Number One 1985

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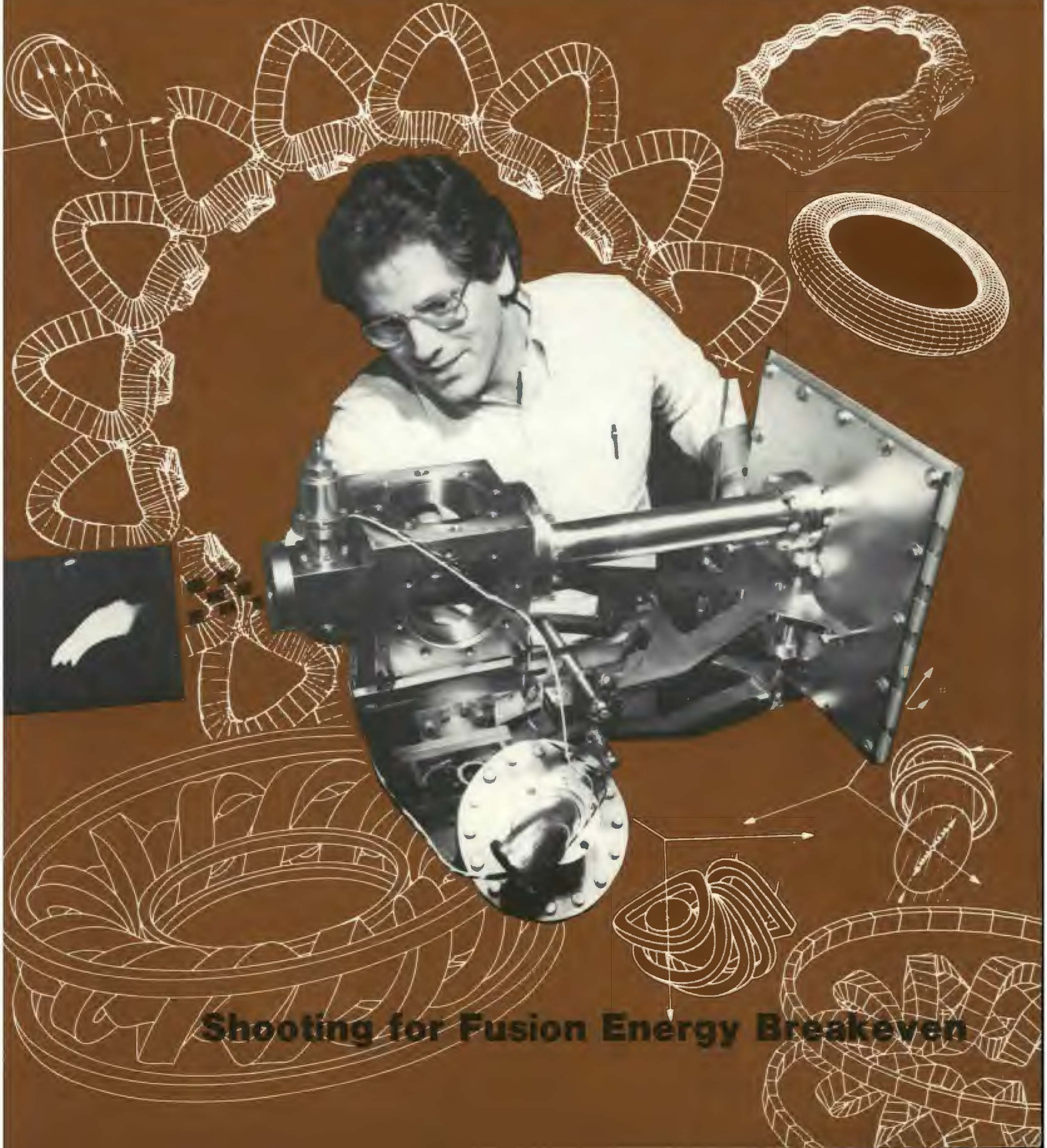
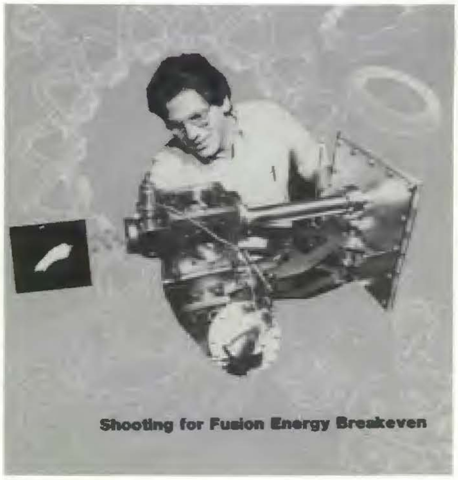


Shooting for Fusion Energy Breakeven



THE COVER: Stan Milora checks a pneumatic pellet injector, which can repeatedly shoot pellets of frozen hydrogen into fusion plasmas to refuel toroidal devices (artists' renderings of which appear around Milora). This ORNL-developed pellet injector will be tested in 1985 on the Tokamak Fusion Test Reactor and will help the tokamak achieve energy breakeven in the late 1980s. See article on page 1.

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review

VOLUME 18 **NUMBER ONE 1985**

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OAK RIDGE NATIONAL LABORATORY

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Stanley L. Milora is manager of the Pellet Fueling Program in ORNL's Fusion Energy Division. A native of Hazleton, Pennsylvania, he received a Ph.D. degree in aeronautics and astronautics from the Massachusetts Institute of Technology (MIT). In 1972 he joined ORNL as a staff member of the Reactor (now Engineering Technology) Division, where he worked on geothermal energy with the late Richard N. Lyon. With Jefferson Tester he coauthored a book entitled *Geothermal Energy as a Source of Electric Power*. In 1976 he joined the Fusion Energy Division. In his current position he coordinates pellet fueling activities for the Department of Energy. He has conducted theoretical and experimental research in pellet fueling at ORNL, MIT, and Princeton Plasma Physics Laboratory (PPPL). His research interests include thermodynamics, fluid mechanics and heat transfer, plasma physics, and advanced energy conversion systems. He is a fellow of the American Physical Society. Here, Milora adjusts the repeating pneumatic pellet injector that will be used this year on the Tokamak Fusion Test Reactor at PPPL. Working in the background are, from right to left, Dan Schuresko, Chris Foster, Stephen Combs, and Larry Baylor.

Shooting for Fusion Energy Breakeven:

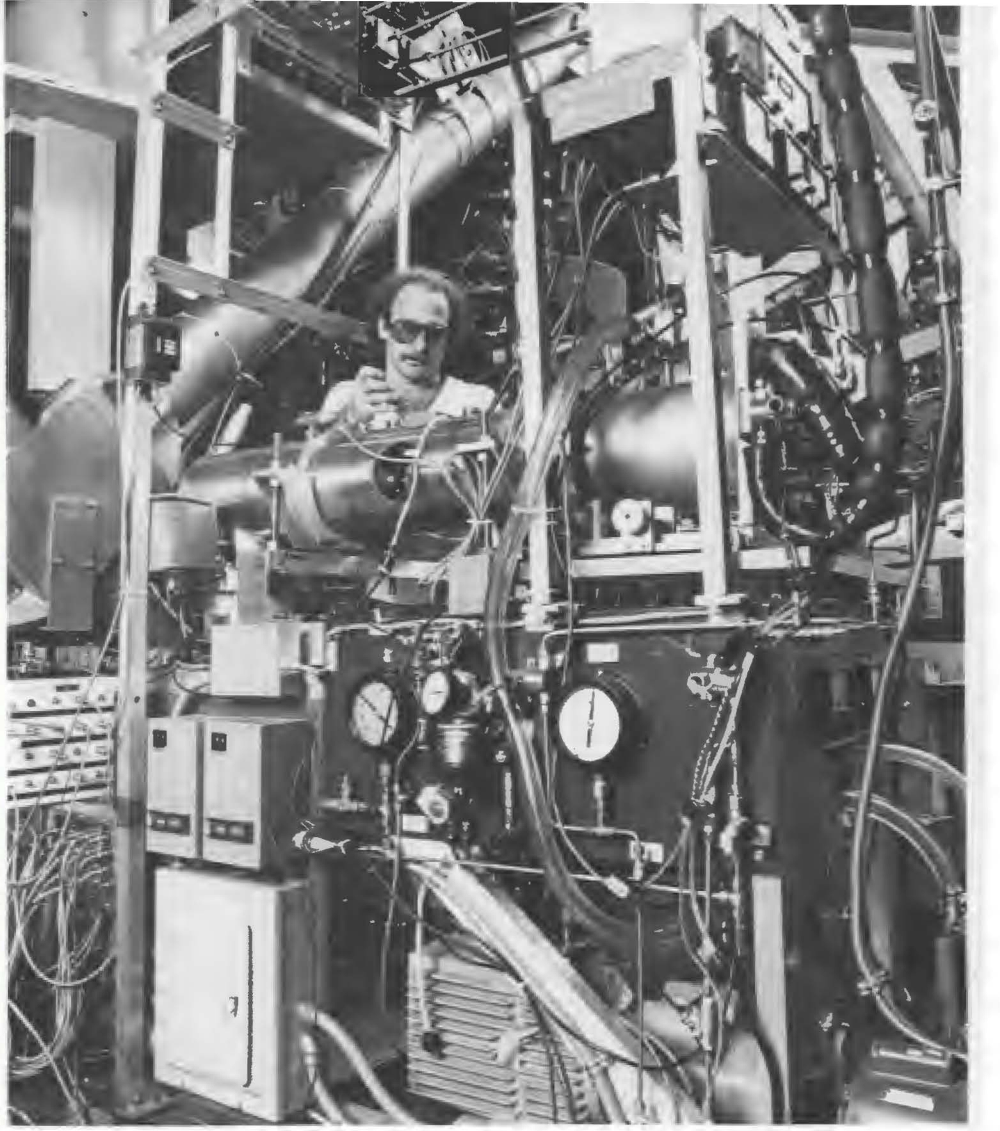
Pellet Fueling Research at ORNL

By STAN MILORA

At the 1983 meeting of the American Physical Society's Division of Plasma Physics, scientists from the Massachusetts Institute of Technology (MIT) reported that they had achieved for the first time the minimum conditions required for demonstration of energy breakeven (energy output equals energy input) in a plasma fusion device. The dramatic announcement, which was made November 3, 1983, at a news conference in Los Angeles, referred to the accomplishments made by MIT plasma physicists on the Alcator-C tokamak device just two days earlier. I learned of the news at my desk the day following the announcement in a telephone conversation with a reporter who was seeking clarification of an Associated Press wire story. This news report described the breakthrough and credited Oak Ridge National Laboratory with having provided the vital ingredient in the success of the experiment.

ORNL scientists have developed a gun and a centrifuge accelerator to "shoot" frozen pellets of hydrogen fuel into tokamak fusion plasmas. One ORNL injector helped MIT exceed the Lawson criterion, another achieved steady-state plasma fueling, and an improved version of ORNL technology is expected to help a Princeton tokamak's energy output equal the energy input.

What Martin Greenwald, Dave Gwinn, and Steve Wolfe at MIT had achieved in November was of great



A technician adjusts an ORNL pellet injector on the Poloidal Divertor Experiment at Princeton Plasma Physics Laboratory.

importance to fusion researchers in general and to the proponents of the tokamak device in particular. A tokamak is a doughnut-shaped device with roughly the same proportions as an automobile tire. Unlike a tire, which confines pressurized gas by an impermeable barrier, the Alcator device and other tokamaks like ORNL's Impurity Study Experiment (ISX-B) confine a heated plasma composed primarily of electrons and deuterons (deuterium, or heavy hydrogen, atoms stripped of their electronic charge by the high temperature) in a powerful magnetic bottle having the shape of a toroid. In principle, the charged particles that form the plasma are constrained by the magnetic lines of force to circle the torus indefinitely on nested magnetic surfaces (like growth rings on a tree). But the problem plaguing fusion researchers ever since the first serious fusion reactor concept was proposed 30 years ago is that magnetic fields in practice are not perfect barriers. The constituent particles and, more importantly, heat can diffuse across the magnetic surfaces.

Minimizing this heat loss is the most vexing problem facing today's fusion researchers. It is important because if the thermal conductivity of the plasma is too large, heating the deuterons and tritons (tritium ions) in a fusion plant to temperatures at which the thermonuclear fusion reaction can occur at a sufficient rate to compensate for the heat losses would be virtually impossible.

For a plasma to put out at least as much energy from fusion reactions as the amount of energy being fed in to heat it (breakeven), certain criteria must be met. In this context, the figure of merit for any given laboratory plasma fusion device is the energy confinement time τ_E, which is roughly analogous to the R-values (resistance to heat flow) of insulation used in homes. More precisely, τ_E is directly related to the characteristic time required for the plasma energy to decay by heat conduction across the plasma boundary. For a fusion reactor to work at all, as the British physicist John Lawson showed long ago, the product of the energy confinement time τ_E and the plasma number density n (given as the number of nuclei per cubic centimeter) must exceed a minimum value given by the expression $n\tau_E > 6 \times 10^{13}$ s/cm^3. This result is known as the Lawson criterion. Unless this criterion is exceeded, fusion devices cannot provide the sustained heat source that utilities require for generating electricity.

Exceeding the Lawson criterion is one of two requirements for achieving energy breakeven in a fusion research device. The other requirement is to raise the temperature of the plasma to more than 100 million degrees Celsius. In 1978 that milestone was nearly achieved by the Princeton Large Torus (PLT) with the help of the neutral-beam heating technique pioneered at ORNL. In 1983 Alcator-C lacked the ability to heat its plasma to such a high temperature.

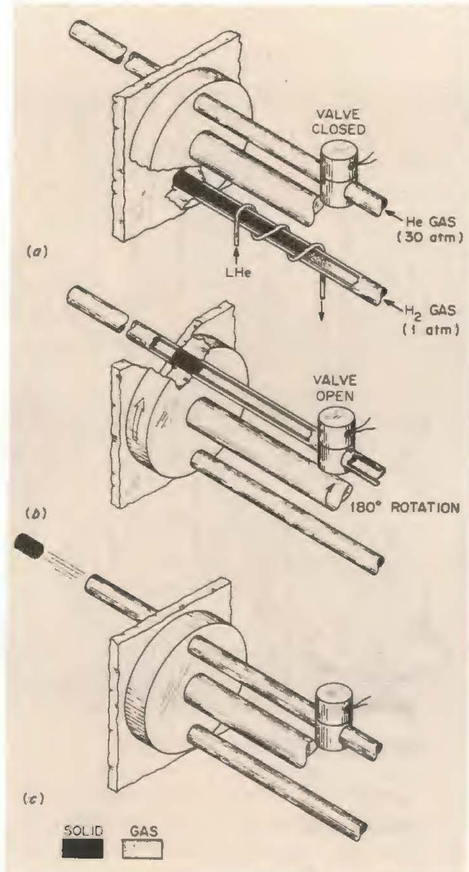
The Alcator-C device was constructed in 1978 with the principal objective of exceeding the

Lawson criterion—that is, of achieving the minimum plasma density and energy confinement time needed for fusion energy breakeven. That Alcator-C could even touch this elusive Holy Grail of fusion researchers was due in large part to its powerful magnetic fields. With a toroidal field strength approaching 12 T, Alcator-C could "hold" plasma densities on the order of 10^{15} cm^{-3}, or one to three orders of magnitude greater than the plasma densities of its competitors. All that was needed for the MIT scientists to accomplish their goal was an energy confinement time of about 50 ms and a way to build up the plasma density to the desired level. The need to increase plasma density prompted the involvement of our pellet fueling group at ORNL in the landmark experiment at MIT.

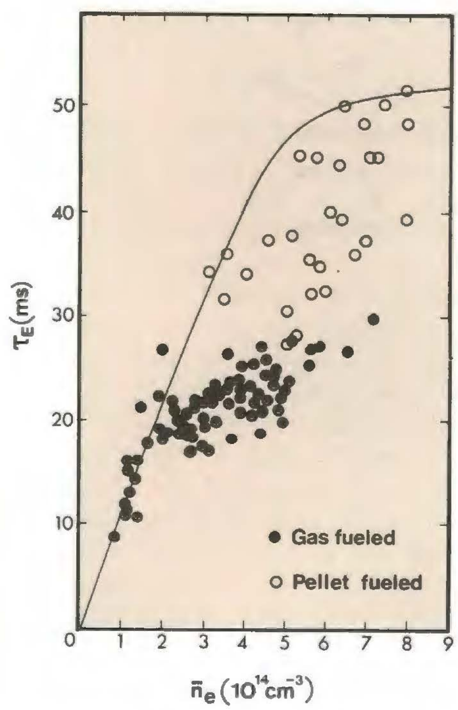
Puzzling Problem

The refueling of a hot plasma proved to be a puzzling problem in the 1950s for the earliest fusion researchers. They recognized that if one simply admitted gaseous hydrogen into the vacuum chamber surrounding the plasma column, the slow-moving molecules of fuel would be ionized by the energetic particles after penetrating only a few centimeters into the edge of the plasma. As charged particles, the fresh fuel could penetrate no further because of the magnetic forces; thus the interior of the plasma would soon be depleted of its reactants.

A team of scientists under the direction of Lyman Spitzer at Princeton University proposed a solution to this problem. They suggested injecting the fuel in the form of a macroscopic solid at high speed. A pellet of solid hydrogen has a neutral charge and, as such, could penetrate magnetic fields, but



This sequence illustrates the operation of ORNL's single-pellet pneumatic injector used on the Impurity Study Experiment and Poloidal Divertor Experiment tokamaks. In (a), room temperature hydrogen gas is liquefied and frozen in a cylindrical cavity in a disk. In (b) the disk rotates 180° to carry the frozen pellet to a position between a miniature gun barrel and a propellant valve. In (c) the valve is energized and admits high-pressure helium gas to the base of the pellet.

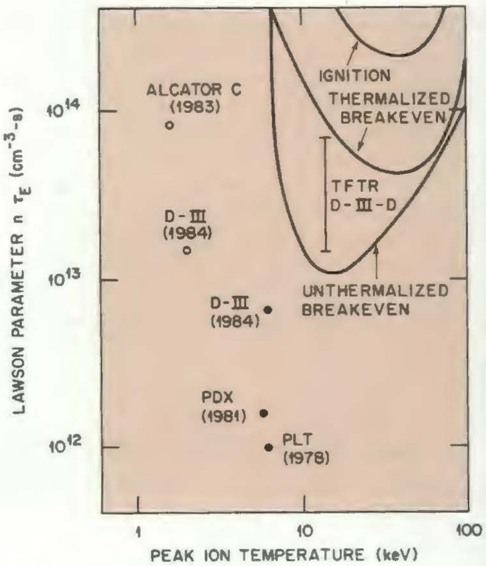


The dependence of energy confinement time on line-average plasma density for Alcator-C. The curve is a prediction based on a mix of theory and empiricism from Alcator-A results. Courtesy Martin Greenwald, Massachusetts Institute of Technology.

its surface would ablate (evaporate) rapidly in the intense plasma heat (like the proverbial snowball in hell). The evaporation of fuel would proceed fastest in the hotter interior regions of the plasma, where the fuel is needed most. But the first calculation of this process made around 1955 suggested that a pellet on the order of 1 mm diam would be consumed in as little as 1×10^{-5} s. To travel across a 1-m plasma column in so short a time, the fragile cryogenic pellets would have to be propelled to the astronomical speed of 100 km/s. The theorists then turned the problem over to the engineers.

Guns and Centrifuges

In the early 1970s the sponsor of the national fusion program—now the Department of Energy—recognized the importance of a credible plasma fueling scheme and began an exploratory research program. In 1976 Chris Foster, who had developed the first practical pellet-injection device as part of his graduate studies at the University of Illinois, performed the first experiments in plasma fueling on the Oak Ridge Tokamak (ORMAK). He used a liquid hydrogen droplet generator to inject 0.1-mm-diam spheres of hydrogen ice at speeds of 100 m/s into the edge of the plasma. The tiny frozen pellets barely perturbed the plasma and penetrated it only a few



Parameter space of the Lawson product for various experimental devices. The open circles represent pellet injection results. Thermalized breakeven refers to conditions in which the fusion power equals the input heating power for a thermal ion energy distribution. Unthermalized breakeven refers to the fusion reaction that occurs primarily between suprathermal deuterons (as produced by energetic particle beam injection) and thermal tritons. The prescription for achieving these conditions on the Tokamak Fusion Test Reactor is to heat a pellet-fueled plasma with 27 × 10⁶ W of injection power.

Overhead view (above) and schematic (right) of ORNL's centrifuge injector, which was installed in the spring of 1984 at the D-III tokamak at GA Technologies in San Diego. The pellet injector is shown in the foreground. Developed by Chris Foster, this apparatus was the centerpiece of a joint collaboration involving ORNL, GA Technologies, and the Japan Atomic Energy Research Institute. With this device steady-state pellet fueling was demonstrated for the first time. In a historic experiment, the gas-fueling valves were finally turned off altogether at D-III, and the plasma responded to pellet injection by increasing in density to record levels for D-III.

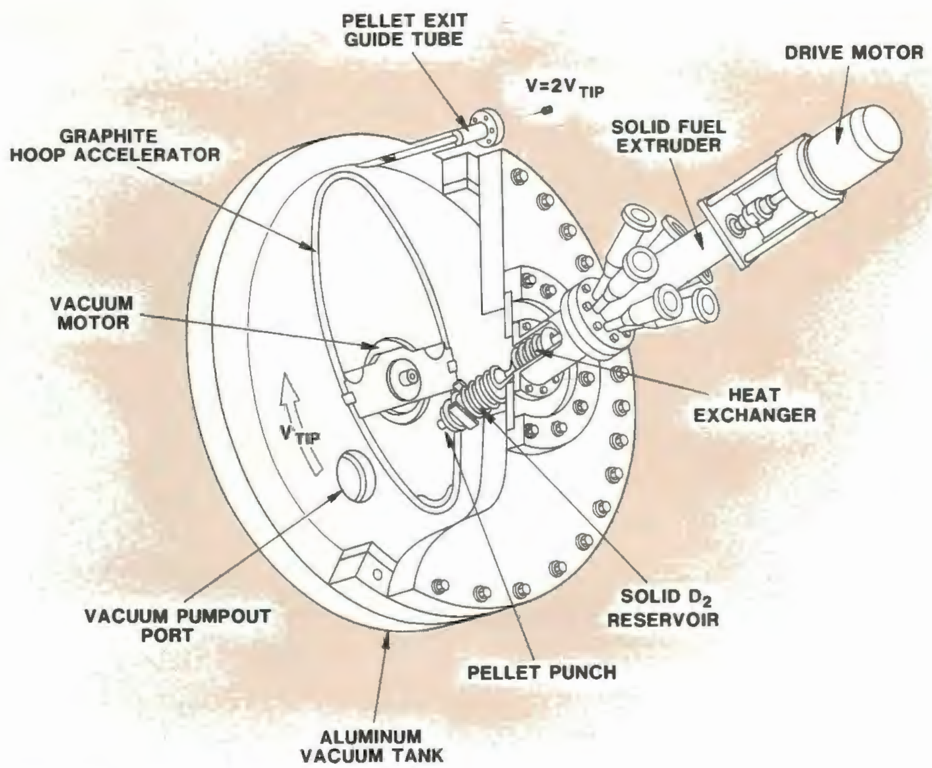
centimeters, but the results substantiated the theoretical predictions made two decades earlier. The experiment led to the development of the modern theory of evaporation of hydrogen ice in magnetized plasmas.

Later in 1976 I joined Foster in ORNL's Fusion Energy Division to start the DOE pellet fueling development program that would contribute so much to the 1983 success of MIT's Alcator-C. From the outset, Foster and I pursued two radically different accelerator concepts to improve on the velocity performance of the early liquid droplet generators. To me, a miniature gun using compressed helium gas as the propellant appeared to be a straightforward way to achieve high-speed pellet injection, even though fabricating and accelerating frozen hydrogen bullets at 260°C below zero (which is only 13° above 0° abs) would be awkward.

I got the gun idea from a Dick Tracy comic strip; Foster, it seemed, was inspired by nightmares. He pursued a more novel and complicated approach that would use a whirling arbor (like a rotary lawn sprinkler) to accelerate pellets by centrifugal forces. The centrifugal accelerator, which the wags likened to a Rube Goldberg contraption, would require several years to develop. However, the first pellet-injection gun was ready in 1978 for its inaugural test on the ISX-A tokamak at ORNL.

These first experiments produced interesting, if not spectacular, results. This time, the hydrogen pellets were large enough (about 1 mm) and fast enough (300 m/s) to penetrate 15 cm into the 52-cm plasma column. The pellet evaporation and ionization were complete in less than 1 ms; but during this time, the plasma density increased substantially, and the size of this increase agreed with the rise expected from the number of nuclei contained in the solid pellet.

This ORNL experiment was hailed worldwide for having demonstrated the technology that would solve the problem of plasma fueling—only no one needed it in 1978. The reason for its unlikely fate was that resourceful plasma physicists in the mid-1970s had found a way to circumvent the need for the technical complications inherent in cryogenic pellet injectors. The fueling method ruled out by the fusion theorists of the 1950s—gas injection—was so simple to implement that it would inevitably be tried and shown to work (albeit for unknown reasons) on all of the laboratory fusion



Schematic representation of the ORNL centrifuge injector as used on D-III. The apparatus fires 40 1.3-mm frozen deuterium pellets per second at 800 m/s. The pellets, constrained in a polished groove formed in a graphite-epoxy composite rotor, are accelerated by centripetal contact forces to twice the rotor peripheral speed; after 150° of rotation, they exit the rotor through a small hole. The pellets are formed by extruding frozen deuterium through a nozzle and by chopping the filament into cylinders with an electromagnetically actuated punch. The punch, which is synchronized with the rotor, injects the pellets into the entrance of the acceleration track.

