Number Four 1987

Oak Ridge National Laboratory review

FUSION RESEARCH: WHERE'S IT GOING?

Oak Ridge National Laboratory
review

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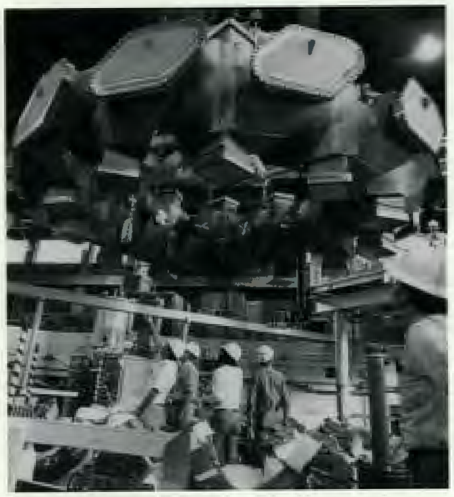

***THE COVER:** The vessel for ORNL's Advanced Toroidal Facility (ATF) is lowered, as workers prepare to install it. The ATF is one of the many fusion research projects described in John Sheffield's "Magnetic Fusion Progress: A History and Review," starting on page 1.*

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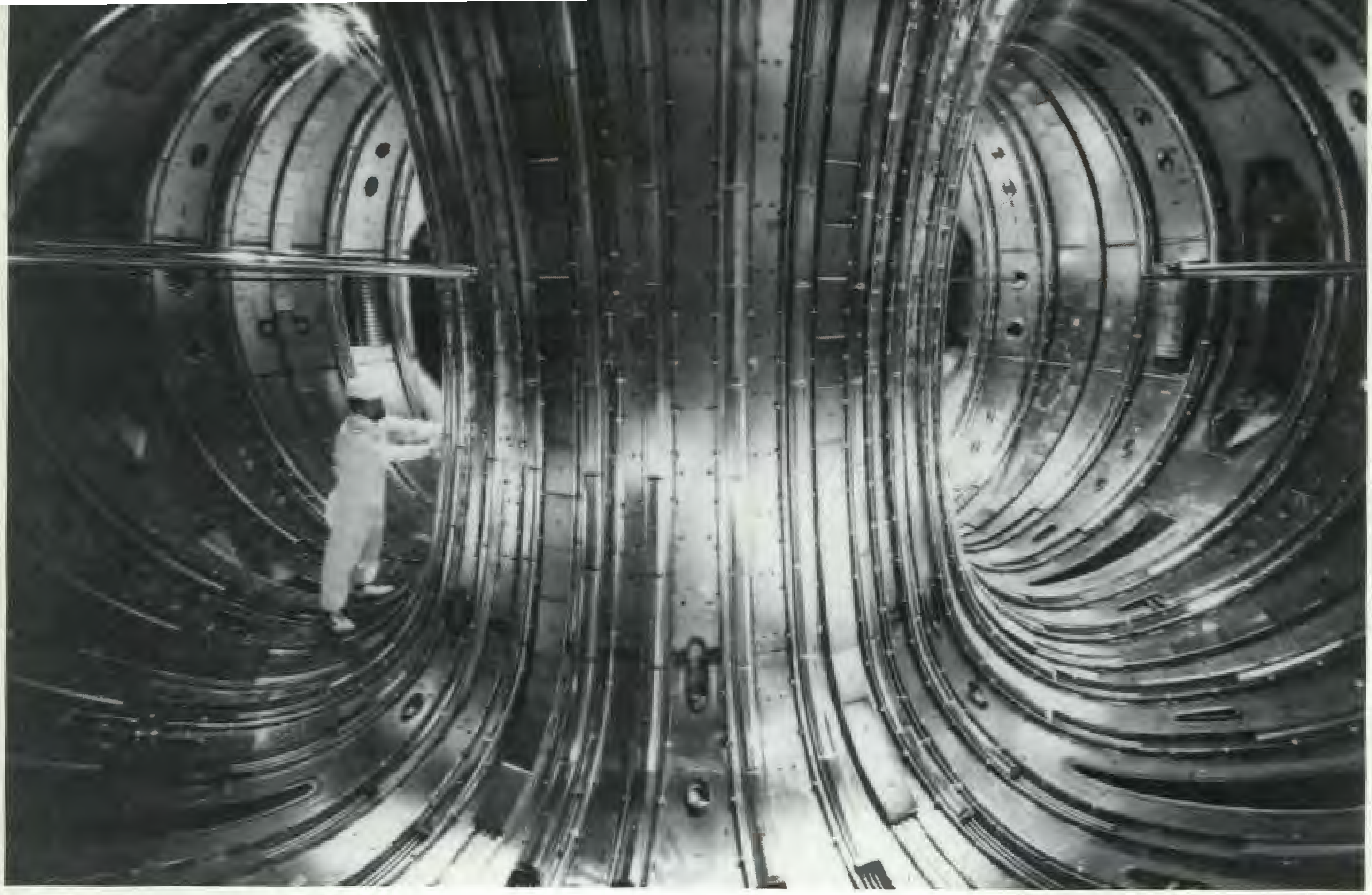


A technician inspects the plasma chamber in the Joint European Torus (JET) of the European Economic Community, an important experimental facility in the international magnetic fusion program. JET will be one of the first experiments to use deuterium-tritium fuel. It will have the potential to produce as much power from fusion reactions as is used to keep the plasma hot. ORNL has provided pellet-fueling injectors to JET to refuel its plasma and has collaborated with JET on a study showing that beryllium could be used to handle plasma edge conditions.

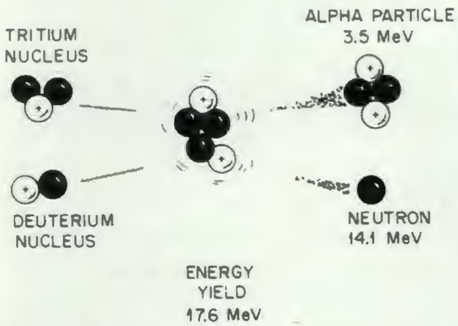
Magnetic Fusion Progress:
A History and Review

By JOHN SHEFFIELD

The development of fusion energy for power production has been under way for 50 years. It is a formidable task, but the rewards are great. Partners in the effort to harness this potential energy source include government, industry, national laboratories, and universities in many countries, including the United States. The partners often work together to share information and increase the rate of progress. One outcome of the worldwide effort is a plan to build an International Thermonuclear Experimental Reactor (ITER) in the 1990s.

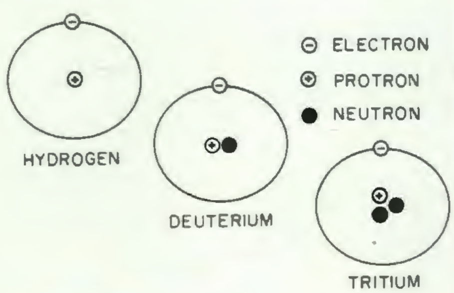
What Is Fusion?

Fusion occurs when the nuclei of light elements combine to form a heavier element. The process releases much more energy than is needed to make the reaction occur. In a typical fusion reaction, the nuclei of two hydrogen isotopes, deuterium (^2H) and tritium (^3H), combine and fuse, creating the nucleus of a helium atom (also called an alpha particle) and releasing a neutron. The energy of the reaction is carried by the alpha particle and the neutron. In a



fusion reactor, the alpha particle energy would sustain the temperature of the deuterium and tritium to perpetuate the fusion process; the neutrons would be absorbed by a surrounding "blanket" that would slow them down and release their energy as heat to a working fluid, generating steam to drive an electric turbine generator.

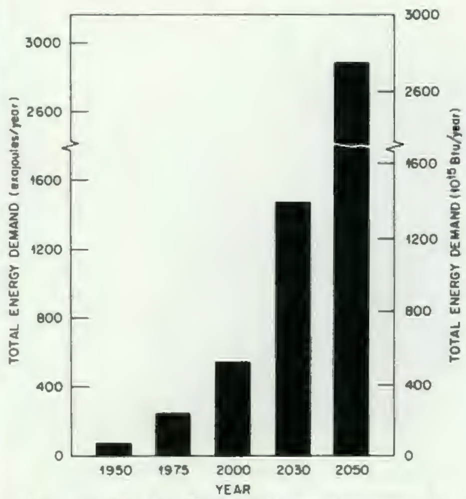
Solar energy, which sustains life on Earth, is actually fusion energy. In the sun and other stars, hydrogen is converted into helium through a complex chain of fusion reactions.



Why Do We Need Fusion Energy?

As the world's energy needs have increased, the limits of its resources have become apparent. Fossil fuels such as coal, gas, and oil can no longer be depended on as abundant sources of inexpensive energy, and they can cause environmental problems such as carbon dioxide buildup, smog, and acid rain. Fission reactors, in which energy is released by splitting the atoms of heavy elements, are providing increasing amounts of electric power. However, the use of fission fuels is limited without

Several different magnetic-field systems for confining hot fusion plasmas evolved throughout the world from the 1930s through the 1970s. In the 1970s the tokamak emerged as the front-runner. Other types of magnetic fusion devices experienced growth, decline, and a renaissance. In the 1980s new goals were set for technology and physics development; some of these goals, such as development of superconducting magnets for fusion, are being achieved at ORNL. In the 1990s the United States will be involved in two major fusion initiatives: the Compact Ignition Tokamak at Princeton, New Jersey, and the not-yet-sited International Thermonuclear Experimental Reactor.



The world's demand for energy is projected to increase rapidly (3 to 4% per year). One exajoule is equivalent to the energy in 160 million barrels of oil.

some kind of breeder technology, and environmental and safety uncertainties are associated with fission. Solar energy technology has advanced considerably in recent years but is likely to remain a supplementary power source rather than a primary source for central electricity generation.

Fusion energy promises to be an attractive alternative source of base-load power because of such advantages as virtually unlimited fuel supplies and minimal potential for radioactivity release. More specifically,

- Deuterium is naturally available (one in every 6500 hydrogen atoms) and inexpensive, so the supply of this form of fuel for fusion is virtually unlimited.
- Tritium, the other principal fusion fuel, is mildly radioactive and, though not available naturally in sufficient quantities to support power-generating plants, it can be created in fusion reactor plants, using the reaction of the fusion neutron with lithium, which is abundant in nature.
- The neutrons produced by the deuterium-tritium fuel will induce radioactivity in materials surrounding the energy source, but materials envisioned for future use in a fusion reactor should become much less radioactive than those in a fission reactor.
- Advanced fusion reactors may be able to use only deuterium or other nonradioactive materials as fuel and produce relatively fewer neutrons. However, the conditions for using such fuels are more demanding (e.g., higher initiating temperature) than for the deuterium-tritium fuel.
- The fusion reaction waste product or "ash," is helium, which is nonradioactive.

For these reasons, although the task of demonstrating economical power generation from fusion is difficult—perhaps one of the most difficult scientific and technical endeavors ever undertaken—nuclear fusion offers a potential long-term solution to the world's need for energy.

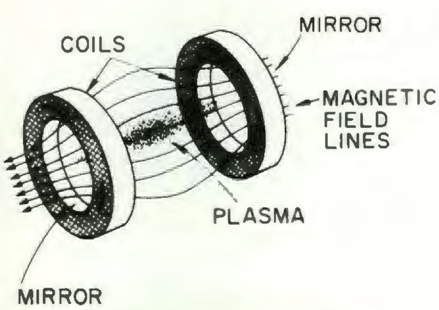
How Is Fusion Power Produced

For significant amounts of energy to be produced from fusion

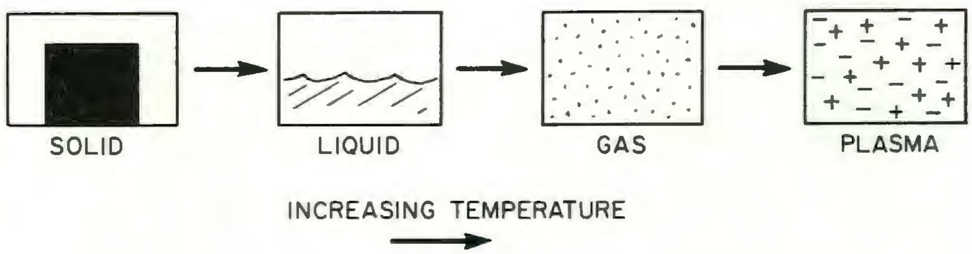
John Sheffield is ORNL's Fusion Energy Division associate director for Confinement. He is responsible for the effort to design, build, and put into operation the Advanced Toroidal Facility (ATF), ORNL's latest doughnut-shaped fusion device. He received his B.Sc., M.Sc., and Ph.D. degrees from London University. Before coming to ORNL he worked for fusion research programs at the Harwell and Culham laboratories of the United Kingdom Atomic Energy Authority in England and served on the faculty of the Physics Department of the University of Texas at Austin. In 1977 he joined the Fusion Energy Division and became associate director in 1982. Sheffield is author of *The Scattering of Radiation from Plasmas*. In the following article, he discusses the evolution of different magnetic-field systems for confining hot fusion plasmas during the 1930s through the 1970s; the emergence of the tokamak as the front-runner and the growth, decline, and renaissance of other types of devices; and the goals of technology and physics development in the 1980s and the major new initiatives for the 1990s—the Compact Ignition Tokamak in the U.S. program and the International Thermonuclear Experimental Reactor in the international program.

three conditions must be met.

- The fusion fuel must be heated to extremely high temperatures. The minimum temperature for fusion of deuterium and tritium is about 100,000,000°C. For deuterium fuel alone, the corresponding temperature is about 500,000,000°C. At these temperatures, the reacting particles have enough energy to overcome the natural tendency of particles having the same charge to repel each other, allowing them to come close enough to fuse.
- The number of particles in the fusion fuel must be high enough for significant power to be produced. The number of particles in a specified volume is called the *density*.



IN A SIMPLE MIRROR, CHARGED PARTICLES ARE REFLECTED BY END REGIONS OF INCREASING FIELD

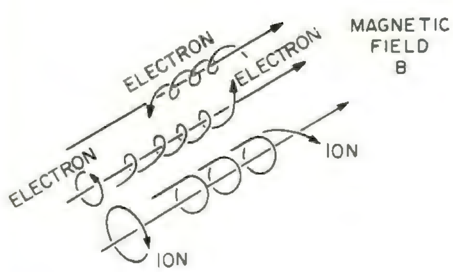


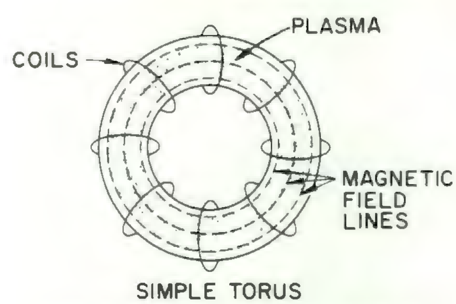
- The fuel must hold its energy for a certain length of time, called the *confinement time*.

To generate fusion power, the fusing particles must remain confined at high temperature long enough to release more energy than was used to confine and heat them. If the confinement time is short, the density must be very high; if the density is not as high, the fuel must be confined longer.

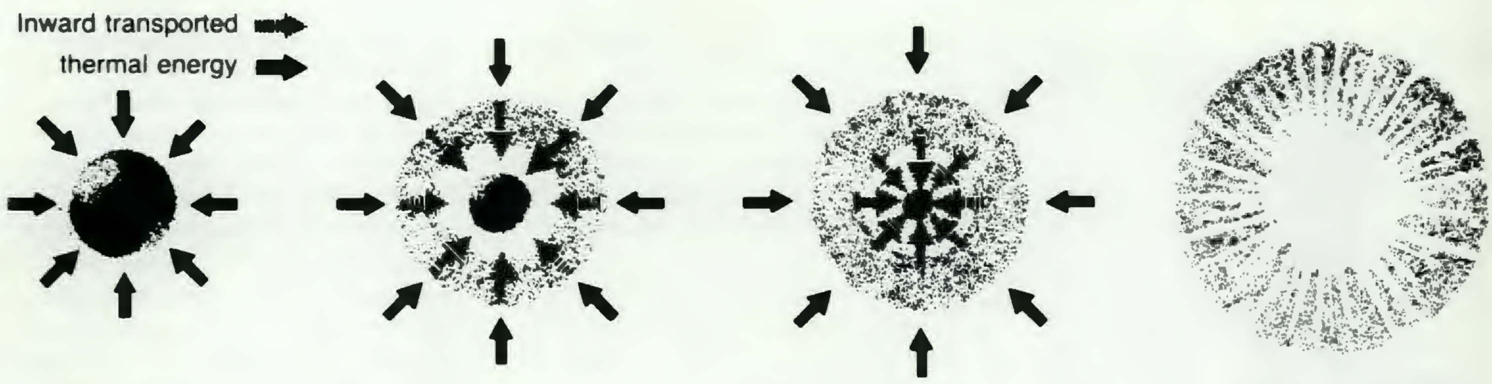
The product of density (n) and confinement time (τ) provides a convenient measure for fusion energy. (Densities are given in number of particles per cubic centimeter; confinement times are given in seconds.) According to the Lawson criterion, developed by British physicist J. D. Lawson, useful fusion energy requires $n\tau = 10^{14}$ particles/cm^3·s.

As temperature increases, the state of matter changes from solid to liquid to gas, and at very high temperatures, collisions between the elements are so energetic that





IN A SIMPLE TORUS, THERE ARE NO ENDS BECAUSE THE MAGNETIC FIELD LINES CLOSE IN A CIRCLE



Atmosphere Formation
Laser or particle beams rapidly heat the surface of the fusion target forming a surrounding plasma envelope.

Compression
Fuel is compressed by rocket-like blowoff of the surface material.

Ignition
With the final driver pulse, the fuel core reaches 1000–10,000 times liquid density and ignites at 100,000,000° C.

Burn
Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the driver input energy

all the electrons are knocked off, and what is left is a gas composed of electrons and positively charged nuclei. This substance—the fourth state of matter—is called a *plasma*. Flames, arcs, neon lights, and stars are plasmas. Because plasmas contain charged particles, they interact strongly with electric and magnetic fields.

Fusion research has focused on two ways of confining the fusion fuel:

• In inertial confinement, a small sphere of liquid or solid fuel is very rapidly compressed and then heated by lasers or beams of charged atomic particles. Because the density is very high, the required confinement time is short (0.00000001 s, or 10 ns).

• In magnetic confinement, the fusion fuel is a plasma that is confined by a "magnetic bottle" in any of several shapes. Because density is lower in magnetic confinement than in inertial confinement, the confinement time must be longer (about 1 s).

The charged particles in a plasma interact with a magnetic field in a way that causes them to rotate around the field lines. Because particles can move freely *along* a magnetic field line, each particle moves in a spiral, or helix, as it travels in a magnetic field. In a curved or varying field, particles follow more complicated orbits that allow them to drift across the field. Nevertheless, careful design makes it possible to create "magnetic bottles" that can effectively confine a fusion plasma.

The basic limit to the ability of magnetic fields to contain both charged particles and their energy is set by collisions between the particles, which cause them to migrate across the field and allow hot particles in the interior of the plasma to transfer heat to colder particles further out. This fundamental diffusion of particles and heat is referred to as a classical process. When particle orbits are more complicated than simple helixes, the process is referred to as neoclassical.

What Are Magnetic Fusion Characteristics?

The remaining discussion will relate to magnetic fusion. Analyses have determined the requirements that a typical deuterium-tritium (D-T) magnetic fusion plasma must meet to sustain its temperature. The conditions to create and maintain a plasma that sustains fusion reactions are

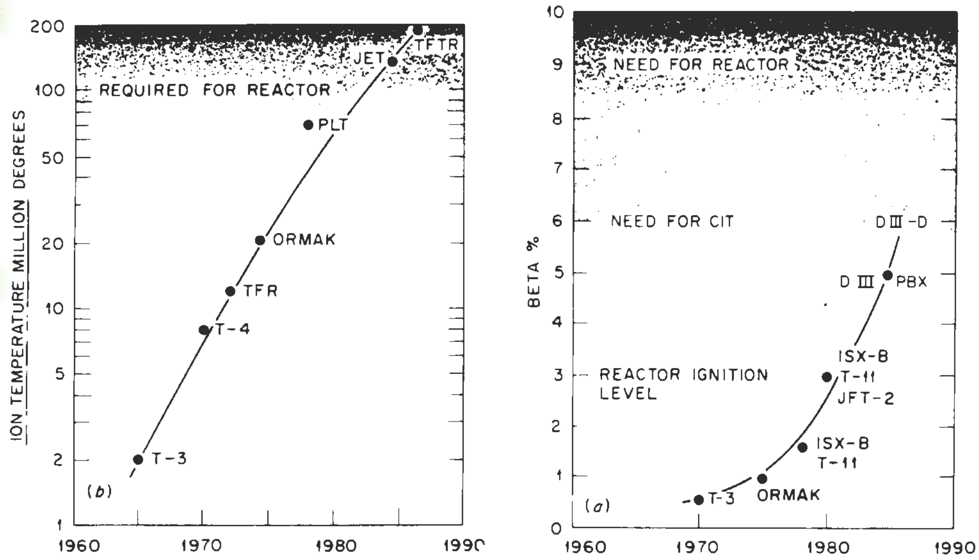
• *Temperature* of 100,000,000°C (for comparison, room temperature is about 20°C).

• *Density* of a few hundred trillion particles per cubic centimeter. A typical magnetic fusion plasma is about 100,000 times less dense than air at atmospheric pressure.

• *Confinement time* for the energy of a second or more (i.e., if the heat source were turned off, the temperature would decrease greatly in about a second). Collisions between particles are the first cause of heat loss, and they also cause the particles to diffuse across the field. Other plasma effects can cause additional losses.

• *Plasma pressure* (the product of density and temperature) of a few atmospheres because, although the plasma is much less dense than air, it is much hotter. This pressure, which acts to expand the plasma, must be counteracted by the magnetic field.

