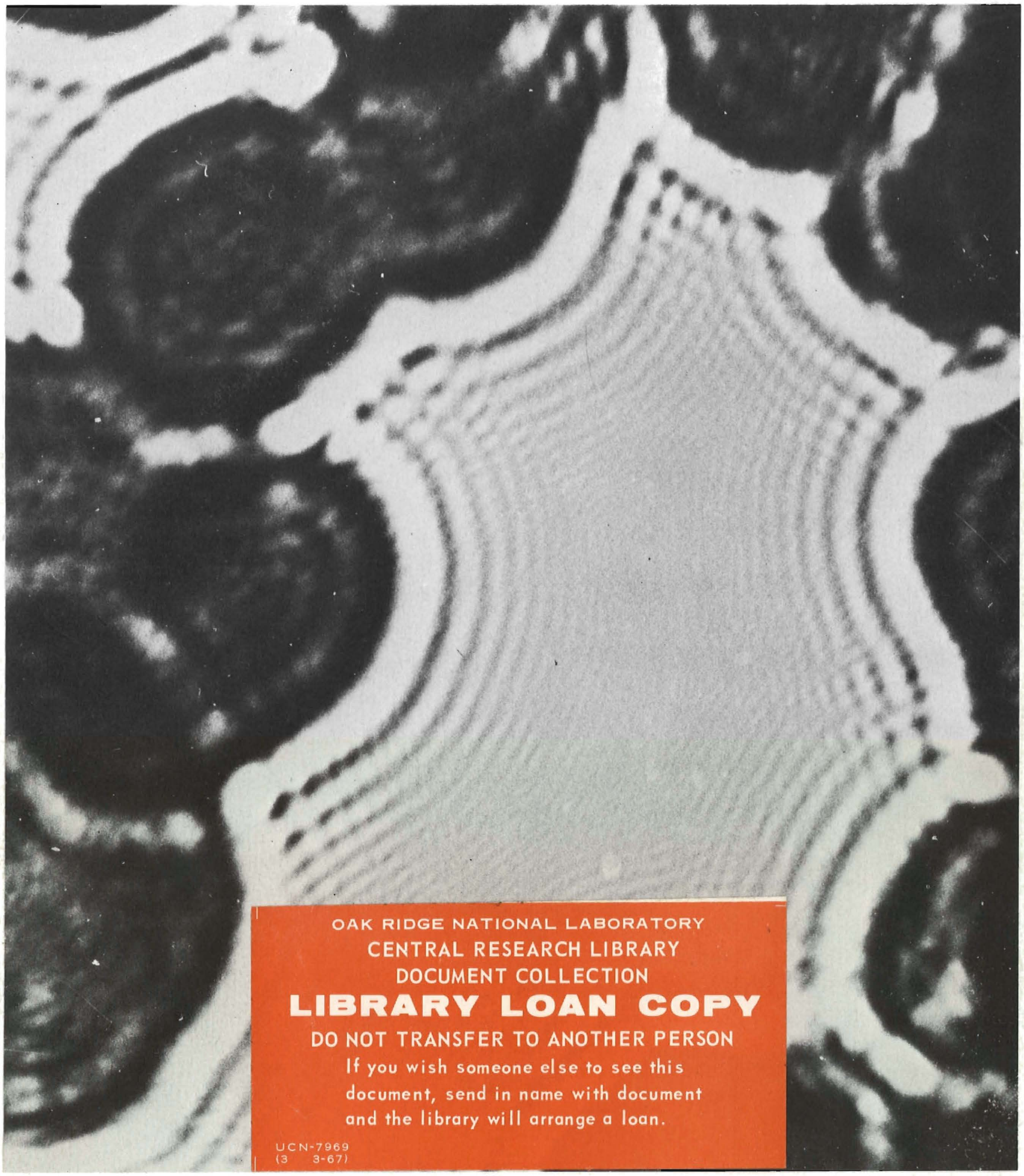
ORNL 73

Oak Ridge National Laboratory



ON THE COVER: *A micrograph made with the High-Coherence Electron Microscope during testing. The Fresnel diffraction fringes, shown at 2,000,000× magnification with the objective lens underfocused, surround particles of carbon smoke. The original micrograph was made at 450,000× magnification with a 15-second exposure at a total field emission tip current of 0.5 microampere.* *(See page 91)*

Oak Ridge National Laboratory

Annual Report 1973

Operated by Union Carbide Corporation for the U.S. Atomic Energy Commission

Foreword

I find it difficult to characterize Oak Ridge National Laboratory during 1973. Surely we have gone through a period of reevaluation with inevitable programmatic dislocations and staff disruptions. But at year's end we are whole again, and I view the future with optimism for both basic research and applied technology.

This optimistic view of the future is based upon the urgency with which institutions such as ours are being thrust into the search for abundant and safe energy sources. This historical central theme for our applied research is now of paramount importance to the national purpose. The basic disciplinary research in chemistry, metallurgy, physics, biology, ecology, and, to a more limited extent, the social sciences is being rejustified and rejuvenated by this thrust to understand energy systems and the societal and environmental effects of energy use.

It is therefore most appropriate that this annual report be focused on energy. We have selected examples of current research and development drawn from a much larger body of work that covers most of the principal elements of energy research and development: conservation, nuclear fission and fusion, coal utilization and other fossil fuels, improved efficiency for energy utilization, research on long-term renewable energy resources, environmental effects and their evaluation, health effects, and research on the curing and prevention of deleterious somatic effects of energy production and use.

Floyd L. Culler

Contents

THE SMALL WORLD: Photographic series of familiar objects, seen through the Metals and Ceramics Division scanning electron microscope.

Energy: the Environment

The Oak Ridge National Laboratory has been working with the energy problem for 25 years or more. At first we confined our efforts to reactor development, and the reader will see that we are still strongly involved in the development of all three of the prime power reactor efforts in the United States: the fast breeder, the high-temperature gas-cooled reactor, and water reactors. Our interest in controlled fusion started around 1956; the effort is now flourishing as never before even if the attitude must still be "Let's see!" Of more recent origin is our interest in the environment, although even here we can claim long priority because of the foresight and ecological interests of our Health Physics Division. But in addition to these activities, the reader will see a concern for the broad aspects of the energy problem; how we can more efficiently use our present fuels, nuclear safety, and what a future energy economy is likely to be. Let us hope that we can realize it without sacrificing the natural beauties of our countryside!

A customary word of caution must be appended to any introduction to our Annual Report. What is presented here is a selection of vignettes of the Laboratory's activities, not a complete catalog. (Our work on the liquid metal fast breeder reactor alone really covers some 45 separately recognized research studies.) Other activities have been described in preceding Annual Reports, and still others will appear in the future.

Reactor Development

The Fast Breeder Program

"Thermal Ratchetting" in the Liquid Metal Fast Breeder Reactor

The cooling system in an LMFBR will contain molten sodium at a temperature around 1100°F. The stainless steel plumbing and structural components that contain the sodium will be subjected to mechanical stress at high temperature. This is a condition that leads to creep, but simple creep can be allowed for appropriately in the engineering design. A more complex situation arises when thermal transients will occur, for example when the reactor is shut down or reduced in power so that cooler sodium goes through the system for a while. Then one can have thermal cycling in addition to the normal operational mechanical stress; this is a condition that can produce progressive incremental straining or permanent distortion, a phenomenon termed "thermal ratchetting." Current design codes and standards contain rules to limit thermal ratchetting effects to acceptable amounts, but the inelastic structural analyses that are required to demonstrate that these rules are met are based on procedures that have not been fully verified experimentally.

The LMFBR will have a sodium system of types 304 and 316 stainless steel pipe, perhaps as large as 36 inches in diameter, with valves, pumps, heat exchangers, and appropriate fittings such as elbows, tees, and flanges. To ensure that the design is sound with respect to thermal ratchetting, Harold McCurdy and Jim Corum have undertaken a series of experiments in which a section of 304 stainless steel pipe is subjected to thermal and mechanical stresses representative of the more extreme ratchetting conditions that might occur in LMFBRs. The purpose of these experiments is to provide reliable, carefully measured experimental data that can be used for checking analysis methods.

The experiments are carried out in the Thermal Transient Test Facility, built for the purpose under the engineering supervision of

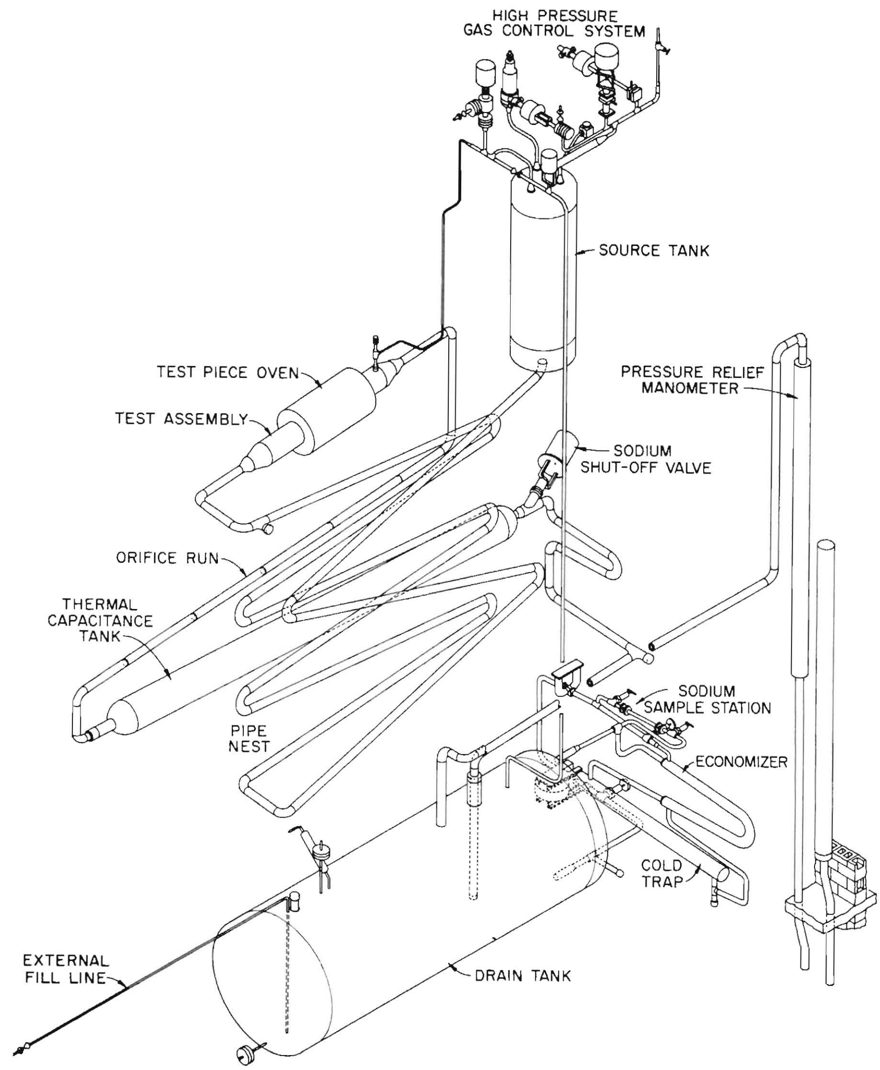
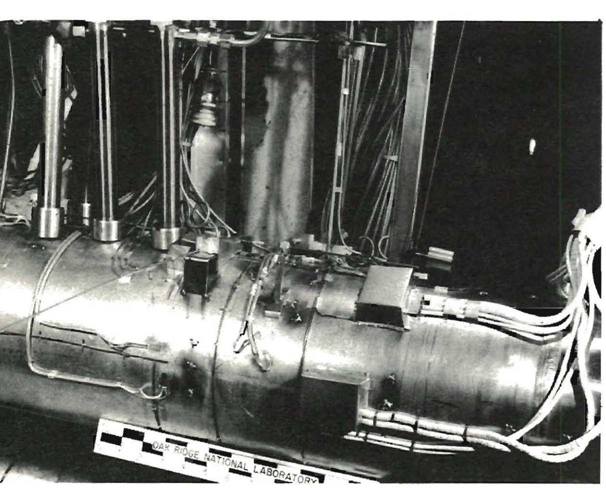
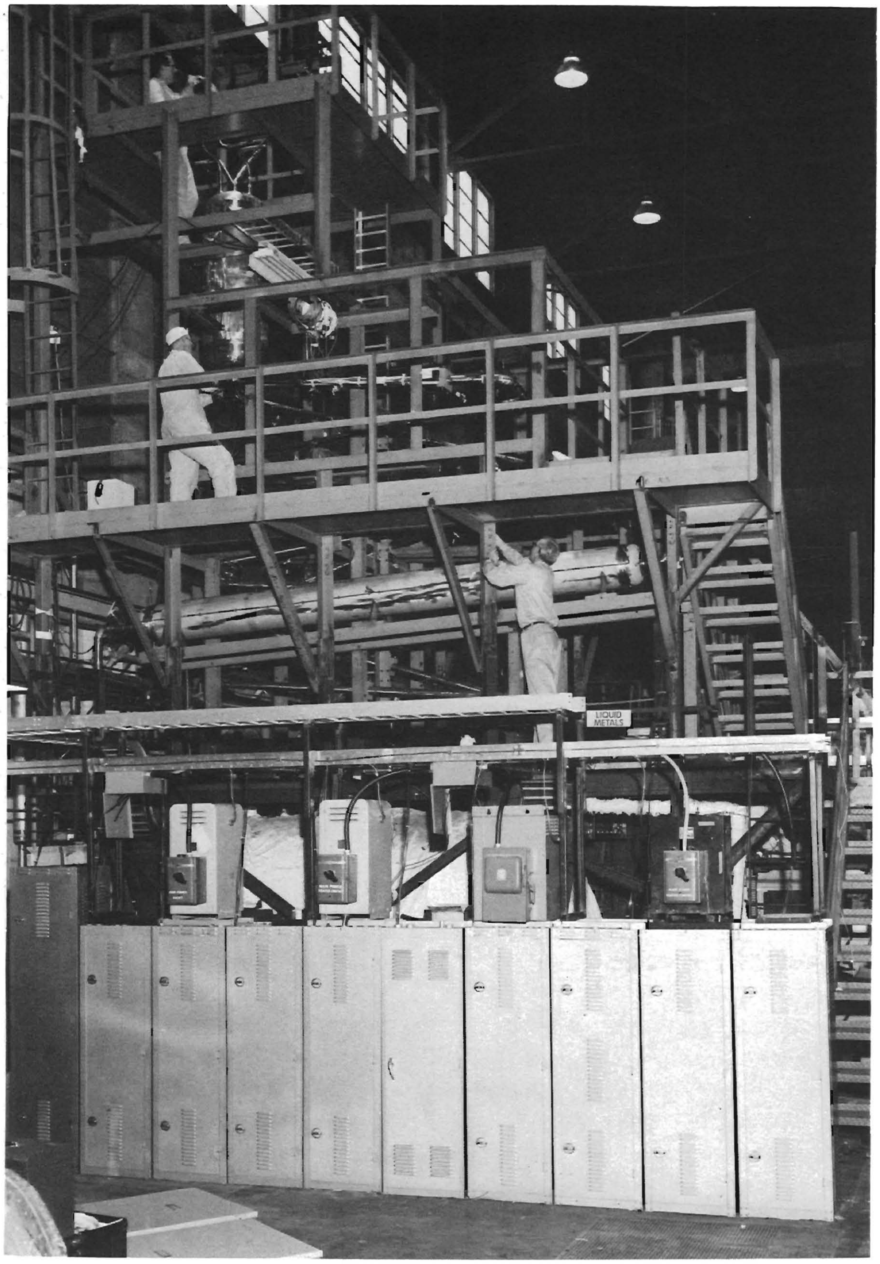