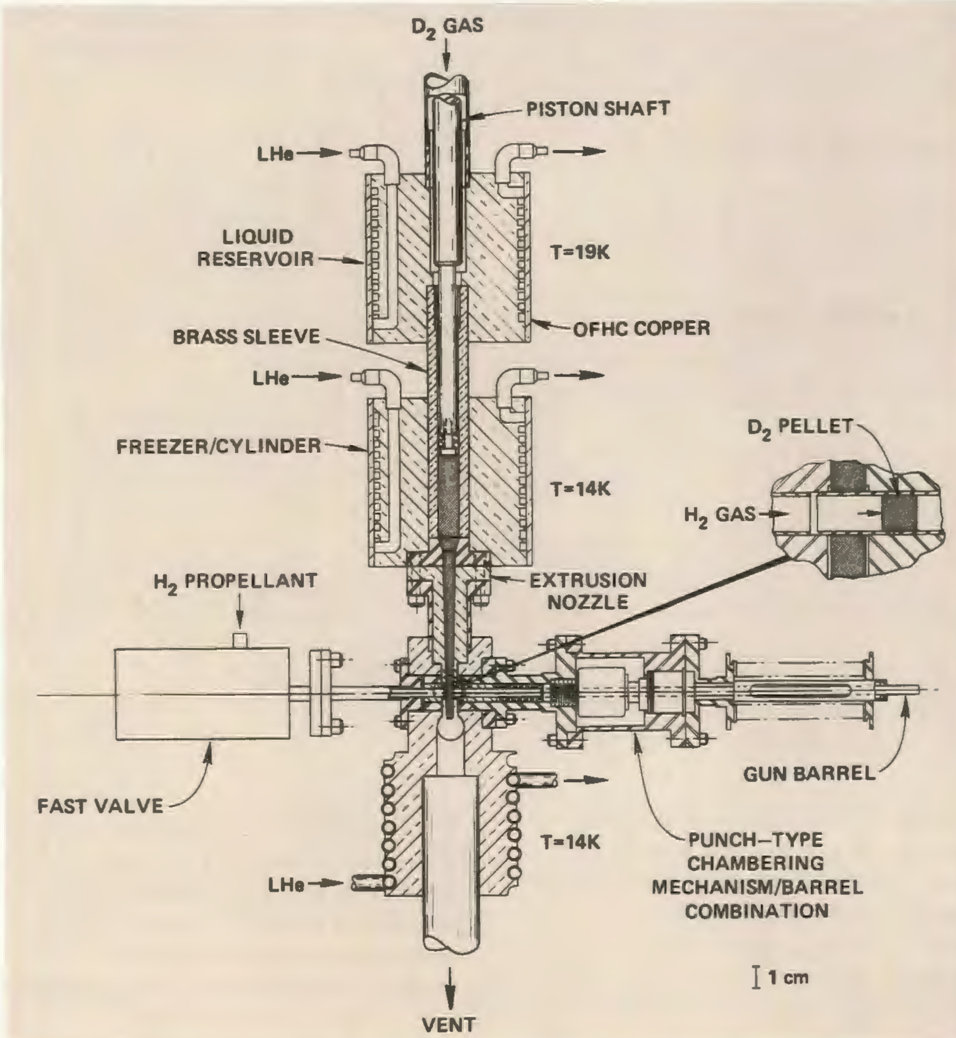
devices of the era. Ironically, the leaders in this approach were MIT scientists working on the Alcator-A device, the predecessor of Alcator-C. By simply injecting gas into the vacuum vessel surrounding the plasma discharge, the MIT scientists found, to their delight, that (1) the plasma density increased in proportion to the amount of gas injected and (2) the energy confinement time τ_E increased proportionally. Consequently as the Lawson product $n\tau_E$ increased as the square of the density, values as high as 3×10^{13} s/cm^3 were achieved routinely at the highest densities that the Alcator-A device could hold.

MIT Hits Refueling Snag

The announcement of this result was the highlight of the 1976 American Physical Society meeting in St. Petersburg, Florida. The larger, more powerful, replacement for Alcator-A seemed certain then to easily eclipse the Lawson criterion. In this regard, however, Alcator-C was a disappointing failure for nearly five years. In its early days of operation, the machine performed as expected, but as the plasma density was increased beyond 2×10^{14} cm^{-3} by intense gas injection, the energy confinement time did not budge from a plateau of about 30 ms. By 1981 Alcator-C had come within only a factor of 2 of the Lawson criterion. Moreover, operational difficulties attributable to the inefficiencies of gas injection cited earlier by Spitzer limited the density to less than 1×10^{15} cm^{-3}. (Larger and denser plasmas turned out to be more difficult to fuel by gas injection from the edge because the plasma essentially becomes opaque to the neutral atoms that are produced by dissociation of the gas at the edge. This opaqueness is apparently due to the scaleup of the Alcator-C plasma, whose diameter is 33 cm compared with 20 cm for the Alcator-A plasma.)

At the American Physical Society meeting in 1980 in San Diego, a team of discouraged physicists reported that the confinement properties of these plasmas were degrading because of an anomalously high ion-heat conductivity (removal of heat from the plasma). The physicists concluded that the optimism expressed only a few years earlier about the future of fusion had been premature. Ron Parker, who leads the Alcator effort, suspected that his confinement problems might be due to the almost flat density profiles that resulted from edge fueling (e.g., gas injection). Intrigued by the success that Foster and I were having with pellet injection at Oak Ridge, he approached us at the meeting to formulate a plan to give Alcator-C a "pellet transfusion." We were then experimenting with a version of the pneumatic injector (the gun) that was capable of delivering four pellets independently into a single discharge at a speed of 1000 m/s. Our calculations indicated that this velocity would ensure pellet penetration to the center of the Alcator-C plasma column. They also showed that, by injecting all four pellets sequentially, we could produce centrally peaked density profiles that could be sustained. Before leaving the meeting, we

Schematic of ORNL's repeating pneumatic injector (RPI), which began operation on the Tokamak Fusion Test Reactor in April 1985. The RPI uses the same extruder arrangement as the centrifuge. Pellets are chambered (inset, by an electromagnetically actuated gun barrel that is driven into the face of a solid deuterium ribbon. A fast electromagnetic valve injects high-pressure (1300-psi) hydrogen gas to propel the 4-mm pellets to a 1500-m/s velocity. The gun can inject six pellets per second into the plasma.



agreed on the basic form of the collaboration, and shortly thereafter DOE endorsed this plan.

Black Art of Pellet Injection

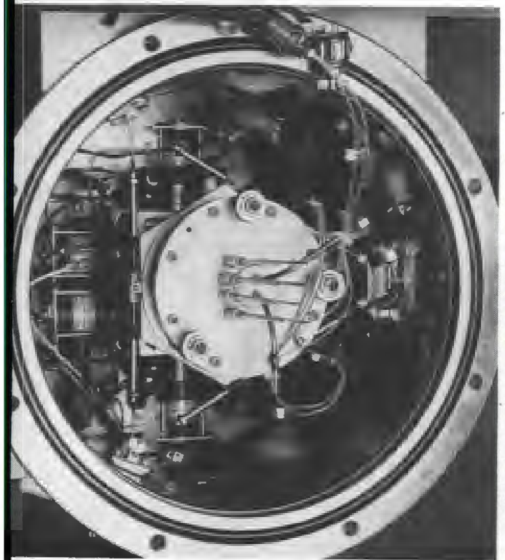
The task of developing what was then an experimental device into a reliable tool for use on a tokamak far from Oak Ridge was not as easy as we had first thought. Although we were able to quickly redesign the pellet injector to incorporate improvements and to accommodate the peculiarities of the Alcator device, a craft workers' strike of 1981 ended any hopes of our building and testing the equipment at Oak Ridge. Instead, we elected to fabricate the entire injector system at MIT and train the MIT staff in the "black art" of pellet injectors.

My family and I spent two weeks in each of three successive summers in Cambridge, and in the fall of 1983, Alcator-C was ready for the dramatic test. To accommodate the higher plasma densities anticipated from pellet injection, the magnetic field system of Alcator-C was upgraded. The extensive modifications allowed the machine to drive a discharge current of 7.5×10^5 A inside the 33-cm toroidal plasma column to ionize and heat the fuel.

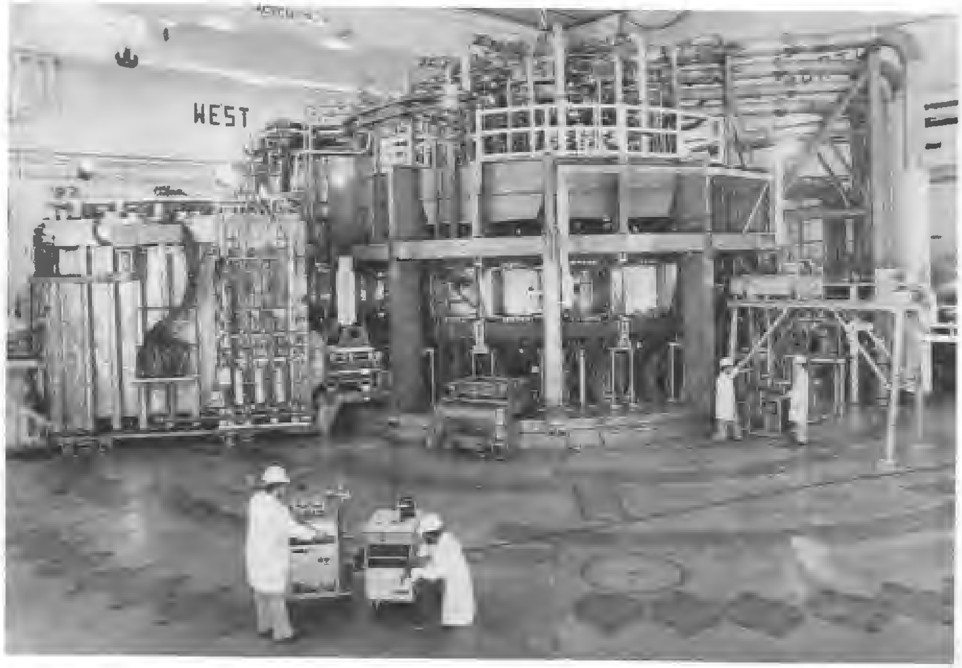
Greenwald set up the tokamak to run at moderate density (about 2×10^{14} nuclei/cm^3) by gas injection; and, about halfway through the 600-ms discharge, two deuterium pellets were fired within 70 ms of each other. The density suddenly rose to 2×10^{15} cm^{-3} on axis, but the temperature dropped precipitously in response to the sudden addition of fuel whose temperature approached 0° abs. However, the massive Joule heating (about 2×10^6 W) reheated the plasma to about 20 million degrees in less than 50 ms. At the peak of the temperature and density perturbation, a burst of neutrons in excess of 10^{13}/s was observed from the fusion reaction of the deuterons in the plasma core. This number is approximately an order of magnitude greater than comparable gas-fueled plasmas—something good (other than refueling) had occurred. MIT researchers analyzed the data hurriedly over the weekend and discovered that the energy confinement time had returned to the scaling law established several years ago on Alcator-A. The bottom line was a Lawson product in the range of 6×10^{13} to 9×10^{13} s/cm^3, which was more than enough to exceed the mimimum required for thermalized breakeven (which would have occurred if the temperatures had been approximately a factor of 5 higher).

Outlook for Pellet Fueling

Encouraged by this result, other laboratories have expressed an interest in pellet fueling. Dan Schuresko, who transferred to the pellet fueling group in 1981 from



Details of ORNL's four-shot pneumatic pellet injector showing four gun barrels (foreground), liquid helium cryostat, and propellant valves (background). The device is capable of delivering four pellets of frozen hydrogen or deuterium independently.



The Tokamak Fusion Test Reactor at Princeton Plasma Physics Laboratory is expected to begin operation in 1986. Exploratory studies of pellet fueling began in April 1985 with emphasis on a repeating pneumatic injector that was prepared at ORNL.

the Chemical Technology Division, recently installed ORNL's ISX-B four-pellet injector on the PLT tokamak at the Princeton Plasma Physics Laboratory (PPPL). The original four-pellet device has been reactivated also at PPPL on the Poloidal Divertor Experiment. But the most important achievement in 1984 in this field was the successful performance of Foster's centrifuge injector on the D-III device at GA Technologies, Inc., in San Diego, California. The centrifuge apparatus, which is capable of delivering deuterium pellets continuously at 40/s at a velocity of 800 m/s, was the centerpiece of a joint collaboration involving ORNL, GA, and the Japan Atomic Energy Research Institute. The project culminated in the first demonstration of truly steady-state pellet fueling. In this historic experiment the gas-fueling valves were finally turned off altogether, and the plasma responded to pellet injection, as it had done in the Alcator-C demonstration.

These successes have had a profound impact on the outlook for the fusion program locally, if not nationally. Our "mom-and-pop" show has grown and matured with the addition of Schuresko, Stephen Combs, and Charles Foust. Furthermore, no modern plasma fusion device can afford to be without pellet fueling (which perhaps should be called pellet "healing" in light of the fact that pellet injection makes the plasma better). The most obvious new candidate for the treatment is the Tokamak Fusion Test Reactor (TFTR) at PPPL. This leviathan, the most ambitious U.S. fusion device yet, will one day achieve energy breakeven by bringing together the necessary ingredients—including a giant plasma heating plant, large plasma volume (reactor scale), and the capability of using tritium fuel. A series of pellet fueling applications is planned for TFTR, starting with exploratory studies in April 1985 that will feature a repeating pneumatic injector (RPI) The RPI, which is being readied by Combs and Foust, is capable of delivering the largest and fastest deuterium pellets (4 mm and 1600 m/s, respectively) in our arsenal. This apparatus will be replaced by a more versatile and powerful deuterium injector in 1986 when TFTR reaches its full potential of 27 MW of neutral-beam heating. And, if everything goes as planned, ORNL will provide the deuterium and tritium pellet fueling system for the historic energy breakeven demonstration scheduled on TFTR for the end of the 1980s. ornl

Editor's note: For their developments of pellet fuel injectors for fusion devices, Stan Milora and Chris Foster in March 1985 received the Outstanding Technical Accomplishment Award from the American Nuclear Society.

BOOKS

Technostress: The Human Cost of the Computer Revolution, *Craig Brod, Addison-Wesley Publishing Company, Reading, Massachusetts, 1984. Reviewed by William S. Lyon, Analytical Chemistry Division.*

Technostress is a modern disease of adaptation caused by an inability to cope with the new computer technologies in a healthy manner. It manifests itself in two distinct but related ways: in the struggle to accept computer technology, and in the more specialized form of overidentification with computer technology.

The primary symptom of those who are ambivalent, reluctant, or fearful of computers is anxiety. The primary symptom among those who have too fully identified with the computer technology is a loss of the capacity to feel and to relate to others. Signs of the technocentered state include a high degree of factual thinking, poor access to feelings, an insistence on efficiency and speed, a lack of empathy for others, and a low tolerance for the ambiguities of human behavior and communication. At its most serious, this form of technostress can cause aberrant and antisocial behavior and the inability to think intuitively and creatively. In some cases spouses report that their technostress partners began to view them as machines.

So opines Craig Brod, psychologist and president of High Performance, Inc., a California firm. Computers and high technology are blamed by Brod for almost all the ailments that send mortals to the psychiatric couch—including some symptomatic behavior (insistence on efficiency, for example) that many would applaud. Here is Brod's thesis.

The computer is causing many of us to confuse machine operations with human thought and to believe that the human brain operates like a computer. As computer users become more adept and more involved, they begin to emulate their machine—a sort of high-tech version of *The Great Stone Face* or *The Picture of Dorian Grey*. They lose interest in human conversation, preferring instead to sit at their terminals and communicate by electronic mail; when they do condescend to converse, it is in unemotional, programlike terms such as "Would you like to go out, and if so, where?" (Open-ended questions are avoided, and ambiguity or nuances are discouraged.) This phenomenon is bad for adults, but "you ain't heard nothing yet." By being exposed to computers, children are being corrupted, their emotional lives are disrupted and changed, and they give up the joys of real-life play for video games that simulate it. Compounding all these ailments is the fact that the computer will eventually put the blue collar worker permanently on the dole (in 1988, 90% of the tasks performed in U.S. auto plants will be computer controlled, and only 50% of the current work force will be employed), middle managers will be gone, and executives will be monitored by a computer run by their chief executive officer.

Can all this be true?

Brod cites a number of case studies of adults and children to bolster his argument. He tries to make us believe that too much computer, like too much candy, is bad for children. But I suspect that most kids will take computers in their stride. The few "hackers" and computer "jocks" that doctors see are probably an infinitesimal sample of the population.

In my observation, many of the "problems" and case histories that Brod describes are rather commonplace among scientists and engineers. Working long hours, deep immersion in a problem, failure to respond to

"Most of us who were around before the computer age can see little change in our colleagues' preoccupation with work—be it computers or experiments. Going overboard on anything can create problems, and computers are no exception."

social chit-chat and neighborhood gossip at parties—these seem normal to most people engaged in technical work. Perhaps such people are sick and do need treatment, but most of us who were around before the computer age can see little change in our colleagues' preoccupation with work—be it computers or experiments. Going overboard on anything can create problems, and computers are no exception.

However, I agree with Brod that the complete orientation of many persons to computers can cause serious problems. One problem is the slow loss of professionals with "hands on experience, the tactile and visual perceptions of the materials they work with," as Brod puts it. Because many computer users seem to lose touch with the real world, creative thought and innovativeness are lost. Closely allied to this deficiency is the danger of unquestioning acceptance of programs and simulations whose creation or comprehension lies beyond the operator's grasp.

For example, in my own area of interest, radiochemistry now includes programs that search out gamma-ray peaks and determine their energies and abundances. Many users of these programs have no conception of how these gamma-ray branchings were originally obtained, how interferences are overcome, or how accurate the programs are. Just as city dwellers have divorced themselves from the realities of growing food, so modern researchers have separated themselves from experiments. Bread, to the urbanite, comes in a plastic wrapper; frequently electronic components for experiments are conceived on breadboards and come concealed with the software in mysterious packages the size of breadboxes.

Persons who work with computers or who have children or spouses who do should read this book with an open mind, taking care to differentiate between the conclusions that exaggerate and those that ring true. The information explosion and the computer age are upon us, so we must study and diagnose ourselves. As Brod says, "There are no generations of retired computer users whose advice we can seek and examples we can follow. We are our own guinea pigs." ornl

BOOKS IN PRINT

The following books were authored or edited by ORNL staff members.

Room Temperature Phosphorimetry for Chemical Analysis, Tuan Vo-Dinh, John Wiley & Sons, Inc., New York, 1984.

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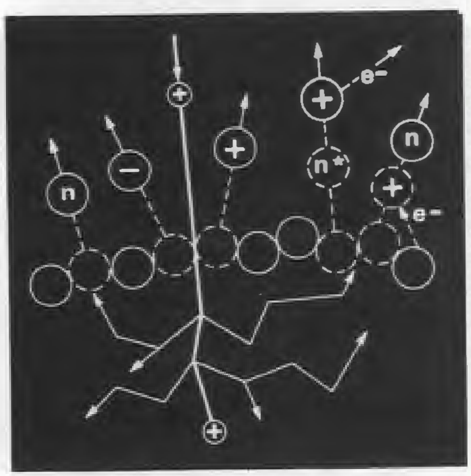
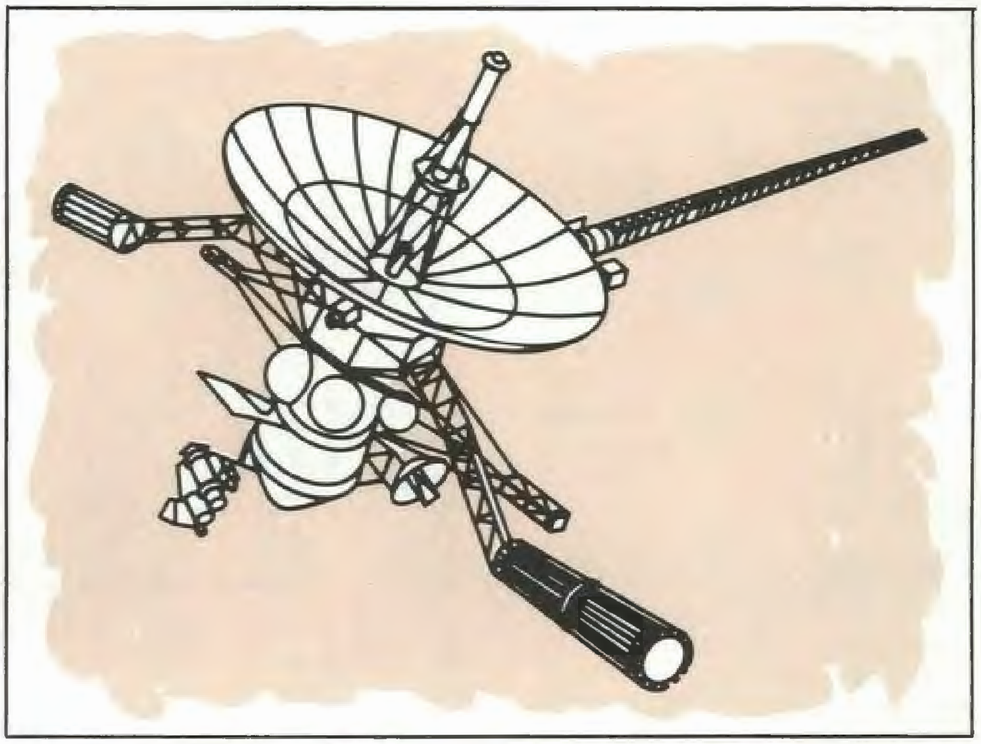


Sleuthing with Secondary Ion Mass Spectrometry

By WARNER H. CHRISTIE

When Dennis Taylor, a colleague at the Savannah River Plant (SRP), called me recently and asked, "Could you analyze a metal sample that's contaminated with plutonium-238?", my first thought was to hang up the telephone. I reacted initially with shock because I was concerned about the possibility of contaminating our ion microprobe with plutonium. Then I realized that Taylor was not talking about scrap metal from a nuclear weapon, a reprocessing facility, or a decommissioned reactor. He was referring to some specimens of an iridium-tungsten (Ir–0.3% W) alloy that had been aged at a high temperature in intimate contact with an oxide of plutonium-238 ($^{238}PuO_2$). Taylor convinced me that

Warner H. Christie is group leader for elemental spectroscopy and secondary ion mass spectrometry (SIMS) in ORNL's Analytical Chemistry Division (ACD). A native of Brooklyn, New York, he grew up in Miami, Florida, and earned his Ph.D. degree in chemistry from the University of Florida. In 1957 he came to ORNL's Chemistry Division as a postdoctoral fellow, and in January 1959 he joined ACD. His research interests include the use of SIMS as an analytical technique and new ways of applying ion sputtering as an ionization technique. Here, Christie, holding an electrostatic lens element used in the SIMS instrument, explains how the energetic ions used in the analysis are generated.



An iridium-tungsten alloy developed at ORNL will be used to contain $^{238}PuO_2$ fuel used as a general-purpose heat source for generating electricity aboard* Galileo *on its mission to Jupiter. The spacecraft will be launched late this year or in early 1986.

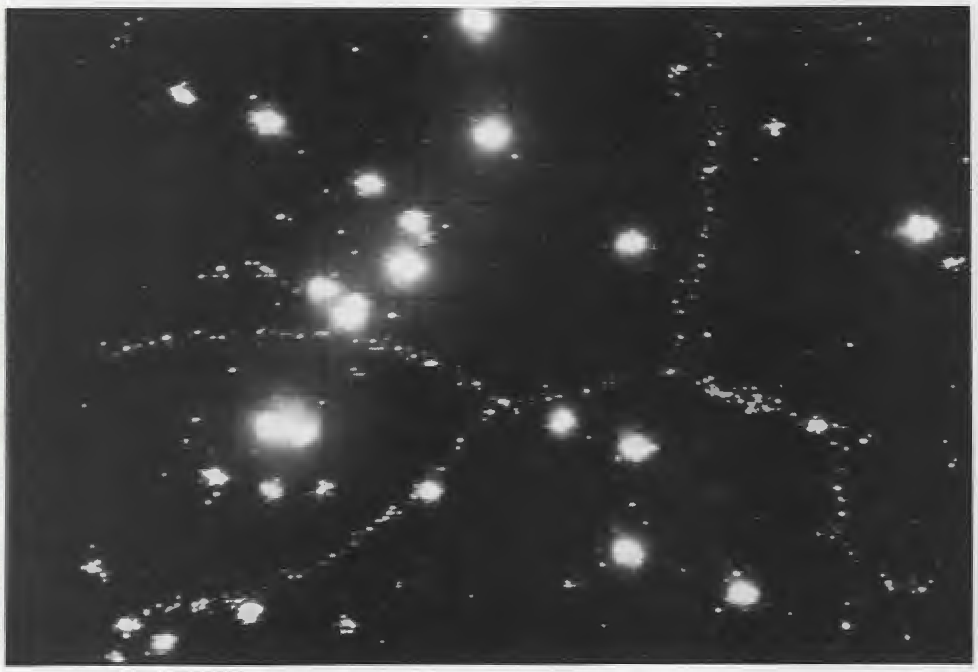
ORNL analytical chemists helped a scientist from DOE's Savannah River Plant determine how the impurities in plutonium fuel degrade the properties of an ORNL-developed cladding alloy used for heat sources aboard spacecraft.

we could use the ultrahigh sensitivity of secondary ion mass spectrometry (SIMS) to advantage and avoid contamination of the instrument.

The iridium-tungsten alloy particularly interested me because it had been developed here at Oak Ridge National Laboratory (see "Alloys for Nuclear Power Systems in Space," ORNL *Review*, Fall 1983). Its purpose is to contain $^{238}PuO_2$ fuel used as a general-purpose heat source for generating electricity aboard spacecraft. Currently the National Aeronautics and Space Administration (NASA) plans to use this alloy in the heat source that will provide on-board power for the mission to Jupiter of the *Galileo* spacecraft, which will be launched in late 1985 or early 1986. Because the alloy must be able to contain the ^{238}Pu in the event of a launch abort and subsequent high-velocity impact with the earth, considerable effort has been devoted to ensuring its reliability.