• *Plasma beta* of about 10%, where beta is the ratio of plasma pressure to the pressure of the confining magnetic field. Beta is a measure of cost-effectiveness for a power



Tokamaks have made steady progress toward fusion conditions. Self-sustaining fusion reactions should be achieved in the proposed Compact Ignition Tokamak (CIT) to be built in Princeton, New Jersey.

reactor because the amount of fusion power produced at temperatures around 100,000,000°C increases with pressure, and the larger magnets required to provide the counteracting pressure are expensive; thus, magnetic pressure is a rough indication of the system cost. The beta required for economic D-T fusion depends on the type of device, but the minimum level is in the range of 5 to 10%.

Conceptual D-T Magnetic Fusion Reactor

A brief description of a conceptual D-T magnetic fusion reactor can help in identifying the goals of magnetic fusion. The reactor will operate with a plasma at 100,000,000°C and a density of some 250 trillion particles/cm^3. The plasma will have a volume of 500 m^3 and, under these conditions, will produce ~3500 MW of fusion power.

About 700 MW of alpha power will be used to sustain the plasma temperature. The remaining 2800 MW of neutron power will be collected in a blanket of lithium contained in a metal structure surrounding the plasma. This blanket and the metal wall nearest the plasma—the first wall—will be cooled by water or gas. The heat removed by this coolant will be used to make steam, which will drive turbine generators to produce ~1400 MW of electricity.

About 200 MW of this electricity will be recirculated to run the reactor, provide initial plasma heating, and sustain the magnetic field. Systems at the edge of the plasma will handle the direct plasma heat load and remove the products of fusion—helium produced by fusion and material ablated from the first wall. Outside the blanket, a thick metal shield will intercept any remaining neutrons and prevent them from reaching the coils and other sensitive equipment.

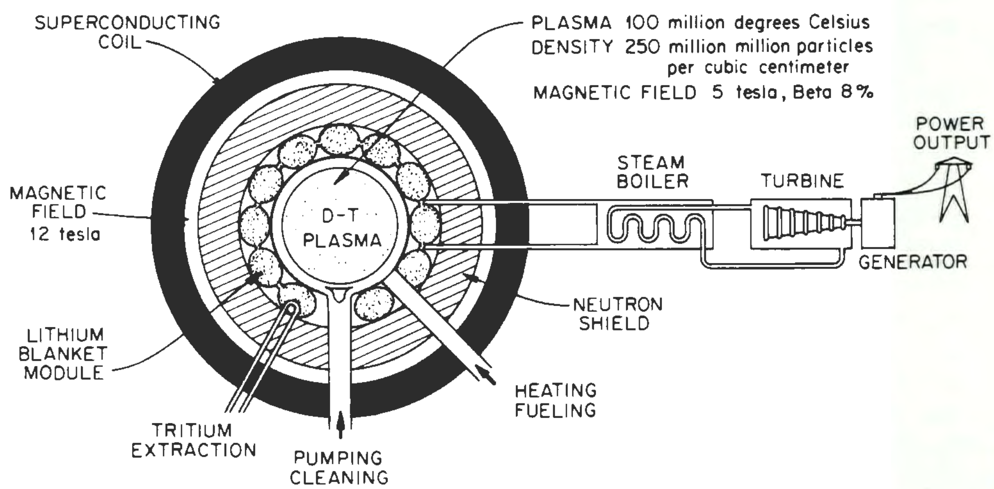
Refueling of the plasma will be achieved by injecting small solid pellets of frozen hydrogen at speeds greater than that of a rifle bullet.

The plasma will be confined by a system of coils, which produces a field at the plasma of about 5 tesla (T), about 100,000 times the earth's magnetic field. Because the field decreases away from the coil, the field strength is highest at the coils (typically 10 to 12 T).

In most conceptual reactors, the coils are made from superconductors cooled by liquid helium because conventional water-cooled copper coils require high power to sustain coil currents large enough to make a 5-T field in such a large volume. In a superconductor, no power is required to sustain the field—only a much lower level of power for refrigeration to supply the liquid helium.

The principal goals of magnetic fusion are

- to find a magnetic coil system—a magnetic bottle—that can contain a fusion plasma at a reactor-level beta in a cost-effective manner,
- to develop methods for heating and fueling a fusion plasma efficiently,
- to develop methods for sustaining and controlling the plasma,
- to develop materials for the first



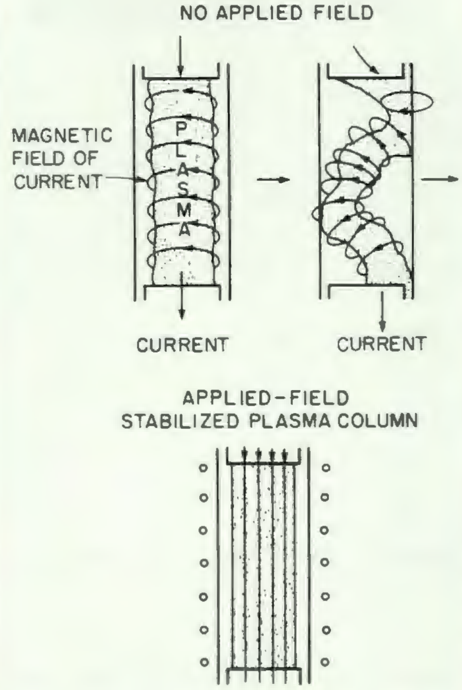
wall and blanket that will have a low induced radioactivity and can withstand the bombardment by neutrons,

- to develop lithium blankets that produce tritium efficiently,
- to develop a reliable reactor system having effective shielding and good handling characteristics for maintenance and repair,
- to develop the superconducting coils required by most conceptual types of reactors, and
- to develop a safe, efficient system having little impact on the environment.

Alternative Magnetic Bottles: A History (1930s–1950s)

The fusion processes occurring in the sun and other stars were first understood in the 1930s. In tests of the first magnetic fusion concept (middle to late 1940s in Britain, the United States, and the U.S.S.R.), large currents were passed down a straight tube containing hydrogen at low pressures—a glorified neon light known as a *pinch*. The plasma was produced and heated by the current, and the goal was to make the current's magnetic field confine the plasma. The gas became very hot, ionized, and changed to a plasma. Unfortunately, the plasma temperature was limited by heat losses (both to the ends of the tube and to the walls) as a result of the plasma's violent wriggling.

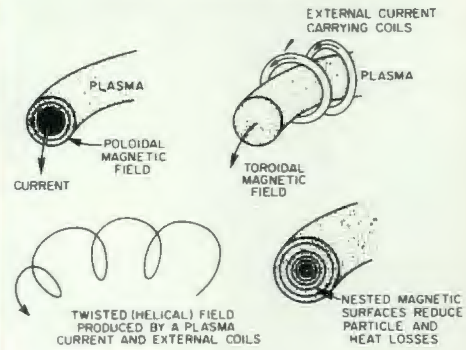
To overcome the end heat losses, researchers bent the tube into a circle, or *torus*. This concept had been promulgated in the 1930s by Arthur Kantrowitz at the predecessor agency of the National Aeronautics and Space Administration. A detailed design incorporating an oscillating electric field current drive was later patented by Sir George Thomson in 1946. Unfortunately, the current-carrying plasma continued to wriggle violently, hitting the walls



of the tube and, again, limiting the temperature.

Many variants of this approach were tried; two notable ones (developed in the mid-1950s) have survived. Separately, in Britain, the United States, and the U.S.S.R., researchers realized that a second magnetic field going around the torus—a toroidal magnetic field—could stabilize the wriggling. The magnetic field lines behave somewhat like elastic bands—an invisible corset. This additional toroidal magnetic field is produced by external, current-carrying conductors.

A twisted field is produced by the combination of the toroidal field and the "poloidal" field (produced by the current). A key feature that contributes to stabilizing the plasma is the change in twist of the field, which the plasma encounters in trying to escape; this change in twist is known as shear. In addition, the combined fields orbiting around the torus lie on toroidal surfaces that are nested like the layers of an onion; they limit the radial motion of the plasma particles and thereby

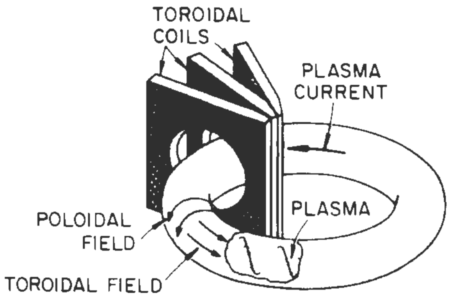


reduce heat conduction.

The U.S.S.R. fusion effort added a strong toroidal magnetic field. In the many experiments conducted using it, a substantial amount of the underlying theory was developed, and by the mid-1960s the device was beginning to produce surprisingly good plasmas. This type of magnetic configuration is known as a *tokamak*.

At experimental devices in Britain and at Los Alamos National Laboratory (LANL), a relatively weak toroidal field was added. Performance was improved, but heat losses remained high because of rapidly fluctuating magnetic fields generated by the plasma itself. Such fluctuating fields cause the magnetic field lines to wander from the pristine flux surfaces and allow particles and heat to move more freely in the radial direction—that is, they make the confinement system "leaky."

For a time, British scientists optimistically thought that a breakthrough had been made because large numbers of neutrons were produced. Unfortunately, it was learned, these neutrons were not produced by thermal fusion reactions; as a result, the program experienced a temporary state of depression. Later, however, researchers noticed that, on occasion, the plasma would spontaneously go into a quieter mode where fluctuations were low and the confinement improved. They observed that during these



TOKAMAKS
(REVERSED FIELD PINCHES)

episodes the toroidal field had reversed direction in the interior of the plasma. This phenomena was explained in the 1960s. Devices that capitalize on this natural, improved magnetic configuration are called *reversed-field pinches* (RFP).

In the U.S. program in the early 1950s, two other important magnetic configurations were developed—the stellarator and the mirror.

It is said that while skiing the Princeton astrophysicist, Lyman Spitzer, had time to think about a topical newspaper report claiming that an Argentinian scientist had developed a fusion reactor. Spitzer asked himself, "What would I do to make such a device?" The ultimate product of his thoughts was the *stellarator*, a toroidal device in which the beneficial twisting of the field lines is accomplished by twisting the coils around the torus.

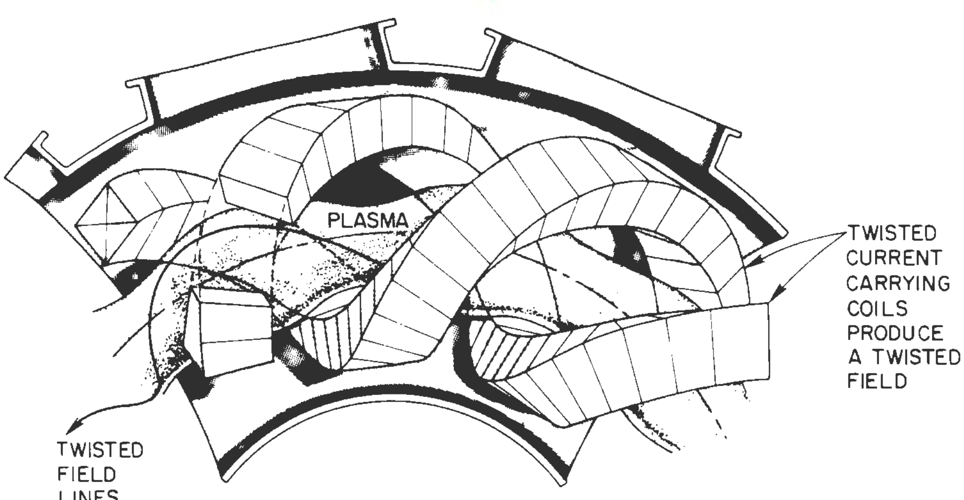
A completely different approach, developed at Lawrence Livermore National Laboratory (LLNL), was based on the knowledge that charged particles can be reflected when they enter a region of increasing magnetic field. In this *simple mirror* fusion device, a straight magnetic field is produced by a line of circular coils having a higher magnetic field strength at each end to produce a region of increased field (see figure on p. 3). Charged particles move back and forth, reflecting at the magnetic mirrors. The same concept was developed independently in the U.S.S.R.

There are two main difficulties with the simple mirror:
(1) particles moving nearly parallel to the field are not reflected and escape through the ends and (2) in terms of the concept of a magnetic bottle, plasma between the mirrors is in one sense on the outside, not the inside. The latter situation exists in a simple mirror because the field decreases away from the plasma in the region between the mirrors, making it possible for the plasma and field to exchange places. The situation is analogous to balancing one fluid on another—as in a multilayered drink. It works only if the upper fluids are lighter than the lower ones.

The solution to the latter problem was proposed separately in the United States and U.S.S.R. It was demonstrated in the U.S.S.R. when extra coils were added to carry currents parallel to the axis of the mirror. With the additional coils, the plasma no longer bulged through the field, hitting the wall, but was contained instead. The explanation for the improvement was a characteristic known as a *magnetic well*. The additional coils "soup up" the field in such a way that the plasma experiences an increasing confining magnetic field as it attempts to escape—the magnetic well. The situation is similar to displacing a ball at the bottom of a bowl or balanced on top of the bowl; unlike the ball on the bowl, which falls off and rolls away, the ball in the bowl returns to stable equilibrium.

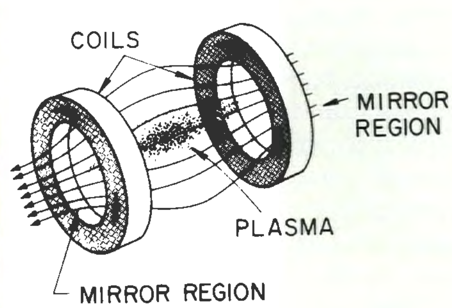
Subsequently, the concept of using a magnetic well to stabilize the plasma (well stabilization) was generalized to any situation in which, on the average, the plasma particles, as they traverse the confining magnetic field, experience more regions in which the field increases to the outside than regions in which it decreases—an *average well*. We now understand that many of the successful devices have an average well (e.g., tokamaks and stellarators).

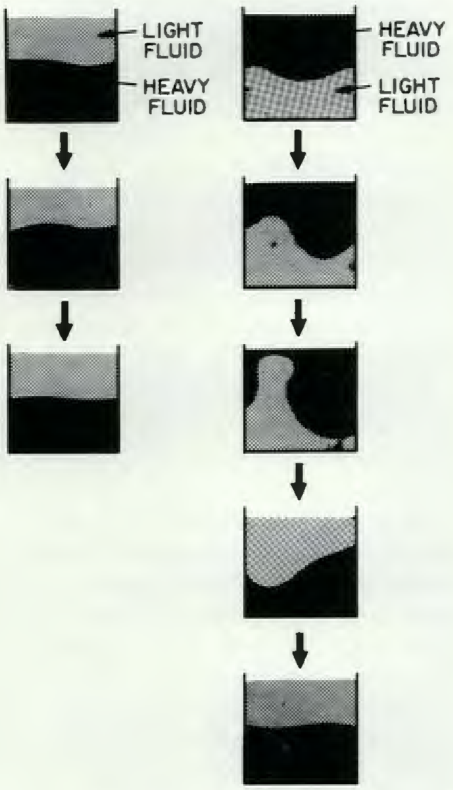
Each of these configurations had strengths (and weaknesses) in overcoming particular magnetic fusion problems and in taking advantage of positive features that



STELLARATOR

SIMPLE MIRROR

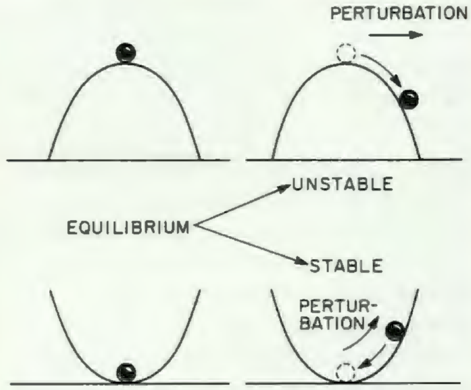




were being discovered (e.g., shear, magnetic well, or lower heat loss). Throughout the following decades, the configurations evolved, periodically gaining and losing favor among researchers who worked to exploit the strengths and understand the weaknesses.

In the early years of the fusion energy program, the work was classified. However, open discussion of such work by the Russians and the obvious difficulties of misusing fusion contributed to its declassification after 1957. A United Nations-supported meeting at Geneva in 1958 was the scene of the first multinational exchange of fusion information.

The growth of theoretical understanding and experimental success from the late 1950s into the early 1960s produced optimism that a breakthrough was in sight. Unfortunately, after the initial gains, the lack of further improvement in plasma performance in stellarators, mirrors, and pinches was



disappointing. However, in 1968 at the Novosibirsk International Atomic Energy Agency conference, the Soviets announced that they had achieved, at useful density and with good confinement in a tokamak, an electron temperature of 10,000,000°C. The announcement was greeted with considerable interest, even though some expressed concern about the accuracy of the Soviet measurements (indeed, diagnosing fusion plasmas remains a difficult task even today).

In a wonderful example of international collaboration, which is characteristic of fusion research, a British team traveled to the Soviet Union and used an advanced technique to measure the machine's electron temperature; the team's data confirmed the Soviet claims. Within a few years, 50% of the world's major experiments were tokamaks (later, as many as 80%).

1970s Through Today

Tremendous progress was made in the tokamak area with the achievement of very good plasma confinement and ion temperatures of 70,000,000°C in the Princeton Large Torus (PLT) device at Princeton Plasma Physics Laboratory (PPPL). In addition, tokamaks became the workhorse for the program, acting as test beds for heating, fueling, and other plasma control systems that are now widely used.

As the tokamak program expanded, the stellarator program in the United States declined. Stellarator research was sustained during the 1970s and early 1980s by the Japanese, the Germans, and the Soviets and in the United States by a small but vigorous program at the University of Wisconsin. The advent of more powerful computers led to improved theoretical analyses and a better comparison of theory and experimental results. Improved types of stellarators were developed—notably, the heliotron (Japan); the related torsatron (France); and the modular and helical axis stellarators (Princeton and Germany). Stellarators achieved a performance level comparable to that of tokamaks at the same stage of development.

New theoretical and experimental insights, obtained from work in Britain and Italy and at LANL, led to a renaissance of the RFP program. Most important was the discovery of the so-called dynamo effect, which sustains the beneficial field reversal against the otherwise natural tendencies of the magnetic fields in the plasma to decay. Other kinds of pinches—the field-reversed theta pinch and spheromak, commonly known as compact tori—have also shown improved performance.

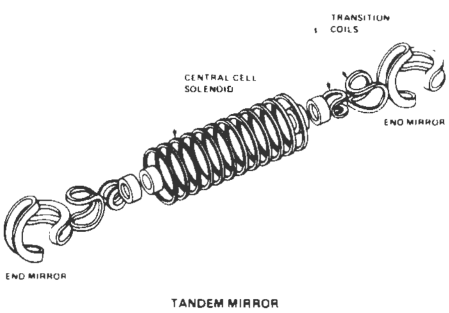
In the early 1970s at LLNL, reasonably high temperatures were achieved in a stabilized mirror by injecting intense beams of energetic hydrogen. This and earlier successes encouraged a renewed interest in finding ways to plug the end losses. Two solutions were proposed.

At ORNL, 24 simple mirrors were arranged end to end in a circle, thereby eliminating end losses; such a device is known as a *bumpy torus*. Stability was provided by driving a current of relativistic electrons in the region between each set of mirrors to produce an average magnetic well. Initial results were encouraging, but subsequent, more-detailed measurements in the United States and Japan, coupled with improved theory, showed that this interesting configuration did not perform adequately. Based on this new understanding, an improved configuration was proposed—the *bumpy square*. The concept is no longer under investigation because of a shift in funding priorities.

At LLNL and independently at Novosibirsk and ORNL, proposals were made to block the end losses of charged particles from a mirror by using electric fields. Such a device is a *tandem mirror*. The effects predicted theoretically have been demonstrated, but efficient plugging has not yet been demonstrated at high densities. Some research is continuing in the U.S. program, and even more is ongoing in the U.S.S.R. and Japan.

Key reasons for the substantial progress that continued through the 1970s are

- improved *theory* models and substantially improved *computing* capability, both for obtaining solutions and for comparison with, and analysis of, experimental results;
- improved *diagnostics* and *data acquisition* techniques;
- improved *experimental techniques*; and
- key developments in the *technology* areas of *heating, fueling,* and *materials* to withstand the plasma.

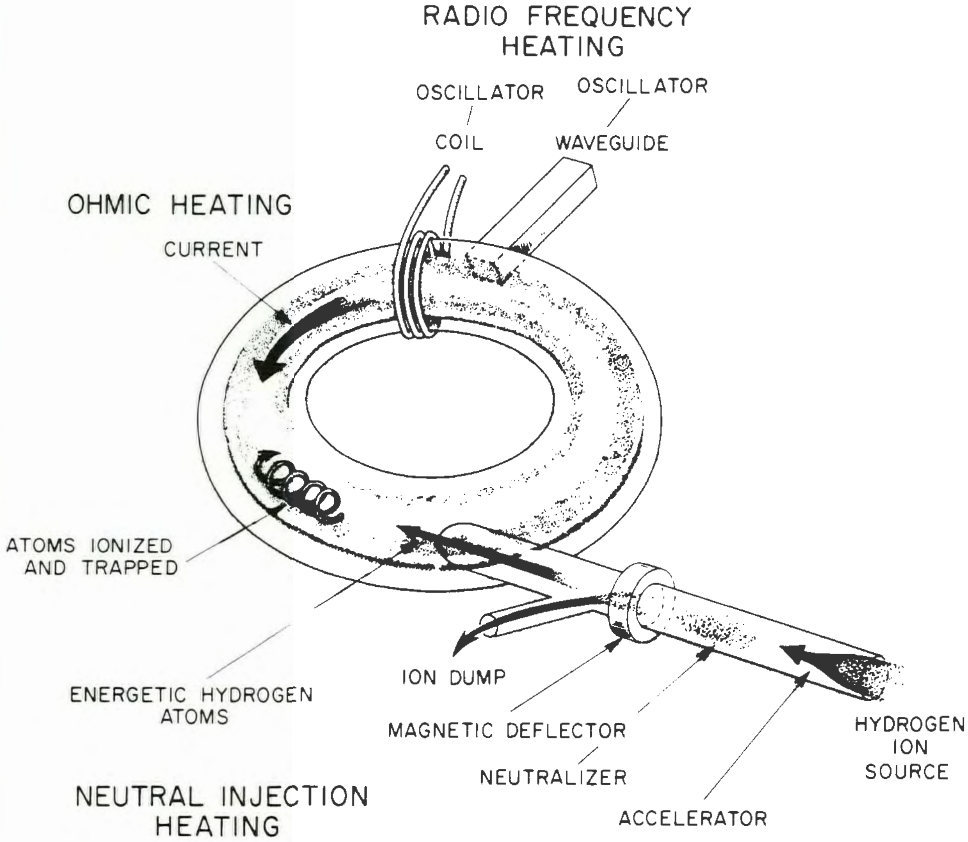


Technology Progress in the 1980s

In the early days of fusion, the technology needed to develop a fusion reactor was identified and steps toward achieving development were initiated. However, in the face of slow progress in the confinement area, development soon became focused on the nearer-term needs of the confinement experiments. The past decade has seen a revival of longer-term research as well as substantial progress in meeting nearer-term needs.

