motor control it needed to move precisely. We could tell it to move one meter, but it might move one-and-a-half instead. And if the drive for the left wheel didn't work exactly in sync with the right wheel, it wouldn't even go straight.

"But with HERMIES I we did get valuable experience with the robot, and we learned what we needed to do to make the next one work better."

The next one was HERMIES II, built in 1985. HERMIES II was several rungs above its predecessor on the evolutionary ladder. It featured improved motor and drive control, an array of 24 sonar sensors to gather its own picture of the world, and the computing capability to use the sonar data for its own map-making and navigation. "It's kind of like Columbus—it knows what direction it wants to go and what it's looking for, but it has to figure out how to get there on its own," Weisbin explains.

Still, HERMIES II was limited. Its sonar scanners were slow, requiring 80 seconds to scan a semicircular arc ahead of the machine. Navigation

HERMIES II, built in 1985, boasted an array of 24 sonar sensors, as well as the computing capability to use the sonar data for map-making and navigation. HERMIES II also featured improved motor and drive control. Shown with this evolutionary stage are Program Director Chuck Weisbin (right) and Bill Hamel (left) of the Instrumentation and Controls Division.

was limited to detecting and avoiding stationary obstacles. And the robot was dependent on an umbilical cord—a tether carrying power and transmitting data to and from off-board computers.

Important advances were made in the two subsequent versions of the robot that were built in 1986 and 1987. HERMIES IIA boasted faster sonar scanning (7 seconds per scan, more than 10 times faster), quicker and more complex task planning ("figuring out what to do and when to do it," Weisbin translates) made possible by an off-board computer with multiple processors, and somewhat primitive analysis using a commercial vision system.

HERMIES IIB, the current version, is the first HERMIES to achieve reliable untethered operation, a feat made possible by battery power and an on-board "hypercube" supercomputer. The hypercube, whose parallel processors provide computing power equal to 16 VAX 11/780s, is programmed with an expert system—a reasoning program that allows HERMIES to learn in somewhat the same way humans learn: by drawing on similar past experiences. HERMIES IIB also possesses sharper vision, the ability to manipulate or move small objects, and, most sophisticated, the ability to detect and avoid moving objects.

HERMIES III is rapidly evolving; it is both better and bigger. At 1400 kilograms (3000 pounds), it weighs as much as a midsize car; beside it,

By 1986, HERMIES IIA had evolved video vision for recognizing and reading a control panel. Other advances included faster sonar scanners and a link with an off-board, multiple-processor supercomputer

HERMIES II looks like a baby. By 1990, HERMIES III will boast more maneuverable and versatile manipulator arms, which can "feel" and adjust the strength of their grip; far more precise "senses," resulting from the fusion of data from sonar arrays, video cameras, and a range-finding laser; and an eightfold increase in on-board parallel computing power.

Looking Down the Evolutionary Road

How far can HERMIES go? The answer depends on whom you ask. At a blackboard on his wall, Weisbin sketches a fork in the evolutionary road of robotics. One direction is artificial intelligence (AI), the track HERMIES is taking. Within a decade, AI advances will produce smart machines that learn and perform specific tasks very well. By 2010, AI may allow automated factories employing only a few supervisory humans. In these factories, robots will perform all manufacturing, control, and maintenance work. But progress in AI, while very useful, may well be application-specific and limited, says Weisbin. In other words, AI is a faster evolutionary track but a shorter one. It may yield the machine counterpart of chimps or orangutans—but not humans.

The other track is cognitive science, understanding and recreating thought processes through detailed research on the structure and workings of the brain itself. Cognitive science will reach its hoped-for evolutionary potential far more slowly than AI, speculates Weisbin, if at all. But the potential implications could be shattering—synthetic brains that would be like something out of science fiction—the electronic equivalents of human beings.

Fred Maienschein, director of the Engineering Physics and Mathematics Division, concurs. "The people who invented digital computers back in the

The heftier HERMIES IIB has an on-board supercomputer, is programmed with an expert system that allows "learning," possesses sharper vision, has the ability to manipulate or move small objects, and most sophisticated the ability to detect and avoid moving objects.

'40s, especially Alan Turing and John Von Neumann, were really interested in cognitive science," says Maienschein. "Computers and cognitive science have developed together, and they will continue to. There'll be more and more interactions among computer scientists, psychologists, physicists, and neuroscientists. As techniques advance, there'll be more and more hard data on the workings of the brain."

Maienschein points to the dependence of cognitive science on computing power. "The speed of computers is a limiting factor in modeling how a neural network like the brain works," he explains. "Right now, computers are just too slow. Researchers can model a network—a brain—of a thousand interconnected neurons. That's roughly the equivalent of a sea slug; it's a factor of 10 million away from a human brain, which has about 10 billion neurons. The gap is even more enormous when the possible interconnections among neurons are considered. But computing speed increases by an order of magnitude every five years, more or less, and as it does, we can model a more complicated neural network, with more interconnections."

Maienschein's predictions are couched in qualifiers and tentatives. "We can expect the beginning of some glimmer of understanding in the next couple of decades," he speculates. "That understanding itself will help advance computer science."

But is the human brain really the best model for artificial thought? "We don't even know enough about our thought processes to be sure of that," he answers. Then, with a laugh, "But there's no reason to be certain that the answer is 'yes'."

A more serious parting observation: "This will probably be the most exciting accomplishment of the next few decades," he muses. "What could be more interesting than beginning to find out how people think?"

By the time the accuracy of Maienschein's predictions is known, today's intelligent robots will have already been displaced by several generations, each representing a major step farther along the evolutionary path. The HERMIES robots will be as unlike that day's robots as the dinosaurish computers of the 1950s are unlike their 1988 descendants.

HERMIES III, now taking shape, will be a museum curio by then, a primitive electronic fossil.

That's what fast-track evolution is all about.

Genetic Damage: New Light on an Old Problem

Birth defects, mental handicaps, and miscarriage—the nightmare of every prospective parent. Each year this nightmare comes true for hundreds of thousands of couples in the United States.

Often, medical science can't even explain why—can't even offer the slim comfort of a cause.

But recent research conducted in ORNL's Biology Division may help to unlock some of the tragic riddles of fetal abnormality and death. A research group led by Waldy Generoso has discovered a new form of genetic damage that occurs in the first few hours after conception—damage that, in chemical-exposure experiments with mice, has proven to cause high rates of fetal death and abnormalities.

Generoso has spent the past 21 years at ORNL studying mutagenesis, chemically induced changes in the structure or number of chromosomes or in the individual genes they contain. During that time, he has conducted perhaps hundreds of mutagenesis studies on chemicals, ranging from health-industry disinfectants to artificial sweeteners. By his reckoning, he has examined tens of thousands of mice.

