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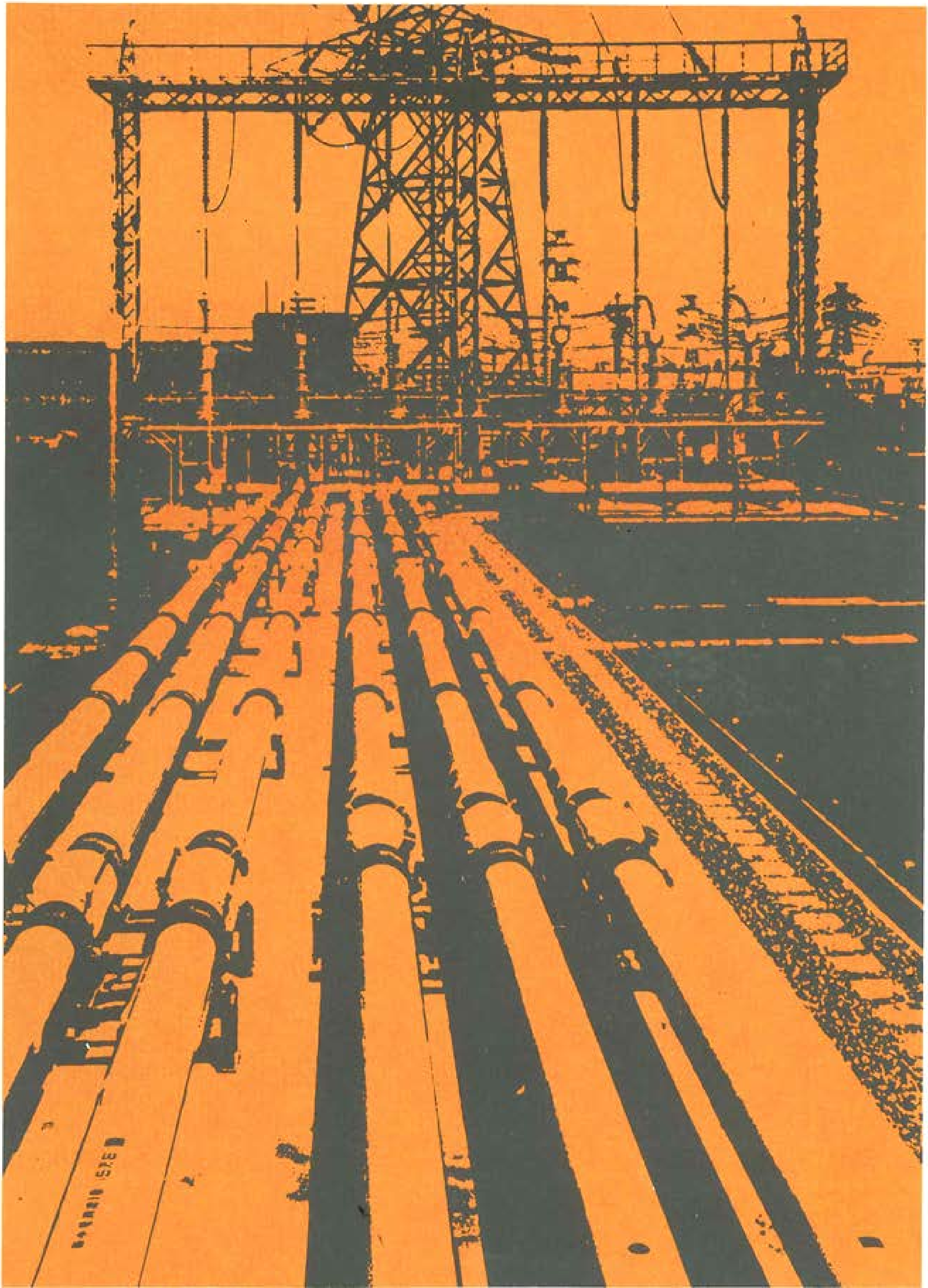

Power Systems Technology

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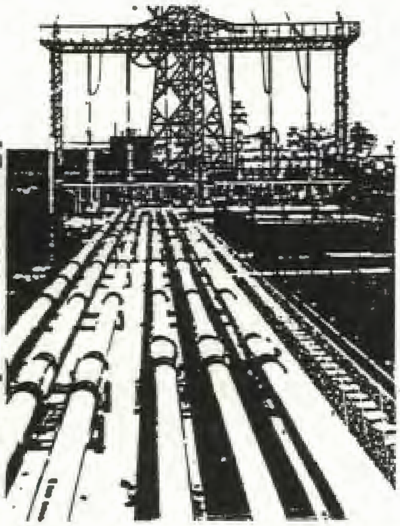

THE COVER: These gas-insulated, high-voltage transmission lines are an example of the new technology being explored by ORNL's Power Systems Technology Program. See special section on page 28.

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VOLUME 17 **NUMBER THREE 1984**

1 New Agents To Detect Heart Disease By F. F. (RUSS) KNAPP

*ORNL's Nuclear Medicine Group has designed and developed radioactive agents for safely and more clearly evaluating heart disease and the effectiveness of therapy. These agents include iodine-123-labeled methyl-branched fatty acids. The group has also developed an improved iridium-191*m *generator to diagnose heart problems in children. The methyl-branched fatty acids will be tested this year in human patients in Boston and Vienna, and the generator has just entered clinical trials in Europe.*

14 The Advanced Toroidal Facility: Improving Fusion's Chances By JOHN SHEFFIELD

Because further improvements in doughnut-shaped, or toroidal, fusion devices are desirable, ORNL has designed an Advanced Toroidal Facility (ATF). An optimized version of a stellarator (which differs from a tokamak in that it lacks a plasma current to magnetically confine the fusion fuel), the ATF will be built in Oak Ridge and is scheduled to begin operation in late 1986.

28 SPECIAL SECTION: Technology for Efficient Power Systems Compiled and edited by CAROLYN KRAUSE

ORNL is managing the Department of Energy program for developing and testing technologies designed to make electric power systems safer, more reliable, and more efficient. ORNL's interdisciplinary staff of experts has taken on a variety of projects, including planning an automated distribution experiment for Athens, Tennessee, and developing a fiber optics measurement device, a low-loss steel alloy, and new insulating materials for use in transformers.

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A five-year plan for managing the resources of the Oak Ridge Reservation of the Department of Energy has been developed at ORNL. The plan, which is described in the third in a series of articles on ORNL and the environment, deals with both natural and technical resources and provides the means for resolving resource issues such as endangered plant species, contaminated sewage sludge, and the fast-growing deer population.

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F. F. (Russ) Knapp is the leader of the Nuclear Medicine Group in ORNL's Health and Safety Research Division. A native of St. Louis, he came to ORNL in 1975 and served as a staff scientist for three years in the Biomedical Radioisotopes Group of the Operations Division before assuming his current position. From 1972 to 1975 Knapp was a senior research scientist in the Biochemistry Department of Rice University in Houston. In 1970 he earned a Ph.D. degree in biochemistry and organic chemistry from the St. Louis University School of Medicine, and he did postdoctoral studies for two years at the University of Liverpool in England. In addition to directing the research efforts of the Nuclear Medicine Group, his responsibilities include establishing and maintaining medical cooperative programs with clinics, universities, and other research institutions for further preclinical testing and clinical evaluation of new agents developed at ORNL. His research interests include the design and development of new radiopharmaceuticals and radiolabeling techniques as well as the development of new agents, including fatty acids, as tools for the evaluation of cardiovascular disease. Here, Knapp (left) and Al Callahan synthesize and purify a radioiodinated fatty acid under a special hood before investigating its usefulness in evaluating heart disease in animals.

New Agents to Detect Heart Disease

By F. F. (RUSS) KNAPP

Heart disease, and related cardiovascular disorders, is the leading cause of death in the United States. It includes the conditions that lead to heart attacks, which usually occur when the coronary arteries are narrowed by the buildup of atherosclerotic plaque, the fatty, yellowish deposit composed largely of cholesterol. Too much plaque can cause a blockage in a coronary artery, significantly decreasing or cutting off the blood supply to one region of the heart muscle. Partial blockage leads to a condition known as ischemia, where a region of the heart muscle (myocardium) is partially deprived of oxygen and nutrients. Ischemia leads to angina, the acute pain suffered during a heart attack (coronary). In more severe cases the myocardium is totally deprived of nutrients and oxygen and suffers irreversible damage (infarction).

Fortunately, two out of three Americans who have heart attacks recover because the myocardium is not irreversibly damaged. However, to keep a patient's heart disease under control, a physician must determine the extent of damage to the myocardium. This information guides the physician in selecting the proper treatment to restore the normal blood supply to the affected region. Treatment can range from a coronary bypass operation to a therapeutic regimen combining exercise with drugs that restore blood flow to affected regions of the myocardium.

An effective means of evaluating heart damage is to inject patients with a radioisotope that is selectively absorbed by the heart. The most desirable imaging agents emit gamma-ray photons that are efficiently detected by "gamma cameras." At the same time, because these agents have short physical half-lives, they expose patients to only a small amount of potentially hazardous radiation. One radioisotope that is used in an estimated four to five million patients a year is thallium-201 (^{201}Tl), which is produced in cyclotrons by particle bombardment of ^{203}Tl. In the free world, the sole sources of ^{203}Tl are the electromagnetic separators (calutrons) of Oak Ridge National Laboratory.

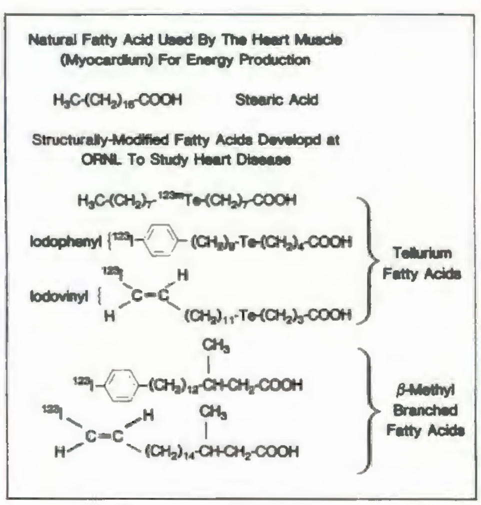
Even though ^{201}Tl and other radioisotopes are valuable diagnostic tools, researchers throughout the world continue to develop imaging agents that are potentially safer for patients, less expensive, and able to provide clearer images in the earliest stages of heart damage. At ORNL our Nuclear Medicine Group in the Health and Safety Research Division has spent the past five years developing new agents for evaluating heart disease. Some of these radioactive agents, such as the fatty acids labeled with iodine-123 (^{123}I), have a strong affinity for the heart and remain there long enough to provide a very clear image of tissue damage.

Because of the unique physiological and metabolic properties of the myocardium, we have had an opportunity to develop new types of compounds labeled with radioactive materials that can be used effectively in the heart. (See "Images of the Heart: ORNL Makes Isotopes for Disease Detection," ORNL *Review*, Fall 1981.) Our work has progressed to the point where we have proved that these agents work in animals. Clinical studies of one new heart-imaging agent will soon be initiated.

ORNL's Nuclear Medicine Group has designed and developed radioactive agents for safely and more clearly evaluating heart disease and the effectiveness of therapy. These agents include iodine-123 labeled methyl-branched fatty acids. The group has also developed an improved iridium-191*m *generator to diagnose heart problems in children. The methyl-branched fatty acids will be tested this year in human patients in Boston and Vienna, and the generator has just entered clinical trials in Europe.

Modified Fatty Acids

Since 1979 we have worked on designing and developing radiolabeled fatty acids. We chose fatty acids because the heart is unique in its need for long-chain fatty acids as its primary energy source (other organs derive their energy chiefly from oxidation of glucose obtained from the blood). That fatty acids can be used as natural carriers of radioisotopes to the heart is well known. However, because the heart breaks down, or metabolizes, fatty acids, our goal was to develop structurally modified fatty acid analogues that would be picked up, but not metabolized, by the heart. We sought to make analogues that would be "trapped" by the heart long enough to provide a picture of the extent of damage. After designing fatty acid agents with the right biological properties and testing these agents in animals, we found that indeed our modified analogues behave like natural fatty acids and are trapped by the heart. We call this property "metabolic trapping."



Fatty acids are concentrated, or extracted, by the myocardium from the blood plasma. Under normal conditions, the cardiac output, or fraction of the total blood pumped from the heart that flows through the heart muscle, is about 3–5%. The remainder of the blood is pumped to the other body organs. Thus if a radiopharmaceutical agent such as radiolabeled fatty acids is totally extracted in the first pass through the heart muscle, a maximum of 4% of the injected material can be localized in the heart. However, if part of the heart muscle has reduced blood flow because of an arterial blockage, the uptake of the radioactive agent will be lower than for the rest of the heart; because of reduced uptake, the camera will detect less radioactivity and thus can pinpoint where the damage occurred.

To solve the problem of the heart metabolizing fatty acids, we sought to introduce into the fatty acid molecule a structural feature

Chemical structures of naturally occurring fatty acids (stearic acid) used for energy production in the heart muscle (myocardium) and structurally modified radiolabeled fatty acids developed in the ORNL Nuclear Medicine Group to study heart disease. The radioiodide is stabilized on these molecules by attachment to either an iodophenyl or an iodovinyl group.

Lynn Cunningham, left, and Kathleen Ambrose check the rats used by the Nuclear Medicine Group for evaluating new radiopharmaceuticals to determine their distribution and uptake properties in the heart muscle.

which does not effect or decrease its uptake from the blood but which would interfere with its metabolism. Such a goal represents a major conceptual and synthetic challenge because drastic structural modification could lead to a molecule that would no longer resemble a fatty acid and thus would not be extracted efficiently by the heart muscle.

Early studies performed at ORNL involved inserting the tellurium-123*m* (^{123m}Te) radioisotope into the fatty acid chain. Tellurium-123*m* in the molecule has two important functions: (1) it is a source of gamma photons and thus makes the fatty acid chain a diagnostic tool and (2) it blocks the heart's attempt to metabolize the fatty acid chain. We found in animal studies that the tellurium-labeled fatty acid shows outstanding trapping properties. In collaboration with Dr. H. William Strauss and his co-workers at Massachusetts General Hospital, we have evaluated this agent in conjunction with other analogues in which the tellurium heteroatom had been inserted into other positions of the chain.

Our early studies were significant because they demonstrated for the first time that such a modified fatty acid would still have a strong affinity for the heart muscle (myocardial specificity). More importantly, we were the first to demonstrate that the modified fatty acid would remain in the heart for a much longer time, presumably because of the metabolic blocking action of the tellurium. This prolonged retention is important for the new generation of imaging instruments that use the technique of single-photon-emission computerized tomography (SPECT), which requires extended imaging periods so that the computer can reveal a three-dimensional structure based on the numerous images taken from different angles by the moving detector. (Photons of light are emitted by electron excitation produced when gamma rays from the radioactive agent in the patient's body impinge on a sodium iodide crystal in the detector; the emerging pattern of photon intensities is proportional to the spatial distribution of the radioactivity, which gives a picture of the extent of tissue damage.) Because of the prolonged retention (only 10 to 15% loss from the heart muscle within 24 h after injection) of our modified fatty acid agent, the radioactivity tends to stay in one place and not be readily redistributed. This minimal redistribution is important for SPECT analyses because the greater the change of the distribution pattern during the imaging period, the larger the error that will be introduced into the final image.

Although ^{123m}Te-labeled fatty acids were crucial for developing the experimental concept of trapping, the radioisotope is not ideal as a clinical diagnostic tool. It has a long physical half-life (120 d), a high production cost, and a low specific activity (amount of radioactivity per unit weight). Therefore, we have attempted to

Mark Goodman, left, and P. C. Srivastava work on the development of the substrates used for radiolabeling, which involves extensive organic syntheses and purification.

retain tellurium in its nonradioactive form as a metabolic blocking agent but to attach to the same molecule a radioisotope with more suitable properties for diagnostic purposes—namely, ^{123}I.

Iodine-123 is a more attractive radioisotope for use in nuclear medicine than ^{201}Tl because when ^{123}I decays, it emits gamma rays at an energy level (159 keV) that can be efficiently detected by today's equipment. It also can be obtained in high specific activity, which makes it safer than radioactive tellurium: Less mass needs to be injected to obtain a detectable level of radioactivity. It is more practical than ^{123m}Te because it has only a 13-h half-life, which is just long enough to permit the isotope's commercial distribution from accelerators to hospitals. A major advantage of using ^{123}I is the tremendous versatility of chemical methods for introducing iodine into a wide variety of tissue-specific molecules such as the fatty acids. (The ORNL calutron units play an important role in the availability of ^{123}I because commercial production of this radioisotope usually involves cyclotron bombardment of electromagnetically enriched ^{124}Te available from the Laboratory.)

Inserting nonradioactive tellurium and attaching ^{123}I to the terminus of our modified fatty acids required some difficult, sophisticated chemistry. The preparation involved stabilizing ^{123}I on model tellurium fatty acids using two different chemical methods. In the experimental fatty acid chains, we stabilized ^{123}I as either an iodophenyl or iodovinyl group. These special groups were designed to minimize iodide losses that occur because of the chemical susceptibility of the carbon iodide bond attached to the fatty acids. The free radioiodide thus released accumulates primarily in the thyroid glands and the stomach.

One major application of this second generation of modified fatty acids is to evaluate the amount of myocardial tissue that can be salvaged after an ischemic attack. These agents have been extensively evaluated in animal studies and appear well suited for SPECT imaging equipment because of the agents' prolonged retention and minimal redistribution and the attractive properties of ^{123}I.

As described earlier, ischemia is localized tissue hypoxia (deprivation of oxygen and nutrients) caused by reduced blood flow in a blocked artery. Usually after a patient has a heart attack resulting from reduced blood flow to regions of the heart muscle, drugs are administered to increase the flow to these damaged regions. Hence, there is also a need for a diagnostic agent to determine how well the drug treatment is working by revealing changes in blood flow to the heart.

The unique ability of our fatty acid agent to detect and characterize ischemia and changes in blood flow patterns as a result of drug therapy has been demonstrated in dogs by Dr. J. A. Bianco at the University of Massachusetts Medical Center. Working with us in a medical cooperative program, Dr. Bianco has removed and dissected the heart of each experimental dog and determined the distribution of the fatty acid agent by measuring the radioactivity from the small sections of the heart muscle.

Besides determining the extent of damage and the effectiveness of therapy, a third, and probably the most important, major application of these agents will be to evaluate changes in regional metabolism of myocardial fatty acids that occur in the absence of coronary artery disease. In this application, the flow of blood in the hearts of test animals is normal, as verified by ^{201}Tl studies. But certain other diseases of the heart such as cardiomyopathies and hypertensive heart disease may be detected by fatty acid agents because these diseases can cause the heart to

An experimental rat is positioned under ORNL's new gamma camera detector following the intravenous injection of a radioactive test compound to determine the distribution of radioactivity in the animal's tissue.

Linda Ailey and Knapp operate the new gamma camera and computer system, which was recently acquired to evaluate the tissue distribution and kinetics of ORNL-developed radiopharmaceuticals in experimental animals. ➤

change the mechanism of uptake or rate of metabolizing fatty acids. This application, which I will discuss later, may offer a unique opportunity to evaluate the early stages of heart disease prior to severe ischemia or when blockage in the coronary arteries is absent.

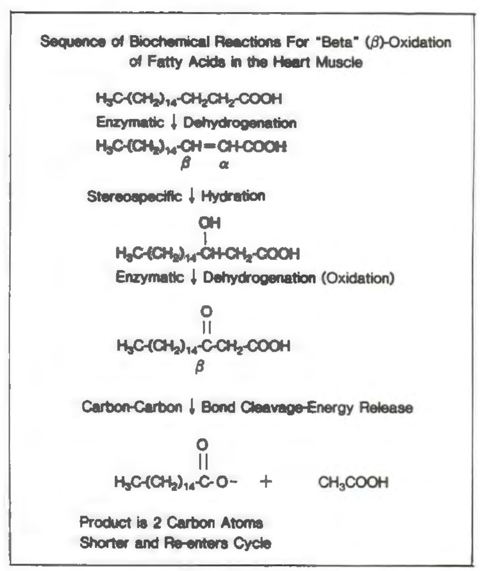
Methyl-Branching

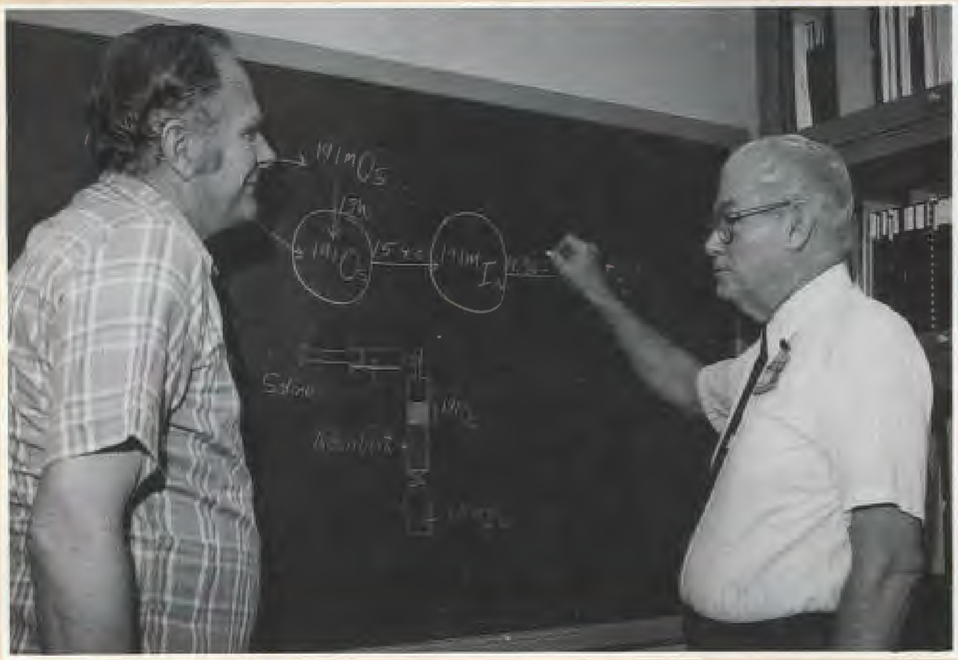
The tellurium fatty acids labeled with ^{123}I are very difficult to prepare, so their availability for experimental studies is unfortunately limited to very few institutions. More recent investigations by our group have focused on a third generation of structurally modified fatty acids in which we have introduced methyl-branching instead of tellurium to inhibit metabolism of fatty acids by the heart. Although this strategy is not as effective as using tellurium fatty acids, it offers a better alternative for clinical application.

Methyl-branching—attaching an alkyl carbon-hydrogen (CH_3) group—can be used to inhibit metabolism because of the well-established sequence of reactions involved in the initial stages of beta-oxidation in the heart muscle for energy production. The term *beta-oxidation* is used because the chemical bond between the second (alpha) and third (beta) carbon atoms is broken to release energy. This sequence is initiated by enzymatic attachment of an oxygen to the beta-carbon. Because the methyl-branched fatty acid cannot be oxidized in the first cycle of beta-oxidation, the resulting fragment of the agent may be more slowly transported or perhaps bound to an enzyme component. As a result, it may be trapped; it will probably be released more slowly from the heart muscle.

To prepare the methyl-branched fatty acids, Mark Goodman, an organic chemist, has developed innovative multistep organic syntheses. A 16-step sequence was required to prepare the "substrate," which was used to introduce the ^{123}I isotope. Our model agent,
(Continued on p. 8.)

Sequence of biochemical reactions utilized in living cells such as those found in the heart muscle for production of energy by the process of beta-oxidation. Introduction of the methyl group in the beta position inhibits breakdown of the fatty acid.





Clarence Guyer, left, listens as Tom Butler explains the chemistry involved in the development of ORNL's new osmium-191–iridium-191m short-lived radionuclide generator system. This development has involved a systematic evaluation of a large number of potential adsorbents of osmium-191.

ORNL's Improved Iridium Generator Is in Clinical Use in Europe

Over the past three years, we have made significant progress in developing an improved osmium-191–iridium-191*m* (^{191}Os-^{191m}Ir) radionuclide generator, which is especially suited to detecting heart defects in children. This ORNL-developed generator is now in clinical use in Liege, Belgium, in conjunction with our collaborators Claude Brihaye and Marcel Guillaume at Sart Tilman University.

Radionuclide generators are widely used in clinical nuclear medicine to produce short-lived imaging agents, which are desirable because they expose patients to only a very low level of potentially hazardous radioactivity. A radionuclide generator consists of a small column containing an adsorbent material (such as aluminum oxide) onto which is placed a "parent" radioisotope (such as ^{191}Os). The parent decays to a "daughter" radioisotope (such as ^{191m}Ir), a different element with properties that make it a useful tracer for clinical diagnostics. Because the parent and daughter are different elements, they have different chemical properties, which can be exploited by selecting the proper adsorbent for their separation.

In the Nuclear Medicine Group, Tom Butler, now retired, had studied the classical chemical problem of separating a large amount of iridium from osmium and of preventing the osmium from contaminating the iridium product (such contamination would increase the radiation hazard to the patient). The key to this development was the selection of the best adsorbent.

The most efficient radionuclide generator uses an adsorbent that tightly binds the parent isotope yet allows the daughter to be removed easily when an aqueous solution is passed through the generator. The process of removing the daughter is known as elution, or "milking" the generator; the generator itself is referred to as a radioactive "cow." The parent radioisotope is generally produced in either a reactor or a particle accelerator (cyclotron). Usually the parent is undesirable for use in humans, however, because of its long physical half-life and high radioactive emissions. Such properties can increase the absorbed radiation dose to the patient and lead to poor images. Elution of the parent, also known as breakthrough, must be completely avoided or, at worst, minimized. Thus the generator design is based upon the ability of the adsorbent to bind the parent tightly and to allow easy elution of the daughter radioisotope.

We have been interested in the ^{191}Os-^{191m}Ir radionuclide generator system since 1981. At ORNL ^{191}Os is produced in the High Flux Isotope Reactor (HFIR), which has a uniquely high neutron flux. The parent isotope is formed in the HFIR by neutron irradiation of highly enriched ^{190}Os, which is produced in calutrons at ORNL. Because the currently used iridium generator has a modest yield of only 10% and the breakthrough increases with use and because ORNL is the main source of the osmium parent, our group has been exploring improved designs for the osmium-iridium generator.

This patient at Children's Hospital in Boston was injected with iridium-191m, which is obtained from a generator system (shown in photograph) loaded with the osmium-191 parent produced in the ORNL High Flux Isotope Reactor. The iridium-191m is used for the evaluation of intracardiac shunts (holes between heart chambers) in children. (Courtesy of Dr. Salvador Treves, Children's Hospital, Boston.)

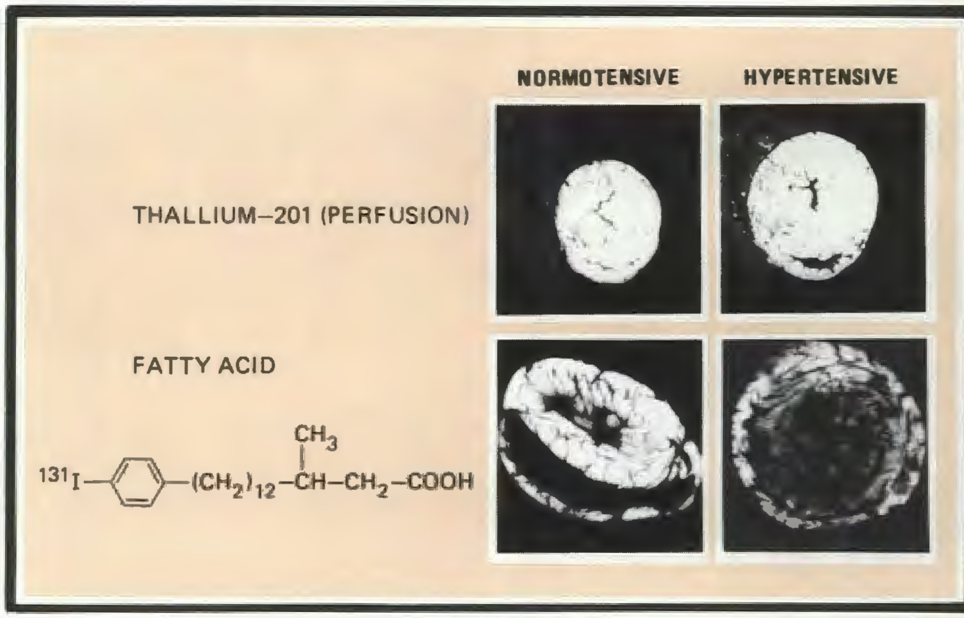
As part of a medical cooperative program, Dr. Salvador Treves, Boston Children's Hospital, pioneered the current iridium generator to detect heart defects in children and adults. Almost 100,000 children in the United States are born each year with congenital heart defects; as many as 20,000 could benefit from the ^{191m}Ir diagnostic procedure.

Treves selected ^{191m}Ir as an attractive radioisotope for several reasons. Unlike fatty acids, iridium stays in the blood and is not extracted by the heart muscle. The agent can thus be used for "blood pool" imaging, in which the radioactive blood is monitored as it flows through the heart chambers and lungs. This type of monitoring is needed to detect a shunt, an abnormal hole between the chambers of the heart.

Because the ^{191m}Ir daughter has an extremely short physical half-life—4.96 s—it is ideal for pediatric patients: The radiation dose is very low, and repeat studies can be performed within a short time. A further advantage of the iridium generator is that the parent ^{191}Os has a relatively long (15-d) half-life; thus the generator could have a potentially useful "shelf life" of two to four weeks, providing that the problems of parent breakthrough and decreasing ^{191m}Ir yields can be overcome. The current generator has a useful life of only a couple of days because of increasing breakthrough.

In collaboration with Brihaye, a scientist who was here on sabbatical from Liege, we evaluated 40 different adsorbents using three different oxidation states of ^{191}Os to find out how to extend the useful life of the ^{191m}Ir generator. These studies, which involved more than 1000 different measurements, consisted of mixing the various osmium species with the individual adsorbents and then measuring the uptake of the radioactive osmium on the adsorbents after centrifugation. If the osmium shows good uptake on an adsorbent, that adsorbent has the desirable property of tightly binding the osmium. The adsorbent that we have found to exhibit very good properties increases the elution yield of ^{191m}Ir from 10% to up to 40%. In addition, we detected very low breakthrough, which remains low for several weeks after many elutions. The useful life of the generator can apparently be increased from several days to several weeks using this new adsorbent.

We recently submitted a patent disclosure to the U.S. Department of Energy describing this improvement. The generator is now being used in adult patients in Europe, and we expect that in a matter of months this generator will be approved for use in the United States to detect heart problems in children and adults.—*F.F.K.*



Autoradiographic images of thin slices of heart muscle obtained from normal and hypertensive rats after intravenous administration of a regional blood-flow marker (thallium-201) and an iodine-131 methyl-branched fatty acid. The nonhomogeneous distribution of the fatty acid demonstrates an aberration in fatty acid metabolism in regions that have normal delivery, or blood flow. (Courtesy of Dr. A. B. Brill, P. Som, and co-workers, Medical Department, Brookhaven National Laboratory.)

15-(*p*-[^{123}I]iodophenyl)-3-*R,S*-methylpentadecanoic acid (BMIPP), is the methyl-branched fatty acid analogue of an unbranched fatty acid that has been used at several institutions in Europe for the evaluation of heart disease. The unbranched analogue, however, shows considerably more rapid washout from the heart than our branched analogue; because our fatty acid analogue is retained in the heart muscle longer than the straight chain version, our agent may be more suitable for SPECT analysis as a probe of fatty acid metabolism.

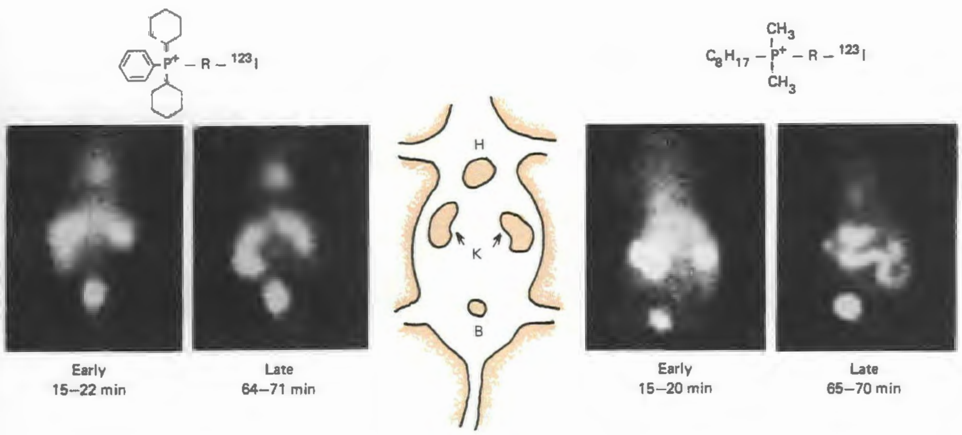
We have also recently developed and evaluated at ORNL a second model methyl-branched fatty acid (BMIVN) in which the ^{123}I has been stabilized by the vinyl iodide approach. This methyl-branched analogue also shows greater retention than the unbranched analogue. The BMIVN may be the agent of choice for clinical study because it seems to be more easily prepared from a "kit" than BMIPP. Both BMIPP and BMIVN are under intensive evaluation in our program and in conjunction with investigators in a medical cooperative program who have special expertise to study selected aspects of the properties of these two agents. These methyl-branched agents will soon be tested in human patients.