Diagram of the Thermal Transient Test Facility.



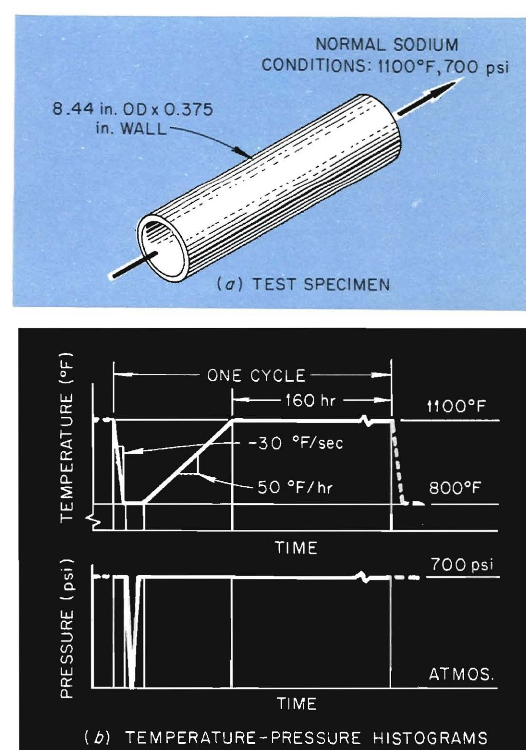
The instrumented test section of stainless steel pipe used in the thermal ratchetting experiments.

A. G. Grindell and H. C. Young. Its operation can be traced from the accompanying diagram. The source tank at the top contains liquid sodium under argon at a pressure selected to give the desired mechanical stress in the test section. From the source tank a pipe leads to the pipe nest, which is a zigzag of pipes going down and then up again to the test section. At present the test section is a piece of straight pipe of 8-in. nominal diameter with $^3/_8$-in. wall, 30 in. long. It is mounted vibration-free and without stress from its supports, and is instrumented with thermocouples and strain gages. The pipe leads thence through an orifice tube (to control the rate of flow of the sodium), through an enlarged section that serves as a thermal capacitance to reduce thermal shocks on the subsequent parts of the flow system, through a shutoff valve, and finally to the drain tank. At the start of a cycle, the shutoff valve is closed and the sodium is static but pressurized. The temperature in the source tank is 800°F, in the test section it is 1100°F, and in the pipe nest it is graded in a programmed way between these extremes. When the valve is opened for a few seconds, the cooler sodium in the pipe nest moves into the test section. Then the valve is closed and the test section is allowed



The Thermal Transient Test Facility. The liquid sodium storage tank can be seen near the top of the framework; the long, almost-horizontal tank is the thermal capacitance.

The test specimen and a diagram of the thermal and pressure cycles used in the ratchetting experiments. The internal pressure of 700 psi is larger than the pressure which would exist in actual large-diameter LMFBR piping. However, a prototypic wall thickness (3/8 in.) was required in the relatively small-diameter test section to simulate the thermal effects properly, and consequently a larger internal pressure was required to produce representative membrane stress levels.



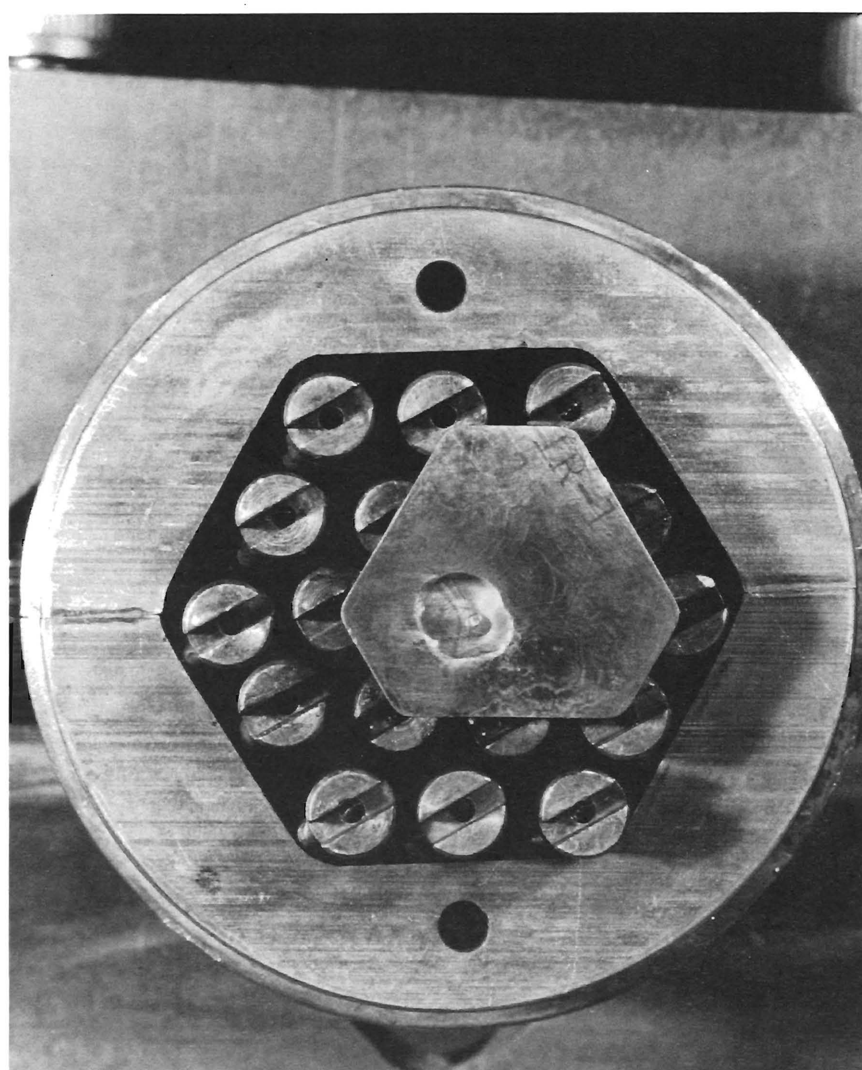
to come into temperature equilibrium at 800°F. In the initial experiments a mechanical stress cycle is imposed at this point by reducing the pressure to atmospheric and then returning it to 700 psi. Then the temperature of the test section is slowly raised to 1100°F again and held there for as long as desired (160 hr in the initial experiments) to obtain measurements of interest.

At present the Thermal Transient Test Facility is working well and the first experiment involving 13 ratchetting cycles has been completed on the 8-in. pipe section. The results agree well with theoretical predictions using the same calculational methods as are currently used in evaluating ratchetting in LMFBR components. As the program proceeds we will develop progressively more firm bases upon which to predict the thermal ratchetting performance of the sodium containment system of LMFBRs.

The Fuel Failure Mockup Experiments

In an LMFBR the fuel rods consist of little $(U,Pu)O_2$ pellets stacked in long, slender stainless steel tubes, about ¼ in. in diameter, with liquid sodium coolant running lengthwise over the rods. What happens if the flow of coolant is partially blocked? Will the fuel rods burn out locally as they did in the Fermi reactor when two subassemblies containing fuel rods were virtually blocked? Can a general calculational code be worked out and checked by experiment so that one can have confidence about the temperature distribution in such an assembly, with or without blockage? How can one develop sensors that can monitor impending trouble?

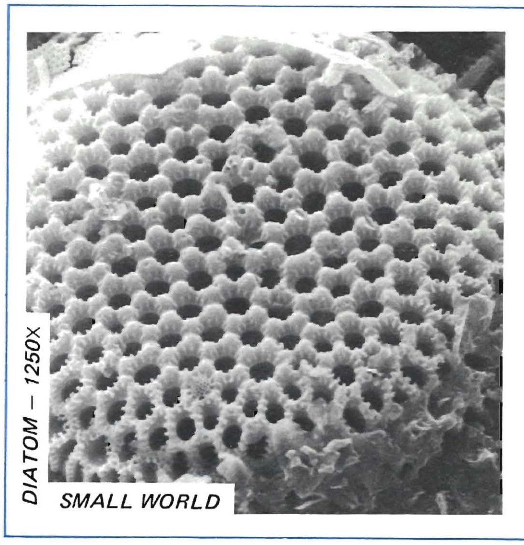
These basic safety questions have been the subject of a series of engineering experiments that were undertaken at ORNL by a group that includes Mario Fontana, R. E. MacPherson, Paul Gnadt, T. S. Kress, L. F. Parsly, and J. L. Wantland. A bundle of 19 fuel rods was mocked up with electric heaters in the rods to simulate the generation of nuclear power in the Fast Flux Test Facility (FFTF) reactor core. Sodium was circulated lengthwise through the bundle,



Blockage plate used in the fuel failure mockup tests. The electrically heated "fuel pins" are about 1/4 in. in diameter, and the blockage plate locally interrupts the flow of liquid sodium coolant through the lattice.

and thermocouples measured the temperature distribution. Acoustic and fast thermometric detectors were installed to sense changes in turbulence or boiling.

First the tests were run under normal conditions and used to test computations. Then an obstacle four times as large as any that could conceivably be carried in the liquid sodium stream in the FFTF design was placed against the inlet end of the rod bundle. The flow restriction produced no worrysome hot spots. Then a rod bundle was partially blocked in the zone where nuclear heat is generated to simulate a blockage produced by local swelling of the fuel rods, for example. Again no alarming hot spots were found. The temperature distributions were compared with the results of an ORNL-developed computer program for calculating sodium flow and temperature in LMFBR subchannels, and the program is now available for extrapolating to variants of this particular subassembly.