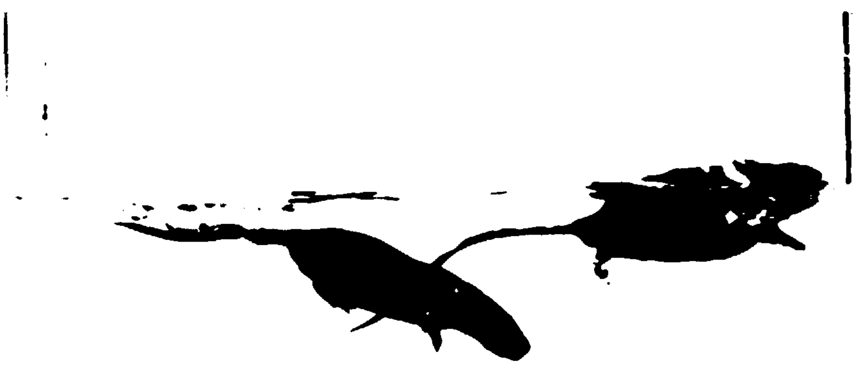
For most of his career, Generoso, like other mammalian mutagenesis researchers, has focused on the effect chemicals have on the genetic material in egg and sperm cells. "In traditional mutagenesis," explains Generoso, "we give the chemical to the mother or father before mating—sometimes many months before." If the chemical is mutagenic, it may cause one or more of the following effects: (1) a change in the number of chromosomes; (2) structural damage to the chromosome (breakage); or (3) more subtle changes, such as deletion or duplication of individual genes or changes in the base composition of deoxyribonucleic acid (DNA).

Over the years, Generoso's research has produced several chromosomal rearrangements that cause

> *"This is an exciting opportunity for research in basic experimental biology."*

Waldy Generoso inspects mouse embryos for abnormalities caused by genetic damage.

Normal mouse (right) and offspring (left) of a mother with genetic damage caused by gamma radiation. Note the deformed feet.



A rearrangement of chromosomes—the result of genetic damage to the mother or father—causes the "diver" mutant (left) to lose its orientation in water. Unless rescued, the diver will swim in random loops until it drowns. Normal mouse (right) is a strong swimmer.

easily recognizable defects. One such mutation produces malformed feet. Another produces what he calls the "diver" syndrome, for reasons that quickly become obvious when he places one of the mice in a narrow tank of water. Unlike a normal mouse, which is a strong lap swimmer, the diver mutant loops and soon plunges toward bottom; Generoso lifts it from the tank so that it won't drown.

But conventional tests of mutagenicity don't reveal a complete picture of the mutagenic effects of chemicals in mice or in humans.

For the past two years, Generoso has been looking at a new time slot in the chronology of reproduction: around the time of fertilization and the first few hours following fertilization (the zygote stage). According to his findings, it's a time when the ovulated eggs and zygotes are especially vulnerable to a new type of genetic damage.

Hope for Understanding Miscarriages and Birth Defects

Each year abnormalities occur in about 10% of human pregnancies in the United States—about 600,000. As in mice, most abnormalities cause death in the developing offspring, resulting in miscarriage. The miscarriage often occurs before the woman realizes she has conceived, but sometimes it occurs later in pregnancy. Surviving fetuses with abnormalities make up 2 to 3% of live births, notes Generoso—perhaps 100,000 or more U.S. cases each year. "You can imagine the extent to which these late miscarriages and birth defects contribute to medical and social problems," he adds.

Traditional wisdom has attributed about 20% of human fetal defects to inherited abnormalities and about 10% to specific agents such as viruses. The others, about 70%, are currently unexplainable.

Complex Research Underscores Simple Advice

Although the molecular explanation of the zygote vulnerability discovered by Generoso has not yet been found, the phenomenon itself clearly has implications of compelling interest to prospective parents. Generoso discusses them.

"Let's look at the genetic effects that are significant in humans. The early deaths are not of much significance, at least medically or socially; a woman may miss a menstrual period but may have no other indication she's conceived. The mid-gestation and late fetal deaths and the malformations in living offspring are clearly the most important problems.

"The question one needs to ask," he continues, "is to what extent 'errors' that occur during fertilization and the zygotic stage, including those resulting from chemical exposure, contribute to fetal abnormalities. In humans, there's plenty of opportunity for exposures because the zygotic period after fertilization is long—many hours longer than in the mouse. The exposure could be to medication, it could be to smoke or alcohol, it could be to chemicals at work the next day."

One of the chemicals Generoso has studied, EtO, is widely used in medical facilities to sterilize instruments. Asked about the implications his findings hold for female clinic workers of childbearing age, Generoso hesitates. "If you work with ethylene oxide and you're going to conceive tonight, stay away from it tomorrow morning," he says slowly. "I will say that. We don't want to alarm people, but we can't avoid the issues these findings raise."

His simple advice—the flesh-and-blood application of this intricate basic research: "If you're planning to get pregnant, play it safe."

Now, though, some of that 70% may be attributable to the phenomenon Generoso's group has discovered—genetic errors arising in the eggs before and soon after fertilization. If further research bears out the early results, the finding will be an important one.

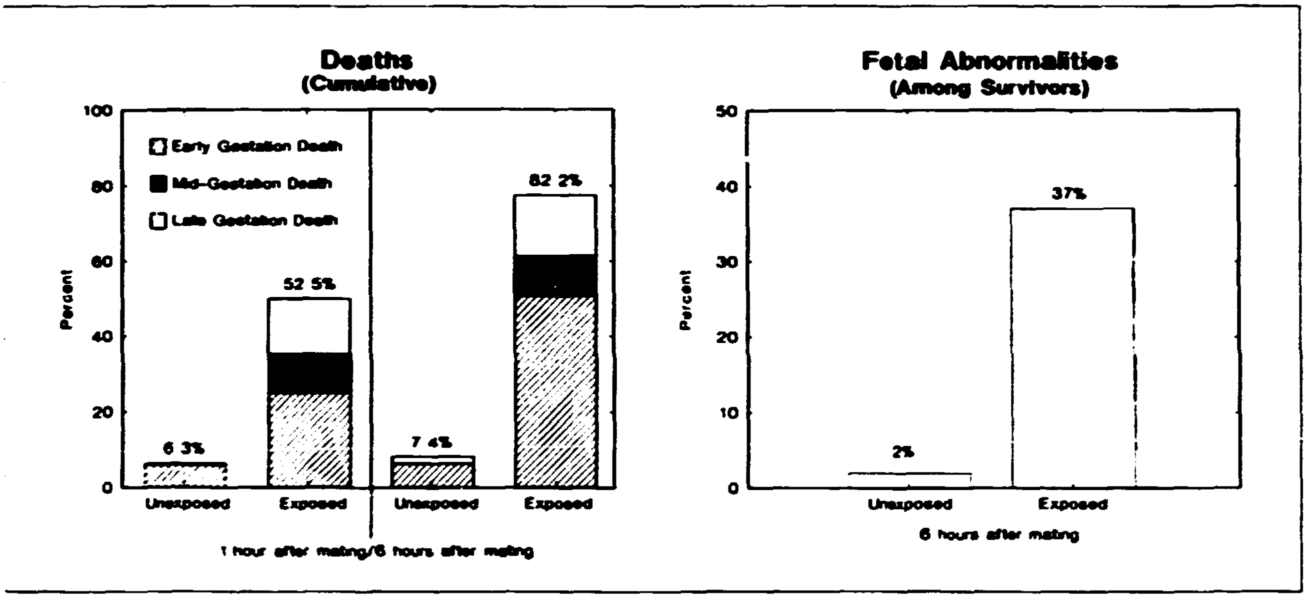
Mouse Studies Allow "Reproducible" Results