Taylor and Dan Pavone of Los Alamos National Laboratory (LANL) had done the first study of the alloy following its exposure to simulated service conditions. Four Ir–0.3% W capsules, loaded with $^{238}PuO_2$ and placed as an array in a graphite block, were put into a vacuum system. They were aged there for six months at a fuel temperature of 1440°C to simulate the searing heat of accidental reentry into the atmosphere. To facilitate an accelerated aging study, the $^{238}PuO_2$ fuel used in each capsule was doped with elevated but known levels of impurities that are normally picked up by the $^{238}PuO_2$ during chemical and mechanical processing. Because these impurities in the $^{238}PuO_2$ might affect the chemistry and mechanical properties of the cladding alloy, we at ORNL were drawn into the picture.

Since the inception of the program to develop the heat source, our mass spectrometry group in ORNL's Analytical Chemistry Division has worked out the techniques required to accurately certify trace impurities in the very radioactive $^{238}PuO_2$ fuel. We also developed methods to analyze the trace dopants—mainly thorium and



Ion micrograph showing thorium segregated to grain boundaries (continuous roadlike network) and present as precipitates (bright spots) in the interior of grains of the iridium-tungsten cladding alloy.

aluminum—which were added to the iridium cladding alloy to give it the required hot mechanical strength needed to contain the fuel upon high-velocity impact. Thus we were qualified to analyze impurities in $^{238}PuO_2$ and its cladding alloy.

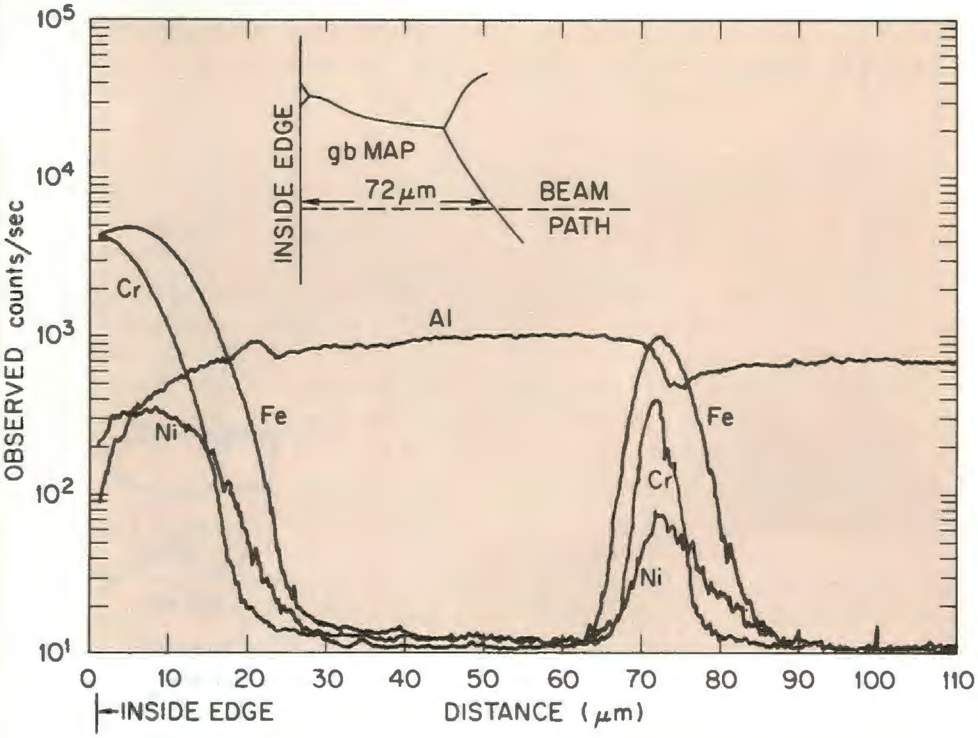
SIMS and Alloy Studies

Ray E. Eby and I originally used SIMS to study the distribution of thorium on grain boundaries in the iridium-tungsten alloy. A grain boundary is a region, about 1 nm wide, where individual crystals (grains) that make up ordinary metals adjoin each other. Metallurgists know that the mechanical properties of an alloy are frequently determined by the chemical impurities present in this region. The developers of this alloy—C. T. Liu and Henry Inouye of ORNL's Metals and Ceramics Division—found that the addition of thorium helps maintain ductility during high-temperature aging by preventing grain growth. Ductility, the ability to deform without breaking, is an important property for a cladding alloy that must withstand high-velocity impact. Thorium is believed to be effective as a grain-growth inhibitor because it exists primarily as discrete particles on the grain boundaries and tends to pin them against movement at high temperature. Our ion micrographs showed that thorium moved to and concentrated in grain boundaries and in the interiors of the alloy's grains to form discrete precipitates. Micrographs such as these illustrate the extreme sensitivity of the SIMS technique, which can detect particles in grain boundaries that, in this case, tend to be about 1 nm wide when exposed edgewise.

SIMS is not only sensitive but also fast in determining the distribution of impurities in grain boundaries of alloys. In this technique, a beam of ions [typically oxygen (O_2^+)] strikes the alloy target. Only a small fraction of the analyzing ion beam intersects a given grain boundary. However, this ionizing method is efficient enough to cause secondary ionization of the impurities (such as thorium) sputtered from the grain boundary region. These secondary ions are detected and quantified by mass spectrometry. Other techniques used to study grain boundary chemistry in this alloy require very elaborate sample handling to allow a specimen to be fractured in an ultrahigh-vacuum environment; as a result, several days may be required to obtain data from a single sample. With SIMS the grain boundary distribution of thorium can be determined in less than 2 h after the sample is placed in the instrument.

SIMS and "Hot" Samples

In 1982 we wrote a report, published in the journal *Analytical Chemistry in Nuclear Technology*, that described how we had exploited the ultrahigh sensitivity of our SIMS instrument in identifying and quantifying radioactive Pu, uranium (U), and cesium (Cs) in nuclear fuel dissolver solutions. In this work we noted that SIMS allowed analysis without chemical steps or appreciable sample handling—two important advantages. Dissolver solutions containing spent reactor fuel and fission products are very radioactive. We had obtained about 0.25 μL of one of these solutions, which had been diluted by a factor of 1000 with distilled water. At that point, we boasted that the amount of radioactivity had been reduced to about the amount one used to receive from a luminous-dial wrist watch. Despite the sample size and dilution, the sensitivity of SIMS allowed us to obtain reasonably accurate isotopic values for the Pu, U, and Cs in the sample. The most important aspect of the SIMS



Line scan showing bulk diffusion and grain boundary diffusion of impurity elements in the cladding alloy. More rapid grain boundary diffusion results in deeper penetration of the impurities into the alloy.

analysis was that by using controlled ion sputtering, we consumed only about 1% of the sample loaded and found no smear-removable radioactivity inside our SIMS instrument. The other 99% of the sample remained on the sample planchet and was readily available for safe disposal.

Taylor read our report and concluded that we could use the imaging capability of our microbeam instrument to help him study the grain boundary chemistry of his four plutonium-contaminated samples. Because he knew that we had experience with the Ir-W cladding alloy and that we could safely handle radioactivity, he gave us a call.

After we agreed to analyze the four alloy samples, Taylor sent the samples to LANL to be decontaminated. There Pavone removed any visible amounts of $^{238}PuO_2$ and shipped the samples back to SRP, where they were further decontaminated and mounted in epoxy and polished to facilitate the SIMS analysis. No smear-removable alpha activity was detected on the sample surfaces at SRP, so the samples were sent to us at ORNL.

Although we knew the exteriors of the specimens were free of radioactivity, we were still concerned that trace amounts of plutonium might be alloyed with the cladding. What worried us was that training our analyzing ion beam onto the alloy surface would sputter an appreciable amount of plutonium onto parts of our SIMS instrument. Because SIMS is an ultrasensitive detector for plutonium (1 ppm or less), we decided to use it to check whether the alloy samples were plutonium free. Our plan was to tune the SIMS instrument to detect plutonium (by adjusting the spectrometer to detect mass 238); at the moment sputtering began, we would evaluate from the magnitude of the plutonium signal (secondary ions) whether we might contaminate our instrument if the analysis continued. Imagine our surprise when we found no detectable plutonium in the cladding alloy! This lack of a signal was really good news because it allowed us to strive for maximum sensitivity in measuring concentrations of other elements of interest by using higher sputtering rates without fear of contamination.

The microstructure and grain boundary chemistry of the iridium-tungsten cladding alloy had already been characterized by others for samples that had been subjected to heat treatment alone. Such information, however, was lacking for samples exposed to radioactive plutonium. Taylor's optical microscopy of polished specimens removed from the four samples sent us showed a significant increase in average grain size in the near-surface regions exposed to $^{238}PuO_2$. The increase in grain size was a major concern because earlier studies had shown that this growth was caused by the loss of thorium from the grain boundaries. Loss of thorium was also linked to significant reduction in the impact fracture resistance of the alloy when it was hot.

Of the four samples we studied, one exhibited less grain growth in this region, suggesting that it might have a larger thorium content than the others. Our challenge was to determine what chemical differences existed between the samples exhibiting large grain growth and the one showing lesser growth. We also sought to pin down whether any impurities in the $^{238}PuO_2$ affected the thorium content and grain size.

A Chemistry Problem

Our approach to analyzing Taylor's four samples was to sputter off a region of the surface about 100 μm wide across the 700-μm width of each sample. After some grain boundaries became visible, the first thing we noticed was the lesser grain growth of the sample previously mentioned. All four of the samples exhibited significant amounts of chromium (Cr), iron (Fe), and nickel (Ni); these elements had diffused out of the $^{238}PuO_2$ fuel and into the alloy along grain boundaries. Other fuel dopants (calcium, silicon, magnesium, and titanium) were not observed to have diffused into the alloy. The Cr, Fe, and Ni showed evidence of rapid diffusion along grain boundaries and a slower diffusion off the grain boundaries into the bulk metal. To obtain these data, we swept a microfocused (2- to 3-μm) ion beam of O_2^+ across the surface, starting where the alloy had been in contact with $^{238}PuO_2$ and moving in a perpendicular direction so that grain boundaries would be intersected at some depth below the surface. We began at a surface location that was not intersected by grain boundaries so that we could look for bulk diffusion of impurities into the cladding in the surface region as well as grain boundary diffusion at a greater depth. In all samples we noted that wherever Cr, Fe, and Ni had intruded into the sample, aluminum (an alloy dopant, like thorium) had been lost from the alloy. Because these effects were observed in all four samples, however, they failed to explain the reduced grain growth seen in one sample.

Our examination of the Fe, Cr, and Ni data suggest that these elements do not exert a primary effect on grain growth. In the first place, the approximate depth of penetration of the iron and chromium does not match the depth to which large grains have grown. In addition, iron and chromium appear to be latecomers, diffusing into the boundaries after they have already been established, whether the grains are relatively small or very large. If these elements had controlled grain growth, the grain size would probably have been more uniform from sample to sample.

Ion micrographs of thorium showed that it segregated to grain boundaries and also was present as discrete precipitates in the interiors of grains and on grain boundaries. These micrographs also showed that the thorium concentration on grain boundaries diminished toward the alloy surface that had been in contact with the $^{238}PuO_2$. As mentioned earlier, this decrease in thorium concentration on the grain boundaries coincided with an increase in grain size. We also found that the number of discrete thorium particles within the large near-surface grains was significantly lower than in essentially undisturbed grains near the middle of the alloy. We surmised that the thorium particles originally in the near-surface grains had been swept away by grain boundaries in the typical fashion: The thorium particles pinned the grain boundary until they "dissolved," after which the boundary continued to move. But we do not fully understand why the thorium particles dissolved.

A Surprising Result

An exception to the above mechanism was observed in the sample that showed reduced grain growth. In this sample thorium was still present on grain boundaries in the near-surface region. In our search to unravel why significant amounts of thorium were still present in this one sample, we found a surprising correlation. Ion micrographs clearly showed that this retained thorium was associated with oxygen. The source of the oxygen was unknown, but it probably came from one of the oxidized impurities or the fuel itself. Earlier studies by other scientists suggested that oxygen does not diffuse along grain boundaries in this alloy. We had clearcut evidence that in this one case it had. Using a nitrogen (N_2^+) ion beam, we studied more regions in this sample and consistently found oxygen to be associated with thorium along grain boundaries more than 100 μm below the surface exposed to the fuel.

These results suggest that if the oxygen pressure is high enough (as it must have been in this case), oxygen can diffuse inward along grain boundaries and oxidize thorium in situ. Evidently the effect of this oxidation was to stabilize the grain boundaries against further grain growth. Careful examination of the other three specimens showed that virtually no thorium oxide (ThO_2) precipitates occur on grain boundaries more than 10 to 15 μm below the $^{238}PuO_2$ exposed regions. In the near-surface region, these three samples showed that significantly larger grains had developed, making the alloy in these specimens potentially more brittle.

A Possible Mechanism

Dennis Taylor was excited over the correlation between reduced grain growth and the presence of ThO_2 in the grain boundaries of the iridium-tungsten alloy. He was excited enough to come to Oak Ridge and examine our data. Using our analytical results, Taylor put together a tentative model that attempts to explain what happens during the six-month aging period.

Taylor surmises that the aging process has two time sequences. In the early stages thorium depletion

and grain growth occur when the oxygen pressure in the capsule is within certain limits. At a later time he expects a lower oxygen pressure, which favors reduction of FeO, a fuel impurity, and the formation of metallic iron at the iridium-tungsten alloy surface. The metallic iron thus formed is then free to diffuse into the cladding.

The sample that had the highest level of FeO added (10,000 ppm wt) was the one that showed the least grain growth. Thermodynamic calculations indicate that the oxygen partial pressure in this capsule could have been as high as 10^{-3} atm. Taylor believes that this high oxygen partial pressure accounts for the oxygen moving inward along grain boundaries to oxidize thorium in situ. At lower pressures thorium would migrate outward along grain boundaries and be oxidized at the surface. Other researchers have shown that this effect begins at about 10^{-8} atm of oxygen.

This finding on the inward diffusion of oxygen was exciting to Taylor because it suggested a way to possibly stabilize the alloy against exaggerated grain growth—that is, introduce oxygen to the cladding alloy to prevent loss of thorium. At this time iridium samples aged in higher oxygen pressures are not available as a means of confirming the consistency of this hypothesis. Furthermore, no information is available concerning the effect of grain boundary ThO_2 on high-temperature impact ductility. Like most scientific investigations, this work opened up a number of interesting avenues that await further sleuthing. ornl

Christie and Ray Eby discuss the strategy for a depth profiling experiment to be performed using SIMS. They recently used the SIMS instrument to study the grain boundary chemistry of a heat source cladding alloy used on spacecraft.

news notes

Tritium lights save life

The following is from a November 9, 1984, DOE Feature written for radio and television by Bob White of the Department of Energy.

A Military Airlift Command C130 comes in for a landing at Clear Creek airfield near Fairbanks, Alaska. The small lights are ORNL's tritium lights, which performed better than the larger lights next to them.

From the air the layout of ORNL tritium lights shows up clearly. The lights in the distance (top of photograph) are from the Hanford reservation (left), a Washington Utility Power System reactor (center), and Richland, Washington (right).

It was late on the afternoon of December 31, 1983, in the tiny Alaskan hamlet of Central—100 miles [160 km] northeast of Fairbanks. The thermometer hovered between 30 and 40 degrees below zero as 71-year-old Andy Bergssen—a retired gold miner—labored to repair his furnace. Somehow, the furnace caught fire, Bergssen ran out into the snow with his clothes ablaze, and his house was destroyed. . . . Bergssen's neighbors found him in critical condition lying in the snow. They immediately called the emergency medical team at Fort Wainwright, a Fairbanks army post. Unless the small Central airport had landing lights, they were told, the Medevac team couldn't get there until morning.

Because of research by the U.S. Department of Energy, Central's airport did have lights and the team landed 90 minutes later in a heavy snowstorm. Bergssen was evacuated and not only survived but is rebuilding his home.

Those landing lights were developed by the Energy Department's Oak Ridge National Laboratory for just such remote, hostile weather uses, and they were at the Central airport as part of a test being run jointly by DOE's Oak Ridge and Pacific Northwest Laboratories and the state of Alaska.

Those lights require no electricity or batteries, produce a yellow-green glow that can be seen for up to seven miles [13 km], need little maintenance, and last for eight to 10 years.

Their secret is radioactive tritium, a heavy isotope of hydrogen.

Oak Ridge Project Manager Karl Haff says the lights are not only safe and maintenance-free but can be easily stored and pressed into service at a moment's notice.

Haff explains: "The lights look and work much like the fluorescent light bulbs in your home and office. However, while the phosphors in fluorescent light bulbs are made to glow by electricity, in our runway lights, the phosphor is excited by radiation emitted by the tritium."

. . . . . .

The lights have been field-tested successfully in North Carolina, Arizona, and Florida as well as Alaska. And, as Andy Bergssen can attest, they represent one more example of how Energy Department research can help us all.

According to Haff, Alaska plans to install tritium lights at remote airfields within the state. Continuing research at ORNL is focused on improving tube designs to more efficiently use the radiation from the tritium and make the runway lights brighter.

University relations: A case study

University officials occasionally charge that the federal government's support of national laboratories deprives the academic world of needed research funds. In response to this charge, DOE recently issued guidelines to encourage national laboratories to contribute their resources to higher education.

As a national laboratory whose primary mission is research and development, ORNL does not grant university degrees. Nevertheless, because of its unique equipment, special facilities, and skilled staff, ORNL has long served as an important educational resource. ORNL is linked to the academic world primarily through its University Relations Program and through Oak Ridge

Associated Universities, which serves as a liaison between ORNL and 49 universities in the Southeast and elsewhere.

The ORNL divisions engaged in basic research have a particularly strong tradition of university interactions. Since 1951, for example, the Health and Safety Research Division (HASRD) has hosted hundreds of academic guests, including graduate students from southeastern universities and faculty experts from universities all over the world. During that time, according to HASRD Director Steve Kaye, graduate students conducting research in the division have produced 191 dissertations: 104 for master's degrees and 87 for Ph.D. degrees.

From October 1982 through September 1984, HASRD hosted 69 students and 53 university consultants and faculty guests—almost as many university representatives as HASRD staff members (there are 125). Most of the students hail from southeastern universities. The consultants and faculty guests at HASRD, however, have come from universities throughout the country and the world: American universities such as Harvard, Yale, Texas A&M, Massachusetts Institute of Technology, and the University of Chicago; foreign institutions including Osaka University in Japan, Cambridge University in Great Britain, and Hebrew University in Jerusalem, Israel.

Says Kaye, "Our interaction with university students and faculty members has been healthy for all parties. We have guided the students in their thesis research, and they have contributed bright ideas to us. We have profited from the expertise of faculty guests and consultants, and they have benefited from interaction with our scientists and from the use of facilities that are not available at universities."

Kaye is particularly proud of the 191 university-ORNL "alumni" who now hold positions in industry, universities, and government. "Many of these people," he notes, "have become university deans and professors or hold high positions in government agencies, such as DOE, the Environmental Protection Agency, and the Nuclear Regulatory Commission.

"Another important aspect of our program is the teaching that some of our staff do at universities, especially at UT," Kaye adds. "Currently, two of our staff hold Science Alliance professorships and six are Ford Foundation professors."

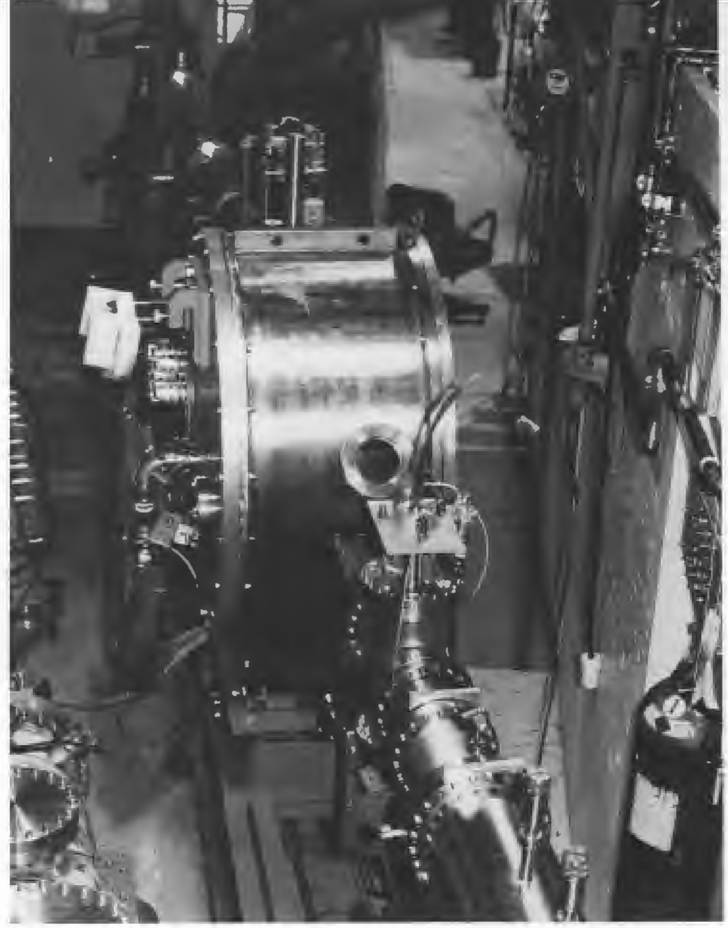
Kaye believes the evidence shows that HASRD, as well as other ORNL divisions, has long met the goals DOE recently set for laboratory-university interaction. "We are contributing 6–8% of our division budget to supporting students and university faculty members. That's a pretty healthy commitment to higher education for a single Laboratory division."

Beam line at Brookhaven

An ORNL-developed X-ray beam line will begin operation as soon as the radiation is turned on at the National Synchrotron Light Source at Brookhaven National Laboratory. X-ray optics for the beam line, which will be used for probing the atomic structure of materials, won a 1983 I-R 100 award from *Research & Development* magazine as one of the year's top 100 technical advances.

Cullie Sparks and Gene Ice of ORNL's Metals and Ceramics Division and Tony Habenschuss of Oak Ridge Associated Universities (ORAU) installed the instrument in November 1984 at the Long Island laboratory. The synchrotron is expected to begin initial operation in early spring.

ORNL has set up a users group through ORAU called ORSOAR. When the beam line becomes fully operational, about 15% of the beam line time will go to outside users from universities and industry. Ice and Habenschuss plan to move to Brookhaven to coordinate the work of ORSOAR and supervise operation of the beam line.



ORNL's X-ray beam line at Brookhaven National Laboratory. The large cylindrical tank is the two-crystal X-ray monochromator, which selects the energy and focuses the beam horizontally.

Atom probe to open in '85

A new atom probe field-ion microscope will become available later this year to researchers at ORNL and from universities and industry. According to Mike Miller of ORNL's Metals and Ceramics Division, the new microanalytical instrument incorporates an energy-compensated time-of-flight atom probe, a field-ion microscope, an imaging atom probe, and a pulsed laser atom probe. The four-in-one tool can determine the shapes and distributions of different size precipitate particles in alloys and identify and quantify all elements in a material, even if an element is present only in a particle as small as 1 nm.

The atom probe and a variety of other structural characterization equipment, including a 1-MeV transmission electron microscope and a new 300-keV analytical electron microscope, are available for collaborative research under the Shared Research Equipment (ShaRE) Program.

European magnet arrives

The last of three internationally supplied superconducting magnets for DOE's fusion-energy Large Coil Program arrived at ORNL in late November 1984. The magnet, provided by the European Atomic Energy Community (EURATOM), joined earlier-delivered foreign magnets from the Japan Atomic Energy Research Institute and the Swiss Institute for Nuclear Research.

The Japanese and Swiss magnets, along with one from the U.S. firm General Dynamics-Convair Division, were successfully tested in the superconducting mode last summer at ORNL's International Fusion Superconducting Magnet Test Facility (formerly known as the Large Coil Test Facility). In December the second U.S. coil was delivered to the facility; the coil was begun by General Electric Company and completed in shops at Oak Ridge Gaseous Diffusion Plant. This summer the five magnets now on hand, plus one from Westinghouse Electric Corporation, will be tested as a group.

The large D-shaped magnets, 6 m (20 ft) high, are one-third to one-half the size of those that will be needed for fusion power reactors. Magnets that are superconducting—when chilled to near absolute zero, they lose their resistivity to electric currents—require little electricity and will thus help cut the cost of power from fusion. Results from the six-magnet testing program will allow DOE to select the best magnet design for future fusion reactors.

Materials lab begun

Work began early this year on ORNL's $19-million High Temperature Materials Laboratory (HTML), a new national center for advanced materials R&D. A $9.3-million contract for construction of the 6000-m^2 (64,500-ft^2), reinforced-concrete structure was awarded to Blaine-Hays Construction Company of Knoxville, Tennessee. The building is expected to be completed in early 1987.

When equipped and ready for occupancy in mid 1987, the HTML will offer laboratory and office space for basic and applied research on high-temperature materials. Such materials are needed for more efficient automobile and aircraft engines and for the harsh environments of power-plant boilers and coal-conversion facilities.

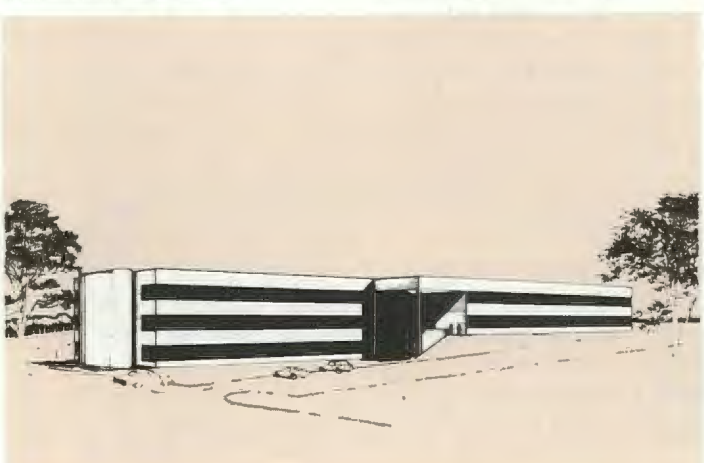
The facility will be designated as a user facility, one open not only to ORNL staff members but also to researchers from universities and industry.

technology transfer briefs:

Innovation Center plans set

Work is scheduled to begin this spring on a permanent building for the Tennessee Innovation Center, a new organization designed to encourage the formation and success of new technology-based businesses.