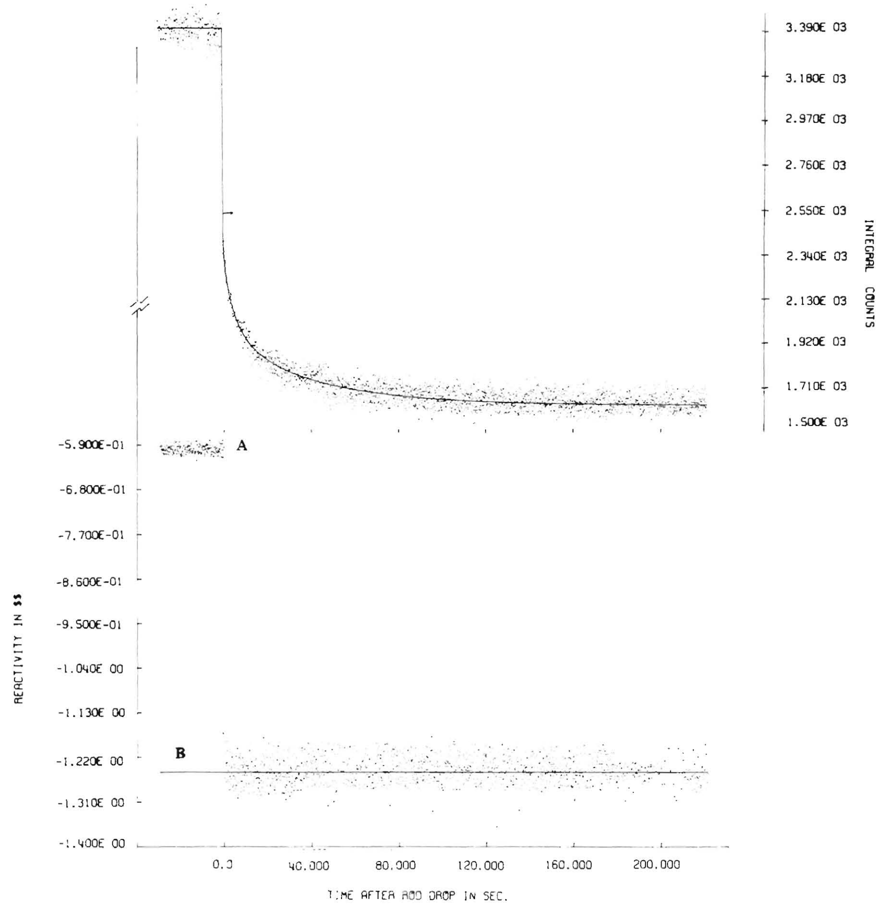


Subcriticality Monitoring in Fast Breeder Reactors

Reliable knowledge of the subcriticality of a nuclear reactor at all times during shutdown, coupled with proper administrative control, should preclude the possibility of accidental criticality or supercriticality. During reloading, a reliable monitoring of the approach to criticality would promise to be especially valuable. The Laboratory has been involved in developing the instruments and computational methods for the continuous subcriticality monitoring of the Fast Test Reactor (FTR) of the Fast Flux Test Facility (FFTF), now under construction at Hanford.

During the past spring, methods and instruments were tested by a group under John Mihalczo using the critical facility ZPR-9 at the Argonne National Laboratory, which was loaded with the engineering mockup of the FTR core. Three methods in particular were investigated. The first, called noise analysis, depends on the fluctuations of the fission chain populations that occur in the reactor. The fission chain initiators are the neutrons from spontaneous fission of ^{240}Pu or delayed neutrons from previously induced fissions. In this method, the reactivity is obtained by comparing the frequency dependence of the cross power spectrum for two detectors in the reactor at any time with the cross power spectrum for those same two detectors in the reactor while at delayed criticality. The second is the so-called "inverse kinetics, rod-drop" method. Here the neutron level is measured before and after a control rod is dropped into the assembly. The neutron count rate is decreased because the poison in the control rod reduces the chance of induced fission, the amount of reduction depending on the degree of subcriticality. In this method both the initial and final reactivities are determined. The third, called modified source multiplication, depends on the steady-state count rate from a detector which is corrected for the effects of changing detection efficiency and reactor source strength during loading of the reactor. To infer reactivity from the last method, a calibration at some known reactivity is required. The calibration is usually obtained by the second method.

In the tests in ZPR-9, 15 detectors of various kinds were distributed in the fuel assembly, in the reflector, and in the shield. Complex on-line data analysis systems were required.

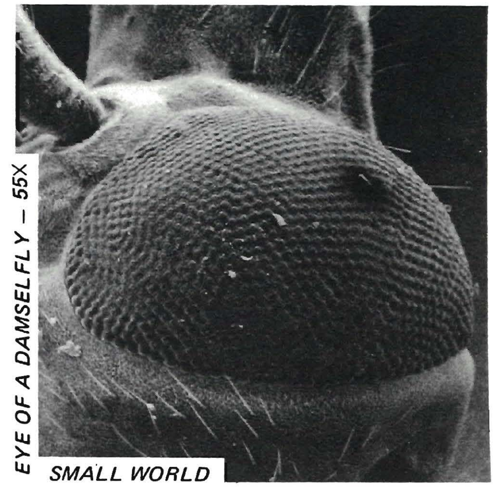


Curves illustrating the rod-drop method of measuring subcriticality in a nuclear reactor. At time zero, a control rod is inserted into the assembly. The upper curve shows how the neutron counting rate drops abruptly and then tails off because of the delayed neutrons. The lower plot gives the output of the on-line computer in subcriticality units. The computer has analyzed the delayed neutron effect, and the drop from level A to level B is a measure (strictly, an inverse measure) of the subcriticality change of the system.

The modified source multiplication method with a calibration at one dollar subcriticality, the proposed method for subcriticality monitoring of the FTR, and the adequacy of using the FTR low-level flux monitors as sensors were established in these measurements. The noise analysis results were used as an independent measurement, and they confirmed the conclusion that satisfactory subcriticality monitoring techniques are now in hand for fast fission reactors.

Shielding for LMFBRs

The general objectives of our shielding program are the development and application of calculational codes for radiation transport problems, the testing of the codes by experiment, and the development of data and techniques that engineers can use with confidence when faced with problems of complex shield design. The program is under the direction of C. E. Clifford; he has strong support in the experimental team at the Tower Shielding Facility, and in the computational groups in the Neutron Physics Division.



The LMFBR work of highest priority continues to be devoted to the Fast Flux Test Facility. Problems there include estimating the amount of neutron streaming that will take place through the sodium cooling ducts that penetrate the reactor cavity shield, the shielding requirements for the heat exchanger vault wall, and the prediction of the secondary sodium loop activity. A detailed study was made of the shielding required above the top head of the reactor. This called for a corroborative experiment in which iron shields 10 to 34 in. thick were examined, with and without an added layer of borated polyethylene. It was gratifying to see that we could predict the gamma-ray spectrum within a factor of 2 even when rather crude cross-section data sets were used.

We also have been active in collaborations with candidate reactor manufacturers concerning preliminary shield designs connected with the reactor for the LMFBR demonstration plant. An experiment at the Tower Shielding Facility showed that no inter-rod neutron streaming occurs in a shield of adjoining round rods containing boron carbide in an aluminum matrix; this means that this type of shield assembly can be considered to be made of a homogeneous medium, and this simplifies the calculational problem. Another set of experiments was performed to assist in the design of the blanket region of the demonstration plant reactor. In these tests we determined the effect of a UO_2 layer 5, 10, or 15 in. thick in simulation of the blanket region. This was followed by a more complete experiment in which the 10-in. UO_2 layer was supplemented by layers of stainless steel, Inconel, and sodium in simulation of possible configurations that might be used in the design of the demonstration plant reactor.

Concurrent with these applied activities, we have of course been developing an expertise in shield computations. In this respect our recent "sensitivity studies" are of interest. When one recalls that total shield attenuations cover many powers of 10, it is clear that errors in the cross-section data that go into the calculations can have a big effect on the final result. The sensitivity studies give answers to questions such as: if the neutron inelastic collision cross section of iron is 10% too low in the energy region 10 to 100 keV, what effect will this have on the predicted neutron transmission through a shield 6 feet thick made of concrete and iron? Clearly many such questions can arise, and to answer them a special code has now been developed. From these studies we will be able to see what cross sections should be measured with better precision in order to make the shielding results more dependable.

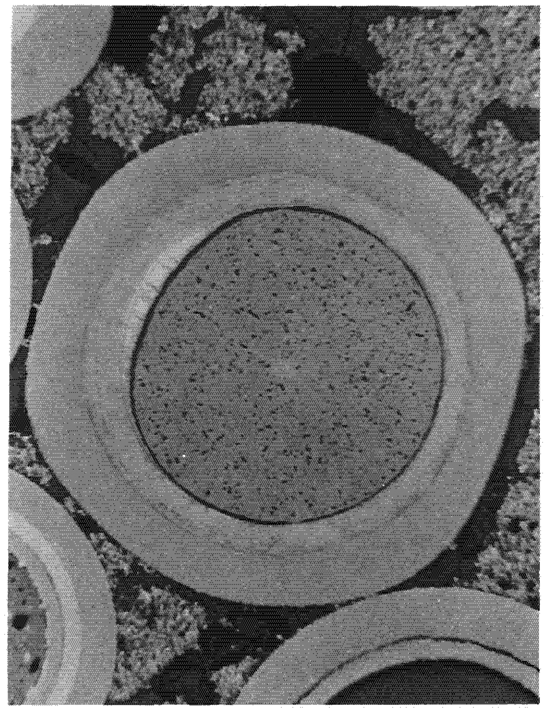
Shielding Studies for Weapons Radiation

A major part of our shielding code development program is carried out for the Defense Nuclear Agency, the basic problem being the attenuation of weapons radiation in air and in various kinds of shields. A specific example is the calculation of the penetration of radiation from a weapons burst in air into the interior of a missile silo. Our shielding codes and their interplay have now become quite elaborate, and they are under continual refinement.

HTGCR Fuel Fabrication

High-temperature gas-cooled reactors, which are now being marketed commercially by Gulf General Atomic, have several attractive features. They are slow-neutron systems and are presently designed to operate on the thorium fuel cycle, although operation on the uranium fuel cycle is also feasible. They promise higher thermodynamic efficiencies than do water-cooled reactors and hence give reduced thermal pollution for a given power output. The helium gas coolant circulates with a low level of radioactivity in the reactor circuit, and the fuel elements are capable of high burnup which aids the development of economic fuel recycle. Further, their component technology is largely applicable to the gas-cooled fast breeder reactor. One experimental HTGR of 40 MW(e) presently operates in this country (Peach Bottom unit I); a large HTGR prototype of 330 MW(e) (Fort St. Vrain) is to start up in 1974; in addition, six large HTGRs have been sold with operation of the first of these units to come on line about 1980. The ORNL responsibilities in HTGR development include the development and irradiation testing of fuels containing thorium and uranium, development of fuel recycle technology, performance testing of prestressed concrete reactor vessels, and HTGR safety studies. This work is carried out in close cooperation with Gulf under AEC-supported gas-cooled reactor programs. Emphasis has been placed on the development and proof-testing of fuels, and on fuel recycle technology development. Through the years ORNL has made major contributions to theoretical fuel modeling methods, practical fuel fabrication and coating procedures, and fuel reprocessing and refabrication processes. During 1973 the work has been led by Ray Wymer, A. L. Lotts, and John Coobs, who have had the able assistance of many associates.

Major advances were made in 1973 concerning fuel fabrication and performance testing; suffice it to say that the reference fuel for the Fort St. Vrain reactor will not only be satisfactory, but that there are many fuel designs which will perform satisfactorily. For a large HTGR, the coated fuel microspheres are fabricated into fuel rods, which are then placed into the fuel channel of a graphite moderator block. The initial fuel contains fissile (UC_2) and fertile (ThO_2) particles, whose kernel diameters are about 200 μ and 500 μ, respectively. The fertile kernels are coated first with a low-density pyrolytic-carbon layer followed by a high-density pyrolytic-carbon layer (so-called BISO coating). The fissile kernel is coated with a low-density pyrolytic-carbon layer and with a silicon carbide layer which is sandwiched between two high-density pyrolytic-carbon layers (so-called TRISO coating). These coatings serve as pressure vessels and retain fission products; the silicon carbide layer around the fissile kernel serves to retain heavy-metal fission products such as strontium and cesium in highly burned fuel.



This ThO_2 microsphere was exposed to fast neutrons for 250 days at a high temperature and under a high temperature gradient. The conditions were somewhat more rigorous than would actually be encountered in a HTGR, but the thoria in the center has migrated into the coating in one region, producing a bulge.

The coated microspheres are mixed with matrix material (containing pitch and graphite filler) to form fuel rods about $^5/_8$ in. in diameter and 3 in. long. After carbonization, the fuel rods are inserted into the fuel holes of the hexagonal graphite moderator block, which is about 31 in. long and 14 in. across the flats.