Hypertension Studies

The promise of ^{123}I-labeled fatty acids for evaluation of hypertensive heart disease (high blood pressure) has been recently demonstrated in studies done in a medical cooperative program in collaboration with Dr. A. B. Brill, director of the Medical Department at Brookhaven National Laboratory, and Dr. Strauss at Massachusetts General Hospital. These studies involved autoradiography, a technique whereby tissues from experimental animals are removed after intravenous administration of radiolabeled agents, frozen, sliced into ultrathin slices, and placed on photographic film. In this technique, which offers very high resolution, the degree to which the radioactivity exposes the film indicates the distribution of radioactivity in the tissue slice. By using quantitative dual tracer autoradiography, Dr. Brill and his colleagues monitored the relative distribution of two different agents.

For example, the fatty acid we labeled with ^{131}I (8-d half-life) is administered to normal rats who were also injected with ^{201}Tl, which has a half-life of 72 h. The same mixture was administered to a second group of rats made hypertensive by sodium chloride (a high-salt diet). As discussed earlier, ^{201}Tl is commonly used for the clinical evaluation of coronary heart disease and is distributed through the heart muscle as a function of blood flow. Thus if the autoradiographic studies show a homogeneous distribution of ^{201}Tl, the blood supply to all regions of the heart muscle is normal.

The first autoradiographs indicated normal regional blood flow in the hearts of rats of both the control group and the hypertensive group because of the homogeneous distribution of ^{201}Tl. After allowing 30 d for all of the ^{201}Tl to decay (10 half-lives later), Dr. Brill's group could determine the distribution of our ^{131}I-labeled fatty acid by examining the later autoradiographs of the same tissue slices. They found that (1) in the normal rats both ^{201}Tl and the ^{131}I-labeled fatty acid are evenly distributed and (2) in the hypertensive rats ^{201}Tl has an even distribution but the ^{131}I-labeled fatty acid clearly shows an uneven distribution. The thallium results show that regional blood flow is normal in the hypertensive rat hearts, indicating that fatty acid delivery to the heart was not impaired. However, the heterogeneous distribution of fatty acid indicates that hypertensive



Gamma camera images obtained of rats after intravenous administration of iodine-123-labeled phosphonium cations. The bright areas represent regions of radioactivity. The center panel illustrates the anatomical relationship of the organs of interest.

heart disease may have altered the ability of portions of the heart to metabolize fatty acids.

These observations are very important because they suggest that a metabolic change occurs in severe hypertension before any differences in blood flow (ischemia) can be detected. Therefore, because agents such as ^{201}Tl, which are widely used to detect and evaluate coronary artery disease, can indicate only differences in blood flow, they may not be effective in evaluating hypertensive heart disease. On the other hand, the combination of ^{123}I-labeled fatty acids and SPECT can potentially evaluate hypertensive disease and assess the effects of drug therapy. Toxicity testing of BMIPP has been completed at Massachusetts General Hospital, and the first clinical tests of the labeled fatty acid will begin soon in Boston and in Vienna, Austria.

Organic Cations

Organic cations are the newest type of radiopharmaceutical that we are developing for heart imaging. Our studies involve the preparation and evaluation of positively charged (cationic) phosphorus and related compounds to which a radioisotope is attached. Interest in these agents was stimulated by cell culture (in vitro) studies by biophysicists that have shown that the uptake of model phosphonium cations from the growth medium by living cells depends upon the transmembrane potential. Thus cells that have a slightly negative charge in their interior environment show uptake of the positively charged cations. Model phosphonium cations, such as tetraphenylphosphonium bromide, also show high myocardial uptake in experimental animals. Thus these agents show promise in evaluating the types of heart disease that cause aberrations in myocardial cell membrane potential.

P. C. Srivastava, a medicinal chemist working in our Nuclear Medicine Group, has developed new methods of preparing these phosphonium cations. One of these cations, in which ^{123}I has been stabilized as a vinyl iodide, shows high heart uptake in dogs and rats. This model agent also shows significant hepatobiliary localization in dogs—that is, it is taken up by the liver and excreted in the bile through the gallbladder into the small intestine. To investigate the relationship between heart selectivity and hepatobiliary clearance of these types of agents, we prepared a variety of structurally modified phosphonium agents and evaluated them in rats.

The recent availability to nuclear medicine groups of a new clinical gamma camera and computer system has added a new dimension to the testing of our agents. At ORNL we are now using our recently obtained camera and computer to routinely evaluate our new agents in small animals. The computer analyzes data to determine the rates at which the imaging agent is lost from tissue in rats and other experimental animals. We used our new gamma camera and computer system to conduct imaging studies, which showed a striking relationship between structure and biological localization.

Because the heart lies so close to the liver and because phosphonium cation analogues show excellent heart selectivity and low liver uptake, these agents could be valuable for diagnosing certain heart diseases. High liver uptake obscures a clear delineation of the lower part of the heart muscle and therefore should be minimized to allow good imaging of this region. Our phosphonium cation agents have been designed and tailored to exhibit the most desirable biological properties for imaging the lower part of the heart muscle.

In our experiments with rats injected with structurally modified phosphonium cations, we observed high heart uptake and moderate liver uptake in the early images. We also found that the background radioactivity is low, indicating rapid clearance of the agent from the blood. This rapid clearance is an important property because our goal is to visualize (image) the radioactivity concentrated within the heart muscle with little or no interference from radioactivity in the blood pooled within the heart chambers. In the later images, we

Cunningham, Ambrose, and Bruce Owen use cells grown in culture to evaluate the distribution of radiopharmaceuticals within the internal cell structures. This information reflects the metabolic fate of these new agents.

could still clearly see the heart, despite a slight increase of radioactivity within the gastrointestinal tract caused by the excretion of part of the agent through the liver.

In our experiments with rats injected with a differently modified cation, we noted from the early and late images the dramatic effects that structural modification can have on an agent's biodistribution properties. In this analogue, which has been modified by replacement of the three rings (see figure on page 9) with fat-soluble saturated organic groups, the heart uptake in the early image is clearly decreased, and radioactivity in the liver (hepatobiliary area) is high. More importantly, in the later image we observed the transit of radioactivity into the intestinal tract. In short, the first analogue is clearly superior to the second one for imaging the lower portion of the heart muscle.

The effects of these structural changes on the tissue specificity and biodistribution properties of these agents cannot be predicted. A comprehensive and systematic evaluation of a series of modified agents (structure-activity study) is required to develop agents with the most desirable biological properties. After several structurally modified agents have been prepared and evaluated in rats, the effects of structural groups on biodistribution properties can be accurately assessed, and these data can be used to design an agent with optimal properties. Such an agent may be studied further and eventually evaluated in clinical trials for possible use in human patients.

Clinical Tests

Although our nuclear medicine program receives funding from DOE's Office of Health and Environmental Research to pursue new ideas and concepts for the development of improved radiopharmaceuticals, we cannot lose sight of our eventual goal of making these new agents available for clinical testing. As an organization, we are not licensed to distribute radiopharmaceuticals, but we are actively associated with a variety of outstanding clinical and research organizations. We supply our collaborators in these organizations with agents developed in our program for further, more extensive preclinical testing or clinical evaluation.

When our agents reach the point of being considered for clinical

Goodman (left), Knapp, Ailey, and Srivastava discuss the development of new radiochemicals to evaluate diseases of the heart.

evaluation, the clinical investigators are responsible for obtaining approval from their human use committee to use these agents on a limited basis in clinical trials. Such approval depends upon the results of chemical toxicity tests and calculations of the expected absorbed radiation dose to the patient. New agents must be shown to be nontoxic and to expose the patient to only minimal radiation at the expected dose levels before they can be used in humans. The chronology of events leading from the development of a concept to use in patients is a very long path; steps along the way include design of an agent, chemical synthesis, radiochemical synthesis, biological evaluation, imaging studies, toxicity testing, and determination of radiation dosimetry. As in the development of therapeutic drugs, only a few new radiopharmaceuticals will reach clinical testing. However, test results from even early steps can guide investigators in designing other radiopharmaceuticals.

Several of the heart-imaging agents that we have developed at ORNL are now being or will soon be used clinically on human patients. We are supplying osmium-191 for iridium-191*m* generators used to diagnose heart problems in children, and we are developing a new generator system that should see widespread clinical use (see box). Toxicity tests have been completed on the methyl-branched fatty acid, and in fall 1984 it was approved by our collaborators at the Massachusetts General Hospital for tests on human patients. This fatty acid, considered a key agent, represents the culmination of several years of intensive investigation at ORNL to develop new agents to detect heart disease. ornl

BOOKS

"Cognition is not enough; action and assertive behavior to increase one's visibility make for success in science."

From X Rays to Quarks: Modern Physicists and Their Discoveries, *Emilo Segrè, W. H. Freeman & Company, San Francisco (1980), and* **Winning the Games Scientists Play**, *Carl J. Sinderman, Plenum Press, New York (1982). Reviewed by William S. Lyon, Analytical Chemistry Division.*

Coincidences usually go unnoticed unless they are startling or out of the ordinary. Thus a man entertaining his woman friend in a restaurant may be virtually ignored by other diners who know him; it is only when his wife is suddenly seated at an adjoining table that a coincidence is noted. Recently, in a somewhat less exciting demonstration of a rare coincident event, I received two books for perusal from the ORNL Central Research Library on the same day. Although seemingly quite dissimilar, these books actually treat in different ways the same subject: success in science.

From X Rays to Quarks is by Emilo Segrè, a name familiar to every radiochemist. A Nobelist, Segrè has written a fascinating account of the evolution of modern physics from 1895 to 1980. He discusses the life and work of all the great ones: Henri Becquerel, Marie and Pierre Curie, Ernest Rutherford, Albert Einstein, Niels Bohr, Enrico Fermi, and E. O. Lawrence. He also describes the contributions of physicists whose names we mainly associate with principles: Louis Victor De Broglie, Wolfgang Pauli, and Paul Dirac, for examples.

Segrè starts his history by describing the physics laboratory of 1895 and the research that occupied physicists prior to the discovery of radioactivity and the establishment of atomic theory. "One way of ranking a laboratory," he writes, "was according to the power of the battery it owned." Because no central source of electrical power existed, making and servicing batteries consumed much time.

Those of us engaged in nuclear analyses and radiochemistry use the concepts and techniques developed by these great scientists in the subsequent 85-year period. So it seems profitable to look at their lives and observe their way of thinking and working. Certainly few if any can attain the heights reached by, say, Lise Meitner or James Chadwick, but all of us can learn something about science and how to think about a problem from observing these successful practitioners. Segrè's book dwells on the cognitive abilities of the great scientists; without a strong cognitive ability, the book suggests, the aspiring scientist is lost.

However, as Segrè's accounts suggest, scientific success may depend on more than mental ability. William Shakespeare, the great recorder of human nature, once wrote: "There is a tide in the affairs of men, which, taken at the flood, leads on to fortune." Opportunistic scientists have a way of making several discoveries and then milking them for almost all they are worth, while other scientists may make only one discovery and then seem to rest on their laurels, allowing their peers and successors to find and prosper from the practical applications. For example, consider the career of Wilhelm Roentgen. In 1895 he made his famous discovery of X rays. The next year about 1000 papers were published on the subject. Yet Roentgen himself wrote only two more papers on X rays in 1896 and 1897, and in the ensuing 24 years he wrote only seven papers. In 1902 he received the Nobel Prize on the strength of his 1895 discovery. But why did Roentgen not have a particularly productive career like the careers of fellow Nobelists Marie Curie and Rutherford?

The answer may lie in certain noncognitive qualities that lead to success in science, the subject of Carl J. Sinderman's *Winning the Games Scientists Play*. A marine biologist, Sinderman has written one of the few self-help books for scientists seeking to climb the ladder

of success. His kind of message used to turn me off, but either a wearing-down process or a gradual enlightenment has caused me to soften my attitude. Probably most introverted, idea-oriented people in technical fields take my earlier point of view. The thought that noncognitive forces such as communication skills and political pull can play some role in determining success and advancement in a scientific career is anathema to most scientists. Sinderman purports to show that this attitude is wrong, and in our hearts we know he is right. The old saying, "If you can't beat 'em, join 'em," seems appropriate here. In short, this book is recommended reading for those who need it most but desire it least.

"Anyone who has ever refereed a paper for a journal or dozed through a technical session at a meeting knows that many scientists lack even a rudimentary knowledge of how to present ideas in a convincing and intelligible manner."

The author begins with several excellent chapters on the mechanics of writing, reviewing, and presenting technical papers. His advice is worth heeding; anyone who has ever refereed a paper for a journal or dozed through a technical session at a meeting knows that many scientists lack even a rudimentary knowledge of how to present ideas in a convincing and intelligible manner. Sinderman also has some encouraging words for those of us who get itchy feet during long scientific meetings: Never sit through a whole session of papers. He maintains that corridor conversations and social-hour contacts are the most valuable sources of information at a scientific conference. He also offers some excellent guidelines for organizing and chairing sessions.

Sinderman then launches into a discussion of the scientist in transition, moving up, acquiring and using power, concentrating more on attracting funding and qualified people than on the mechanics of getting the research done. To get ahead, he suggests, a scientist should seize opportunities to contribute to committees, organize sessions and meetings, give talks at scientific conferences, and find other ways to become visible. He advises scientists to work hard and long at these tasks.

The final section of the book—and the weakest—attempts to treat such sticky subjects as the roles of women in science and how to cope with bureaucracy, lawyers, and the news media. Some of this material seems marginal and arbitrary.

Nonetheless, *Winning the Games Scientists Play* has much to commend it, as does Segrè's book. And for coincident reading, they seem ideally suited. In Segrè's accounts one sees many applications of rules that Sinderman has observed and codified. For example, consider this episode recounted by Segrè on the failure of Fermi and his colleagues to recognize uranium fission. In 1935 a woman chemist, Ida Noddack, wrote a note criticizing some experiments done in Rome on uranium. She said that Fermi, Segrè, and others had failed to prove that uranium does not break into two big fragments when bombarded with neutrons. At that time, Fermi was trying to use neutrons to transmute uranium into a heavier, man-made element. Apparently, Noddack's criticism was known to Otto Hahn, Marie Curie, and others, but no one—including Noddack—bothered to check it out. Perhaps fission would have been discovered four years earlier if Noddack had been perceived by her colleagues as more authoritative or if she had been ambitious enough to go ahead and make the discovery herself. Cognition is not enough; to paraphrase Sinderman, action and assertive behavior to increase one's visibility make for success in science.

John Sheffield (at the model of the Advanced Toroidal Facility) is associate director of ORNL's Fusion Energy Division. He received his B.Sc. degree from Imperial College, London University, in 1958. From 1958 until 1966 he worked in the fusion research programs at the Harwell and Culham laboratories of the United Kingdom Atomic Energy Authority in England. The work involved the study of shock waves in plasma and the development of high-voltage switching systems and diagnostics. In 1962 he obtained an M.Sc. degree in molecular spectroscopy and gas discharge physics from Northern Polytechnic, London. In 1966 he obtained a Ph.D. degree from London University on the experimental and theoretical study of the helical instability in the positive column and joined the faculty of the Physics Department of the University of Texas at Austin. He continued working on shock waves and diagnostic development, in particular, on the use of Thomson scattering of radiation for the measurement of plasma parameters. In 1971 he returned to Culham Laboratory to work on the development of high-power neutral atomic beam systems and their application to tokamaks. Sheffield joined the Joint European Torus group at Culham in 1973, working on heating, diagnostics, and cost-effectiveness assessments of tokamaks. In 1975 he published a book entitled *The Scattering of Radiation from Plasmas.* Two years later he joined ORNL's Fusion Energy Division and has been involved since then, primarily, in the experimental confinement area—first as head of the Tokamak Experimental Section, then as head of the joint Tokamak and Elmo Bumpy Torus Experimental Sections, and, since 1982, as the division's associate director.

The Advanced Toroidal Facility

Improving Fusion's Chances

By JOHN SHEFFIELD

The energy released in the fusion of the lighter elements, such as the hydrogen isotopes deuterium and tritium, is one of the few inexhaustible sources of energy for the future. Research in harnessing this energy for peaceful uses has been in progress for more than 30 years. The time scale of this research and the additional long period expected for commercialization indicate the difficulty of the task. Under normal conditions, atomic nuclei will not join together because particles of like charge repel each other; thus the difficulty in achieving fusion stems in large part from the requirement that atomic particles in the fusion fuel be heated to temperatures of 100 million degrees or more. At very high temperatures all matter is fully ionized, thus forming a mixture of free charged particles—electrons and positive ions—called a plasma.

At Oak Ridge National Laboratory we have been involved in the development of magnetic fusion since the 1950s. In our experimental machines, we use magnetic fields to confine the hot plasma and to isolate it from the vessel wall. Because charged particles are constrained to follow the magnetic lines, we can construct "magnetic bottles" to contain the plasma. Of central importance to the development of magnetic fusion as a practical source of energy is the creation of magnetic bottles, or magnetic field configurations, that can contain a hot plasma efficiently. This efficiency has three characteristics:

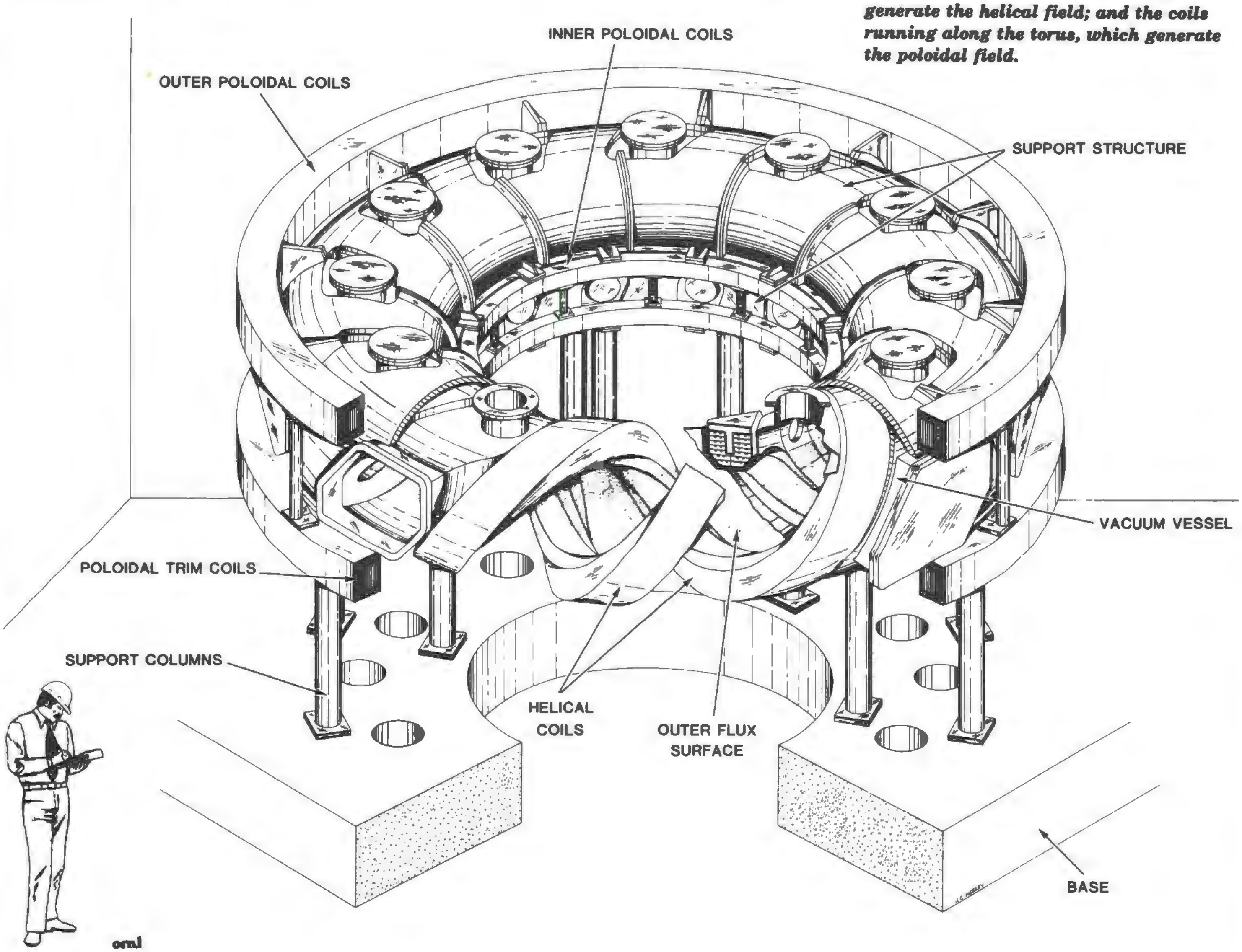
- The thermal conductivity of the plasma in the magnetic field must be low so that the plasma can be heated easily and kept at a constant temperature.
- Beta, the plasma pressure taken as a percentage of the magnetic pressure, must be high, approaching 10%, to ensure that the fusion device is cost effective. For a fusion reactor we must be able to support a plasma pressure of about 10 atm, with a magnetic field of about 5 T.
- The reactor system should operate in steady state—that is, operate without interruption, unlike today's experimental tokamak machines, which are pulsed. This characteristic is desirable from the electric utilities' point of view, but it is not absolutely essential.

Tokamaks and Torsatrons

The front-running magnetic fusion concept in the United States is the tokamak, a doughnut-shaped (toroidal) device originally developed in the Soviet Union in the 1950s. The concept has been tested in the United States for more than a decade. At ORNL we have had a coordinated program of theoretical and experimental work at three tokamaks—ORMAK, from 1971 to 1976; Impurity Study Experiment (ISX-A), from 1977 to 1978; and ISX-B, from 1978 to 1984.

In 1981 we were faced with a number of important issues in the tokamak program. In particular,

Artist's impression of the Advanced Toroidal Facility (ATF) showing the vacuum vessel; support structure; the coils spiraling around the torus, which generate the helical field; and the coils running along the torus, which generate the poloidal field.



Because further improvements in doughnut-shaped, or toroidal, fusion devices are desirable, ORNL has designed an Advanced Toroidal Facility (ATF). An optimized version of a stellarator (which differs from a tokamak in that it lacks a plasma current to magnetically confine the fusion fuel), the ATF will be built in Oak Ridge and is scheduled to begin operation in late 1986.

there were concerns about confinement in tokamaks at high beta and the pulsed nature of the basic tokamak. Since then, plasma performance has been improved, and alternative schemes for driving the plasma current in steady state have been demonstrated. Nevertheless, further improvements are desirable.

In response to this need, members of the Fusion Energy Division have developed a modified "torsatron" configuration, which is an optimized version of the stellarator (another toroidal concept that, unlike the tokamak, does not employ a plasma current for confinement). Called the Advanced Toroidal Facility (ATF), this torsatron is designed to operate in steady state and, theoretically, can achieve low thermal conductivity and high beta. The understanding of fundamental physics that this device will provide should lead to improvements in the toroidal reactor concept.

The U.S. Department of Energy has approved the construction of the ATF device at ORNL; the cost will be $19.3 million. It will start operation in fall 1986.

To save money, we will use on the ATF $60 million worth of ISX support systems, power supplies, fueling, heating, and diagnostics. The ATF will have a plasma with a major radius of 2.1 m and an average minor radius of 0.3 m, confined in a field of 2 T. The ATF plasma will be the largest one to be contained by this type of magnetic field configuration in the world fusion program.

How was the ATF idea conceived? What is its history? And why is it an exciting project and program for ORNL as well as for the U.S. fusion program? The answers follow.

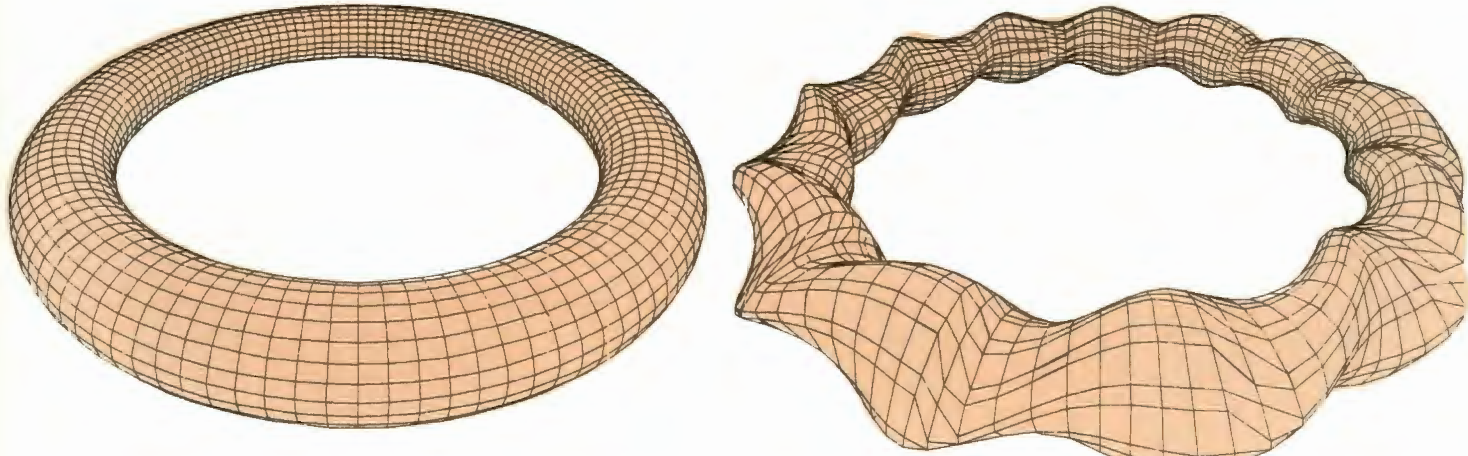
Genesis of the ATF

Fusion research at ORNL is managed by the Fusion Energy Division under the directorship of Bill Morgan. It is part of the Advanced Energy Systems work, headed by ORNL Associate Director Murray Rosenthal, who acts also as head of the Fusion Program. Our work involves extensive collaboration within the Laboratory and with the Computing and Telecommunications and the Engineering divisions of Martin Marietta Energy Systems, Inc. Our research is characterized also by national and international collaborations. The genesis of ATF is a good example of the benefits of such widespread interactions.

In 1981 participants in the toroidal program were confronted with a number of important issues that needed resolving. Along with colleagues in the U.S. toroidal community, we advised DOE that the toroidal mainline, the basic tokamak configuration, should be improved. We argued that an "advanced toroidal facility" was needed. An ATF, we said, should be designed to offer these advantages: (1) attainment of a very long pulse, or steady-state operation; (2) attainment of higher beta, approaching 10%; (3) maintenance of a hot, clean, high-beta plasma for long pulses; and (4) control of plasma disruptions, which, in the tokamak, lead to the rapid dumping of the plasma energy on the walls of the containment vessel.

At that time the focus for advancement was on adjustments to the basic tokamak rather than on designing a radically different type of configuration. Consistent with that approach, DOE accepted our proposal for the ISX-C tokamak, which was designed to integrate our theoretical, experimental, and technology expertise to tackle the problems of producing and maintaining a hot, clean, high-beta plasma in a tokamak for a long pulse.

In early 1982, DOE canceled the ISX-C project, and we were faced with the problem of finding a way to continue our contributions to the toroidal program. Rosenthal then asked an important question that led to a solution. He requested that DOE clarify its position with respect to the cancellation of ISX-C and the future of the ORNL toroidal program. DOE's Office of Fusion Energy issued a quick response, which had two points: (1) the important problems that ISX-C would have tackled could be addressed by other, less specialized facilities and (2) ORNL should investigate and propose a new toroidal configuration that could operate at high beta in steady state and offer improvements over the tokamak concept. This response not only indicated a significant change in policy but also gave us the opportunity to create the ATF.



(*a*) THE TOKAMAK AXISYMMETRY LEADS TO SMOOTH TOROIDAL FLUX SURFACES

(*b*) THE HELICAL COILS OF A STELLARATOR LEAD TO HELICALLY CONVOLUTED SURFACES

The tokamak magnetic surfaces are smooth toroids (like a conventional doughnut). In contrast, the stellarator surfaces are deformed (like a cruller doughnut) by the local fields from the helical coils.

An ATF team was assembled rapidly in the Fusion Energy Division to analyze the wide range of known toroidal configurations. Ben Carreras, Tom Jernigan, and Jim Lyon were appointed to coordinate the theoretical effort, to manage the project, and to manage the program, respectively. Computing and Telecommunications Division personnel under Ron Fowler were brought in to conduct the extensive computer studies needed for both the theory and the engineering of the ATF. An engineering team was set up under Ray Johnson and Phil Thompson.

To ensure that we remained open-minded in our research and communicated well with toroidal researchers at other fusion laboratories, we set up an advisory group of representatives from GA Technologies, Los Alamos National Laboratory, Massachusetts Institute of Technology, New York University, Princeton Plasma Physics Laboratory (PPPL) of Princeton University, and the University of Wisconsin. These people gave us advice and support as did our DOE colleagues.

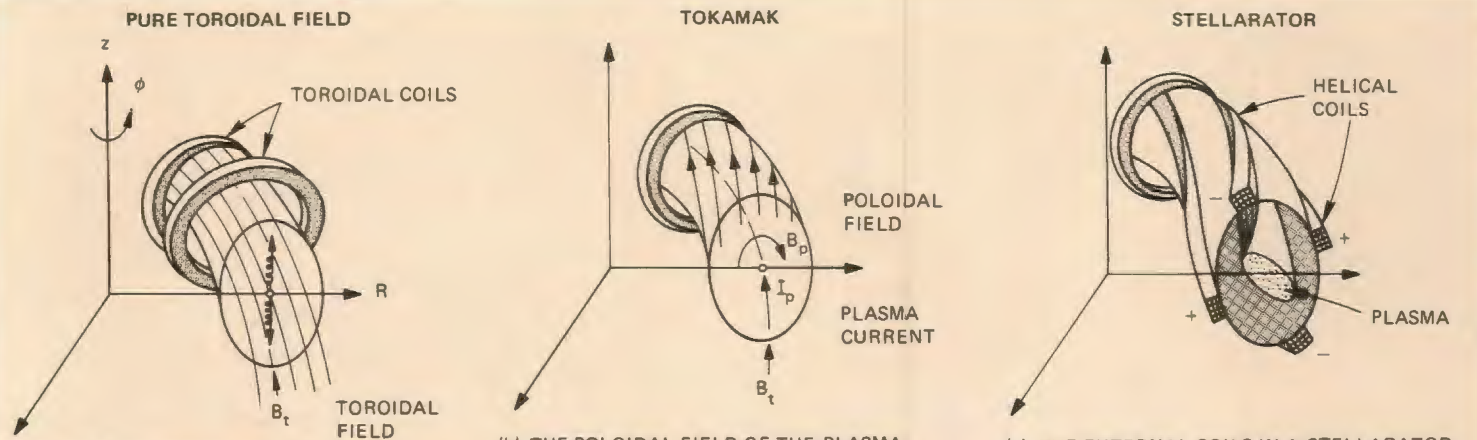
Toroidal Configurations

From the point of view of the ORNL investigation, the candidate magnetic configurations were those in which the field lines orbit the torus, thus forming nested magnetic flux surfaces that resemble the many layers of an onion. Because the charged particles tend to remain close to these surfaces, their transverse motion and ability to conduct heat are reduced; therefore, it is easier to keep the plasma hot. The nested surfaces are the basis for the good thermal insulation of toroidal configurations. Such surfaces may be created in toroidal geometry when the field lines twist around both the toroidal (major) and poloidal (minor) directions. A key characteristic is the rotational transform, or iota bar, which is a measure of the twist. When the iota bar = 1, a field line makes one orbit poloidally for each toroidal orbit. There are three classes of toroidal configurations:

- Systems in which a toroidal field is provided by external coils and additional fields are provided by a current flowing in the plasma. The tokamak is one example. Its iota bar is <1 (i.e., the poloidal field is smaller than the toroidal field). Another example is the reverse field pinch device. Its poloidal and toroidal fields are comparable, so the iota bar is >1.
- Systems in which the magnetic field is produced by external coils alone. These systems are known generically as stellarators.
- Hybrids of the two systems in which the poloidal field is produced partly by a plasma current and partly by external coils.

It became clear to us that the second type of configuration—the stellarator—offered the best opportunities for arriving at an ATF. This configuration has several advantages over tokamaks and reverse field pinch devices: it is inherently steady state; it is disruption free; and, if a plasma current is introduced, it could be used to study the hybrid configuration, making the link to the first class of fusion devices, including the tokamak. Supporting this conclusion were the good results coming from the existing world stellarator program.

Our main objective then was to find a configuration capable of attaining a high beta. Our



(a) IN A PURE TOROIDAL FIELD UNLIKE CHARGES SEPARATE VERTICALLY AND THE PLASMA ROLLS OUT

(b) THE POLOIDAL FIELD OF THE PLASMA CURRENT IN A TOKAMAK TWISTS THE TOTAL FIELD AND LEADS TO CHARGE CANCELLATION

(c) THE EXTERNAL COILS IN A STELLARATOR ALSO TWIST THE TOTAL FIELD AND LEAD TO CHARGE CANCELLATION

Helical magnetic fields in toroidal devices lead to good confinement of the charged particles in a plasma.

secondary goals were to refine the theory of plasma transport, that is, thermal conductivity; to show that the device could achieve high beta with moderate plasma heating, that is, at the ISX-B level of a few megawatts; and to indicate how the device would contribute, generally, to improved plasma confinement in a torus.