Architect's sketch of the Tennessee Innovation Center, which will provide space and assistance to new technology-based companies.



Founded in September 1984, the Tennessee Innovation Center is a joint venture of Martin Marietta Corporation (the parent corporation of Martin Marietta Energy Systems, Inc., ORNL's operating contractor) and Tran Tech Services, Inc. Tran Tech Services owns the Utah Innovation Center, the model for the Tennessee center.

In January, Thomas Yount, former president of EG&G-ORTEC (a highly successful ORNL spin-off company founded more than 25 years ago), was named president of the Tennessee Innovation Center. Yount comes to the job from the position of commissioner of Tennessee's Department of Employment Security.

The Tennessee Innovation Center will be the first resident of the Oak Ridge Technology Park, a new industrial complex being developed by Martin Marietta Corporation as part of the Tennessee Technology Corridor.

Innovation Center backs spin-offs

The Tennessee Innovation Center announced in February that it plans to provide financial and marketing aid to two new companies that ORNL staff members have organized to commercialize ORNL-developed technologies. According to Mel Koons, the Center's vice-president, the companies are Redox Sciences, Inc., and Technology Corridor Instrumentation, Inc.

Redox Sciences will produce Deoxid, a new particulate material used to make culture media for anaerobic, or oxygen-shunning, bacteria. The company's founders are Deoxid's developers, Howard Adler and Weldon Crow of ORNL's Biology Division, and Harold Schmitt, a former ORNL researcher who now heads another spin-off company, Atom Sciences, Inc.

According to Adler, Deoxid is likely to replace some current clinical tests for anaerobic bacteria such as those that cause gangrene and tetanus infections, because it is faster and much more reliable than the present tests.

Technology Corridor Instrumentation (TCI) will produce specialized mineral-insulated sheathed thermocouples, heater cables, and thermocouple-heater based instruments for industry, research institutions, and universities. According to TCI President Reg McCulloch, a member of ORNL's Engineering Technology Division (ETD), the thermocouples and heater cables can be combined to make unique devices for measuring temperature, fluid levels, heat, or flow. TCI will also make gamma thermometer systems by combining its thermocouples and heater cables with technology developed in ETD's Advanced Equipment Development Laboratory. Gamma thermometers made by TCI will be used to measure coolant level and heat flux in Arkansas Power and Light Company reactors.

New patent policy to speed transfer

A new federal policy greatly broadens patent rights for Martin Marietta Energy Systems, Inc., ORNL's operating contractor: it allows Energy Systems and similar contractors to own and license the patents on most inventions developed at the DOE facilities they operate. In the past, DOE has had automatic first rights to the patents, although it has transferred some patents to inventors, contractors, and other companies. An amendment to a federal law passed in November 1984 (P.L. 98-620) gave nonprofit government contractors the patent rights to most of their inventions; before leaving DOE in February 1985, then-Secretary Donald Hodel extended that policy to DOE's profit-oriented contractors, such as Energy Systems.

According to Bill Carpenter, Energy Systems vice-president for Technology Applications, the new policy will simplify and speed up the commercialization of technical developments. It applies to all patents except those related to (1) technologies to which the federal government needs to retain title, such as uranium enrichment; and (2) international agreements of the U.S. government.

When Energy Systems receives a patent, the company will license rights to companies interested in commercializing the development. Inventors will be given first consideration in evaluations of licensing proposals. Notes Carpenter, "None of the money received in royalties and licensing fees will become Energy Systems income. Instead, all of it will be reinvested in product refinement, prototype production, royalty shares for inventors, university programs, and other technology-transfer activities. As a result, our early successes in commercialization will pave the way for future successes."

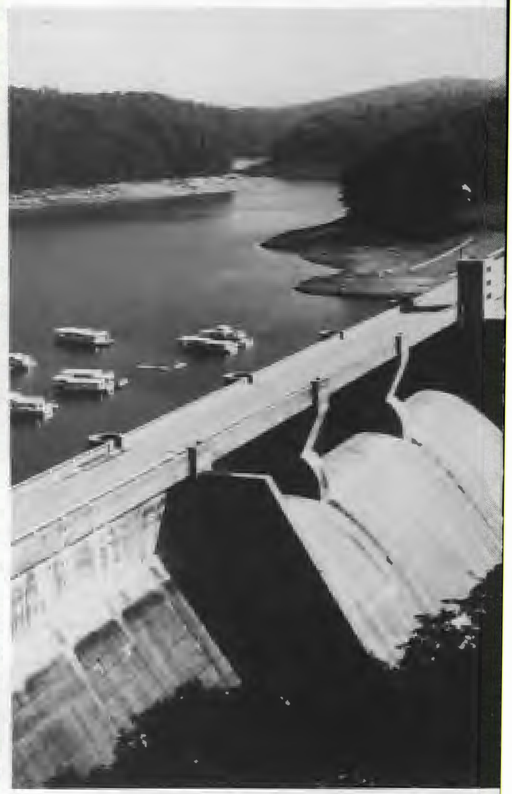
Hitting the streets: Technologies in transfer

- **Nickel aluminides,** a new class of ductile intermetallic alloys developed at ORNL. Nickel aluminides offer greater high-temperature strength than stainless steel and superalloys, and they avoid the brittleness of most structural ceramics. Promising applications include diesel-engine valves and turbine-engine disks. Currently a major diesel manufacturer is seeking exclusive rights to the materials.

- **Lead-iron phosphate glass,** a new disposal medium for high-level radioactive waste. The glass, featured on the cover of *Science* magazine October 5, 1984, was developed by Brian Sales and Lynn Boatner of ORNL's Solid State Division. It possesses far greater stability and resistance to radionuclide leaching than previously developed materials, such as borosilicate glass. The glass also promises to have useful optical qualities. Three companies have indicated interest in obtaining rights to market the glass.

- **Hazardous Materials Tracking System.** A computerized information system for monitoring the location and movement of hazardous materials at ORNL is now undergoing a pilot test at a new telephone-company R&D facility, Bell Communications Research. The facility is the research arm of Bellcore, a collection of the seven separate Bell companies formed by the breakup of AT&T. The computerized system, which uses bar-code labels on containers of hazardous materials, allows complete tracking of the containers at ORNL from receipt through use or disposal. Bellcore has expressed interest in marketing the system nationwide.

- **Ion-implanted artificial joints.** ORNL researchers have found that implanting nitrogen in the titanium alloy used in artificial hip joints can increase the durability of the joints by hundreds of times. Current replacement hip joints have lifetimes of about 10 to 15 years, so many of the 75,000 to 100,000 patients per year receiving today's artificial joints will require repeat operations. Nitrogen-implanted hip joints, however, would apparently last a lifetime and thus eliminate the need for multiple operations. A major medical manufacturer plans to produce a number of ion-implanted joints during 1985 for clinical tests in human patients. ornl



Norris Reservoir, located on the Clinch River in eastern Tennessee, is a site of ORNL reservoir ecology research.

The Organic Matter Base of Reservoir Food Webs

ORNL Studies the Ecology of Man-made Lakes

By BRUCE KIMMEL

The impoundment of flowing waters has played a significant role in the development and spread of human civilization since the beginning of recorded history. For example, the oldest known regional civilizations, located in the Tigris-Euphrates valley and along the Nile River about 3000 B.C., depended on diversion channels and dams constructed to store water for domestic use and for irrigating crops. About 4800 years later, the Industrial Revolution spawned the widespread use of water power for manufacturing and processing activities. However, when water power was applied to the generation of electricity during the past half century, large impoundments became predominant bodies of surface water in many parts of the world. Today, many of the world's major rivers have been converted to regulated series of reservoirs.

Since 1930 thousands of dams and other impoundments have been constructed in the United States. These include countless small impoundments such as farm ponds, stock tanks, irrigation and soil conservation reservoirs, municipal water supply reservoirs, and fishing "lakes." More importantly, by 1980 more than 1600 reservoirs of greater than 2 km^2 each (about 200 ha, or 500 acres) existed, embracing 40,000 km^2 (about 4 million ha, or 10 million acres) in water surface area. Most of these larger impoundments were constructed by federal agencies such as the Tennessee Valley Authority (TVA), the U.S. Army Corps of Engineers, and the Bureau of Reclamation for flood control, navigation, and hydroelectric power generation. Many large reservoirs also serve as sources of public and municipal water supply and cooling water for nuclear and coal-fired power plants and as sites for recreation, as well as being recipients of a variety of municipal, industrial, and agricultural wastes.

Despite their worldwide distribution and importance as multiple-use water resources, reservoirs are not well understood ecologically. Unlike natural lakes, large impoundments have not often been the focus of ecosystem-level investigation. However, ongoing research in the ORNL Environmental Sciences Division (ESD) is improving basic knowledge of reservoir ecosystems. In addition to me, members of the group conducting limnological research on reservoirs are Marshall Adams, an ORNL-ESD research staff member; David Soballe, a University of Tennessee (UT) faculty research associate; Alan Groeger, a University of Oklahoma doctoral candidate, who is conducting his dissertation research at ORNL; Jim Elser, a UT graduate student (now at the University of Notre Dame), who completed his master's thesis research at ORNL; and Mark Bevelhimer, who recently completed his master's degree at Ohio State University and is now beginning his doctoral studies at UT.

The primary goals of our research efforts are to improve basic understanding of the structure and function of reservoir ecosystems and thereby to develop the scientific basis necessary for anticipating the responses of reservoir ecosystems to natural and man-induced environmental

Bruce Kimmel leads the Ecosystem Dynamics Group and heads the Reservoir Studies Project in the Aquatic Ecology Section of ORNL's Environmental Sciences Division. He came to the Laboratory in November 1980 from the University of Oklahoma, where for the previous three years he had served as an assistant professor of zoology and the assistant director of the Biological Station. In 1977 he received his Ph.D. degree in ecology from the University of California at Davis. His principal research interests are organic matter dynamics, nutrient cycling, and factors controlling biological productivity in aquatic ecosystems. Although Kimmel has previously conducted research on natural lakes, he maintains that, in many ways, reservoirs are more complex, more dynamic, and more challenging scientifically. The ecology of reservoirs is the subject of much of his research at ORNL and of the article below. Here, he uses a laboratory fluorometer to determine the chlorophyll fluorescence emitted by a sample of phytoplankton, i.e., microscopic, free-floating algae that are the major producers of organic matter in lakes, reservoirs, and the oceans. Chlorophyll fluorescence measurements can indicate the amount of algal biomass present and provide information about the relative photosynthetic ability and physiological status of the phytoplankton.

What determines the biological productivity of man-made lakes? ORNL ecologists are using a variety of research approaches to address a fundamental question about large reservoirs as aquatic ecosystems.

perturbations. Our research is supported primarily by the Ecological Research Division, Office of Health and Environmental Research, U.S. Department of Energy, with additional funding received from the Corps of Engineers Waterways Experiment Station and TVA.

Sources of Organic Matter

Much of our research has focused on investigating the factors controlling the biological productivity of reservoirs. As for any aquatic ecosystem, reservoir productivity depends on the amount of energy, in the form of organic matter, that enters the food web from both internal and external sources.

The primary internal source of organic matter in most reservoirs is phytoplankton production. Phytoplankton are microscopic, chlorophyll-containing algae that are suspended in the water and that produce organic materials by photosynthesis—the process by which green plants use light energy to convert carbon dioxide and water to simple sugars and oxygen. Like terrestrial green plants, these tiny aquatic plants depend on the availability of light and critical nutrients (especially carbon, nitrogen, and phosphorus) for growth.

The major external source of organic matter for reservoir food webs is terrestrial plant photosynthesis and the subsequent transport of terrestrially produced organic matter into reservoirs by watershed runoff and river inflow. Organic matter from terrestrial plants includes leaves, branches, and, sometimes during floods, whole trees. Less visible, but quantitatively more important, is the soluble organic matter that leaches into the water from decaying vegetation.

One of the most basic questions that we can ask about any aquatic ecosystem (and one that is particularly important for understanding the ecological

Kimmel watches as Marshall Adams (center) and David Soballe check the limnological status of Melton Hill Reservoir near the Melton Hill Dam. Adams is using a submersible water quality monitoring system to measure water temperature, pH, conductance, and dissolved oxygen concentration. Soballe is obtaining a sample of the reservoir zooplankton with a plankton net.

structure and functioning of reservoirs) is, What forms the organic matter base of the food web? That is, what is the relative importance of internal versus external sources of organic matter to the biological productivity of the ecosystem? Because their watersheds—units of land that drain into a body of water—are usually quite large, most impoundments receive large quantities of terrestrially derived organic matter by river inflow. This input of external organic matter is widely assumed to be a significant supplement to reservoir food webs and therefore a major determinant of reservoir productivity. However, because much of the organic matter transported into reservoirs by rivers is the residual of terrestrial decomposition processes and is thus relatively resistant to further degradation, less of it may be incorporated into reservoir food webs than is generally assumed.

Organic Matter Budgets

Our first attempt to examine the organic matter base of reservoir food webs was to compare the organic matter budgets available for various aquatic ecosystems (streams, rivers, reservoirs, and natural lakes) that receive differing proportions of internally and externally derived organic matter. Our comparison revealed that because of reservoirs' larger watersheds and higher annual rates of water inflow, (1) terrestrial organic matter contributions to the total annual organic matter supply are usually larger for rivers and reservoirs than for natural lakes, and (2) in reservoirs, the external organic matter contribution often greatly exceeds that from internal production.

However, although organic matter budgets reflect large external contributions to the total organic matter supply to reservoirs, they cannot reveal the extent to which the terrestrially derived organic matter is incorporated into

Jim Elser, a former University of Tennessee graduate student, records phytoplankton chlorophyll fluorescence readings from an on-board fluorometer during studies on Normandy Reservoir in south central Tennessee.

reservoir food webs. The external organic matter loading to reservoirs is high relative to the internal organic matter production, so even if only a small fraction of the external input is incorporated into the food web, it could significantly supplement reservoir productivity. Therefore, our next step was to consider potential mechanisms by which externally derived organic matter might enter the reservoir food web.

Availability of Planktonic Algae and Bacteria

About 90% of the terrestrially produced organic matter is transported into reservoirs in a dissolved form. To enter the reservoir food web, this dissolved organic matter (DOM) must be converted to particulate organic matter (POM) that can be readily harvested by planktonic, filter-feeding animals (zooplankton) or by bottom-dwelling detritus feeders. For the planktonic food chain (i.e., that composed of organisms living in the water rather than those living in or on the sediments), the most probable and most energetically efficient mechanism for this DOM-to-POM conversion is by bacterial uptake of the terrestrially derived DOM followed by zooplankton feeding on the bacteria.

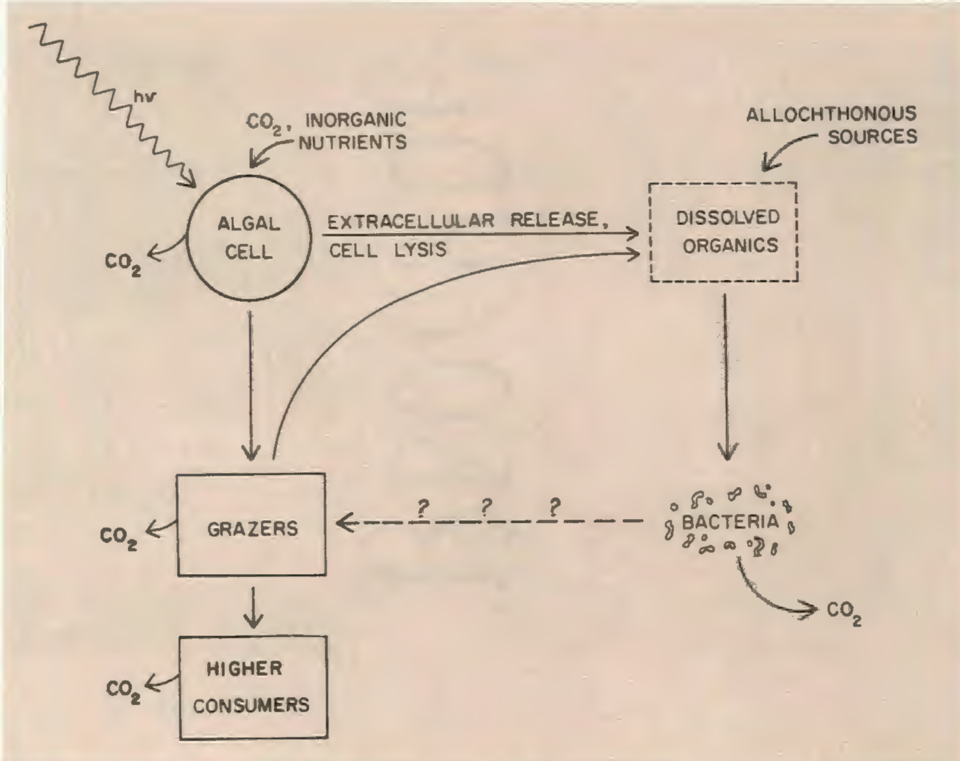
Compared with algae (phytoplankton), planktonic bacteria are smaller (usually <1 μm versus >3 μm for algae) and are less efficiently collected by the

Man-Made Impoundments as Aquatic Ecosystems

Limnology, the sister science of oceanography, is the study of the physics, chemistry, geology, and biology of inland waters (e.g., lakes, ponds, streams, rivers, springs, bogs). Historically, limnology has been dominated by the students of north temperate zone natural lakes; consequently limnological concepts (and dogma) are rooted firmly in a century of investigations of the relatively small, glacially created lakes of northern Europe, Scandinavia, and North America. Because large impoundments appear lakelike, they are often presumed to behave like lakes; thus attempts to manage reservoir water quality and biological productivity are often based on preconceptions derived from knowledge of natural lakes.

Certainly, many similarities exist between natural and man-made lakes; however, important differences separate the "typical" natural lake from the "typical" reservoir. For example, large reservoirs are, by origin, impounded rivers, and as such they retain, to varying degrees, their riverine nature. In fact, because they combine numerous features of both river and lake environments, ecologists consider reservoirs to occupy an intermediate position between rivers and natural lakes on a conceptualized continuum of aquatic ecosystems. Such a view encourages the use of existing knowledge of rivers, natural lakes, and river-lake interactions to form a conceptual framework for investigating and understanding reservoir ecosystems. This view also provides a basis for interpreting the marked spatial heterogeneity in environmental conditions commonly observed within reservoirs, the variations in limnological and ecological properties that occur among individual reservoirs and among different types of reservoirs, and the differences and similarities of natural and man-made lakes.—*B.K.*

The coupling of algal primary production, bacterial secondary production, and planktonic grazers is important in defining carbon flow pathways through reservoir foodwebs.



larger zooplankton that are directly fed upon by fish. However, planktonic bacteria are known to clump together and to attach to other suspended particles such as aggregates of organic detritus and silt and clay particles that can be consumed by zooplankton and detritus feeders. If bacterial attachment to, or aggregation with, other particles occurs to a significant extent, then bacterial production of POM from terrestrially derived DOM could form an important link to the planktonic food chain.

To determine the relative availability of planktonic bacteria and of phytoplankton to reservoir zooplankton, we conducted experiments in a number of reservoirs that represented a wide range of limnological conditions (e.g., differences in nutrient availability, water clarity, reservoir flushing rates, and algal productivity). We used a carbon-14 (^{14}C) labeled inorganic salt (sodium bicarbonate) to radiolabel the algae and a tritium-labeled organic salt (sodium acetate) to radiolabel the bacteria in reservoir plankton assemblages. We then employed size-fractionation filtration techniques to separate the plankton into various particle sizes, and we conducted feeding experiments. To determine the extent to which reservoir zooplankton actually fed upon the labeled algae and bacteria, we measured the amounts of ^{14}C and tritium radioactivity in filtered plankton samples and in zooplankton that had been allowed to feed on radiolabeled plankton assemblages. By this technique we distinguished algal from bacterial production and determined the zooplankton's preferred source of food.

Our results showed that, relative to phytoplankton, most bacterial production is associated with very small particles (<1 μm) in the reservoirs sampled. We found very little bacterial activity associated with larger particle aggregates or clumps of bacterial cells. In contrast, most of the phytoplankton production occurs in size ranges that are generally more available and more efficiently collected by reservoir zooplankton. Our feeding experiments confirmed that the zooplankton fed primarily on algae rather than on bacteria. Therefore, the hypothesized sequence of terrestrially produced DOM-to-bacteria-to-zooplankton-to-fish appears unlikely to be a major organic carbon pathway in reservoirs in which significant phytoplankton production occurs.

From Algae to Fish

The possibility remains that input of external organic matter to reservoirs may contribute to reservoir productivity by nourishing bottom-dwelling (benthic) organisms that are eaten by higher consumers such as fish. In addition, very small zooplankton that feed on individual bacteria may form a link in the planktonic food chain. (Small zooplankton are consumed by larger zooplankton, which, in turn, are eaten by fish.) Therefore, to consider the entire food web—that is, both the planktonic and benthic food chains—and to include all possible food web linkages, we compared phytoplankton production to fish production in a number of U.S. reservoirs for which reasonable data on both were available. Our primary question was, Can phytoplankton production account for the fish production in reservoirs, or is invoking an external (terrestrial) source of organic matter or other internal sources (e.g., aquatic weed production) necessary to explain the observed levels of fish biomass?

We developed and applied an energetics model to calculate the levels of phytoplankton production necessary to support the reservoir fish communities and then compared our estimates with field measurements of phytoplankton

Normandy Reservoir, located on the Duck River in south-central Tennessee, is the site of ORNL reservoir research being conducted in collaboration with the Tennessee Valley Authority.

production. Our analysis indicated that invoking inputs of externally produced organic matter to explain reservoir biological productivity is usually not necessary and that, in most cases, phytoplankton production alone can account for observed levels of reservoir fish production. Only in a very turbid (muddy) Kansas reservoir in which phytoplankton production is severely limited by low light availability was the input of terrestrial organic matter clearly required to explain the observed fish production. However, it became apparent in conducting the analysis that not enough is known about reservoir food web dynamics or about the energetic efficiencies of various food chain transfers (e.g., algae to zooplankton, zooplankton to fish) to obtain a clear answer to our question.

Carbon Isotopes as Natural Tracers

A more direct way of determining the relative importance of external and internal sources of organic matter to reservoir productivity would be to use a natural tracer to reveal the major organic matter source for the food web. For example, if the organic matter sources for reservoir food webs were color coded (e.g., white for terrestrial plant organic matter, black for reservoir phytoplankton), we might expect to find the consumer organisms colored white, black, or various shades of gray depending on the relative importance of internally and externally produced organic matter to their diets. Although the carbon atoms in terrestrially and aquatically produced organic matter are not color coded, they may be isotopically coded; therefore, the nutritionist's adage "you are what you eat" may have potential application to our research question.

Previous studies in marine and terrestrial ecosystems have shown that the organic matter in consumer organisms has a carbon and nitrogen isotope composition similar to that of the consumer's diet. Therefore, a comparison of the isotopic "signatures" of potential organic matter sources for reservoir food webs (terrestrial plants and reservoir phytoplankton) with those of various ecosystem components (e.g., reservoir zooplankton, fishes, benthic organisms, and bottom sediments) could indicate the primary organic matter supply to various organisms and to the reservoir food web in general.

With seed money from the ORNL Exploratory Studies Program and in collaboration with Pat Mulholland of ESD, we are now attempting to determine if carbon and nitrogen isotope analyses can help us identify the organic matter sources supporting the biological productivity of streams, rivers, and reservoirs. To determine isotopic signatures of organic materials, we are using isotope ratio mass spectrometry for stable carbon and nitrogen isotopes (^{12}C, ^{13}C, ^{14}N, ^{15}N) and tandem mass spectrometry or

ORNL ecologists use this MonArk research boat in their studies of reservoirs. Here, the boat is on Normandy Reservoir.

gas-phase counting of low-level radioactivity for ^{14}C. The success or failure of this approach will depend on the distinctiveness of the isotopic signatures of the organic matter sources—that is, whether we are starting with white and black or with indistinguishable shades of gray.

The Challenge of Reservoir Ecology

Determining the organic matter base of the reservoir food web is an essential, if difficult, first step toward gaining an understanding of reservoir ecosystem structure and function. Subsequent steps will not be easy either. We often find in studying the ecology of large reservoirs that we are dealing with shades of gray rather than with black and white because of the heterogeneous and dynamic nature of these man-made environments. But although their riverlike nature and their spatial and temporal dynamics make reservoirs difficult to sample and even more difficult to categorize, the resulting environmental variability also affords opportunities to ecologists and limnologists.

The diversity of environmental conditions existing within and among impoundments offers unique possibilities for addressing a variety of research questions. For example, reservoir plankton communities provide excellent opportunities for examining ecological responses to and recovery from episodic environmental disturbances and for investigating the determinants of ecosystem stability.

Additionally, because most large reservoirs are managed and operated for multiple purposes and because reservoir operational strategies sometimes change, opportunities exist for both planned and opportunistic large-scale experimentation. Indeed, if we are clever enough to use them to our advantage, many of the unusual features of reservoirs (e.g., their intermediate riverlike nature, seasonally fluctuating water levels and volumes, subsurface outlets, and a variety of operational regimes) should permit valuable insights into the structure and function of river, lake, and reservoir ecosystems.

Clean freshwater is becoming an increasingly precious resource. As I stated in the introduction, our research goals are to improve our understanding of reservoirs as aquatic ecosystems and, in doing so, to provide the scientific basis required for anticipating the responses of river-reservoir systems to a variety of potential environmental perturbations (such as floods, changes in land-use patterns, altered reservoir operations, or a sudden influx of toxic contaminants). Our research efforts are providing the technical data and scientific knowledge that will ultimately lead to improvements in predictions of technology-related environmental impacts, benefit-risk assessments for energy technology development, regulatory criteria for municipal and industrial facilities in reservoir watersheds, and management strategies for multiple-use water resources. A thorough understanding of reservoir ecosystem processes is required if we are to continue using these important water resources for diverse, often conflicting purposes (e.g., municipal drinking water supply versus waste disposal) while simultaneously preserving their recreational benefits and aesthetic qualities. ornl

take a number

BY V. R. R. UPPULURI

Triangles with Random Lengths

A triangle has three sides whose lengths can be easily determined. However, not every set of three random lengths can form a triangle. One can be constructed only when the sum of the lengths of any two sides is larger than the length of the third side. For example, a triangle cannot be made from three sides whose lengths are equal to 1, 2, and 4 units, respectively, because $1 + 2 < 4$.