Heating. In the 1960s, sources of intense beams of energetic hydrogen atoms (neutral beams) were developed to heat plasma in devices, such as mirrors, that lacked heating by a plasma current. For stellarators, heating by electromagnetic waves was used; this is known loosely as radiofrequency (rf) heating. The realization of limitations in heating by plasma currents in tokamaks led, starting in the early 1970s, to a more aggressive auxiliary heating program. Successes in the world program (notably the achievement of an ion temperature of 70,000,000°C in the PLT using neutral beams developed at ORNL) were a key factor in the promotion of major tokamak initiatives: the Tokamak Fusion Test Reactor (TFTR) at PPPL, the Joint European Torus (JET) of the European Economic Community, JT-60 (Japan), and T-15 (U.S.S.R.). In 1986 the TFTR achieved ion temperatures of 200,000,000°C using injectors developed at Lawrence Berkeley Laboratory (LBL).

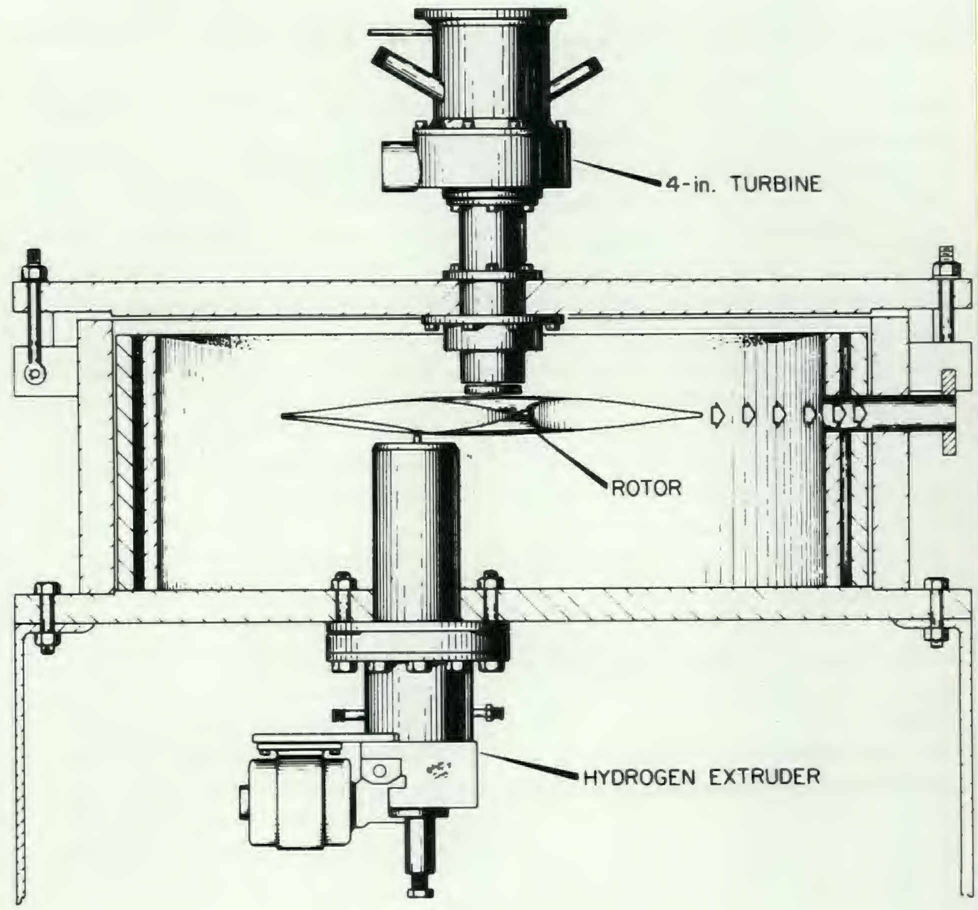
The 1980s have seen the emergence of a variety of powerful rf systems, which are now widely used in the world's fusion experiments for selectively coupling heat to ions or electrons—in a manner similar to the workings of a microwave oven—and for driving



large plasma currents (e.g., 2,000,000 A in JT-60). Future efforts will concentrate on the development of more efficient higher-power sources. More advanced sources of rf, such as the gyrotron (first demonstrated at high power by the Soviets and later commercialized by the Varian Corporation), are being developed for the next generation of fusion experiments.

Fueling. Originally, plasma was fueled either by an initial charge of gas by neutral injection or by puffing of gas at the edge of the plasma. These techniques do not extrapolate well to meet most future needs; therefore, especially in the U.S. program, a substantial effort was initiated to develop solid-hydrogen pellet injectors. In these devices, hydrogen is frozen at liquid-helium temperatures and pellets a few millimeters in size are extruded from something similar to a toothpaste tube. The pellets are then accelerated to 2 km/s. Two acceleration techniques are used: high-pressure gas (similar to the propellant in a BB gun) and centrifugal acceleration from the tip of a rotating arbor (similar to a lawn mower blade). The pellet techniques are superior to the gas techniques because they force the fresh fuel to the center of the plasma, where most of the fusion reactions occur.

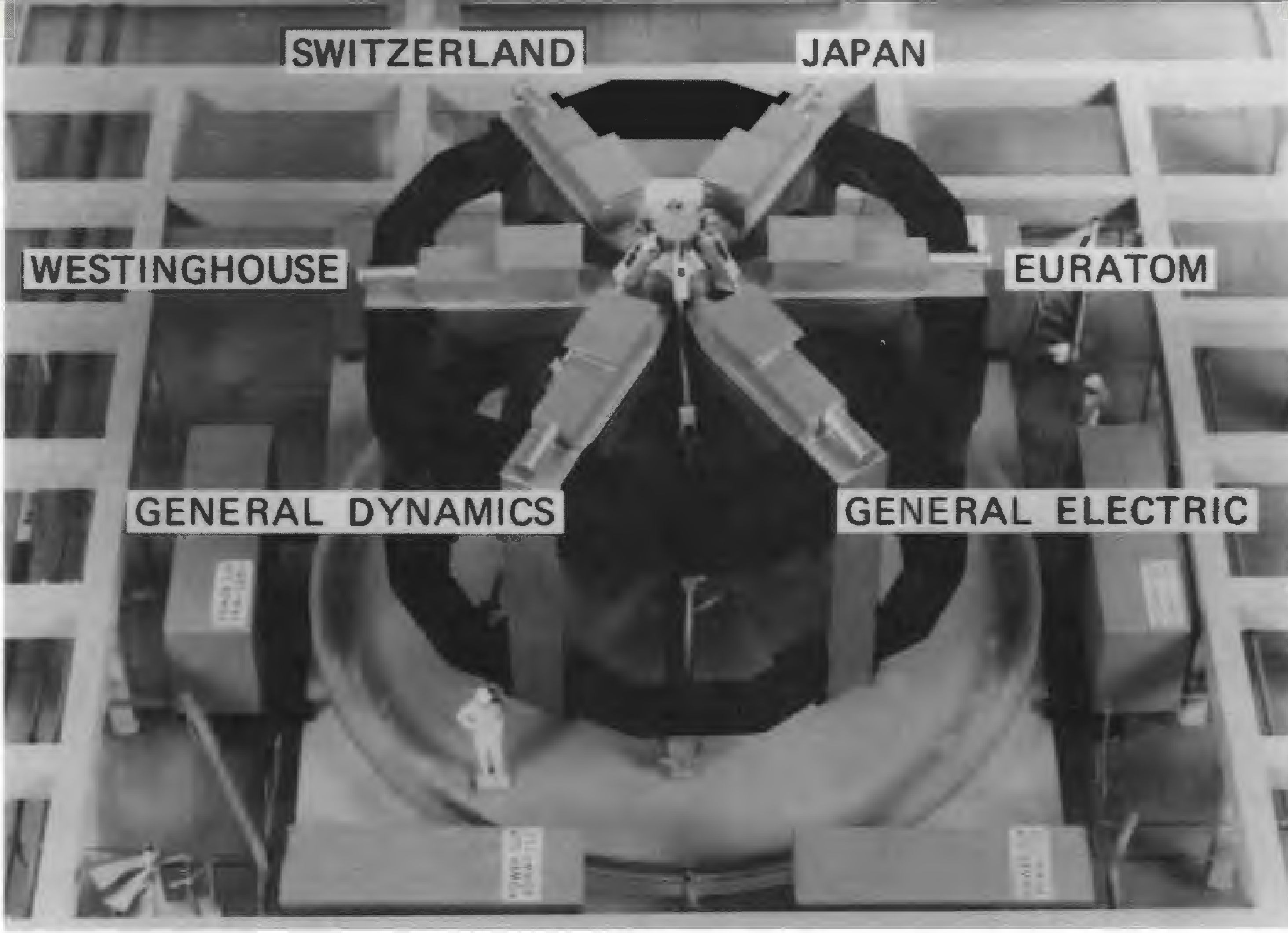
Injectors developed at ORNL have been widely used in the U.S. program and are part of international collaboration on the JET and Tore Supra (France) experiments. Work is now under way to boost the speed of the pellets, using arcs and electron beams, to 5 or even 10 km/s.



Superconducting magnets. Superconducting magnets are needed in most conceptual fusion reactors to minimize the energy used in producing the steady magnetic field. However, they have not received widespread application to date because most experiments have used short-pulse devices optimized for physics studies. Nevertheless, a variety of devices, including mirrors and modest-size tokamaks, have been built in the United States, Europe, Japan, and the U.S.S.R. Their successful operation has paved the way for wider application.

Four major superconducting initiatives were undertaken in the mid to late 1970s: two TFTR-scale tokamaks, the Soviet T-15, and the French Tore Supra (which will operate in 1988); the Mirror Fusion Test Facility (MFTF) at LLNL; and the Large Coil Task (LCT) at ORNL. Both the MFTF-B and the LCT coils have operated, at their full fields of 7.5 and 8 T, respectively. In the LCT, six 45-ton coils [about half the scale required for an Engineering Test Reactor (ETR)] were built, respectively, by General Dynamics, General Electric, Westinghouse, Brown Boveri (Switzerland), Hitachi (Japan), and Siemens (Federal Republic of Germany for Euratom). All coils have been operated above their nominal current at 8 T or even as high as 9.2 T (at 140% of the rated current in some cases). For the future, work is under way in the international program to develop 12-T coils for an ETR.

Materials. Three main classes of materials must be developed and tested for magnetic fusion: materials to line the inside of the vacuum vessel that can withstand plasma particle bombardment; materials for the vacuum chamber and support structure, which must retain structural integrity in the face of multiyear bombardment by fusion neutrons; and specialized



materials such as insulators and the lithium compounds required for tritium breeding. Progress has been good in all areas.

Specialized forms of carbon have proven effective in handling the plasma edge conditions, and beryllium has been tested as an alternative in collaborative efforts by JET, ORNL, and Sandia National Laboratory. Variants of stainless steel have been developed that exhibit substantially increased resistance to neutron damage in tests at Hanford Engineering Development Laboratory, Idaho National Engineering Laboratory, and ORNL. Initial tests of lithium blanket components at Argonne National Laboratory and other laboratories are encouraging. A key area for the ongoing program is the development of vacuum wall and structural materials that have a low induced radioactivity. Several candidates are being studied, including modifications of steels and vanadium alloys.

Safety, environment, and economics. Numerous studies of the safety and environmental aspects and economic potential of magnetic fusion have refined the understanding of what is required to make fusion a viable energy source. Projected needs in the technology area appear to be a reasonable extrapolation from current experience, although the developmental challenge is substantial. These studies continue to show that, compared with the major energy alternatives, fusion has the potential to offer competitively priced power without adversely affecting the environment.

Physics Progress in the 1980s

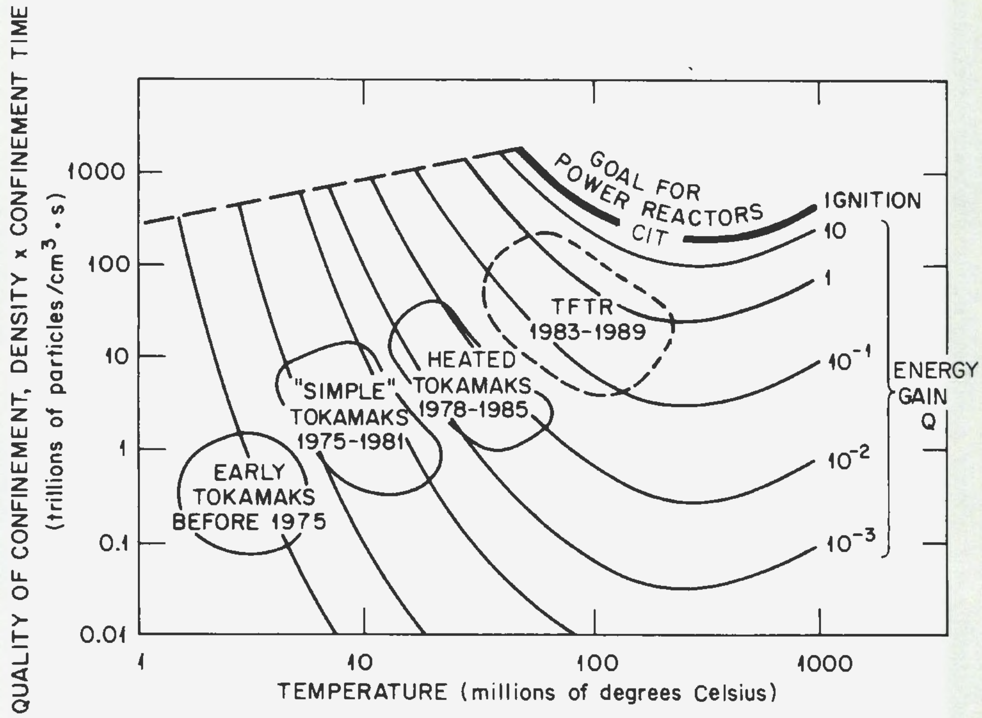
Using these improvements in the supporting disciplines, the program is now focusing on five toroidal physics areas:
- the connection of theory and experiment in confinement,
- beta limitations,
- methods of driving currents in plasmas,
- particle control and minimization of impurities (matter other than hydrogen), and
- the physics of D-T burning plasmas.

Confinement. In tokamaks, stellarators, and mirrors, conditions have been set up in which the ion heat losses are no more than the levels predicted to result from collisions between the plasma particles. At these loss levels, there is a wide margin for designing an efficient reactor. However, under certain conditions the losses exceed the collisional level.

Progress has been made in understanding such behavior, and remedial action has worked in some situations. It is generally observed that the electron heat losses far exceed calculated values. The connection between theoretical models of this behavior and experimental results is a topic of current research. In the absence of proven theory, we rely on empirical models that are based on the wealth of experimental data, much as we rely on such empiricism to calculate the flow of water through a pipe. Confinement times of about 1 s have been achieved in TFTR and JET.

Beta. As the pressure increases in a magnetic confinement device, currents are induced that modify the magnetic field. As a result, the plasma can become unstable and, generally, a beta limit is reached in which the plasma can no longer be stably supported by the field. It has been suggested that the magnetic confinement of plasma is analogous to trying to hold a blob of jelly in a mesh of elastic bands. This is the case in a conventionally operated tokamak, stellarator, or RFP. However, progress has been made toward reaching a reactor level of stability. The DIII-D tokamak at GA Technologies has sustained a beta of 6%. The RFP has already achieved 15% beta; a new device (ZT-H) is being built at LANL to advance the concept further.

In the 1970s, researchers at the Massachusetts Institute of Technology (MIT) and in France realized that, in a conventional tokamak, if it were possible to raise the pressure even higher than this initial limit, the plasma could again be held stably. Two theoretical solutions have been found which lead to this so-called "second stability" region: a tokamak having

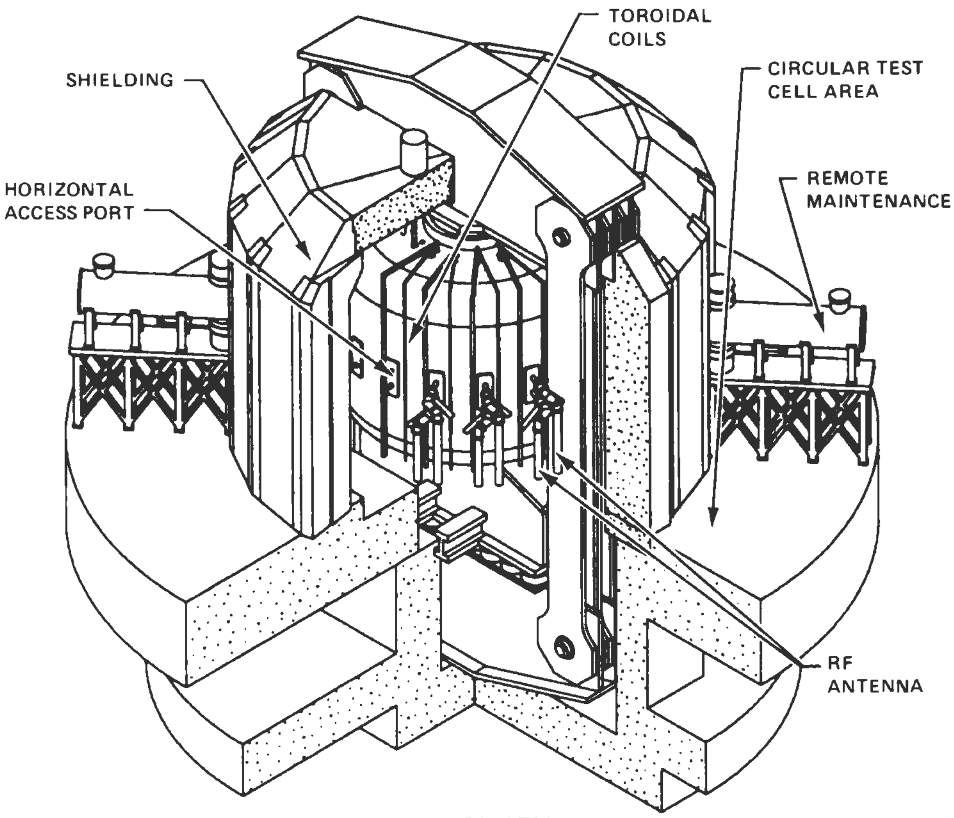


a modified plasma cross section, or "bean" (Princeton Beta Experiment), and a carefully designed torsatron (ATF at ORNL). In the compact torus, very high beta (up to 90%) has been achieved, and a new device to increase understanding of this configuration will be built by Spectra Technologies.

Current drive. A weakness of the basic tokamak and RFP is that their plasma current is driven by a transformer action, which limits the pulse length. In contrast, stellarators require no plasma current and are inherently capable of running continuously as long as the plasma is heated. The key development issues are efficiency of the drive and control of the current distribution in the plasma. Techniques for driving plasma current by the use of rf waves have been developed, notably at MIT and Princeton. These techniques allow the tokamak to operate continuously and give a measure of plasma control, which should lead to enhanced performance. An alternative method, which uses the oscillation of the confining fields, has been proposed for the RFPs in England and at LANL. A new development, which may alleviate the problem, is the observation on TFTR of the "bootstrap current" driven naturally by the plasma pressure gradient; it has been given this name because it is theoretically predicted to be "picked up by its own bootstraps."

Particle control and impurities. The use of various kinds of divertors and fueling by pellet injection has led to much better particle control, which has in turn contributed to the improved confinement of plasmas—near the level needed for a reactor.

Slow progress in the early days of fusion often resulted from plasma contamination by impurities—materials other than hydrogen coming from the walls surrounding the plasma and from air leaks. At high temperatures, such impurities radiate large amounts of electromagnetic radiation, which cools the plasma. In modern experiments, careful



CIT FACILITY

attention is paid to cleanliness; the choice of wall materials near the plasma, such as carbon, which do not radiate significantly; techniques for isolating the plasma from the walls (divertors); and techniques for flushing impurities from the plasma—note that ultimately in burning D-T plasmas, the helium produced by fusion must be removed. A simplified divertor developed on the DIII tokamak at GA Technologies is being used on a variety of tokamaks and will be used on the Compact Ignition Tokamak (CIT).

D-T burning plasmas. The TFTR at Princeton and the European JET tokamak are the first experiments designed to use D-T fuel. They have the potential to produce as much power from fusion as is used to keep the plasma hot. Under this "breakeven" condition (known as $Q = 1$), the alpha power in the plasma will be 20% of the externally applied power, and the plasma will not be self-sustaining—"ignited." Therefore, this achievement will give only a first glimpse of the fusion process.