"Genetic damage and abnormalities are things that are difficult to study in humans," Generoso notes. "You just don't get a second look."

Using mouse strains that are genetically uniform and very well-defined, however, researchers can get a second look and a third and many more. Through a close collaboration with Dr. Joe Rutledge, a pediatric pathologist at the University of Texas Health Sciences Center in Dallas, Generoso can directly compare mutagenic effects in mice and humans. The collaboration has turned up many similarities between unexplained human abnormalities and experimentally induced malformations in mice caused by exposing the zygotes to chemicals.

Over the past two years, Generoso's work has clearly demonstrated the early zygote's extreme vulnerability to two chemicals: ethylene oxide (EtO), a gas used in many medical facilities to sterilize instruments, and ethyl methanesulfonate (EMS), a liquid similar to EtO in effects but easier to administer.

In the EtO and EMS studies, groups of female mice were exposed to the chemical at a selected time, including one hour after mating (the time required for the sperm cell to contact and enter the



Exposing female mice to ethylene oxide one hour or six hours after mating produced lethal defects in a majority of developing offspring. Exposure also produced dramatic increases in abnormalities among surviving fetuses.

egg) or six hours after mating (before the first chromosome replication—the forerunner to cell division—has occurred).

Exposure one hour or six hours after mating yielded dramatic results: high rates of fetal death and, among both dead and surviving fetuses, many abnormalities. The abnormalities included swollen ("hydropic") fetuses or organs; cleft palate; and defects in eyes, ears, feet, heart, abdominal wall, and tail. By comparison, few abnor[illegible] occurred in mice exposed earlier (bef[illegible]ting) or only a few hours later (during the first chromosome replication).

A New "Window" of Vulnerability

The results suggested that, for several hours after fertilization, the zygote was especially vulnerable to damage.

"If the mother or father is exposed prior to mating," Generoso elaborates, "the main effect we see is lots of resorption bodies—embryos that die within three or four days and are absorbed by the uterine lining. But when we exposed mothers shortly after mating, we saw many mid- and late-gestation deaths. That raised a red flag for us."

Since the mother was exposed after mating, the researchers faced a key question: Were the abnormalities caused by direct damage to the zygote itself or was the damage indirect—a result of harm to the mother?

Surrogate Mothers Provide the Answer

"The fact that the effect was very 'stage specific'—high at 1 to 6 hours and gone by 25 hours—suggested that it was direct, not due to maternal toxicity," explains Generoso. "But we needed to be sure of that."

The proof came from another study using hundreds of surrogate mothers. Generoso's group transferred exposed zygotes into unexposed surrogate mothers, and, as a control, put normal zygotes into exposed females.

Even though they'd been exposed, the females implanted with normal zygotes bore normal litters. By contrast, the normal surrogate mothers implanted with exposed zygotes bore litters that were high in fetal deaths and abnormalities. Concludes Generoso, "This convinced us that whatever EMS did, it did to the zygote, not to the mother."

A New Genetic Mechanism?

EtO and EMS are well-known mutagens. "Naturally, the conventional expectation was that fetal anomalies that develop from exposed zygotes would be caused by gross changes in chromosome structure or number," says Generoso. "Surprisingly, this has proved not to be the case. The damage caused by chemicals in the zygote is clearly different from that which is usually produced in many other cell types.

"This is an exciting opportunity for research in basic experimental biology," he continues. "We believe that in order to understand the nature of mutagenic damage, we have to look at the molecular level. The zygote is uniquely suited for in-depth molecular studies. Unlike whole groups of tissues in developing organs, which are the focus in traditional teratology, the zygote gives us a single cell to focus on. It and its direct descendants are accessible for direct molecular and biochemical studies. Bob Fujimura, a molecular biochemist in our division, is applying his molecular expertise to this problem.

"Whoever is the first to find out the basis for this response will be very famous," Generoso muses. "We may be lucky enough to do that here; Fujimura's work may give us a lot of insights.

"If we can find out what it is . . . that's the interesting thing about this kind of study—to discover a phenomenon and be able to follow up on it, find the explanation.

"That's why it's nice to work here. Because we have the opportunity to do these kinds of things."

Protecting the Eyes of SDI

Since President Reagan inaugurated the Strategic Defense Initiative (SDI) in March 1983, ORNL has shouldered a steadily increasing load of SDI research and development. The goal of the multilayered SDI, in President Reagan's words, is to render nuclear-tipped ballistic missiles "impotent and obsolete" by spotting, intercepting, and destroying them in flight.

One of the Laboratory's largest SDI programs is a group of projects designed to enhance the "eyes" of SDI—the optical systems that would spot and track enemy missiles.

SDI will have many eyes: systems in space platforms that are alert for the telltale flares of launched missiles and are poised to steer defensive projectiles or beams at the missiles during their boost phase—before their multiple warheads go their separate ways—or in midtrajectory when the warheads are dispersed; systems in aircraft, scanning the skies for incoming weapons; and systems in the nose cones of interceptor missiles, the final layer of defense.

The eyes of SDI must be both keen and tough. After all, you can't shoot something you can't see.

An attacker would know that as well as we and would try to blind those eyes with blasts that produce radiation levels calculated to cloud optical windows or distort the precision surfaces of focusing mirrors. Then, too, there are harsh natural conditions to guard against: pressures, droplets, and particulates in the atmosphere that will buffet and abrade windows in aircraft-borne systems and, especially, those in the nose cones of supersonic interceptor missiles.

So protecting the eyes of SDI requires hardening them, toughening them, immunizing them against abrasion, pressure, and radiation.

Finding ways to provide eye protection is now a $3-million per year program at ORNL, according to Program Manager Steve McNeany of the Engineering Technology Division. "We started with a fairly small program in 1985 to improve the mirrors used in infrared detection systems," he says. "Now we're also working in several areas of 'window' technology, including surface modification, hardening, and testing."