In fabricating fuel microspheres it is desirable that the kernel diameter be carefully controlled so as to permit better thickness control of subsequent coatings, and better separations between "fissile" and "fertile" particles. The ORNL Sol-Gel Process, which is utilized in fabricating oxide kernels for both fertile kernels and recycle fuels (which are mixed U-Th oxides), has recently been significantly improved to give excellent control of kernel diameter. This was accomplished by vibrating the nozzle or orifice fluid used to form sol droplets at a frequency in resonance with the natural frequency of drop formation. Remarkably good size control has thereby been achieved.

Because of the time element and large number of parameters involved in testing HTGR fuels, extensive use of the High Flux Isotope Reactor (HFIR) is made in accelerated testing of fuel performance. The first demonstration of the successful performance of Fort St. Vrain reactor fuel made in production equipment was carried out in the HFIR. We continue to make use of the HFIR for fuel testing, investigating the performance of various fuels, various type coatings, and fuel kernels. Recent irradiation results have shown that a potential problem exists because of amoeba-like migration of the thoria through the coating at very high temperatures and temperature gradients.

As previously mentioned, matrix material needs to be dispersed among coated fuel particles in the fabrication of the fuel rods. The process developed at ORNL for remote refabrication of fuel rods is termed the Slug Injection Process, and involves pouring coated particles into a mold, and forcing a cylinder of preformed matrix material into the particle bed. A laboratory-scale fuel fabrication machine which carries out the above process in an automated manner has been developed and is being operated routinely.

As a result of work at ORNL, there is increased confidence that the Fort St. Vrain reactor fuel element will indeed perform satisfactorily; that fuel for large HTGRs can be fabricated economically and achieve desired reactor performance; and that HTGR fuel refabrication technology can be developed which permits economical fuel recycle.

Water Reactors

Heavy Section Steel Technology

This program goes to the heart of the power reactor safety program, because it deals with the integrity of the primary vessels for pressurized water and boiling water reactors. The program deals with other things too, such as how fatigue affects the toughness of steel alloys, at various temperatures, with and without irradiation. Much of the work is carried out under subcontract, and cooperation with industry is close. Grady Whitman is in charge.

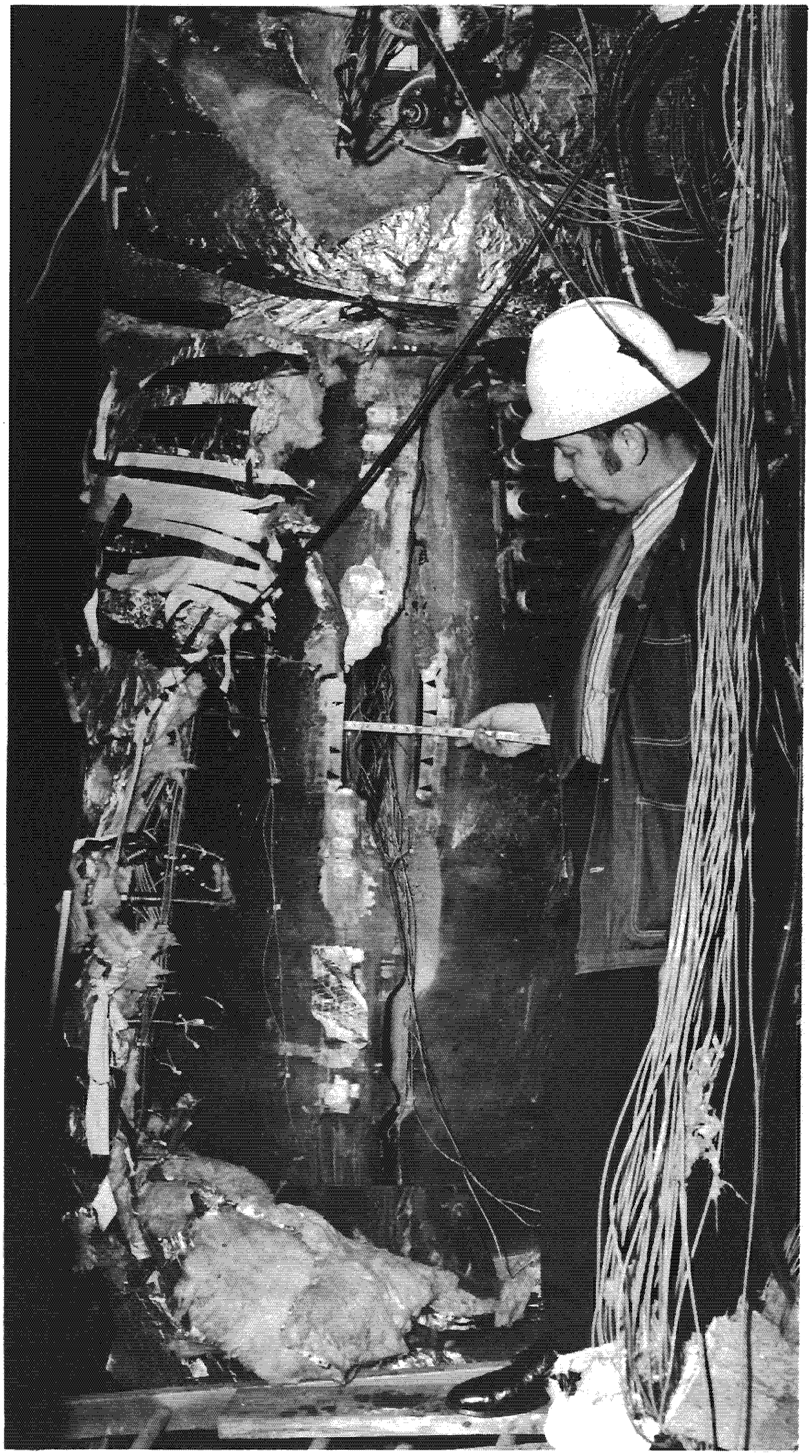
The ORNL tests become most spectacular when mockup reactor vessels are tested to bursting. The steel vessels are heavy; they are several feet long, approximately 3 feet in diameter, and have walls 6 inches thick. A temperature is chosen, the vessel is instrumented with strain gages inside and out, and the assembly is set up in a vault (which is actually at K-25). To simulate a flaw, the vessel is nicked with a saw cut an inch or more in depth at some strategic place, inside or out; for example, the nick might be inside in a corner weld where a side pipe enters the vessel. The machined cut is then fatigue-sharpened by local pressurization. The vessel is hydrostatically tested to failure with water to pressures exceeding 30,000 psi. As the pressure is increased, the strains and dimensional changes are registered, and from the analysis one seeks the knowledge that is needed for the peace of mind of the engineers and the public, namely a quantitative measure of the margin of safety that a reactor vessel will have under actual operating conditions.

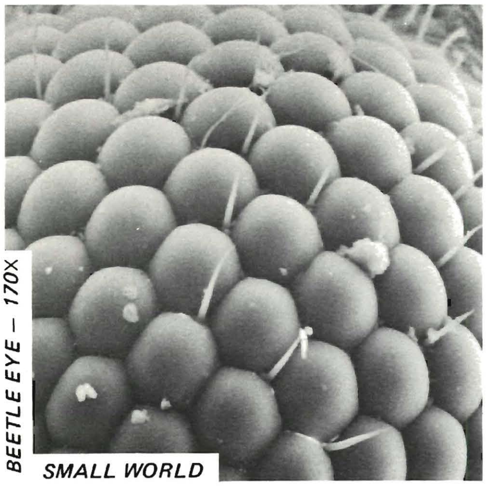
Capital Costs of Future Electrical Power Plants

In the 1960's the Oyster Creek plant brought nuclear power abruptly into economic importance because of its promise to compete with a coal-fired plant burning 25¢/MBtu fuel. Dresden 2 and 3 soon after were estimated at a capital cost of $123/kW(e) and Brown's Ferry followed at $115/kW(e). In 1967 the Atomic Energy Commission published estimated costs for light-water reactors of $134/kW(e) for a 1000-MW(e) first-unit plant at a new site.

Such were the estimates for early nuclear central-station generating plants. The optimism was short-lived. A year later, announced nuclear plants showed capital cost figures more like $225/kW(e). Estimates and experience have continued upward, and plants ordered today are estimated to cost about $550—$650/kW(e).

A ruptured pressure vessel in the Heavy-Section Steel Technology program.





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SMALL WORLD

The rocketing costs are not confined to nuclear plants. Coal-, oil-, and gas-fired plants have also become more expensive; their fuel costs are rising, and environmental protective facilities will not be cheap.

In a fast-changing situation like this, it is clearly important for the AEC and for utilities to be able to make rapid cost projections for power stations of all types, as adapted to various locations and sensitive to local economic factors such as cost of labor and materials and interest rates. Customarily this has been done in rather general terms, since projections based on the various constituents of a power station were too time-consuming for most studies.

An Oak Ridge code called CONCEPT has been set up to handle the problem. In CONCEPT, Howard Bowers and L. L. Bennett have broken down the various components of plant capital cost into over a hundred individual accounts, separately adjustable. The code has access to cost index data files for 20 key cities in the U.S. The files contain data on cost of materials and wage rates for 13 construction crafts, extending back over ten years. If desired, the escalation can be based on only a selected portion of historical data. The code also allows for adjustments as to site labor productivity and escalation of manufactured equipment costs. CONCEPT is supplemented by another code, ORCOST, which allows for quicker and less detailed variation of parameters.

These two codes have apparently filled a real need in the business of central-station engineering. Following their announcement in an article in *Power Engineering*, a number of utilities and construction companies requested the codes. At present, the CONCEPT code is being used by five architect-engineer construction companies, five equipment manufacturers, five large utilities, three consulting companies, Atomic Energy of Canada, and the International Atomic Energy Agency — as well as by several branches of the AEC. Work is in progress to extend their applicability to high-temperature gas-cooled reactors, and to broaden the options for heat rejection schemes so as to include cooling ponds and spray canals.

Operating Costs of Electric Power Stations

Operating costs of electric power stations are rising because of higher fuel prices and the increasing cost of meeting environmental constraints. In 1973, Oak Ridge National Laboratory and Ohio Valley Electric Corporation made a study of the cost of complying with 1975–1977 standards for sulfur dioxide emissions at an existing coal-fired station. Among the near-term and longer-term possibilities considered were the use of low-sulfur western coal, low-sulfur fuel oil from petroleum, flue gas desulfurization, low-Btu gas made from coal, solvent-refined coal, and coal liquefaction. The resulting increases in the cost of electricity were estimated at between 2.7 and 8.5 mills/kWhr. In addition, it is expected that the real prices of fossil fuels will continue to rise. A 50% increase in the price of coal would add about 1.6 to 1.8 mills/kWhr to the cost of power. To put these figures in perspective, a tripling of the cost of U_3O_8 from the present figure of about $10/lb would add about 1.2 to 1.6 mills/kWhr to the cost of producing electricity in a nuclear plant of the current light water type.

Fusion

ORMAK

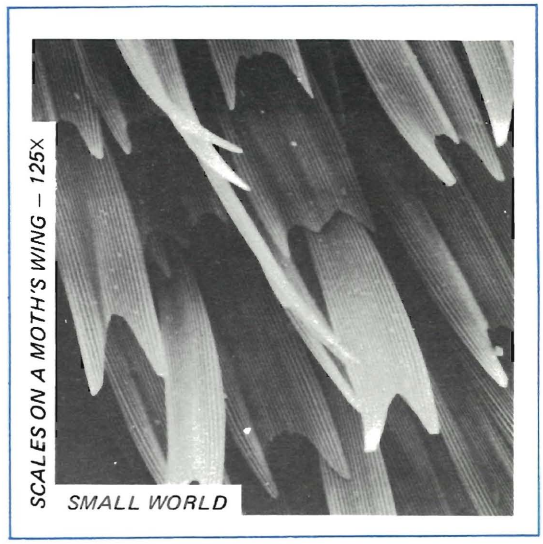
In 1968, when the success of the Russian Tokamak experiments became known in the United States, five separate Tokamak experiments were started in this country. All had different names, and they also had somewhat different objectives. At Oak Ridge, ORMAK was built primarily to test the possible advantages of a close, fat torus rather than the larger, more slender rings that were planned elsewhere.

But now we must back up and say what a Tokamak is. The main constituent is a strong toroidal magnetic field that is generated within a number of circular coils (ORMAK has 56) that are themselves arranged in a circle. A ring-shaped metal vacuum tube threads through the coils; this tube is to contain the experimental plasma. In ORMAK, the minor diameter of this tube is 46 cm, and the major diameter is 158 cm. A big iron transformer core links through the hole of the complete doughnut, and the primary coil is connected through a switch to a large battery bank. When the switch is closed, a discharge in the low-pressure gas within the toroidal vacuum tube acts as a single-turn secondary in the transformer (actually with some coils running the long way around the outside of the tube as an intermediary), and the plasma current around the ring can amount to hundreds of thousands of amperes. The pulse lasts nearly a tenth of a second, and during this time the diagnostic instruments extract information about the plasma density and the electron and ion temperatures, as functions of both position and time.