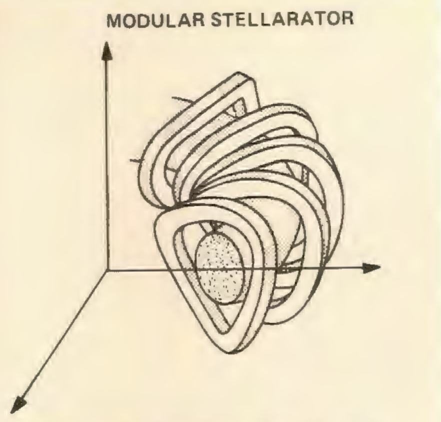
Plasma confinement in a torus cannot occur unless the plasma and field are in equilibrium (i.e., the bottle is the correct way up) and the equilibrium is stable. Equilibrium and stability can best be explained by a ball-and-bowl analogy. A ball placed on top of an inverted spherical bowl can balance there in equilibrium—particularly if there is a small amount of friction. If the bowl is returned to its conventional position (open end up), the ball can be placed in equilibrium in the bottom of the bowl. In the latter case, the ball is in stable equilibrium for, if it is displaced, it will return to the bottom of the bowl. However, when it is on top of the inverted bowl, the ball is in an unstable equilibrium because, if it is displaced, gravity will cause its displacement to increase and it will roll off the bowl.

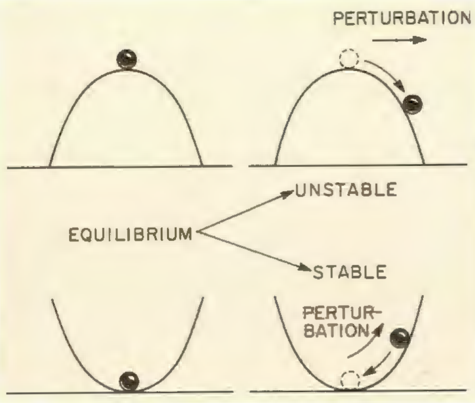
Instabilities caused by beta effects (increased plasma pressure) tend to break up the magnetic surfaces, which provide good thermal insulation important to maintaining the high plasma temperatures necessary for fusion. At the worst level these instabilities can cause the plasma to leave the magnetic bottle and hit the walls of the containment vessel, where the plasma loses its energy. Two main routes to obtaining stability are (1) to design a configuration in which the magnetic field, on the average, increases with distance from the plasma (a magnetic well), and (2) to use a rapidly changing twist in the magnetic field to minimize magnetic surface breakup (magnetic shear).

In most plasma-magnetic field configurations, the magnetic bottle is modified in an undesirable fashion as the plasma pressure is raised, thereby limiting beta. The new powerful analytic techniques allowed ORNL researchers to identify an improved configuration where, in some sense, the depth of the bottle (bowl) increases with increasing plasma pressure. The improved stability leads to a very high beta capability.

Helical Systems—Stellarators

The stellarator was first proposed in the early 1950s at Princeton University by Lyman Spitzer. In fact, the name is now used generically to describe the many helical configurations developed later at Princeton and other laboratories—designs in which the magnetic coils spiral around the plasma. Throughout the 1950s and the early 1960s the stellarator was the cornerstone of the Princeton program. The concept was dropped in the late 1960s because of unsatisfactory results from Princeton's Model C experiment. Princeton then turned its attention to the Russian tokamak, which was enjoying great success. Stellarator research was sustained by a growing effort at Culham Laboratory (England), Garching (Federal Republic of Germany), Kyoto University (Japan), and the Kharkov and Lebedev institutes in the Soviet Union. Subsequently, the U.S. stellarator program was revived by a small but innovative effort





A ball in or on a bowl illustrates how an equilibrium may be stable or unstable.

started at the University of Wisconsin.

The many types of stellarator configurations that have evolved since the early 1950s differ in rotational transform, the number or shape of the helical coils, the number of helical twists, and the aspect ratio of the toroidal plasma. (The aspect ratio is the ratio of the major to minor plasma radii; by analogy, an automobile tire has a small aspect ratio, and a bicycle tire has a large one.) Despite these many differences, stellarator configurations fall into three basic categories:

• The stellarator, which has pairs of helical coils carrying currents in opposite directions.
• The torsatron, proposed independently at Fontenay-aux-Roses Laboratory in France by C. Gourdon's group, at Kyoto University by K. Uo (where it is known as a heliotron), and at Kharkov Institute by V. F. Aleksin. In a torsatron or heliotron, the coil current is carried in only one direction toroidally.
• The helical axis stellarator, in which the coils are displaced so that the magnetic axis follows a helical path, as originally proposed by Spitzer.

All of these devices may be constructed from discrete (modular) coils rather than from continuous helical coils. The modular stellarator has been studied extensively at Princeton and Garching. The Interchangeable Modular Stellarator (often called IMS), which is operating at the University of Wisconsin, and WVII-AS, under construction at Garching, are modular stellarators. The Symmotron, designed and patented in 1983 by Jeff Harris and Jim Rome at ORNL, is a modular torsatron. The heliac, a modular helical axis stellarator, has been proposed by Soichi Yoshikawa and co-workers at Princeton.

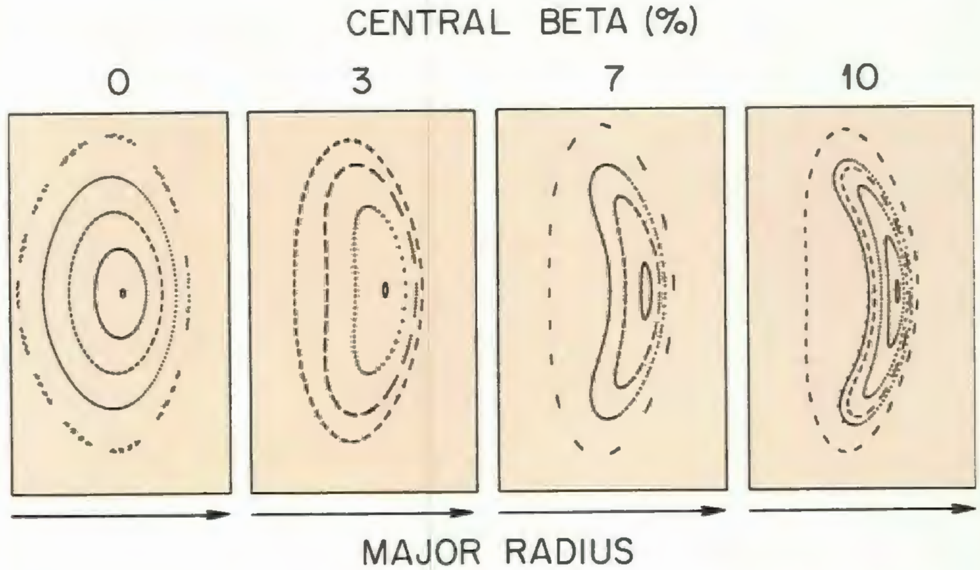
ATF Development

The toroidal group at ORNL has played a major role in the theoretical and experimental development of the tokamak concept. Because of this wide experience, we could rapidly make analytic calculations and construct a variety of computer codes that supplement analytic calculations to study the wide range of options possible in a new stellarator configuration. Because the bumpy helical magnetic field leads to a greater need to incorporate three-dimensional effects, the calculations are more complex for a stellarator than for a tokamak. The computer codes include physics codes and engineering codes. The physics codes provide a magnetic field configuration for a given set of coils, follow charged-particle orbits in the magnetic bottle, calculate the change in the fields that occurs when the plasma pressure (beta) is raised, and study the stability of the plasma and magnetic field. The engineering codes compute the stresses caused by the magnetic field on the coils and the electromagnetic, vacuum, and thermal stresses on the containment vacuum vessel.

We spent months iterating these calculations, looking for clues to a good magnetic field configuration. Some configurations were quickly rejected because they could not confine particles well, could not sustain high beta, imposed high stresses on the coils, or required a complicated coil configuration. Eventually a number of configurations were found that did not have these disadvantages. Our problem was to adapt one of these desirable configurations to obtain high beta and low thermal conductivity in the plasma.

In many previous studies, work had concentrated on configurations with a large aspect ratio (like a bicycle tire), where the toroidal system may be treated as a small deviation from a straight system, thereby making the theoretical analysis more tractable. Fusion researchers were concerned about the value of developing stellarators with a large aspect ratio because studies indicated that devices with a smaller aspect ratio would be more attractive as reactor candidates. On the other hand, for devices with a small aspect ratio, there were concerns that high thermal conductivity would result from the large variations in the magnetic field along the helical

A cut through the plasma shows the nested magnetic surfaces that are obtained from the intersection of magnetic field lines as they go around the torus. As the plasma beta is raised, these surfaces are distorted by the plasma pressure.



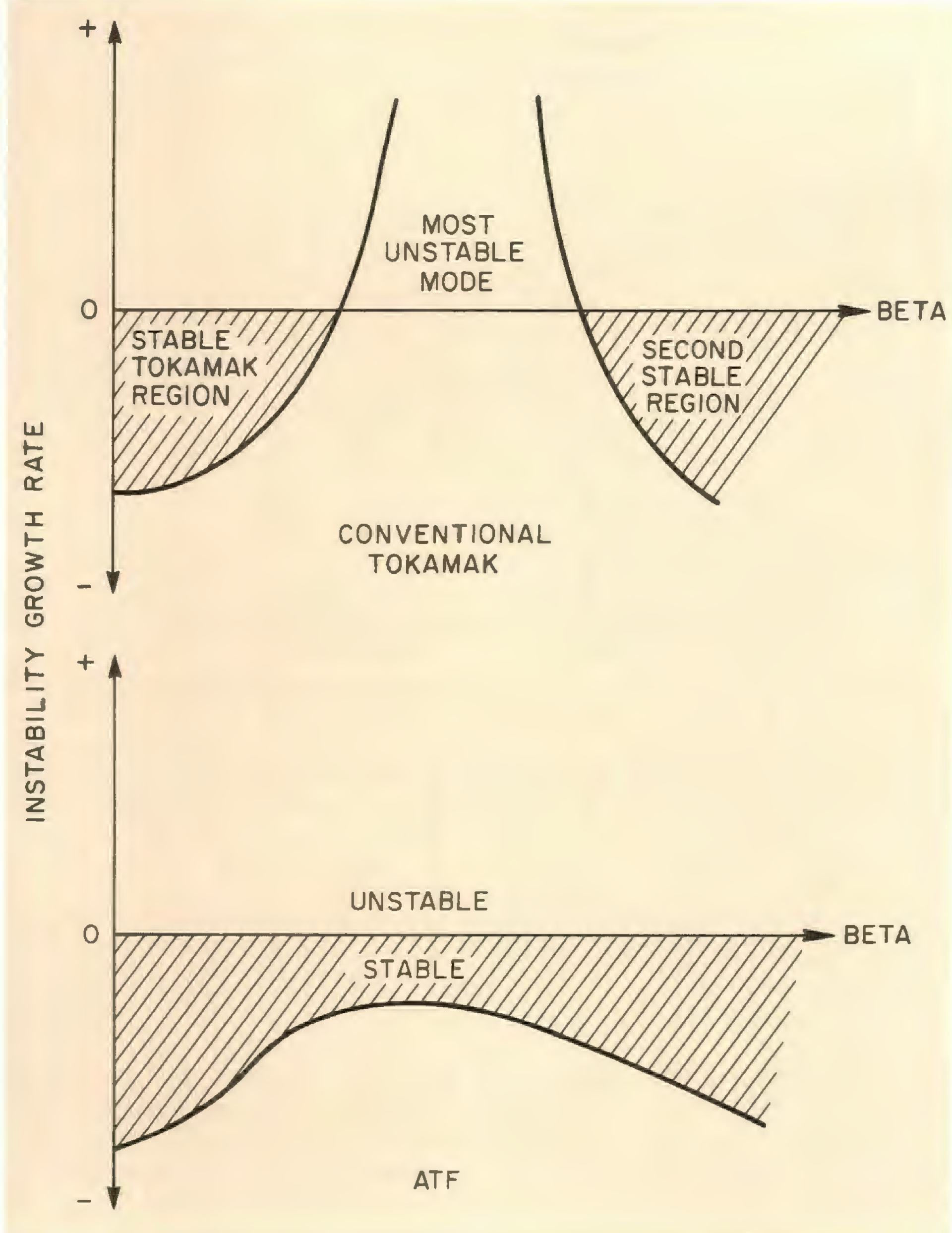
field lines. It was known also that at small aspect ratio (like an automobile tire), the shift of the plasma center outward with increasing beta (pressure) could lead to a loss of equilibrium, in effect turning the magnetic bottle upside down even before instabilities were encountered. By contrast, it was known that for circular axis configurations, the maximum stable beta attainable would decrease with increasing and large aspect ratios. Thus conventional wisdom held that the maximum beta would occur at some intermediate aspect ratio (but closer to being large than small). The ATF studies have led to a smaller aspect ratio torsatron with the capability for both high beta and low thermal conductivity.

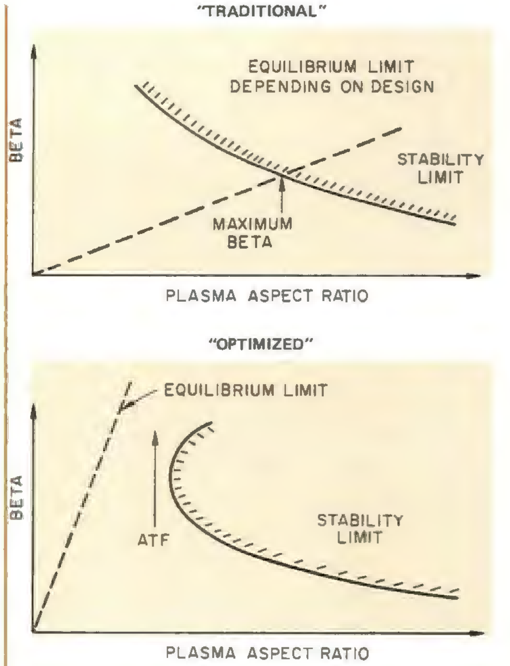
By careful detective work and by using the new powerful computer codes and analytic tools developed at ORNL and other laboratories, the ATF team tracked down a torsatron configuration with unique properties. By tailoring the rotational transform profile in a range of smaller aspect ratio torsatrons, we found it was possible to maintain stability by a subtle combination of magnetic well and magnetic shear. This discovery fitted in well with the realization of fusion researchers in recent years that if it were possible to raise beta even further in tokamaks, the plasma and magnetic field would adjust to reestablish a stable situation—the so-called second stability region. Work is under way to identify routes to this region in the tokamak. The key feature of the ATF torsatron is that it has direct access to this second stability region because of subtleties of its magnetic configuration and because of its relatively small aspect ratio. Theoretically, because of this direct access to the second stability region, the ATF should achieve a beta of at least 8%, an improvement over the ISX-B tokamak, which achieved a beta of only 3%.

In related studies of thermal conductivity, new calculations have been made to better account for electric field effects and complex particle orbits. The electric field arises from differences in the motion of the electrons and ions in the nonaxisymmetric magnetic field. These calculations at ORNL and other laboratories show that plasma confinement should be much better than suggested by previous pessimistic projections. This work benefited from the experience in the Elmo Bumpy Torus program at ORNL in which electric field effects play a major role. Recent encouraging results from the WVII-A stellarator at Garching and the Heliotron-E device at Kyoto support the new optimism about plasma confinement. Both devices have good thermal insulation, and Heliotron-E has already achieved a beta of 2%. Plans are under way to strengthen ORNL collaboration with these excellent stellarator groups.

Thus the ATF device should achieve both a high beta and good plasma confinement and, because (unlike tokamaks) it has no plasma current, it will operate in steady state. These capabilities offer major opportunities to improve the toroidal plasma confinement concept through the ATF's own interesting configuration, through the ORNL Symmotron version, and through hybridization with a tokamak. In this latter role, the external coils of the tokamak would be modified to incorporate some helical twist of the stellarator coils. Previous work has shown that adding this twist can reduce unstable behavior. In addition, the role of the plasma current in tokamaks may be reduced, making steady-state operation easier to achieve.

As a footnote to this discussion, I should point out that the helical axis stellarator may also have high beta, even in a device with a very large aspect ratio or in a straight system. In our studies we were unable to find a simple coil configuration for such a device, so





The ATF aspect ratio and the rotational transform profile are carefully chosen to avoid the unstable region, which occurs at higher aspect ratio, and to maximize the equilibrium beta limit, thus permitting stable access to the second stability region at high beta.

◄ ***A study of stability in a conventional tokamak and in the ATF shows the presence of a second stable region in both devices at high beta. In the conventional tokamak, this region is not readily accessible because of the unstable region at intermediate beta. In the ATF there is direct stable access to the high-beta region.***

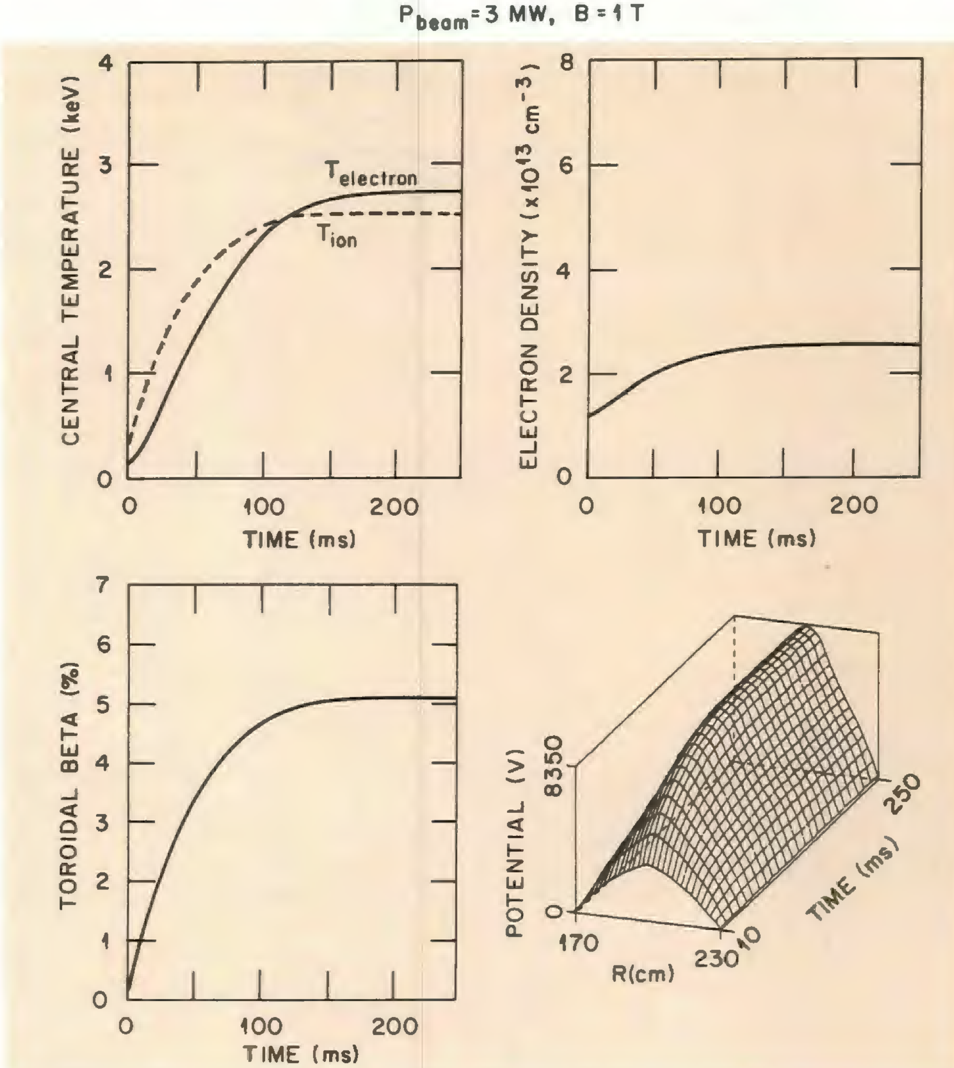
we dropped it in favor of the torsatron. Nevertheless, helical axis effects may be studied in the ATF by using unbalanced currents in the helical coils.

Engineering of the ATF

The design of the ATF is elegant from an engineering as well as a physics point of view. To meet important requirements, our engineers designed the ATF device to be easily assembled, to allow heating devices and measuring instruments good access to the plasma, and to fit ISX-B power supplies. The open-coil configuration of the torsatron allows good access to the plasma, but the accuracy required of the coils (±1 mm in a device with a major radius of 2.1 m) presents a challenge in design, construction, and assembly. In 1982 we decided to build the device with continuous helical coils rather than with modular coils, as in the Symmotron version. They will make comparing the results of theory and experiment easier and will minimize cost. The coils will be made of copper and will be water cooled (in the future we will use superconducting magnetic coils similar to those now being tested at ORNL's Large Coil Test Facility).

In the ATF the two 6-turn helical coils are made in 24 identical segments. The segments are then joined in the median plane. The advantage of making the coils in segments is that each

A computer code is used to model the time evolution of an ATF plasma heated by 3 MW of neutral beam power. The central temperature of electrons and ions rises to some 2.6 keV (30 million degrees). The beta attains a level of 5%. These good parameters result in part from the strong radial electric field, whose potential rises to 8350 V.



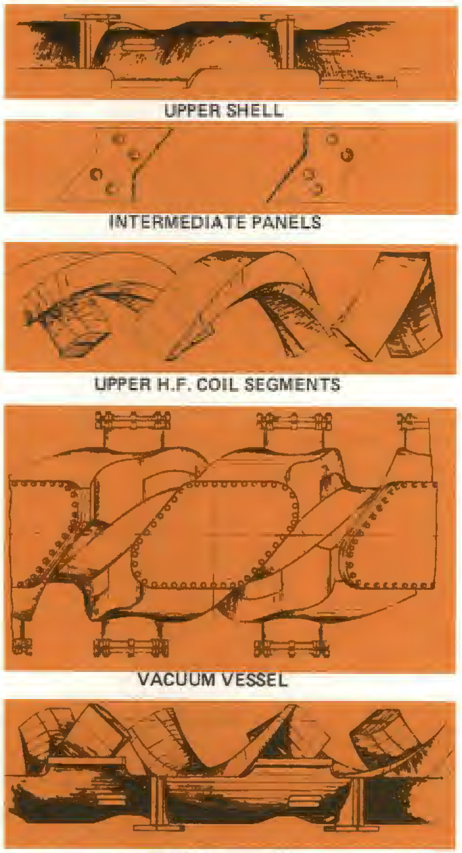
segment may be carefully prepared in a clean laboratory and can be measured for accuracy relatively easily. However, there is a price to pay: the complexity of joining the 14 massive copper conductors, which make up each segment, 24 times. After extensive testing, we have developed a simple joint configuration that satisfies the accuracy requirements and can withstand pulsed operation with a 2-T field and steady-state operation at 1 T. Although the vacuum vessel has an awkward shape, it does not have to fit the coil accurately, and it has a tolerance of some 10 mm or more. The vessel also does not have to withstand the coil forces because these are absorbed by a simple toroidal structural shell. Completing the device are a number of poloidal coils, which are used to create the variety of magnetic configurations that may be realized in the ATF.

Outlook

The genesis of the ATF is a good example of the broad strength of ORNL and its associated divisions in doing innovative, integrated research and development. The ATF will make important contributions to the improvement of toroidal confinement because it can help us understand the fundamental physics underlying plasma confinement and because it is a forerunner of advanced devices that will have high beta and steady-state capability. Results from the ATF, combined with those from the mainline tokamak program in the Tokamak Fusion Test Reactor and the Poloidal Divertor Experiment at PPPL and in the Doublet III-D device at GA Technologies, will lead to an improved Engineering Test Reactor (ETR). This ETR will follow the Ignited Plasma Experiment (which may be built at Oak Ridge) and will advance fusion from the scientific phase to the engineering phase of its development.

In April 1984 the operation of ORNL was taken over by Martin Marietta Energy Systems, Inc., whose parent company is largely an aerospace organization. This organizational change is of particular interest to fusion researchers at ORNL because in recent years when fusion emerged from the physics cradle, aerospace companies became more involved in the engineering development of fusion energy. These companies are contributing the vast experience they have gained in integrating high technology into projects in aircraft development and space exploration.

Fusion is a new and more difficult challenge for aerospace companies. It is more complex because of the interactions between components induced by electromagnetic forces and because of the radiation environment. Another difference is that the paths to the goals of aerospace companies and fusion researchers are different; in the case of fusion, the direction to our ultimate goal is not yet settled. Several years ago at



The ATF will be assembled in the following manner. The lower segments of the helical field (HF) coils are positioned accurately in the lower support shell. Next the vacuum vessel is lowered into place. The upper segments of the HF coils are positioned accurately, and the joints are connected. The side and upper support sections are then bolted in place, and the upper poloidal coils are attached. Finally, the services—water, power, and vacuum—are connected to the assembled ATF.

a meeting, an aerospace colleague expounded the view that it was time for fusion to be taken over by those who had the experience to really move it along. "Just give us the money, and let us get on with it," he said. "Hell, we went to the moon!" Somebody in the audience, startled by the view, shouted, "Yes, but you had an advantage—you knew where it was!"

Many of us at ORNL believe that the ATF is pointing the way to where "it" will be in fusion. ornl

Contributors to the Development of the ATF

Many people within and outside the ORNL organization have contributed to the development of the Advanced Toroidal Facility. The following staff members of the Fusion Energy, Computing and Telecommunications, and Engineering divisions have helped develop the ATF:

O. B. Adams, E. E. Bartlett, L. R. Baylor, D. E. Brashears, C. Bridgeman, A. Y. Broverman, R. L. Brown, W. D. Cain, J. L. Cantrell, B. A. Carreras, L. A. Charlton, K. K. Chipley, M. J. Cole, W. A. Cooper, D. L. Coppenger, R. A. Dory, P. H. Edmonds, O. C. Eldridge, A. C. England, J. W. Forseman, R. H. Fowler, W. A. Gabbard, L. Garcia, D. Goodman, E. L. Halstead, J. H. Harris, T. C. Hender, G. H. Henkel, H. R. Hicks, S. P. Hirshman, D. J. Hoffman, S. Hokin, J. A. Holmes, W. A. Houlberg, R. C. Isler, T. C. Jernigan, R. L. Johnson, V. E. Lynch, J. F. Lyon, B. F. Masden, J. F. Monday, M. Murakami, G. H. Neilson, B. E. Nelson, J. A. Rome, M. J. Saltmarsh, K-C. Shaing, J. Sheffield, C. K. Thomas, P. B. Thompson, L. M. Vinyard, J. E. Warwick, J. A. White, J. C. Whitson, D. E. Williamson, A. J. Wootton, W. L. Wright, R. B. Wysor.

We also acknowledge the contributions to the ATF made by the Plasma Technology and Magnet Development Sections of the Fusion Energy Division. From the former, we have the fueling and heating systems so successfully applied to ISX-B and other U.S. tokamaks. From the Magnet Development group, we have had valuable support in the design of the copper coils.

We appreciate very much the advice and encouragement of the ATF Advisory Committee and colleagues from the following organizations: Culham Laboratory (England), Fontenay-aux-Roses (France), Garching (Federal Republic of Germany), GA Technologies, Kharkov Institute (U.S.S.R.), Kyoto University (Japan), Lebedev Institute (U.S.S.R.), Los Alamos National Laboratory, Massachusetts Institute of Technology, New York University, Princeton Plasma Physics Laboratory, and the University of Wisconsin.

We also gratefully acknowledge the continuing support of our colleagues in DOE, both in the Office of Fusion Energy and in the Oak Ridge Operations Office.—*J.S.*

At the model of the Advanced Toroidal Facility are some key contributors to the ATF development: from left, Ken Chipley, Tim Hender, Jim Lyon (back), Luis Garcia, Jim Rome (sitting on ATF model), Vickie Lynch, Tom Jernigan, and Mike Cole.

▪ technical capsules

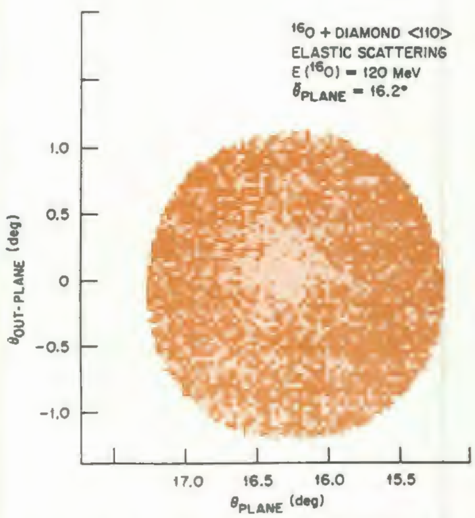
Diamonds Can Measure Very Short Times

Diamonds may be forever, but physicists at Oak Ridge National Laboratory have shown that these crystals of carbon can do more than last a very long time. The researchers have used a diamond to "clock" the shortest time ever measured.

The ability to measure very short times is essential for determining the lifetimes of products of nuclear reactions between the collisions of heavy ions. The researchers have measured a time as short as 10^{-19} s, a factor of 10 smaller than the previous shortest measured time.

Measuring time intervals below 0.01 s has long challenged scientists. Atomic clocks have been used since the mid-1950s to measure times down to a picosecond (10^{-12} s); these clocks work on the principle that vibrating molecules can control electric currents, which in turn control time-measuring devices with great precision. Times less than a picosecond can be measured by careful study of the X-ray and gamma-ray emissions of atoms and nuclei. Recently, crystal blocking has been used to measure times down to 10^{-18} s.

Crystal blocking, discovered in the mid-1960s, involves measuring time on the basis of the distance traveled by nuclear reaction fragments before they decay, and their velocity, which can be determined independently (time equals distance divided by velocity). The distance is determined by measuring the intensity of particles emerging from open regions, or channels, in the crystal. To produce the nuclear reaction, a beam of particles strikes atoms of the crystal. The intensity of particles emerging along exact directions of the channels is directly proportional to the lifetime of the nuclear process taking place. For extremely short lifetimes the emerging particles cannot "see" the channels and are therefore blocked by the atoms distributed along the rows in the crystal—thus the name crystal blocking. For longer lifetimes the reaction fragments are displaced a small distance (usually 10^{-9} cm) from the rows; because these fragments see the channels, their intensity along the channel direction increases.



By analyzing the spatial distribution of the fragments that emerge from the diamond crystal following decay of the silicon fusion product into magnesium and other particles, physicists at ORNL determined the lifetime of the magnesium decay product. Magnesium particles were emitted after silicon was formed in a nuclear fusion reaction that resulted from a beam of oxygen-16 (^{16}O) ions bombarding the carbon-12 (^{12}C) atoms in the crystal. The accelerated ^{16}O ions had an energy of 120 MeV. The dark color represents the maximum intensity detected in particles emitted after the silicon nuclei moved out to the center of the crystal channel; the white represents the minimum intensity. The clear hole in the center illustrates the fact that when the time of decay is too fast to be measured, the particles cannot emerge along the exact direction of the channel (16.2° in the figure) because they are shadowed or blocked by the atoms distributed along the rows at the crystal. Because of this blocking effect, the intensity of the emitted particles that reach the detector is relatively low.

In 1983 a group of physicists collaborating at ORNL's Holifield Heavy-Ion Research Facility (HHIRF) designed an experiment using crystal blocking to achieve the shortest time measurement ever made. The scientists are Jorge Gomez del Campo, Dan Shapira, John Biggerstaff, Charlie Moak, and Phil Miller of ORNL's Physics Division; R. W. Fearick and J. P. F. Sellschop of the University of Witwatersrand in South Africa; and N. Neskovic of the Boris Kidric Institute in Yugoslavia.

In their experiment the researchers used a beam of oxygen-16 (^{16}O) ions from the HHIRF tandem accelerator to bombard a diamond (12 μm thick by 2 mm diam). Nuclear fusion reactions are produced between the incoming ^{16}O ions and the carbon-12 (^{12}C) atoms of the diamond. As a result of the fusion reactions, short-lived silicon nuclei are produced. Within the crystal the silicon nuclei decay, emitting protons, neutrons, and helium and heavier nuclei; and the residual fragments—magnesium, neon, fluorine, and lighter nuclei—emerge from the fusion site into a wide cone in the direction of the oxygen beam. The ORNL physicists focused on measuring the lifetime of the magnesium decay product.

Silicon atoms that decay promptly emit particles of magnesium and other nuclei that are "blocked" by collisions with other atoms in a string along the channel sides (if a channel were compared to the inside of a pipe, the channel sides would be the pipe wall). Very few of these particles emitted by prompt decay enter the open part of the channel, so most emerge from the crystal at low intensities after colliding with other atoms along the channel sides. Other fused silicon atoms do not decay immediately and thus have time to move out into the center of the channel before emitting particles; the "delayed" emitted particles undergo virtually no blocking and can move in the exact direction of the channel. They therefore have higher intensities than their promptly emitted cousins. The detector measures the intensities of all particles that have emerged from the crystal in the channel direction. By analyzing the spatial distribution of the fragments and calculating the ratio of intensities from the center to the sides of the channel, the researchers at ORNL extracted a lifetime of 4×10^{-19} s for the magnesium decay product.