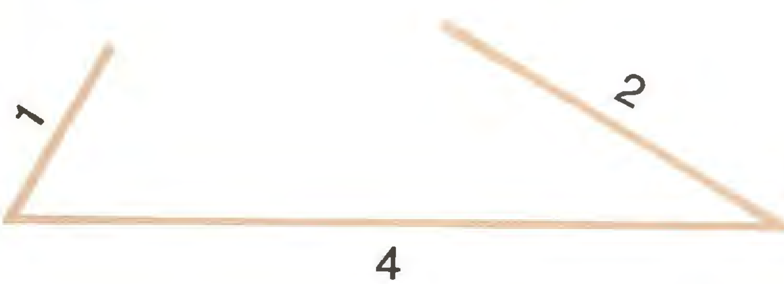
Suppose we choose three random numbers between 0 and 1. The chances are only 50-50 that a triangle can be constructed from sides equal in length to the three selected random numbers.

Numbers Expressible as Sums of Squares of Parts

Several numbers have the interesting property of being equal to the sum of the squares of their parts. Examples of such numbers are 1233 ($12^2 + 33^2$) and 8833 ($88^2 + 33^2$). These two numbers are the only four-digit numbers with this property.

Only two three-digit numbers are equal to the sum of the squares of their parts: 100 ($10^2 + 0^2$) and 101 ($10^2 + 1^2$). No two-digit numbers have this property.

B. Suryanarayanarao provides a method of generating these numbers in the September 1984 issue of *Mathematics*.



Dick Tyndall, research associate professor in the Department of Zoology of the University of Tennessee at Knoxville, has been a visiting investigator at ORNL since 1975. In 1961 he earned his Ph.D. degree in microbiology (with a minor in biochemistry) from Pennsylvania State University, where he received the Gamma Sigma Delta and Phi Sigma academic awards. Then while serving in the U.S. Army at the Walter Reed Army Institute of Research, he helped isolate and characterize the etiologic agent of infant diarrhea. In 1963 after being awarded an Atomic Energy Commission fellowship, Tyndall became a staff member of ORNL's Biology Division. His work with Arthur Upton (who later became director of the National Cancer Institute) and Bruce Jacobson involved the development of RNA fingerprinting in normal and virus-infected cells as well as viral and radiation carcinogenesis. In 1973 he joined the staff of Oak Ridge Associated Universities (ORAU) as head of the microbiology department, which was responsible for detecting and controlling microbial infections in cancer patients subjected to chemotherapy and radiation treatments. At ORAU he discovered a new species of amoeba. He left ORAU in 1977 for his present position. Since then he has studied the prevalence of pathogenic amoebae and Legionnaires' disease bacteria in artificially heated environments. Here, Tyndall undertakes to examine under a microscope *Acanthamoebae*, which will be tested in mice for pathogenicity.

DISEASE-CAUSING MICROBES:

The Energy Connection

By RICHARD L. TYNDALL

In the 1970s scientists at Oak Ridge National Laboratory and elsewhere pinned down some of the effects of energy production on fish and other aquatic life in rivers and lakes. For example, they found that the use of surface waters to cool power plants dissipated so much waste heat that fish migrated to habitats where water temperatures were more to the fishes' liking. Other scientists developed models to predict what fraction of certain fish would be trapped or killed by power plant cooling systems. However, the environmental impact of heated waters and cooling systems is not limited to fish populations; in the last eight years it has become increasingly clear that heated waters and cooling systems can promote the growth of microorganisms that cause disease in humans. This article recounts how ORNL and the University of Tennessee (UT) played a role in understanding this energy-related problem.

While these ecological studies were being conducted, the

A natural-draft cooling tower at a nuclear power plant in Pennsylvania. Cooling towers can be a source of* Legionella *bacteria.

Heated waters and cooling towers associated with energy production can be a source of disease-causing microbes, including the* Legionella *bacteria responsible for the potentially fatal Legionnaires' disease. ORNL and UT researchers have discovered two new species of* Legionella *in artificially heated water.

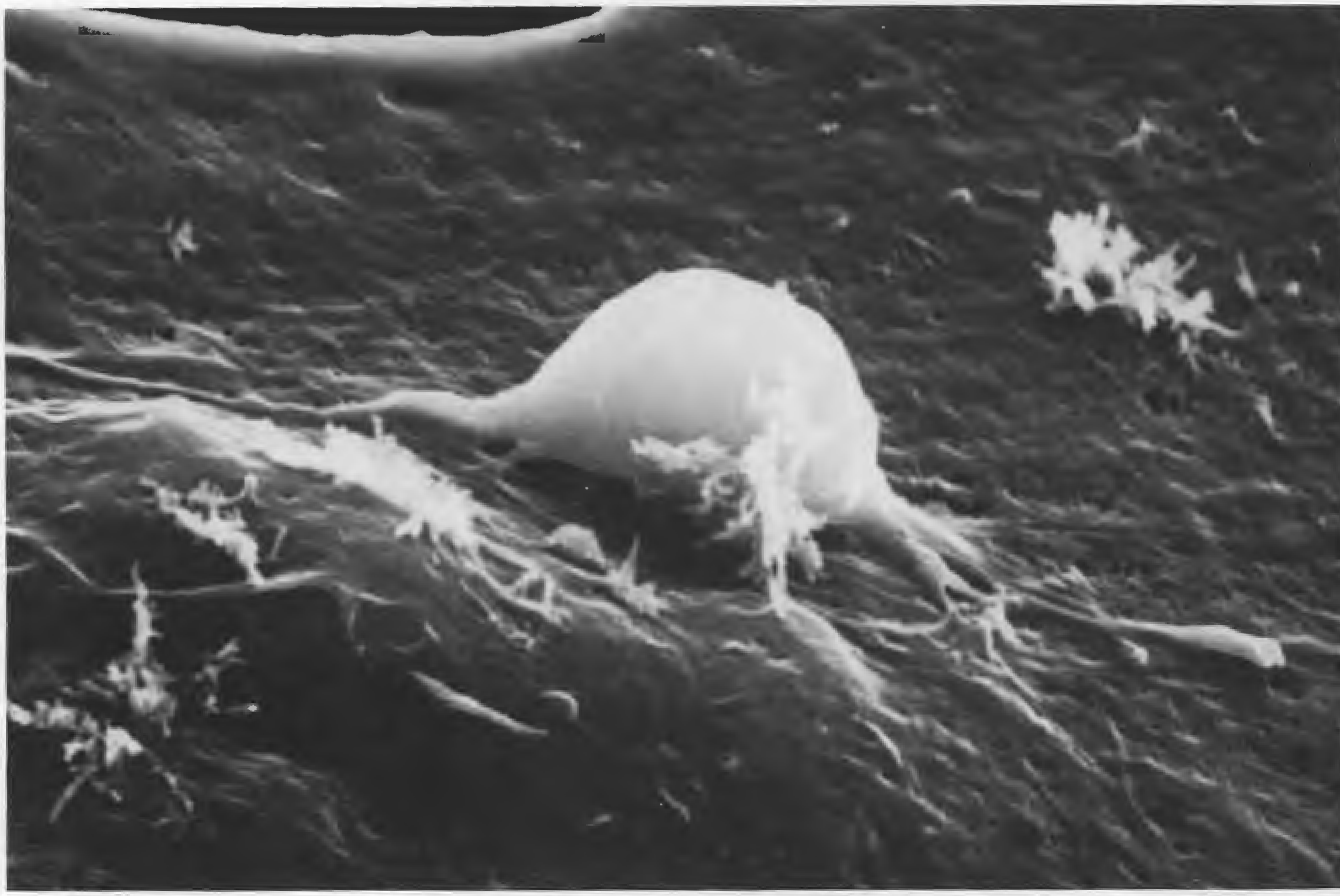
microbiology laboratory that I headed from 1973 to 1975 at Oak Ridge Associated Universities (ORAU) was studying the clinical microbiology problems of patients whose immune defenses were weakened by disease or therapeutic regimens. My ORAU colleagues and I were trying to determine if particular microbes were more likely to infect people with immune system deficiencies than people with normal defenses. In the course of our studies, we discovered a new species of pathogenic free-living *Acanthamoeba*, which was named *Acanthamoeba royreba*.

When we conducted a literature search on the occurrence of human infection by pathogenic free-living amoebae of the genera *Acanthamoeba* and *Naegleria*, we noted a relationship between such infections and naturally or artificially heated waters. Most people diagnosed with such infections bathed or swam in warm shallow waters in southern latitudes, in thermal springs, or in waters heated by industrial processes. Most *Acanthamoeba* infections involve the eyes but encephalitis (infection and inflammation of the brain) can occur. *Naegleria* causes a rapid, generally fatal encephalitis. Fortunately, amoebic encephalitis is relatively rare.

Aware that Chuck Coutant of ORNL's Environmental Sciences Division (ESD) had extensively studied the thermal preferences of fish, I discussed with him the possibility that a significant addition of heat not only alters aquatic environments but also could increase the populations of disease-causing amoebae in rivers and lakes. Free-living pathogenic amoebae are generally a minute component of the aquatic environment, but if amplified by thermal additions, they could pose a potential industrial or public health problem.

Thermal Discharges and Amoebic Pathogens

In response to this concern, the ORNL Exploratory Studies Program provided seed money in 1976 for our initial investigation of the relationship between thermal discharges from electric power generating stations and the presence of *Naegleria fowleri*. This preliminary study found *N. fowleri* in some but not all heated waters. We found no evidence of this



An electron micrograph of an* Acanthamoeba royreba *eating a cultured mammalian cell. Dick Tyndall discovered this species of the amoeba and named it after his parents, Roy and Reba Tyndall.

amoebic pathogen in unheated waters.

To determine whether these findings held true for other heated waters, in 1977 we launched a more extensive study of thermal discharges from electric power plants. In this study, supported by the Nuclear Regulatory Commission and the Electric Power Research Institute, we confirmed the results of the preliminary study. Although we could not isolate the amoebic pathogen in any of the source waters for the power plants, we repeatedly isolated it from some, but not all, thermal discharges from the plants. The *N. fowleri* apparently was present in very small quantities in the cool source waters but could not be detected until after it proliferated in the heated discharge water. The infestation was so pronounced at some sites that we could isolate the pathogen from water samples as small as 1.0 mL.

At one site this concentration was deemed unsatisfactory because of the possible exposure of workers involved in cleaning the cooling systems during the yearly maintenance operations. Consequently to destroy the pathogens in the power plant cooling system, the management instituted a premaintenance shock chlorination program. When we analyzed the heated discharge water after chlorination, we had difficulty finding any *N. fowleri*. Our studies showed that chlorination had reduced the pathogen concentration more than a hundredfold and that the reduction in pathogen levels persisted until the following summer, when high concentrations were again evident. As a result, chlorination is routinely performed each fall at the power plant; monitoring results show that treatment markedly reduces the concentration of *N. fowleri*.

The Legionella Story

In August 1976 the world's attention was focused on a mysterious lung disease that caused 34 deaths following an American Legion convention at the Bellevue

Tyndall at a typical cooling tower of Oak Ridge Operations, which is routinely monitored for presence and concentrations of **Legionella.**

Stratford Hotel in Philadelphia, Pennsylvania. Because the outbreak of pulmonary disease occurred among dozens of conventioneers, it was named Legionnaires' disease. The disease-carrying agent, which causes high fever and a pneumonia, was found to be a rod-shaped bacterium. It was identified in infected chick embryo yolk-sac tissue using serological techniques by Joseph McDade in December 1976 at the Centers for Disease Control (CDC) in Atlanta. In early 1977 the Philadelphia agent was isolated on nonliving culture media by Robert Weaver at the CDC. The bacterium was appropriately named *Legionella pneumophila*.

Since the 1976 outbreak of Legionnaires' disease, several hospital outbreaks have occurred. A particularly devastating epidemic was the May 1977 outbreak at Medical Center Hospital in Burlington, Vermont, which killed 17 people. The hospital's air-conditioning cooling tower was implicated, as it was in a similar outbreak at about the same time at the Veterans Administration Center hospital in Los Angeles, California.

In 1978 Carl Fliermans at the Department of Energy's Savannah River Laboratory demonstrated that *Legionella* are normally present in aquatic habitats. The bacteria exist in most, if not all, nonsaline surface waters such as ponds, lakes, streams, and rivers. Moreover, they can be found in waters with a wide range of temperatures and of acidity and alkalinity. In addition, Fliermans showed that by-products of other aquatic life such as algae enhanced the growth of *Legionella*. However, the presence of *Legionella* in fresh surface waters is not considered a public health threat because pulmonary infection generally results from inhalation rather than ingestion of the bacteria.

Two different lung diseases can result from infection with *Legionella*: Pontiac fever, a short-term flu-like illness, and Legionnaires' disease, a true pneumonia with prolonged aftereffects. From 50,000 to 200,000 people a year are afflicted with Legionellosis, with 25,000 having Legionnaires' disease. Both syndromes are effectively treated with the antibiotic erythromycin. More than 20 species of *Legionella* have been isolated. However, more than 80% of the diagnosed clinical cases thus far have implicated only one species, *L. pneumophila*, as the causative agent.

Because *Legionella* are present in natural, and some potable, waters, they can seed cooling towers and evaporative condensers used to dissipate waste heat from industrial and air-conditioning processes. Once the *Legionella* bacteria enter these environments, their growth may be enhanced by the presence of other microbes or organic material and by the addition of heat. The amplified bacteria population is then dispersed by the cooling devices into the air, where it becomes inhalable and potentially infectious.

As a natural outgrowth of our studies of the effects of thermal discharges on the growth of pathogenic amoebae, we began in 1979 to investigate the distribution of *Legionella* in thermally altered waters of power plants. Aiding me in the ecological and statistical analyses were Sig Christensen and Jean Solomon of ESD, Steve Gough (formerly of ORNL), and Fliermans. Technical assistants from UT were Elizabeth Domingue, Carol Duncan, Rebecca Jernigan, Cynthia Evans, and Mary Lyle.

To cool power plant condensers, water is routed either through a once-through (open-cycle) or a recirculating (closed-cycle) cooling system. In the open-cycle system, water is drawn from the natural water source, passed through the condensers, and discharged downstream from the plant intake. In a closed-cycle system, the intake water is passed through the condenser and then through cooling towers or cooling canals or lakes before being returned to the condenser for recycling.

In testing for *Legionella* in power plant cooling waters, we analyzed water at various points in

Wearing respirators, Sig Christensen (front) and Jean Solomon collect water samples from a cooling tower in their search for Legionella *bacteria.*

the cooling process: ambient source water, precondenser, postcondenser, and discharge waters. We determined concentrations of the *Legionella* populations by microscopic counting of the bacteria after staining the microbes with a fluorescent antibody specific for *Legionella*. To determine the infectivity of the *Legionella* population, we inoculated guinea pigs with test samples and studied the onset of disease in the animals. We also sacrificed some animals and isolated the bacteria from their infected tissues in an attempt to identify the disease-causing species of *Legionella*. Some populations of *Legionella* may be highly infectious for guinea pigs, whereas the same concentration of the same species in other populations may be minimally infectious.

We found that the average concentrations of *Legionella* in the plants' cooling waters were statistically indistinguishable from or occasionally lower than those in their ambient source waters. Further, we observed no consistent difference in the *Legionella* concentrations in water from open- and closed-cycle plants, even though the water in closed-cycle cooling systems is repeatedly heated.

However, although the *Legionella* concentrations in open- and closed-cycle plants were the same, the infectivity of the bacteria populations for guinea pigs differed significantly: A greater proportion of bacteria samples from the closed-cycle plants (e.g., cooling towers) caused disease in guinea pigs.

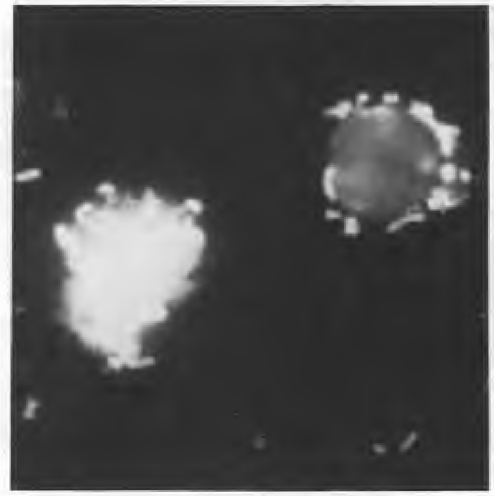
New Species Found

In 1982–1983, we isolated two additional *Legionella* species from the cooling waters of closed-cycle plants; scientists at CDC in Atlanta determined them to be new species. Although these species have been detected in unheated water by fluorescent microscopy, we have not yet detected infectious populations of them (for guinea pigs) in such waters. So far there is no evidence that these species pose a public health problem.

We named one of the new species *Legionella cherrii* in honor of William Cherry of CDC, a pioneer in developing the serologic tests for detecting and classifying *Legionella*. We named the other species *Legionella oakridgensis* in honor of Oak Ridge National Laboratory and the Oak Ridge community. The serological analysis that helped identify this isolate as a new species was carried out by Leta Orrison, formerly of Oak Ridge and currently on the staff of CDC.

L. oakridgensis is the most unusual *Legionella* species discovered so far. Unlike most (if not all) other species, *L. oakridgensis* has no flagella (elongated appendages used to propel an organism) and does not require certain amino acids for growth. Also, the cell wall of this species is composed of fatty acids not prevalent in other species. Some taxonomists believe that *L. oakridgensis* may be a new genus of bacteria rather than a new species of the genus *Legionella*.

Unlike most known species of *Legionella*, which were isolated from infected lung tissues of human patients, the two newly discovered species were isolated from thermally altered waters and so far have not been implicated in human disease. In cooperation with Drs. Brad Camp and Charles Bruton, staff physicians at Methodist Medical Center of Oak Ridge, we are now analyzing sera drawn from hospital patients with pulmonary disease to determine whether elevated antibodies against these two new species exist in blood serum. High levels of serum antibodies specific for these *Legionella* would strongly indicate that these new species are infectious for human populations.



Cynthia Evans of the University of Tennessee isolates* Legionella *bacteria from an infected guinea pig. To test for the presence of infectious* Legionella *in clinical and environmental samples, the material is injected into guinea pigs. When the animals become ill, their tissues are removed and plated on laboratory media to culture the bacteria. The presence of the bacteria is confirmed by serologic and microscopic methods. At right are amoebae surrounded by* Legionella *bacteria (bright white). The amoebae supply the nutrients necessary for the* Legionella *to multiply and grow.

Legionella Amplification

In human *Legionella* infections, the bacteria infect and multiply in a variety of lung cell populations, including the macrophage cells that normally engulf and destroy invading microbes. Like macrophages, free-living amoebae such as *N. fowleri* also engulf and destroy bacteria and even use them as a food source. Because of this phenomenon, we undertook to expose laboratory cultures of amoebae to *Legionella*.

We observed that the *Naegleria* and *Acanthamoebae* amoebae will ingest the *Legionella* and, depending on the growth conditions, become chronically infected by the bacteria. In addition, the amoebae support the growth and multiplication of the ingested bacteria: Cultures of infected amoebae can produce 100 million *Legionella* per milliliter of culture fluid. By contrast, no growth results from the inoculation of the culture fluid with *Legionella* in the absence of amoebae.

Our observation that the ingested *Legionella* usurped the amoeba's growth processes in order to increase its own numbers was the first evidence that such intracellular parasitism by *Legionella* occurs in cells other than those of lung tissue. Subsequently, other investigators have also demonstrated this process in amoeba and other protozoa.

Hot-Water Systems

Besides air-conditioning towers, hot-water systems may play a part in Legionellosis outbreaks in some hospitals, hotels, and communities. As previously noted, some of the cases of encephalitis caused by *N. fowleri* were linked to bathing or swimming in heated water, including potable water. We have isolated *Naegleria* and other free-living amoebae from such waters, and *Legionella* has been found in some potable waters, albeit in very low numbers. Although shock chlorination dramatically reduces the levels of both *Naegleria* and *Legionella*, chlorination of potable water does not guarantee the total elimination of the organisms. The few remaining *Legionella* may be amplified in potable hot water systems by repeated thermal additions in selected niches such as hot water heaters and shower heads.

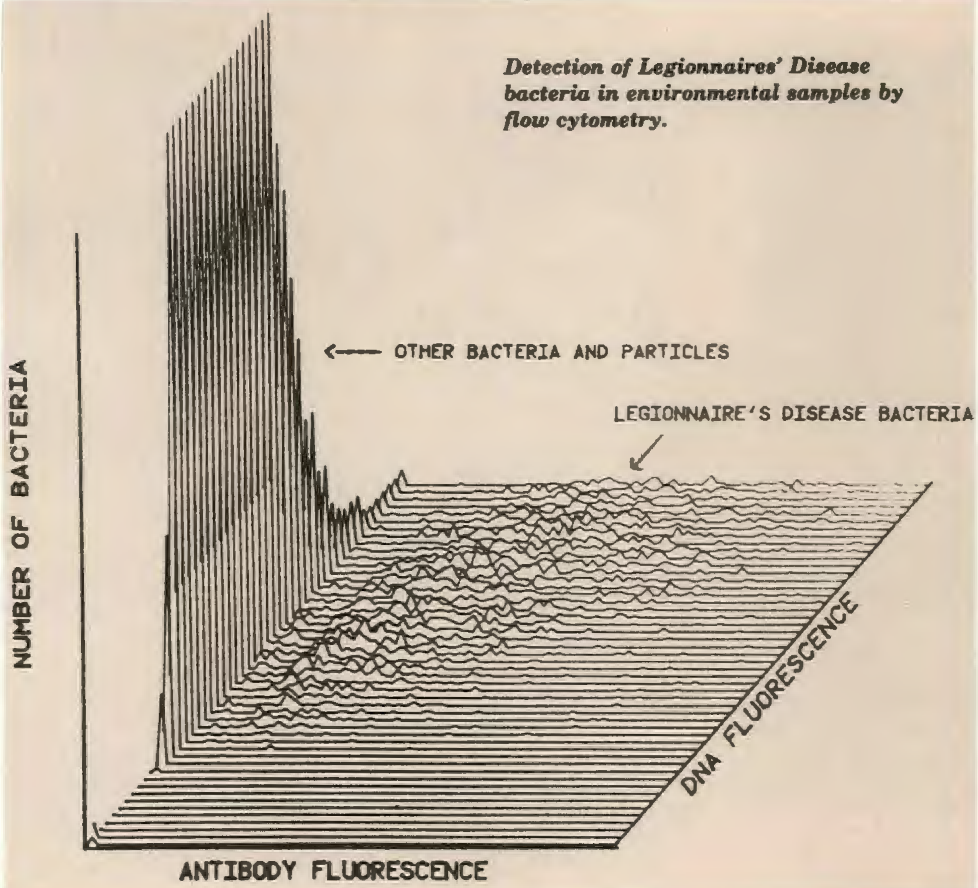
Not surprisingly, hospital patients are more prone to infection with *Legionella* than the general population. In patients with impaired immunological defenses, such as organ transplant patients given immunosuppressive drugs, the *Legionella* may gain a foothold and multiply in their tissues. In some hospital outbreaks, shower heads or humidifiers contaminated with *Legionella* are thought to have been the source of infection: while taking hot showers, patients inhaled the sequestered organisms, which were dispersed into the air with the spraying water. Our studies of thermally altered waters suggest that in addition to promoting the bacteria's growth, repeated thermal additions from the hot water system might also select for infectious *Legionella*. Both increased numbers and infectivity of the *Legionella* population would increase the chances of infection in patients exposed to the bacterial aerosol when showering.

Not only energy production and use but also energy conservation may increase the numbers of and chances of infection from amoebic and *Legionella* populations in the human environment. For example, lowering water-heater thermostats to save energy facilitates the survival of *Legionella* populations. Reducing the volume of makeup air (fresh outdoor air) drawn into office buildings leads to greater concentration of airborne microbial pathogens generated within the buildings by shower heads, humidifiers, and air-conditioning systems. Pulmonary disease outbreaks in some government buildings have been linked to such reductions of makeup air.

Some Legionellosis outbreaks in hospitals or industrial operations might have been averted by preventing cooling tower discharges from entering the building air intakes and by controlling the *Legionella* in the potable hot water systems by chlorine treatment. Although Legionellosis occurring in hospitals and industries can often be traced to a source and then controlled, Legionellosis affecting members of a community is less readily traced to a point source.

Oak Ridge Monitoring

Because of the known association of Legionellosis with cooling tower discharges, we were asked to start a program for monitoring the *Legionella* populations in cooling towers at the facilities of DOE's Oak Ridge Operations (ORO), including ORNL. We began this program in 1979. No known cases of Legionellosis have occurred among employees at the ORO facilities. In Oak Ridge and surrounding communities, however, incidents of Legionnaires' disease persist.



Detection of Legionnaires' Disease bacteria in environmental samples by flow cytometry.

The ORO plant cooling systems are regularly treated with biocides to keep the *Legionella* populations at acceptable levels. When an occasional system shows an increased *Legionella* population, further treatment is initiated to lower the numbers of bacteria. The industrial hygiene departments of ORO and the Savannah River Plant were among the first organizations to inaugurate such monitoring and control of *Legionella* in thermally altered waters of various industrial and air-conditioning processes. Results from this effort are being used to establish guidelines to protect DOE workers who clean and maintain industrial and air-conditioning cooling systems throughout the nation.