The CIT, by contrast, is designed to go to the ignited state in which the plasma is entirely sustained by the fusion alpha power. Following the development of the CIT, an ETR will be constructed that can extend the burning plasma over much longer periods and validate technology and engineering solutions. The ultimate development will be a power-producing fusion reactor.

Summary

Fusion research has been characterized throughout its history by its breadth of requirements in physics and technology, by the innovativeness of its contributors, and by the extent of its collaborative ventures. The program has often been criticized for retaining such breadth, but a study of its history shows that the program has not been reluctant to stop nonproductive lines of research or to revisit old areas when innovation revitalizes them. However, the time scale for most carefully documented tests is at least 5 years; consequently, changes tend to occur on the timescale of a decade.

The tokamak is the most successful of the magnetic bottles, and because we know it so well, we can more readily see its faults. In the international program, we are working to overcome tokamak weaknesses and to understand the tokamak and related configurations so that we can identify the most attractive configuration. At the same time, while focusing on both the ongoing program and on the future, we are developing the supporting theory, diagnostics, computing, and technology necessary to support fusion applications.

This brief history of fusion progress shows that international collaboration has played a key role in the development of fusion. The emphasis on collaboration is increasing—multinational efforts have been organized under the auspices of the International Atomic Energy Agency, the International Energy Agency, and various bilateral agreements.

An important new initiative is the proposal for joint studies of an ETR—the International Thermonuclear Experimental Reactor (ITER)—by the United States, the European Economic Community, Japan, and the U.S.S.R. The ITER will follow CIT, and with parallel development programs in theory, diagnostics, advanced concepts, and technology, it will establish the scientific and technological base for fusion energy. ornl

International Fusion Magnets Set World Record

A new world record has been set, and major milestones have been reached at ORNL in the development of superconducting magnets for fusion power. These achievements were noted at a September 28, 1987, ceremony celebrating the recent completion of the test program of the International Large Coil Task (LCT).

Over an 18-month period, six experimental magnet coils from four countries and three continents were extensively tested to determine their operating limits. In the final test on September 3 at the International Fusion Superconducting Magnet Test Facility, all six coils showed they could operate well beyond their original design goals.

The six D-shaped coils, each 6 m (20 ft) tall and weighing about 40 tons, reached peak magnetic fields of 9 teslas (T)—180,000 times the earth's natural magnetic field. The design goal for the coils was 8 T. The force on each coil in the final test exceeded 5000 tons.

"No other magnet this large—in terms of size, weight, or stored energy—has achieved such a high field strength," said Paul N. Haubenreich, manager of ORNL's Large Coil Program and the U.S. project officer in the $180-million International LCT.

"All our original goals were achieved," said Haubenreich of the six-coil array tests. "By testing six different, highly instrumented coils that gave revealing information, we can identify the magnet designs and manufacturing techniques that could provide reliable, cost-effective magnet systems for fusion power.

"Another result of the LCT program," he added, "is that the industries and laboratories involved developed capabilities for designing and building superconducting magnets. Also significant for the future of fusion is this demonstration that the development of high-tech hardware can be achieved efficiently through international collaboration."

The LCT experiment marks the first time that four countries—the United States, Federal Republic of Germany, Japan, and Switzerland—have contributed different versions of the same equipment to a fusion hardware experiment and collaborated in tests to evaluate equipment performance, reliability, and economics.

With ORNL as the leading laboratory, DOE supported the development of the three U.S. coils. They were designed and constructed primarily by General Dynamics Convair Division, General Electric Company, and Westinghouse Electric Corporation.

The EURATOM coil was designed and built by Siemens in West Germany under the leadership of the Nuclear Research Center at Karlsruhe. The coil of the Japan Atomic Energy Research Institute (JAERI) was designed and built by Hitachi under the guidance of the Tokai laboratory. And the Swiss coil was designed and built by Brown Boveri Company in cooperation with the Swiss Institute of Nuclear Research.

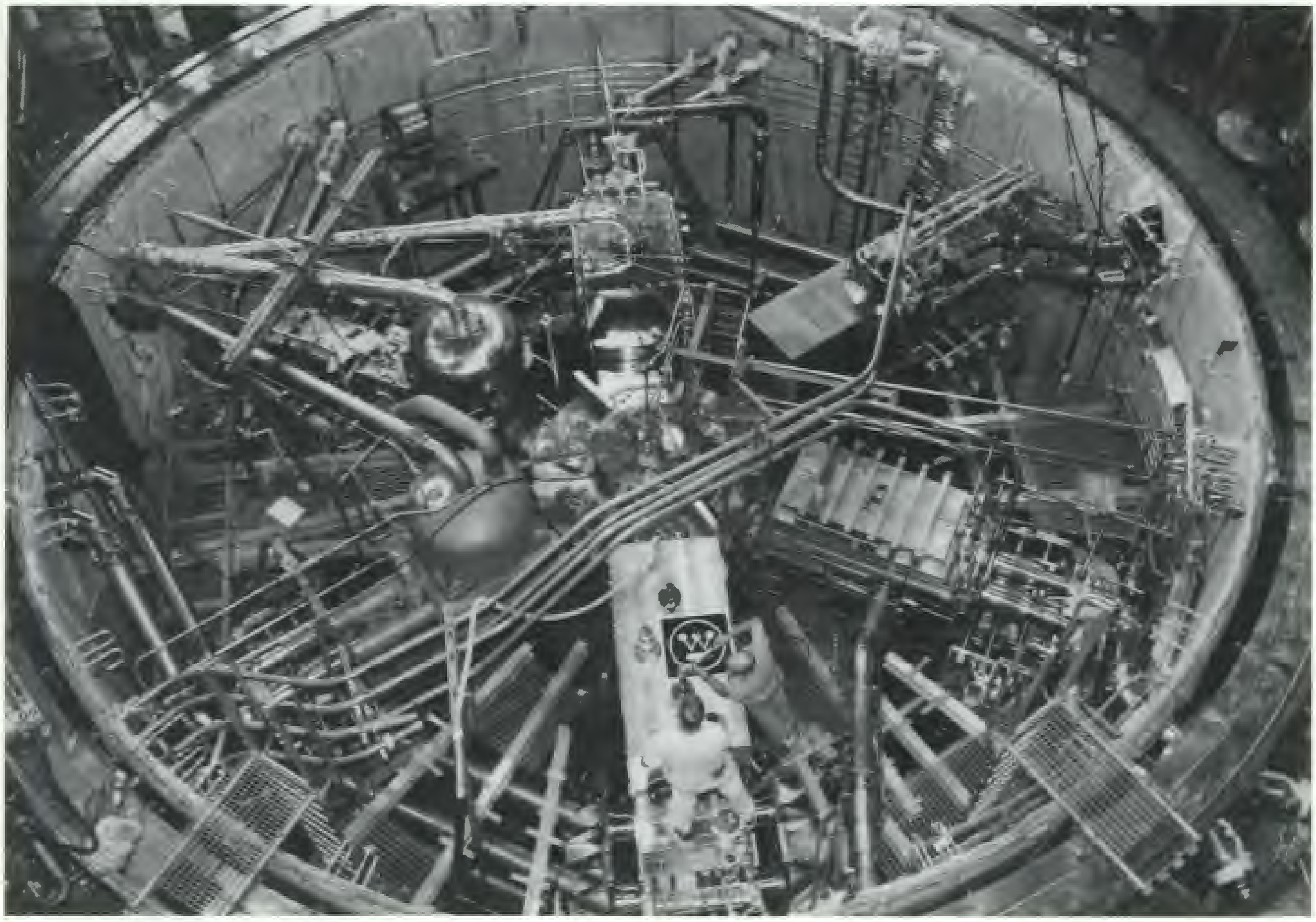
The LCT concept originated in 1975, and the international collaboration was formally organized in 1977 through the International Energy Agency. The $36-million test facility, in ORNL's Fusion Energy Division at the Oak Ridge Y-12 Plant, was completed in December 1983.

After installation and shakedown of the facility with the first three coils, assembly of the six test coils (and two pulsed coils to simulate the operation inside the vacuum tank extended from November 1985 through September 1987. Cooldown to the operating temperature of −452°F and test operation inside a vacuum tank extended from November 1985 through September 1987.

The project has produced valuable data that will help participants design and build magnets twice as large for fusion machines designed to produce electricity. Jointly, they are comparing the performance, reliability, and economics of different magnet designs and manufacturing processes.

In a magnetic fusion reactor, the hydrogen fuel—a plasma, or gas composed of charged particles, that is heated to 100,000,000°C—will be contained within the reactor vessel by strong magnetic fields that keep the superhot fuel away from the vessel walls. To make the fusion device an efficient power source, the electromagnets producing these fields must be large and powerful but use little electricity.

Copper magnets would consume large amounts of power to produce the strong magnetic fields required for big fusion devices. However, magnets made of conventional superconducting materials—metals



Six 40-ton superconducting magnet coils are positioned in the 35-ft-diam vacuum vessel of the International Fusion Superconducting Magnet Test Facility at ORNL. The 18-month test, completed in September 1987, established a world record for field strength—more than 9 teslas—in magnets of this size.

that have virtually no resistance to the flow of electricity when chilled by liquid helium to extremely low temperatures—use very little power. Most of the electricity needed for such a system is used for refrigeration to liquefy the helium.

Five of the magnets tested at ORNL have superconducting filaments made of niobium-titanium. The superconducting material of the Westinghouse magnet, however, is niobium-tin. The Westinghouse magnet also differs from the other five coils in its support structure; it has bolted aluminum plates, whereas the structures of the other coils are stainless steel.

Liquid helium was used to cool the conducting material of all six coils by two different methods. In three coils, helium at 15 times the earth's atmospheric pressure was forced to flow through channels in the conductors. In the other three coils, conductors were immersed in a bath of helium that filled the structural shell of the coil.

Preliminary analysis of the results of the LCT tests shows that

- both forced-flow and bath cooling methods are practical for large coils, but each has distinctive advantages that can now be evaluated; and
- the niobium-tin conductors could perform at full potential if manufacturing flaws that limit the performance of the material are eliminated.

Analysis of all the test data and comparative evaluation of the features of the six coils will require several more months. A joint technical report by the LCT participants, comparing performance and reliability of different designs and manufacturing procedures, is expected in the spring of 1988.

The ATF—ORNL's New Fusion Device To Begin Operation Soon

ORNL's new experimental fusion device, which will begin operation soon, will pave the way for improvements in toroidal (doughnut-shaped) magnetic fusion devices. Called the Advanced Toroidal Facility (ATF), this $20-million experiment has already won an engineering prize because of its precise fabrication and positioning of large components.

The ATF is a stellarator which, unlike the more widely studied tokamak, uses only externally applied magnetic fields to confine a plasma (a hot gas of free electrons and positively charged ions). In the fusion reactor of the future, the plasma will be fueled by the hydrogen isotopes, deuterium and tritium. Kept hot enough and dense enough, the plasma can sustain fusion reactions that result when the superheated ions overcome their natural repulsion and eventually fuse. Fusion reactions release large amounts of energy, which can be used to perpetuate the fusion process or be converted to electricity.

Long-awaited vessel. In June 1987 the 9-ton circular vacuum vessel was delivered to ORNL's Fusion Energy Division at the Oak Ridge Y-12 Plant, about a year later than expected. The vessel, the last of the ATF components to arrive, was difficult to build because of the tight dimensions of the design. The vessel was manufactured by the Pittsburgh Des-Moines (PDM) Corporation.

In 1986 the twenty-four 1400-kg (3000-lb) segments of the two spiraling (helical) magnetic coils were connected with a precision of up to 0.25 mm (0.05 in.) over distances of about 3 m (16 ft). The parts for the segments, which now wind around the vessel, were built by Chicago Bridge and Iron (CBI) Company.

In 1987 the ATF received an Energy Resources Technology Award from the American Society of Mechanical Engineers for fabrication meeting difficult dimensional specifications. The ATF was cited as "one of the most outstanding examples of advancing mechanical engineering in energy-resource-related technology."

In addition to the vacuum vessel (to contain the plasma) and the helical field coils (to produce twisting magnetic fields), the ATF consists of three sets of poloidal coils and a doughnut-shaped structural shell to support the magnetic loads. The poloidal coils were built by the Princeton Plasma Physics Laboratory (PPPL) Coil Shop, and the shell was built by Westinghouse Electric Corporation.

The ATF has been connected to the services required for its operation, such as water and electricity for the copper coils, vacuum pumps for the vessel, and neutral-beam injectors to heat the plasma to 30 million degrees Celsius.

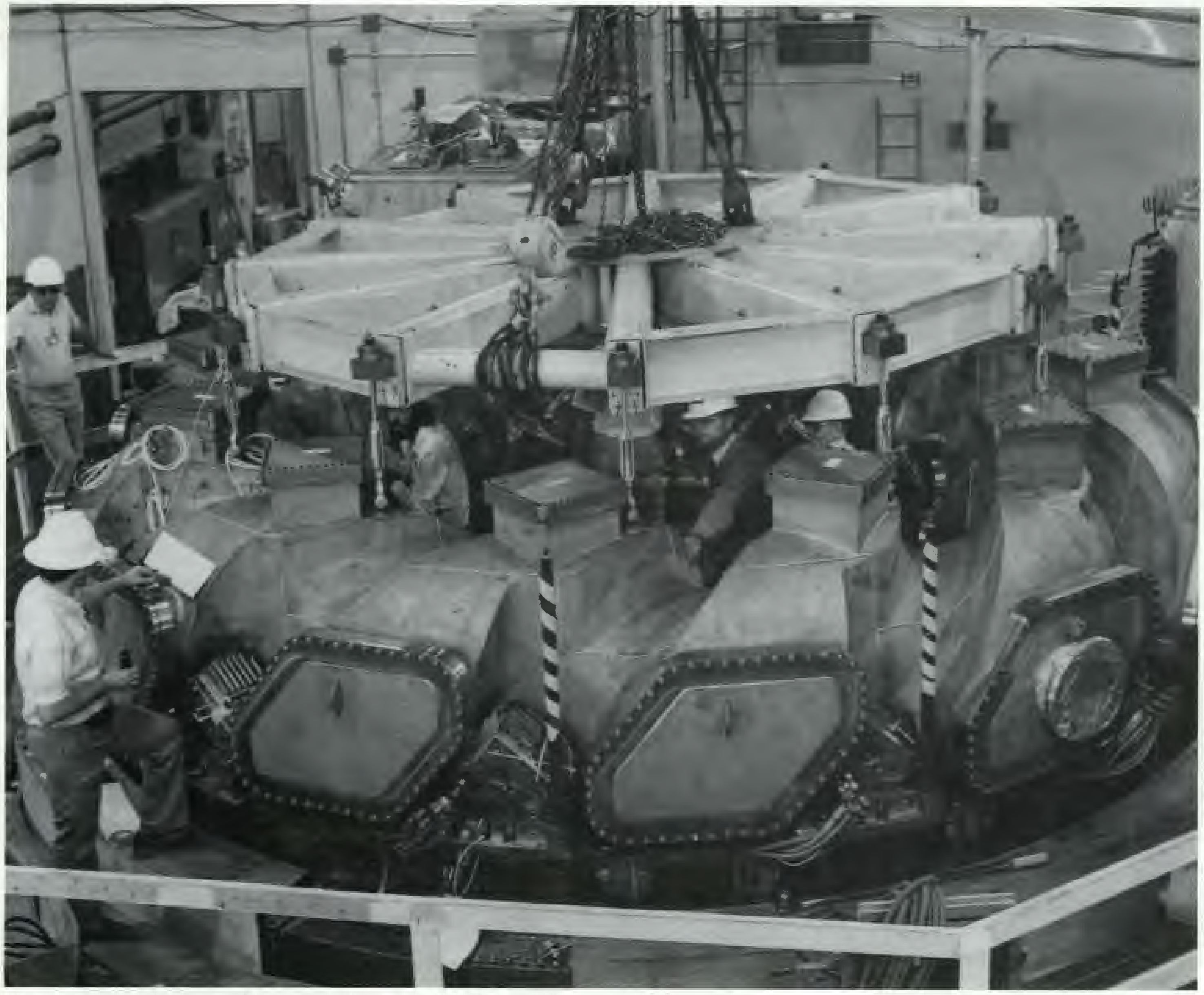
The high-precision design, fabrication, and assembly of ATF components resulted from collaboration among personnel from ORNL's Fusion Energy Division, the Maintenance Division of the Y-12 Plant, Westinghouse Electric Corporation, CBI, PDM, PPPL, and the Engineering and the Computing and Telecommunications divisions of Martin Marietta Energy Systems, Inc.

Scientific case for the ATF. Several types of toroidal fusion devices exist. The most commonly studied is the tokamak, which was developed in the Soviet Union in the 1950s. Other related concepts are the stellarator, invented in the United States, and the reversed-field-pinch (RFP) device, invented in Great Britain.

All fusion devices must be designed to accomplish three objectives simultaneously: achieve a high plasma pressure, adequately confine the plasma energy, and sustain the hot plasma.

One method of retaining the plasma energy is to use a magnetic field to confine it and keep it away from the wall of the vacuum vessel. A principal cost issue is, how much plasma pressure can be supported by a given magnetic field. Beta is the plasma pressure taken as a percentage of the magnetic pressure. A desirable beta is 10%.

For a fusion reactor to be cost effective, it should support a plasma pressure of about 10 atm using a magnetic field of about 5 teslas. The amount of fusion power generated is proportional to the square of the plasma pressure. Thus, the higher the plasma pressure, the more power is produced. However, the high-pressure plasma must be contained by strong magnetic fields, which require huge magnetic coils. The cost of the device depends to a



Workers inspect the new ATF vessel, which arrived in June 1987.

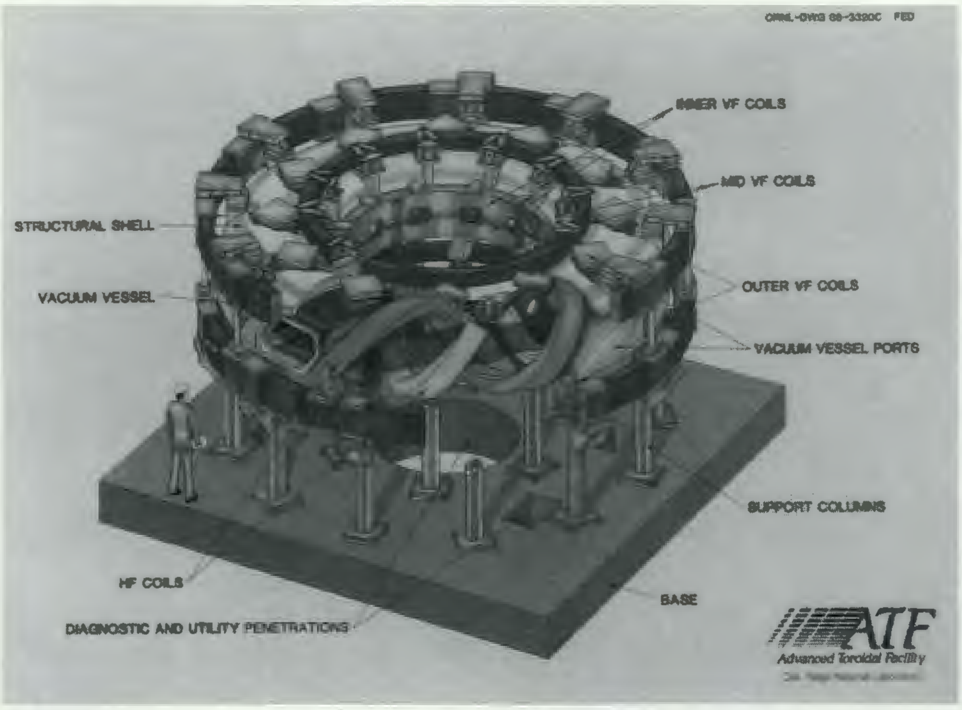
large degree on the size of the coils.

Each type of toroidal device produces a characteristic "magnetic bottle" (i.e., a plasma contained in a special shape conferred on it by the device's magnetic field configuration). Different magnetic bottles have differing abilities to support high beta and thermally isolate the plasma from the wall.

The tokamak has achieved the best simultaneous values for both beta and confinement. The RFP has achieved the best beta but has not yet achieved a high level of confinement. The stellarator has achieved intermediate values for both beta and confinement.

The tokamak and RFP use a plasma current to provide part of the magnetic bottle; to operate in the steady state, additional systems would be required to sustain the plasma current. The stellarator is inherently steady-state (because its fields are produced entirely by currents flowing in external coils) and offers the possibility of a less complex reactor embodiment. Until recently it was thought that stellarators like the ATF would not be able to realize a reactor level of beta. However, through the use of sophisticated computer analysis, ORNL scientists developed the ATF configuration, which theoretically can achieve high beta levels.

In the U.S. fusion program, the mainline device is the tokamak.



Model of the ATF, a fusion research machine that will explore the physics of beta limits and second stability and may guide the improvement of toroidal magnetic fusion devices.

Research on the stellarator and the RFP is undertaken as part of a broader world program to develop the overall best fusion device.

ATF is a torsatron. The ATF is a torsatron, an improved version of a stellarator. The stellarator, which was developed in the early 1950s at Princeton University, has pairs of helical coils that carry currents in opposite directions; the torsatron coil current is carried in only one direction around the torus. The ATF device is an optimized torsatron that theoretically can achieve high beta (5–10%), maintain good confinement, and operate in the steady state.

In addition to its high beta and steady-state operation, the ATF will be efficient because of its low thermal conductivity. That is, its plasma will be heated easily and be kept at a constant high temperature, with minimal heat loss.

The key to the ATF's capabilities is its special magnetic field configuration in which one set of coils spirals around the torus to generate a helical field and another set of coils runs along the torus to generate a poloidal field. The combination of the two field sets gives the ATF a unique flexibility to explore the physics of beta limits and, in particular, the concept of second stability.