This tenfold improvement in measuring time opens exciting possibilities for precisely measuring lifetimes of transient fusion products formed by collisions between heavy ions. The physicists plan other studies using silicon and germanium crystals. Will they be able to measure even shorter times? The answer is not yet crystal clear.

New Way To Identify Environmental Carcinogens

Because of the rapid growth of industry over the past few decades and the recent increase in the use of coal and synthetic fuels, a growing amount of hazardous chemicals has been introduced into the environment. These chemicals include perhaps the largest class of cancer-causing agents—polycyclic aromatic hydrocarbons (PAHs). Because of the variety of chemicals present in the environment, sensitive and selective analytical methods are needed to detect and identify carcinogens and other toxic substances.

One analytical tool widely used for identifying PAHs in environmental samples is combined gas chromatography and mass spectrometry (GC/MS). The virtue of this method is its ability to separate the chemical components of a sample with a gas chromatograph immediately before analyzing the sample with the mass spectrometer. This technique simplifies the interpretation of the resulting mass spectra, allowing the individual components in a complex mixture to be identified directly in one step, without labor-intensive separation prior to the analysis.

A major limitation of mass spectrometry, however, is its general inability to detect structural differences in isomeric compounds—that is, compounds which are composed of the same atoms but which have different atomic arrangements. For example, the conventional electron impact mass spectra of the two PAH isomers fluoranthene and pyrene are virtually identical despite their distinct structural differences. Also, these two isomers have vastly different biological activities: Fluoranthene is a known carcinogen, while pyrene is not considered to be a cancer-causing compound. Thus the ability to unambiguously identify these compounds is important when assessing potential environmental hazards.

Recently, Michelle Buchanan of the Analytical Chemistry Division of Oak Ridge National Laboratory developed a GC/MS method for unambiguously identifying a number of PAH isomers without the need for the authentic compound for spectral comparison. Instead of employing conventional electron-impact ionization techniques in which a beam of electrons knocks electrons from target molecules to create positively charged ions (cations), she uses a negative chemical ionization technique. In this technique, low-energy electrons are ejected from a molecule, in this case methane, by electron impact. These low-energy electrons, in turn, ionize the PAH molecules by electron capture processes, thus producing negatively charged PAH molecules (molecular anions). Then, the mass spectrometer sorts the ions by their relative mass-to-charge ratio prior to detection.

Buchanan has found that some PAHs, such as fluoranthene, are readily ionized by this method and that other PAHs, such as pyrene, are not. Because the latter have no charge, they are not detected and therefore cause no interference. A particularly important finding is the ability of her technique to differentiate between benzo[*a*]pyrene (BaP), a chemical with high carcinogenic activity that is found in cigarette smoke and certain coal conversion by-products, and its relatively noncarcinogenic isomer, benzo[*e*]pyrene. This difference in ionization behavior allows BaP to be identified and quantitatively determined in a sample without interference from its isomer, which, until now, has been a difficult analytical task.

Because the ionization behavior of PAHs under negative chemical ionization conditions is thought to be related to their electron affinities (the characteristic ability of given molecules to hold on to extra electrons), this technique may be used to unambiguously identify PAHs without the need for standards. The limited availability of PAHs for standards has severely restricted the usefulness of other previously developed methods for the identification of PAHs.

Says Buchanan: "An additional benefit of this negative chemical identification technique is the increased responsiveness of high molecular weight PAHs to being detected by mass spectrometry over that observed with conventional ionization techniques. This technique will allow more information to be obtained on these large PAHs, which often have high carcinogenic activities, than has been possible with other analytical techniques."

Quest for Quicksilver in Local Lakes

After disclosure in spring 1983 that about 900 Mg (2×10^6 lb) of quicksilver—mercury—was unaccounted for at the Y-12 Plant, there was considerable interest in finding the residual mercury in the Y-12 area and in off-site environments. Records at Y-12 indicated that about 12% of the missing mercury (about 110 Mg) had been discharged to East Fork Poplar Creek since 1951, when mercury was first used at Y-12. The time trend for discharges also indicated that mercury losses to the creek peaked sharply between 1956 and 1959, when 85 Mg was discharged. Prior to the congressional hearing on the mercury situation held July 1983 in Oak Ridge, the Department of Energy wanted an answer to this question, Where is the mercury that was previously discharged to the creek?

Because of his experience in tracking mercury in the environment, geochemist Ralph Turner of the Environmental Sciences Division of Oak Ridge National Laboratory was asked to address this issue for the Y-12 Mercury Task Force. High concentrations of mercury (up to 600 μg per gram of soil) in sediment and floodplain soils of East Fork Poplar Creek suggested to Turner that some of the mercury was still in the environment immediately downstream of Y-12, but his rough estimates of the quantity indicated that only about 10 Mg was likely to be found locally. Because mercury has a high affinity for fine-grained suspended particles (e.g., clays and organic matter), which settle out of water very slowly, Turner believed the most likely repository for the discharged mercury would be the sediments of the large downstream reservoirs—Watts Bar and Chickamauga lakes. Previous investigations of radionuclides in these sediments had demonstrated that particle-associated contaminants from Oak Ridge, such as cesium-137 (^{137}Cs), could be detected hundreds of kilometers downstream. Thus Turner thought that mercury from Oak Ridge could be easily detected in lower Chickamauga Lake, 200 km downstream.

Accordingly, Turner launched a sediment-coring investigation extending from upper Watts Bar Lake near Kingston to lower Chickamauga Lake near Chattanooga. His objectives were to verify the Y-12 mercury discharge history and to estimate the quantity of mercury in the sediments of these downstream reservoirs.

Where lake sediments are deposited continuously and remain undisturbed, they often reflect in their chemical composition the history of contaminant discharges into upstream waters. Watts Bar Dam was first closed in January 1942; Chickamauga Dam, in January 1940. Thus Turner and his colleagues Curtis Olsen and Lauren Larsen expected undisturbed sediments in these reservoirs to contain a complete record of mercury discharges at Oak Ridge. Because sedimentation rates in these reservoirs are typically 2–5 cm/year, slicing a core into 2- to 5-cm layers for analysis yields a time resolution of about one year per layer.

Expectations notwithstanding, Turner, Olsen, and Larsen were amazed when analytical results for the first core from Watts Bar Lake showed a single, well-defined peak in mercury concentration buried 34 cm below the present sediment surface. Near-perfect coincidence of this mercury peak with a similar peak in ^{137}Cs activity suggested a 1957 date for the sediment layer with the highest mercury concentration. The discharge history for ^{137}Cs is well known back to 1949, and 1956 represented a peak discharge (170 Ci) year for ^{137}Cs from White Oak Lake at ORNL. Thus the near-coincidence of the ^{137}Cs and mercury peaks in a downstream reservoir core provided the first independent evidence of the accuracy of the Y-12 mercury discharge history. As additional cores from Watts Bar Lake were analyzed, the same patterns of buried coincident peaks in mercury and ^{137}Cs continued to emerge.

"The precise dating allowed the ORNL researchers to determine that Y-12 had contributed approximately 40% of the total mercury present in Chickamauga Lake."

The ORNL researchers found the patterns in Chickamauga Lake to be different and more complex. The peak in mercury concentration did not coincide with the peak activity in ^{137}Cs, and the mercury profile lacked a single, well-defined peak. However, Turner knew that an industrial chloralkali plant, which used large amounts of mercury to produce chlorine and caustic soda, had been built in 1963 on the Hiwassee River—a direct tributary to Chickamauga Lake. He expected that sediments in Chickamauga Lake would reflect contributions of mercury from both Y-12 and the chloralkali plant, with the former appearing earlier (deeper) in undisturbed cores.

Variations in ^{137}Cs as a function of depth in Chickamauga cores suggested that the first increase in mercury above natural background, which began at a depth of about 60 cm, could be attributed to releases at Oak Ridge, whereas the peak in mercury, which occurred at about the 30-cm depth, was caused by the chloralkali plant. To provide independent proof of this scenario for Chickamauga Lake, Olsen and Larsen used the vertical distribution of lead-210 (^{210}Pb), a natural radionuclide, to assign deposition dates to sediment layers in one core from Chickamauga Lake. The atmospherically derived component of ^{210}Pb in sediment (called excess ^{210}Pb) typically shows an exponential decrease with increasing depth in cores. The slope of this relationship and the half-life of ^{210}Pb (22.3 years) can be used to calculate sedimentation rate and thereby deposition dates for each layer. The ^{210}Pb dates matched the chronology of deposition based on ^{137}Cs, demonstrating that both Y-12 and the chloralkali plant had contributed mercury to Chickamauga Lake sediments. In fact, the precise dating allowed the ORNL researchers to determine that Y-12 had contributed approximately 40% of the total mercury present in the lake.

According to Turner, "Core data currently available are insufficient to accurately estimate the quantity of mercury in Watts Bar Lake and Chickamauga Lake. Based on our data, we estimate that for both reservoirs, the minimum is about 50 Mg and the maximum is about 300 Mg. Because the estimated total discharge from Y-12 is 110 Mg, we concluded that a substantial fraction of the Y-12 mercury discharged to the creek almost certainly resides in the two downstream reservoirs."

Estimates of the quantities and distribution of mercury in the local Oak Ridge environment and in the downstream reservoirs will be improved by the efforts of the Oak Ridge Interagency Task Force, which must also address whether fish, wildlife, or human health is threatened by past or current contaminant discharges from the Oak Ridge facilities. Other ORNL staff members are assisting in this assessment. The quest for quicksilver is not yet over.

awards and appointments

Lee Berry has received the Department of Energy's Distinguished Associate Award, one of the highest honors that DOE bestows upon nongovernment employees. The award cites Berry's "superior technical leadership and insight in managing the national Elmo Bumpy Torus program" and adds that DOE's Magnetic Fusion Program has "benefited significantly" from Berry's contributions.

ORNL received 4 of the 100 awards presented this year by *Industrial Research & Development* for innovative developments. The winning entries and developers are an enzyme system that grows oxygen-shunning bacteria, developed by **Howard Adler** and **Weldon D. Crow**; a servomanipulator control system, by **H. Lee Martin**, **Joseph N. Herndon**, and **Paul E. Satterlee** (formerly of ORNL); a detector to identify and count single atoms of rare gases, by **G. Samuel Hurst, Chung-hsuan Chen, Steven D. Kramer, Marvin G. Payne, Steve L. Allman, and Ronald C. Phillips**; and a high resolution, ultrasonically pulsed neutron time-of-flight spectrometer that increases reactor-produced neutron intensity for scattering research, by **Herbert A. Mook** and **Gerald K. Schulze**.

Louis K. Mansur and **Robert T. Santoro** have been named Fellows of the American Nuclear Society.

Nuclear Safety received a Blue Pencil Award (first prize) in the periodical category in the recent publications competition sponsored by the National Association of Government Communicators. The editor of the journal is **Ernest Silver**, and the editorial reviewer is **Sharon McConathy**.

David Shriner has been appointed coordinator for acid deposition activities at ORNL.

Jim Mason has received the Gutenberg Award from the Printing Industries of America.

E. Kaye Johnson has been named head of the Technical Support Section of the ORNL Chemical Technology Division.

Susan Whatley has been appointed program manager of engineering analysis and planning in the ORNL Nuclear and Chemical Waste Programs. She has also been elected first vice-president of the Society of Women Engineers.

James D. Regan has been named a recipient of a Japanese Government Research Award for Foreign Specialists from Japan's Science and Technology Agency. Under the terms of the award, Regan spent three months at the National Institute of Radiological Sciences in Chiba, Japan.

Rodney W. Brewer has been promoted to process supervisor at the Transuranium Processing Plant.

William S. Lyon has been elected chairman of the Isotopes and Radiation Division of the American Nuclear Society.

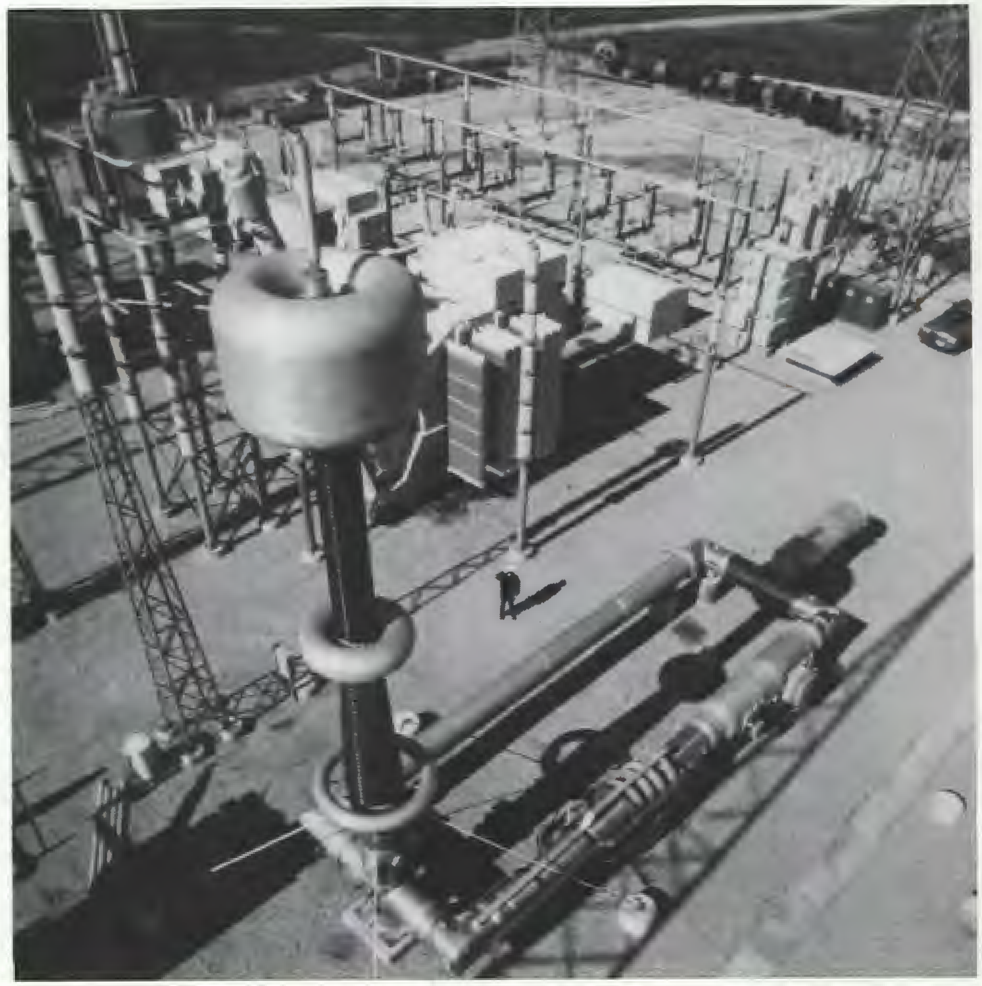
Jagdish Narayan has been elected a Fellow of the American Association for the Advancement of Science.

Robert W. Swindeman has been elected member of the Executive Committee of the Pressure Vessels and Piping Division of the American Society of Mechanical Engineers.

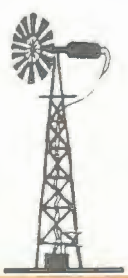
In the technical art competition sponsored recently by the Boston Chapter of the Society for Technical Communication, four ORNL graphic artists received awards for their color renderings in the cutaway category. They are **Michael W. Darnell**, award of distinction for "Two-Axis Laser Probe" and award of distinction for "EBT—Elmo Bumpy Torus"; **Susan Scott**, award of excellence for "ATF-1—Advanced Toroidal Facility"; **Sandra Schwartz**, award of merit for "ATF-1—Coils with Plasma"; and **Judy Neeley**, award of merit for "ATF—Advanced Toroidal Facility." The award-winning ATF cutaways appear in John Sheffield's article in this issue.

Kimiko Bowman has been appointed to the National Science Foundation's Advisory Committee on Equal Opportunity in Science and Technology.

Donna Griffith, chairman of the ORNL General Energy Conservation Committee, has received one of three individual In-house Energy Management Awards from the Department of Energy.



This Waltz Mill, Pennsylvania, test facility for high-voltage equipment, operated by the Electric Power Research Institute, uses equipment developed by DOE subcontractors working under the technical management of staff members of the ORNL Power Systems Technology Program.



Technology for Efficient Power Systems

Compiled and edited by CAROLYN KRAUSE

In the 1970s energy prices rose, consumers began demanding better service and more efficient appliances, and new computer-driven equipment and small power sources became available. For electric utilities these trends have led to the demand for the new technologies to increase the reliability and efficiency of the nation's power system.

The U.S. Department of Energy has responded to these trends through the work of its Electric Energy Systems (EES) Division. In 1983 Oak Ridge National Laboratory incorporated several EES-sponsored projects into a new Power Systems Technology Program established to manage DOE's power systems research and development (R&D). DOE's Oak Ridge Operations serves as the principal field office for this work; ORNL, as the principal national laboratory.

According to Paul Gnadt, manager of the Laboratory's Power Systems Technology Program and a participant in the program since 1980, "Our ORNL goals are to conduct basic research, investigate new concepts, and develop future technology and systems for the electric utility industry. Our DOE program addresses these issues: making sure that the new technologies will contribute to a reliable and economical electric

Tom Reddoch is former manager of the ORNL Power Systems Technology Program. He left ORNL in April 1984 to become vice-president of the newly formed company Electrotek Concepts, Inc. On a map of investor-owned electric utility service areas in the United States, he points to Tennessee, where the Athens Automation and Control Experiment will take place and provide information of interest to many utilities.

Paul Gnadt is manager of the ORNL Power Systems Technology Program, whose goals are to conduct research on and develop new technologies to help the electric utility industry make the nation's power systems safer, more reliable, and more efficient.

ORNL is managing the Department of Energy program in developing and testing technologies designed to make electric power systems safer, more reliable, and more efficient. ORNL's interdisciplinary staff of experts has taken on a variety of projects, including planning an automated distribution experiment for Athens, Tennessee, and developing a fiber optics measurement device, a low-loss steel alloy, and new insulating materials for use in transformers.

energy supply, minimizing the health and safety risks of the new technologies, and conserving fuel and managing resources by making the electric system more efficient and by relying less on scarce, costly fuels for our energy."

Because of the availability of new technologies, utilities are now moving toward automating their transmission and distribution systems to assume closer control of where and when power is delivered to users. They are also interested in buying and using the power that can be made available to them by some of their own customers, who produce limited amounts of extra electricity from their own windmills, solar collectors, and other small dispersed generation systems.

Although the program was started in 1983, many of its elements have existed at the Laboratory for eight years or more. Research on gaseous dielectrics (electrical insulators) was begun in 1974 by Loucas Christophorou of the Health and Safety Research Division, and a load management project was started in 1976 by Hugh Long, formerly of the Energy Division.

Long perceived the need to change the patterns of electricity use (**load management**) so that utilities would not have to build additional peaking power plants, which are used only when demand for electricity is heaviest (peak loads). Long and his colleagues realized that the country could save its oil and gas and that utilities and consumers could save money by evening out the demand for electricity.

Long's group studied the impact of devices that **store thermal energy** produced during off-peak hours for later use during periods of peak demand. The group also explored the possibility of using communication systems to automate the distribution system and reduce peak loads. The culmination of this work is **an automated distribution project** under way at Athens, Tennessee.

Says Gnadt: "The Laboratory has done experiments with storage technology, communication technology, and use of electronic controls in switching loads on and off—that is, turning on and shutting off water heaters, air conditioners, and space heaters. For example, we have been involved in utility experiments in which transponders, on a signal from a computer, temporarily interrupted electric service to water heaters during peak-load periods. Now we want to demonstrate that these technologies can be integrated and put to use on a larger scale. Athens will be the great melting pot in which we put all these ideas together in one big experiment."

Other staff members in the Energy Division have examined the implications of tying small power sources (wind energy and photovoltaic systems, for example) into a large distribution system. This work, no longer conducted at ORNL, has stimulated the electric utility industry and the Institute of Electrical and Electronic Engineers into looking at how to integrate small power sources into big systems.

Solving Utility Problems

The staff members in the Energy Division who now form the core of the Power Systems Technology Program have supplemented the work of the Electric Power Research Institute, the research arm for the electric utility industry, which is concentrating on the industry's near-term problems. The ORNL program is looking at the industry's long-range, high-risk research needs. In the 1970s the industry faced the challenges of making power systems safer, more reliable, and more efficient. The Energy Division therefore assembled a staff who understood the problems, bringing some staff members to ORNL from electric utilities and electric equipment manufacturers. This group concluded that the interdisciplinary staff of a national laboratory could address special

An important product of the Power Systems Technology Program is reports. Doris Slaughter, left, and Miriam Miller do the word processing to generate the hundreds of pages written by program researchers.

utility problems such as developing improved insulations and a device to monitor hot spots in transformers. "That's where the talents of a national laboratory become useful," Gnadt says. "We have identified problems of the electric utility industry and found specialists at the Laboratory who can solve them."

Taking advantage of his knowledge of utility industry problems and the solutions offered by automation and control technology, Tom Reddoch, manager of the ORNL program until late April 1984, helped form a new company called Electrotek Concepts, Inc., which is headquartered in Mountain View, California. Reddoch, who is vice-president of the company, works at a Knoxville office as a consultant for utilities, government officials, and other customers. He provides advice on automating electric distribution systems to improve their efficiency, using load-control devices to reduce the peak demand for electricity, and integrating small power sources into distribution systems. Electrotek, he says, also will develop computer programs (software) for communicating with devices (hardware).

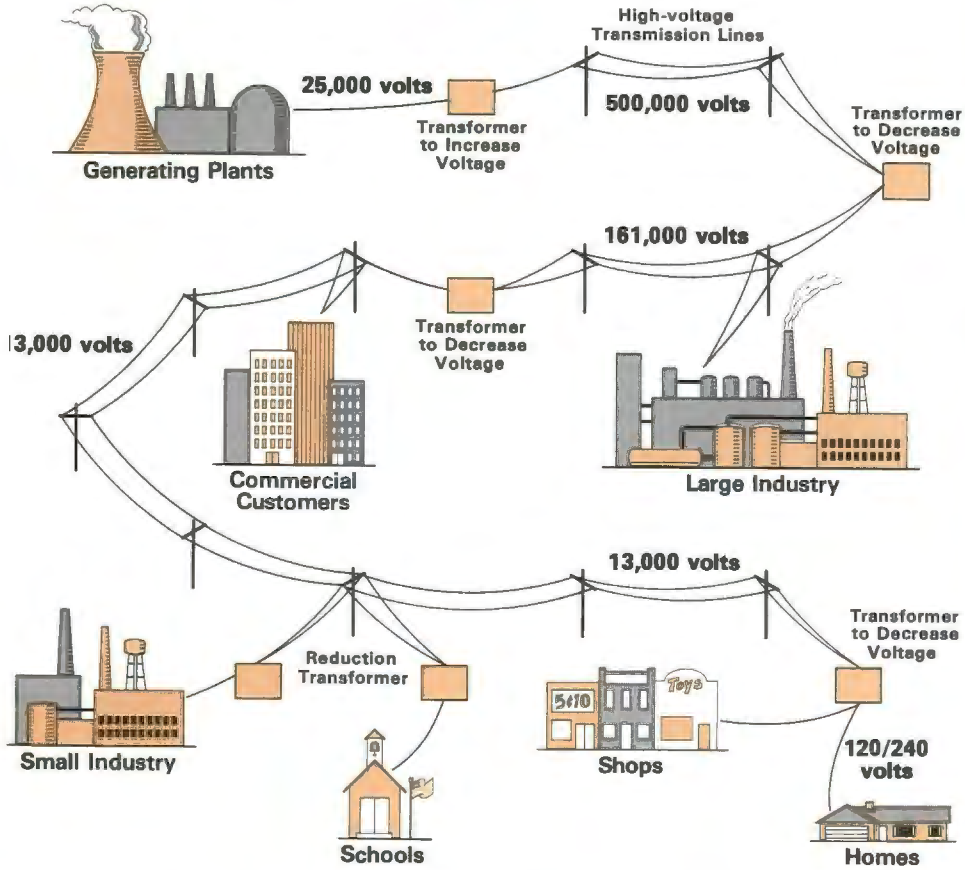
ORNL not only spins off technology in the form of small companies like Electrotek but also transfers technology to large companies. The Power Systems Technology Program is set up to expedite this transfer.

"Because the Laboratory deals with so many subcontractors, ORNL staff members are close to many people employed by the electric utilities and related equipment suppliers," Reddoch observes. "Thus the program has an effective mechanism of putting ideas directly into the hands of the people who can use them or turn them into commercial products."

Although the Energy Division is the home of the Power Systems Technology Program, other divisions provide appropriate expertise and support. They are the Engineering Division of Martin Marietta Energy Systems, Inc., and ORNL's Engineering Technology, Health and Safety Research, Instrumentation and Controls, Metals and Ceramics, and Solid State divisions.

Development and testing of innovative technologies for the electric utility industry are the purpose of this program. Utilities need such R&D to (1) reduce capital investment in power plants; (2) increase efficiency of power transmission, distribution, and use; (3) maintain safety and reliability in power transmission and distribution; and (4) minimize power disruptions. In short, the goals for utilities are safety, efficiency, and reliability.

These are also the goals for DOE's EES Division, which was



A power system includes the generation, transmission, and distribution systems. The Tennessee Valley Authority bulk power system generates electricity at 25 kV, which is stepped up by transformers to 500 kV and transmitted to distributors by high-voltage transmission lines. The distributors, such as the Knoxville Utility Board and the Athens Utilities Board, step the power down to 161 kV for large industries and to 13 kV for small industry, schools, stores, and homes. These customers use transformers to reduce the voltage further to get the appropriate current.

created in the Department of the Interior in 1970 and transferred to the Energy Research and Development Administration in 1975 and to DOE in 1977. In support of these goals the ORNL program was created to conduct R&D and to manage many of DOE's efforts. The $5.5-million-a-year program spends about half its funds on in-house R&D and the other half on managing the program and subcontracts with industry and universities. The annual EES budget is $18.5 million.

Subcontracts

About 41% of the DOE money channeled to ORNL's Power Systems Technology Program is used for subcontracting R&D projects to industrial firms that have the expertise needed in a particular area. Of the $5.5 million, 7% goes to small businesses and 34% to large commercial organizations. These subcontracts are managed by the ORNL program staff.

Projects subcontracted include development of high-efficiency motors, technology for transporting more power through existing transmission corridors, solid-state circuit breakers, and high-speed current limiting devices used for reducing current during short-circuit conditions. Other subcontractors perform complex studies of power system stability and special materials. From 1 to 2% of the program funds go to utility companies for subcontract work in areas where expertise in power system design and operation is required.

The ORNL program also subcontracts work to various universities for basic technology studies. Approximately 11% of the program funding is used for these university contracts. Projects include studies of the basic phenomena of electrical insulation and dielectric interfaces, techniques for measuring electric fields in the presence of charges, system studies for high-voltage, direct-current (dc) power transmission, and risk assessment of the effects on humans of electric fields (at this time, there is no evidence of harmful effects).

With the University of Tennessee (UT) ORNL contracts both for theoretical studies and for program support. Several UT professors work part-time at the Laboratory and at university facilities to carry on this work.

In-house Projects

ORNL researchers in the Power Systems Technology Program are involved in developing technologies for power systems as well as managing subcontracts for technology development and tests of new technologies on utility networks. The projects include work in developing

- An **automation and control experiment** for the power distribution system in Athens
- Gas and liquid **materials for insulating** high-voltage power lines

• Fine-grained **metal oxides to make compact varistors** that protect high-voltage lines from lightning and other voltage disturbances
• An optical-fiber device that can **identify hot spots in transformers**
• An understanding of which **thin-film polymers** would serve as the best insulators for the compact transformers needed for high-voltage systems of the 1990s
• Amorphous **ferromagnetic alloys** that can be used for magnetic cores to make transformers more efficient
• An understanding of how well **thermal energy storage systems** work and how cost-effective they are for utilities and consumers
• An understanding of the **damage that could result from electromagnetic pulses (EMP)** caused by nuclear detonations and how to protect power system components
• An understanding of how to improve the **reliability** of power delivery
• An understanding of how to use **new information technologies** to improve the efficiency of power systems
• An understanding of how to protect power systems using **small dispersed power sources** such as wind turbines
• Technical means for **moving power from wind turbines** to large electrical systems
• An understanding of the impacts (if any) on **human health** of electric fields from high-voltage power lines
• An understanding of the problems of linking **high-voltage dc systems** to conventional alternating-current (ac) systems to transfer power between regional ac systems and thus defer the need for new generation.

These projects are described in more detail in the following sidebars.

Athens Project To Demonstrate Efficiency By Automation

Now that communication technologies have been developed and successfully demonstrated on power networks, these technologies are available for controlling the distribution of electricity and altering the pattern of electricity consumption. A large-scale advanced automation and computer control demonstration for managing the distribution of power to a community will begin in the mid-1980s in Athens. The Athens Automation and Control Experiment is expected to point the way for major improvements in the efficiency and reliability of utility power distribution systems.

The Athens experiment, however, is only part of a large program on distribution automation sponsored by DOE's Electric Energy Systems (EES) Division. This DOE program examines the effects of performance of the electric distribution systems.

The Athens experiment will address several utility needs by
• Obtaining information on how an automation and computer control system can improve the efficiency, reliability, and economics of power distribution, thereby encouraging its use by utilities.
• Developing and demonstrating technologies to flatten the demand

for power (altering the natural load shape and reducing peak loads) so that utilities can defer investment in additional generating capacity and distribution facilities, thus cutting their capital requirements and reducing operating expenses.

• Reducing costly energy losses. Utilities currently must produce more power than is actually delivered to and paid for by customers; of the two types of power—real and reactive—only real power is measured at the customer's meter. The key to minimizing losses, then, is to reduce the reactive power to zero. This reduction can be achieved by switching large distribution capacitors on and off.

• Developing methods for faster detection of faults (such as short circuits caused when trees fall across power lines), isolation of the faulted line section, and automatic operation of distribution switches to restore power quickly.

• Automatic transferring of loads among distribution feeders (power lines) to avoid overloading equipment.

• Coordinating the operation of the power distribution system with that of the bulk power generation and transmission system.

The $15-million experiment will result in installation of the Integrated Distribution Control System (IDCS), a system of hardware and software capable of detailed monitoring of the distribution system, switching various distribution devices, turning customer loads on and off, controlling real and reactive power during normal and emergency conditions, and coordinating the control of the distribution system with the operation of the bulk power system.

An innovation for which ORNL is responsible is the integration of existing and evolving distribution and load control automation technologies into a single, highly flexible control system. Under the direction of Steve Purucker of the Energy Division (formerly of Baltimore Gas and Electric Company), ORNL researchers have been designing and procuring the communication and control system, designing field installations, and procuring equipment to link the communication computer hardware with the Athens distribution system hardware. ORNL will complete the preparation of its experiment plans in 1984 and finish installation of equipment by October 1985. The experiments will run from October 1985 through 1992.

Three Experiments

ORNL researchers are designing three experiments to be conducted on the Athens system: (1) the load-control experiment, which involves developing computer models that accurately reflect customer demand for electricity and anticipate the impact of load control during the day and then applying control to orchestrate customer loads to improve efficiency and maximize use of existing resources; (2) the "volt/var control" experiment, which involves controlling capacitors, transformer tap settings, and voltage regulators to control voltage and reduce energy losses; and (3) the system reconfiguration experiment, which involves the automatic control of switches at substations and at various points on the feeders to restore power more quickly after outages occur as a result of faults.

After the IDCS is installed, the experiments will take place

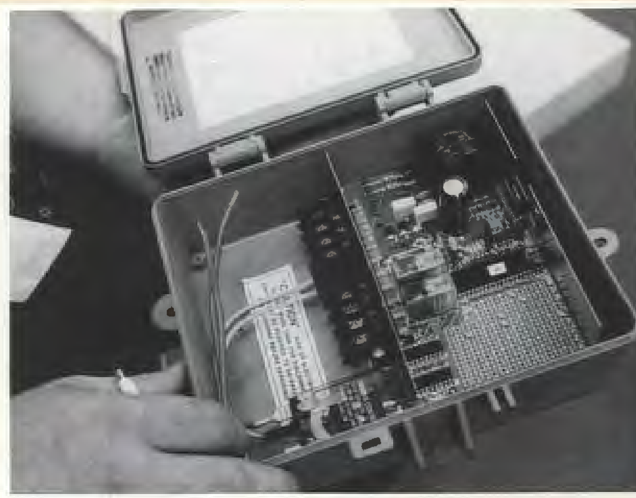
Athens was selected for the automation and control experiment because, of the Tennessee Valley Authority (TVA) distributors, its pattern of peak demands for electricity was the most typical of the whole TVA system. Above are, from left, the Athens courthouse (the city is county seat of McMinn County); an Athens substation, where control devices will be installed to monitor power consumption; and a home in Athens that may be part of the load-control experiment.

individually during the first year and then simultaneously during subsequent years to determine the interaction of the three experimental areas. Evaluation and data analysis will be performed after each experiment is completed.