Such are the bare essentials of all Tokamak experiments. The associated details in ORMAK include another set of windings, parallel with the vacuum tube, producing a weak vertical magnetic field for positioning the plasma, a set of big motor generators and contactors for the magnetic pulse in the main windings, an outer vacuum vessel, and a cooling system that cools the complete internal system (windings, core, and all) down to liquid-nitrogen temperatures so as to take advantage of the increased electrical conductivity in the main windings at that temperature and thus get a higher magnetic field. Then, of course, there is all the instrumentation and computer handling of the data. The design, construction, and use of ORMAK constitute a major effort involving the help of many people; leadership has been given by George Kelley, Mike Roberts, John Clarke, and Lee Berry.

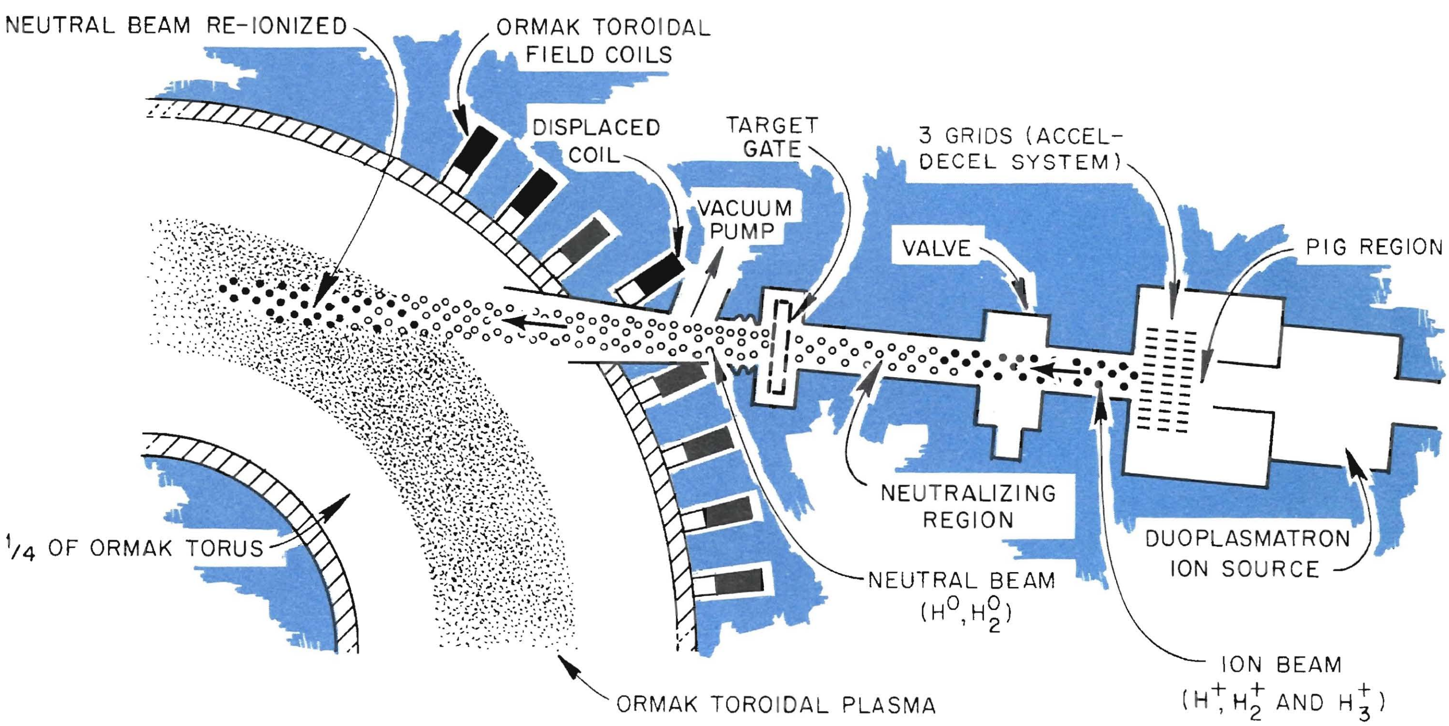
After a year spent in debugging and in gaining operational experience on ORMAK, some important results have been established. To explain them, we must first consider for a moment the nature of the particle orbits in a Tokamak. The electrons and ions move in helices whose axes are directed along the direction of the resultant field of the main toroidal coils combined with the self-field due to the large plasma current flowing around the torus. This is a field direction that twists as it goes (mainly lengthwise) around the torus. We are concerned with the length of the particle tracks as they follow this twist. In a fusion reactor, the particles will on the average pass completely around the torus several times before they suffer a Coulomb collision with another particle. This is the "collisionless regime" — a term that is confusing because a fusion reactor certainly will not work without collisions, but which is acceptable in the context of the gentle direction-changing collisions. In all Tokamak experiments so far, the particles on the average progress only a fraction of the way around the torus before their paths are disturbed by collisions. Clearly the particle motions are qualitatively different in the "collisional" and the "collisionless" regimes, and in this respect experimental Tokamaks have so far not given a fair test of what is to be expected in a fusion reactor.

ORMAK has ventured into the "collisionless" regime — not completely as yet, but four times farther than any other Tokamak. The encouraging observation is that *no new energy or particle loss phenomena have appeared.* Next year's effort will be to go completely into the collisionless regime; this can be done by raising the temperature of the ions from the present value of about 350 eV to about 1000 eV. Thus, step by step, new territory is explored toward the goal of controlled fusion.



Intense Beams of Neutral Hydrogen

In the discussion of ORMAK, mention has been made of ion heating by means of injection of neutral atoms. The need for this arises because the toroidal discharge in ORMAK heats initially the electrons of the plasma, and as they get hotter their transfer of kinetic energy to the ions becomes less efficient. At the present stage of Tokamak development, the toroidal (Ohmic) heating has gone



Neutral beam injection scheme for ORMAK. An ion source is at right; the H^+, H_2^+, and H_3^+ ions from it are neutralized with or without dissociation in the central region, thence they pass into the magnetic field of the ORMAK torus to be reionized and trapped when they strike the ORMAK plasma at the left. About 100 kW of ion heating power per injector can thus be applied to the ORMAK plasma during an ORMAK pulse, which lasts about 0.1 sec. Particle currents are equivalent to 8 A during the pulse. The target gate is opened when ORMAK is fired but is usually left closed between the infrequent ORMAK pulses.

nearly to its limit; there is little payoff in ion heating to be derived from going to more intense toroidal currents. A supplementary heating mechanism is needed, and it is best if it works directly upon the ions.

Because of Oak Ridge experience, it has been natural to think of neutral beam injection as a possible answer. If the neutral particles are injected tangentially into the ORMAK toroidal plasma at some appropriate energy they will penetrate into the magnetic field, become ionized so as to be trapped with high efficiency, and their energy will be dispersed into the plasma. Computations have shown that within acceptable limits their disturbing influences should be tolerable, particularly if pairs of beams are injected in opposing directions.

The development of these beams under O. B. Morgan has been one of the major Oak Ridge successes in the past few years. Let us see how such a system works.

One starts with a hydrogen ion source called a duoplasmatron, well known in the trade. For Oak Ridge purposes, however, the duoplasmatron had to be modified to give beams of larger current and cross section, and the resulting source is called the duoPIGatron. In the duoPIGatron, a system of three grids extracts ions from a PIG region,* the ion beam being about 7 cm in diameter, and the acceleration voltage being 25 kV. The beam is pulsed with a duration of 0.1 to 0.2 sec (to match ORMAK), and the peak current is 8 amperes. The beam is a mixture of H^+, H_2^+, and H_3^+ ions, which is an advantage, as we shall see. The beam then passes through a length of tube containing neutral hydrogen gas, and the ions neutralize themselves by electron attachment, with or without dissociation. The result is a beam of H^0 and $H_2{}^0$ particles. This beam then runs into a target gate that is left closed while the neutral beam is being pulsed to get rid of impurities, but it is opened when ORMAK is fired, so that the neutral beam shoots into the ORMAK torus.

The injection of 101 kW of these neutral particles into ORMAK to give trapped protons of initial energy 8.3, 12.5, and 25 keV was accomplished successfully in 1973. Such a mixture of injection energies gives an initial and desirable randomization of the velocities of the trapped ions. It also includes some low-energy particles which are more effective at the start of the plasma heating cycle. The 101 kW figure is expected to be pushed to the injector design level of 125 kW, which would put 0.25 MW into the plasma when using a pair of injectors. This would double the heating power into the plasma, while use of all four injectors would triple the input power over pure Ohmic heating alone.

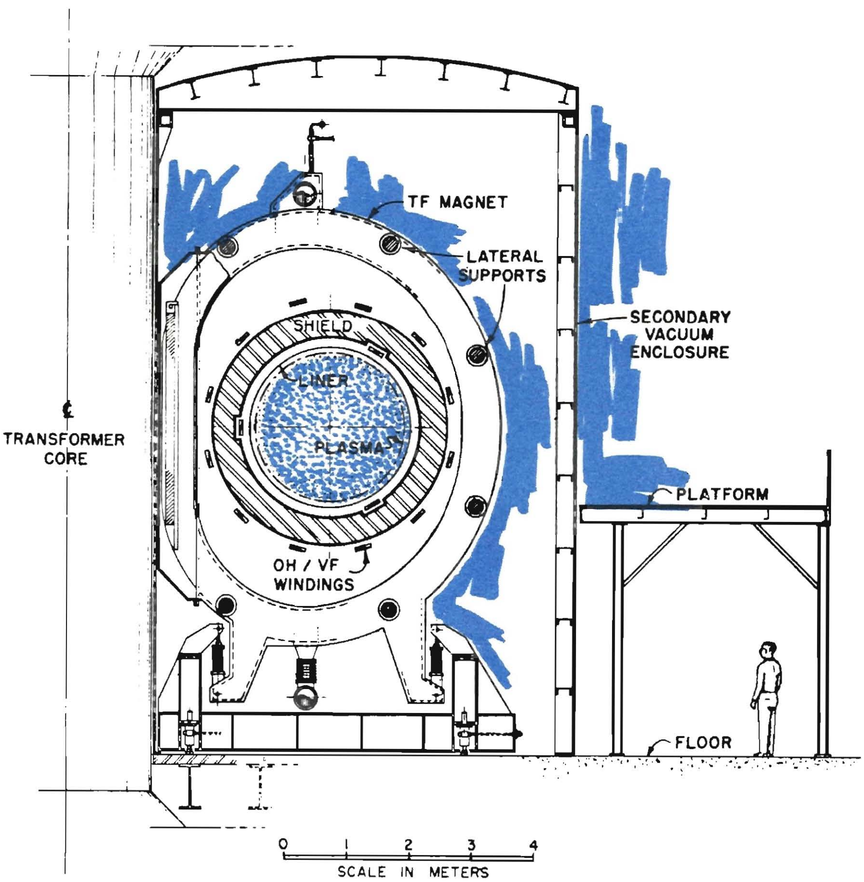
One attractive feature of these injectors is their overall efficiency, and another is that they are scalable to higher beam currents. This can be done by increasing the cross-sectional area of the ion source PIG region and the extraction grids. If the beam becomes too fat, focusing can be introduced by shaping the grids. At present we are limited only by our power supply, but we have enough to see if we can get the ORMAK ions up to a temperature of one kilovolt and thereby enter the "collisionless" or reactor regime of plasma operation.

*A potential well arrangement used in the Philips ionization gage.

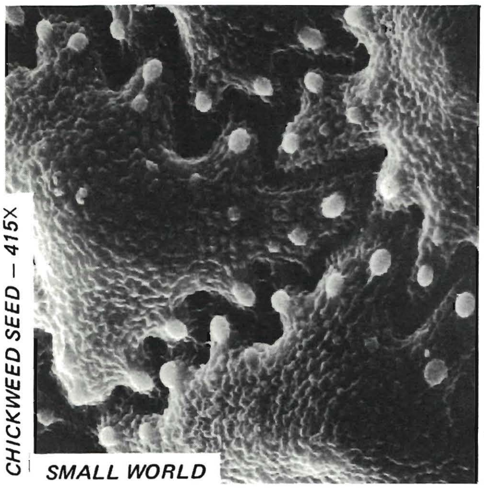
Future of ORMAK

The Tokamak approach with injection heating offers one of several prospects for a sequence of experiments leading hopefully to a prototype fusion reactor. ORMAK scientists and engineers devoted to the Tokamak reactor concept visualize five major steps which would, if successful, lead in about ten years from ORMAK with injection (ORMAKWIN?) to a scientific feasibility demonstration using hydrogen plasma. The crucial test of scientific feasibility is the product of density and confinement time, that is, $n\tau$. This $n\tau$ product would have to increase by a factor of about 1000 through the complete series of experiments — a major test of scaling laws as well as the ingenuity of the ORMAK scientists and engineers. Success in the feasibility stage would permit one to then convert the prototype device into an actual fusion burner using deuterium fuel and eventually deuterium and tritium fuel.