In most configurations, as the plasma pressure is raised, the magnetic field of the bottle is disturbed in a way that decreases the ability of the bottle to support the plasma. Thus, at some limiting beta, the system becomes unstable and the plasma is lost. Theoretically, in both tokamaks and in certain stellarators such as the ATF, the increasing pressure can act to improve the bottle, giving access to a second region of stability. In conventional tokamaks, an unstable gap exists between the two regions, whereas in the ATF there should be direct access to this higher-beta region.

Direct access to second stability in the ATF is possible, in part, because of the device's relatively small aspect ratio. Aspect ratio is the ratio of the major radius of a torus to its minor radius; thus, a bicycle tire has a large aspect ratio, whereas an automobile tire has a small aspect ratio.

Because of its external coils and flexible configuration control, the ATF is the best device for studies of second stability. Understanding this important concept will guide the improvement of tokamaks and stellarators.

ORNL's studies of various kinds of stellarators have had a major influence on the designs of other stellarators in the international program. Information provided by the ATF combined with that obtained at tokamaks and stellarators in the United States, Europe, Japan, and the Soviet Union could contribute to the development of toroidal fusion devices that will be reliable and economical sources of electrical power.—*John Sheffield.* ornl

Ralph N. McGill of ORNL's Energy Division is manager of the Department of Energy's Federal Methanol Fleet Demonstration Project. He is also a project management staff member of the Alternative Fuels Utilization Program in the Engineering Technology Division. A native of Charlotte, North Carolina, he holds three degrees in mechanical engineering, including a Ph.D. degree, from North Carolina State University. From 1969 to 1978, McGill was associate senior research engineer at General Motors Research Laboratories in Warren, Michigan. There he conducted research on fuel economy and emissions control of spark-ignition engines and helped develop electronic fuel-control systems for spark-ignition engines. McGill joined the ORNL staff in 1978 as a member of the Engineering Technology Division. He worked there on two-phase flow instrumentation for studying simulated loss-of-coolant accidents in light-water reactors. Later he conducted research on thermal energy storage. In 1982 he transferred to the Energy Division, where he managed research projects on ground-coupled heat pumps and developed computer models of vehicular fuel consumption and emissions for the Federal Highway Administration. He has worked in his current positions since 1984.

Introducing Methanol-Fueled Vehicles

By RALPH N. MCGILL

In fiscal 1985, the U.S. Congress started the Federal Methanol Fleet Demonstration Project. It directed the Department of Energy (DOE) to assess the performance of vehicles that run on methanol—an alternative fuel alcohol that can be made from coal, wood, natural gas, or biomass. DOE began integrating methanol-fueled vehicles into its fleets under its existing Alternative Fuels Utilization Program, directed by E. E. Ecklund of the Office of Transportation Systems.

DOE then selected Oak Ridge National Laboratory to manage the project. I was named project manager and have been assisted in this task by Ron Graves, program manager of Alternative Fuels Utilization in ORNL's Engineering Technology Division (ETD); John Wantland of ETD; and Stephen Hillis of the University of Tennessee's Transportation Center. Today, ORNL participates in this national project not only as its manager but also as the newest site for one of the methanol fleets.

Between August and December 1987, ORNL placed ten special vehicles into service to begin its participation in the Federal Methanol Fleet Demonstration Project. Five of the vehicles are methanol-fueled, and the other five are comparably equipped gasoline-fueled cars. At the beginning of the ORNL participation, other DOE methanol fleets were already operating at Lawrence Berkeley Laboratory (LBL) and Argonne National Laboratory (ANL).

The fleet at ORNL is unique because it alone uses methanol made from coal. ORNL is purchasing the methanol from Eastman Chemical Products, Inc.,

in Kingsport, Tennessee. Eastman, which operates the only large-scale coal-to-methanol production plant in the United States, makes methanol from high-sulfur Appalachian coal. Thus, the ORNL methanol vehicles are operating on a liquid fuel derived from domestic coal—an example of how to use national energy resources to reduce reliance on insecure, foreign supplies of fuel.

Only the ORNL fleet uses turbocharged cars. Cars in the other fleets have a variety of engines of different types and sizes; some have mechanical carburetors, fuel injection, or high-compression-ratio engines.

Standing with two of ORNL's gasoline-fueled cars (to be used for comparison with methanol cars) in the Federal Methanol Fleet are, from left, Roger Carlsmith, director, ORNL Conservation Programs; Ron Graves, program manager, Alternative Fuels Utilization Program; Ted Fox, section head, Engineering Technology Division; Ralph McGill, project manager, Federal Methanol Fleet Demonstration Project; John Wantland, Federal Methanol Fleet Project staff; and Steve Hillis, University of Tennessee Transportation Center staff member assigned to the Federal Methanol Fleet Project staff.

The five methanol-fueled automobiles at ORNL were converted to run on methanol at the Michigan Automotive Research Corporation in Ann Arbor. The performance and operating characteristics of these five vehicles will be compared statistically with those same characteristics of the five similar gasoline-fueled vehicles. All ten ORNL vehicles are 1987 Buick Regals that are identically equipped except for the difference in fuel. The cars were not purchased by the government but were, instead, leased from Twin City Buick in Alcoa, Tennessee, for a minimum of 3 years and a maximum of 5 years.

The overall goal of the project is to demonstrate that the technology for methanol-fueled vehicles is mature enough for vehicles used in ordinary light-duty service.

ORNL is manager of the Federal Methanol Fleet Demonstration Project. In the fall of 1987 ORNL became the newest site for a methanol fleet—five gasoline-powered and five methanol-fueled Buick Regal cars. The project tests how well different types of vehicles altered by conventional technologies can operate on methanol—a fuel alcohol made from coal, wood, natural gas, or biomass. Early results from the project are reported.

Therefore, during the 3-to 5-year demonstration at ORNL, various assessments will be made of the vehicles' fuel economy, maintenance costs, engine wear characteristics, and emissions. Also, drivers will assess the vehicles' driveability and acceptability.

Operation of the ORNL fleet will conclude the first phase of the Federal Methanol Fleet Demonstration Project. A second phase will entail the purchase by the government of a large number of methanol-fueled vehicles and the placement of those vehicles into federal fleets in a number of locations. The start of a second phase will depend on action by the U.S. Congress.

The Alternative Fuel

Methanol, or methyl alcohol, is a carbon-hydrogen-oxygen (CH_3OH) compound. The simplest of the alcohols, it can be produced from natural gas, biomass, wood, or coal. Because all of these resources are abundant in the United States and because, in the long term, they may be less expensive than petroleum, methanol is considered one of the most likely substitutes for gasoline in meeting future transportation energy needs. Widespread use of methanol instead of gasoline in U.S. vehicles could considerably reduce both oil imports and the nation's trade deficit.

Methanol also offers an environmental benefit: methanol-fueled cars normally emit lower levels of hydrocarbons and oxides of nitrogen than gasoline-fueled cars, and the emitted hydrocarbons are believed to be less likely to promote the formation of photochemical smog. All methanol cars used in the project meet the 49-state federal emissions standards. Clearly, the introduction of methanol as fuel could benefit air quality as well as national energy security.

For a number of years, methanol has been used instead of gasoline at the Indianapolis 500 road race because of its higher octane and lower flammability. Taking advantage of methanol's higher octane (about 100, as compared with regular unleaded gasoline's octane of 87), the methanol-fueled Buicks at ORNL should have slightly more power than their gasoline counterparts.

The methanol used to fuel the vehicles in this project is not "pure" methanol but is known as "fuel methanol" because it consists of 85% methanol and 15% regular unleaded gasoline. The addition of the gasoline helps cold-starting of methanol vehicles, gives the fuel a bad taste (to discourage drinking of fuel), and makes a fuel fire more visible.

Methanol itself is poisonous and cannot be made nonpoisonous. Drinking methanol can cause blindness and even death. However, it is not considered to be any more hazardous than gasoline, which is also poisonous. Methanol is more biodegradable than gasoline and should be less harmful to the environment in the event of a spill.

The ORNL Cars

A number of changes must be made to a production gasoline car to make it run on methanol. Many of the elastomers (components made of elastic substances similar to rubber) and fuel-system components used satisfactorily in gasoline cars are incompatible with methanol; they must be replaced with methanol-resistant components. Furthermore, methanol contains only one-half the specific energy of gasoline; thus, the fuel system must deliver about twice as much methanol as gasoline in a similar operating condition. To achieve this goal, flow capacities and fuel-tank capacity must be increased, and changes must be made in the electronic engine controller, ignition timing, and other engine specifications. If these alterations are made properly, a methanol vehicle should perform quite satisfactorily and, in many cases, with more power than the gasoline vehicle.

For the Buick Regals, the production 68-L (18-gal) fuel tank was replaced with a stainless steel 106-L (28-gal) fuel tank; as a result, the driving range for a single tank of the methanol Buick is about the same as that of the gasoline Buick. Many of the components of the converted vehicles are quite expensive because they are specially made. For example, each of the methanol Buicks has two electric fuel pumps made to be compatible with methanol—each costing $400. The total cost of converting each of the ORNL Buicks was $16,000, which was less than that for some of the other conversions in the project and more than that for others.

Some commonly asked questions and answers about the ORNL cars are:

• **Why turbocharged Buick Regals?** A program policy guideline established at the beginning of the project for Phase I dictated that only "tried-and-proven" technologies would be used for converting gasoline vehicles to methanol operation. By using all available proven technologies, an informed decision can be made about which technology should be used for the large number of vehicles to be purchased for Phase II. All available tried-and-proven technologies, except that associated with turbocharged Buick Regals, had been used for converting the LBL and ANL vehicles. The turbocharger feature of the Buick Regal allows the engine to exploit the methanol's high octane without requiring an expensive and difficult-to-obtain higher-compression-ratio engine. The 3.8-L, V-6 General Motors (GM) engine is the only reported turbocharged gasoline engine in this country that has previously been converted to a methanol engine. Because GM uses this engine only in its Buick Regals, Regals were selected for the methanol fleet tests at ORNL.

• How are these cars being used at ORNL? They are supplementing the regular transportation needs of various Laboratory divisions. As with all other passenger vehicles in fleet operation at ORNL, they are for official use only.

• Who can use the vehicles? They have been assigned to nine divisions, and the division directors specify who can use the vehicles. One has also been assigned to DOE's Oak Ridge Operations. The participating divisions were chosen by random selection from the applications of the interested divisions.

• How much do the cars cost? They have been leased, not purchased. The average monthly cost is $400 per car for the 36-month lease period. Options are available for fourth- and fifth-year leases, and the lease costs will decrease greatly during those years, if the options are exercised.

• Where can methanol be obtained for filling the cars? A methanol filling station was prepared at ORGDP at a cost of $12,500. To keep the cost down, a surplus underground storage tank is used to hold the fuel. A new fuel pump, fuel lines, and electrical hookups were added to operate the station.

• How much does methanol cost relative to gasoline? Currently, in the United States, methanol costs between 35 and 40¢/gal—untaxed and undelivered. Methanol has only about one-half the energy content of a similar quantity of gasoline; thus, at this methanol cost, it equates to about 70 to 80¢/gal of equivalent energy in gasoline (also untaxed and undelivered). Current Tennessee and U.S. taxes on gasoline total 21¢/gal.

Results from Operating Fleets

Lawrence Berkeley Laboratory fleet. The LBL fleet, which has been operating since November 1, 1985, uses ten 1984 Chevrolet Citations having 2.8-L, V-6 engines and mechanical carburetors. Five of the Citations were converted to methanol operation by the Bank of America, which operates its own fleet of about 300 methanol vehicles. The conversion involved replacing fuel-line and carburetor materials, nickel plating of the carburetor, enlarging the fuel metering jets, replacing the head gaskets, and installing a larger fuel tank.

The ten Citations in operation at LBL have logged over 320,000 km (200,000 miles). Methanol-related problems have been few and simple. Drivers have accepted the methanol vehicles as completely satisfactory in performance, although they have expressed some uneasiness about the scarcity of refueling locations. Survey information from the drivers indicates that they are favorably impressed by both the gasoline and methanol vehicles and that they show no statistically significant preference for one over the other. The LBL methanol fleet experience has been deemed satisfactory in terms of project management and achievement of project goals. Some interesting summary data from the LBL fleet operation is presented in Table 1.

Argonne National Laboratory fleet. The ANL fleet, which has been in operation since the fall of 1986, consists of 19 vehicles, 10 of which are fueled by methanol. Ten vehicles are Chevrolet S-10 pickup trucks having 2.5-L, 4-cylinder engines and throttle-body fuel injection. Five of the S-10s use methanol; five, gasoline. The other nine vehicles, five fueled by methanol and four by gasoline, are Ford Crown Victorias having 5-L, V-8 engines and sequential-port fuel injection. The Fords are used by the Argonne security forces as patrol vehicles, and the S-10s are used by various Argonne maintenance personnel for transportation around the laboratory site. The methanol vehicles at ANL all have compression ratios of about 11:1 vs the standard 8:1, thus taking advantage of the high-octane feature of methanol.

Because ANL is located in the Chicago area, where temperatures on many winter days remain below freezing, the Argonne vehicles have been outfitted with special features for cold-starting and cold-weather operation with methanol. Normally, methanol vehicles do not operate well in cold climates. The Congress, when mandating this project in fiscal 1985, recognized that the cold-weather problem could inhibit the

Table 1. Fleet data summary—Lawrence Berkeley Laboratory (Through July 15, 1987)

	Total miles[a]	Average miles[a] per trip	Average fuel efficiency (mpg)	Average energy efficiency (km/GJ)
Chevrolet Citations				
Methanol (5 vehicles)	62,658	37.2	11.5	276
Gasoline (5 vehicles)	115,403	49.6	24.1	318
Total	178,061			

[a]1 mile = 1.6 km.

Table 2. Fleet data summary—Argonne National Laboratory (Through July 1, 1987)

	Total miles[a]	Average miles[a] per trip	Average fuel efficiency (mpg)	Average energy efficiency (km/GJ)
Chevrolet S-10 pickups				
Methanol (5 vehicles)	25,389	15.5	9.4	220
Gasoline (5 vehicles)	29,015	14.9	16.5	218
Ford Crown Victorias				
Methanol (5 vehicles)	41,506	7.6	6	140
Gasoline (4 vehicles)	67,237	8.8	10.3	136
Total	163,147			

[a]1 mile = 1.6 km.

introduction of methanol as a national alternative fuel. Thus, it required the testing of at least one methanol fleet in a cold climate. The ANL fleet satisfies this requirement, but special equipment is needed to operate the methanol vehicles in winter.

Auxiliary starting systems are installed on both the methanol-fueled S-10s and the Crown Victorias to aid in cold-starting at temperatures as low as −29°C (−20°F). In the S-10s, the auxiliary system is a gasoline-only system, whereas the Fords use a proprietary system developed by Ford Research to enable the methanol vehicles to start at low temperatures using a methanol-gasoline mixture.

Methanol-related failures have occurred in both types of vehicles at Argonne, but it has not been determined whether the failures are generic to methanol and cold weather or are the result of oversights during vehicle conversion to methanol operation. Nevertheless, the problems have been significant and have put vehicles temporarily out of service. When the sources of and solutions to the problems are identified, the Argonne project should proceed to a successful conclusion. Some summary data from the operation of the Argonne fleet are presented in Table 2.

ORNL fleet. For the methanol Buicks at ORNL, no special provisions have been made for cold-weather operation even though winters in Oak Ridge can include several frigid days. A commercial customer who purchased some methanol Buick Regals converted by the same company as the ORNL fleet reported experiencing no problems with winter operation in a climate even colder than that of Oak Ridge. On the basis of that experience, we decided no provisions would be made for Oak Ridge's cold weather. Should temperatures hover around −17°C (0°F)—a worst-case situation—we expect that the methanol Buicks will be difficult, but not impossible, to start. Comparing the cold-weather operation of the ORNL and ANL fleets will help us determine which winter provisions are most needed for production methanol vehicles.

Data from operating the ORNL fleet is much too preliminary to form any conclusions.

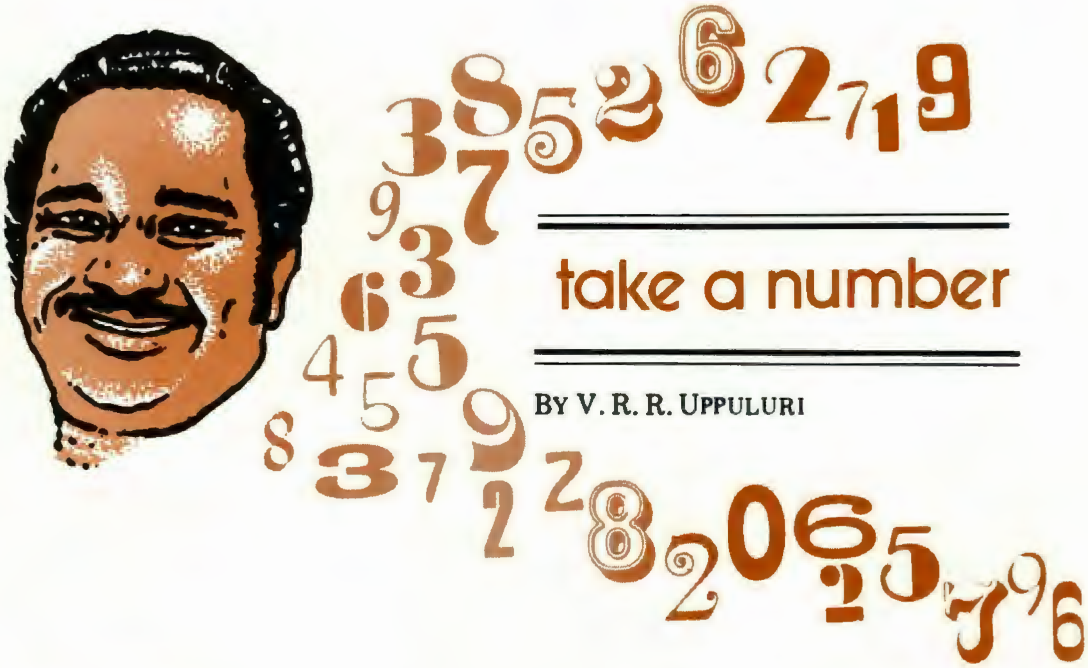
The Future

Congress has not approved an appropriation bill to provide funds for Phase II of this project. A number of bills currently being considered in Congress would constitute the essence of a Phase II. Some of the bills propose that the federal government purchase as many as 5000 methanol vehicles per year, starting in fiscal 1990. Others seek to promote the manufacture of methanol vehicles by offering certain incentives, such as credits toward the Corporate Average Fuel Economy requirements, for "flexible-fuel" vehicles—cars that can run on gasoline, methanol, or any mixture of the two. In short, it

The first load of methanol for the ORNL fleet is delivered to the fueling station at Oak Ridge Gaseous Diffusion Plant. Methanol is being purchased from Eastman Chemical Products in Kingsport, Tennessee, where methanol is made from coal.

is not clear what Phase II will be, if it comes about at all.

In the meantime, the objective for the remainder of Phase I is to take data from each of the operating fleets for at least two years and to continue operating the methanol cars through their useful lifetime. After accumulating and analyzing two years' data, we should be able to determine the relative merits of the technologies used to convert vehicles to methanol operation. Conclusions of this assessment will be an important milestone in the ORNL-managed Federal Methanol Fleet Demonstration Project. ornl



take a number

BY V. R. R. UPPULURI

More Prime Numbers

The number 733,333 is a prime number because it is divisible only by 1 and itself. However, 33,333 and 2,733,333 are not prime numbers because they are divisible by 3. Are many other numbers ending in 33,333 prime? The answer is yes. An infinite number of integers ending in 33,333 are prime (e.g., 1,133,333; 2,833,333; 3,233,333; 3,433,333; 3,733,333; 4,933,333; 5,633,333; 6,233,333; . . . 1,000,133,333 . . .).

A Paradox in Committee Elections

Because 1988 is a Presidential election year in the United States, Take a Number *will examine several different aspects of voting and elections from a mathematical point of view. My source for some of the concepts presented is Mike Hilliard of ORNL's Energy Division, who did his doctoral thesis at Cornell University on measures of voting power.*

• • •

A winner of the most votes in the election of a two-person committee in which each voter selects *two* candidates from a slate may not be a winner in an election in which each voter chooses *three* candidates from the same slate. Suppose that we have six voters (denoted by 1, 2, 3, 4, 5, and 6) and a slate of five candidates (denoted by A, B, C, D and E). The outcomes of the two types of two-person committee elections are different, as shown in the table:

Voter	1	2	3	4	5	6
(Top to	A	A	B	B	C	C
bottom	E	E	D	D	A	B
choice)	D	D	E	E	D	E

Note that in the election in which voters select 2 candidates, candidates A and B received 3 votes each and candidates C, D, and E received 2 votes each; thus, A and B are the winners. However, in an election in which each voter selects 3 candidates, D and E are the winners because they each received 5 votes, whereas A and B got 3 votes each and C received 2 votes.

In conclusion, a candidate elected to a two-person committee by a process in which voters have N choices (where $N =$ the number of candidates that each voter is allowed to select) cannot be certain that he or she would be elected if the voters have $N + 1$ choices. Organizations that elect persons to committees should be aware of this paradox.

EPA Adopts ORNL Test for Hazardous-Waste Toxicity

The U.S. Environmental Protection Agency (EPA) has adopted a new test developed at ORNL for characterizing hazardous wastes. The new procedure, called the Toxicity Characteristic Leaching Procedure (TCLP), will replace the EPA waste extraction procedure (EP) used for this purpose.

Under the Resource Conservation and Recovery Act, the EPA is responsible for defining the characteristics of those hazardous wastes that must be identified and managed in specific ways to protect human health and the environment. Wastes classified as hazardous or toxic under these rules include those that could release toxic constituents through leaching if disposed of in municipal landfills.

The TCLP is a waste-leaching procedure used to identify those wastes that would leach toxic constituents following disposal in a municipal waste landfill. The EP test has been limited by its inability to simulate a real-world disposal environment and to identify toxic organic compounds in wastes.