Of the three experiments, the load-control experiment (see box) will be most visible, at least to one-fourth of the Athens power customers. These customers will have communication devices installed in their homes to turn heating and cooling units off and on. These devices will reduce use of expensive peak electricity without causing major discomfort. Load control will directly affect 2100 households and 5000 controlled customer loads—that is, water heaters, air conditioners, and space heaters.

ORNL also will conduct characterization studies and experiments until October 1985 on data subsystems recently installed in Athens. These subsystems represent partial installation of the IDCS and are designed to acquire baseline and modeling data as well as to detect hardware and software defects. An ORNL computer system, called the Athens Automation and Control Experiment Test System (AACETS), is located at and supported by ORNL's Instrumentation and Controls (I&C)

View of the interior of a load-control receiver, which, on the signal from a computer, can activate relays to temporarily turn off and later restore power to a water heater, space heating unit, or air conditioner in a customer's home. At center, Fred McDonald installs a smart meter, which is hooked up to the customer's telephone box. The smart meter, which is placed on a regular meter whose revolving disk has a black stripe painted on it, optically counts the times that the stripe passes by—that is, each time that the disk makes a revolution—and relays this information periodically by telephone to the central computer in Athens. At right are homes in Athens.



Computer To Control Power Use By Athens Customers

On a signal from a computer, "smart" hardware in Athens homes will daily shut off and restore power to water heaters, air conditioners, or space heaters. These measures should result in lower electric bills, yet people will still be able to take hot showers and will feel little discomfort on hot or cold days.

Between 1985 and 1988 some 2100 of the 9000 power customers (households) in Athens will participate in an ORNL-managed "load-control experiment" designed to show that careful control of power consumption in people's homes and other buildings can reduce the overall peak demand for electricity. Less peak demand by utility customers saves the utility money by reducing the need to install additional generating capacity and new distribution facilities.

Participants in the experiment, drawn by the prospects of lower electricity bills, will have load-control receivers installed in their homes. The Athens central control computer will send a signal by telephone line to signal injection units at three substations. This signal will cause a "ripple" on the power line, which will be recognized by the load-control receivers. They will interpret the ripple and activate one or more relays to cut back the water heating, cooling, or space heating in selected homes.

The signal injection unit transmits onto the power line a 50-bit message, which is decoded by the load-control receiver. Every 267 ms, there is a burst (a 340-Hz tone) or absence of a burst. For example, the signal injection unit can send a signal in which there are bursts at bits 1, 10, 22, and 37 in the 50-bit stream. That signal contains a message telling load-control receivers at all houses in a specific group (having about 300 customers) to turn off their air conditioners. Each load-control device in this group, which has been warned by a long tone that a message is coming, is programmed to respond to this particular bit stream by shutting down an air conditioner. Load-control receivers respond to only certain groups of

Division. AACETS is being used to develop and test applications software before it is used on the Athens distribution system.

Besides Purucker, three other members of the Energy Division have technical responsibility for the design of the Athens experiments. John Reed is in charge of the load control experiment, Tom Rizy manages the volt/var control experiment, and John Stovall, along with Jack Lawler of the University of Tennessee, is in charge of the system reconfiguration experiment. Randall Wetherington of the I&C Division is developing and testing control software on the AACETS computer, and Dick Thomas is leading the efforts of the Engineering Division in developing specifications for installing the interface equipment.

A number of other organizations are supporting DOE and ORNL in the project. The Tennessee Valley Authority (TVA) is providing bulk power coordination and technical support, the Jet Propulsion Laboratory of the National Aeronautics and Space Administration is providing expertise for the evaluation of the communication system, DOE's Sandia National Laboratory is supplying photovoltaic devices for installation at Athens, the Electric Power Research Institute is loaning equipment to evaluate appliance

bits (which can include combined messages to shut down two or more loads); they ignore messages that are not intended for them.

Brown Boveri Control Systems, Inc., an ORNL subcontractor, is supplying the load-control receivers and other communication and control system devices that make up part of the Integrated Distribution Control System of the Athens Automation and Control Experiment.

Besides the load-control receiver, another communication device will be installed in 200 Athens homes. This "smart meter" optically counts the revolutions of the electric meter and calls the computer by telephone to report on the customer's whole-household energy usage. Also, equipment provided by the Electric Power Research Institute will measure power usage by individual water heaters and central heating and cooling units. By monitoring selected customers' energy use, the Athens Utility Board will be able to determine the economic impact of switching loads on and off.

ORNL staff members are examining the implications of turning people's heating and cooling units off and on. John Reed of the Energy Division is developing customer profiles to determine patterns of energy use. This information will be used to determine when power to these units should be switched off and on to minimize customer inconvenience.

For power customers signing up for the Athens experiment, the goal is reasonable comfort at a low cost. For ORNL and DOE, however, the chief goal of the Athens load-control experiment is to demonstrate to utilities that control systems can (1) alter patterns of energy use to cut daily operating costs and (2) reduce the peak demand for power to defer the need for new generation.

Steve Purucker, project manager of the Athens Automation and Control Experiment, outlines the strategy for conducting three major experiments on the Athens system. Technical leaders of these experiments are, from left, Jack Lawler (University of Tennessee), who with John Stovall is in charge of the system reconfiguration experiment; Tom Rizy, who manages the volt/var control experiment; and John Reed, who is supervising the load-control experiment.

In Athens Larry Monteen works at the keyboard of an Apple II next to a communications interface for the smart meters installed in the field. Monteen is temporarily using this computer to acquire field data for ORNL researchers, who will provide baseline characterization data about customer energy use patterns.

loads, and an 11-member Utility Advisory Board is providing utility feedback and perspective. Thus the Athens project has broad-based support in the electric utility industry.

The "brains" for the Athens experiments will be the central computer to be installed at the Athens Communication Control Center. It will have the capability to automate the distribution system and control customer loads of the Athens Utilities Board, which receives electricity at 161 kV from TVA (the bulk power supplier) and by means of transformers at three substations steps it down to 69 kV or 13 kV for distribution to customers.

Two kinds of software have been developed to communicate with the field devices. One type of software, known as the real-time software, was developed and supplied by Brown Boveri Control Systems, Inc.; it tells the devices how to monitor

Jerry Bentz, an electrical engineer, checks out a remote terminal unit (RTU) at ORNL that is part of the Athens Automation and Control Experiment Test System (AACETS). It is similar to the RTUs to be installed in the Athens substation and on the distribution feeder that sends data to the Athens Communication Control Center.

Purucker taps the touchscreen of the smart test panel (at ORNL's Instrumentation and Controls Division), which simulates the electrical system of the Athens Utilities Board. This smart test panel is part of AACETS, which will be used to develop the experimental control ideas into real-time software to be employed during the Athens experiment beginning in 1985.

and control various components such as motors, switches, relays, and transducers.

A second kind of software, called applications software, tells the hardware what to do and when to do it. This software is being developed at ORNL by project personnel in the Energy and I&C divisions. It will perform such functions as telling the hardware when to switch loads or distribution equipment on and off and how to calibrate models to forecast customer energy usage.

Besides developing the software, ORNL researchers have participated in the specification and design of communication devices, particularly the pole-top units to be used for the system reconfiguration experiment. Says Purucker: "Because the utility industry seeks to provide reliable low-cost electric power, the results of our experiments will be of interest to most utilities. We expect to identify the economic benefits—such as increased efficiency and reliability—and the minimum amount of hardware required to support these benefits. In addition, as the experiments are conducted and evaluated, we will use the knowledge gained to define a second-generation control system. By quantifying benefits, determining minimal hardware requirements, and defining a second-generation system, we will provide valuable information that can help utilities decide what level of automation can be justified on the nation's distribution systems, which currently represent $80 billion of utility investment."

Distribution Automation

As previously mentioned, the Athens Automation and Control Experiment is only part of a systematic study of the effects of distribution automation on the performance of electric systems. Since 1981 the EES Division of DOE has sponsored work to identify and evaluate the effects of integrating distribution automation and control, load management, dispersed generation, and dispersed thermal and electric storage with conventional electric-distribution planning and design practices. An additional goal of this research is to offer techniques for appraising

Eva Broadaway, an ORNL electrical engineer, shows some components of a data system that will be installed in an Athens substation to gather preexperiment (characterization) baseline data on power consumption and weather variables. These data will be compared with data obtained during the experiment, which is designed to improve the distribution efficiency.

Randall Wetherington uses a light pen to call up information from the AACETS supervisory control and data acquisition (SCADA) system, which is based on a Digital Equipment Corporation PDP 11/44 minicomputer. The results of the electrical system simulation (performed by the smart test panel) are made available to the SCADA system through interfacing analog and discrete signals (exactly like those that will be present in Athens). The smart test panel sends the signals to the RTU, which digitizes them and telecommunicates the data for processing by SCADA real-time software. A larger SCADA system will be installed at the Athens Communication Control Center to monitor and control the Athens electrical system.

the technical effects of various utility- and customer-controlled uses of load management, electric and thermal storage, and dispersed generating devices.

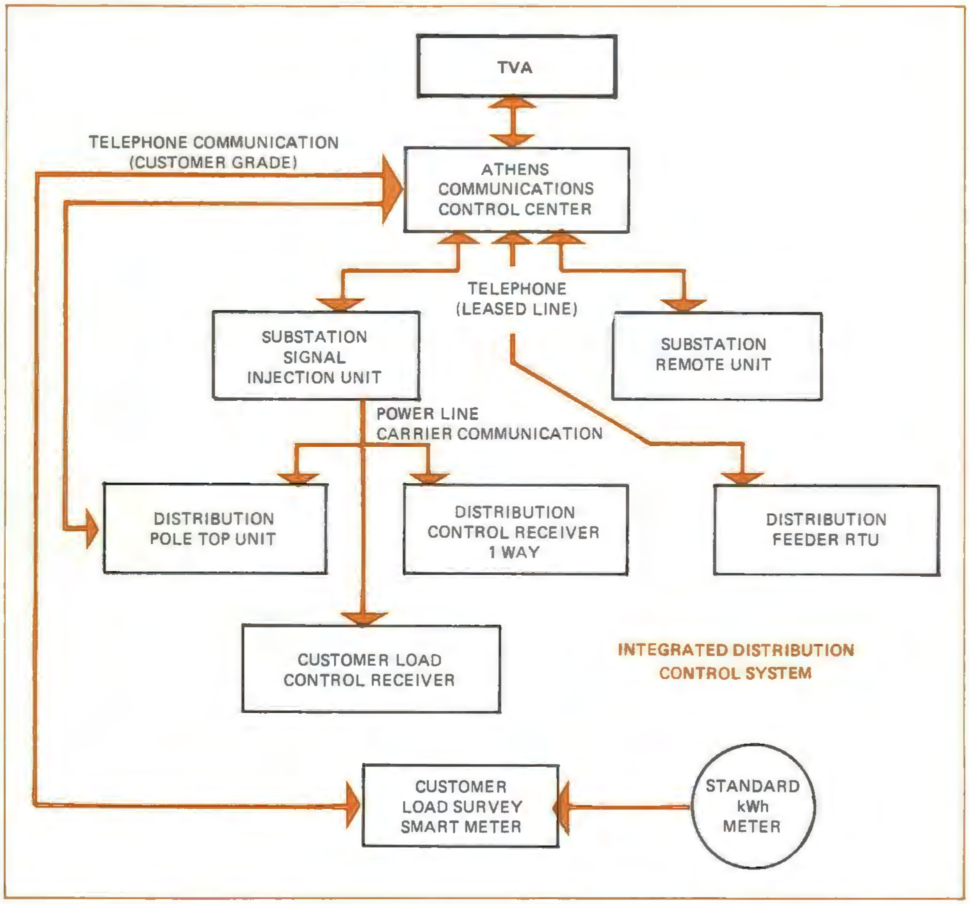
According to Stovall, utilities can expect to experience relatively large changes in load characteristics—that is, power inputs and demands—as a result of increased use of energy storage, photovoltaic systems, wind energy systems, and cogeneration systems. "For example, dispersed generating sources such as wind turbines are now creating reverse power flows on the distribution system and resulting in unique interactions with conventional protection equipment," says Stovall. "Thus changes in system protection plans may be needed for modern power distribution systems to ensure that they are safe, efficient, and reliable."

Utilities are now faced with the question: How will sophisticated distribution controls (for example, automation) and increased use of dispersed generating resources, load management, and thermal energy storage influence the conventional planning and design process?

In examining this question of distribution planning, DOE program researchers at ORNL and elsewhere have looked at the differences in utility distribution systems and how they affect future decisions on system designs. Says Stovall, "From utility to utility, distribution systems differ in load density, geography and climate, local code and practices, and system age. Thus any generic methods we develop will not be useful unless we also address the specific design problems of individual utilities."

Whether utilities move toward distribution automation depends on economics as well as the specific design problems that such a move would entail. As Elgin G. Enabnit put it in an editorial in the March 1984 issue of *Transmission & Distribution*:

"The technical know-how is available to automatically control transmission and distribution systems, but the economics needed to justify expenditures for automatic meter reading and



Schematic of the Integrated Distribution Control System. Each block represents equipment, and the lines represent the communication links tying the equipment together. The top block represents the TVA operations control center, which coordinates the operation of different distributor communication control centers. The remaining equipment is located at the substation on the distribution feeder and in customers' homes.

automatic control of distribution systems have been slow in becoming a reality.

"With the present state of the art, almost every function of a distribution system can be automated. However, no standard system can be designed to control all the elements of all electric utility systems. Also, each utility has its own preference for the communications and control medium."

To solve the problems of system economics and design for the 1980s, ORNL researchers have been working with utility engineers and subcontractors. By the late 1980s, distribution planning concepts are expected to be shaped by the results achieved in the Athens Automation and Control Experiment managed by ORNL's Power Systems Technology Program.

At the Athens Utilities Board (AUB) Larry Monteen (left), Athens project leader; George Uery, AUB manager; and Nick Fortson, installation engineer, discuss a plan for installing communication devices at substations and customer homes.

New Dielectric Materials Needed To Increase Power-System Efficiency

Because energy costs have increased in recent years, utilities have searched for methods to deliver electric energy as efficiently and reliably as is practical. One way is to operate power transmission lines at higher voltages. For the same power delivery, this increased voltage results in a proportional reduction in electrical current and a concomitant reduction in energy losses. Another way of reducing energy waste is to build more reliable and energy-efficient transmission, substation, and distribution equipment, which can reduce dielectric losses (losses of electric energy caused by the insulating material). Dielectric materials with improved performance are therefore needed in conjunction with more efficient and higher voltage equipment.

To assist utilities in increasing the efficiency and reliability of power systems, ORNL is helping DOE's Electric Energy Systems (EES) Division manage a national R&D program on electrical insulation and development of advanced dielectric materials for use in future electric power generation, transmission, distribution, and substation equipment. The program will further the fundamental understanding of dielectric materials and provide a data base for the development and application of these materials. New dielectric materials will be developed for future electric power equipment, which will have improved efficiency and reliability.

Future growth in the transmission and distribution system may require increasing use of underground or compact installations because of opposition to overhead and exposed equipment for aesthetic, environmental, and safety reasons, as well as the limited availability of power line rights-of-way. Thus to achieve compactness and economy with improved reliability and reduced energy losses, the requirements of electrical insulation for the transmission and distribution equipment will be more demanding.

Richard Mathis adjusts the electrode separation in a chamber where measurements of breakdown strength of dielectric gases are performed under varied experimental conditions. He is working in an ORNL program to develop and test new dielectric materials for insulating high-voltage, energy-conserving systems.

According to Steinar Dale, a researcher formerly with Westinghouse Electric Corporation in Pittsburgh, Pennsylvania, and now with ORNL's Power Systems Technology Program, the design of electrical equipment is limited to the use of dielectric materials with a proven history of reliability. "Because the properties of the insulating materials are critical factors in the equipment design and performance, we need to assess the properties of various dielectric materials, the processes for making them, and the requirements of the equipment," says Dale.

"To achieve the goals of making future equipment more reliable, efficient, and compact, we must determine the limitations of today's materials in the various equipment designs and establish the requirements of the dielectric insulation systems for the future. The DOE-EES program, in which ORNL will have a lead role, will provide a vehicle for collaboration among industry, universities, and national laboratories."

The overall goal of the DOE-EES Program for Advanced Dielectrics is to develop improved dielectric materials that will reduce life-cycle costs and offer more reliable and efficient operation of electric power equipment and systems. The program's specific objectives are to (1) develop fundamental understanding of the mechanisms occurring within dielectric materials and the phenomena at the boundary between the metal conductors and the insulation, (2) develop new dielectric materials and equipment

At DOE's 1200-kV Compressed Gas Insulated Cable demonstration project at the Electric Power Research Institute (EPRI) Underground Cable Test Facility in Waltz Mill, Pennsylvania, are, from left, Steinar Dale, ORNL; John Shimshock, EPRI; and Philip Bolin, Westinghouse Electric Corporation.

concepts and test their performance, and (3) foster the transfer of the new materials and concepts to the electric power industry.

Several projects that deal with the fundamental understanding of electrical insulation and dielectric materials have been pursued. The most prominent of these projects (which are discussed in detail in subsequent technical capsules) is the ten years of research on gaseous dielectrics headed by Loucas Christophorou of the Health and Safety Research Division. Under the new Dielectric Materials Program Plan, this effort will be expanded to cover fundamental studies of liquid dielectrics for transformers, cables, and capacitor banks and for phenomena at the interfaces between the metal conductors, the solid insulation, and the insulating gas or liquid.

Another ORNL research effort is probing the aging process of polymeric insulating materials. The changes that occur in electrical insulation with time and stress (aging) are often responsible for premature failure of electrical equipment and result in millions of dollars of lost revenue and replacement costs for the utilities. In this project, the changes that occur in polymeric insulating materials are studied under mechanical and thermal loads and load cycling.

Protection of the electrical transmission and distribution system against lightning and other overvoltages is an important factor for system reliability and availability as well as economic designs of electrical equipment. One ORNL project is studying metal oxide varistors, devices that provide such protection. Improved, more compact varistors will offer better protection against overloads and could increase the reliability of electric utility power systems and reduce the size of the utility equipment.

ORNL Studies Gases and Liquids for Insulating High-Voltage Lines

Electric power travels inside a "pipeline" of insulation that surrounds the high-voltage conductors and contains the moving energy. The earliest, and still most common, insulation is simply air. Because this insulation requires a large distance between the high-voltage conductor and other objects, high-voltage lines must be strung between towers and tall poles to separate them sufficiently from ground. More recently, liquids or sulfur hexafluoride (SF_6) gas has been used to insulate electric power transmission apparatus, including transformers and circuit breakers. Because these insulating materials are more effective than air, they allow utilities to use more compact equipment, underground cables, and higher voltages. Less land is therefore required for equipment, and absence of power lines contributes to a more attractive landscape. The higher voltages save energy because they permit a lower current, which in turn reduces electrical energy losses caused by electrical resistance. Today 5 to 10% of the electrical energy transmitted in the United States is dissipated to the environment.

To reduce electrical energy losses and protect electrical equipment, a group under Loucas G. Christophorou in ORNL's Health and Safety Research Division is seeking to understand how gases and liquids can be effective insulators for the power industry. The strategy is to inhibit motion of the few free electrons that can trigger "breakdown," a process in which these electrons are sufficiently energized by high-voltage fields to free more and more electrons from molecules, thus "rupturing the pipeline" for electric energy. When breakdown occurs, equipment is damaged and the power system goes out of service, sometimes resulting in catastrophic blackouts of large areas.

The group has developed several means to inhibit the effect of these

Jim Carter (left), Scott Hunter, and Loucas Christophorou in the laboratory where basic knowledge on electron-molecule interactions is obtained and used to develop gases that are both good conductors and good insulators for pulsed power technologies.

Part of an impulse generator used to study the properties of dielectric gases under steep voltage pulses such as would be encountered in the new pulsed power technologies being developed for fusion energy, particle beam weapons, and other applications.

troublesome electrons. One way is to attach them to certain molecules, such as the perfluorocarbons [namely, perfluorocyclobutane (c-C_4F_8), perfluorobutene (2-C_4F_8), perfluoro-2-butyne (2-C_4F_6), and perfluoropropylene (1-C_3F_6)]. Because electrons are often too fast to be easily attached, a second gas is used to first slow them down. The ORNL group found that good slowing down, or buffer, gases are hydrogen, nitrogen, carbon dioxide, and carbonyl sulfide; and they identified the mechanisms by which these gases retard electron motion. Thus after considering the fundamental processes involved, the ORNL group has found the ideal combinations of gases to give a dielectric strength (resistance to breakdown) up to 20% higher than that of SF_6 alone.

The principles of preventing electrical breakdown in gases are also being applied to *allow* gas breakdown when desired, as in gas switches. The ORNL group has worked on developing gas switches that could be used, for example, in the new pulsed power technologies; electrical energy gradually stored in large coils could be released very suddenly if a switch were available that had sufficient speed and current-carrying capability. Quick, repetitive delivery of such large amounts of energy will be needed for such applications as fusion energy and particle-beam weapons. Gas switches could also remove the electric charge from power apparatus in imminent danger of damage due to uncontrolled charge.

The group has also assessed the quality of these new gaseous dielectric mixtures in the face of unusual problems found in power apparatus. These include very fast-changing voltages (such as those caused by lightning), adventitious particles in the apparatus, elevated temperatures caused by heavy loads or sparks in switches, and long-term chemical changes in gases. The ORNL group has developed a wax to trap stray conducting particles, which have adverse effects on dielectric gases.

Another problem investigated by the group is that the conventionally used insulating gas, SF_6, as well as some others, can form highly toxic gases containing fluorine when exposed to high voltage. Chemists and biologists in the group are studying how these gases form and how they affect living cells.

Understanding how gases can be used to prevent electrical breakdown is important for liquid dielectrics as well. Some scientists believe that a liquid insulator fails by first entering a gas phase. The ORNL group is therefore studying the effects of additives in strengthening liquid insulators.

The ORNL group has also organized four symposia on gaseous dielectrics, the latest one of which was held in spring 1984 in Knoxville. Representatives from 20 attending nations discussed important matters—including keeping the "pipeline of insulation" around high-voltage conductors from rupturing and disrupting power service.

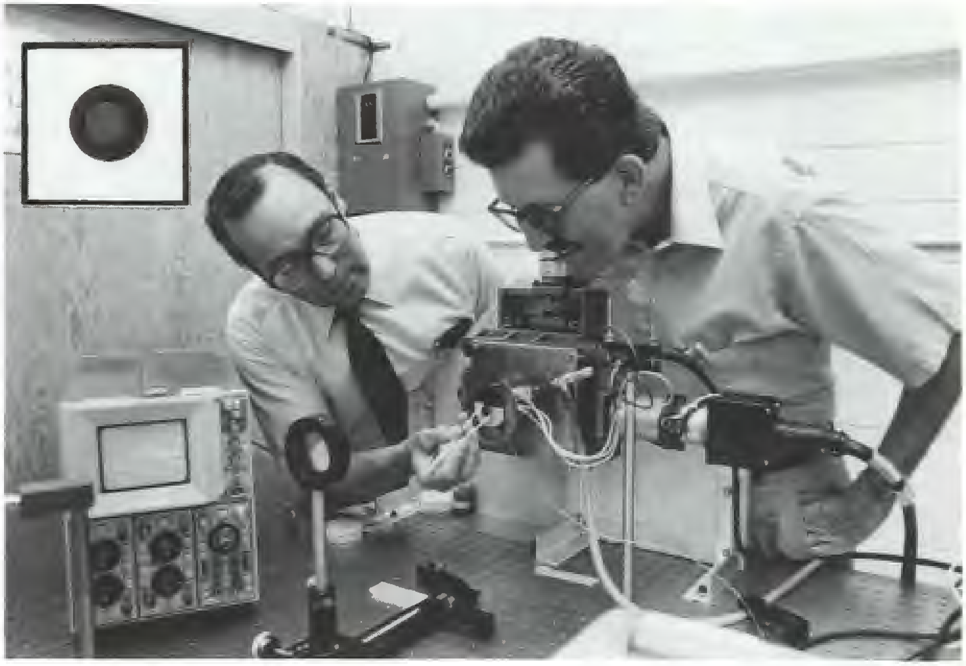
ORNL Develops Compact Varistors To Protect High-Voltage Lines

Zinc oxide (ZnO) varistors are used to protect electrical equipment and power transmission lines from destructive electrical surges. Their ability to absorb surges in line voltage arises from their highly nonlinear electrical conductivity: At low voltages the resistivity is very high; at high voltages it becomes low. This effect is attributed to the formation of 2- to 3-V Schottky barriers by dopants, such as bismuth, which concentrate in the ZnO grain boundaries. The voltage at which the varistor will conduct electricity to ground (set at some level above the normal line voltage) is therefore determined by its thickness and grain size. Thus a finer grained varistor would have more grain boundaries and therefore more Schottky barriers per unit of thickness, making it possible for a small varistor of this type to short out electrical overloads as effectively as the larger conventional varistors.

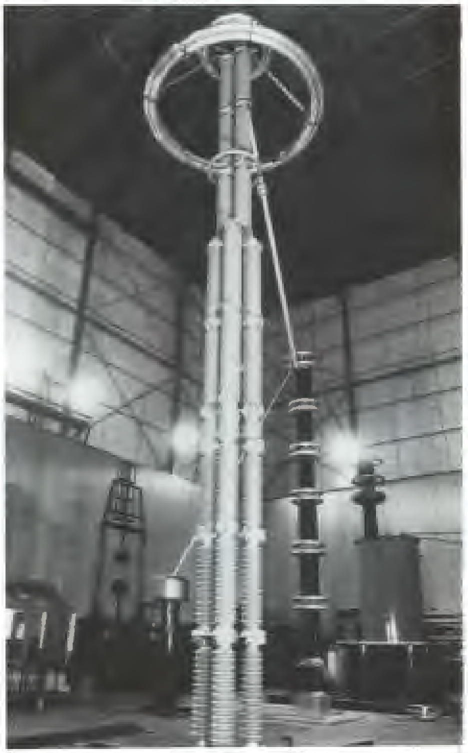
At ORNL Robert Lauf and R. K. Williams of the Metals and Ceramics Division, Frank Modine and Ed Sonder of the Solid State Division, and Walt Bond of the Chemical Technology Division have been working on

- Developing very fine-grained ZnO varistors for use in very high-voltage equipment and transmission lines (up to 1200 kV), especially where size is critical (for example, in congested urban areas or underground transmission lines)
- Characterizing the structure and properties of these new varistors to understand the fundamental relations between processing and properties
- Determining the response to extremely fast pulses such as those caused by nuclear explosions

To develop fine-grained varistors, the researchers have used very fine powders of ZnO and additives (bismuth, cobalt, antimony, and chromium oxides) synthesized by the sol-gel process, which has been developed at ORNL over many years. These fine powder mixtures can be densified at temperatures lower than those necessary for commercial materials (800°C vs 1300°C), minimizing grain growth and evaporation losses of the additive. Hot-pressed varistors made by this process break down at voltage levels as high as 4000 V/mm, compared with about 300 V/mm in commercial materials; because the ORNL varistor can resist a voltage 13 times as great as that required for breakdown in conventional varistors, a smaller device using the finer grained material could be used for a given operating voltage. Sintered varistors made from sol-gel powders break down at about 1000 V/mm, but development work on sintered materials just started recently at ORNL, and further gains are expected. ORNL researchers are investigating sintering because it is less expensive than hot pressing.



Frank Modine, left, and Doug Lowndes show where an electrode would be placed in a beam from an excimer laser in the Solid State Division. The beam vaporizes oxygen from the zinc oxide disk, leaving a film of zinc about 1000 Å thick. Inset: a laser-implanted electrode made at ORNL (left) and a conventional silver electrode.



This conventional surge arrester (varistor) is being tested at a Westinghouse Electric Corporation plant.

The very fine-grained materials have prompted the ORNL group to conduct new fundamental studies. For the first time it is possible to study changes in varistor electronic properties that occur as the grain size varies over two orders of magnitude. A preliminary finding that the voltage drop per grain boundary exceeds that predicted by theory in the fine-grained materials suggests that the basic theory of varistor conduction needs revision.

For the ORNL group, the response of varistors to very fast electrical pulses, such as those brought on by detonation of nuclear explosives, is another area of special interest. Although ZnO varistors are very fast, they do not turn on instantly, and they provide only a reduced level of protection during a turn-on transient that typically lasts 100 μs or less. The ORNL researchers are investigating the origin of the transient behavior with a goal of improving the speed of varistor response.

The Solid State Division has developed a novel method of fabricating varistor electrodes. A submicrosecond laser pulse is being used to heat the surface of a varistor to its vaporization temperature. Because oxygen in the ZnO is lost more readily than zinc and the dopant metals, a highly conducting zinc electrode forms on the surface. The laser-fabricated electrodes are comparable to commercial electrodes prepared by such methods as flame spraying of metals.

In January ORNL held a technology transfer workshop in Knoxville to inform varistor manufacturers and users about the ORNL process for making fine-grained varistors. Representatives of utilities, manufacturers, universities, and other government laboratories attended. As a direct result of this workshop, one manufacturer has expressed an interest in licensing the process for commercial development.

ORNL Optical-Fiber Device Can Identify Transformer Hot Spots

One way to reduce the loss of electrical energy, which dissipates as heat when it travels over wires from generating stations to destinations such as homes and factories, is to use transformers. Such devices permit the transmission of electricity at a low rate of flow (current, or amperes) by stepping up the voltage. Thus if the voltage is multiplied by the transformer, the amount of current (and energy loss) is reduced. At the receiving station, the voltage can be stepped down again by other transformers so that the current is correspondingly increased for use in household appliances or industrial motors, for example.

The transformer works by using the primary current to induce a current at high voltage in a secondary coil. This induction requires an alternating current to vary the magnetic field through the secondary coil. If the secondary coil has more windings than the primary coil, the voltage will be stepped up; if it has fewer windings, the voltage of the transmitted electricity will be lowered.

The transmission of power could be made more economical if loading transformers more heavily were safe. Utilities normally avoid subjecting transformers to the design load current to avoid overheating the insulated wires coiling around the steel cores. Hot spots could lead to failure of insulation, thus

Dick Fox adjusts the rotary table, which carries an optical-fiber sensor. A beam from the laser (left) is injected into the entrance of the fiber at a measurable launch angle. From the launch angle that produces light in the fiber cladding, he can measure peak temperatures. This sensor could be used to detect hot spots in transformers.

This circuit board interprets launch angle information to give a temperature readout.

requiring that the transformer be taken out of service and increasing the likelihood of a temporary power outage.

Currently utilities use analytical models to estimate whether or where a hot spot might exist. However, if an accurate and economic method of measuring the temperature of hot spots in wires existed, utilities would be more likely to "squeeze" the maximum amount of power from transformers.

A new development spearheaded by Dick Fox of ORNL's Instrumentation and Controls Division shows promise of precisely measuring the temperature of transformer wires in real time. Fox has developed a fiber optics system that could be embedded in the transformers of a distribution system. If the fiber optic sensors were linked to a computer, a dispatcher could constantly monitor the temperatures of transformers in the distribution system and shift electrical loads from one transformer to another when remote readouts indicated that the temperature of a particular transformer was dangerously high. Such a monitoring system, which is under development, would permit utilities to extend the life of their transformers.

Fox selected optical fibers for distributed line detectors because they are immune to electric fields. He used a hollow silica optical fiber filled with a liquid silicone core to measure the peak temperature (hot spot) over an experimental distributed line. In the temperature range from ambient to 190°C, Fox found that the maximum error of the optical fiber sensor was only 1°C and that this deviation was essentially independent of the length or position of the hot zone.

How does this fiber optics system work? Laser light is injected into the silicone core of the fiber in the transformer and is guided through the fiber core at ambient temperatures. If a hot spot on the transformer wire develops, the silicone core is heated, thus reducing its refractivity. This lowered refractivity causes the light to escape from the core into the silica cladding, where its intensity can be measured by a photometer. By calibrating the core index of refraction versus temperature, information can be obtained and fed into a computer, which calculates the temperature rise in the transformer.

The optical fiber method does have some limitations. The fibers should not be used when sharply bent because this can produce a small error in the temperature reading. However, this error can be corrected if the bend radius is known.

Fox hopes to overcome another limitation of the new technique. Although it can indicate the existence of a peak temperature along the fiber, it cannot tell where the hottest spot is. He plans to develop a technique to locate hot spots in transformers and in underground cables.

Thin-Film Polymers Tested for Transformers of the 1990s

Transformers being developed for the 1990s have their magnetic cores wound with sheet conductors instead of wires to make them more efficient and reliable, safer, and easier to fabricate. The wire-wound transformer core, which resembles a spool of thread, will be replaced by a core that looks like a jelly roll. The material originally proposed for the insulation between these sheets (the jelly part of the roll) is oil-impregnated paper. The paper, however, is not ideal; it lacks some good insulation properties, and it is bulky, thus requiring the transformer to be larger than desirable.