Despite widespread interest in controlling *Legionella*, however, large-scale testing of industrial and potable water systems to determine *Legionella* concentrations and infectivity is impractical with current techniques, which generally require counting the bacteria under a microscope and inoculating guinea pigs. Consequently, in conjunction with Reinhold Mann and Russ Hand of ORNL's Biology Division, we are assessing the applicability of cytofluorography as a rapid assay for quantifying *Legionella* populations and possibly detecting the fraction of bacteria that are infectious. We selected this technique because of our previous success in using it to detect small numbers of the amoebic pathogen *N. fowleri* in thermally altered waters.

In cytofluorography, a population of different kinds of cells is stained with multiple dyes, each of which has an affinity for a different chemical component of a cell. Each dye fluoresces at a

characteristic wavelength when struck by a laser light beam. In addition, light is scattered at different wavelengths and intensities from the cells as they pass single file in a suspension through the highly focused beam of an argon laser. The scattered light and fluorescent signals are detected by photodetectors and analyzed by a computer, which sorts and displays information on a screen about particular cell types. This system permits the counting and identification of 100,000 individual cells every few minutes.

We have shown in preliminary studies of *Legionella* populations by cytofluorography that *Legionella* concentrations in cooling tower water can be rapidly determined. We are also particularly intrigued by preliminary results obtained after *Legionella* cells were simultaneously stained for DNA content and for content of specific antigens (proteins) on the cell surface. By such two-dimensional analysis, environmental *Legionella* that were highly infectious for guinea pigs and those isolated from patients at Methodist Medical Center of Oak Ridge were distinguishable from the same species of minimally infectious *Legionella* isolated from environmental sources.

If further cytofluorographic studies show that we can repeatedly differentiate highly infectious from minimally infectious *Legionella* populations, the rapid detection of highly infectious *Legionella* in hospital and industrial water samples on a large scale could become a reality. Once an infectious population is identified, a hospital or industry can target sources of *Legionella* that should be monitored and controlled to avoid a serious threat to human health.

Legionnaires' disease has not disappeared since the Philadelphia convention of 1976. Legionellosis will persist as long as there are heated waters and cooling systems associated with energy production and other industrial processes. We must take the necessary precautions—monitoring and treatment of water, diagnosis and treatment of workers with pulmonary disease—to ensure worker health. ornl

Reinhold Mann (left) and Russ Hand operate the flow cytometry system to quantify and characterize* Legionella *populations.

Lynn Till of the University of Tennessee, Ralph McGill, and David Greene discuss how the popularity of compact cars (such as these parked at ORNL) has contributed to the overall improvement in fuel efficiency of the fleet of automobiles on the road today.

Transportation Energy Conservation:

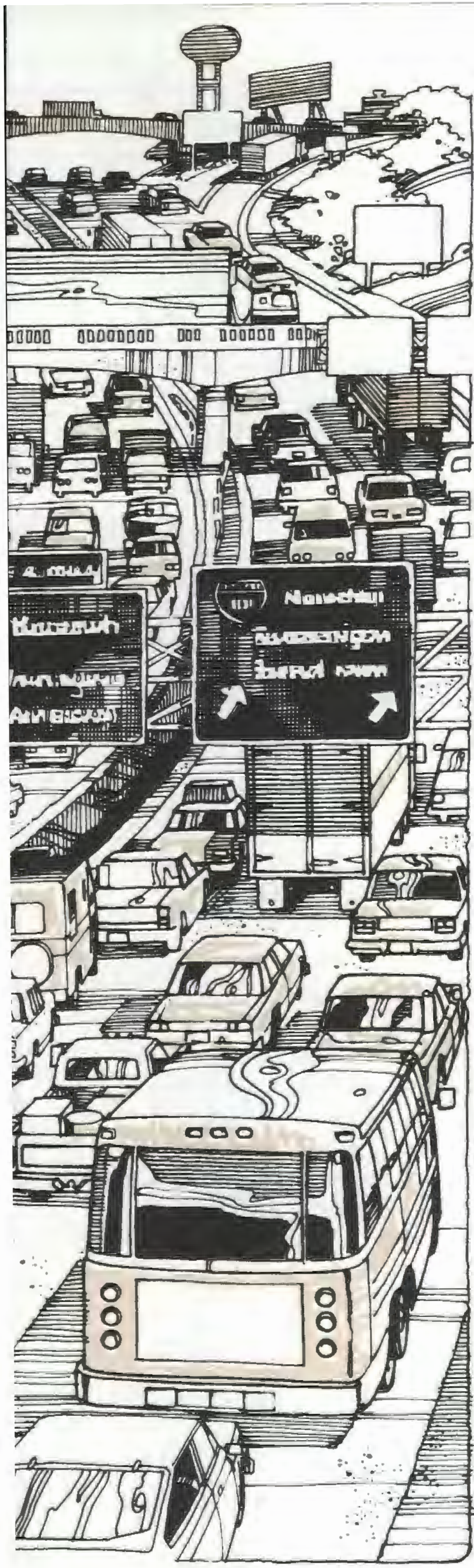
What ORNL Models and Analyses Show

By CAROLYN KRAUSE

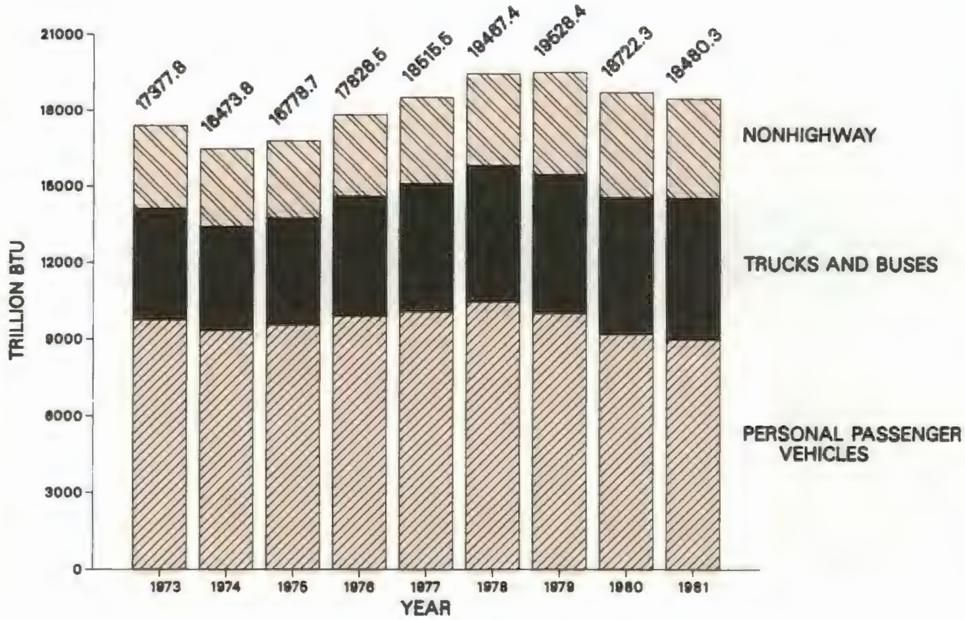
Like a car traveling over a steep hill, the price of motor fuel—and the demand for it—has risen and dropped dramatically in ten years. These changes have been followed closely at Oak Ridge National Laboratory since 1977. That was the year when Andy Loebl and Debbie Shonka of the Energy Division started compiling data for the annual *Transportation Energy Data Book.* Since then the effort to track, understand, and predict changes in transportation energy use has been spearheaded by David L. Greene, leader of the Transportation Group in the Energy and Economic Analysis Section led by Bob Shelton.

When Greene started a transportation energy research effort for Loebl in 1977, the nation was still responding to the effects of the Arab oil embargo of 1973–74. To reduce the need to import oil, President Jimmy Carter had inaugurated energy conservation programs and research programs to develop other sources of fuel (e.g., synthetic oils from coal liquefaction, oil shales, and biomass). Then in 1979–80, another gasoline shortage and jump in prices occurred as a result of turmoil in Iran.

In the early years of President Ronald Reagan's first term,



however, an oil glut developed because the oil-producing nations had overreacted to what they perceived to be rising demand by the oil-consuming nations. In fact,



Energy consumption by mode of transportation in the United States in 1973-81.

oil-consuming countries such as the United States were cutting back on demand for imported oil. Americans curtailed travel and began buying more efficient cars (in many cases, foreign ones) in response to the rising price of gasoline. American car manufacturers also responded to the market demand and government regulations. They nearly doubled the fuel efficiency of newer cars and trucks of all sizes, largely by reducing vehicle weight and engine size and by improving the ability of vehicles to slip through the wind (aerodynamics). These trends in transportation energy and the ways they are influenced by fuel prices have been carefully measured by the Transportation Group.

The demand for and price of motor fuel have fluctuated considerably in recent years. David L. Greene and ORNL's Transportation Group have followed these fluctuations closely and analyzed consumer responses to fuel price changes and more efficient cars on the market. The group also has studied how to drive to save fuel.

Gasoline Demand Model

Greene's first project was to compile, analyze, and validate data on transportation energy. For example, he kept tabs on the consumption of gasoline, diesel fuel, and jet fuel from year to year in the United States by the various modes of transportation: automobile, truck, train, ship, and aircraft. This information was published in the *Transportation Energy Data Book*, seven editions of which have been published by ORNL. Today the data books are used extensively by about 1200 people, including the transportation industry and researchers and employees in federal and state, and local governments.

In 1979 Greene and Axel Rose, an electrical engineer, developed the U.S. Department of Energy's only state-level gasoline demand model, a set of computer programs and data bases developed for the agency's Energy Information Administration. The model captured wide variations in gasoline demand per capita from state to state. For example, in one year state consumption rates ranged from 2226 L (589 gal) per vehicle in Pennsylvania to 3400 L (900 gal) per vehicle in Arkansas, and from 3266 L (864 gal) per household in New York to 8399 L (2222 gal) per household in Wyoming. To explain these differences, Greene and Patrick O'Connor (formerly of ORNL) conducted an analysis of historical usage patterns.

"The key factor in explaining state-to-state variations in gasoline use was the travel environment of the state," says Greene. "In states like Wyoming where the population is sparse, people drive long distances to their jobs, stores, churches, and cultural and entertainment facilities. In urbanized areas common to states like New York, people frequently reach these destinations by walking or taking the subway. Our study disputed the contention that differences in state consumption can be attributed to extravagant or frivolous gasoline use by residents of high-consumption states. Our analysis may have influenced the decision of the Carter Administration to base gasoline rationing allotments on historical usage patterns."

The Energy Information Administration used the ORNL model only briefly for forecasting regional motor fuel demand. "But people in state and local governments have used it more extensively," says Greene. "For example, for several years the state energy department of Texas used it to forecast gasoline demand. More recently, people in industry and government have used the model to predict the effect of new car fuel economy on demand for gasoline."

Transportation Energy Expert on a Fast Track

David L. Greene is an international transportation energy authority who has been moving in the fast lane for eight years. In 1977 he came to Oak Ridge National Laboratory directly from Johns Hopkins University, where he had just received his Ph.D. degree in geography and environmental engineering. He started out collecting and evaluating transportation energy data as a member of Andy Loebl's Data Analysis Group in the Energy Division. After two years, he was made leader of the new Transportation Group, which eventually expanded to seven researchers. Within four years he was asked to supply information needed in a hurry by the White House. In the next several years, local and national news media occasionally alluded to his work, if not his name. As chairman of the Committee on Energy Conservation and Transportation Demand of the National Research Council's Transportation Research Board, he is now influencing the direction of transportation energy research.

A native of Manhattan Island who grew up in New York state, the hard-driving Greene has managed to steer through masses of transportation data and stay on top of the information, making it more accurate and interpreting it for the rest of us. He has helped policymakers and motor industry executives understand trends in transportation energy use in a tumultuous period of fuel shortages, an oil glut, and rapidly rising and declining motor fuel prices. In analyzing the surprising changes that have affected transportation energy, Greene has encountered a few surprises of his own. For example:

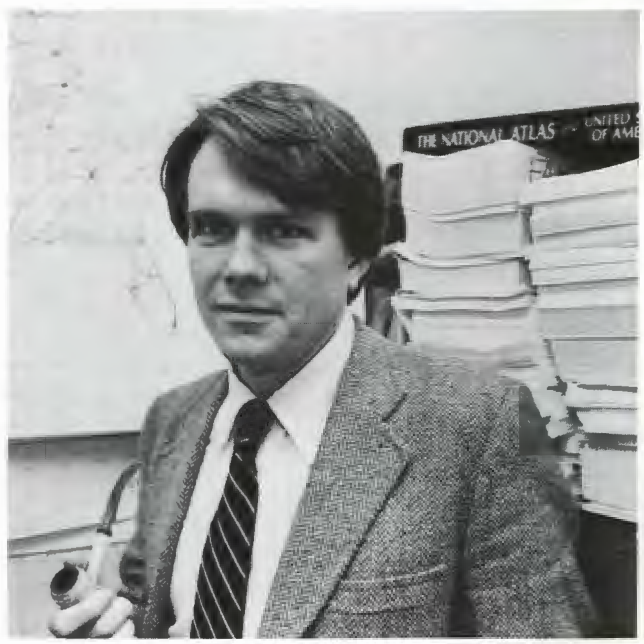
- In October 1982 he was surprised to receive in his mail a copy of an article in the *National Enquirer*, which has a larger circulation than any other American newspaper. The article quoted Greene's sponsor, Philip Patterson, chief economist of the Department of Energy's Office of Transportation Systems. Citing work performed by Greene and his colleagues at ORNL, Patterson pointed out in the article that the overall fuel economy of all new cars, including big cars, has risen by more than 75% since 1973.
- One morning in 1980 as he woke up to his clock radio, Greene heard a guest on a local talk show discuss a new study reporting that domestic cars were just as long-lived as imported cars and maybe more. Greene sprang out of bed, saying, "That's our study, but it hasn't been published yet!" An employee of a U.S car manufacturer who reviewed the draft of the study, he surmised, had leaked the information because it was favorable to U.S. manufacturers.
- At 3 p.m. on March 13, 1980, Greene received a call from DOE with a surprising request: produce 500 pages

Greene said the model was once used to determine the relative demand for unleaded and leaded gasoline during the period when the motor vehicle stock was switching from predominantly leaded to predominantly unleaded fuel. "We estimated what the demand should be for leaded and unleaded gasoline and compared that estimate to what the demand really was. We determined that the rate of cheating—that is, the proportion of 'unleaded' vehicles that were 'misfueled' with cheaper leaded gasoline—was 10 to 15%. Our estimate was consistent with an Environmental Protection Agency [EPA] survey of motor vehicle lead misfueling."

The gasoline demand model is one of several models that the Transportation Group has generated, using principles of economic theory and rigorous statistical methods. Developing a model involves gathering data, for example on vehicle and fuel sales, prices, and other factors and performing econometric analyses to infer the values of basic parameters of the model equations. Statistical inference based on historical data ensures a certain agreement between model and reality. Once the models are implemented as computer programs, they can be further tested by comparing their predictions—for example, of sales of leaded gasoline, unleaded gasoline, and diesel fuel—with actual data. Models of this type are used not only for forecasting but also for exploring the effects of policies such as fuel economy standards on future levels of energy use.

From 1979 to 1982, consumption of motor fuel declined in the United States, a dramatic turn from previous years when fuel consumption had steadily climbed. In one of his papers, Greene noted that before 1979 "there had been only three instances of declining gasoline demand: the Great Depression (1932-33), World War II (1942-43), and the OPEC oil embargo of 1973-74. In each case consumption quickly rebounded and

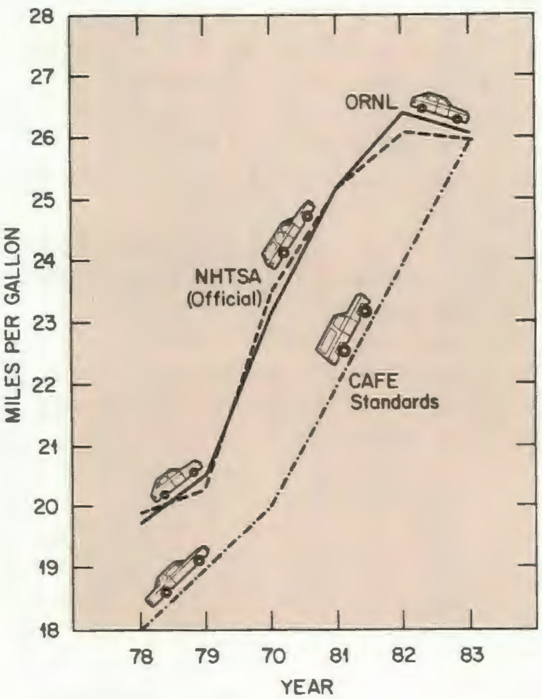
of information needed the next day by the White House. On March 14, President Jimmy Carter was to announce that the government would deal with its boycott of imported oil from Iran partly by setting lower gasoline conservation targets for each state. Immediately Greene and his colleagues began computing revised limits for gasoline demand for all the states. By 10 a.m. the next day, the exhilarated but exhausted Greene had flown to Washington and hand delivered to DOE the needed information. The key to ORNL's responsiveness was its state gasoline conservation targets computer system.



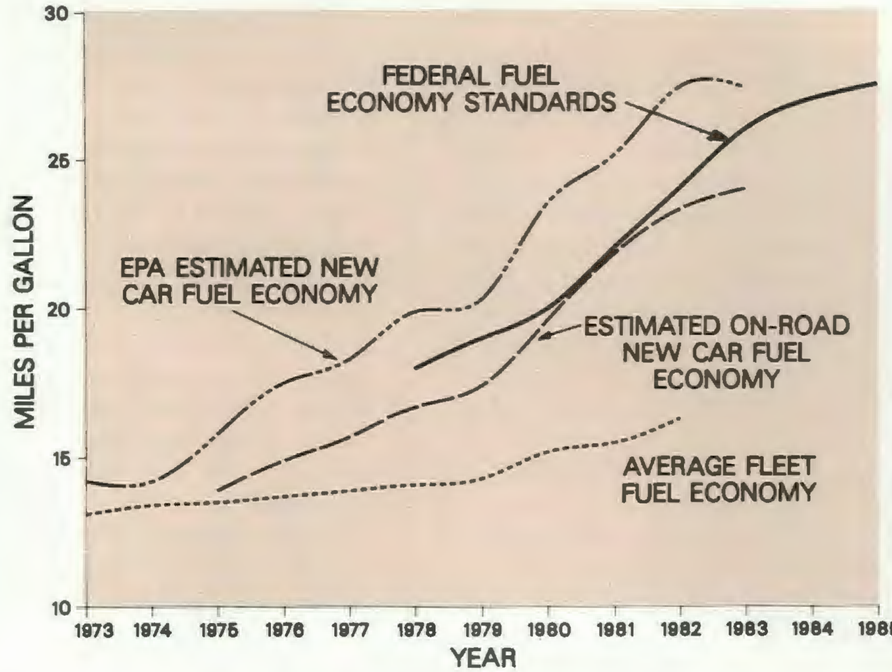
Another surprise came with the change in presidential administrations. "We used to think that the President's people were keenly interested in what we were doing. Then when the Administration changed, we suddenly realized that we were regarded as a department that probably should be abolished.

"Later when energy conservation was deemphasized at DOE, we were forced to diversify to maintain the group. Although more than half of our funds come from DOE, we now receive substantial support from the Federal Highway Administration in the U.S. Department of Transportation and from the U.S. Army. We also had support from the U.S. Agency for International Development. Because we had developed an expertise that was useful to other organizations besides DOE, we found several stable sources of support."

Greene and the Transportation Group are still cruising in the fast lane—and are more confidently negotiating the sharp turns that characterize funding from government agencies.



The average fuel efficiency (miles per gallon) of recent fleets of cars in the United States has fallen short of the Corporate Average Fuel Economy (CAFE) standards. The 1983 fleet is less efficient than the 1981 fleet. The 1985 CAFE standard of 27.5 mpg is not expected to be met by this year's fleet of cars.



Automobile fuel economy estimates, 1973–1983.

continued growth." He added, however, that the current gradual decline is likely to continue even if the economy rebounds and gasoline prices do not rise above their present level because of the continuing improvement of new car and light truck fuel economy. Since then, however, fuel prices have fallen dramatically in constant dollars. As a result, gasoline use has increased slightly, but at a rate 2–3% less than it would have risen had no improvements in vehicle fuel economy occurred.

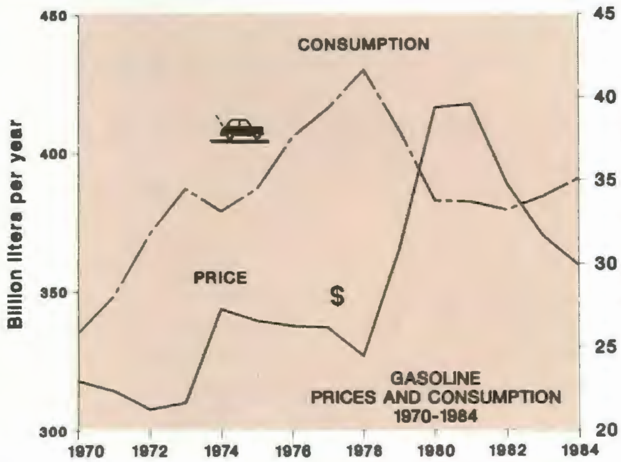
By careful analysis of the data using the ORNL highway gasoline demand model, Greene and his colleagues concluded that (1) most reduction in gasoline use between 1979 and 1980 resulted from less travel, a response to rising gasoline prices, and (2) reductions in demand for gasoline from 1981 on were primarily due to improved vehicle efficiency. The motivating factors behind the widespread availability of more efficient vehicles in the United States were consumer demand in response to rising fuel prices and the Corporate Average Fuel Economy (CAFE) Standards, established in 1978 as called for by the Energy Policy and Conservation Act of 1975.

According to CAFE standards, an automaker's fleet of new motor vehicles in 1985 should average at least 8.6 L/100 km [27.5 miles per gallon (mpg)]. Greene's group, which keeps close tabs on fuel economies of all model cars by means of Pat Hu's MPG Data System, has long tracked the fuel efficiency of new cars. Says Greene: "We found that the fuel efficiency of new cars was at its lowest point in 1974—16.6 L/100 km (14.2 mpg)—after years of gradual decline. Then when the worldwide increase in petroleum prices occurred and gasoline prices jumped from $0.39 to $0.53 in a single year, consumer demand for more efficient vehicles led to dramatic increases in fuel economy. By 1982 new cars—both large and small—were rated at an average efficiency of 8.9 L/100 km (26.36 mpg), up 90% from the 1974 average. However, the overall efficiencies of new cars since then have leveled off."

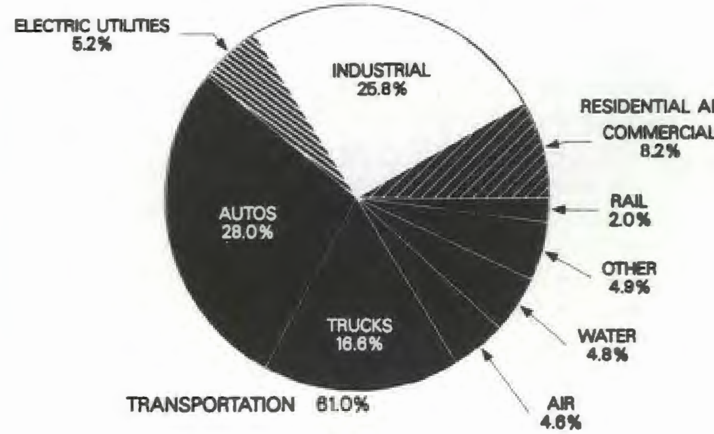
Will the fuel economy of the 1985 motor vehicle fleet reach the 8.6-L/100 km (27.5-mpg) limit called for by CAFE standards? "Probably not," says Greene. "Not all automakers will achieve the CAFE standard by 1985 because they are not making enough design changes and engineering improvements and because consumer preference is shifting back toward less efficient vehicle configurations—that is, larger vehicles, larger engines, more automatic transmissions, fewer diesels, etc. Because of the change in the attitudes of new car buyers, manufacturers have postponed production changes that would have increased the efficiency of their vehicle offerings."

In January 1985 the Energy Conservation and Transportation

The rising price of gasoline in the United States during the past 15 years eventually influenced consumers to reduce gasoline use by curtailing travel, ridesharing, and driving more efficient vehicles.



Percentage of petroleum consumption by end-use sector in 1983.



Demand Committee (chaired by Greene) of the National Research Council's Transportation Research Board sponsored two sessions on CAFE standards at its annual meeting. "We decided to emphasize CAFE standards because they are a timely topic. This year Congress may have to decide whether to continue, reduce, or increase standards that the automobile manufacturers so far are not able or willing to meet."

Another change since 1978 has been the market shift to smaller cars, which has improved new car fuel economy by 470 L/100 km (0.5 mpg). In 1973 46% of the vehicles sold were large, according to the EPA vehicle classification system. In 1984, by comparison, large cars made up only 13% of total sales. Since 1978 fuel efficiency for all cars has improved by 35.4 L/100 km (6.65 mpg).

The Transportation Group has reported that manufacturers have made cars more efficient by reducing weight and making design changes. Mass has been reduced "by decreasing the exterior vehicle dimensions of all size classes and substituting lighter materials to reduce vehicle weight," according to one paper. Greene notes that the interior space of most cars has not been significantly reduced (as is commonly believed). Cars have been made lighter, he added, by replacing heavy steel with plastics and aluminum. The ORNL report noted that vehicle manufacturers have also improved overall fuel efficiency by making various design changes and engineering improvements, such as greater use of lock-up automatic transmissions, increased number of gears in manual and automatic transmissions, and improved aerodynamics. The automobile industry has also helped fuel economy by manufacturing and marketing a higher number of motor vehicles with manual transmissions and diesel engines.