It's Done with Mirrors

To illustrate the role of mirrors in SDI's optical systems, McNeany takes a yellow note pad and sketches a series of alternating curves and flat surfaces, then links them with lines that run parallel, then converge, and then go parallel again. The lines

Two polished beryllium mirrors, being developed for SDI applications, illustrate the high precision required in SDI optics. Visually inspecting the mirrors is Uly- Tulmer of the SDI Optical Component Characterization Facility.

represent infrared energy emitted by a small circle, which McNeany says is a nuclear warhead showing up hot against the cool background of space. "The system is like a reflecting telescope," he explains, "but it's looking at infrared instead of visible light, and it focuses on an infrared detector instead of your eye or a camera.

"Now, these guys want to destroy your eyes, so suppose they detonate a weapon up here," he says, adding a crude starburst to the doodle. "The radiation may darken your window temporarily or permanently. If you don't have a window—and you won't on a space platform and maybe not on every interceptor because some interceptors don't 'look' until they get above the atmosphere—then you have to worry about the effect of the radiation on your mirror.

"Beryllium is a good mirror material because it withstands radiation better than other materials," he continues. "But these mirrors are tough to fabricate. They require very precise shapes, sometimes very complex shapes, with multiple curves on a single mirror. They have to be highly polished, and the normal abrasive polishing process is long and tedious."

The long, tedious polishing process becomes a critical problem when viewed in the light of future SDI production and deployment. "If you figure on making thousands of these mirrors of varying sizes and shapes, you find that there just isn't the capacity in this country right now to produce that many," McNeany notes.

One way to reduce production time (or increase capacity) is to start with a pre-polishing surface that's smoother and, therefore, closer to its desired final curve. Over the past three years, a group in the Development Division at the Y-12 Plant has achieved impressive smoothing and shaping results with a machining technique called single-point turning.

The equipment used for single-point turning is like a cross between a lathe and a phonograph. A mirror blank—a beryllium disk—is fastened to a rotating assembly. Starting at the rim, a computer-controlled cutting point of cubic boron nitride (diamond can't be used with beryllium) spirals its way in toward the center, chipping away precise amounts of metal from its path. The resulting surface looks like that of a record album without the label or the hole in the center. The surface is not of high-optical quality—its reflection is fuzzy; still, an hour of this precision machining can cut polishing time for a beryllium mirror from 100 hours down to 10 hours. Eventually other techniques, such as noncontact polishing (a form of chemical etching) or the ion-implantation methods developed in ORNL's Solid State Division, may allow further gains in the quality or production efficiency of the mirrors.

Windows on the World

If the optical systems are the eyes of SDI, the windows through which they watch are the corneas. Candidate materials for these windows include sapphire, ALON (a clear ceramic containing aluminum oxide and nitride), yttria, and zirconia.

Some of the areas in which ORNL is working to ensure that the windows can survive and perform when needed are determining the effects of radiation bursts on window transmittance, developing surface-modification techniques to harden and strengthen the windows, forming windows from pressed powders rather than slices of hard-to-grow crystals, and carefully measuring the optical characteristics of a number of components produced here and elsewhere.

In the radiation-burst tests conducted at the Health Physics Research Reactor, specimens of window material are positioned virtually against the reactor core. The burst—a single, intense pulse of fission neutrons and gamma rays—is not fully representative of the radiation spectrum that would be released by a fusion weapon; however, it is far easier and cheaper to produce than an underground nuclear explosion at the Nevada Test Site, which McNeany calls "the true test."

ORNL's radiation tests have shown considerable variation in the effects on the materials. Sapphire, for example, shows no loss of transmittance at any of the 3 wavelengths tested; yttria, on the other hand, shows an immediate 38% loss at 1 wavelength, followed by a partial recovery (to 95% of its original transmittance).

The strength and hardness of windows are also critical to their survival. In studies with sapphire and ALON, surface-modification techniques have shown great potential for improving the resistance of the windows to abrasion and fracture. Implanting silicon or carbon ions in sapphire, for example, can increase the hardness by up to 40%; similarly, implanting chromium ions in sapphire can double the fracture strength. Other surface-modification research involves the use of noncontact polishing to improve surface smoothness and fracture resistance and the use of ion-beam mixing to treat sapphire and ALON surfaces for better adhesion to diamond-hard coatings of carbon.

An additional window-technology project is studying windows made from pressed powders, such as cesium iodide. "Currently we're using single-crystal slices for window samples," says McNeany. "But to grow the large sizes needed for aircraft windows would be difficult and expensive. Our early pressing experiments with cesium iodide powders look very promising, but we have a way to go before we can match the infrared transmittance of, say, single-crystal sapphire."

Eyes Tested Here

To determine just how well the optical components needed for SDI really perform and withstand severe conditions, a highly filtered "clean

Fulmer compares sample infrared "windows" for SDI optical systems. Samples are tested for transmittance, light scattering, surface smoothness, and other optical properties.

room" at the Oak Ridge Gaseous Diffusion Plant has been outfitted as a state-of-the-art optical-testing laboratory. In addition to Oak Ridge-manufactured components, the laboratory also receives test specimens from other SDI programs, including radiation-effects specimens from the Nevada Test Site. Data from the optical performance studies are giving new insight into how keenly the eyes of SDI will eventually be able to see.

The eyes of SDI must be both keen and tough. ORNL is working to make them that way.

Directions

The next 15 years promises to be the most exciting and productive period in the history of ORNL. It will be a period of revolutionary changes in science and technology with unparalleled opportunities for applying these developments to improve the human condition. The ORNL staff and management have always believed that the purpose of the Laboratory is to serve important national needs. The intersection of important national needs with ORNL's R&D capabilities represents the broad direction we want to take over the next 15 years.

Planning Assumptions

Indications are that two major trends will converge early in the next decade to present the nation with a challenge of significant proportions. First, the current deficiencies of the United States in international commerce will likely continue and may even worsen. Second, it is highly probable that the current trend of rising oil imports, coupled with Middle-East instabilities, will lead to increased concern about energy by the mid-1990s. The convergence of increased reliance on imported oil and the inability to compete in international markets will cause significant stress to the U.S. economy. Unlike the conditions of the 1970s when the United States' positive trade balance for manufactured goods helped to offset the trade deficit related to oil, the 1990s will very likely be characterized by huge deficits in both categories. If this scenario becomes reality, the social and political pressures for change will be large. In particular, the traditional sharp boundaries between the roles of industry, government, and universities will become intentionally blurred as it becomes painfully evident that the challenge of global economic competition will require the nation to call upon all of its intellectual resources—universities, industry, and national laboratories—to work together toward a common goal.