Recalling first that the goal is a value of $n\tau$ of 2×10^{14} sec cm^{-3}, the plasma parameters and operating characteristics that are hoped for may be cataloged as follows:



ORNL's ORMAK-F/BX — a large experimental facility designed for fusion feasibility and D-T burning and technology experiments in the early 1980's.



1972 *ORMAK.* Magnetic field 25 kG, ion temperature 350 eV, $n\tau = 4 \times 10^{11}$ sec cm^{-3}. Accomplished. Plasma behaves well partly into the collisionless regime.

1973 *ORMAK with injection heating.* Here the objective is to raise the ion temperature from 350 eV to about 1000 eV. This will move ORMAK well into the collisionless regime and test plasma confinement under more reactor-like conditions than have been realized before. The ion heating will be accomplished by injecting at first two strong beams of energetic hydrogen atoms into the ORMAK plasma. There the atoms will be ionized, and the kinetic energy of the beams will heat the whole plasma. Later, additional beams can be added. $n\tau$ might be edged up a little, to 6×10^{11} sec cm^{-3}.

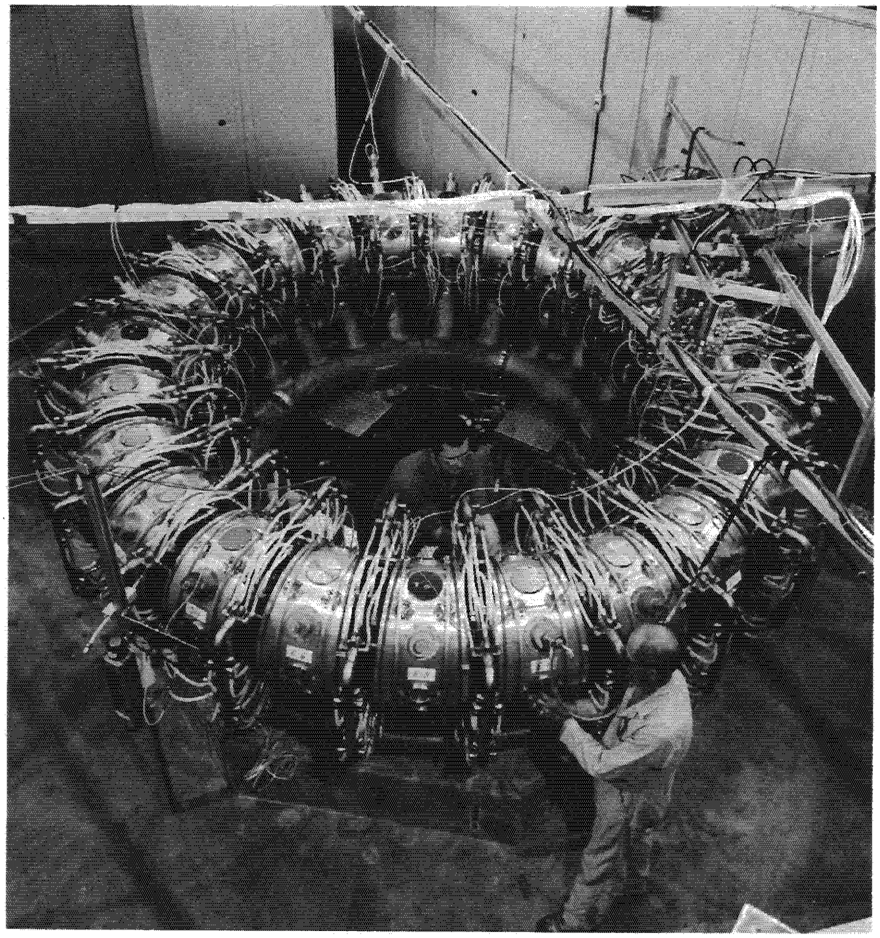
1975 *High-field ORMAK.* Dimensions are the same as preceding ORMAKs, but the magnetic field strength will be doubled (from 25 to 50 kilogauss), the maximum toroidal plasma current will be doubled (from 350 kiloamperes to 700 kiloamperes), and the injection heating power will be doubled (from 500 kilowatts to 1 megawatt). The $n\tau$ goal is between 2×10^{12} sec cm^{-3} and 10^{13} sec cm^{-3}. The high-field ORMAK will require a redesign of the main magnetic coils that surround the torus.

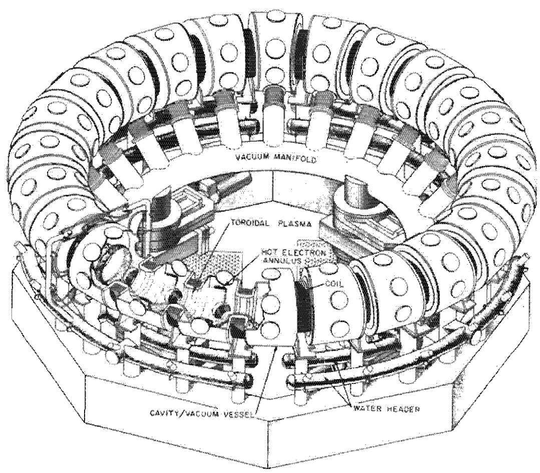
1977 *Microwave heating* (100 kW) may be added to the high-field ORMAK in addition to the injection heating. The ion temperature desired is 3 keV.

1980 The whole apparatus is now vastly expanded into a Feasibility/Burning Experiment (F/BX). The feasibility part of the experiment is designed to reach and test with hydrogen the Lawson criterion of $n\tau = 2 \times 10^{14}$ sec cm^{-3}, where with a DT mixture and an ion temperature of 5 keV the plasma would be expected to generate enough nuclear power to keep itself hot. Tritium, however, would not actually be introduced at this stage. The main coils are expanded so as to have a 4-meter bore, and the torus has a major diameter of 6 meters. The coils may be either cryogenic or superconducting. There will be lots of room inside this big torus, and the plasma won't occupy much of it. Divertors may be added; these are devices that purify the plasma. The toroidal plasma current is 2100 kA, the injection power is increased to 5 MW, and the pulse length for the whole machine is greatly increased — from 0.2 to 0.3 seconds to 100 seconds.

1983 *The Burning Experiment.* This is the second part of F/BX, and it is the culmination — a plasma test reactor. The same coils are used as in the feasibility experiment, but there are more of them and they are arranged in a bigger torus. The plasma is now centered in the torus, and a shielding blanket is introduced because the DT mixture will be used, and all of the nuclear and radiation problems will be encountered. The injection heating power will be boosted to 10 megawatts, and the pulse length will again be 100 sec, the duty cycle being 1/10. The minor radius of the plasma is at least 75 cm, because at 50 kG this size is needed for retention of the alpha particles from fusion, which will supply the nuclear heat to the plasma.

Such would be the road ahead. We must proceed along it to see how far we can go!





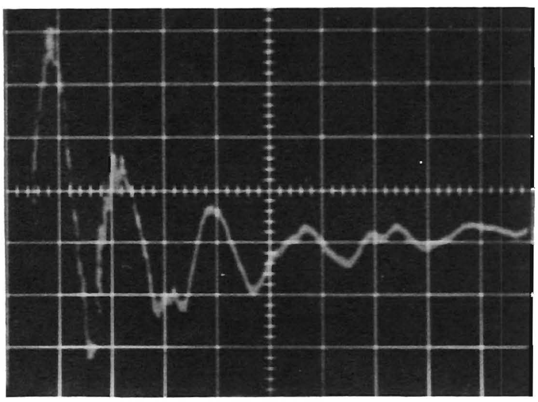
The ELMO Bumpy Torus. Nineteen seventy-three saw the assembly and initial testing of this unique plasma confinement experiment. Earlier work at ORNL by R. A. Dandl and his colleagues had shown that a microwave-heated plasma could be held stably between two parallel magnetic mirror coils, losses occurring mainly at the ends — that is, through the throats of the coils. When the coils were tilted one with respect to the other, the stability was still good, so the logical step has been to arrange 24 coils in a circle so there can be no end losses from the system. Hence the torus shown in this picture. The light-colored sectors are walls of the vacuum chamber; they contain microwave cavities, and the pumping manifold can be seen inside the circle. The magnetic coils are in the intervening dark regions. The word "bumpy" refers to the magnetic field, which has 24 alternating strong and weak regions around the circle, or to the plasma shape, which expands in the weak-field regions. The next 12 months should tell us how the apparatus performs as a plasma confinement and heating system.

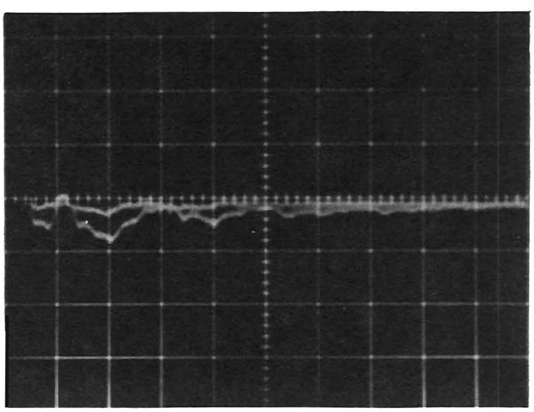
The Blascon

One of the major active fronts in controlled fusion research at present is the use of short, powerful laser pulses to heat pellets of frozen deuterium-tritium mixture to fusion temperatures. In this process, a D-T pellet less than a centimeter in diameter would be dropped or impelled into a reaction space, the pulse of light would strike it in flight, implode and heat the mixture to nearly a billion degrees centigrade in about a billionth of a second, and cause the fusion reactions to take place before the material could blow apart. There would then be a waiting period of some tens of seconds while the laser power supply recharged and the nuclear heat was removed for use, after which the next pellet would be dropped and the process would repeat.

Such a system has two great advantages over fusion systems that depend upon a confined plasma, and it also has two great difficulties. The advantages are that all of the problems of stable magnetic confinement disappear, and that (as we shall see) the vital radiation damage problem in the fusion reactor wall may also disappear. The difficulties are that the powerful, efficient laser systems have to be developed (with their associated optics) and that the reactor vessel must be able to withstand millions of explosions, each of which is equivalent in energy to about 100 kilograms of TNT, because smaller explosions will not provide the required energy gain.

Oscillograph traces of shock waves that reach the wall of the Blascon model. The upper trace shows the strain produced in the wall by a central explosion when the plastic sphere is filled with static water. The lower traces show the reduction in strain when swirling water is used with small air bubbles; the upper of these was obtained with a small vortex and the lower with a larger vortex.

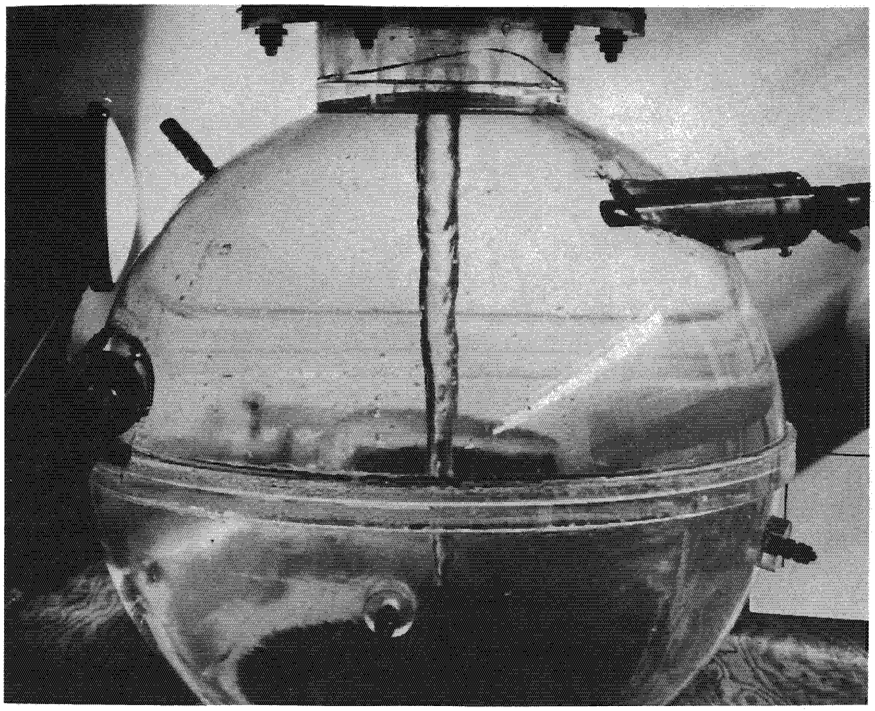




For some years a group under A. P. Fraas has been working on this last problem on a modest scale, using what we call the "Blascon" concept. The idea is that the fusion explosions would take place in the vortex cavity of a sphere of swirling molten lithium, and that bubbles in the lithium would absorb the shock of the explosions. The lithium would then serve a quadruple function: as a radiation shield (thereby alleviating the radiation damage problem), as a shock absorber, as a fluid for heat removal, and as a breeder of tritium.