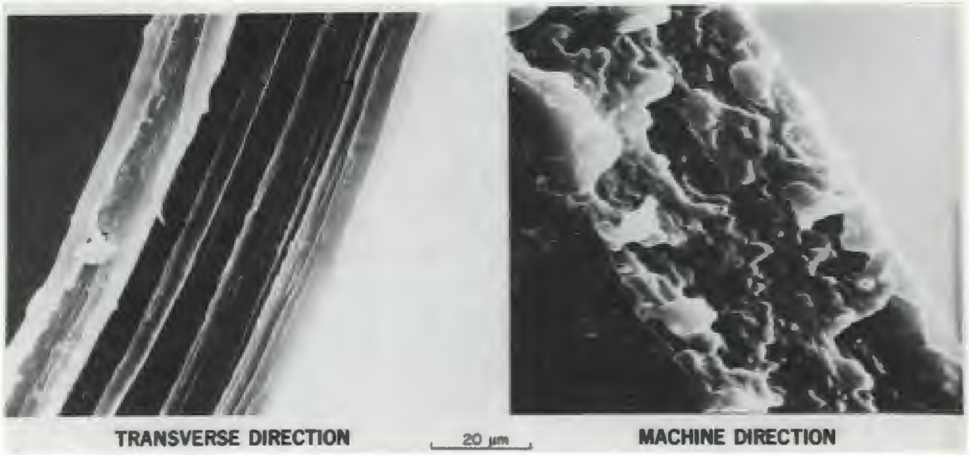
As a result of these problems, scientists are looking at the possibility of replacing oil-impregnated paper insulation with thin-film polymers. Some polymer films have a greater electrical strength than paper, and because the films are thin, they would allow the construction of a more compact transformer. Smaller transformers are desirable because they are cheaper and require less installation space.

Materials scientists are concerned that thin polymer films may not hold up under certain stresses imposed by transformer operation, particularly thermal cycles (alternating hot and cold exposures) brought on by variations in the load current. At ORNL Herb McCoy and Chuck Brinkman of the Metals and Ceramics Division have been examining whether thermal cycles can cause certain polymer films to tear, expand, or respond in other undesirable ways. They have looked at a number of different polymers (for example, polyethylene, polycarbonate, and polysulfone), including those suitable for sandwich and trash bags. They have also examined the polymer polyethylene teraphthlate (Mylar®), used in Europe for bottling vodka and catsup.

McCoy and Brinkman have tested sheets of polymers that have been aged for 25,000 h. They have examined the materials for indications of electrical breakdown and degradation of insulation properties and have measured changes in mechanical properties and crystallinity (the more crystalline the film, the less ductile).

For an aging test, the researchers made a stack of polymer sheets 7.6 cm^2 (3 $in.^2$) and compressed the polymer insulator between the aluminum conductors. They compressed the insulation at different temperatures (70, 110, 135, and 160°C) to determine tensile properties because compressing the material to stress it is easier than pulling it. They found that polymer films that can withstand the highest temperatures tend to be the most expensive, suggesting that a tradeoff exists between cost and temperature capability.

Creep properties of different polymer films—the extent to which these materials deform over time at different pressures and temperatures—are also being examined at ORNL. For a creep test, McCoy and Brinkman converted a transformer coil test chamber to a creep test apparatus. Small strips of the various polymers were stressed while



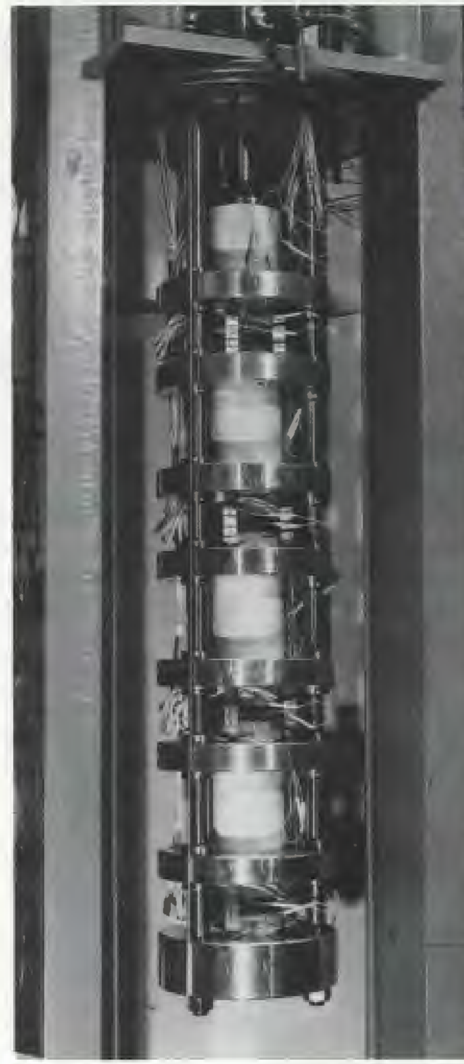
Scanning electron micrographs of the fractures of polyethylene terephthalate tensile samples. The basic structure of the material is rodlike. When the material is stressed in the machine direction (right), the ends of the rods are pulled in parallel. When the rods are pulled in a transverse direction (left), the material's properties are different from those of the sample at right.

being heated in an environment of sulfur hexafluoride (a possible future replacement for oil as the conventional insulating material used in transformers in the United States). They found that the creep strengths vary considerably for the different materials.

They also are looking at the effects of fabrication on the polymer film properties. Because polymers are anisotropic—that is, have different properties in different directions—small changes in fabrication could alter their properties.

McCoy and Brinkman observed that the polymers tested vary in electrical strength properties, temperature limitations, and susceptibility to environmental conditions. They also found that polymers are sensitive to temperature differences between metal conductor and polymer insulation. Temperature differences can lead to differences in thermal expansion and to stresses. Says McCoy, "Although several types of thin polymer films can be wrapped around conductors, the type of polymer selected should be one that can meet service conditions."

McCoy adds that experiments are needed to determine the effect of electrical stress on these films because resistance to electrical stress may be dependent on imperfections in the materials. Such information could be useful to manufacturers of thin polymer films for electrical applications, including sheet-wound transformers.

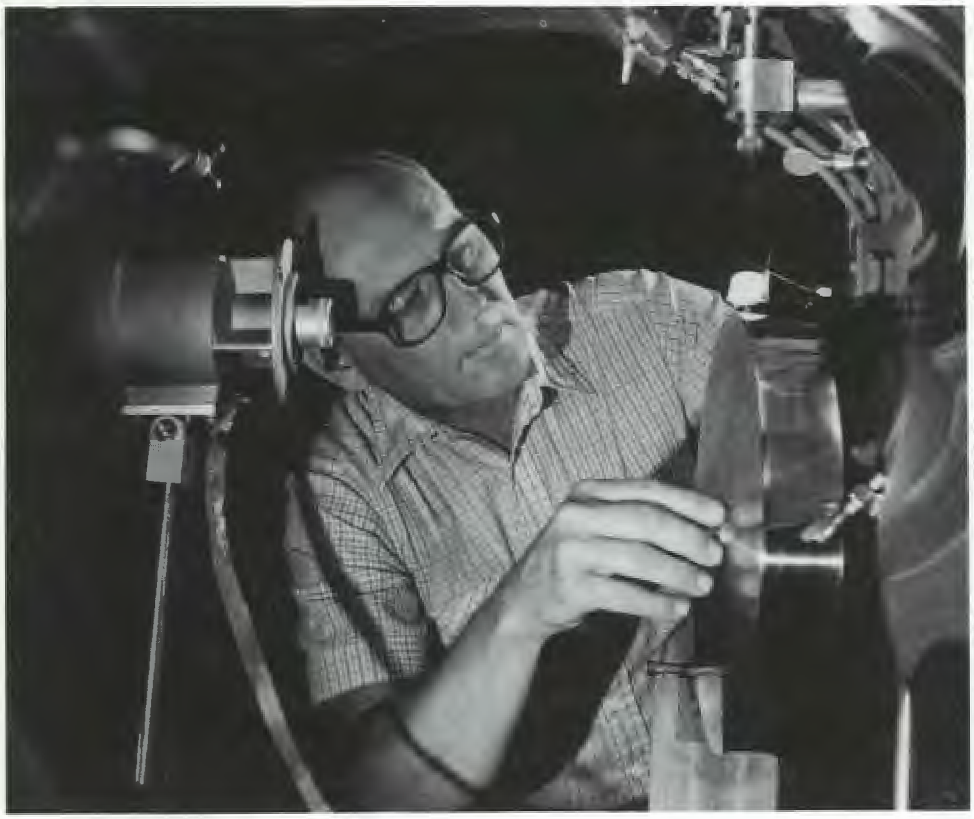


Interior of an aging chamber with four groups of polymer film samples in place for aging. The white pieces are alumina insulators to help isolate the temperature zones of 70°C at the bottom and 110, 135, and 160°C at the top.

Amorphous Ferromagnetic Alloys Being Developed for Transformers

Transformers and motors are made of iron and its alloy, steel. Iron is used because it readily produces a magnetic field in the presence of an electrical current. Electromagnets—iron bars wrapped with copper wires—are the workhorses of transformers and motors. Iron, however, has a deficiency: When heated, it loses its strong magnetic properties, so it is not well suited for high-voltage equipment. Metallurgists have therefore turned their attention to developing low-loss steels that retain their magnetic properties even when heat is produced in high-voltage systems.

In the Processing Science and Technology Section of ORNL's Metals and Ceramics Division, Don Kroeger and his colleagues Claudette McKamey, Dewey Easton, and Jim Scarbrough are studying low-loss steels with the goal of improving their properties. They are particularly interested in reducing



Jim Scarbrough adjusts a crucible in which an amorphous ferromagnetic steel alloy is melted. The crucible, which has a hole in the bottom, is positioned above the polished rim of a rapidly spinning copper wheel (shown from another angle in the center photograph). When the alloy is molten, an overpressure of an inert gas is used to force the liquid alloy through the orifice onto the moving wheel surface. As the molten stream contacts the wheel, it is rapidly spread into a thin layer, permitting rapid transfer of heat. The result is a very thin, continuous metallic glass ribbon (right).

embrittlement in amorphous ferromagnetic alloys—iron-based metallic glasses, which, because of their unusual magnetic properties, promise to make transformers and motors more efficient.

A metallic glass is a nonequilibrium form of a metal in which the atoms occupy random positions relative to each other rather than being arranged in a regular crystalline array. The production of such a state requires very rapid cooling of the liquid alloy to temperatures well below its melting point. The cooling rate required varies from alloy to alloy: For many alloys it is unattainably high; for others it is within the range of cooling rates producible by a special fabrication process known as melt-spinning.

In this process the alloy is melted in a crucible with a small hole in the bottom. The crucible is positioned above the polished rim of a rapidly spinning copper wheel, and after the alloy is molten, an overpressure of an inert gas is used to force the liquid alloy through the orifice onto the moving surface. As the molten stream contacts the wheel, it is rapidly spread into a thin layer, permitting rapid transfer of heat. The result is a continuous ribbon with uniform width and a thickness of about 25 μm (0.001 in.). The average cooling rate for the process is estimated to be 10^5 to 10^6 K/s. Continuous melt-spinning operations to produce metallic glass ribbon up to several centimeters wide have been developed commercially.

Because of their homogeneity and isotropy and their lack of microstructural features, some iron-based metallic glasses exhibit very low rates of energy dissipation—that is, low power losses—when placed in an alternating magnetic field. This property suggests that using these metallic glasses for magnetic cores for transformers and motors would result in significant increases in efficiency. Model transformers and motors have demonstrated this potential.

However, differences in properties between metallic glass ribbons and the crystalline materials normally used for magnetic cores necessitate changes in transformer and motor design and manufacturing procedures. Unlike magnetic properties of conventional materials, those of metallic glasses are sensitive to stress; and these amorphous metals embrittle during low-temperature annealing to minimize alternating current power losses. As a consequence, the finished core must be supported and enclosed to prevent undue flexing and release of amorphous metal fragments into the device.

In their study of annealing embrittlement of an iron-based metallic glass ribbon of a composition that may be used in transformers and motors, Kroeger and his colleagues have obtained results which may lead to new materials that embrittle more slowly. The ORNL researchers have measured the bend ductility of melt-spin ribbons of an iron-based glass containing boron, silicon, and carbon ($Fe_{80}B_{16}Si_2C_2$) to which they have added small amounts of cerium. The results suggest that the cerium in proper amounts strongly retards the embrittlement process. How the cerium reduces embrittlement is not yet known, so the researchers are investigating several possible mechanisms. If a ribbon that remains ductile after annealing could be made, then requirements for support and enclosure of magnetic cores in high-efficiency electrical devices may be relaxed.

ORNL Manages Tests of Thermal Energy Storage

An important characteristic of the electric power system is that electricity must be generated, on demand, to serve customers' needs. Electric utilities must therefore build sufficient generating capacity for periods when demand for electricity is the greatest, even though much of this capacity is used only occasionally. Often this peak demand is met by gas- and oil-fired peaking plants—which are expensive to operate.

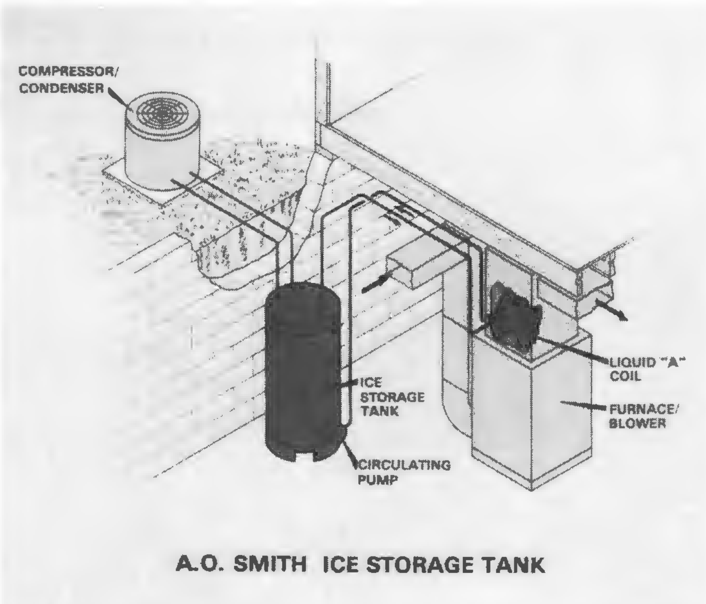
One solution to the problem of growing peak demands is to persuade consumers to change their patterns of electricity use. The concept of trying to change electricity use to meet available generation rather than building generation to meet any demand is called electric load management. The load management options available to utilities include promoting building weatherization and high-efficiency appliances, convincing customers to change their lifestyles through rate incentives such as lower rates for electricity use during low-demand times of the day, and promoting thermal energy storage.

Thermal energy storage can help solve the problem of storing electricity, at least indirectly, by converting it to heat or cool storage for later use. Several storage heating and storage air conditioning systems are now available for use in commercial and residential buildings. In one of these systems, for example, heat is stored in a pile of ceramic bricks in an insulated cabinet. During off-peak hours, electricity is used to heat the ceramic bricks to as high as 760°C. During peak hours, air is blown over the hot bricks to provide space heating. A typical storage air conditioner is run during off-peak times to produce ice that is stored in an insulated tank. During peak hours, water is circulated through the ice tank and a cooling coil in the building to provide air conditioning without consuming additional electricity.

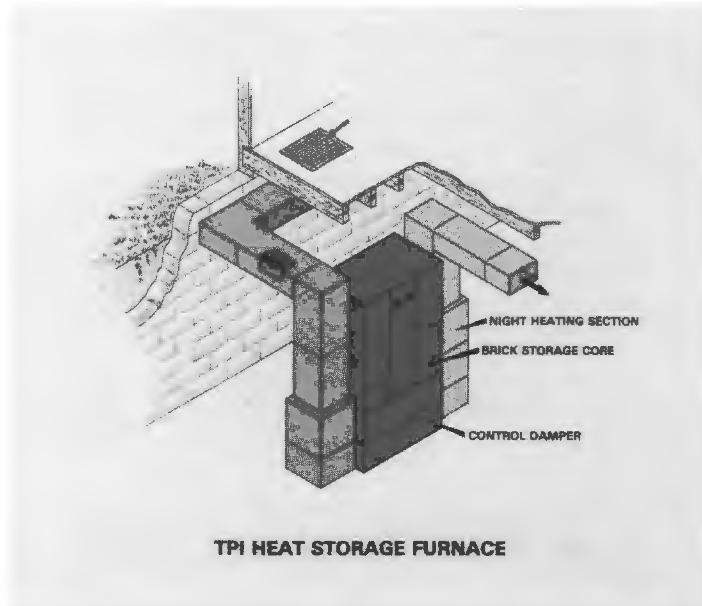
Thermal energy storage is particularly attractive to customers because it lets them use energy when they want it, and it allows electric utilities to provide electricity when it is the least expensive. Even so, storage systems have not been widely used in the United States, partly because questions remain about their performance, reliability, and economics. In an effort to answer the technological and economic questions surrounding the use of residential storage systems for load management, DOE's Division of Electric Energy Systems funded a nationwide field test program of residential thermal energy storage systems. The tests—managed by Mike Kuliasha of the Engineering Technology Division and Paul R. Barnes, John Klein, Tom Rizy, and John Stovall of the Energy Division—were carried out by eight utilities across the United States.

Five cool storage tests were conducted by Arkansas Power and Light Company, Long Island Lighting

A crane lifts and later lowers a cool storage tank (made by Girton Manufacturing Company of Millville, Pennsylvania) into the backyard of a house in Fresno, California. The house is part of a thermal energy storage test conducted by Pacific Gas and Electric Company.



Typical cool storage installation.



Typical central ceramic brick heater installation.

Company (LILCO), Pacific Gas and Electric Company, Virginia Electric and Power Company (VEPCO), and Wisconsin Electric Power Company. The five heat storage tests were conducted by LILCO, Niagara Mohawk Power Corporation, Public Service Electric and Gas Company, United Power Association, and VEPCO.

In total, the field test program resulted in data being collected from 208 cool storage test homes, 122 homes with conventional air conditioning, 153 heat storage test homes, and 141 conventionally heated homes. Also, the participating utilities were given the option of examining storage water heating in conjunction with the space conditioning tests; as a result, storage water heaters were installed in 124 homes. These homes and 111 other homes with conventional water heaters were instrumented to compare performance.

Data were collected every 5 to 30 min during the summers of 1980 and 1981 and the winter of 1980–81. In addition, one utility continued testing heat storage equipment during the winter of 1981–82. All together, more than 30 million data points were collected and analyzed.

The qualitative results of these field tests showed the concept of residential storage systems to be a viable option for load management. However, the tests also found a variety of deficiencies in the storage equipment then available that would prevent the widespread commercialization of these systems in the residential market.

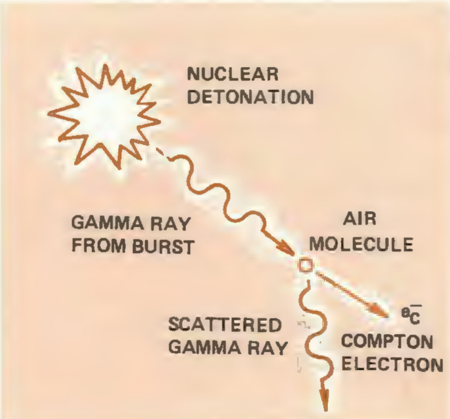
With an eye toward the next generation of storage equipment, the Electric Power Research Institute (EPRI) is supporting research at ORNL to analyze the data from the field tests to determine equipment load characteristics, quantify the performance of the storage equipment, and identify needed improvements in the equipment design and controls. Kuliasha, Therese Stovall, Lincoln Jung, and Gordon Beard of the Engineering Technology Division are working with EPRI on the project.

ORNL Is Principal Laboratory for Studying EMP Impacts on Power Systems

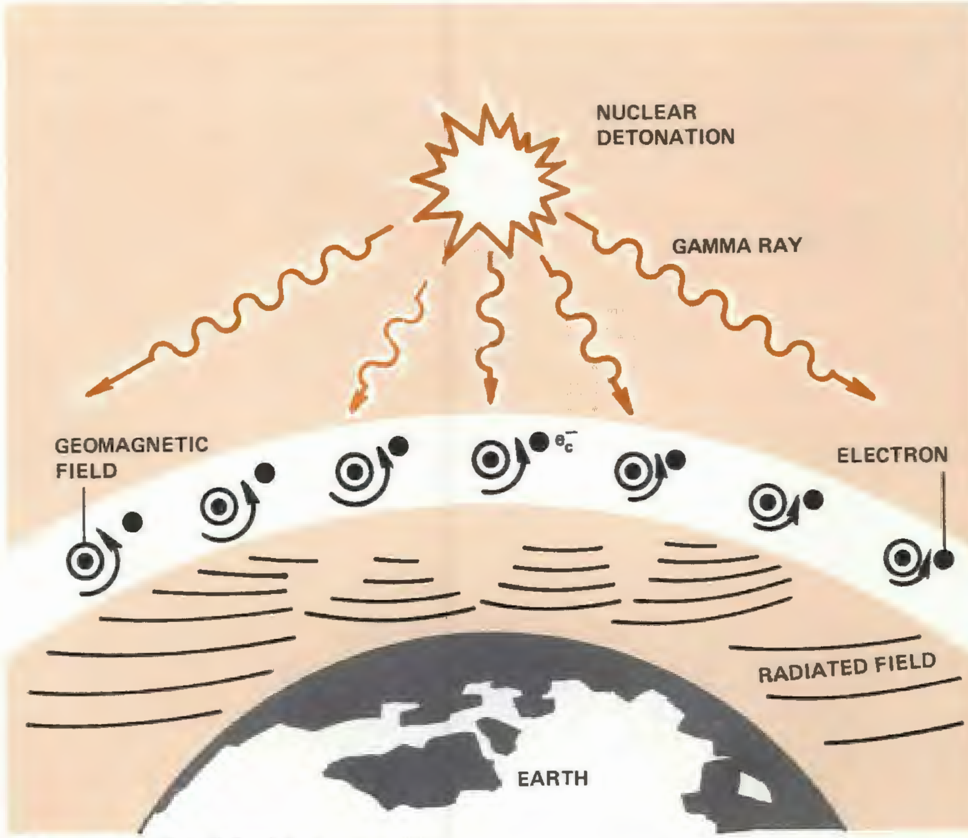
Detonation of a nuclear weapon in space about 500 km (300 miles) over the central United States would not cause heat and shock waves below because of the high altitude. But the radiation from a single high-altitude burst could subject most of the nation to a very intense electromagnetic pulse (EMP). The intense electric field associated with this pulse could disrupt the electric power system and cause massive power outages.

An EMP is generated when gamma rays interact with the atmosphere. As gamma rays propagate through the atmosphere, they knock electrons out of the air molecules. Earth's magnetic field forces the free electrons to spiral forward and thus radiate electromagnetic energy. This radiation from the spiraling electrons produces an intense EMP on Earth's surface.

An EMP is similar to the electromagnetic radiation produced by a stroke of lightning. The EMP electric field can rise as high as 50,000 V/m in less than 10 ns and decay to near zero after only 1 μs. Although very short, an EMP is billions of times more intense than an average radio signal.



A Compton electron is produced by the interaction of a gamma ray and an air molecule.



An intense radiated field is generated by the spiraling Compton electrons.

The intense fields associated with an EMP can cause surges similar to lightning surges in conductors. An EMP could induce surges in transmission and distribution circuits and in control and communication elements in electric power systems throughout the nation's grid. Such widespread disturbances could upset the stability of the electric power system and result in massive power failures. However, the extent and nature of EMP-caused damages in electric power systems is not well known.

Disruption of the nation's electric power supply has grave implications for our economic and social well-being. Financial, manufacturing, retail, transportation, and communication industries, as well as basic utilities, are highly dependent upon electrical power. As part of its goal of helping to make the nation's power systems more reliable, DOE's Electric Energy Systems Division is sponsoring research to assess the potential impacts of an EMP on the nation's electric power and to recommend protective measures to minimize disruptions.

The area of the United States affected by an electromagnetic pulse depends on the altitude (HOB, or height of burst) of the nuclear detonation: The higher the altitude, the greater the area of coverage.

ORNL has the lead role in managing DOE's research activities and providing technical guidance to DOE subcontractors conducting studies on the impacts of EMP on power systems. Paul R. Barnes and Ben McConnell of the Energy Division are developing a method for assessing the vulnerability of the nation's power systems to EMP and have characterized EMP-induced surges. In collaboration with a subcontractor firm, they have determined that (1) surges induced in overhead transmission and distribution lines by EMP (0 to 50 ns) for early times and (2) for transmission lines the peak amplitude per phase is several kiloamperes and the peak rate of rise is about 160 kA/μs.

The fast rise may have important consequences. Surge energy may couple by mutual capacitance and inductance to instrumentation and control circuits. Sensitive solid-state electronic components in these circuits could be upset or damaged. Also, insulation systems used in major components, such as transformers, may be damaged by a fast surge. While the effect of a surge is difficult to assess, insulating materials could apparently break down under steep-front, short-duration pulses of adequate intensity. Experimental data are needed to further quantify this behavior. Impurities or prior damage may provide additional breakdown mechanisms that effectively reduce breakdown times. This effect may be especially common in liquid insulation. Damaged insulation could cause immediate or delayed failure in transformers and other components, interrupting the delivery of power to businesses and homes.

Westinghouse Electric Corporation, an ORNL subcontractor, is developing a method for assessing the vulnerability of the nation's power systems to EMP. This method will employ a systems analysis approach that statistically includes the effects of EMP on the system components and, consequently, on the system as a whole. Westinghouse will assess the effects of EMP on the transmission, distribution, communications, controls, and generation subsystems as well as on load flow, load shedding, and the stability of the nation's electric power grid.

ORNL Helps with National Electric Reliability Study

In the 1983 book *Electricity*, written by Bill Sims of the Tennessee Valley Authority and illustrated by the well-known artist David Macaulay, this story is told: "When Thomas Edison died in 1931, someone suggested to President Herbert Hoover that Americans might honor the inventor of the light bulb by turning off all of the country's electricity for one minute. Hoover considered the idea only a moment before rejecting it. He realized that to interrupt the supply for even 60 seconds could be disastrous."

Today we flip switches, push buttons, and take electricity for granted. We expect our electric system to be reliable, to serve us without any interruption. Yet power system reliability in the United States is not perfect, and we are still trying to find ways to improve it.

Five years ago DOE, in consultation with the Federal Energy Regulatory Commission, was required by the Public Utility Regulatory Policies Act of 1978 (PURPA) to study and provide Congress with answers to three basic issues regarding power system reliability: (1) the level of reliability appropriate to adequately serve the needs of electric consumers, taking into account cost and the need to conserve energy, (2) the various methods available to achieve such a level of reliability and the cost-effectiveness of such methods, and (3) the kinds and cost-effectiveness of procedures that might be used in case of an emergency outage to minimize its disruption and economic loss to the public.

Because of the experience of some ORNL researchers with power system reliability and planning methods, DOE asked ORNL for assistance with the National Electric Reliability Study. ORNL researchers and subcontractors, under the project management of Mike Kuliasha of the Engineering Technology Division, performed the study and assisted DOE in preparing the report to Congress.

The study addressed the three major issues raised in PURPA by examining the costs to consumers of electricity supply interruptions and shortages and the costs to utilities of avoiding those interruptions and shortages. The appropriate level of reliability was deemed to be that level at which total consumer costs, including both supply and outage expenses, are at a minimum.

In the process of the study, ORNL researchers developed new procedures for including consumer interruption costs in power system reliability calculations. The resulting PICES computer code is now used by several utilities.

Among the conclusions of the studies were the following:

• Consideration of total consumer costs showed that generation system reserve margins significantly higher than present values are appropriate for many regions of the country. This is because the high cost of oil makes it economic to replace older oil-fired generation with lower cost coal and nuclear generation. As new generation is installed, each utility's planning reserve margin temporarily increases until older generating units are retired. Even in those regions of the country not heavily dependent on oil, the consequences of interruptions were not judged a significant factor in determining the appropriate level of generation system reliability. Over the range of reliabilities found to be economic on the basis of supply costs alone, expected consumer interruption costs were less than 10% of the supply costs.

• The greatest opportunities for improvement in power system reliability were found in the transmission and distribution systems, not in the generation system.

• Current state and local plans for mitigating the consequences of electricity interruptions were found to be inadequate. However, ORNL researchers identified and described a number of steps that governments, businesses, and consumers could take to greatly reduce the consequences of interruptions. For example, governments could develop a blackout response plan, which designates responsibilities and outlines steps to maintain critical services in the event of a major interruption. Businesses can use auxiliary power supplies to protect critical equipment such as computers. Consumers can greatly reduce the inconveniences of an interruption by having on hand a variety of household and outdoor recreational items that can serve as alternate sources of heat, light, food, and communication.

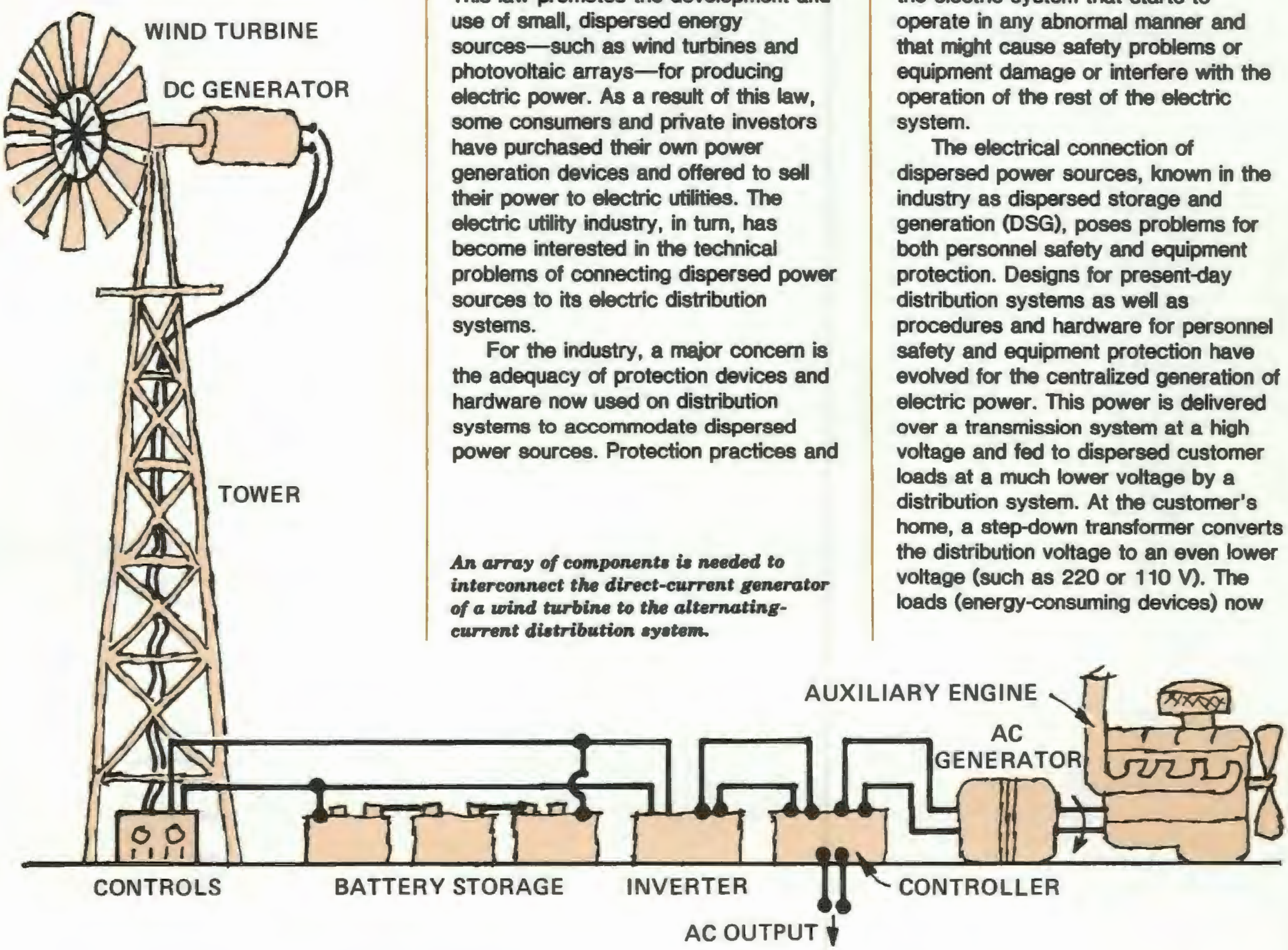
President Hoover would probably have approved of these ideas for reducing the likelihood of a disaster from interrupted electrical supplies.