DOE and its national laboratories will become more important in the quest to restore a favorable balance of trade. DOE possesses the country's largest collection of scientific and technical talents and research facilities, and most observers believe that the mobilization of these resources is a key ingredient to the future health of U.S. industry. An even more obvious reason DOE and its laboratories are important is that energy products and energy technologies are, and will continue to be, two of the largest components of international trade. For the United States, oil imports will be the single largest contributor to the negative balance of trade.

On another topic of importance to DOE and its laboratories, the issues related to hazardous chemical and radioactive wastes will increase in importance nationally throughout this century and beyond. DOE's interest in these areas stems from (1) the need to clean up its own facilities and (2) the responsibility for safe management of radioactive wastes from the nuclear fuel cycle. The techniques and technologies for neutralizing existing waste sites will be the highest priority objectives of national R&D programs on wastes. But the high cost of cleanup will lead to research on processes that produce fewer wastes and less environmental damage. Results from R&D work directed toward DOE's waste problems will, in many instances, be transferable to national waste problems.

Concurrent with the worsening energy and trade trends and the increased emphasis on wastes, there will be a decline in federal expenditures for the production and deployment of weapon systems, including nuclear weapons. The decline in defense spending will be influenced partly by arms control agreements with the Soviet Union. Even though defense spending will decline, funding for R&D on advanced defensive weapons systems will continue at a relatively high level.

The consequences of these trends and events will be a restructuring of national priorities, including those of DOE and its national laboratory system. Nuclear weapons production and spending for that activity will decline. Basic research will continue at a relatively high level but with a lower priority. Applied research and engineering development on energy technologies and other technologies of importance to the trade issue will be elevated to the highest priority. Government sponsored developmental activities that move a technology toward a commercial product will not only be permitted but will be encouraged. More emphasis will be placed on collaborative R&D involving DOE's laboratories and industry. There will be less concern about maintaining separation of industry and government and more concern about restoring the United States to a leading role in international commerce.

Research and Development Trends At ORNL

Overall Trends

Four themes will dominate the ORNL environment during the next one and one-half decades: energy, competitiveness, global environmental effects, and collaborative research based on the Laboratory's unique user facilities. Although R&D related to energy will remain the central theme of ORNL's programs, the Laboratory will have major roles in the basic sciences, waste R&D, and defense technologies. About 80% of the Laboratory's effort will be in support of the missions of DOE and NRC. Work for other government agencies and for private industry will consist of R&D activities that are important to the nation and that complement DOE's programs.

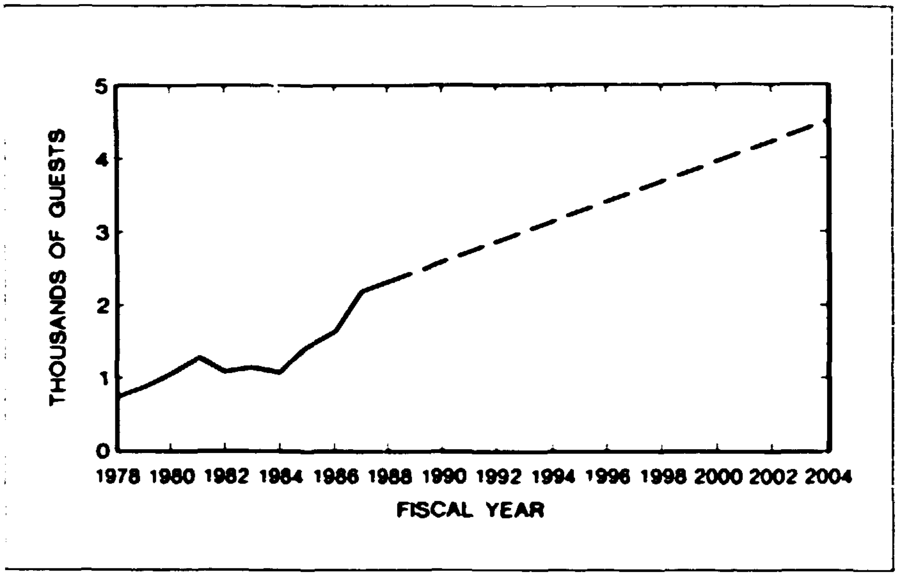
Even though continuity in basic missions is expected, the Laboratory will, nevertheless, undergo major changes. One of the driving forces for change will be the growing role of DOE and its national laboratory system in helping American industry to regain a leading position in international commerce. This role will cause some R&D activities at ORNL to be carried much further toward commercial products and processes than has been true in the 1980s. Much more thought and effort will be given to moving technological innovations to the marketplace. Patents on technologies and exclusive licenses to industry will be commonplace. Collaborative research, centered around major user facilities, will become a very important component of the Laboratory's intellectual output.

As a consequence of the emphasis on collaborative R&D, guest researchers at ORNL will continue to increase. By 2004, the number of guest researchers will approach 4500, about double the number (2304) for 1988. Much of the increase in collaboration with outside researchers will be associated with the expansion of existing user facilities and the addition of new facilities. Major new facilities put in operation over the next 15 years will include the Advanced Neutron Source (ANS), the Heavy Ion Storage Ring for Atomic Physics (HISTRAP), the Advanced Control Test Operation (ACTO) facility, and some important experimental fusion facilities.

Energy Technologies

The Laboratory will strive for strong, balanced programs in all four of the major energy technology areas—conservation, fusion, fission, and fossil.

Conservation and Renewables. The Laboratory will continue to conduct the nation's largest and most diverse R&D program in conservation and



Guest researchers at ORNL (1978–2004).

renewable energy. Energy conservation holds promise for significant gains for the nation in both economics and environment. The ORNL program over the next 15 years will include the following elements:

- Buildings
  - equipment
  - envelopes
  - integrated concepts (e.g., the "smart house" concept)
- Materials
  - energy Conversion and Utilization Technologies (ECUT) materials
  - ceramic technology for heat engines
  - materials for heat recovery
  - High Temperature Materials Laboratory (HTML) user centers
- Biomass
  - production
  - conversion
- Other
  - industrial chemical heat pumps
  - alternative fuels utilization
  - power systems technology
  - thermal energy storage

Fusion. The energy released when light elements are "fused" offers mankind the potential for a limitless source of energy. ORNL plays an important role in the international quest to transform the potential of fusion into reality. The Laboratory's long-term strategy for fusion is to strive for scientific and engineering excellence in a broad program emphasizing technology and materials. ORNL's major 15-year goals in fusion are to

- maintain leadership in advanced plasma technology components,
- establish a strong program in remote technology for fusion,
- lead the world in materials development and testing for fusion reactors,
- maintain U.S. leadership in stellarators, and
- build major fusion facilities in Oak Ridge including an upgraded Advanced Toroidal Facility (ATF) and the ATF-2.