Consumer Response to Fuel Prices

Greene and his colleagues have also studied the effect of rising gasoline prices on consumer decisions. They have examined these questions: How much do factors such as driving less, buying more efficient models, and manufacturers' design decisions contribute to conserving energy? How much more money are people willing to pay for energy-efficient technology in cars or trucks to save on fuel costs in the long run? Do people in households with two or more vehicles—big cars, small cars, light trucks—tend to drive the highly efficient vehicles more than the less efficient ones when gasoline prices are rising? In answering these questions, the Transportation Group found:

- Despite forecasts five years ago that 20–30% of domestically produced cars would have diesel engines because of rising fuel prices and because of the diesel engine's efficiency advantage over the gasoline engine, the market share for diesel vehicles rose from 1.2% in 1979 to a peak of only 5.6% in 1981 and then declined to a mere 1.9% for the first half of model year 1984. Reasons cited for the reversal include some diesel engines' mechanical problems and high cost as well as the declining prices for unleaded gasoline, which dropped from a peak of \$0.42/L (\$1.57/gal) in March 1981 to \$0.30/L (\$1.15/gal) two years later. (For additional information on ORNL research related to the design and

(Continued on page 44.)

How To Save Gasoline: Toward an Automotive Dream Machine

David L. Greene does not drive a Dream Machine, a car with the highest possible fuel efficiency [currently about 5 L/100 km (47 mpg)]. Actually, he laughs, while puffing on his pipe, he can justify the purchase of his Chevrolet Chevette, which achieves only slightly above average fuel efficiency [7 L/100 km (34 mpg)]. "I bought it because the purchase deal included free airline tickets. I traded the highest possible fuel efficiency for a nice vacation in the Virgin Islands."

From his research, however, Greene can give advice on how to buy a highly efficient car and how to maintain and drive it to save motor fuel.

Before making a purchasing decision, car buyers should consult the gasoline mileage guide published by the Department of Energy, which contains the fuel economy ratings of motor vehicles calculated by the Environmental Protection Agency. "The government has encouraged the market shift to more efficient cars by disseminating useful information," he says. "People are now making more intelligent decisions in purchasing cars and light trucks." ORNL's Transportation Group also collects data on the fuel economy of vehicles, given for each nameplate (e.g., Ford Escort). "We are the only people in the United States," he says, "who track the fuel economy of cars on a monthly basis. We publish this information in biannual reports."

Consumers should be aware that the chief characteristic influencing fuel efficiency is weight. "Cars with front-wheel drive are lighter," Greene notes, "because heavy components such as the drive shaft and rear-axle differential are eliminated." Greene says that radial tires offer less rolling resistance (thus better fuel efficiency) than bias ply tires. Diesel engines and manual transmissions are generally more fuel efficient than gasoline engines and automatic transmissions (which waste energy through slippages). "Lock-up automatic transmissions are more efficient than those without lock-up torque conversions," he adds. "Also, the more gears you have, in general, the more efficient the vehicle. Electronically controlled fuel injection gives more precise control of air-fuel ratios and reduces fuel waste."

How can consumers save money on fuel through vehicle maintenance? Advises Greene, "Check and adjust idle fuel-flow and idling speed, align front wheels, adjust brakes, replace the air filter periodically, raise tire pressure to the maximum (listed on the tire sidewall) to reduce rolling resistance, change the oil to a fuel saver grade to reduce internal engine friction, and lubricate properly."

Research conducted at ORNL suggests that certain driving techniques can increase vehicle fuel efficiency. Several years ago Axel Rose, John Hooker, and Glenn Roberts, all formerly in ORNL's Transportation Group, performed studies that offer guidance on how to drive to save fuel. They developed an automotive simulator (a set of equations that relates fuel consumption to velocity and acceleration for each gear) and dynamic programming algorithms to determine optimal control of driving. Their data included the experimental results obtained from operating a stationary device called a chassis dynamometer and from driving an instrumented 1979

This car with the fifth wheel is the 1979 Ford Fairmount used by ORNL researchers to determine how different driving behaviors influence fuel efficiency. The fifth wheel was used to accurately monitor the station wagon's velocity.

Ford Fairmount (which had a fifth wheel to monitor velocity).

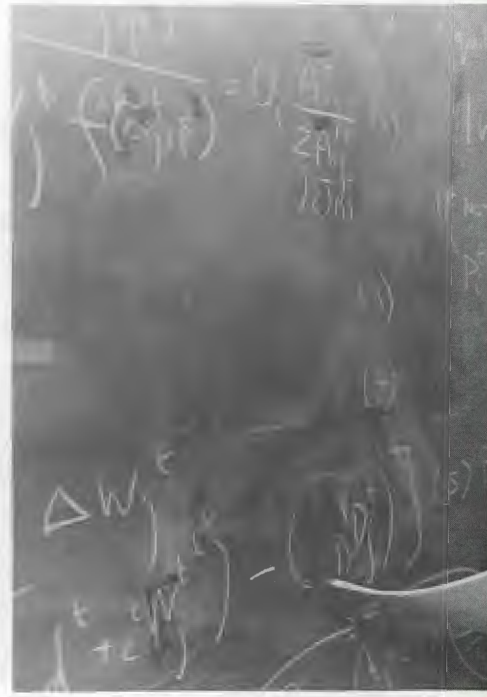
Based on their results, Greene says that fuel can be saved by driving properly. For example, when driving over hills with a 6% grade, "maintaining a constant speed up and down the hills is not fuel-efficient," he says. "The fuel that you consume if you go at a constant speed can be reduced 6–12% if you increase your speed slightly to at least 80 km/h (50 mph) about 50 m (55 yards) before the hill, let gravity slow your speed to 70 km/h (45 mph) going uphill, then increase it to 80–85 km/h (50–53 mph) going downhill. In general, it appears to be more efficient to hold the throttle position (accelerator pedal) constant and allow speed to vary, than to hold speed constant."

The speed at which you drive also affects fuel economy. Says Greene, "If you drive in a range of 48–80 km (30–50 mph), the wind resistance will be less than if you drive faster. The most fuel-efficient speed depends on the vehicle model." Greene's studies of the effect of speed on fuel consumption show that fuel economy in cars on the average declined 8% as average speeds rose from (64 to 80 km/h (40 to 50 mph), 12% as speeds climbed from 80 to 97 km/h (50 to 60 mph), and 13% as speeds increased from 97 to 113 km/h(60 to 70 mph). "The smaller your car's engine or the faster you drive," says Greene, "the more a 'heavy' foot hurts your fuel economy." These results suggest that maximum fuel efficiency is not achieved by using cruise control or even by driving at a constant speed of 89 km/h (55 mph) on interstate highways with hills.

To save gasoline, buying the most efficient car available is only part of the answer. How you maintain and operate your Dream Machine contributes to its overall fuel economy.

Glen Roberts checks the data logger in the back of the 1979 Ford Fairmount used to determine the effect of acceleration and velocity changes on fuel consumption.

S. M. Chin and Greene discuss a problem in network analysis at a computer terminal used by the Transportation Group.



Frank Southworth checks trip chain equations.

operation of diesel engines, see page 51.)

- Consumers are willing to pay a higher price for cars with high fuel efficiency if they can recover the extra cost in fuel savings in two to four years. This finding, based on an econometric analysis of monthly sales of gasoline and diesel engines within the same make and model, revealed that consumers heavily discount future cost savings. Inferences based on a sample of 18 nameplates for the period 1979–83 revealed discount rates of about 30% per year. That is, new car buyers appear to value $1.00 worth of fuel saved next year at $0.70 today.
- Drivers in the two-thirds of all U.S. households that own two or more vehicles tend to increase their use of more efficient vehicles relative to less efficient vehicles in response to fuel price increases. According to economic theory, they do this because the cost per kilometer of using a car has two major components: (1) the fuel cost per kilometer and (2) the value of time spent driving. Because the vehicle velocities remain unchanged but the cost of fuel increases, the relative costs per kilometer for efficient versus inefficient vehicles will change. This change in relative usage costs is what causes households to adjust their patterns of use. To measure this relationship, Greene and Hu developed vehicle use models for one-, two-, and three-car households. They found that in response to a 25% increase in gasoline price, the American public's use of vehicles declines 5% and that shifts to smaller vehicles increase the overall U.S. fuel efficiency by only 0.2%. They reported these findings in their paper "Vehicle Usage in Multi-Vehicle Households and the Price of Gasoline"; and for that paper, received the 1984 Pyke Johnson Award of the National Research Council's Transportation Research Board, which is given each year for the best paper in planning and administration of transportation facilities.

ORNL Aids Traffic Engineers

One aspect of the Transportation Group's research has been vehicle testing to determine how to drive to save motor fuel (see sidebar on page 42). The vehicle testing program, initiated by DOE and completed for the Federal Highway Administration (FHWA), involved the testing of 15 different vehicles. The purpose of the tests was to determine the effect on fuel consumption of different patterns of velocity and acceleration. Such information could be used to determine the optimum timing for changing traffic signals to improve the overall driving efficiency of a typical fleet of motor vehicles in a

Pat Hu (left) and Mary Holcomb confer over a bar chart printed in the recent edition of the Transportation Energy Data Book, *which Holcomb edits. The book has been published annually since 1977. Hu now compiles the* Motor Vehicle MPG and Market Shares Report *(formerly compiled by Holcomb), which keeps track of the fuel efficiency and sales of new cars. The stack of books in the foreground are the products of these women's efforts.*

city network. A member of the group, Ralph McGill, developed simulators for 15 different vehicles for FHWA to use in traffic simulation models to estimate the impact of different traffic management strategies on fuel consumption.

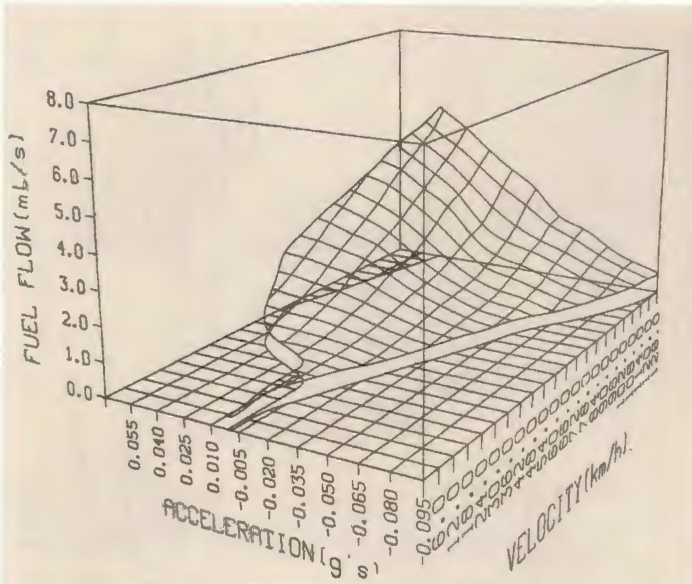
As an outgrowth of this work, ORNL researchers developed computer programs to aid traffic engineers with personal computers in accessing traffic signal optimization models and data available only on large mainframe computers. Glenn Roberts, formerly with the group, developed the Integrated Traffic Data System (ITDS) to help city traffic managers obtain normally inaccessible models. Developed with FHWA support to permit access to models and data on FHWA computers, ITDS is now being tested by the city of Memphis, University of Florida, University of Alabama, and Vanderbilt University. Greene says that eventually a software package for incorporating traffic signal optimization models, data, and graphics will be available for microcomputers.

Network Analysis and Travel Demand Modeling

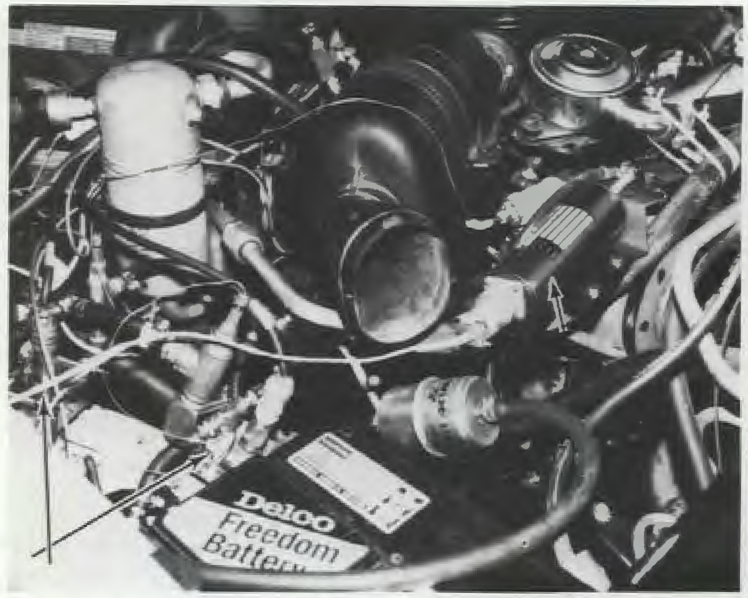
In the early 1980s as energy conservation was deemphasized, the Transportation Group diversified and took on other projects. A new initiative is network analysis, understanding and predicting optimal routing of passenger and freight transportation vehicles and the effects on travel behavior of trips with multiple destinations.

ORNL's Bruce Peterson has studied transportation flows in networks. Working with ORNL's Chemical Technology Division, he has developed a sophisticated railroad routing algorithm that predicts the routes that railroad firms will use in transporting nuclear wastes (taking into account other deliveries that railroad firms make along their routes to increase their profits). In related work, the Transportation Group has worked with Sam Carnes of the Energy Division in evaluating the risks of shipping obsolete chemical weapons materials to U.S. Army disposal facilities.

Joining Peterson in network analysis is Frank Southworth, who is internationally known for modeling and analyzing travel behavior. Traditional transportation planning theory and models have dealt with unit trips from a single origin to a single destination. Recognizing that many trips involve multiple stops and that all trips have the potential to do so, Southworth has pioneered development of theory and models for multidestination trips. Says Greene, "Southworth is trying to forecast travel behavior based on



This computer-generated plot shows fuel flow, acceleration, and velocity for a 1983 Ford Escort in third gear (automatic transmission). According to the plot, at a cruise speed of 48 km/h (30 mph), the fuel economy peaks at 4.95 L/100 km (47 mpg).



Under the hood of this Chevrolet Silverado pickup truck (with a 6.2-L V8 diesel engine) are special instruments to measure fuel consumption. They include the fuel meters (arrows at left) and a throttle position sensor (arrow at right).

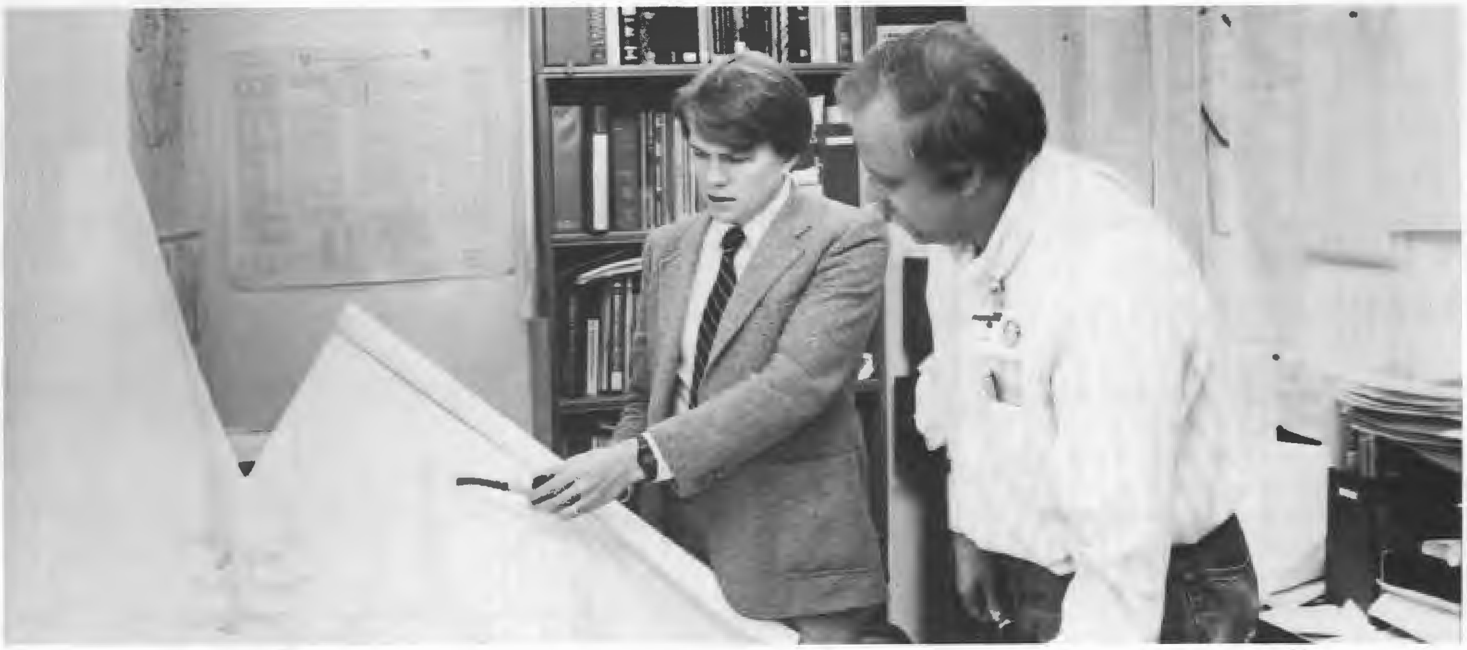
the premise that most people take trips not just from A to B and back again but from A to B to C, etc., before returning to A. Many of us go from home to work to school or to the store and gas station before we are back home again. It is these 'trip chains' that Southworth is studying. This work has applications in transportation planning and land use planning, particularly in urban areas."

Southworth also heads the DOE ridesharing program, a research and technology transfer program devoted to developing better ways to market employee-based carpool and vanpool programs. The DOE program currently is collecting data from around the nation on the benefits to employers of starting their own ridesharing program. This information will then be used to develop a cost-benefit model of company ridesharing. On the mathematical modeling side, the program is working on the simulation of the energy and financial benefits of high occupancy vehicle lane, park and ride lot, and parking management policy use. Both Knoxville and Memphis ridesharing agencies, two of the nation's most successful and innovative programs, are also involved in this research.

A third expert in traffic and network analysis is S. M. Chin, a civil engineer who joined the group in November 1984. Chin has expertise in traffic engineering and topology.

The member of the Transportation Group who, says Greene, "made the vehicle testing program work," is McGill. Ron Graves of ORNL's Engineering Technology Division and McGill run the Alternative Fuels Utilization Program (AFUP), for which ORNL is the lead laboratory. "AFUP," says Greene, "is the only program that is examining how to make optimum use of the engine fuel system for all promising alternative fuels (such as alcohols, gaseous fuels, and synthetic fuels) and assessing whether changing engine design and using a particular alternative fuel can result in energy and economic efficiency."

The other members of the group are Hu and Mary Holcomb. Hu compiles the *Motor Vehicle MPG and Market Shares Report.* She worked with Greene in analyzing data from the north African country of Tunisia, and they coauthored the previously mentioned prize-winning paper on how gasoline price changes affect the way multivehicle households use their vehicles. Holcomb is editor of the *Transportation Energy Data Book.* "The book is crammed with important facts," says Greene. "For example, the most recent edition shows that the share of U.S. petroleum used for transportation rose from 54% in 1978 to 61% in 1984. The rest of the petroleum is used for residential heating, electricity generation, industrial uses, and chemical feedstocks. The statistics show that the transportation sector demand for imported and domestic petroleum continues to rise despite gains in transportation energy conservation."



Greene points to a section of the national highway network data base developed by Bruce Peterson (shown above).

Energy Use in Transportation Abroad

In response to requests by the U.S. Agency for International Development (AID), Greene worked in Tunisia and Costa Rica (along with Southworth) studying their transportation energy use and recommending ways to conserve fuel. "One of the interesting things we learned," says Greene, "was that Tunisia uses almost five times as much diesel fuel in transportation as gasoline, whereas in the United States the ratio is reversed."

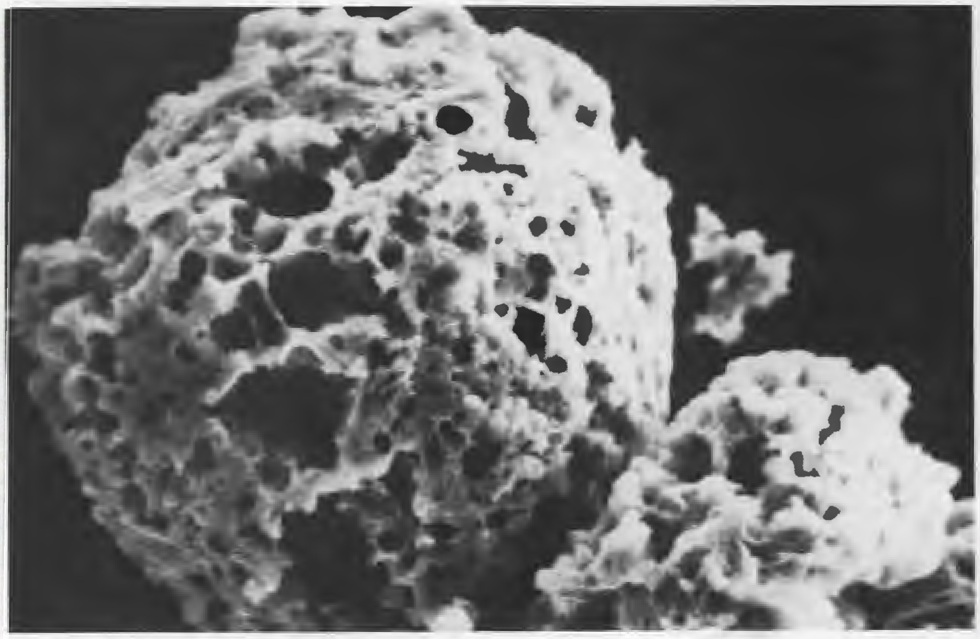
Greene and Hu analyzed results of a National Survey of Vehicle Energy Use, a study of automobile and light truck energy use conducted by Tunisia's Ministry of National Economy with assistance from AID. The survey examined vehicle use and fuel consumption. Axel Rose, formerly in the Transportation Group, designed the survey with assistance from the U.S. Census Bureau. Hu and Greene's chief contribution was to help the Tunisians edit, analyze, and understand the data. They also made these recommendations to the government:

- Improve vehicle maintenance and increase use of radial tires, especially on light trucks.
- Set up public information programs to promote greater use of fuel-saver oils and maintenance of tire pressures.
- Disseminate vehicle efficiency information to the public to encourage purchases of more efficient vehicles.
- Consider raising the price of diesel fuel to encourage energy conservation.

Energy policy recommendations were also made for Costa Rica. ORNL advised the government to study the need for improving the quality of motor fuels, especially diesel fuel, which may be responsible for problems with air pollution, as well as fuel economy, because of clogging of injectors and pipes, and increased engine wear. Energy conservation training programs for drivers were also recommended so that vehicle operators can learn what to do—and not to do—to make their vehicles more efficient. Ways to substitute locally produced energy for imported petroleum were also suggested. For example, trolley buses powered by hydroelectricity, in abundance in Costa Rica, could replace much of San Jose's diesel bus fleet, without the heavy capital cost of electric rail transport. Surplus sugar cane might be economically converted to ethanol for use as an octane-enhancing substitute for tetraethyl lead in Costa Rican gasoline.

ORNL now has a $1-million grant to provide technical assistance to AID in promoting energy development and efficient energy use in less developed countries. Greene and his ORNL colleagues can expect to be asked to provide technical advice on transportation energy to other Third World countries. Now that ORNL's Transportation Group is reputed for its expertise on international transportation energy problems, surely many interesting research projects will be down the road. ornl

A New Look at Carbonaceous Particulate Matter Emitted to the Atmosphere



Scanning electron micrograph of carbonaceous particles.

Atmospheric carbon particles, such as those emitted from coal-burning power plants, contribute to haze and lowered visibility. They also increase solar heating of the earth's atmosphere and hasten the chemical alteration of atmospheric pollutants. The organic matter sorbed onto these and other particle types also may cause adverse health and environmental effects. However, unlike other pollutants, carbonaceous particulate matter (carbon particles plus sorbed organic compounds) is poorly understood. Chemists are now seeking to determine the structure of particulate carbon particles and of the organic compounds associated with them.

Recently, analytical chemists at Oak Ridge National Laboratory have provided an insight into the complex nature of particulate organic matter by studying one important source—coal combustion stack ash. Wayne Griest, Bruce Tomkins, Sue MacDougall, and Del Manning of ORNL's Analytical Chemistry Division (ACD) performed the study with help from Larry Harris of ORNL's Metals and Ceramics Division and Chris Liebman of the University of Tennessee.

The investigators first separated the ash physically by particle size, density, and magnetic properties and later added radiolabeled organic tracers to the separated fractions to study interactions between particles and organic compounds. Griest and Tomkins found that elemental carbon, a specific type of particles, dominates the interaction between stack ash and organic matter. The carbon particles sorb and retain organic matter more strongly than the other particle types. Carbon particles appear to be the "vehicle" by which organic matter from coal combustion is emitted into the atmosphere.

"Proving that organic matter is preferentially attracted to carbon particles is difficult," says Griest, "not only because of the ultratrace levels of organic matter normally associated with stack ash but also because of the very small quantities of sample that can be isolated. Our hypothesis is based upon total organic carbon measurements and gas chromatographic analyses." Collaborative studies involving laser microprobe mass analysis measurements are being performed at the University of Pittsburgh to confirm the organic matter–carbon particle association in a different way.

The ORNL group also has observed that coal stack ash actually contains several morphologically distinct types of carbon particles. Scanning electron microscopy and optical microscopy with polarized light show that these range from uncombusted coal macerals and intermediate semicokes to fully coked coal particles. "The sorptivity and organic compound content of these different types of carbon particles," says Griest, "probably varies according to the degree of heating in the power plant furnace."

Another question under study by the ORNL group is, Why do conventional analytical procedures characterize only a small fraction (10 to 40%) of the organics in stack ash or ambient air particulates? Using size exclusion chromatography, the ORNL group has demonstrated that the apparent molecular weight distribution of particulate organic matter ranges up to about 800 atomic mass units (AMU) in rural air particulates and even higher in coal stack ash. About two-thirds of the readily extractable organic mass in air particulates has molecular weights exceeding 500 AMU. The investigators at ORNL also found that these extractable organic compounds were substituted with oxygen-containing functional groups that make the organic matter more chemically reactive. Says Griest: "Most conventional identification procedures work well when the compounds involved have molecular weights less than about 400 AMU and have reasonable thermal stability. This combination of a high molecular weight and a tendency for chemical reactivity explains why conventional identification procedures have been unsuccessful in accounting for most of the particulate organic matter."