ORNL researchers Chet Francis of the Environmental Sciences Division and Mike Maskarinec of the Analytical Chemistry Division developed the TCLP by comparing concentrations of the toxic constituents measured in field leachates with concentrations measured in laboratory extracts. The TCLP procedure is unique because it is the first laboratory waste-extraction test to be validated using field leaching conditions. The ORNL researchers verified that the TCLP simulates disposal leaching conditions more accurately than the EP test.

ORNL Computer Model Demonstrates Learning

Some of ORNL's computers have "bugs." They are not the kind that smash into windshields, cause colds, or crash computer programs. They are "adaptive, synthetic insects" created by a program for personal computers that demonstrates that an artificial "neural network" can learn from and improve its responses to stimuli.

These bugs, the stars of a program developed by physicist William Dress of ORNL's Instrumentation and Controls Division, have simulated brains, eyes, mouths, and feelers. They can "eat" their computer "food" and explore the computer screen using simulated muscles.

According to Dress, the bugs must first learn about their environment before they can respond to it. "Each insect is created lacking any knowledge of its environment," he says. "It must learn how to respond to pain encountered at the edges of the computer screen and to pleasure available near the center of the screen, where the food is located.

"Evolution is also important in this model," says Dress. "The operation of the brain and its mechanisms for processing incoming data from the simulated sensory organs are just too complex for us to program in detail, so we let the bug 'tell' us the right parameters."

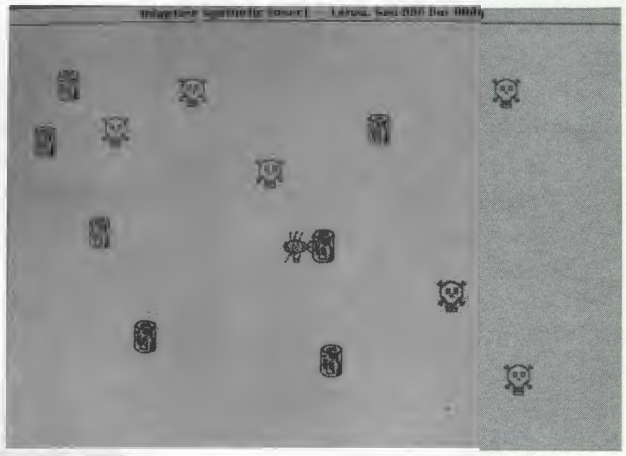
In the ORNL computer model, the synthetic, adaptive insect "brain" consists of around 200 simulated nerve cells, or neurons, each of which communicates to about 10 other neurons by means of connections. By contrast, more than 10 billion neurons make up the human brain, each communicating to hundreds, to perhaps 10,000, other neurons.

The human brain is also vastly superior to the ORNL program because its neurons operate simultaneously as a parallel processing machine. The ORNL simulation partially compensates for this lack of parallelism by using a very-high-speed microprocessor in conjunction with a personal computer.

To develop the model, Dress wrote a program for an Apple Macintosh personal computer that simulates the environment and serves as an experiment-control station for the insect. To simulate the insect's central nervous system, he uses a high-speed Novix NC4016 microprocessor that has nearly the processing speed of a much more expensive IBM 3033 mainframe computer.

Because of its highly parallel internal organization, this advanced microprocessor executes the neural network model at rates exceeding 100,000 connection updates per second—much more efficiently than the typical microprocessor. This speed allows the neural network to respond almost as quickly as humans do to new sensory information.

Bill Dress of the Instrumentation and Controls Division has developed a program for personal computers that demonstrates that an artificial "neural network" can learn from and improve its responses to its environment.



On the screen of an Apple Macintosh personal computer is a synthetic insect that learns from and adapts to its environment. After about 20 or 30 tries, spanning perhaps five or six generations, the bug's performance greatly improves —it learns to like the food (Diet Coke) and avoid pain (skull and crossbones).

"With a few hundred of these high-speed microprocessors, each processing a network of a few thousand 'neurons,' a reasonably large 'brain' could be built in the near future," says Dress. "It would have enough power and speed to give a robot the intelligence to learn and function in rather complex environments."

Why is evolution needed in the model? "We lack both the experience of creation and comprehensive theory of synthetic intelligence to design a viable, fully functional creature from scratch," notes Dress. "The model has about 50 parameters, representing neuron firing rates, intensity of touch and vision information, contraction strengths of muscle cells, and so on. Each of these parameters may be thought of as a gene ready to be improved in a process of evolution."

How does the evolutionary process work in the ORNL model? "The first few bugs barely functioned, ignoring the food and caring little about the pain," says Dress. "After a few generations, a descendant creature learns to avoid the edges of the screen—pain. It also learns to like its food when its 'taste buds' sufficiently evolve to convey the right frequency of information to its brain."

Each synthetic insect is allowed to bear one offspring at a time. The computer program measures the performance of the offspring and compares it to that of its parent. If the offspring shows no improvement over the parent, the computer program "kills" it and creates a new descendant by making a small random mutation to one of the parent's genes. After about 20 or 30 tries, spanning perhaps five or six generations, the bug's performance greatly improves—it learns to like the food and avoid the pain of the screen edges.

The neural network, which uses the principles of mutation and natural selection to "evolve" a neural architecture for a particular use, is designed to process information coded as the frequency of a train of pulses. Dress calls his computer simulation a frequency-based model of an artificial neural network.

The insect at the wall "feels pain" because it is receiving a "pinch" or a "jab" of high-frequency input from a few feeler cells. The high frequencies disrupt the flow of information through the network. Says Dress, "Being jabbed with a pin will break anyone's concentration." At the food center, the insect "feels pleasure" because it is receiving lower-frequency input from a much larger number of taste cells.

The ORNL work on "neural nets" is a step toward designing fully adaptive, synthetic intelligent systems to perform complex, boring, and dangerous jobs. As humans demand more from machines, the machines must function successfully without elaborate instructions in difficult and complex environments.

"In the future," says Dress, "you may be able to tell your house robot to 'go to the corner store and pick up a paper and a quart of milk, the kind I usually get.' No program known or seriously imagined today would allow a robot to carry out such complex actions that demand such detailed, common-sense knowledge."

Such a robot would have to know enough to decide which corner store was meant, to understand that "paper" referred to newspaper, not toilet paper or writing paper, and to accept a liter container of milk if a quart container was unavailable. In addition, the robot would have to know how to pay for the items and make sure that the returned change is correct.

"The robot must be *taught* all it needs to know to function at the factory or in the home," says Dress. "Today's computer programmer may be replaced tomorrow by a teacher or psychologist specializing in robot education and behavior."

Antibody-Laser Technique May Detect Toxic Chemicals

A new portable device that could sensitively and selectively measure human exposure to trace levels of hazardous environmental chemicals and infectious agents has been developed by ORNL and University of Tennessee (UT) scientists. The instrument could be used for early detection of cancer and to monitor patient response to drug therapy.

The device, a winner of a 1987 I•R 100 award from *Research and Development* magazine, is based on a unique concept combining recent developments in fiber optics, laser technology, antibody development, and immunofluorescence spectroscopy. This laser-based fiberoptics fluoroimmunosensor (FIS), which uses fibers as thin as human hair, could be used to analyze samples *inside* as well as *outside* the body.

ORNL and UT scientists have demonstrated that the FIS device can detect trace amounts of carcinogenic (cancer-causing) compounds and their metabolites (products of metabolism) in very small samples of body fluids and other complex mixtures.

Recently, the scientists used the technique to detect very small amounts of "DNA adducts" of the carcinogen benzo[*a*]pyrene (B*a*P) in body fluids; B*a*P is present in cigarette smoke and industrial emissions. DNA adducts are formed by metabolized products (in this case, B*a*P metabolites) that are attached to genetic material in cells. According to a current theory, DNA adducts disrupt genetic coding of the cells, possibly causing cancer. The FIS device can detect 1 femtomole (10^{-15} mole) of B*a*P in a 5-μL droplet.

Detection of specific carcinogenic chemicals and adducts that bind to DNA sites might be of importance in understanding the mechanism by which cancer develops. A goal of the ORNL–UT group is to extend the technique to detect a wider variety of carcinogenic chemical–DNA adducts in humans. The technique could then be used to screen for potentially adverse health effects from exposure to toxic agents in the workplace and in the environment.

The new technique could have several advantages over conventional immunoassays for detecting in blood samples tiny amounts of chemicals or viruses like HTLV-III/LAV, which causes Acquired Immune Deficiency Syndrome (AIDS). First, it requires much smaller samples—a few drops of blood obtained by a finger stick—and, thus, could be used for routine analyses in the clinic or at the patient's bedside. Second, results of analyses using this technique can be obtained much faster—in about 10 min vs hours. Third, by using a hairlike fiber as a "smart catheter," the technique could painlessly detect target chemicals within complex tissues inside the body, such as the wall of the stomach.

The FIS technique is preferable to the radioimmunoassay because it does not require expensive reagents and detectors, potentially hazardous radionuclides, and special precautions for shipping, handling, and disposing of the radioactive materials.

How does the FIS technique work?

Foreign substances and viruses in the body are known as antigens. Each antigen stimulates the body's immune system to produce a specific antibody that fits in a lock-and-key fashion into the antigen, rendering it harmless. The FIS device exploits the ability of an antibody to seek out and lock onto a specific antigen, just as a guided missile zeroes in on a target.

To determine whether a person has been exposed to a specific

This laser-based detector sensitively and selectively measures human exposures to trace levels of hazardous environmental chemicals and infectious agents. Fibers as thin as human hair are used as a kind of "smart catheter" to analyze samples inside as well as outside the body. Members of the development team, from ORNL's Health and Safety Research Division and the Chemistry Department of the University of Tennessee at Knoxville, are, from left, Tuan Vo-Dinh, Michael Sepaniak, Guy Griffin, Kathy Ambrose, and Bruce Tromberg.

chemical or virus using the FIS technique, a specific antibody to that chemical or virus must be made using well-established techniques. That antibody is then attached to the sensor tip of a hairlike optical fiber probe, which is introduced into a body fluid sample either inside or outside the body.

Any antigens present in the body fluid will bind to the antibody at the tip of the fiberoptics sensor. To detect the bound antigens, laser light having a frequency selected to "excite" the antigen molecules is transmitted through the fiberoptic waveguide to the sensor tip. As these excited molecules return to the ground state, they fluoresce. The light they give off is directed to a fluorescence detector. The intensity of the fluorescence signal is measured and recorded. This intensity is proportional to the amount of antigen bound to the sensor tip.

"The increased sensitivity of the FIS device is due to the specificity of the antigen-antibody interaction and laser excitation," said ORNL's Tuan Vo-Dinh, one of the developers of the instrument, which incorporates a helium-cadmium laser, beamsplitter, monochromator, and photomultiplier.

Vo-Dinh and Michael J. Sepaniak of UT are team leaders for instrument development of the FIS device. Other ORNL investigators are Guy Griffin, task leader for biochemical development; Bruce Tromberg, who has been involved in all phases of the development for his doctoral work, and Kathy Ambrose, who is responsible for immunological studies. ornl

ORNL researchers have shown that clear alkali-halide crystals can monitor laser beams. The color tracks produced when the laser beam passes through the crystal give a three-dimensional profile of the beam and measure its divergence. No expensive instrumentation or computer printout is required. Developers are, from left, Steven Kramer, Chung-Husan Chen, and Michael McCann of the Health and Safety Research Division.

Bruce Jatko and team members from ORNL's Instrumentation and Controls Division developed an integral passive electronic circuit that simplifies the design and installation of large-scale control systems requiring many cables for connecting transducers and actuators. The device, which could be miniaturized as an integrated circuit chip, is used as a part of connectors or terminal blocks to identify wire-pairs and remote sensors.

Five Oak Ridge Developments Win 1987 I•R 100 Awards

On September 17, 1987, Oak Ridge researchers were recognized by the editors of *Research and Development* magazine for five of the year's top 100 technical innovations.

In ceremonies at the Museum of Science and Industry in Chicago, four ORNL developments and an Oak Ridge Y-12 Plant development received 1987 I•R 100 awards. These winners are selected annually from among thousands of U.S. scientific and engineering achievements on the basis of importance, uniqueness, and usefulness.

Besides the portable fiber-optics sensor described in detail in the previous technical capsule, this year's award-winning Oak Ridge developments are:

- A crystal monitor that allows researchers to quickly and inexpensively measure the three-dimensional profile and divergence of a laser beam (ORNL);
- A process for inexpensively fabricating tougher, stronger fiber-reinforced ceramic composite materials for industrial applications (ORNL);
- A remote sensor and cable identifier that simplifies design and installation of large-scale electronic control systems (ORNL); and
- A low-density ceramic fiber insulation that can be used at temperatures up to 4200°F—1000°F above conventional ceramic fiber structures (Y-12 Plant);

The five awards bring to 60 the total won by the DOE facilities here since 1967—30 of them since 1982.

Members of the winning groups are Chung-Husan Chen, Steven D. Kramer, and Michael P. McCann of ORNL's Health and Safety Research Division for the "Crystal Laser Monitor"; Tuan Vo-Dinh, Michael J. Sepaniak, Bruce J. Tromberg, Guy D. Griffin, and Kathy R. Ambrose of ORNL's Health and Safety Research Division and the Department of Chemistry at the University of

ORNL researchers have shown that a rapid, efficient chemical-vapor-infiltration process produces much tougher, stronger ceramic composite materials for industrial applications. Processing times are reduced from weeks or months for other methods to less than a day. The low-temperature, low-stress process also avoids damage to the reinforcing fibers. Developers of fiber-reinforced ceramic-composite fabrication are, from left, Anthony Caputo, David Stinton, Theodore Besmann, and Richard Lowden.

Tennessee, Knoxville, for the "Fiberoptics Fluoroimmunosensor" (see previous Technical Capsule); Charles A. Mossman, David R. McNeilly, Bruce Jatko, Richard L. Anderson, and George N. Miller of ORNL's Instrumentation and Controls Division for the "Remote Sensor and Cable Identifier"; David P. Stinton, Anthony J. Caputo, Richard A. Lowden, and Theodore M. Besmann of ORNL's Metals and Ceramics Division for the "Fiber-Reinforced Ceramic-Composite Fabrication Process"; and George E. Wrenn, Jr., Cressie E. Holcomb, Jr., John Lewis, and Leonard Berry of the Y-12's Development Division for "ZZX-4200 Ceramic Fiber Insulation."

Crystal laser monitor. Important to any laser-related research or application is the ability to monitor the beam profile, the radial distribution of photons in the laser beam. Until now, available instruments were bulky and very expensive (more than $20,000), required computer assistance, or offered only a narrow dynamic range (e.g., photographic film). The ORNL development has demonstrated that clear alkali-halide crystals can be useful for monitoring ultraviolet (UV) and vacuum ultraviolet (VUV) laser beams.

When UV or VUV laser beams pass through the crystal, they produce color tracks, or F centers, in the crystal by promoting electrons from the valence band to the conduction band, where they become entrapped. By doping the alkali-halide crystals with extra alkali metal atoms, the ORNL scientists significantly increased the crystal's efficiency for producing F centers.

In the doped crystals, the color pattern is easily seen, even for laser energies of <1 mJ/pulse and a few nanoseconds' duration. The colorful patterns can be evaluated with the naked eye.

Because the crystals are clear, colorful UV patterns can be shown in three dimensions, enabling the measurement of both beam profile and divergence, the way a laser beam differs from a perfectly parallel beam. The patterns can be cold-stored in the dark for weeks or erased by heat and light within a few seconds. The crystals themselves are not damaged and can be used indefinitely.

Remote sensor/cable identifier. Large control systems in power plants, chemical-processing facilities, buildings, ships, and airplanes use many sensors to measure temperatures and pressures, actuators to operate valves, and other devices to perform other control functions. Many signal leads are required to connect these devices to the central control system. Traditionally, when installing the wiring, each connection and signal line must be identified and verified, a time-consuming, labor-intensive process. To save time and money, ORNL engineers developed a new device to automate the identification of signal leads and remote sensors.

The ORNL device is a passive electronic circuit that ultimately can be made on a chip and could be built into connectors and terminal blocks. This special circuit, called a sensor identifier, could be used in many locations in control systems in conjunction with a computer.

In a sensor-identifier system, each sensor and actuator has an identifier circuit. When the control system introduces a medium-frequency signal (nominally 50 kHz) to the circuit, the identifier circuit responds with an identification code unique to the device at the end of the circuit. The code can be a simple serial number or a more complex description (e.g., "Thermocouple #12 on exit of steam generator"). By interrogating each circuit in the control system, the computer can construct a table of the connections of each signal lead to a particular sensor or actuator.

In constructing a control system using sensor identifiers, it is not important which sensors are installed on particular signal leads. Installation merely requires connecting the correct number of signal leads from the control system to various sensors and actuators. Later, the control computer can interrogate each circuit and identify each control device and its location in the system. Wiring errors are eliminated because the control system can adapt to the configuration of the control system that actually exists.

Fiber-reinforced ceramic-composite fabrication process. An exceptionally rapid and efficient chemical-vapor-infiltration process developed at ORNL produces ceramic composite materials of greatly improved toughness and strength. Unlike conventional ceramic fabrication, this low-temperature, low-stress process does not mechanically and chemically damage the reinforcing fibers.

Based on a new approach, using both thermal gradient and pressure gradient principles, reactant gases are forced into a low-density fibrous preform. There they decompose and are deposited as dense silicon carbide on and around the fibers to form the matrix of the composite. This process results in uniform matrix deposition throughout unidirectional fiber, cloth, or random chopped-fiber preforms to produce composites having densities close to 90% of the theoretical density. The increased efficiency also allows fabrication of much thicker composites.

By far, the most important advantage of the ORNL technique is that it reduces processing times from weeks or months (for other methods) to less than a day. This feature significantly reduces potential production costs, promising to make the composite materials practical for many industrial applications.

ZZX-4200 ceramic fiber insulation. Researchers at the Y-12 Plant have developed a low-density ceramic fiber insulation material that can be used at an operating temperature up to 4200°F—more than 1000°F above the operating temperature range for conventional ceramic fiber structures. Known as ZZX-4200, the material is composed of zirconia-bonded zirconia fibers, which can be molded for a variety of uses in vacuum, inert, and oxidizing environments.

Typical applications include backup insulation for aerospace leading edges and supersonic entry and exit cones, furnace chamber insulation, conformal shape insulation for refractory specialty shapes, low-pressure combustion chambers, and hot-gas filters. The technology will allow development of new classes of research and industrial process furnaces that must operate at temperatures above 3650°F in oxidizing atmospheres.

ZZX-4200's thermal efficiency is maximized by the technique used to produce the molded shapes. This unique molding method ensures that the fibers are oriented perpendicular (85–95°) to the wall of the structure. This orientation reduces heat flow twice as much as homogeneous materials and randomly oriented fiber structures. ornl

ORNL awaits reactor restart permission

DOE's Oak Ridge Operations (ORO) is expected to authorize in early 1988 the restart of three of the four ORNL research reactors it ordered shut down March 26, 1987, because of concerns about management and oversight of reactor operations. The reactors are the Tower Shielding Facility, the Health Physics Research Reactor, and the Bulk Shielding Reactor. The other ORNL reactor shut down at the time—the Oak Ridge Research Reactor—was permanently closed July 20, 1987, after more than 29 years of operation.

HFIR may restart by March 1988

Because the Atomic Trades and Labor Council strike was settled October 4, 1987, and DOE responded favorably to an ORNL proposal, ORNL's High Flux Isotope Reactor (HFIR) is expected to be ready for low-power operation by January 31, 1988. However, DOE is not expected to authorize HFIR's restart until completion of its final inspection in February or March. The HFIR was shut down in November 1986 because of concerns that the pressure vessel was embrittled as a result of 21 years of neutron irradiation.

On September 30, 1987, ORNL submitted a formal "HFIR Restart Proposal" to DOE-ORO containing key milestones, a comprehensive program plan, and a detailed action plan for preparing the reactor for a safe restart. ORNL then completed management and safety documents required for obtaining DOE-ORO approval.