Fission. Planned directions for ORNL in fission energy R&D include leading roles in modular high-temperature gas-cooled reactor technology, nuclear

Fusion Power

Murray W. Rosenthal
ORNL Deputy Director
(formerly Associate Director
Advanced Energy Systems)

Some say that developing fusion power is the greatest technical challenge ever undertaken. Its realization requires the production and control of plasma at over 100 million degrees—hotter than the sun! While substantial progress has been made, we do not yet know which fusion concept will be best. John Sheffield made the point well when an aerospace manager indicated that he could do the job. "Hell," he said, "we got to the moon!" John's reply was, "Yes, but you knew where it was!"

Although fusion is difficult, many able people think the goal important enough and the chances of success high enough to stake their careers on it. So do the U.S., the European Community, Japan, and the USSR, which together put up over $1 billion a year. ORNL has participated in this effort from its beginning. By most measures the Laboratory's program is being successful, but our budget has been falling, along with DOE's. Consequently, we have been thinking about our goals, and I believe they are threefold.

First, we want ORNL to become regarded as the world's best fusion laboratory. That's a big order, because there are many top-notch fusion labs, but it is a short-hand way of stating our commitment to excellence. To be recognized as best will take more than doing high-quality work—the work also has to be important and prominent. And the latter is a problem. ORNL's program has been outstandingly effective, but we don't have one of the big tokamaks that make the headlines. Nevertheless, the ATF is the world's largest stellarator, and it will keep us near center stage.

Second, we want to be a major contributor to the international fusion effort. We are, in fact, already that. ORNL technology has made many of the physics advances of recent years possible: our neutral-beam heaters, pellet injectors, and RF components are used worldwide. No fusion experiment without a collection of things developed at ORNL can hope to be world-class. Our theorists make leading contributions in many areas, and five stellarators based on ORNL concepts are being built around the world. The Design Center participates importantly in all of the major U.S. and international design studies. Finally, the Large Coil Program is heralded as a major technical success and fusion's leading example of international collaboration. Indeed, it is often cited as evidence that the multi-nation project proposed by Secretary General Gorbachev and President Reagan is actually feasible.

Our third goal is to have a power-producing tokamak built in Oak Ridge. A few years ago we identified an excellent site near ORGDP that has access to some underutilized facilities and is isolated enough to handle tritium safely. We introduced it to DOE and the fusion community and received recognition that it's almost ideal; and Martin Marietta Energy Systems has stated an intention to push for its use. To be successful, we will have to maintain Oak Ridge as a fusion center capable of handling big projects, participate in the big tokamaks wherever they are, and press our claim when the time comes.

The potential payoff of fusion is enormous. However, its successful development will require top people, a breadth of capability, and long-term continuity of effort and purpose. It will also require institutional commitment, the participation of many organizational elements, and an in-bred dedication to quality research and development. That's why ORNL, which meets these standards, is an ideal place to pursue it.

fuel reprocessing, improvements to existing light water reactors, and selected areas of reactor safety research. The Laboratory will also play a supporting role for all reactor concepts through its work on strategic technologies including

- advanced instrumentation, control, and automation;
- robotics and teleoperations;
- high-temperature materials and structural design;
- advanced shielding methods and materials;
- fuels and cladding; and
- probabilistic risk analysis.

Fossil. The planned directions for fossil energy reflect the Laboratory's deep-seated, long-term conviction that fossil energy, especially coal, is one of the nation's most important subjects for R&D. Fossil energy R&D will focus on three important areas: materials; environment, health, and safety; and innovative coal processing concepts. Materials work will include

- fundamental research on materials erosion and corrosion;
- alloys for high-temperature, advanced steam cycles;
- fiber reinforced ceramics for high-temperature combustors and hot gas filters;
- ceramic membranes for gas separation;
- materials for advanced fossil technologies including coal liquefaction and gasification, combustion, heat engines, and fuel cells.

Work on environment, health, and safety will include support for clean coal projects and the development of information systems. Innovative coal processing concepts will include microbial liquefaction and gasification.

Other Technologies

Space and defense technologies and waste R&D will become important components of the Laboratory's activities within the next 15 years.

Areas of work on space and defense technologies will be closely related to ORNL's civilian R&D roles. Examples of areas for future emphasis are: space applications of robotics and teleoperations, engineered materials, space structures, and survivable space optics.

The planned program in waste R&D is strongly oriented toward supporting DOE's missions in this area. The scope includes both chemical and radioactive wastes. One area of emphasis will be on expanding the Waste Management Technology Center.

The Sciences

The Laboratory will maintain vital programs in both the physical and life sciences over the planning period. The science programs serve two purposes: they add to the storehouse of fundamental knowledge, and they create a strong scientific base in support of the Laboratory's technology programs.

Physical Sciences. Areas of research in the physical sciences will include

- materials,
- computations,
- robotics and intelligent systems,
- nuclear and atomic physics, and
- the chemical sciences.

The goals of the Laboratory's materials program are to achieve world leadership in high-temperature materials development and to excel in certain areas of solid state physics including surface research.

Advanced Neutron Source

Fred R. Mynatt
ORNL Associate Director
Reactor Systems

Materials research using neutron beams began soon after initial operation of the first nuclear reactor, ORNL's Graphite Reactor, November 4, 1943. Through the following years, ORNL research reactors were developed and used for in-core and near-core materials irradiation, neutron beams for neutron cross-section measurements, and materials research using neutron scattering. These developments culminated in the High Flux Isotope Reactor (HFIR) which began operation in 1965 with the world's highest thermal neutron flux in the core flux trap and several powerful neutron beams for scattering research.

We now predict the usable life of HFIR to be about ten more effective, full-power years; therefore, the recent R&D leading to a new high-density neutron source, the ANS, is extremely important.

The ANS concept began in November 1984 as a project funded by the Director's R&D Fund. The objective is the development of a new steady-state neutron source with a thermal neutron flux for beam experiments of 5 to 10 x 10^{19} neutrons $m^{-2}s^{-1}$. By combining the higher neutron flux with improved experimental facilities, the ANS will surpass existing capabilities by a factor of 10 to 20. For many neutron scattering experiments, this improvement opens up a whole new range of research.

To achieve such capability, the ANS will push forward the boundaries of high-flux reactor technology. As a new reactor near the turn of the century, ANS must also push forward the concepts of reactor safety to greatly reduce the risk of significant accidents. To optimize neutron beam performance, the ANS will utilize a HFIR-like reactor core with a D_2O moderator and coolant (HFIR uses H_2O). With the broad thermal neutron peak, a large number of neutron beams can be routed to users. Current plans call for 8 thermal beams, 12 cold neutron guides, and 4 hot beams. To use these beams, a major guide hall is to be provided for up to 35 scattering experiment stations. This would support a user research community of about 1000 scientists.