Do Hot, Spinning Nuclei Change Shapes?

We are all familiar with the behavior of rotating objects such as toy gyroscopes or the earth itself. We know that if the rotation is rapid enough, changes can occur. For example, an object that is not strictly rigid will change shape under the influence of forces generated by the rotation. Thus because of centrifugal force, the earth has acquired a bulge at the equator and a flattening at the poles. Atomic nuclei can also rotate and may become deformed in response to rotational forces. Other properties, too, that pertain to the rotation of macroscopic bodies also apply to nuclei.

However, the behavior of rotating nuclei is much more complex than that of large, spinning bodies. Nuclei are extremely small and must be described by quantum, rather than classical, mechanics. Furthermore, nuclei consist of relatively few constituent particles (protons and neutrons). The interactions between individual particles, rather than the collective motion of the nucleus, often are extremely important.

The effect of very rapid rotation, or high angular momentum, on the structure of nuclei is one of the frontier fields of nuclear physics. To nuclear physicists, one of the most fascinating research areas is the influence of angular momentum on the shape of nuclei, particularly those formed by the "fusion" of projectile ions with target nuclei. Heavy-ion accelerators, such as Oak Ridge National Laboratory's Holifield Heavy Ion Research Facility (HHIRF), are capable of bringing together two massive nuclei to form compound systems with the largest amount of angular momentum they can sustain (typically ~60 to 100 $\hbar$ units) without flying apart because of the centrifugal force. High-resolution gamma-ray spectroscopy under such conditions has made it possible to follow shape changes in "cold" nuclei with increasing angular momentum. A cold nucleus has an excitation energy that is almost all tied up in generating its angular momentum; very little energy is left over for intrinsic excitation, which "heats" the nucleus.

Hot, rapidly rotating nuclei are also formed in heavy-ion collisions. However, they cannot be studied by the standard techniques of gamma spectroscopy because they seldom emit gamma rays until they have cooled by evaporation of particles (mostly neutrons, protons, and alpha particles, which are clusters of two protons and two neutrons apiece, as in helium nuclei). Because of the importance of and interest in studying shape changes in hot, rotating nuclei, a different technique is needed.

Recently, ORNL physicists Jim Beene, Mel Halbert, and Dave Hensley in collaboration with Avraham Dilmanian and Demetrios Sarantites of Washington University at St. Louis used the nation's only spin spectrometer—the 72-detector "crystal ball" at the HHIRF—to detect cascades of gamma rays associated with alpha-particle emission. This technique is expected to be a powerful probe of shape effects at high angular momentum. Unlike standard gamma spectroscopy, this technique allows the detection of almost all gamma radiation emitted by the nucleus and the accurate determination of the direction of emission of each gamma ray.

Detection of gamma rays from hot rotating nuclei gives a reliable estimate of the angular momentum of the alpha-emitting nucleus because most of the angular momentum is removed by gamma rays (which, in this case, almost always carry away two units of angular momentum each). The second piece of information that the gamma cascade provides is the orientation in space of the angular momentum vector for each alpha-emitting nucleus. The physicists can determine this orientation because decaying nuclei tend to emit gamma rays in a preferred direction—perpendicular to the nuclear angular momentum, or spin direction.

A typical emission event includes 15 to 20 gamma rays. Because the ORNL spin spectrometer detects almost all emitted gamma rays, a good estimate of the spin direction is possible. The physicists were able to determine the direction each individual nucleus was "pointing" at the time the alpha particle was emitted. Consequently they can determine the distribution in the direction of alpha particle emissions with respect to the orientation of the parent nucleus itself. In a conventional nuclear reaction experiment, the distribution of alpha particles is measured with respect to a direction fixed in the laboratory (usually the beam direction). The nuclear reaction produces nuclei with a wide range of orientations relative to any fixed direction in the laboratory, resulting in a smeared out alpha emission distribution and a loss of crucial information.

How can the study of the direction of alpha emission with respect to the nuclear spin direction provide information on the shape of hot, rapidly rotating nuclei? Consider the forces "felt" by an alpha particle about to be emitted from the surface of a nucleus. The alpha particle is positively charged, as is the rest of the nucleus. Because like charges repel like charges, it "feels" a strong electrostatic, or Coulomb, repulsion, while at the same time it feels the strong short-range attractive force that binds the nucleus together.

For a deformed (i.e., aspherical) nucleus, the repulsion depends on the location of the alpha particle. Figure 1 shows a one-dimensional representation of the associated potential energy for two locations of the alpha particle. The deep well at short distances results from the attractive nuclear force; the positive potential at larger distances is the Coulomb repulsion. To be emitted, an alpha particle must get across or through the potential "barrier." The alpha particle at position 1 on the nuclear surface feels the potential barrier indicated by the solid line, while the particle at position 2 sees a lower (dotted line) barrier because it is farther from the center of the nucleus. Emission of an alpha particle with an eventual kinetic energy E_A (see the figure) can occur *over the barrier* for position 2, while it can occur only *through* the barrier for position 1. That is, the particle effectively "tunnels" through the bottom of a "hill" instead of traveling over it. The latter would be strictly forbidden in classical mechanics but is possible, though unlikely, according to quantum mechanics. Emission at E_A is orders of magnitude more probable via the *over the barrier* path. For a spherical nucleus the potential barrier would be intermediate to the two shown. Emission at E_A, just at the top of the dashed barrier, would be below the top of the equivalent spherical nucleus barrier (it is therefore sometimes referred to as subbarrier emission). So, if the nucleus has, for example, a football shape, emission out the ends becomes more likely than emission out the sides. This example illustrates how the most probable direction of alpha emission can be sensitive to the shape of the nucleus.

In the ORNL experiment a neodymium-150 target was bombarded by a beam of 175-MeV neon-20 nuclei. The resulting nuclear reaction produces ytterbium-170 compound nuclei with angular momenta ranging from 0 to about 70 $\hbar$ units. For larger values of angular momentum, ytterbium-170 cannot hold together and fissions almost instantaneously. Data on the angular distribution of alpha particles (the relative number of particles flying off at different angles) with respect to the direction of the angular momentum vector in each emitting nucleus are shown in the second figure as a function of the alpha-particle energy. The vertical axis measures the anisotropy of the alpha emission. A correlation coefficient of zero reflects isotropic emission, while a negative coefficient reflects an excess of emission perpendicular to the spin direction. The data (dots) are shown for two values of the magnitude of the angular momentum (determined from counting the number of gamma rays) and for a range of alpha-particle emission energies (horizontal axis) extending below the equivalent spherical barrier. The heavy line is a calculation of what would be expected for a spherical nucleus. The data follow the

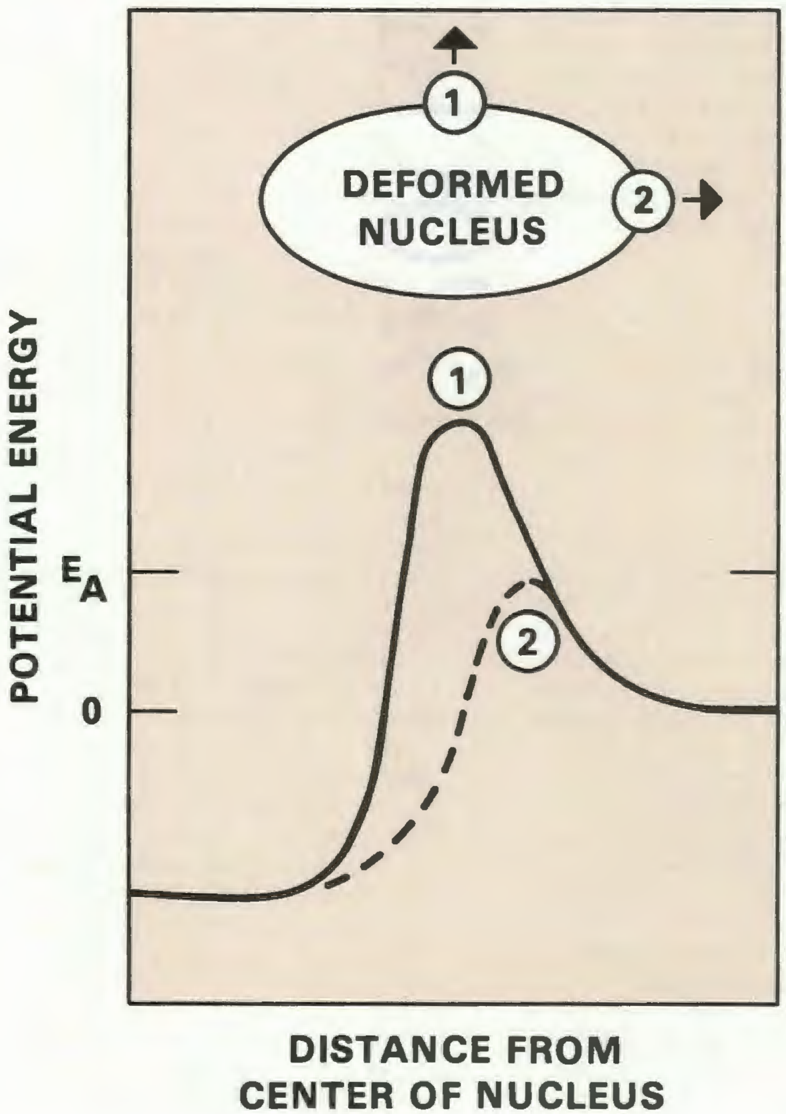
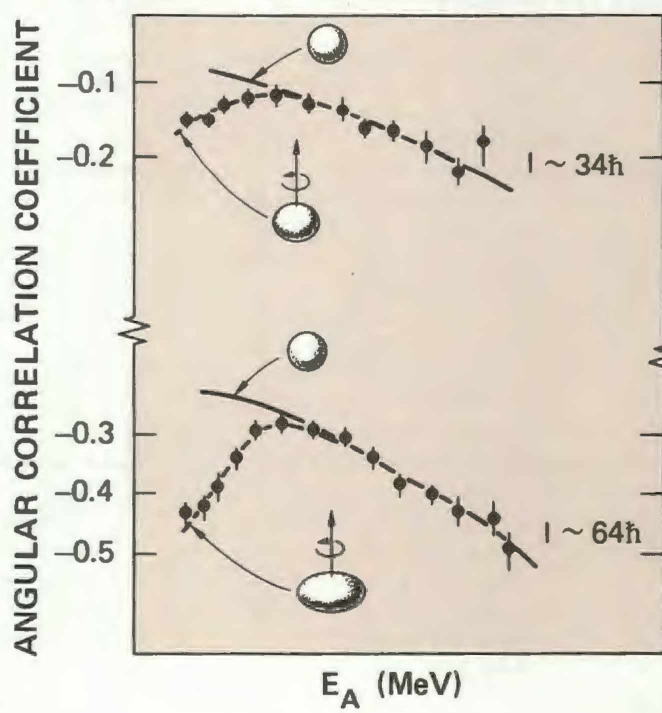


Fig. 1. Illustration of the sensitivity of alpha emission to nuclear shape. An alpha particle with energy E_A can be emitted over the Coulomb barrier (dashed curve) from the ends (2) of a deformed nucleus; emissions from the sides (1), however, are very much suppressed by the higher barrier (solid curve).

Fig. 2. Ytterbium-170 nuclei have different shapes at different angular momenta (spin). The spin spectrometer selects nuclei produced with given orientations and with given rotational velocities. The decay of nuclei reveals shape differences between nuclei with high ($I \sim 34\hbar$) and very high ($I \sim 64\hbar$) rotational velocities.



spherical nucleus prediction closely for alpha-particle energies exceeding the potential barrier height for a spherical nucleus. The physicists found that subbarrier alpha particles, however, are much more likely to be emitted perpendicular to the angular momentum than predicted, and as shown, this tendency increases dramatically as the angular momentum increases. [An early report of this work was published in *Physical Review Letters 49*, 1909 (1982).]

According to the simple picture outlined above, this enhancement of subbarrier emission at high angular momentum may reflect an increasingly large deformation (or deviation from spherical shape) with increasing angular momentum. In other words, the ytterbium-170 nuclei have different shapes at different angular momenta, and enhanced alpha emission appears to be a signature of superdeformation at very high spin.

This tendency toward deformation is qualitatively the way a hot, rapidly rotating nucleus is expected to behave. A much more elaborate analysis is required, however, say the physicists, before quantitative deductions can be made from the data. The framework needed for this analysis is being constructed by theoretical physicists at the University of Lundt in Sweden. This technique shows great promise as a quantitative tool for the study of hot, rapidly rotating nuclei.

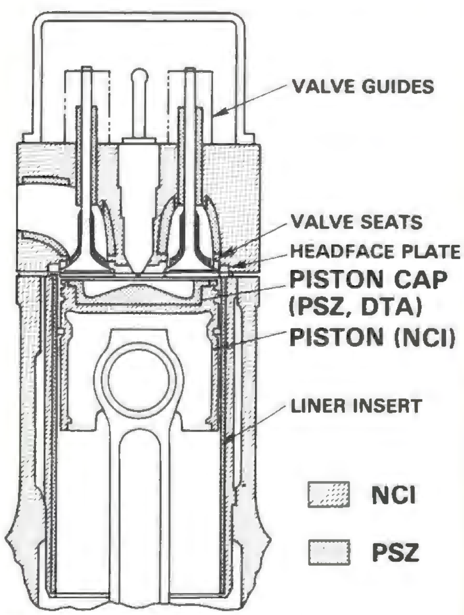
DIESEL-RELATED RESEARCH AT ORNL

Ceramic Cap Joined to Metal Piston

Current heat engines, such as the internal combustion gasoline engine of most automobiles, use only about one-third of the energy of the burning fuel to drive them. The rest escapes through friction losses, the exhaust, and the coolant (which is used to remove heat to prevent the metal parts from melting). To save fuel, engines should be designed to safely use a greater proportion of the fuel's energy; more efficient use of fuel can be achieved by operating these engines at high temperature.

In addressing this problem of increasing engine efficiency, engineers are designing "minimum-cooled" adiabatic (no-heat-loss) engines that will use exhaust heat to drive turbine blades for additional power. To contain the heat, these engines must have their combustion chamber components thermally insulated with ceramic parts or coatings as thermal insulators (which are more resistant to heat than metal components).

One technical problem facing designers of the adiabatic diesel engine has been joining monolithic ceramics to metallic combustion chamber components, such as the piston, to protect them from heat damage. Engineers have looked at the possibility of brazing—joining by fusing a suitable filler metal and allowing it to wet and bond on solidification—the favored materials: nodular cast iron for the piston and partially stabilized zirconia for the ceramic insulating cap. However, conventional brazing and other means, such as mechanical fastening of the cap and thermally spraying ceramic powders on the piston, have failed.



Joining the ceramic insulation cap to the piston of a minimum-cooled diesel engine is a critical problem that appears to have been solved by ORNL researchers in the Metals and Ceramics Division. Joe Hammond and Stan David have found a way of joining a piston cap made of partially stabilized zirconia (PSZ) to a piston made of nodular cast iron (NCI).

Recently, Joe Hammond and Stan David in ORNL's Metals and Ceramics Division have developed a method of joining the two materials by single-cycle brazing under conditions of time and temperature that do not alter the structure and mechanical properties of the cast iron. The method uses a transition piece to minimize the strain on the ceramic and a special brazing technique they have termed the "active substrate process." Instead of using an active filler metal commonly employed for such joints, the ORNL method uses an active substrate. "In this technique," says Hammond, "the agent for promoting reaction and wetting of the ceramic is introduced by a preliminary treatment of the ceramic substrate rather than by incorporating it into the filler metal. In this way the components can be joined at low temperature without damage to the nodular cast iron."

Small test specimens made by this method showed excellent shear strength at braze interfaces. Intermediate size joints exhibited good resistance to thermal shock. Hammond and David are scaling up the brazing process for engine size components to transfer the technology to industry.

The Toxicology of Diesel Fuel Aerosol

Diesel fuel aerosol is a visual obscurant produced by military vehicles. Not a combustion product, the aerosol is formed when diesel fuel is heated, creating a vapor that recondenses to form an aerosol upon contact with cooler air. Under field conditions, the visual obscurant resembles a relatively thick fog and limits visibility to 3 to 10 m (10 to 32 ft).

Until recently, it was not clear whether such a visual obscurant jeopardizes human health. In 1979 the

U.S. Army Medical Bioengineering Research and Development Laboratory at Fort Detrick in Frederick, Maryland, asked Oak Ridge National Laboratory to study the biological effects of diesel fuel aerosol to determine whether a health hazard existed. The Biology Division and Analytical Chemistry Division collaborated on a five-year study, which was recently completed.

The study involved exposing rats to aerosolized diesel fuel in inhalation chambers. For all of the experiments, ORNL biologists used systems designed and built at ORNL for generating, monitoring, and controlling concentrated petroleum aerosols in the inhalation chambers. These systems were developed in 1979 by Bob Holmberg and Jack Moneyhun of the Analytical Chemistry Division and Tom Gayle of the Instrumentation and Controls Division.

In 1980 the first studies of the effects of aerosolized diesel fuel on Sprague-Dawley rats were performed by Walden Dalbey and Simon Lock of the Biology Division. Groups of male and female rats were exposed to concentrations of aerosol particulates ranging from 2.7 to 16 mg/L for 2, 4, or 6 h. Such concentrations are significantly greater than the concentrations to which humans are most likely to be exposed. Most of the rats subjected to the higher concentrations died within 48 h of exposure. Autopsies showed that the respiratory tract, primarily the lungs, was the target of the toxicity: Darkly reddened lungs and fluid in the trachea were characteristic features. Rats exposed to lower concentrations also died if exposed for the longest duration (6 h). It was concluded that mortality was highly correlated with the multiplication product of particulate concentration and duration of exposure.

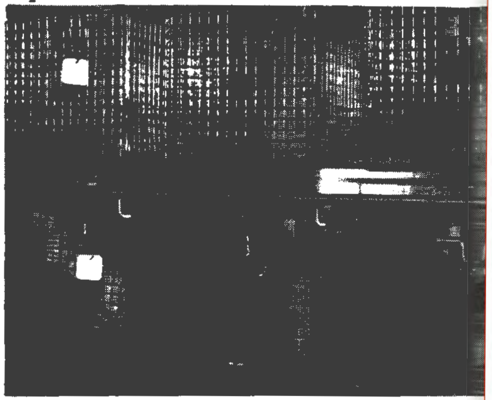
An attempt was made to identify biological changes that occurred in response to certain exposure levels, or "doses," of the diesel aerosols. In separate experiments, Dalbey and Lock studied the number of pulmonary free cells after single exposures and the breathing pattern before and during exposure. These experiments were done to determine whether dose-response relationships existed. The researchers found that the number of pulmonary free cells increased over a four-day period following a single exposure. Breathing frequency decreased as a result of exposure to diesel fuel aerosol; maximal depression was reached after, at most, 30 min of exposure. An inverse linear relationship existed between maximal depression of breathing frequency (at 30 min) and increasing aerosol concentration over the range of 0.5 to 6 mg/L. For diesel fuel aerosol, the RD_{50}—that is, the concentration necessary to cause a 50% reduction in respiratory rate (measured at 30 min)—was estimated to be 3.75 mg aerosol particulates.

In subsequent experiments, 12 groups of rats were exposed 1 or 3 times per week for a total of 9 exposures. Those exposed three times per week lost body weight during the course of exposure. Lung weight increased in exposed animals probably as a result of the thickening of the alveolar walls and the presence of excess pulmonary free cells, which accumulated in the lung spaces. The researchers also found that the more frequent exposures (three per week) caused more changes than occasional exposures (one per week). Variation in duration of exposure appeared to have very little effect, and a dose-response relationship was not usually apparent with differences in concentration.

How much of the diesel fuel smoke particles actually were deposited in the lungs of rats inhaling them? To find out, Dalbey and Lock collaborated with Roger Jenkins, Del Manning, Mike Maskarinec, and Moneyhun of the Analytical Chemistry Division in using the dosimetric tracer decachlorobiphenyl (DCBP), which was added to the fuel prior to aerosolization. The analytical chemists determined the amount of DCBP in tissue extracts of rats exposed to DCBP-containing smoke by purifying the extracts on activated Florisil and by analyzing them by gas liquid chromatography using an electron capture detector.

The largest internal amounts of tracer were deposited in the lungs.

These mice are exposed to diesel fuel aerosols in an inhalation chamber designed by ORNL's Analytical Chemical Division. Biology Division researchers have found no significant cumulative toxicity in animals exposed to levels to which humans are most likely to be exposed.



Animals exposed to higher aerosol concentrations had greater levels of tracer deposited in their lungs than those exposed to lower concentrations for the exposure duration. The fraction of inhaled particles actually retained in the lungs ranged from 4 to 8%, with the rest being excreted.

What are the biological effects of relatively low concentrations of diesel fuel aerosol—the levels to which humans are most likely to be exposed? Lock, Richard Schmoyer, and Richard Griesemer, director of the Biology Division, examined this question in experiments involving rats exposed to concentrations of 0, 0.25, 0.75, and 1.5 mg diesel fuel aerosol per liter for 4 h/d, 2 d/week over a 13-week period. No deaths occurred during the exposure or recovery periods. Slight changes in the rats' response to a loud sharp sound (startle response) were noted. These changes were apparently an acute effect because no evidence of permanent changes in the central nervous system changes was detected as measured by the startle response. Other slight changes observed included an elevated number of pulmonary cells—lavaged alveolar macrophages—and changes in tissue weights of the exposed animals. No significant cumulative toxicity, however, may be attributed to these diesel fuel aerosol exposures. ornl

awards and appointments

The following ORNL and Martin Marietta Energy Systems, Inc., staff members received awards in the 1985 publications competition of the East Tennessee Chapter of the Society for Technical Communication: **Kenneth Cowser** and **Vivian Jacobs**, Francis E. McKinney "Best of Show" award and award of distinction in the book category for *Synthetic Fossil Fuel Technologies*; **John E. Till** and **H. Robert Meyer**, award of merit in books for *Radiological Assessment*; **B. Z. Egan, N. E. Lee, C. A. Burtis, J. Y. Kao, J. M. Holland**, and **Martha Stewart**, award of distinction in scholarly and professional articles for "Use of Laser-Excited Fluorescence To Measure Mixed-Function Oxidase Activity," *Clinical Chemistry*, September 1983; **Irene Brogden, David Stinton, E. W. McDaniel**, and **H. O. Weeren**, award of excellence in scholarly and professional articles for "Characterization of Hydrofracture Grouts for Radionuclide Migration," *Advances in Ceramics: Nuclear Waste Management*, 1984; **Carolyn Krause** and **Susan Hughes**, award of excellence in scholarly and professional articles for "Communicating Health Risks to the Public," ORNL *Review*; **Jonathan Woodward, Elias Greenbaum**, and **Martha Stewart**, award of merit in scholarly and professional articles for "An Immobilized Chloroplast-Ferredoxin-Hydrogenase System for the Simultaneous Production of Hydrogen and Oxygen," *Biotechnology and Bioengineering Symposium*, No. 25, 1983; **Robert B. Honea**, award of excellence in technical reports for *National Inventory of Abandoned Mine Land Problems: An Emphasis on Health, Safety, and General Welfare Impacts*; **Robert A. Langley** and **Margaret Nestor Johnson**, award of merit in technical reports for *Data Compendium for Plasma-Surface Interactions*; **W. R. Huntley** and **Carolyn Srite**, award of achievement in technical reports for *Performance Test Results of a Lithium Bromide-Water Absorption Heat Pump That Uses Low-Temperature Waste Heat: Final Report*; **Bill Clark, Steven Wyatt**, and **Jack Rich**, award of merit in promotional materials for *Martin Marietta Career Opportunities*; **Jon Jefferson**, award of achievement in trade and news articles for "ESD Probes Links Between Stream Flow, Fish Population," *Lab News*; **Ernest G. Silver, Sharon H. McConathy**, and **Joan Roberts**, award of merit in whole periodicals for *Nuclear Safety*; **William Fulkerson** and **Janice M. Asher**, award of excellence in periodic activity reports for *Energy Division Annual Progress Report for Period Ending September 30, 1983*; **Robert L. Wendt** and **Deborah Stevens**, award of excellence in periodic activity reports for *ORNL Site Development and Facilities Utilization Plan*.

Stan Milora and **Chris Foster** received the Outstanding Technical Accomplishment Award from the American Nuclear Society for their developments of pellet fuel injectors for fusion devices.

Bill R. Appleton has been appointed to a three-year term on the Solid State Sciences Committee of the National Research Council.

Ron Leinius has been appointed director of the new Computing and Telecommunications Division.

Ron Bradley has been appointed manager of ORNL's Fossil Energy Program.

Benjamin A. Carreras, Ralph Isler, Stanley L. Milora, and **David W. Swain** have been elected fellows of the American Physical Society.

Martin Marietta Energy Systems, Inc., has been named employer of the year for 1984 by the McGhee-Tyson National Guard Base.

Suman P. N. Singh has been appointed to a task group of the National Acid Precipitation Assessment Program (NAPAP). He will serve as national laboratory representative to NAPAP Task Group H, which is responsible for the development and assessment of effluent control technologies to control the release of sulfur and nitrogen oxides from fossil-fueled steam plants.

Richard G. Haire has been appointed to the editorial board of the new journal *Lanthanide and Actinide Research*.

ORNL's Information Division and the information functions of the other two Oak Ridge plants of Martin Marietta Energy Systems, Inc., have been consolidated into a new Information Resources Organization, which is managed by **G. Daniel Robbins**.

Terry Donaldson has been named coordinator of ORNL's Biotechnology Program.

The Society for Risk Analysis presented its first Distinguished Service Award to **Curtis Travis.**

Cullie Sparks has been named a member of the National 6-GeV Synchrotron Steering Committee.

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The High Temperature Materials Laboratory, now under construction, will take two years to build. For more on the HTML's construction and other ORNL news, see "News Notes," pages 16–19.