ORNL Studies Protection Needs for Small Dispersed Power Sources

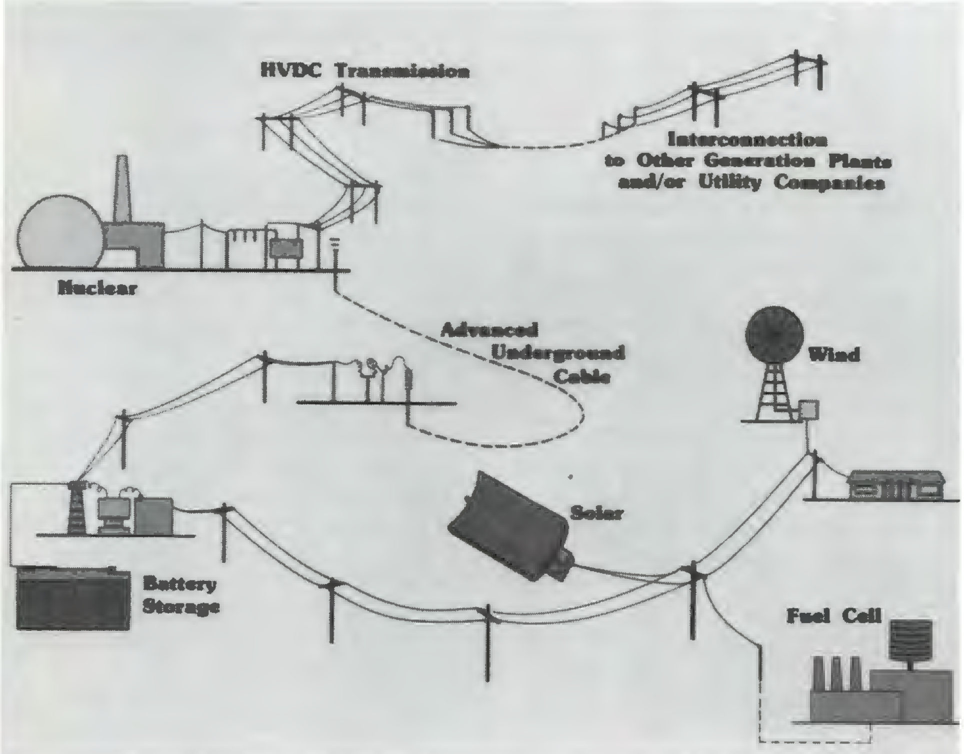
To encourage greater energy production from renewable sources, Congress passed the Public Utility Regulatory Policies Act of 1978. This law promotes the development and use of small, dispersed energy sources—such as wind turbines and photovoltaic arrays—for producing electric power. As a result of this law, some consumers and private investors have purchased their own power generation devices and offered to sell their power to electric utilities. The electric utility industry, in turn, has become interested in the technical problems of connecting dispersed power sources to its electric distribution systems.

For the industry, a major concern is the adequacy of protection devices and hardware now used on distribution systems to accommodate dispersed power sources. Protection practices and hardware provide for the prompt removal from service of any element of the electric system that starts to operate in any abnormal manner and that might cause safety problems or equipment damage or interfere with the operation of the rest of the electric system.

The electrical connection of dispersed power sources, known in the industry as dispersed storage and generation (DSG), poses problems for both personnel safety and equipment protection. Designs for present-day distribution systems as well as procedures and hardware for personnel safety and equipment protection have evolved for the centralized generation of electric power. This power is delivered over a transmission system at a high voltage and fed to dispersed customer loads at a much lower voltage by a distribution system. At the customer's home, a step-down transformer converts the distribution voltage to an even lower voltage (such as 220 or 110 V). The loads (energy-consuming devices) now



An array of components is needed to interconnect the direct-current generator of a wind turbine to the alternating-current distribution system.



Examples of dispersed storage and generation interconnections are the wind turbine, fuel cell, and solar array shown here. These dispersed small power sources can supply electricity to large electric distribution systems.

supplied by electric utilities are generally not capable of also supplying electric power to the distribution system.

However, DSG devices are capable of not only consuming power but also feeding electric power to other parts of the distribution system. As a result, safety practices and hardware and equipment protection schemes and hardware now in use may be affected by the location and capacity of the DSG devices connected to the system.

To address the adequacy of present safety practices and protection procedures and hardware for distribution systems with DSG, Tom Rizy of ORNL's Energy Division, working with subcontractors McGraw-Edison, Systems Control, Inc., and General Electric Company, identified and analyzed potential safety and protection problems. Rizy is technical manager for the project.

Dispersed electric sources at a customer's site pose a new safety problem to utility repair workers. The problem is that these sources are capable of continuing to energize or reenergize a part of the distribution system that is under repair. Says Rizy, "Our study of personnel safety for distribution systems with DSG indicates that present safety standards, which require the manual deenergizing of sources of electric power in the distribution system, may be adequate with some modification. However, as the concentration of DSG devices in the electric system increases significantly, current manual procedures will greatly increase the cost and time required to maintain electric utility systems." Also, Rizy notes, the higher DSG penetration levels will increase the potential of safety hazards that could result if a DSG device continues to energize the system during repair. Because it will become increasingly difficult to use manual switching to deenergize a distribution system with many DSG devices, utilities are considering replacing manual switching with automatic schemes. A control center and a two-way communication system may become a more practical and safer method for electric utilities to connect and disconnect DSG devices from the distribution system for maintenance and emergencies.

ORNL was asked to lead a study of the functional requirements of such proposed automatic schemes. Rizy and his colleagues concluded that, for these schemes to be economical, they will probably have to provide additional automation functions that can be implemented to improve the operation and efficiency of the electric power system, such as monitoring and controlling customer loads and distribution equipment. Finally, automatic schemes must be designed to meet the safety standards set by the federal government and the electric utility industry.

To study the problem of equipment protection, Rizy and his colleagues used digital computer programs and models to simulate the effects of DSG devices on the operation of distribution systems during abnormal occurrences such as three-phase faults (as when a tree falls across three distribution lines), DSG islanding (isolation of a DSG from the rest of the electric system by a broken connection), and resonant overvoltages. They found that electric utilities can accommodate low concentrations of DSG devices by making the protection changes necessary for each specific DSG installation.

Says Rizy: "If the concentration, or penetration level, of DSG devices is kept low, most potential protection problems can be corrected or avoided by minor hardware changes without requiring sophisticated control schemes. In addition, we determined that a special protection package for small and medium-size DSG installations is needed to reduce the cost and simplify the connection of DSG devices to electric systems.

"In the long term," he continues, "as the concentration of both small- and large-capacity DSG devices connected to the electric system increases, greater communications and control of protection hardware and DSG devices will be required. The system will need to be flexible so that it can be applied for different loading and generation situations."

Power System Information Management Could Increase Efficiency

Recent dramatic improvements in computer technology now make it feasible to extend and adapt computer-aided information management techniques to power systems. These improvements come at an appropriate time because the U.S. power system faces a number of developments that make efficient and reliable operation an increasingly complex task. These developments include regional planning and operations, increased regulatory and environmental constraints, customer-owned generation, and the emergence of conservation and demand management programs. Advanced power system information management (PSIM) capabilities will be required to meet these challenges while maintaining and improving system reliability and efficiency.

Measuring a power system's voltage, current, and frequency and retrieving, storing, controlling, and intelligently using this information are the goal of a DOE program that may receive funding in fiscal year 1985. This program will examine currently available information-handling technologies and advanced techniques now under development. These PSIM technologies encompass advanced measurement and data-base management concepts, information processing, communications, computer-aided design, large-scale system control and decision support, and artificial intelligence ("expert") systems.

The DOE program aims at developing new PSIM technologies that can improve power system reliability and efficiency through (1) more effective control of large, complex power systems, (2) new concepts for design of more reliable and cost-effective networks, and (3) integration of advanced generation and load management technologies.

How might new PSIM technologies help utilities? Advances in distributed data base design, for example, will allow the utility operating controls to react more quickly to local conditions, such as a hot spot in a transformer, and provide consistent, accurate information for decision making, such as deciding where to shift the load from the transformer in trouble. In addition, the development of "expert" systems will enable system operators to better react to emergency situations such as a major power failure.

Under the direction of John Stovall of the Energy Division, ORNL researchers have prepared a PSIM program plan for DOE's Electric Energy Systems Division. When funding is allocated to this program later this year, ORNL will implement the plan.

New Procedures May Blow Away Problems of Wind Power

One renewable source of electricity of interest to power companies is wind. To harness wind energy for use by power customers, arrays (or "farms") of megawatt-size wind turbines will be connected to the utility grid. An array may contain tens or even hundreds of individual wind turbines with a combined power generation capacity of up to several hundred megawatts—roughly equal to that of a moderate-size conventional power plant. Designing, operating, and connecting wind-turbine arrays to the utility grid, however, pose several technical problems. These problems have been addressed in three projects recently conducted for ORNL's Power Systems Technology Program under the technical direction of Paul R. Barnes.

The first project focused on linking the wind-turbine array with the control power system. Designing the interconnection for a large array, containing numerous individual wind turbines, is much more complex than designing a conventional power plant, which has only a few individual units. Interconnection equipment includes the transmission lines, transformers, circuit breakers, and switches necessary to collect and transmit the power generated by the array and to protect the individual wind turbines from damage following electrical disturbances. Zaininger Engineering Company, an ORNL subcontractor, developed an assessment method to evaluate alternative designs for the interconnection of the wind-turbine array with the power system.

Zaininger's assessment method took into account site characteristics, wind-turbine characteristics, wind-turbine spacing, equipment costs, reliability data, and the candidate interconnection designs. The output of the procedure is the present worth of the revenue (including the cost of borrowing money) needed to purchase and install the equipment and the fraction of wind turbines expected to be available at any time for each candidate design. The method will allow utility system planners to develop interconnection designs that meet their cost and reliability targets.

The second project comprises two studies that addressed the development of system operating procedures for utilities with large wind-turbine arrays. Conventional generating units are operated in a "load-following mode" in which the total output from all on-line generating units is continuously adjusted to match the total system load—that is, total demand for power. Generation-load balance is achieved by a closed-loop automatic generation control (AGC) system, which also performs economic dispatching to shift power loads to maximize power generation efficiency. The AGC system of a utility with a large wind-turbine array will face more difficulties in

In the mid-1970s the U. S. Energy Research and Development Administration and the National Aeronautics and Space Administration built this 100-kW experimental wind turbine at Plum Brook Station in Sandusky, Ohio. It has provided electricity to the Ohio Edison Company power system.

maintaining a match between generation and load because of fluctuations in array power output due to variations in the wind.

A major concern is that wind-induced variations in the array power output will cause excessive ramping (sudden increases and decreases in power output) of conventional generation, resulting in degraded performance of the AGC system unless the short-term load-following capability of the conventional generating units is increased. A utility can increase its short-term load-following capability by altering the system's unit commitment (equipment placed in service) and by economic dispatching to shift loads from efficient but slow-responding units (such as nuclear and large coal-fired plants) to less efficient but fast-responding regulating units (such as oil-fired turbines). Thus one effect of increasing the load-following capability is an increased cost of energy production from conventional units—a cost increase that must be applied against the value of wind generation.

For one part of this project, Michigan State University (MSU) developed a unit commitment procedure for utilities with large arrays. It selects from the available generating equipment the specific units that will be used to meet the forecasted system load over the next one to three days. Equipment commitment decisions are made by an optimization computer program whose inputs include plant startup and shutdown costs, fuel cost and efficiency, unit maintenance needs, and generation ramp rate. The output of the program is a mix of generating equipment that will allow the AGC system to reliably follow long-term (hour-to-hour) and short-term (minute-to-minute) load variations while minimizing the cost of electricity production.

Because power output from a wind-turbine array cannot be accurately forecast over the one- to three-day time horizon used in conventional unit commitment procedures, the MSU researchers developed a modified technique that updates the utility's unit commitment in three time frames—24, 1, and 0.25 h. The hourly and quarter-hourly updates allow a utility the flexibility of fine-tuning the unit commitment as more accurate forecasts of power from wind-turbine arrays become available.

The other part of the project, conducted for ORNL by General Electric (GE) Company, developed two control strategies to compensate for variations in array power. Both strategies make use of short-term (10-min) prediction of the maximum available array power. The simpler strategy, called feedforward control, accepts the unregulated output of the array while manipulating the output of selected conventional units. The use of short-term wind power prediction in the feedforward control provides more time for the conventional regulators to respond to array output changes and reduces the ramp rate requirements on the regulators.

The second strategy, called closed-loop array control, reduces the magnitude and rate of change of array power by coordinated control of the blade pitch angle mechanisms of the wind turbines within the array. The blades of each wind turbine are slightly feathered to spill some power available into the wind. Operating the array at less than the maximum possible output allows the array power to be held fairly constant as the wind varies. For example, if the wind decreases, the degree of blade feathering can be reduced to maintain the target power output from the array.

GE's simulations of these control strategies indicate that adequate AGC system performance can be maintained for utility systems with up to 20% of their generation from wind power.

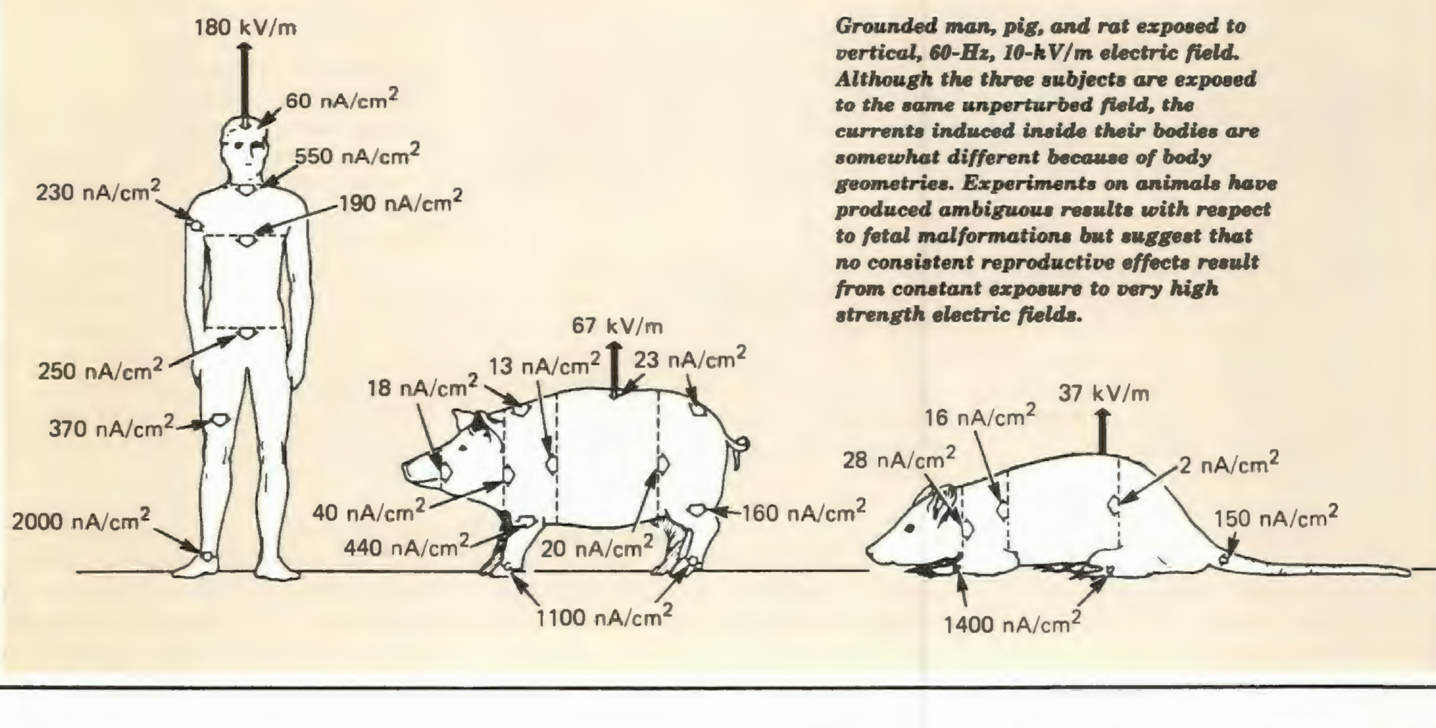
The results of these studies will point the way for utilities to reduce the technical problems of designing large wind-turbine arrays without sacrificing the economic benefits derived from producing power by wind energy.

Potential Health Effects May Be Associated With Electric Fields from High-Voltage Power Lines

During the past decade, public concern has grown over possible safety and health hazards of exposure to electromagnetic radiation produced by high-voltage transmission lines. People have worried about safety and environmental hazards, such as electric shock, audible noise, and radio and television interference, and have suspected that electric fields might cause subtle health effects such as disturbances of the nervous system. These concerns have more recently resulted in delays and possible cancellation of new high-voltage transmission systems. In an effort to understand potential health effects, DOE (and its predecessor the Energy Research and Development Administration) has sponsored biological research since 1975.

In 1982 DOE's Division of Electric Energy Systems asked ORNL's Health and Safety Research Division to evaluate the data accumulated by the biological research program and to address the question of which health risk analyses were appropriate for these data. ORNL researchers Clay Easterly, Eugena Calle, Phil Walsh, Tim Aldrich, and Emily Copenhaver of the Health Effects and Epidemiology Group therefore began a systematic review of the literature.

According to their findings, most of the data are negative—that is, few responses to electric field exposures had been detected. In addition, those that had been detected were usually for subanimal systems (cells and tissues) and cannot easily be linked to any serious human health effect. Thus



Grounded man, pig, and rat exposed to vertical, 60-Hz, 10-kV/m electric field. Although the three subjects are exposed to the same unperturbed field, the currents induced inside their bodies are somewhat different because of body geometries. Experiments on animals have produced ambiguous results with respect to fetal malformations but suggest that no consistent reproductive effects result from constant exposure to very high strength electric fields.

normal health risk studies, which focus on causes of cancer, birth defects, and reduced reproduction rates, seem to be out of the question. Finally, exposure conditions had nearly always been limited to electric fields with a constant 60 Hz and no magnetic component. Such 60-Hz field conditions do not simulate normal human exposures very well.

Studies had also been conducted on the effects of these electric fields—the strongest man-made fields in the environment—on the growth and productivity of trees, crops, and laboratory plants. Virtually no appreciable effects had been found, except for necrosis (localized death in living tissue) of leaf and needle tips.

To deal with the diversity of biological systems studied and biological effects possibly detected, the ORNL researchers adopted a very general health risk approach: to compare effects from the electric field exposures with similar effects caused by more common and well-characterized agents. For example, they could see whether biological effects from one electric field experiment were similar to effects produced by a constant level of 200 ppm of caffeine in the blood. By comparing many different biological effects and different levels of biological organization (e.g., cell, organ, animal), the ORNL researchers hope to obtain a reasonable picture of possible ranges of health effects from electric fields.

Unfortunately when the study began, only two experiments that were useful for application to the risk methodology and that showed effects gave reproducible results. A greater number of experimental designs were earlier thought to be useful, but they failed to produce similar results in replicated experiments and could not be included in the analysis.

Experiments on honeybees sponsored by the Electric Power Research Institute did yield a detectable response. The experiments showed that bees in hives exposed to the highest field strength had the least weight gain and the lowest rate of reproduction compared with bees subjected to lower strength electric fields or none at all. By designing the hives to eliminate possible electric shocks to bees, however, the detrimental effects of the electric fields were eliminated. How these effects relate to humans is unclear.

The obvious next step is to examine the many experiments that failed to produce detectable responses. The group this year is determining what can and cannot be said about health effects based on negative data.

In addition to development of health risk methods, the group will begin epidemiological studies. Their first task will be to prepare a methods document outlining types of studies that could be conducted to determine possible long-term effects of electric fields on humans. Along with methods descriptions will be discussions on data sources and reliability, costs, and possible strengths of analyses. The primary use of this document will be to aid electric utility managers in making informed decisions about sponsoring epidemiological studies.

Plans Are Under Way for High-Voltage Direct-Current Systems

The first electrical system in the world was the Pearl Street Station in New York City. Built by Thomas Alva Edison in 1882, the station supplied electricity in the form of direct current (dc) to illuminate lights and run motors. The dc power systems like Pearl Street Station flourished in the 1880s and 1890s. However, the further development of dc systems was interrupted because, to meet the rising demand for power, utilities had to transmit electricity to cities and towns from distant generators. Unfortunately dc cannot be generated at a high voltage. The dc generators were limited to producing current at several hundred volts, so large currents and large expensive copper conductors would have been required to deliver large amounts of power over a long distance. Furthermore, there was no feasible method of raising the voltage and lowering the current to a usable level. Because of these disadvantages, dc power systems declined at the turn of the century and alternating current (ac) systems rose in their place.

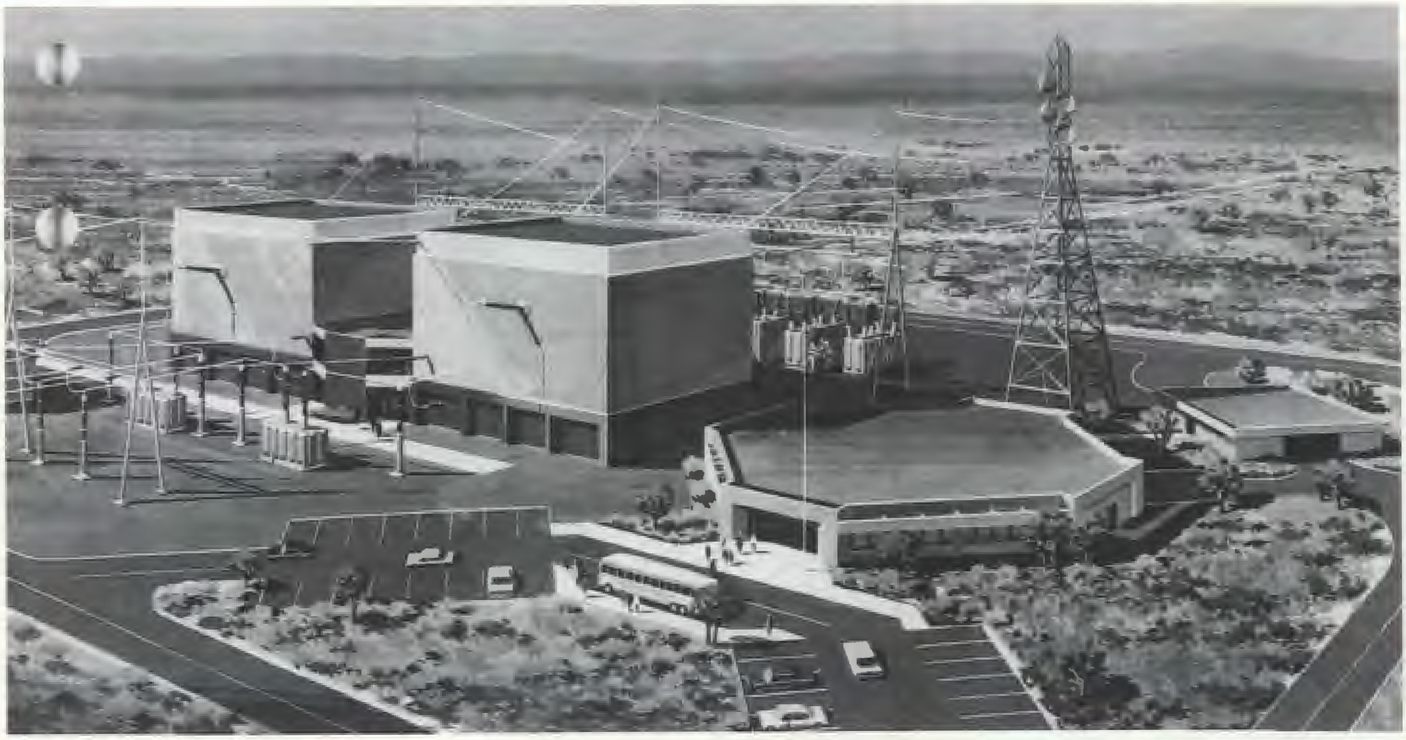
Unlike dc systems, ac systems use transformers to convert low voltages produced by generating stations to high voltages for the long-distance transmission of electrical energy. Then power transformers lower the voltage for distribution and use by customers. The current decreases for a given amount of power as the voltage increases, so the conductor required is smaller and less expensive in high-voltage ac systems. Because of their ability to operate with inexpensive conductors and to change voltage levels, ac systems continue to flourish.

Today dc systems are making a comeback. Their resurgence is due to two driving factors: (1) technology has been developed to convert high-voltage alternating current (HVAC) to high-voltage direct current (HVDC) and (2) HVDC systems can provide economical transfer of electric energy.

The inability of dc systems to convert from low to high voltages is overcome by using the ac system to raise the voltage level and then using a converter station to change the HVAC to HVDC. The power can then be transmitted via an HVDC transmission line. At the other end of the dc line, another converter station transforms the current from dc to ac.

The heart of the converter station is the thyristor, a silicon-based semiconductor device that acts as an on-off switch. The power-carrying capabilities of this device have increased significantly during the past decade and have greatly improved the overall economics of HVDC systems in comparison with HVAC. State-of-the-art thyristors can carry 1500 A at 4000 V. However, at this power level, several hundred thyristors must be connected in series and parallel combinations because a typical converter station operates at about 400,000 V and 1000 to 2000 MW.

Thanks to converter stations, HVDC systems have two unique features that give them advantages over HVAC systems. First, HVDC systems can control the direction and magnitude of the electrical energy flowing in the dc

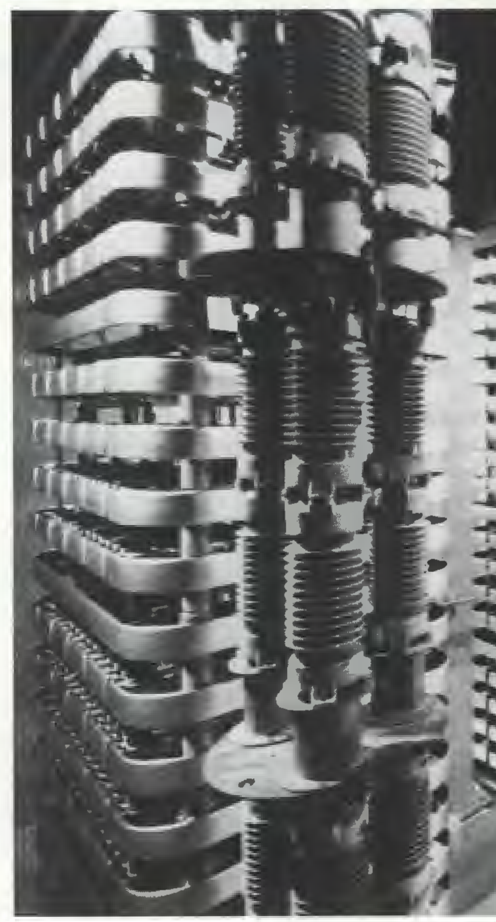


line between the two converter stations. Second, the dc converters and line act as a buffer between the two connected ac systems. This buffering allows two ac systems with dissimilar electric characteristics to be interconnected to exchange electrical energy.

The other influencing factor leading to reexamination of HVDC transmission by utilities is the uncertainty associated with construction of new generating facilities. This uncertainty encompasses unknowns about future environmental rules, electric utility regulations, energy demands, and the financial impact of a changing economy and regulatory climate. As an alternative to installing new generating capacity, utilities are trying to best use existing capacity by transferring electrical energy from one region of the United States to another.

For example, electric utility systems in the northern region of the country that have excess generating capacity in the summer but use all their available capacity to meet peak demands during the winter heating season need the capability to transmit power to (or obtain power from) another region of the country. A region in the South might have the reverse problem: It has excess generating capacity in the winter but needs to supplement its generating capacity in the summer to meet peak demands for air conditioning. HVDC transmission offers an ideal method to transfer electrical energy between regions that are far apart and have different needs.

Artist's impression of one of the converter stations for the Intermountain Project, which will pump power by direct-current transmission to California from an alternating-current system in Utah. The 1000-kV, 805-km (500-mile) transmission line, which is to be installed and operating by 1986, will deliver 1600 MW to Los Angeles.

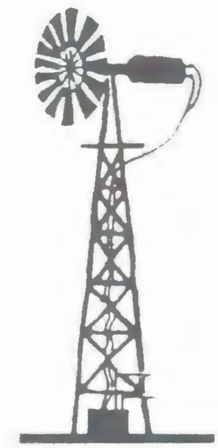


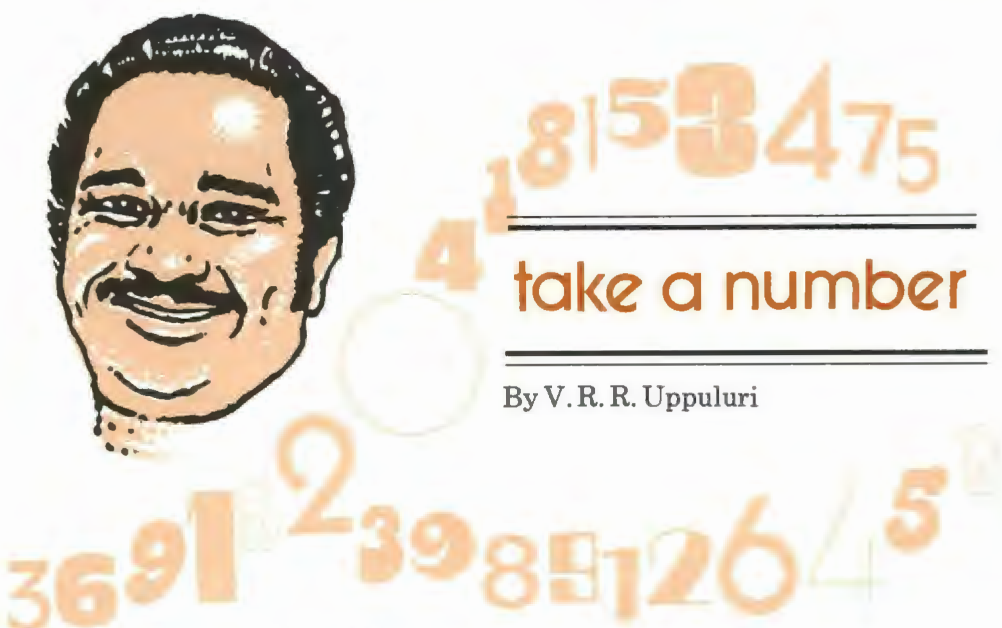
Thyristor valve hull of the Itaipu direct-current transmission project in Brazil. Each of the four water-cooled valves contains 384 thyristors.

In response to the renewed interest in HVDC systems, DOE's Electric Energy Systems Division has developed an HVDC research and development (R&D) program plan with the help of ORNL staff members led by John Stovall. The overall goal of the R&D program is to provide the electric utility industry with HVDC alternatives that can be compared with the HVAC options when designing or modifying power systems.

The research objectives of the HVDC program plan are to (1) develop a fundamental understanding of the interactions and economics of HVDC and HVAC systems, (2) determine various methods and schemes for the transfer of large amounts of power, (3) investigate the feasibility of using HVDC transmission to deliver power to high-density urban areas with heavy demands for electricity, and (4) develop HVDC components and systems such as new and better switching devices to replace the thyristor.

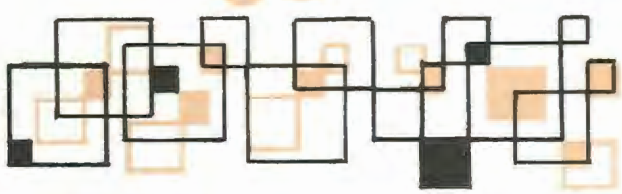
Although HVDC systems show promise for connecting ac power networks and deferring the need for more generation capacity, the consensus of ORNL and DOE experts is that money for this research will have to come from the federal government. Because the private sector probably will not invest in the development of HVDC power transmission and delivery systems and associated dc components, DOE is planning to fund development work to expedite the return of dc systems. ornl





take a number

By V. R. R. Uppuluri



Not Too Many Squares

The numbers 16 (= 4^2) and 9 (= 3^2) are perfect squares. Interestingly, $2^m + 3^n$ is a perfect square if and only if $m = 4$ and $n = 2$. Assume that m and n can be any natural number (i.e., any positive integer: 1, 2, 3, 4, 5, . . .). For all other values of m and n, $2^m + 3^n$ cannot be a perfect square.

Series Representation

$1/7 = 7 \times [(0.02) + (0.02)^2 + (0.02)^3 + \ldots]$

$1/3 = 3 \times [(0.1) + (0.1)^2 + (0.1)^3 + \ldots]$

$1/2 = 2 \times [(0.2) + (0.2)^2 + (0.2)^3 + \ldots]$

$1/1 = 1 \times [(0.5) + (0.5)^2 + (0.5)^3 + \ldots]$

Except for 1, 2, 3, and 7, this type of representation is impossible for all natural numbers. Although the proof is not easy, this observation may be verified by a computer.

This 1924 photo shows the high school in Wheat, one of four small communities on the Reservation prior to World War II. Today this site, located about 1.6 km (1 mile) east of Oak Ridge Gaseous Diffusion Plant, is completely forested. Right, the main complex of ORNL.

The Oak Ridge Environment:

By THOMAS W. OAKES, HELEN M. BRAUNSTEIN, and J. THOMAS KITCHINGS

In August 1982 a committee was assembled to develop a plan for managing the resources of the Oak Ridge Reservation of the U.S. Department of Energy. The committee was formed in keeping with DOE's desire to treat the entire Reservation as a single entity rather than as three separate units incidentally connected by their proximity to one another. The resources to be considered included the Reservation's forests, streams, and wildlife as well as those resources serving technical research and production facilities. The committee first identified all the Reservation's resources and then located a set of experts for each resource. Each set of experts assembled a working group to develop a management plan for that resource. When all the individual resource management plans had been formulated and an overall plan had been drafted, the committee then framed a charter for a Reservation-wide resource management organization to implement the plan.