Because its emphasis is on neutron beam research, the ANS will meet or slightly exceed the HFIR's capability for heavy element production. For other isotope production and materials irradiation, the ANS will far exceed HFIR's capacity. Therefore, it is planned that HFIR will be permanently shut down when ANS comes on line.

preparation of new materials, advanced materials processing, and neutron scattering. One area of emphasis in computations will continue to be research on parallel processing. In robotics and intelligent machines, research topics will include teleoperations and autonomous systems with man-machine symbiosis as the ultimate goal. Heavy ion research, including operation of the Holifield Heavy Ion Research Facility (HHIRF) as a national user facility, will continue to be the centerpiece of the nuclear physics program at the Laboratory. In atomic physics, the addition of the HISTRAP will extend the research program to frontier energy regions. The chemical sciences will stress four major areas: (1) chemistry of and with radioactive materials, (2) environmental chemistry and waste technology, (3) materials chemistry, and (4) separations sciences.

Life Sciences. The life sciences—biology and environmental sciences—will continue to grow as essential elements of the Laboratory's activities. In biology, the plan is to build on the core areas of mammalian genetics, radiation carcinogenesis, and protein engineering. In addition, it is planned to expand multidisciplinary research in structural biology and genome mapping. In health and safety research, a man-oriented program provides a sound basis for the measurement and assessment of human health, radiological, and chemical substances. The main areas of research include

- atomic, molecular, and radiation physics;
- biophysical transport of pollutants and radiation dosimetry;
- nuclear medicine;
- health risk analysis;
- surveys and measurements of environmental pollutants; and
- information research and evaluated data bases.

In the environmental sciences, the broad goal is to retain the Laboratory's status as the nation's premier ecological-environmental research center. The environmental sciences program will cover both energy-related environmental issues and global science. An important objective is to study and understand the interactions of physical and chemical agents with living organisms, including the ultimate consequences in humans and their environment. Important long-term goals in environmental research are to

- anticipate future environmental problems,
- understand atmosphere-biosphere boundary interactions and feedbacks,
- improve time-space scaling of nonlinear environmental systems and regional extrapolation,
- develop predictive environmental models,
- understand mechanisms of subsurface transport,
- understand global environmental systems, and
- quantify environmental risk and cumulative effects.

Managing for Change

Changes of the magnitude suggested above will present significant management challenges to the Laboratory over the next 15 years. Management attention will be required in several areas including physical facilities, human resources, and administration.

Central to accomplishing the missions outlined here is the acquisition of a few key research facilities. The ANS is of critical importance to a number of the Laboratory's research areas including materials, nuclear physics, biology, and the chemical sciences. The HISTRAP is the key to maintaining the HHIRF as a state-of-the-art user facility. An important part of the Laboratory's contributions to DOE's nuclear missions will be advanced control R&D centered around the ACTO facility. Completion of the Life Sciences Complex is essential to achieving the biological research objectives.

One of the highest priority management objectives is to bring a first-rate computing environment to the Laboratory's research staff. Both equipment and development funding will be required to bring about a modern distributed computing system consisting of powerful workstations and special-purpose central machines linked by high-bandwidth data networks.

The Laboratory management will need to give considerable attention to office and laboratory space, cafeteria facilities, parking space, and other support facilities. Expansion is required in support facilities to accommodate an increase of 50 to 100% in the resident research staff during the next 15 years. Part of this increase will come from

Space and Defense Technologies

J. R. Merriman
Energy Systems
Vice President for AVLIS
and Work for Others
Programs

Oak Ridge recently expanded its work in the areas of space and defense technologies. The programs have grown from a total of about $12 million and 56 full-time people in FY 1985 to more than $30 million and 150 full-time people in FY 1988. These programs serve several functions:

- to contribute to the solution of problems that are vital to our national defense,
- to maintain and expand our technology base for future applications to DOE and other missions,
- to transfer technology to other government agencies and to the private sector, and
- to capitalize on the integrated capabilities and multidiscipline expertise within Oak Ridge.

The space and defense technologies programs will open windows into government and private areas where Oak Ridge previously has had little, if any, interaction. Although there is a tendency to think of civilian programs as divorced from space and defense technologies programs, there are, in fact, large areas of overlap of particular interest to Oak Ridge. Thus, work within the areas of space and defense technologies can serve to enlarge our interaction with and knowledge of the broader national technology scene. Indeed, because of this, the related Oak Ridge programs have even greater potential for being on the technological forefront.

One of the keys to a successful space and defense technologies program is to capitalize on the capabilities and expertise within Oak Ridge regardless of plant site. ORNL is, of course, a premier research facility; the Oak Ridge Y-12 Plant is at the forefront of advanced manufacturing; and ORGDP has marvelous capabilities in engineering and applied technology. The space and defense technologies efforts serve to facilitate these exchanges with synergistic benefits. One example of such a program is the optics program for the U.S. Army Strategic Defense Command. This program utilizes the precision machining and beryllium capabilities of the Y-12 Plant, does optical component characterization at ORGDP, and performs advanced R&D on ion implantation at ORNL.

The broad benefits of the space and defense technologies programs to Oak Ridge can be further illustrated by a few additional examples of active, ongoing programs: environmental analysis and assessments; materials R&D in fiber-reinforced and carbon/carbon composite ceramics intermetallics; instrumentation and controls R&D; research in artificial intelligence and expert systems; advanced fuels research and energy storage; and space power. Although this list is not all-inclusive, it indicates the strong ties to the total Oak Ridge capabilities base that has grown from prior and ongoing DOE programs.

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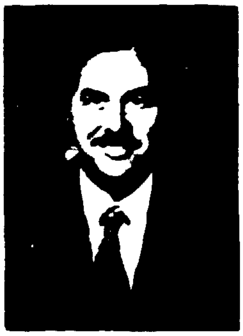
employees, but a larger component will be from growth in the number of guest researchers.

Perhaps the most significant management challenge of all will be to learn how to help American industry turn the results of government-sponsored R&D into commercially important products. This will require interactions between the Laboratory and industry on an unprecedented scale. New institutions and new ways of dealing with old institutions will be needed. Major reforms will be required in administrative, legal, and contractual policies and procedures.

Advanced Processing and Materials Research



Bill R. Appleton
ORNL Associate Director
Basic Physical Sciences

Materials R&D is gaining an increasingly prominent role in the world's scientific and technological development. Materials have always been essential for fashioning the tools and machines of civilization, but recently, the explosive evolution of our technologies has demanded extraordinary materials properties that can no longer be met by conventional processing methods. ORNL has pioneered in advanced processing technologies and new materials development and has a broad multidisciplinary R&D organization that should keep it at the forefront in coming years.