During the past year our work has been aimed principally at understanding more fully the shock absorbing properties of lithium. The energy of the explosion will be transmitted to the lithium in two ways: about one-quarter will be carried by x rays and alpha particles, and about three-quarters by fast neutrons. The sudden absorption of the energy in the lithium creates an outward-moving stress wave that must eventually reach the containment vessel, and the maximum stress ought not to exceed the fatigue limit of the wall material, remembering that the vessel will be hot. In full scale, the fusion energy release would be some 10^9 joules per explosion, and in the Blascon concept we have taken the (spherical) containment vessel to be 3.6 meters in diameter.

As the x rays and alpha particles hit the lithium they will immediately vaporize a layer about one millimeter thick from the inner surface, using 93 percent of their energy in doing so. Assuming



A model of the proposed laser fusion containment scheme uses swirling water instead of molten lithium. The plastic sphere containing the water is 18 in. in diameter. The picture was taken without bubbles in the water and shows the deep vortex cavity where in an actual reactor the fusion explosions would take place.

no bubbles, the remaining 7 percent is transmitted as a shock wave in the liquid lithium, which attenuates and heats as it goes. By the time it reaches the vessel wall it will be degraded to an acoustic wave, and it will have lost 98 percent of its energy in heating the lithium. The peak radial strain produced in the vessel wall is calculated to be 1.6×10^{-3}.

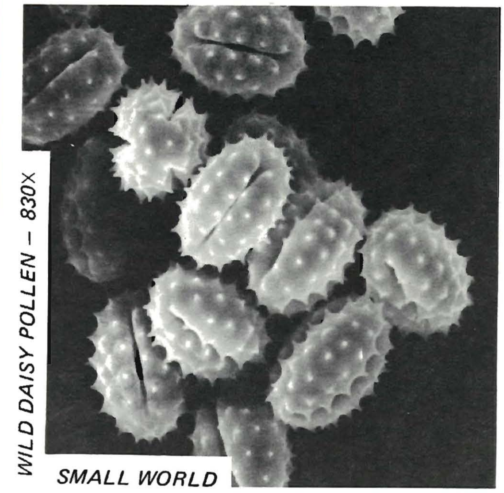
The neutrons will have a larger effect. Since they penetrate deeply, the energy will be more evenly distributed through the lithium and will amount to a sudden heating. This drives a pressure wave toward the wall. Treating this as an acoustic wave, the peak radial strain from the source is found to be 9.8×10^{-3}.

Together, these two radial strains are about ten times larger than one would like, so we now introduce the bubbles. We find that if one percent of the volume of lithium is occupied by gas bubbles, the situation is not improved (indeed, it may be worsened), but that when 5 percent of the volume in the central region near the exploding pellet is occupied by bubbles, they absorb the volumetric expansion of the lithium to such an extent that the pressure wave is simply of no consequence.

These ideas have received qualitative confirmation in tests using a small mockup comprising a water vortex in a Lucite sphere 18 inches in diameter. Shocks were introduced by exploding wires in the middle of the vortex, and strain gages attached to the Lucite registered the impulse felt by the shell. With static water, the pressure stress felt by the Lucite was 138 psi; with swirling water and a cavity in the vortex but with no bubbles, the stress was reduced to 24 psi; and when small bubbles were introduced in the presence of a small vortex, the stress dropped to 3 psi.

A better scaling test is now needed, but at least the prospect exists that a laser fusion engine may not demand a steel confinement shell about one meter thick.

Energy Utilization and Conservation



Potassium Vapor Cycle

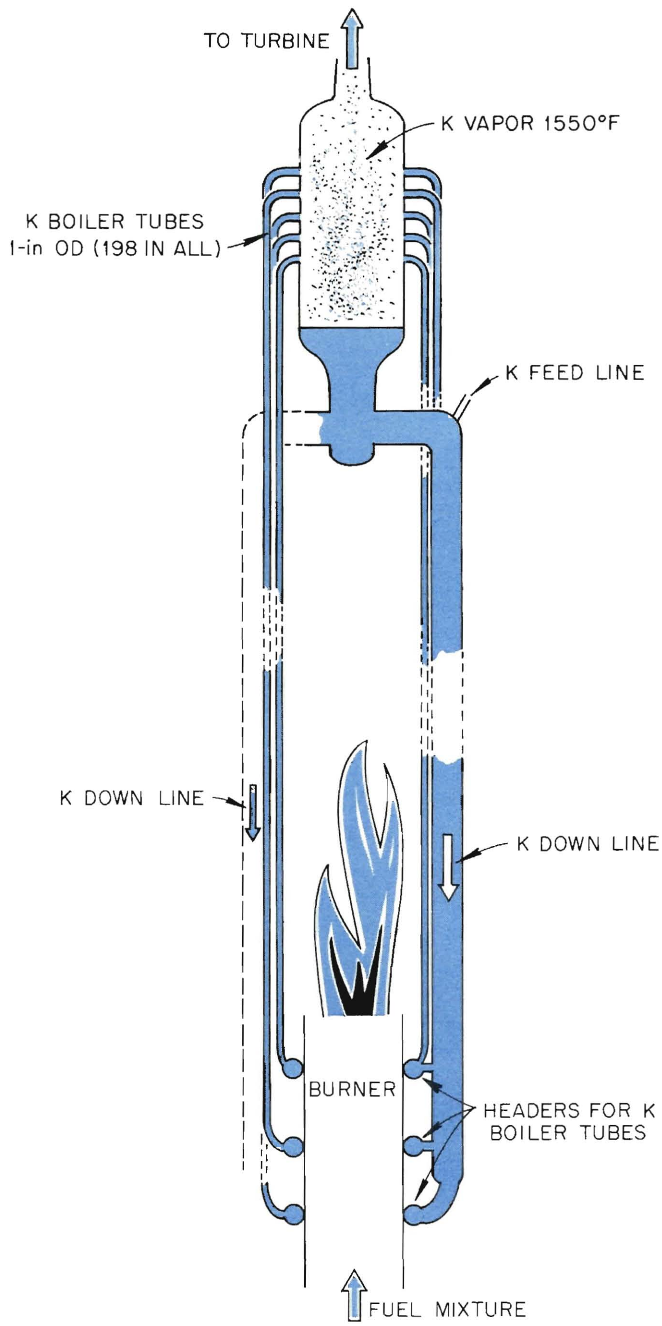
The efficiency of large electric generating plants is clearly of central importance not only as a matter of direct economics of the plant operation, but also from the points of view of good use of natural resources and reduced environmental threats. Modern fossil-fueled plants run at efficiencies of up to 40%; water-cooled nuclear plants run at about 30%.

A basic limitation upon the efficiency is associated with the almost universal use of the steam cycle. The maximum temperature of the steam entering the turbines is about 1000°F; above this temperature steam becomes too corrosive, and furthermore the structural strength of materials goes down, which is bad in view of the high pressures involved (4000 psi). Yet if the temperature at the inlet to the turbines could be raised to 1500°F, keeping the same outlet temperature, the plant efficiency would be raised correspondingly.

The idea of the potassium vapor topping cycle is to do just that. The boiler would boil potassium at 1540°F, where its pressure would be only about 15 psi above atmospheric. At this low pressure, strengths of appropriate metals will still be sufficient even if they *are* bright red. The potassium would expand through a low-pressure turbine, and emerge at 1000°F. Then it would be used to heat steam to 1000°F, and a conventional steam plant would take over. The promise is that the efficiency of the overall plant would be raised to 50%; the fuel consumption for a given power output would be reduced by 25%, and the waste heat rejection to rivers, lakes, or cooling towers would be cut nearly to one-half.

We had considerable experience in running potassium-vapor turbines in research for the Space Nuclear Program several years ago. At that time A. P. Fraas and his colleagues had red-hot turbines running almost unattended for thousands of hours, because in the space nuclear work reliability was a prime consideration. The development stopped when the program stopped, but during the last year interest has revived with central generating stations in mind, supported at ORNL by funding from the National Science Foundation. Since the biggest engineering uncertainties appear to lie in the potassium boiler, the present work has concentrated in that direction. A 600-MW(e) gas- or oil-fired plant would have a boiler consisting of 148 "modules" in the ORNL concept, each module being a bundle of about 150 tubes. Thus the work has centered about the design, construction, and testing of one tube bundle and burner module of a gas-fired prototype boiler.

When the prototype is complete, it will be tested for power output, operability, corrosion, and economics. Later steps in the program will deal with the condenser and the turbine as adapted to central-station use.



Section through a 22-ft-long, 28-in.-diam potassium boiler tube bundle module of the type being built under the NSF-RANN-ORNL program. The flame from the burner is directed upward into the cylindrical cavity formed by the boiler tubes.

It should be noted that the potassium-steam binary cycle is not limited as to the nature of the primary heat source. It could be adapted to coal, oil, or gas-fired plants, and to nuclear plants. It seems to be peculiarly well adapted to a controlled-fusion power plant inasmuch as such a plant would likely have a niobium reactor vessel cooled with lithium to provide the necessary tritium breeding. Potassium seems to be happily compatible with these materials. The binary cycle could also be adapted to the fluidized-bed coal burners that are now under discussion because of their promise in control of sulfur emissions, provided that corrosion problems do not arise in the boiler.

Cold Vapors and the Bottoming Cycle

There are a number of sources of low-temperature heat in the world which, if skillfully exploited, might aid in meeting our energy demands. Among them are solar radiation, geothermal sources, and the available steam of power generating stations that has gone through turbines but is still at pressures above atmospheric. A group under R. N. Lyon (including S. L. Milora, L. C. Fuller, and D. G. Thomas) has been working, with support from the Division of Applied Technology of the AEC, to see what practical thermodynamic cycles can be found that can produce work in going from initial temperatures as low as 80°F to a final temperature as low as that of winter air or perhaps deep ocean water. The appropriate working fluid would be a substance whose boiling point is below the temperature of the "heat sink." We call such media "cold vapors."

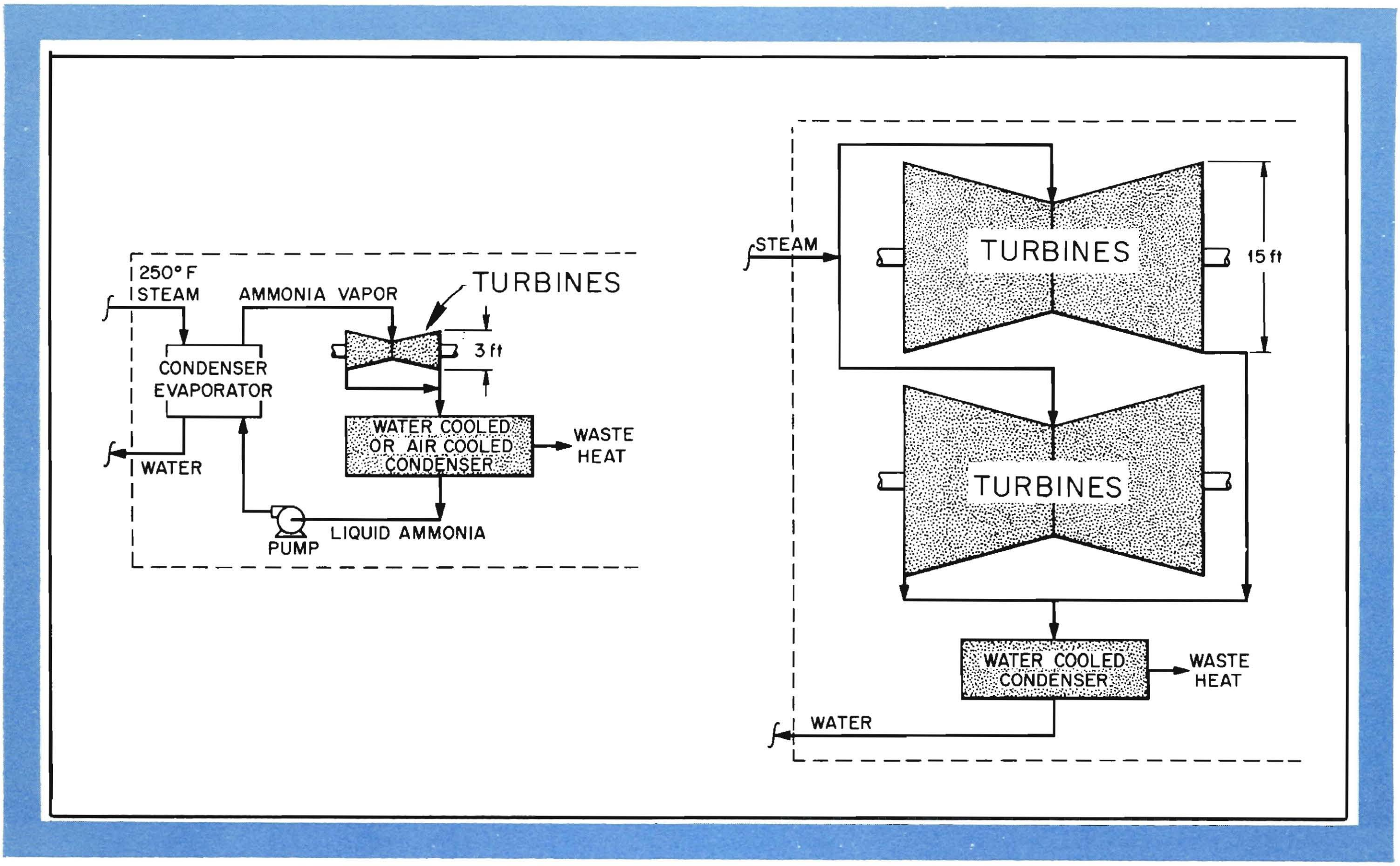
When the source supplies heat at a constant temperature, as does low-pressure steam, the critical temperatures of the best working fluids are above the temperature of the heat source. When the source is hot water, or some other fluid that delivers heat over a temperature range, the best working fluids may have critical temperatures below the initial temperature of the source fluid.