To be effective, the organization needed a structure that would allow it to interact with all components of management that participate in planning activities: DOE, contractor management, and managers at the three major facilities—Oak Ridge National Laboratory, Oak Ridge Gaseous Diffusion Plant (ORGDP) and the Y-12 Plant. By the end of 1983, a 17-volume resource management plan had been prepared and the machinery for an operating Reservation Resource Management organization had been designed, approved, and set in motion. In little over a year 35 people, from disciplines as widely separated as utilities engineering and aquatic ecology, had worked together to create a resource management plan, using a relatively new discipline based on a blending of old ideas in new packages and new ideas in old packages (see box on pages 64–65).

The Oak Ridge Reservation

In comparison with other public lands, the Oak Ridge Reservation is no more than a postage-stamp-size parcel. Of the 930 million ha (2.3 billion acres) of land in the United States, almost 40% is publicly owned, and 83% of that, or

A Resource to be Managed

300 million ha (740 million acres), is federally owned. With its 15,000 ha (37,000 acres), then, the Oak Ridge Reservation constitutes only 0.005% of federally owned land; nevertheless, it is an area with interesting and unique resources.

The decision to prepare a plan for managing this parcel of federal land as a resource was motivated by a sense of its unique qualities. The term "resource" is usually applied either to an impressive gift of nature or to a great and irreplaceable work of human hands. The Oak Ridge Reservation is both. As a gift of nature, the Reservation is a microcosm of the natural resources of the eastern deciduous forest, and as a work of human beings, it represents a scientific and technical resource unavailable elsewhere in the world. The realization that the Reservation constituted an integration of two exceptional resource capabilities prompted the establishment in 1982 of the resource management committee and the subsequent development of the resource management plan.

Reservation History

When acquired by the U.S. Army Corps of Engineers for the Manhattan Project in 1942, the Oak Ridge Reservation was a typical portion of the ridge and valley section of eastern Tennessee. However, it was not a pristine area. It contained about 1000 individual land tracts complete with farmsteads, schools, churches, and communities.

In September 1942, shortly after the United States had become involved in World War II, the Oak Ridge site had been chosen for the production of fissionable material. Enriched uranium was produced electromagnetically at the Y-12 facility and, after the war, by gaseous diffusion at ORGDP. The graphite reactor at ORNL operated both during and after the war.

In 1947 the Atomic Energy Commission (AEC) was established to take charge of the U.S. nuclear-weapons program from the Army and to administer a new program for developing nuclear energy for additional peacetime applications. For the next 28 years, programs at Oak Ridge were generally oriented

Three species of owl, including the barred owl (Strix varia), *are common on the Reservation, and four others are occasional visitors.*

The Reservation is enclosed on three sides by the Clinch River, on the fourth side by a ridge. Other ridges within the Reservation form three parallel valleys, each of which contains one of the installations.

toward this single goal, the use of nuclear energy. In 1975 the AEC became the Energy Research and Development Administration (ERDA), and the mission of the agency began to expand to include considerations of other forms of energy use. In 1977 all the ERDA programs became a part of the newly created DOE. This department brought together many of the fragmented energy programs and offices created over the years within the federal government.

As the goals of the government agencies changed, the emphasis of nuclear research and production activities at the Oak Ridge facilities also changed; concomitantly, investigations into other energy technologies grew. The expansion of technology brought an increase in environmental and ecological research, and work at the Oak Ridge facilities took on, as a key interest, applications of ecological concepts to environmental problems. In time, environmental research and technological operations began to coexist on the Reservation, and the opportunity for coordinated management of these resources became apparent.

Reservation's Natural Resources

Located near the foot of the escarpment of the Cumberland Plateau, the Reservation is abundantly forested on the ridges and richly pastoral in the valleys. From the air, the Reservation blends into its surroundings. Alternating parallel ridges and valleys, characteristic of eastern Tennessee, give it a "banded" appearance; and a network of small streams, tributaries of the Clinch River, cut through it.

The river winds along the southern and western borders of the Reservation until it reaches Black Oak Ridge, which bounds the Reservation to the north and gives the area its name. These features afford a strong sense of enclosure while permitting distant views of the Great Smoky Mountains to the east and the Cumberland Plateau to the west.

The Reservation is roughly rectangular, 28 km (17.5 miles) long by about 9 km (5 miles) wide at its midpoint. The entire tract is within the city limits of Oak Ridge. The city, with a total area of almost 24,000 ha (nearly 59,000 acres), was, at its inception, one of the largest U.S. cities in land area.

The Reservation is located near the exact center of the country east of the Mississippi River and south of the Great Lakes. Physiographically it is within the region of ridges known as the "folded Appalachians," which were formed originally from sediments deposited in nearly horizontal layers during the Paleozoic era (200 million–600 million years ago). Late in the era, crustal movements caused the

During the past decade, the Reservation's deer herd has grown from 300 animals to 5000 or more.

faulting and folding of these compressed sediments. Subsequent weathering and erosion removed the less resistant strata, leaving ridges of compressed sandstone or cherty rocks. Also left were valleys of limestone, such as the Chickamauga Group, or of weathered shales from the Cambrian period, such as the Conasauga Group.

The Smoky Mountains to the southeast and the Cumberland Plateau to the west protect and moderate the area's climate. Severe storms such as tornadoes or high-velocity windstorms are rare, and the hot, dry, southerly winds associated with large, stable air masses known as "Bermuda highs" are diverted. The result is a mild, moist region where a cool northern temperate zone meets a hot southern humid zone. Plant and wildlife communities on the Reservation reflect this dichotomy. Some species, such as those on the western slopes of the ridges, are typical of the northern Appalachian Mountains, while others—sometimes on the opposite slope of the same ridge—are more representative of southern oak-pine forests. This meeting of northern

The ground pine (Lycopodium digitatum), *common on the Reservation, was once threatened because of its popularity as decorative greenery.*

and southern ecological range extensions provides the Reservation with a unique setting for plants and animals.

Technical and Scientific Resources

The technical facilities and projects on the Reservation constitute a formidable resource in land, buildings, equipment, utilities, people, and programs. The combined original cost of just the three primary facilities was $2.5 billion, which in today's dollars would be $7.7 billion. The replacement cost—if the facilities were replaceable—would be far higher. There are 623 major buildings with more than 2 million m^2 (23 million ft^2) of floor space. Current employment at the facilities exceeds 17,000 persons; the annual payroll is over $400 million.

Of the three major facilities, one is primarily production oriented (Y-12), one is research oriented (ORNL), and one combines production with research (ORGDP). The Y-12 Plant is a fully implemented industrial site: Underground utilities include raw and treated water, demineralized water, sanitary sewer, and natural gas; aboveground utilities include steam and condensate return, plant and instrument air, electrical power, industrial gases, and

East Fork Poplar Creek, the Reservation's major Clinch River tributary, is the major drainage system for the northern part of the Reservation. The box elder, willow, and sycamore forests along the banks of the creek are typical floodplain forest communities.

telephone lines. The plant's primary mission is producing nuclear weapons components, which involves fabricating various materials into components and producing subassemblies from some of the components. Because of its expertise and facilities for materials design and fabrication, Y-12 occasionally makes special products for other uses, including geologic sample boxes for the *Apollo* moon landings and highly reflective metal mirrors for applications ranging from fusion energy research to astronomy.

As a national laboratory, ORNL pursues missions determined by the nation's research needs. Areas of concentration include nuclear fission and fusion, life sciences, and basic science. ORNL has unique and rare facilities and resources such as reactors, heavy ion facilities, a National Environmental Research Park, and animal research capabilities. The Laboratory's major research facilities and programs are readily available to both university faculty and

More than half the Reservation is bordered by the Clinch River system, including Melton Hill and Watts Bar reservoirs.

Loblolly pines cover 2000 ha (5000 acres) of the Reservation. Most of the large trees were planted between 1947 and 1956, but planting continues today.

Caverns and sinkholes are common in the Reservation's dolomite and limestone ridges.

university students, who can use facilities and techniques during collaborative research training that would not otherwise be available to them.

ORGDP's primary function is the enrichment of uranium to provide fuel for nuclear reactors. The plant is one of the largest industrial facilities in the world, with over 70 ha (173 acres) under roof. Because enrichment by gaseous diffusion consumes large amounts of electricity, research programs are also under way at ORGDP to find a more energy-efficient process. As with the other two facilities, the technical talent, state-of-the-art computing equipment, abundant utility systems, and secure site make ORGDP a valuable technical and scientific resource for the nation.

From Taming to Managing: the Changing U.S. View of Resources

Throughout America's history, economic growth has been an overriding goal. The colonists cleared forests to grow crops that would guarantee their survival; with money from export crops like tobacco, they purchased the civilization they had left behind and bought tools to further tame the wilderness they found here. An unsettled wilderness was as much a challenge to them as an undeveloped dam site is to engineers today.

The stage was set very early, then, for an ethic dominated by the struggle to overcome and control the environment for personal and commercial gain. As a people, Americans have equated expansion and development with success, and success with survival. The drive for development was additionally fueled by the desire of individuals to better their own positions. Often the powers of government were influenced to support resource development if it improved the economic status of individuals.

Private ownership of land and of other resources has always rested upon public acceptance, as reflected in laws and customs; however, the rights and privileges of that ownership have been changeable. Similarly, publicly owned land has always existed in the United States, but the disposition of that land as a resource and the obligations associated with transferring that resource to private ownership have changed considerably within the past 15 years. These changes are largely a result of the passage of the National Environmental Policy Act of 1969 (NEPA).

America's rapid economic growth had usually meant exploitation and mismanagement of resources. NEPA, however, was a declaration of a new national policy calling for "harmony between man and his environment." This was a clear statement that the "taming" impulse, which had produced success and survival in the past, was becoming detrimental and

Sparrows are among the most common birds on the Reservation. They are drawn to the grassy and shrubby fields found mainly around the facilities.

Evolution of the Planning Process

Planning for management of the resources within the boundaries of a specific site or region has generally been confined to two contexts: national park resource management and urban zoning (or land-use planning). Both types of planning are highly directive, the first because it is derived from legislative action and the second

More than 200 km (125 miles) of powerlines carry electricity to the Reservation's facilities. Power consumption totals 500 MW, roughly equal to that of a city of 180,000 people.

because it is intended to control or direct development within cities. Rarely has resource management planning been applied by choice, and rarely has it been applied to an operating industrial site as diverse as the Oak Ridge Reservation.

The Oak Ridge National Environmental Research Park (NERP) includes about 5500 ha (13,500 acres). Shown here at the Park's boundary is Elizabeth Preston, author of the NERP management plan.

Fifteen different resources were defined and treated equally in management planning. Those resources are highlighted separately throughout the text.

threatened to create a serious clash between Americans and their resources. One purpose of the act was "to enrich the understanding of the ecological systems and natural resources important to the Nation," a goal that expresses a desire for the insight and comprehension necessary to arrive at a new arrangement or agreement between people and resources.

Under NEPA and a host of other laws passed during the next 12 years or so, it became clear that the total environment, including land, water, air, and all life forms, constituted a common resource, a public trust. The public was demanding that the resource be protected no matter who owned it or what development incentive existed. The pioneer standards, which had abolished scarcity and ensured survival, were no longer serving the nation.

This new awareness of the need to protect the environment and conserve resources led eventually to the emergence of new ideas regarding resource management. Environmental management had evolved amid serious concerns about the deleterious environmental effects of human activities. As environmentalists strove to correct the results of past practices, they also focused their attention on halting current activities they considered environmentally harmful. This attitude established the turbulent atmosphere within which the discipline of environmental management developed. Resource management, on the other hand, had its beginnings in early conservation movements and was concerned largely with the future, that is, with preservation and conservation.

As both management technologies matured, they grew together. Scientists assumed a more future-oriented planning perspective, and resource managers substituted multiple-use concepts for static preservation. The common goal they now share is planned management for future use of America's resources.

Jim Loar of the Environmental Sciences Division headed the study of the Reservation's aquatic habitats.

Sandy Sanders, author of the archeological plan, on the porch of the Freels cabin, one of the best-preserved historical structures on the Reservation.

Pat Parr of the Environmental Sciences Division, shown here with a specimen of blue lobelia (Lobelia siphilitica), *authored the endangered plants plan.*

Aquatic habitats—tailwaters, impoundments, reservoir embayments, large and small streams, wetlands, and floodplains—support a wide-ranging and varied assemblage of aquatic plants and animals on the Reservation. In managing these habitats, the first need is to provide habitat for any threatened or endangered aquatic species within the Reservation; the second is to maintain the valuable diversity of aquatic habitats on or contiguous with the Reservation.

Past resource-management efforts on the Reservation centered on three broad areas:
(1) DOE land-use needs, including those pertaining to expansion and development of the three major facilities; (2) forest management; and (3) an environmental-research-park program. Activities ranged from harvesting timber in areas marked for facility expansion to the creation of a computerized resource-data system. Many needs were short term and required a rapid response with a minimum of advance planning (e.g., clearing a road to a new facility or cutting timber in response to pine-beetle infestation). Other needs, such as maintenance of forest diversity, required longer-range planning.

Archeological considerations date back 10,000 years, to the area's first occupation by native Americans. Numerous aboriginal and early historic Euroamerican homestead sites exist on the Reservation: 1 aboriginal site is classified in the Paleo-Indian period (6000–10,000 years ago), 8 in the Archaic period (2000–6000 years ago), 24 in the Woodland period (1000–2000 years ago), and 5 during the Mississippi period (300–1000 years ago). These sites are distributed along the Clinch River drainage system, mostly beside the main stream. Management of these early sites, as well as the later homestead structures and cemeteries that remain, calls for identification of historic sites and for consideration of their protection during land-use planning.

The first resource management plan, written in 1965, was for only the Reservation's forest resources. The next was not formulated until 1975, when the first Oak Ridge Reservation Land-Use Plan was published as a basis for current and projected DOE program requirements. In considering how to meet DOE's technological requirements, this plan also recognized the value of multiple uses of land. Unique biological areas, lands containing rare and endangered species, and safety zones for protecting human and environmental health were regarded as areas that should be protected and maintained. In 1980 DOE updated and revised this plan.

Endangered and threatened plant species on the Reservation include 14 species on the official Tennessee list of endangered and threatened plants. Their locations are widespread. Protection of these species, which requires only native habitat preservation, is a continuing management responsibility, easily overlooked in the haste that sometimes accompanies major program and land-use decisions.

Also in 1980 DOE established a

Karen Daniels of the Environmental and Occupational Safety Division, author of the environmental management plan, shown here at a groundwater monitoring well near ORNL's New Hydrofracture Facility.

Carl Petrich of ORNL's Energy Division and Jim Hines of the University of Tennessee pore over maps they used in the plan for geography, demography, topography, and soils.

Forest management plan chairman Dennis Bradburn, right, and Everett Rosenbalm at a sycamore plantation in the southwest portion of the Reservation.

Geology can enhance or limit the use of the Reservation's land, so management is oriented toward establishing a data or information system that will provide basic information on the origin, composition, location, and structural configurations of the main geologic units of the Reservation. Another aim is to identify resources of industrial minerals such as quarry rock and clay present on the Reservation.

National Environmental Research Park (NERP) on the Reservation, as an expansion of the research-park program that had existed since 1975, and a management plan for the NERP was developed. This program interacted with forest management in identifying unusual or threatened plant communities and removing the areas containing these communities from the timber-harvesting program.

These and other planning groups dealt with each other on a fairly informal, ad hoc basis, an arrangement that was satisfactory as long as additional demands on

Geography, demography, topography, and soils are the focus of an automatic geographic information system begun in late 1983. The system is based on digitization of maps and other geographic data, storage and retrieval of data, analysis and integration of data bases, and graphic displays of results.

the Reservation land were minimal. In the late 1970s, however, as user demands increased—for facility expansion, research sites, and construction of new technological industries—conflicts over land use became more common. These conflicts threatened to undermine the DOE concept of multiple use of the Reservation's resources. In response, DOE's Oak Ridge Operations Office and Martin Marietta Energy Systems, Inc., established a resource management organization as a means for assisting future decisions about land and resource utilization. Through this organization, all plans, forest management, the NERP, land use, and site

Wildlife management on the Reservation is new, although ecological research involving some wildlife species has been done in the past. The management plan is addressing problems such as overpopulation of white-tailed deer, poaching of species on Reservation lands, and lack of information on threatened or endangered animal species. A need exists for estimating the resident wildlife population, for including wildlife in all planning efforts, and for dealing with specific wildlife concerns as soon as they arise.

development would be integrated into a Reservation Resource Management Plan.

Policy for Resource Management

The first Resource Management Committee was well aware of the years of discussion that had preceded the emergence of this management outlook; it also recognized the antagonism with

Hydrology, in the humid environment of the Reservation, has a major influence on the mobility and fate of contaminants as well as on the functioning of natural ecosystem processes. Major uses of the hydrologic system, and ones that affect water quality, include assimilating radioactive and nonradioactive waste and supplying water for facility operations. Although very little on-site water is actually used, whatever is used requires protection with regard to both quality and quantity.

which environmental and resource-oriented persons often regarded technical or industrial growth. Therefore, to overcome previous notions or biases and to include all of the resource potential at Oak Ridge in the plan, the group set forth a policy to govern the organization's inception, development, and function. The policy, given below, has been accepted by DOE, the operating contractor, and the senior managers at each of the three major Reservation facilities.

The Oak Ridge Reservation constitutes an important physical, fiscal, and natural resource for the nation, the Department of Energy, and the operating contractor. To assist continued effective and efficient operation of the site facilities and to plan for long-term use, development, and maintenance of the Reservation resources, a Resource Management Plan has been adopted and a permanent resource management organization has been established, acknowledging resource management as a necessary system for major site programmatic and operational planning and decision making.

Planning was considered essential both for managing current activities and for expanding in new directions. It was intended to provide a means for meeting engineering expectations within a socially, environmentally, and esthetically favorable atmosphere.

Resource Selection and Grouping

The long-term goal for managing the resources of the Reservation involved maintaining an equilibrium between the desire for conservation and preservation of all resources and a need for fulfilling operational expectations that required the consumption of some resources. To meet that long-term goal, the appointed group assumed that the Reservation's resources could, and should, support multiple uses. As a reflection of the group's broad view of what constituted a resource, 15 different resources—not just traditional natural resources—were defined and treated equally in management planning. Each resource was assigned a set of experts charged with developing a management plan for that resource.

Two kinds of resource management were identified—active and passive. In active management, a resource is manipulated or modified to achieve a definable goal; usually the goal is something other than conservation or preservation, but it is not necessarily in conflict with them (e.g., timber harvesting in forest management). In passive management, a resource receives little or no direct action itself (e.g., data acquisition for inventory of aquatic habitats). Most resource management schemes contain elements of both active and passive management.

The 15 resources were arranged into groups, called natural, administrative, and functional resources. Although the groupings are logical, their names were selected mainly as convenient labels rather than as precise scientific descriptors of the resources.

Each of the three groups was considered to contribute differently to the total resource of the Reservation. Most of the resources in the administrative category exist as a result of legal requirements, regulations, guidelines, or other agreements. These resources include health, safety, and environmental affairs; laws, regulations, and guidelines; the NERP; archeological sites; and environmental monitoring. Their primary function is more often management than service. In contrast, resources in the functional group—forestry management, waste management, site development, and utilities—either provide a service or require active management. Some of the resources in the natural subgroup can be managed passively (geology; hydrology; and geography, demography, topography, and soils); others are either administrative or functional (aquatic habitats, endangered plants, and wildlife).

Environmental monitoring on the Reservation is used to measure the radioactive and nonradioactive releases from the Department of Energy facilities and to evaluate their impact on the ecosystem by monitoring important uptake pathways. Each of the three major DOE facilities has its own monitoring network; stations outside the immediate facility boundaries are part of a perimeter network that is designed to measure releases to the general Oak Ridge area; a remote network provides background data for comparison.

Health, Safety, and Environmental Affairs management consists of programs administered by both DOE and the operating contractor. These programs ensure the protection of on-site and off-site personnel, the facilities, and the environment. While significant environmental problems resulting from past and current practices within the Reservation have been identified and are receiving major attention, long-range activities and plans are also under way to anticipate and alleviate any future problems.

Brian Kelly and author Tom Kitchings, both of the Environmental and Occupational Safety Division, check the layout of one of the Reservation's solid-waste storage areas.

Resource Management Organization

The responsibility for administering resource management activities now rests with the Reservation Resource Management Committee. It consists of seven persons—six committee members and a committee secretary. The environmental coordinators at each of the three major facilities are automatically members of the committee. The three additional members are selected to represent the three major groups of resources (i.e., administrative, functional, and natural). The committee was structured to include management representation from each major facility on the Reservation and to establish direct, ongoing communication between the resource management committee and the operating contractor's executive planning committee. Through this organization, all pertinent Reservation resource considerations can be incorporated into management's programmatic and operational plans. In this respect, the Reservation Resource Management Committee has three objectives:

- to provide DOE and contractor management with the information needed to understand and assess Reservation resources,
- to assist both DOE and contractor management in planning for optimal use and development of those resources, and
- to implement and coordinate the resource management plans accepted by DOE and contractor management.

Issues Resolution

Issues involving the use of the various Reservation resources come to the committee for a hearing and an exchange of views. The committee's main focus is on resources outside the security buffer zones of the three major installations. In the past these undeveloped land and water areas have not received sufficient consideration during planning, even though they account for most of the DOE holdings.

When an issue or problem arises, the committee sets up a task group of resource experts who can define the problem, examine

Birds of a Valley: Return to Wilderness

Before the Oak Ridge Reservation was purchased in 1942, Melton Valley, which lies within a loop of the Clinch River about 1.5 km (1 mile) wide and 9 km (5 miles) long, was typical East Tennessee farmland. The area was a succession of cultivated fields, closely cropped pastures, and lawns. The land was largely bare of vegetation that rose above the heads of small birds. It had been at least a century since white settlers had "tamed" the wilderness by clear-cutting the indigenous oak-hickory forests to grow crops. Wilderness as a bird habitat was not one of the issues of the day, and the question of someday returning the land to its original state was not considered.

But when Melton Valley became part of the Reservation, the farmland was abandoned, and the effects of the 100 or so years of human intervention rapidly disappeared. A natural succession of plant communities ensued, culminating in a regrowth of oak-hickory forests, which provide more habitat for more species of birds than do other stages of plant growth. Within 15 years, 55% of the valley was reforested and the birds of the wilderness had returned.

Laws, regulations, and guidelines apply to the Reservation's programs and operations in virtually the same way they apply to any other industrial enterprise. As a result of a 1978 Executive order, federal installations such as those in Oak Ridge immediately became subject to pollution control laws and regulatory programs of the federal government as well as those of the states, counties, and cities in which the facilities were located.

possible solutions, and provide recommendations to the committee. The committee, in turn, discusses these and forwards recommendations to management. For example, information regarding the impact of a research and development or construction project on Reservation resources comes to the committee, which disseminates that information to the appropriate resources experts (e.g., site development and forest management) and coordinates the formation of a task group made up of these experts. After the task group and committee have aired the conflicts, considered alternatives, and made recommendations, feedback from management groups is documented for and submitted to DOE, which is the decision-making body for resource-related activities on the Oak Ridge Reservation.

A crucial component of all decision making is a strong information base. Therefore, at the outset, the Resource Management Committee was chartered to develop and maintain a computerized base of numeric and graphic resource data and to provide DOE and contractor management with data as needed. When the system is completed in December 1984, for the first time, all the Reservation resource data will be assembled in one place, updated regularly, and kept ready for use, especially for issues resolution.

In the very short time that the committee has existed, its problem-solving capacity has been tested three times.

The Sludge Field

In 1978 the city of Oak Ridge and the DOE Oak Ridge Operations Office began discussing the land disposal of treated sludge from a new city sewage treatment plant that was scheduled for completion in 1983. The sludge, to be spread on several parcels of Reservation land for a trial period of five years, was to be used as a nitrogen and phosphorus nutrient supplement for tree-planting operations on poor-quality forest sites. The first sludge disposal site consisted of 26 ha (65 acres) on the southeast side of Chestnut Ridge, bordered on the south by the old Bethel Valley Road and on the west by Mount Vernon Road. Deposition on this site began in November 1983.

Four months later, it was learned that some of the deposited sludge had been contaminated with various radionuclides. Radiation readings above the city's sewage main on Emory Valley Road were as high as 45 μR/h (five times background-radiation level) in one industrial area. The cause of the contamination was later found to be improper disposal of radioactive material by an organization located in the area.

Disposal of sludge on the Reservation was temporarily halted on March 25, 1984. Because the holding capacity for sludge was limited at the new treatment plant, immediate action was necessary.

Wayne Chance, in charge of site planning, at overlook above ORGDP, one of the world's largest industrial complexes.

An identification of the extent and type of radioactivity was needed so that the potential environmental and health impact of the existing activity could be assessed. Next, a decision was needed regarding the potential impact of continued sludge deposition. To meet these needs, ORNL's Department of Environmental Management rapidly prepared a sampling plan; collected the needed samples; and, with the aid of the Analytical Chemistry Division, analyzed the samples—all in a span of five days.

Evaluation of the field data showed the total radioactivity on the disposal site to be about 6.2×10^9 Bq (170 mCi), mostly from cesium-137 and cobalt-60. The total annual exposure to a maximally exposed individual from five different environmental pathways was calculated to be 4.2 millirem to bone and 1.1 millirem to the total body. The annual background dose from natural radiation is about 100-200 millirem. Although the radioactivity on the site was not considered to be a serious health

Gordon Jones of Martin Marietta Energy Systems' Office of Health, Safety, and Environmental Affairs prepared the plan for those concerns, with the help of colleague Irv Speas.

hazard, recommendations were formulated to ensure that any similar incident would be prevented in the future.

The Resource Management Committee did not yet exist when the initial decision was made to deposit the sewage sludge; had it existed, it would have been an appropriate group to examine the proposal. The committee could have considered the plan in light of the individual management plans for resources such as forestry, site development, aquatic habitats, health, safety and environmental affairs, and environmental monitoring.

Deer

During the past ten years, 845 white-tailed deer have been killed by vehicles on Reservation roadways—more than 200 of them in 1983 alone. These deaths represent not only a loss of wildlife but also a significant safety hazard to facility personnel, who could be injured in a deer-vehicle collision. The rising collision rate is mainly the result of rapid, uncontrolled growth of the size of the deer herd. Studies indicate that the deer herd has grown exponentially over the past decade, primarily because of the availability of prime habitat and the lack of population control. The Reservation deer population, estimated at 300 in 1975, is now thought to be 4000–6000.

In early 1984 the Resource Management Committee was asked to formulate recommendations on how to reduce the deer-vehicle collisions. After discussions and a review of available data, the committee eliminated all potential control methods except reduction of the deer herd itself, because the other methods were only temporary or had been shown to be ineffective (e.g., construction of fences and installation of reflectors).

Once the committee judged that reducing the deer herd was the most effective action, five methods to achieve this goal were discussed:

- trapping and removal,
- use of drugs to immobilize animals, which would then be removed,
- roundup and removal,
- controlled public hunting, and
- the use of professional government hunters.

Each of these options is being evaluated to determine which single option or which combination of options will best alleviate the problem on a long-term basis.

Endangered Plants

Certain portions of land within the Reservation are habitat for 14 plant species that the State of Tennessee considers threatened or endangered. Of these 14, 3 have been proposed for inclusion on the federal list of threatened and endangered species. The best means of ensuring their survival is habitat preservation, which can be accomplished only by planning for this resource in future land-use considerations.

In February 1984 the Oak Ridge City Council expressed an interest

The Oak Ridge National Environmental Research Park, which includes about one-third of the Reservation, is one of five NERPs established by DOE to provide protected land areas for research and education in the environmental sciences. Demonstration of the environmental compatibility of energy technology with the natural environment is only one of the park's objectives. The NERP lies in the heart of an eastern deciduous forest of streams and reservoirs, mesic hardwood forests, and extensive upland mixed forests. It provides habitat for rare plant and animal species and ensures the preservation of areas that are representative of the southeastern region's natural resources.

Forest management on the Reservation has completed three cycles of a five-year management program. Objectives of the program are multiple use of forest lands and sustained yield of quality timber products. Currently, the Reservation provides 1 million board feet of harvested sawtimber each year—enough to build 50 average-size houses; it can sustain up to 8 times that amount. Both natural and planted stands are maintained through silvicultural treatments and through protection from wildfire, insects, and diseases.

More than 200 Reservation deer were killed by vehicles in 1983.

in acquiring two tracts of DOE land along the southern side of Bethel Valley Road. The westernmost tract borders one of the Reservation's natural areas, an area in which rare plant populations occur. Its designation provides protection of the critical habitat as outlined in the 1980 version of the DOE Oak Ridge Reservation Land-Use Plan. The particular plant species found

Site development requires effective management to protect the multi-billion-dollar investment in the Reservation's facilities. Cost-effective and efficient operation is a day-to-day management responsibility, but planning for site development to meet ever-changing national needs and societal conditions is a management challenge, one that must be met within the policy defining the Reservation as a national resource.

Utilities are the lifeline of DOE's Oak Ridge facilities. The four major lifeline systems of telecommunications, electrical power, transportation systems, and pipelines are indispensable resources for support of the Oak Ridge operations. Transportation systems on the Reservation consist of state highways, government highways and access roads, and railroads.

in this area is the tall larkspur (*Delphinium exaltatum*). This plant, which is on Tennessee's endangered species list, is known to occur very infrequently in Tennessee—only in Anderson County, Roane County, and two others. The largest known population is within the Oak Ridge Reservation; the population ranges over several hectares, including woodland, roadbanks, and powerline rights-of-way.

Concern for the plant's habitat prompted the ORNL personnel who administer the NERP to alert

Waste management—waste handling, treatment, and disposal—has always been an important function for the Reservation facilities. Both radioactive and nonradioactive wastes have been disposed of here. The geology is well suited to this use, and land areas have been dedicated to such disposal, so waste management constitutes a valuable and effective resource for the Reservation.

Contributors to the Oak Ridge Reservation Resource Management Plan

Resource Management Committee

T. W. Oakes, ORNL, chairperson
L. B. Maudlin, ORNL, secretary
D. B. Slaughter, ORNL, secretary
H. M. Braunstein, ORNL
T. R. Butz, Y-12
W. W. Chance, ORGDP
J. T. Kitchings, ORNL
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Resource Management Plan Chairpersons

Aquatic Habitats: *J. M. Loar*, ORNL
Archeological Considerations: *M. Sanders*, Y-12
Endangered and Threatened Plant Species: *P. D. Parr*, ORNL
Environmental Management: *K. L. Daniels*, ORNL
Forest Management: *D. M. Bradburn*, ORNL
Geography, Demography, Topography, and Soils: *W. D. Barton*, Y-12; *W. E. Manrod*, ORGDP; *C. H. Petrich*, ORNL
Geology: *T. R. Butz*, Y-12
Health, Safety, and Environmental Affairs: *C. G. Jones* and *I. G. Speas*, Martin Marietta Energy Systems, Inc.
Hydrology: *E. R. Rothschild*, ORNL
Laws/Regulations/Guidelines: *L. F. Willis*, Martin Marietta Energy Systems, Inc.
Oak Ridge National Environmental Research Park: *J. T. Kitchings* and *E. L. Preston*, ORNL
Site Development: *W. W. Chance*, ORGDP
Utilities: *R. O. Daugherty*, ORGDP
Waste Management: *B. A. Kelly*, ORNL
Wildlife Management: *J. T. Kitchings*, ORNL

Author Helen Braunstein, center, briefs members of the Resource Management Committee about the Reservation's functional resources; others, from left, are Kitchings (natural resources representative), Donna Slaughter (committee secretary), author Tom Oakes (committee chairperson), Wayne Chance (administrative resources representative), and Leslie Maudlin (committee secretary). Not shown are Todd Butz, Y-12 Environmental Coordinator, and Larry Long, ORGDP Environmental Coordinator.

Leland Willis of the Martin Marietta Energy Systems Law Department reviews laws, regulations, and guidelines affecting the use of Reservation resources.

DOE-ORO to the possible impacts on the natural area. Subsequently a subcommittee of the Resource Management Committee was convened to discuss the potential impacts of transferring the two tracts desired by the city. The subcommittee suggested that resolving the specific problem would require additional information, first to delineate the distribution of *Delphinium* within the natural area and then to establish buffer zone requirements to ensure adequate protection of the species.

Conclusion

Planning for optimum use of the resources of the Reservation is an ongoing process. It is guided by a commitment to find the best mixture of preservation, conservation, consumption, and improvement of the resources within the constraints imposed by present and future program demands and facility goals that are sometimes in conflict. The process has been implemented by establishment of a permanent resource management organization that can respond quickly to administrative information needs, anticipate potential conflicts, and coordinate and integrate the various resource functions. Because the organization includes management representation from each major facility on the Reservation and communicates directly with the operating contractor's executive planning committee, Reservation resource considerations can be fully, fairly, and effectively incorporated into management's programmatic and operational plans and decisions.

The work done by the first Reservation Resource Management Committee, which was assembled in August 1982, is reflected in a 17-volume report. But the report is little more than a faint echo of the weeks and months of discussing and thinking and shaping that preceded the plan. It was a dedicated effort by a group devoted to the preservation and best use of the Oak Ridge Reservation. ornl

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Raccoons and other forms of wildlife constitute one of fifteen resources on the Oak Ridge Reservation. An article describing how all fifteen resources are considered in land-use planning begins on page 60.