Ion-implantation doping and ion-bombardment techniques at ORNL's Surface Modification and Characterization facility have been used to form metastable near-surface alloys, to create buried insulating layers in semiconductors for three-dimensional device structures, to fabricate optical waveguides and switches, to increase the surface hardness and fracture toughness of high-temperature ceramics, to produce improved catalysts, and to reduce the corrosive wear of artificial knee and hip joints. The technique of direct ion-beam deposition, which directs isotopic ions at very low energies (~10 to 1000 eV) onto the surface of a solid in an ultrahigh vacuum environment, has been used to fabricate isotopic heterostructures of metals and semiconductors with atomically sharp alternating layers, to induce epitaxial growth of semiconductor and metal layers at low-substrate temperatures, to induce silicide and oxide growth on silicon, and to deposit adherent metal layers on semiconductors.

Pulsed-laser, direct-laser, and electron-beam techniques have been used for ultrarapid melting and solidification studies of solids and to produce supersaturated substitutional semiconductor alloys, extended solid solutions, amorphous metglasses of extended composition, and a variety of metastable alloys and compounds. Laser-assisted photochemical vapor deposition methods have been developed that can deposit semiconductor heterostructures and superlattices with atomic resolution. Pulsed excimer lasers have been used to fabricate crystalline films of the new, high-transition temperature superconductors by laser ablation.

Although microwaves commonly used to heat foods barely interact with ceramics, the much higher frequency microwaves used to heat plasmas in fusion devices have been found to greatly accelerate the sintering of ceramic powders and produce parts with unique microstructures not possible with radiant heating. These same plasma sources have been adapted for deposition and etching applications in semiconductor device processing, and they appear to be superior to the radio frequency techniques currently employed.

Ceramics have not been used often in structural applications because they are extremely brittle and fabricated parts have properties that vary widely from batch to batch. The new HTML at ORNL has assembled a host of state-of-the-art processing and characterization techniques in a single laboratory to develop new methods of designing microstructures with high toughness and strength and new manufacturing techniques that yield reliable, reproducible materials. Tough ceramic composites are being produced by infiltrating fibrous preforms with gases that can be reacted to produce a ceramic matrix around the strong fibers. Sol-gel techniques developed for producing nuclear fuels are now employed to produce ceramic powders of exceptional purity and uniformity of size, composition, and microstructure. All of these ceramic fabrication and processing techniques now are being applied to the new high-T_c superconducting oxides in an effort to overcome some of the mechanical and fabrication problems that limit their commercial applicability.

Not only is ORNL pioneering in advanced materials R&D, but these studies are being shared with university and industrial collaborators through our many user facilities, collaborative research centers, and industrial consortia. We believe this approach is the short path to commercial utilization for the processing techniques and new materials developed at ORNL.

Protein Engineering

Chester R. Richmond
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Environmental
Sciences

Throughout history, plants and animals were bred to produce desired inheritable traits, primarily through trial and error approaches.

In 1865, Gregor Mendel published his pioneering work that provided the basis for the discipline known as genetics. Just four years later, F. Miescher introduced the word "nuclein" for material he obtained from cell nuclei. We now recognize nuclein as deoxyribonucleic acid (DNA), the basic material that determines inheritance for all plants and animals. In 1905, W. Bateson coined the word "genetics" from the Greek "genesis," meaning "to generate."

The *annus mirabilis* in this field was 1953, almost a century after Mendel's experiments, when Watson and Crick published their work on the structure of DNA. It is of interest to note that the diploid number of human chromosomes containing our DNA was not established until 1956 when Tijo and Levan examined 265 dividing cells and determined the diploid number to be 46. Thus, the basic structure of DNA was known before we knew the accurate number of human chromosomes!

A person's 46 chromosomes have about 3 billion base pairs (cytosine, guanine, adenine, and thymine) contained in about 50 to 100 thousand genes. Yet, all of our genetic information is coded by just a four-letter alphabet (c, g, a, and t) in which the order of three letters specifies the linear arrangement of the 20 amino acids (words) that comprise all of the body proteins (sentences). Such elegant simplicity.

The possible combinations of amino acids is mind boggling. The following is from a Navy report:

"Consider for instance a small protein, consisting of about 150 amino acids. The number of all possible arrangements is about 20^{150} or about 10^{200}. If only one copy of each modification is made and the universe is filled densely with these prototypes, about 10^{100} universes are needed to accommodate all."

Clearly, comprehension, not trial and error, is required.

An explosion of knowledge followed the classic work on recombinant DNA molecules in the early 1970s. Many papers were written on recombinant DNA techniques, and companies were developed to exploit these advances. Gene products (proteins) that are normally produced by other organisms could be made or "generated" by man in the organism of his choice. Another major breakthrough occurred when scientists learned to modify an organism's DNA in situ by introducing selective mutations at precise locations in the genome to create new gene products not found in nature. This technique is called site-directed mutagenesis or protein engineering.

ORNL provided exploratory funds to accelerate development of a protein engineering program under the direction of Fred Hartman in the Biology Division. These researchers systematically alter the amino acid sequence of proteins to better understand mechanisms and structure-function relationships. Hartman's group started by designing variants of a carbon dioxide fixing enzyme, one of the more important and the most abundant protein in nature. Currently, they are also working with proteins that regulate cell growth and differentiation and with proteins that repair chemically damaged DNA.

The potential applications of protein engineering to biomedical, biomaterials, industrial, and agricultural problems are enormous, and the challenges are great. We expect this program to flourish and prosper in the future.

Acronyms

ACTO	Advanced Control Test Operation
AI	artificial intelligence
ANS	Advanced Neutron Source
ATF	Advanced Toroidal Facility
DARPA	Defense Advanced Research Project Agency
DNA	deoxyribonucleic acid
DOE	U.S. Department of Energy
EBT	ELMO Bumpy Torus
ECUT	Energy Conversion and Utilization Technologies
EMS	ethyl methanesulfonate
EtO	ethylene oxide
HERMIES	Hostile Environment Robotic Machine Intelligence Experiment Series
HFIR	High Flus Isotope Reactor
HHIRF	Holifield Heavy Ion Research Facility
HISTRAP	Heavy Ion Storage Ring for Atomic Physics
HTML	High Temperature Materials Laboratory
M&C	Metals and Ceramics
NRC	Nuclear Regulatory Commission
NSF	National Science Foundation
ORGDP	Oak Ridge Gaseous Diffusion Plant
ORNL	Oak Ridge National Laboratory
R&D	research and development
rf	radio frequency
RISP	Robotics and Intelligent Systems
SDI	Strategic Defense Initiative
U.S.S.R.	Union of Soviet Socialist Republics

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