Assuming resolution of all restart issues, the actual date of restart was to be based on the estimated time needed to

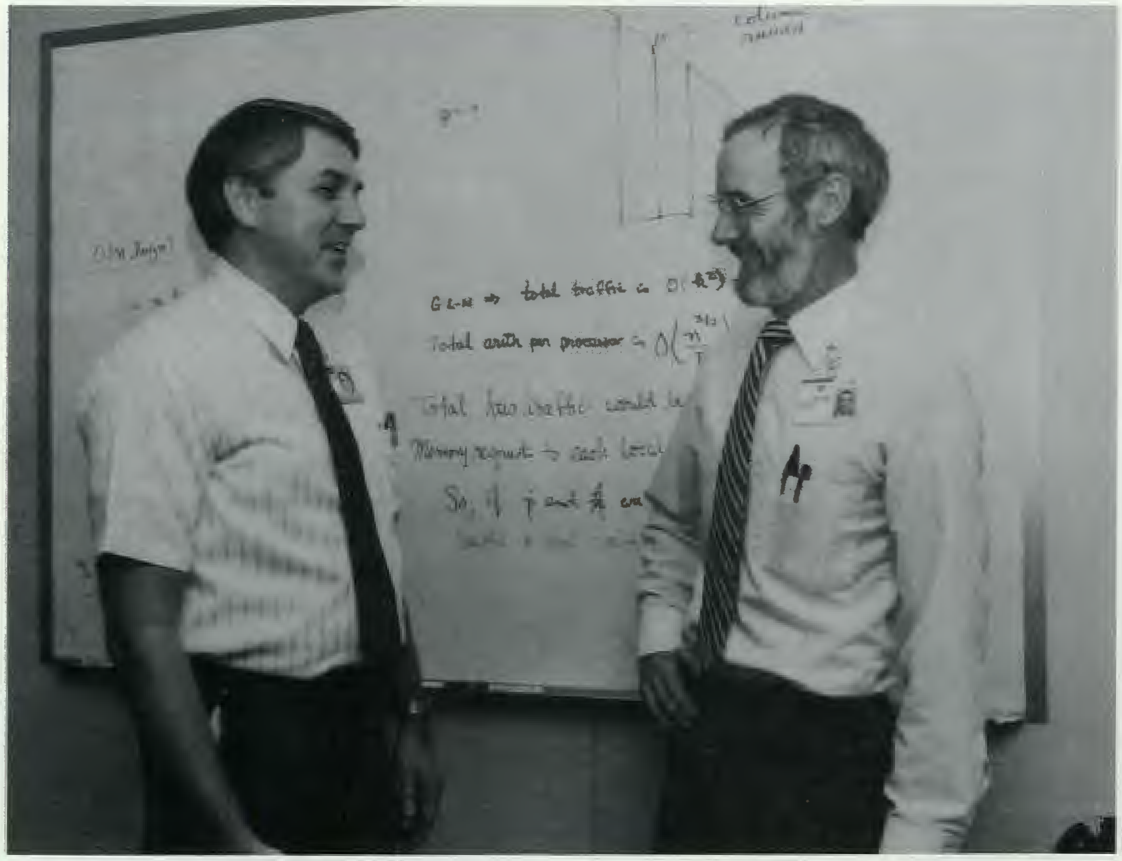
The pressure vessel of the HFIR was monitored by video camera for signs of leaks during a recent successful hydrostatic test. From left are Ken Belitz, Mike Farrar, Greg Kickendahl, Bobby Cupp, and Bill Hill, all of ORNL's new Research Reactors Division. The hydrostatic test showed that the HFIR vessel, although subject to some additional radiation-induced embrittlement, can be operated safely for another ten years.

retrain and requalify the HFIR operators who had been on strike from June 20 to October 4. The HFIR is a Category A reactor; the other three ORNL research reactors are Category B reactors. DOE requires that operators be retrained for any Category A reactor that has been shut down for more than six months. Retraining and requalifying testing usually take about three months.

Although HFIR has been idle for more than a year, much effort has been devoted to upgrading the reactor and improving its research capabilities. When the HFIR restarts, it will have a new Neutron Activation Analysis Laboratory and activation analysis pneumatic irradiation facility, two new heat exchangers to supplement the two replaced in 1985 and 1986, and improved facilities and instruments for irradiating test materials.

On August 4, 1987, the first of a once-a-year series of hydrostatic tests was conducted on the HFIR to confirm the integrity of its pressure vessel. In this test the vessel was internally pressurized by water to 900 pounds per square inch (psi)—nearly twice the operating pressure proposed for future reactor operation. The test showed that, even though the vessel is subject to some additional radiation-induced embrittlement, the HFIR can be operated safely for at least another 10 years.

The restarted HFIR will operate at lower pressures—475 psi instead of 750 psi—and lower power—85 MW(th) instead of 100 MW(th)—to ensure its safe operation.



Bob Ward (left), head of ORNL's Mathematics Science Section, and Alan George, UT-ORNL Distinguished Scientist, discuss the upcoming events of Numerical Linear Algebra Year.

Numerical Linear Algebra Year observed

A Numerical Linear Algebra Year is being observed between now and June 30, 1988, by ORNL and the University of Tennessee (UT) at Knoxville. During this time, about 40 leading researchers in numerical linear algebra and related areas of scientific computation and computer science will visit UT and ORNL.

The major celebration event for the year was the 10th International Symposium on Numerical Algebra, held October 18–23 at Fairfield Glade, Tennessee. Workshops are also to be held at the beginning of each quarter on systems of linear equations, eigenvalue problems, and least squares computations.

The special year is supported by Tennessee's Science Alliance, DOE, the Air Force Office of Scientific Research, the National Security Agency, and the National Science Foundation. The sponsors are UT's Departments of Computer Science and Mathematics and the Mathematics Sciences Section of ORNL's Engineering Physics and Mathematics Division.

Numerical linear algebra was pioneered at

ORNL and UT in the 1950s when the first large computers became available. Advances in computer applications of this type of mathematics continue to be made by a core of UT and ORNL researchers, including Alan George, UT-ORNL Distinguished Scientist.

George, formerly dean of mathematics at the University of Waterloo in Ontario, Canada, began his appointment in mid 1986. He is an expert in sparse-matrix computations and parallel computer applications.

ORNL and UT are rapidly developing the capabilities of parallel computing to make large-scale matrix computations, using numerical linear algebra, to solve scientific problems. Parallel computing—using computers connected in parallel to process information simultaneously, the way the human mind does—is also being developed at ORNL for intelligent control of robots.

"ORNL is a rich source of problems in numerical linear algebra," says Robert C. Ward, head of ORNL's Mathematics Sciences Section. "Visiting mathematics researchers will have a unique opportunity to interact with scientists at ORNL at the forefront of knowledge in their own areas of expertise. From this information exchange, the visitors can contribute to computational modeling of complex phenomena such as the movement of contaminants through the atmosphere."

One of the pioneers of numerical linear algebra was Alston Householder, formerly a UT faculty member and head of ORNL's Mathematics Department. He began his research in this area in the 1950s, about when ORNL acquired the Oak Ridge Automatic Computer and Logic Engine (ORACLE), one of the nation's earliest vacuum-tube computers.

Many distinguished mathematicians and computer scientists, such as Wallace Givens and G. W. Stewart, joined Householder's staff during his career at ORNL and UT. Some of his other collaborators included leading experts in numerical linear algebra.

Two of the most fundamental tools of numerical linear algebra, "Householder reflections" and "Givens rotations," were developed at ORNL in the 1950s. These tools are used to simplify the solution of complex problems such as those encountered in designing bridges and earthquake-resistant buildings.

11th Distinguished Scientist named

Francis E. Close, a British physicist who specializes in the theory of elementary particles, particularly subnuclear quarks and gluons, has accepted appointment as a Distinguished Scientist at the University of Tennessee and ORNL.

Close's appointment is the 11th under the Distinguished Scientist Program, established in 1984 to attract a select additional number of scientists of national and international stature to the Knoxville–Oak Ridge research community.

Close, who begins his appointment in January 1988, has been on the staff at the Rutherford Appleton Laboratory in Chilton, England, since 1975.

An interpreter of science for the public, he is the author of numerous scientific articles and several books, including a physics text and two books of general distribution: "The Cosmic Onion—Quarks and the Nature of the Universe" and "The Particle Explosion." He also developed 12 science broadcasts for the BBC World Service's "Discovery" series.

ORNL researchers facilitate cleanup at Three Mile Island

During a briefing sponsored by the U.S. Nuclear Regulatory Commission, two ORNL researchers were praised for their efforts in making possible the resumption of the cleanup of Three Mile Island (TMI) reactor No. 2. TMI-2 was severely damaged by a major loss-of-coolant accident March 28, 1979.

The lauded researchers, David Campbell and Emory Collins, both of the Chemical Technology Division, worked with other consultants from the nuclear industry to devise a filtration method to remove particulates from water in the reactor vessel. The water in the vessel had become turbid and infested with algae.

Although it posed no health risk, the cloudy water effectively halted fuel removal operations because it obscured visibility. Cleanup crews rely on television viewing to control manipulation of long-handled tools for removing reactor fuel and core debris.

Efforts to remove damaged reactor fuel and debris had been stalled since March 1986. However, workers were able to resume cleanup activities in early 1987, thanks to the filtering method devised by Campbell, Collins, and their colleagues. Since the resolution of the water clarity problem, over half the damaged fuel has been removed and shipped off-site.

A human life is worth how much?

Just how much in dollars is a human life worth? About $2 million, according to an analysis of actions of U.S. government regulators regarding chemicals suspected of causing cancer.

Curtis Travis and Samantha Richter Pack of ORNL's Office of Risk Analysis, along with teams of researchers from Tufts University and Harvard University, determined this value by making a cost-benefit analysis of 137 decisions by federal regulatory agencies. These decisions dealt with the regulation of chemicals suspected of causing cancer. The researchers found that regulatory actions costing less than $2 million per life saved were usually approved; those above this cost ratio were usually not.

Results of the findings were published in the May 1987 issue of the *Journal of Environmental Science and Technology*.

Compression of ORNL waste demonstrated

The reduction and immobilization of solid, low-level radioactive waste was demonstrated recently at ORNL using the nation's most powerful portable waste compactor. The project was conducted by the Low-Level Waste Disposal Development and Demonstration (LLWDDD) Program of DOE-ORO.

U.S. Ecology, an Energy Systems subcontractor in Louisville, Kentucky, compressed the ORNL wastes using its mobile supercompaction unit. This compactor can deliver 2200 tons of compressive force to a standard drum of waste. About 300 drums were crushed in the test. The drums were then cemented into larger "overpack" drums (reinforced with steel bars) and buried at ORNL's Solid Waste Storage Area 5.

A secondary goal of the demonstration was to determine the effectiveness of real-time-radiography (RTR) examination in detecting liquids in the drums. Before compaction, all the drums had been examined by the RTR unit, which indicated that no free liquids were present. During compaction, liquids were squeezed from many of the drums. The RTR tapes for these drums indicated that only absorbed liquids (in wipes and mop heads) were present. From this demonstration ORNL researchers concluded that the RTR unit can detect free liquids but cannot determine the amount of absorbed liquids.

The LLWDDD Program is evaluating technologies that can be used to better manage low-level radioactive wastes at six ORO facilities. These technologies include compaction methods, which have attracted local interest because of dwindling space in the waste burial grounds.

TECHNOLOGY TRANSFER BRIEFS

ORNL inventors get royalty checks

On December 7, 1987, Energy Systems distributed royalty checks totalling $24,148.03 to seven employees whose inventions produced patents that have been licensed to industry.

This is the first time royalty checks have been given to Oak Ridge inventors for their work at DOE facilities. This action is the result of a change in the DOE–Energy Systems operating contract to stimulate technology transfer.

Under this change, royalties received by Energy Systems from licensing intellectual property, waived by DOE to Energy Systems, are to be used to reward inventors and technical staff members for their creative developments. Royalties from licensed inventions are to be used for technology transfer initiatives, including the development of other inventions having commercial potential.

The payments represent royalty fees made by private companies under 11 patent licenses. In the two years since Energy Systems started its technology transfer program, its licensed technologies have generated nearly $6 million in sales for licensees.

The rewarded ORNL inventors, their inventions, and the licensees are **Terry Tiegs** and **Paul Becher**, silicon-carbide whisker-reinforced ceramic, American Matrix, Inc., ARCO Chemical Company, Dow Chemical Company, Iscar Ceramics, Inc., and High Velocity Tool Corporation; **Ken Liu**, ceramic gripper assembly for tensile testing, Instron Corporation; **C. T. Liu** and **Jim Stiegler**, modified nickel aluminide alloys, Armada Corporation and Cummins Engine Company; **Dan Kuban** and **Steve Killough**, Advanced Servomanipulator, Remote Technology Corporation.

BOOKS

The Dragon's Tail: Radiation Safety in the Manhattan Project, 1942–1946, *by Barton C. Hacker, University of California Press, Los Angeles (1987), 258 pp. Reviewed by James E. Turner, ORNL's Health and Safety Research Division.*

The Dragon's Tail is a carefully researched and documented account of radiation protection during the development, testing, and use of nuclear weapons from 1942 through the end of 1946. It is the first single document that describes radiation-safety practices during all phases of the Manhattan Project.

The idea for producing this work originated in 1977 at the Nevada Operations Office of the Department of Energy. A second volume, starting with the creation of the Atomic Energy Commission on January 1, 1947, is in preparation. It will deal with the conflict between the testing of nuclear weapons and mounting concerns about the long-term effects of low-level radiation exposure of the population.

Barton Hacker, a professional writer and historian, extensively researched his subject. He had access to DOE repositories throughout the country and interviewed numerous persons who played a part in this story. The chapters had to pass the scrutiny of a peer review group of some 50 scientists and key participants. The author has done a thorough job of providing extensive, detailed notes (over 50 pages); lists of sources, persons interviewed, and reviewers; a 20-page bibliography; and an excellent index. The work is scholarly and well written; the focus on personalities and use of narration enliven the story and sustain reader interest.

The first of the book's six chapters describes the origins of radiation-protection standards and the state of knowledge about the harmful effects of radiation on humans in 1942, when the Metallurgical Project started at the University of Chicago. "The Role of the Chicago Health Division" is the title of Chap. 2. According to Robert S. Stone, director of the new division, when the first self-sustaining fission reaction was observed on December 2, 1942, the "problems of the Health Division" ceased to be "mainly theoretical."

Chapter 3 describes radiation safety at Los Alamos. Unprecedented problems were anticipated and, indeed, became real in 1944 when plutonium started arriving in quantity from the pilot plant in Oak Ridge. Techniques for monitoring plutonium, methods of assessing exposure (e.g., nasal swabs), systems of personnel dosimetry, "acceptable" levels in the work place, and "acceptable" body burdens for workers were all unknown.

Chapter 4 describes the planning and execution of the Trinity test. This chapter is more exciting than most fiction. It recounts the drama, the uncertainties, and, finally, the success of Trinity. It also describes the concerns for radiation safety and the followup surveys.

Chapter 5, "From Japan to Bikini," briefly describes the Hiroshima and Nagasaki events and the collection of effects data. Also discussed is the development of plans, approved by President Truman, for conducting a series of atomic tests in the Pacific Ocean. Chapter 6 covers Operation Crossroads and radiation safety during these tests. The epilogue "Continuity and Change in Radiation Safety" completes the text.

Several ingredients make this book outstanding: the important story, the intriguing way in which it is told, the care in documentation, and the philosophical perspective in which the events are placed. In addition, the author has a clear grasp of the underlying radiation-safety issues as they surfaced in the Manhattan Project and as they continue today, with extensive public involvement in trying to balance risks and benefits.

Hacker arrives squarely at a fundamental point in radiation protection: "Commonly cast as questions for science, the real debate often involved philosophy and public policy. Social concerns in the widest sense always molded safety standards, science at best setting guidelines for decision makers. The key issue was and remains: How much radiation exposure should a worker or a member of the public be allowed? Controversial from the outset, this question nonetheless had, in one sense, an easy answer: not enough to cause harm. Unfortunately, the easy answer simply translated the first question into a second: How much is harmful? And that question, after almost a century of research, has yet to receive a final answer." A notable achievement of the book is the way it catches the fundamental essence of issues in the philosophy of radiation protection.

The Dragon's Tail should be of special interest to Oak Ridgers who recall when Clinton Laboratories at Site X became Oak Ridge National Laboratory (1945, after the war). Activities at Oak Ridge are described or mentioned throughout

the book. The names of prominent Oak Ridge researchers in the book include Waldo E. Cohn, Karl Z. Morgan, and Ernest O. Wollan.

Why the title, *The Dragon's Tail*? Hacker describes events at Los Alamos in late 1944 and early 1945 that were aimed at finding out just how much enriched uranium would be needed for the first bomb. He writes, "No one doubted that the nearly ready uranium gun would work, but no one had yet seen uranium explode, either. Blocks of the metal hydride would be assembled as a bomb. A large hole left in the center would preclude a chain reaction. The missing core, mounted on rails, could then be dropped through the hole. For a split second, it would just barely create the conditions for an explosion, as near an approach as could be conceived." Otto R. Frisch compared the situation to "starting an atomic explosion without actually being blown up." The experiment worked perfectly, despite a large burst of neutrons and a temperature rise of several degrees in the split second of supercriticality. A member of the review group likened the experiment to "tickling the tail of a sleeping dragon."

Alan J. Witten is leader of the Applied Physical Sciences Group in ORNL's Energy Division. He came to ORNL in 1975 as a staff member of the Engineering Technology Division. A year later, he transferred to the Energy Division, where his projects have included developing mathematical models of air pollution, evaluating acoustic emissions from "hush houses" for the U.S. Air Force, developing ultrasonic diffraction tomography for imaging tumors, and developing an acoustic technique for imaging underground features. A native of Massachusetts, he holds a Ph.D. degree in mechanical and aerospace sciences from the University of Rochester in New York. He received a 1986 Technical Achievement Award from Martin Marietta Energy Systems, Inc., for "advancing the state of the art in subsurface characterization methodology through the development of acoustical imaging techniques for both geophysical and medical applications" (see the sidebar at the end of the article).

Ultrasonic Diffraction Tomography for Imaging Tumors

By ALAN J. WITTEN

Locating and imaging tumors in soft tissue is essential in diagnosing cancer and preventing its spread within the body. Medical technologies currently available for locating tumors are computerized axial tomography (CAT) scanners, nuclear magnetic resonance imaging (MRI) machines, and conventional medical ultrasound, which uses high-frequency sound waves.

At Oak Ridge National Laboratory, we have developed an ultrasound technique that promises to complement these other medical technologies in tumor imaging. Called ultrasonic diffraction tomography, our technique uses high-frequency sound waves and the principles of optical imaging to provide sharp, computer-generated pictures of soft tissue.

Advantages

A diagnostic tool based on the ORNL concept would provide high-resolution, quantitative images comparable to those offered by $500,000-CAT scanners and $3-million MRI devices but at a fraction of the cost. Thus, the technology would be affordable for small hospitals and clinics. In addition, such a device would be small enough to be portable—if necessary, the machine could go to the patient in the emergency or operating room—rather than having the patient go to the machine.

Because it uses ultrasound rather than ionizing radiation, the ORNL technique is potentially safer than CAT scanners, which use X rays. It also offers several improvements over B scanners, the medical ultrasound technology widely used today. These scanners, which cost $100,000 apiece and are available in almost every U.S. hospital, provide only *qualitative* information about tumor location, and the results require expert interpretation.

By comparison to B scanners, the ORNL technique can provide sharper images of tumors and easily interpreted *quantitative* information, permitting precise determination of the tumor shape, size, density, and location. In addition, an instrument based on the technique requires less ultrasonic energy to be transmitted through the body to obtain an image. For this reason, possible

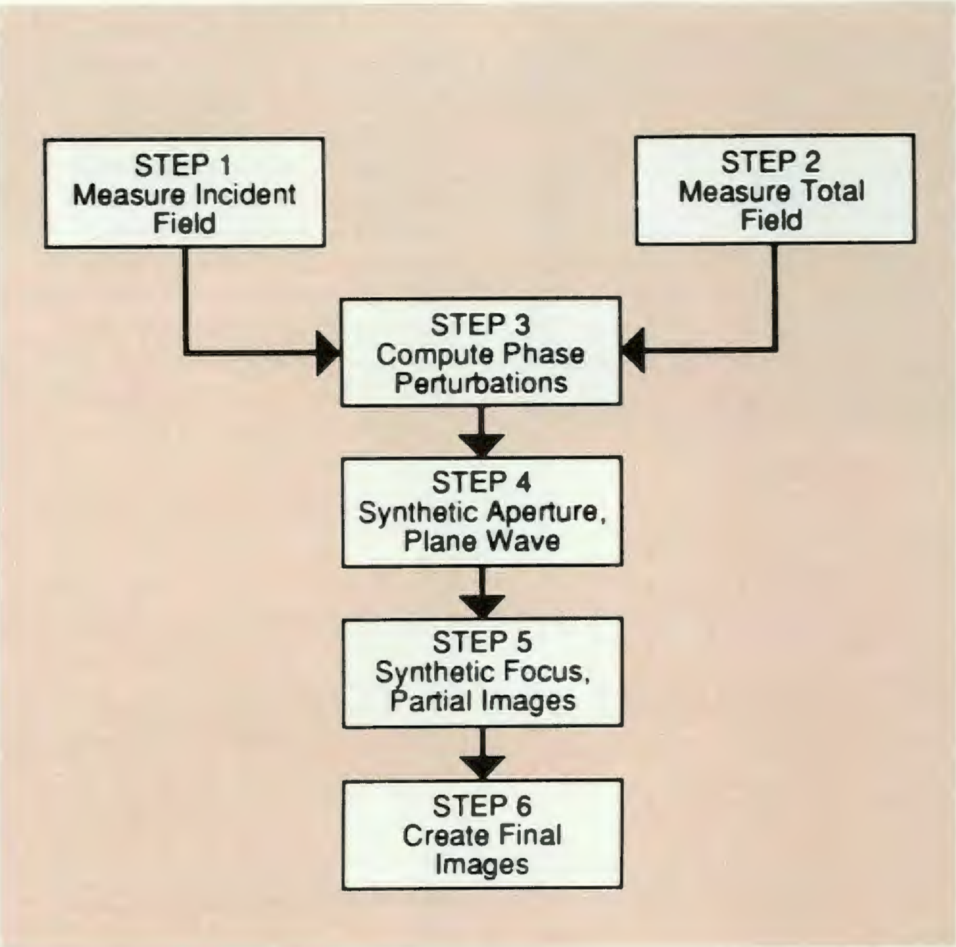
ORNL has applied the principles of optical imaging to an ultrasound technique to image tumors. Called ultrasonic diffraction tomography, the technique provides sharp, computer-generated pictures of soft tissue. A device based on the technique could complement other imaging methods and could be safer, less expensive, and more affordable for small hospitals and clinics.

adverse side effects are virtually eliminated, making the technique even safer than conventional ultrasound technology. We estimate that a prototype device based on the new technique can be designed and built for less than $100,000.

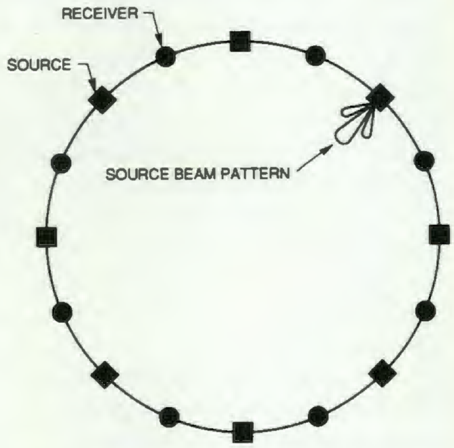
Development of Theory

Ultrasonic diffraction tomography is based on a theory for optical imaging published in 1969 by Professor Emil Wolf of the University of Rochester's Institute of Optics. The field of diffraction tomography was established by Anthony J. Devaney, a faculty member at Northeastern University in Boston. Recognizing that the theory of Wolf could be applied to sound as well as light, Devaney laid the theoretical groundwork for diffraction tomography. The work of Devaney generated interest in the development of ultrasound CAT scanners and led to experimental studies at the Mayo Clinic.

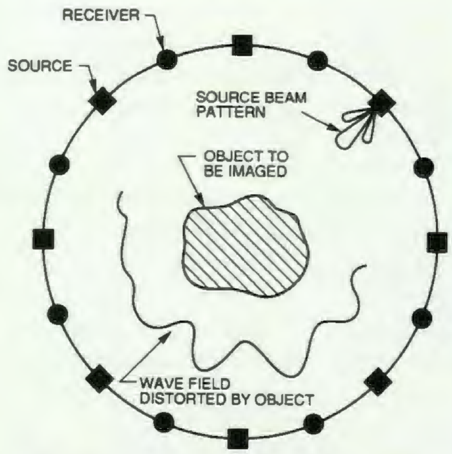
A group of researchers from ORNL and the University of Rochester realized that an



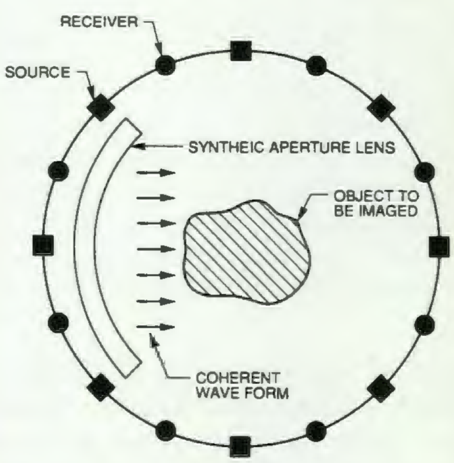
The sequence of steps in the ultrasonic diffraction tomography procedure for imaging soft-tissue inclusions (e.g., tumors).



The ORNL-Rochester development uses a fixed ring of ultrasound sources and receivers. The ultrasonic signals are fired sequentially around the ring and the received signals are sent to a computer. The first step of the soft-tissue imaging procedure is to measure the incident, or unperturbed, ultrasonic field, which is analogous to the pattern of a reference laser beam.



The second step of the imaging procedure is to measure distortions in the field resulting from the presence of the object to be imaged.



Another step of the imaging procedure (Step 4) is the physical depiction of the mathematical procedure for synthesizing a plane (coherent) wave.

ultrasonic device that mimics a CAT scanner would not be practical in the clinical setting. Unlike conventional CAT scanners, which measure only the intensity of X rays passed through the body, ultrasonic tomography requires the measurement of both acoustic wave amplitude and phase. A rotating CAT-scanner-like ultrasound device would lack the capacity to measure phase precisely because of the movement of the device.

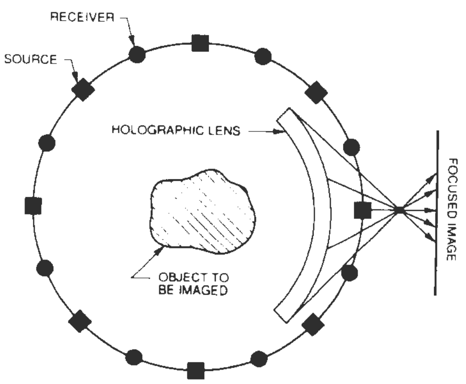
Medical ultrasound uses sound waves having lengths of about 1 mm. Uncertainty in the location of the detector of only a fraction of one wavelength is too large for successful imaging with diffraction tomography. Thus, for ultrasonic imaging, the minute mechanical detector vibrations resulting from rotation (as in a CAT-scanner-like device) are unacceptable. Such rotating devices must operate very slowly, allowing time for damping of vibrations before collecting data, and scans take several hours or more to complete. Because patient motions have the same detrimental effect as instrument motion, data collection must be accomplished in one second or less.

A New Concept

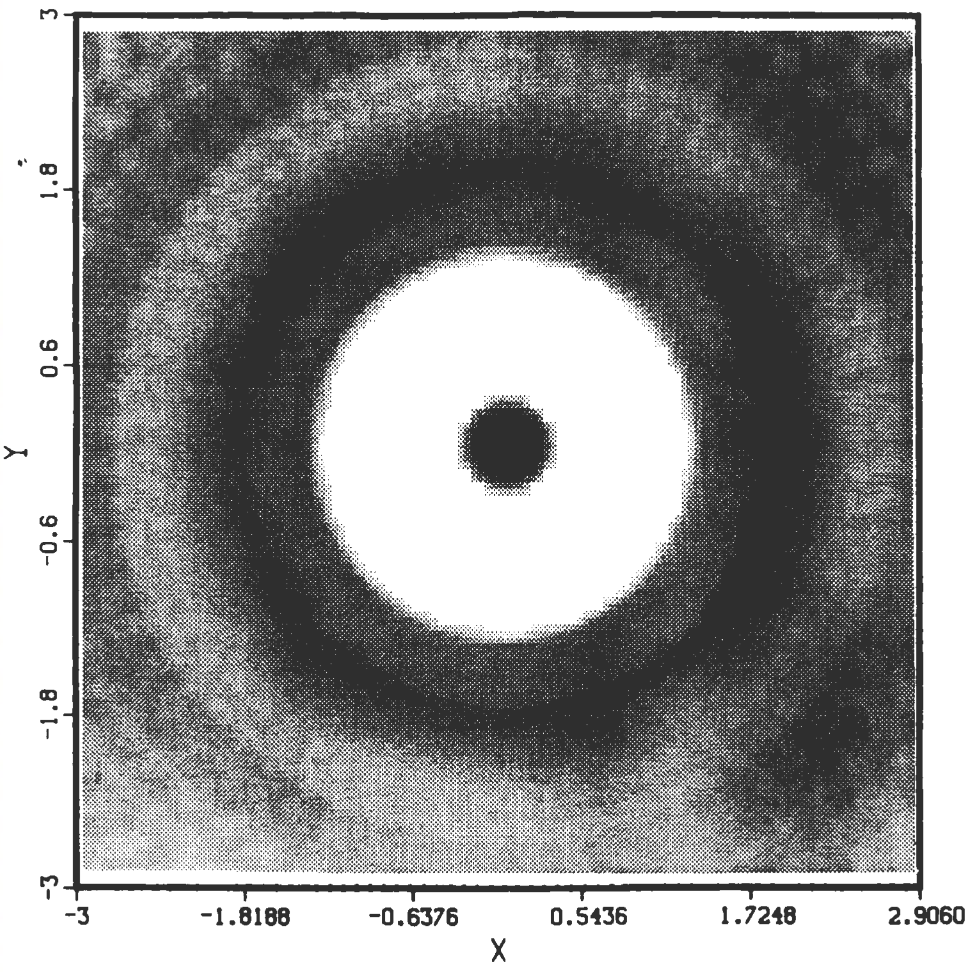
To overcome this limitation, Joe Tuggle of the Computing and Telecommunications Division and I, together with Robert Waag at the University of Rochester, developed a new concept for an ultrasonic device. Our idea was to use an instrument having no moving parts—a fixed array of ultrasonic transmitters and detectors that can surround the body part to be imaged (e.g., the breast).

Our team also modified the theory of diffraction tomography. Previously, the theory assumed perfect instrumentation—that is, ultrasonic transmitters that emitted "perfect" waves and receivers that detected these waves perfectly. Tuggle, Waag, and I extended the theory to incorporate the performance of real instruments. This extension was based on a concept suggested earlier by John Molyneux of Widener University and me for geophysical imaging.

The new concepts for ultrasonic tomography were proven by Tuggle, Waag, and me in a pioneering experiment at the University of Rochester. In this experiment, we used ultrasound to image a soft-



Step 5 is the physical depiction of the mathematical operation of image formation by the application of a holographic lens. In holography, a hologram is produced on a photographic plate using information from the interference of a reference laser beam with another beam illuminating the object to be imaged. In ultrasonic diffraction tomography, the "holographic" image is created instead in a computer's memory.



The final image shows variations in sound speed in the region of the soft-tissue-mimicking target to be imaged—concentric cylinders of gelatin and agar. The dark inner circle represents the cross-section of the inner cylinder; the white annulus, the cross-section of the outer cylinder; and the gray area is the water bath. The faster the sound speed, the darker the shading.

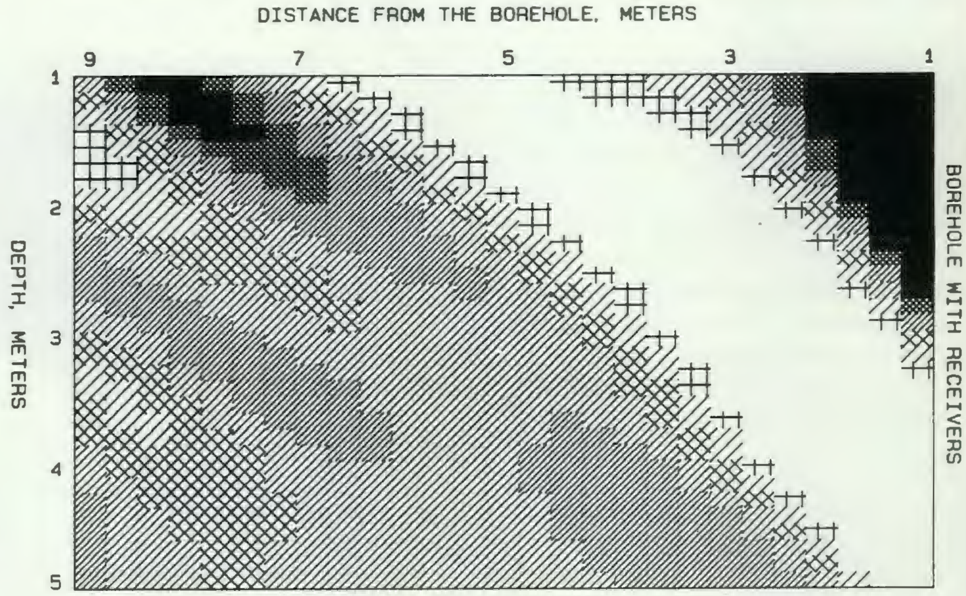
ORNL Acoustic Technique Images Underground Features

A new technique that employs sound waves and an innovative data-collection device for imaging underground features has been developed at ORNL. The technique has been used to locate and identify small subsurface features such as a large rock and a buried pipe, and it has produced a high-resolution picture of the undulating surface of a shallow shale formation.

The ORNL apparatus consists of a commercially available "noise source"—a cannon-like device that is used aboveground to create low-frequency sound waves in the soil; a streamer—an array of listening devices lowered to a desired depth in a borehole; an innovative 32-channel data-acquisition system; and a "supervisory" personal computer that controls data collection.

The sonic-geophysical-imaging apparatus was developed by Alan Witten and Scott Stevens, both of ORNL's Energy Division. Witten and Chris King of the U.S. Army have tested the device at two sites on the ORNL reservation. In August 1987, Witten and King reported on the new technique and presented a software demonstration at the international conference of the International Union of Geodyssey and Geophysics in Vancouver, British Columbia. More recently, Witten and King have applied the imaging technique, described in the accompanying article for medical imaging, to geophysical data collected at Chestnut Ridge on the ORNL reservation.

The computer-driven data-acquisition device can image underground features by measuring the time it takes for transmitted sound waves to penetrate the ground and reach the microphones at various depths from the source, perhaps as far as 300 m (1000 ft) away. The speed at which a sound wave travels depends on the



This gray-scale image of the cross-section of a subsurface of ground at Chestnut Ridge on the ORNL reservation was generated by a computer. The image indicates the presence of a large rock (upper left, black squares) and a buried pipe (black squares in upper right corner) as well as dry soil and moist soil. The faster the speed of sound transmitted through the ground, the darker the shading in the image.

tissue-mimicking target molded from gelatin and agar.

Ultrasound vs X Rays

Medical ultrasound technology today relies on the pulse-echo mode. Sound waves are transmitted into the body and the amplitude of the reflected sound (echo) and the time lag between transmission and echo reception are measured. This information allows the location of soft-tissue inclusions such as tumors, which reflect ultrasound because they are either softer or harder than the surrounding tissue. This is the same concept employed in radar and sonar detection.

The ORNL technique focuses on the ultrasound *passing through* tissue rather than on its echos. As is the case with X rays, the energy of sound waves is reduced, or attenuated, by all tissue penetrated by sound. But tissue inhomogeneities, such as tumors, attenuate ultrasound differently, and the difference can be measured easily. Also, unlike X rays, which travel in straight lines through the body, mechanical properties of the material it travels through. Sound travels faster in moist soil than dry soil and faster still in rock. By analyzing the time it takes for sound waves to travel from a source to a receiver over many paths, it is possible to construct images of below-ground features.

"Our tests," says Witten, "have shown that we can determine the depth of groundwater or the precise location of a buried pipe or hazardous wastes in a small area. The technique could be used to guide a safe cleanup of hazardous-waste sites."

The 32-channel data-acquisition system that Witten developed to process geophysical information promises to be more efficient and offer greater resolution than conventional geophysical devices used for this task. Conventional seismic geophysical systems were developed for "stratigraphic" applications—that is, mapping geologic layers. Such seismic exploration looks for gross features on the order of hundreds or thousands of meters in size. In addition, studies of this type require little analysis of data in the field.

In shallow-ground explorations that focus on identifying small buried features such as pipes or hazardous wastes, two capabilities are required: very high spatial resolution (visualization of small details) and data analysis during field studies. The ORNL device processes 32 signals simultaneously from 32 receivers, or microphones. This device amplifies and converts the analog signals to digital data, which are stored in the local memory of a supervisory personal computer. Data can be processed on this supervisory computer or immediately transferred to another portable computer for rapid analysis and display while the supervisory computer is controlling the collection of additional data.

A data-acquisition device based on the ORNL design is expected to cost $20,000. This price would be at least competitive with commercially available systems but would offer greater flexibility, sensitivity, and data-analysis capabilities.—*Carolyn Krause.*

These concentric cylinders of gelatin and agar served as a soft-tissue-mimicking target in a large tank of water at the University of Rochester. A pioneering experiment using this target showed that ultrasonic diffraction tomography can be used to image soft-tissue inclusions such as tumors.

sound waves are bent, or refracted, by inhomogeneities. This ray bending is the basis of diffraction tomography; it allows measurement of tissue properties such as density and compressibility as well as attenuation. Thus, ultrasound can distinguish among hard and soft areas of soft tissue, enabling the location and imaging of tumors.

Small differences in soft-tissue hardness and softness produce small changes in X-ray attenuation but large changes in ultrasound signals. Measurements of ultrasound phase and attenuation provide data that can be used to calculate the density and compressibility of various portions of soft tissue. In short, ultrasound gives better soft-tissue differentiations than X rays.

Ultrasound is also safer than X rays and therefore could be used for extended and more frequent scanning to provide even more information, increasing the probability of tumor detection. X-ray scans of breast tissue must be limited in time and frequency to minimize body exposure to hazardous radiation; such limitations increase the possibility that a tumor could be missed.

Imaging Principle

The ORNL-Rochester development uses a fixed ring of transducers, which contain rapidly vibrating piezoelectric crystals that transmit and receive ultrasound. For imaging breast tumors, a ring of as many as 100 or more small transducers may be needed. The ultrasonic signals are fired sequentially around the ring and the signals received are sent to a computer.

The imaging process is based on the principles of optical holography. Holography uses two laser beams—one to illuminate the target and the other as a reference. The laser beam illuminating the target is distorted, and this distortion is measured by its interference with the reference beam. This information is encoded on a photographic plate to produce a hologram.

In ultrasonic tomography the optical system is simulated by

awards and appointments

Five Oak Ridge developments were recognized by the editors of *Research and Development* magazine for five of the year's top 100 technical innovations. These five I•R 100 awards bring to 60 the total won by the DOE facilities since 1967—30 of them since 1982. Members of the four ORNL winning groups are **Chung-Husan Chen**, **Steven D. Kramer**, and **Michael P. McCann** for the "Crystal Laser Monitor"; **Tuan Vo-Dinh, Bruce J. Tromberg**, **Guy D. Griffin**, and **Kathy R. Ambrose** (with **Michael J. Sepaniak** of the Department of Chemistry at the University of Tennessee, Knoxville) for the "Fiberoptics Fluoroimmunosensor"; **David P. Stinton**, **Anthony J. Caputo**, **Richard A. Lowden**, and **Theodore M. Besmann** for the "Fiber-Reinforced Ceramic-Composite Fabrication Process"; and **Charles A. Mossman**, **David R. McNeilly**, **W. Bruce Jatko**, **Richard L. Anderson**, and **George N. Miller** for the "Remote Sensor and Cable Identifier." The winners at the Oak Ridge Y-12 Plant are **George E. Wrenn, Jr.**, **Cressie E. Holcomb, Jr.**, **John Lewis**, and **Leonard Berry** for "ZZX-4200 Ceramic Fiber Insulation." (See "Technical Capsules" for details.)

Stanley I. Auerbach has received DOE's Distinguished Associate Award in recognition of his "outstanding contributions to the science of ecology and application of ecological knowledge to national environmental problems."

G. W. Suter has been appointed to a Scientific Review Group for development of water quality standards for the State of New York Department of Environmental Conservation.

Thomas H. Row and **Cynthia M. Kendrick** have received a Certificate of Merit from the American Chemical Society's Division of Environmental Chemistry for their paper "The Oak Ridge Model: A Case Study in Waste Management Trends."

Bruce L. Kimmel is a member of the editorial boards of *Limnology and Oceanography* and *Lake and Reservoir Management*.

ORNL has received three awards for its safety performance. The National Safety Council gave ORNL an Award of Honor for 8.7 million hours worked without a lost workday injury and an Award of Honor for specified improvement in safety performance based on three previous years. The Department of Energy gave an Award of Achievement to ORNL Director **Herman Postma**.

R. B. Fitts has been named Oak Ridge Program Manager of the DOE Environmental Survey.

Norman H. Cutshall chaired the Second Research Coordination Meeting on Migration and Biological Transport of Radionuclides from Shallow Land Burial. The meeting, held in Oak Ridge, was sponsored jointly by ORNL and the International Atomic Energy Agency.

Paul N. Haubenreich received a Certificate of Appreciation from the U.S. Department of Energy for his work as U.S. project officer for the international Large Coil Task, which successfully met its experimental goals at ORNL's International Fusion Superconducting Magnet Test Facility.

Vance K. Wilkinson has been elected to the editorial board of *The Engineering Economist*.

means of computer, using an image reconstruction algorithm. The algorithm calculates (1) a "synthetic aperture lens," or front-end lens, which simulates the coherent wave form of the reference beam, and (2) a "holographic lens," or back-end lens, which receives the wave form that has been distorted by the target. Rather than forming an image on a photographic plate, the image is created in the computer's memory and displayed on a high-resolution graphics monitor.

Summary

We have demonstrated that ultrasonic diffraction tomography can provide high-resolution quantitative images of soft tissue. Results indicate that the technique is potentially useful for locating and identifying tumors and that a medical diagnostic instrument based on this technique could be designed for practical use. We are optimistic that support will be forthcoming for designing and constructing a prototype instrument for clinical diagnosis. ornl

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Linda C. Cain has been named program administrator in ORNL's Office of University Relations. She is responsible for administering precollege education activities and undergraduate semester programs.

William R. Busing was named the 1987 S. C. Lind Lecturer by the East Tennessee Section of the American Chemical Society. He delivered a lecture October 13 on "Computers and Crystallography, an Informal History" and October 14 on "Chemical Information from Observed Crystal Structures via Computer Modeling." Busing has authored or coauthored about 60 articles and reports, including an ORNL report on a least-squares program for interpreting diffraction data that was hailed as a Citation Classic in 1982 by *Current Contents*.

Tommy Wright has been elected chairman of the American Statistical Association Advisory Committee to the U.S. Census Bureau.

William R. Hamel has been named head of the new Telerobotics Systems Section of the Instrumentation and Controls Division.

Stanley I. Auerbach has been appointed to the National Academy of Engineering, National Research Council Committee on Magnetic Fusion in Energy Policy.

Martin S. Lubell has been elected chairman of the Standing Committee on Fusion Technology of the Institute of Electrical and Electronics Engineers and Nuclear Plasma Science Society.

Mark W. Kohring has been named Laboratory Training Coordinator in ORNL's Office of Operational Safety.

Energy Systems has received three newly created awards from DOE's Oak Ridge Operations in recognition of innovative achievements in waste minimization. The awards recognize three highly successful projects to reduce the amount of wastes generated at ORNL and the Oak Ridge Y-12 Plant. The three projects—Liquid Low-Level Waste Reduction and Implementation of a Waste Treatement Chargeback System, Waste Acid Reduction, and Rinse Water Re-use—are expected to save more than $5.5 million a year in waste disposal and chemical procurement costs.

ORNL photographer Curtis Boles shows the photograph he took that was published in the November 1987 issue of Life magazine.

A photograph of a hand-held button of remolded uranium from a dismantled missile, made at the Oak Ridge Y-12 Plant by photographer **Curtis Boles**, was published on page 32 of the November 1987 issue of *Life* magazine. The photograph appears in an article on procedures for deactivating missiles, entitled "Swords into Plowshares." ornl

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Alan Witten (right) and Chris King of the U.S. Army inspect new ORNL equipment for imaging underground features. The apparatus consists of a commercially available "noise source"—a cannon-like device that is used aboveground to create low-frequency sound waves in the soil; a streamer—an array of listening devices lowered to a desired depth in a borehole; an innovative 32-channel data-acquisition system developed by Witten, and a "supervisory" personal computer that controls data collection. See sidebar on pp. 42–43.