One might at first think that a system operating at low temperatures would necessarily require ducts and turbines that would be uneconomically large. This turns out not to be true. The potential rate of work production from heat in the vapor near the end of its expansion cycle is roughly proportional to the latent heat carried by the vapor multiplied by the difference between the initial temperature of the vapor and the temperature in the condenser. Thus the volume of vapor required to carry a given amount of heat (measured for example in cubic feet per 1000 Btu) becomes a relative measure for duct areas for vapor moving at a given velocity in a power station of given output. The following table gives roughly the relative sizes for the ducts (and incidentally the turbines too) when four selected cold vapors are used, in contrast to steam.

Vapor at 100°F	Cubic feet per 1000 Btu (relative duct sizes)
Ammonia	3.0
Freon 12	5.6
Isobutane	7.0
Propane	4.1
Water	340

From these figures it is apparent that an ammonia bottoming cycle attached to a steam generating plant may be physically quite a

These two flow diagrams contrast the compactness of the two 3-ft-diam ammonia turbines (left) in the bottoming cycle of a large [1000 MW(e)] binary-cycle power plant with the four 15-ft-diam low-temperature steam turbines required in a comparably rated conventional plant. The binary cycle increases the practical alternatives for heat rejection, because the heat is rejected at a lower temperature, and allows better exploitation of low cooling temperatures. Moreover, the ammonia turbines operate more efficiently than the low-temperature steam turbines. Single cycles using ammonia or other low-boiling-point fluids can also be used to extract useful power efficiently from geothermal sources, from simple solar-heat collectors, or from industrial waste heat.



modest affair, and we are centering our study on such a system. It may turn out that the main advantage will be a lessening of the thermal output of the plant; this would ease the environmental impact, and introduce economies in the plant's cooling system.

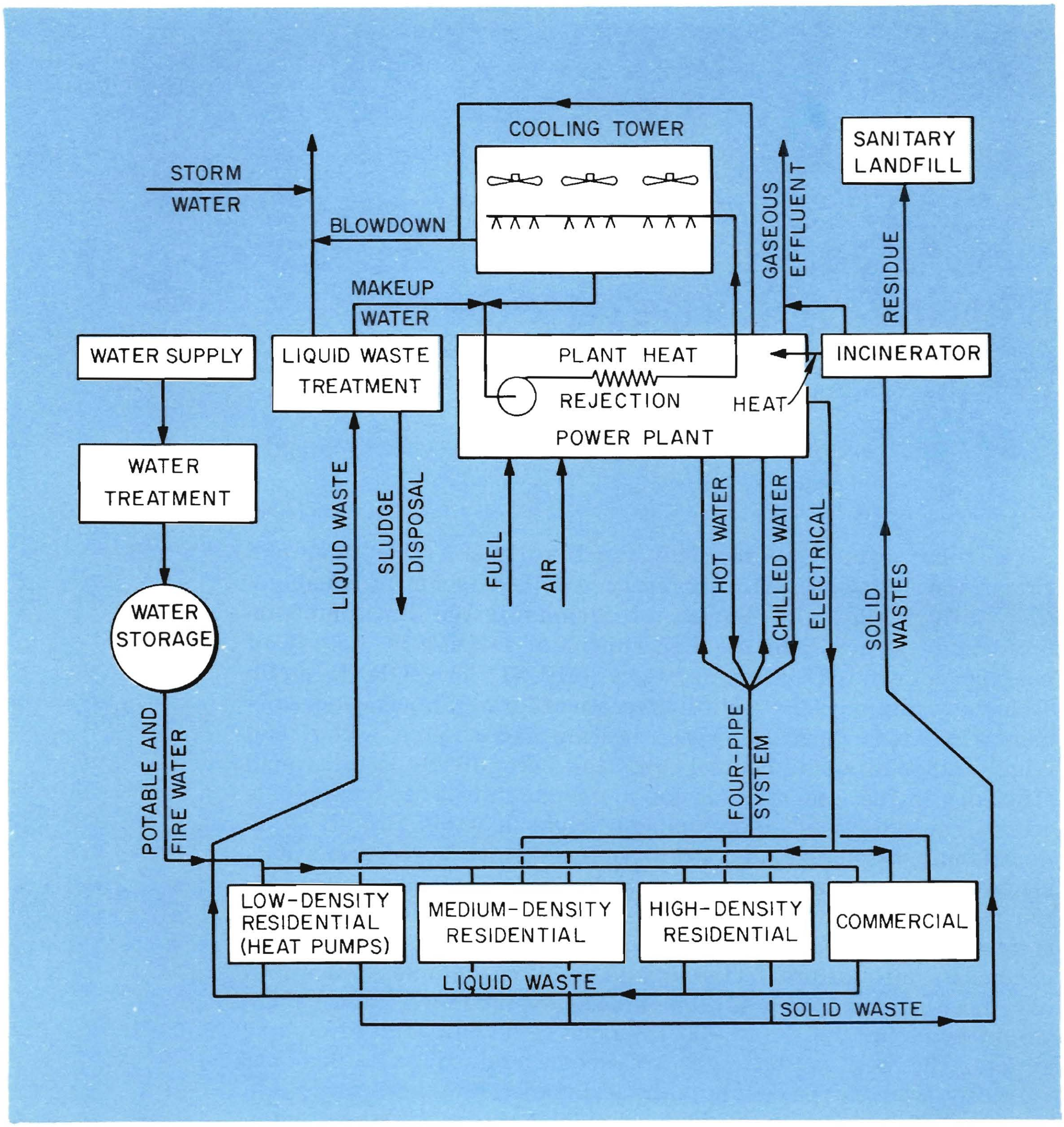
It is perhaps obvious from the above that if the waste heat from a generating plant were to be used for space heating or air conditioning, the use of a cold vapor for heat transport would permit the use of smaller pipes than would be needed if the steam were used directly. More efficient heat transport also improves the practicality of dry cooling towers that condense the vapor directly and dispose of the waste heat without any requirement for, or impact on, rivers or other large bodies of water. Thus cold vapors open new possibilities for siting large power stations.

Modular Integrated Utility Systems

In this program sponsored by the Department of Housing and Urban Development, the Laboratory provided technical collaboration with NASA, the Bureau of Standards, the Environmental Protection Agency, and the Department of Defense in a study of modular integrated utility systems (MIUS). The ORNL group evaluates various on-site utility alternatives for new housing developments in which electrical, space heating and cooling, water, and liquid and solid waste disposal subsystems are integrated for overall efficiency in fuel use, minimal environmental impact, and acceptable costs. The "housing" development might include 100 to 3000 multifamily dwelling units, nearby single-family houses, and associated commercial facilities.

The HUD study is aimed mostly at combinations of utility system components which are available now, with only modest excursions into future technology. Thus, for example, evaluations have been made of the best prime movers for the power plant (which would be in the 300 to 10,000 kW range), the best kind of cooling system, the best waste water treatment, and so on, which are currently available. Several hypothetical models have been set up and evaluated; for example, a 720-dwelling-unit garden apartment complex of 60 buildings located in a climate similar to that of Philadelphia. On this may be built variants, such as whether or not some of the apartments have heat pumps rather than service from district heat and chilled water systems. The best prime movers now available commercially for this MIUS power plant appear to be internal combustion piston engines. Whenever possible, the MIUS employs heat recovered from their cooling and exhaust systems for building heat, water heating, and absorption air conditioning. The study extends to a survey of the environmental effects of the system (acceptable), whether or not it pays to incinerate the community's solid wastes in the MIUS plant (on this scale today it usually does not), and to what extent liquid wastes could be reused (with available on-site treatment, the water would be acceptable for most uses except human consumption).

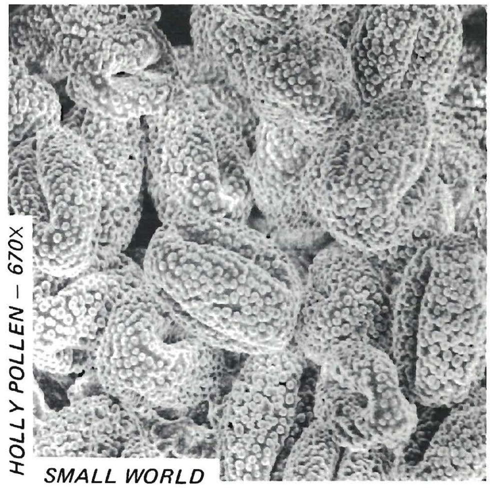
The main conclusion so far of the ORNL study is that a well-designed MIUS could be 10 to 50% more efficient in fuel energy utilization than new conventional systems in most parts of the



Schematic of one MIUS concept.

United States. If several such systems were operated and maintained by a single organization, the cost of energy-type utility services would be in the same range as that of most conventional systems. The cost of incorporating on-site liquid and solid waste treatment would depend on the community size and growth pattern and the capacity of the community's utilities.

The study provides HUD with information that will serve as a basis for demonstration systems of various kinds to be built and evaluated under actual living conditions. The experience provided by these demonstrations will bear heavily on the acceptance of on-site utilities by developers, regulatory agencies, and the general public. The probability for significant use of MIUS will also depend on trends in housing density and the availability and cost of various types of fossil fuel. With the latter factor in mind, studies on the potential for development of on-site coal-fired prime movers are now being accelerated.

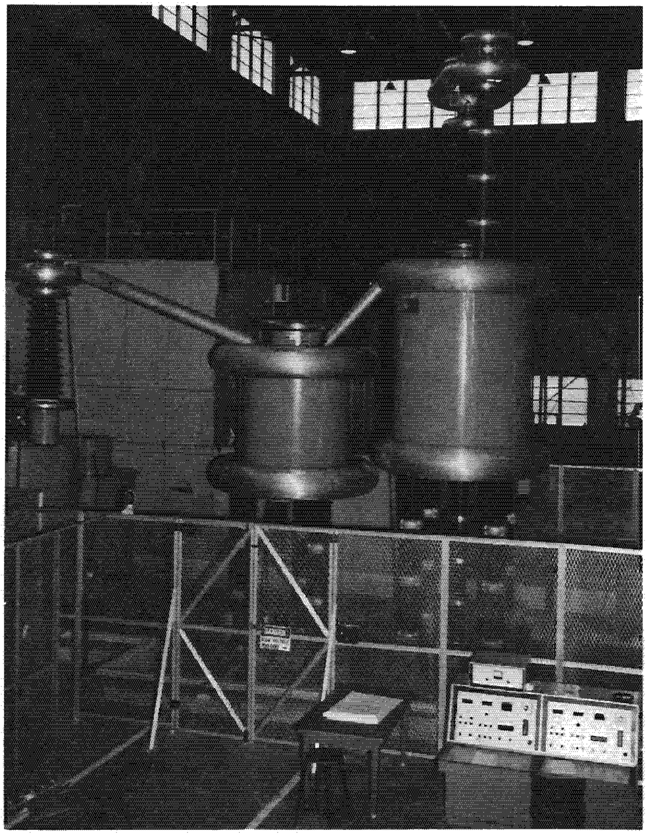


Superconducting Cables

Reduction in the cost of underground electric power transmission is recognized as a critical task if the utility industry is to meet the nation's needs without undue cost while preserving the amenities around power plants and load centers. Cryogenic and superconducting cables operating at temperatures from 90°K down to 4°K are being developed with expectation of power capabilities 4 to 10 times larger than those of present cables, while at the same time offering substantial reductions in investment. The Laboratory is engaged in this work from the point of view of supplementing our knowledge of the basic properties of the conductors and insulators that must be used in cables of this kind. The studies are directed by Hugh Long.

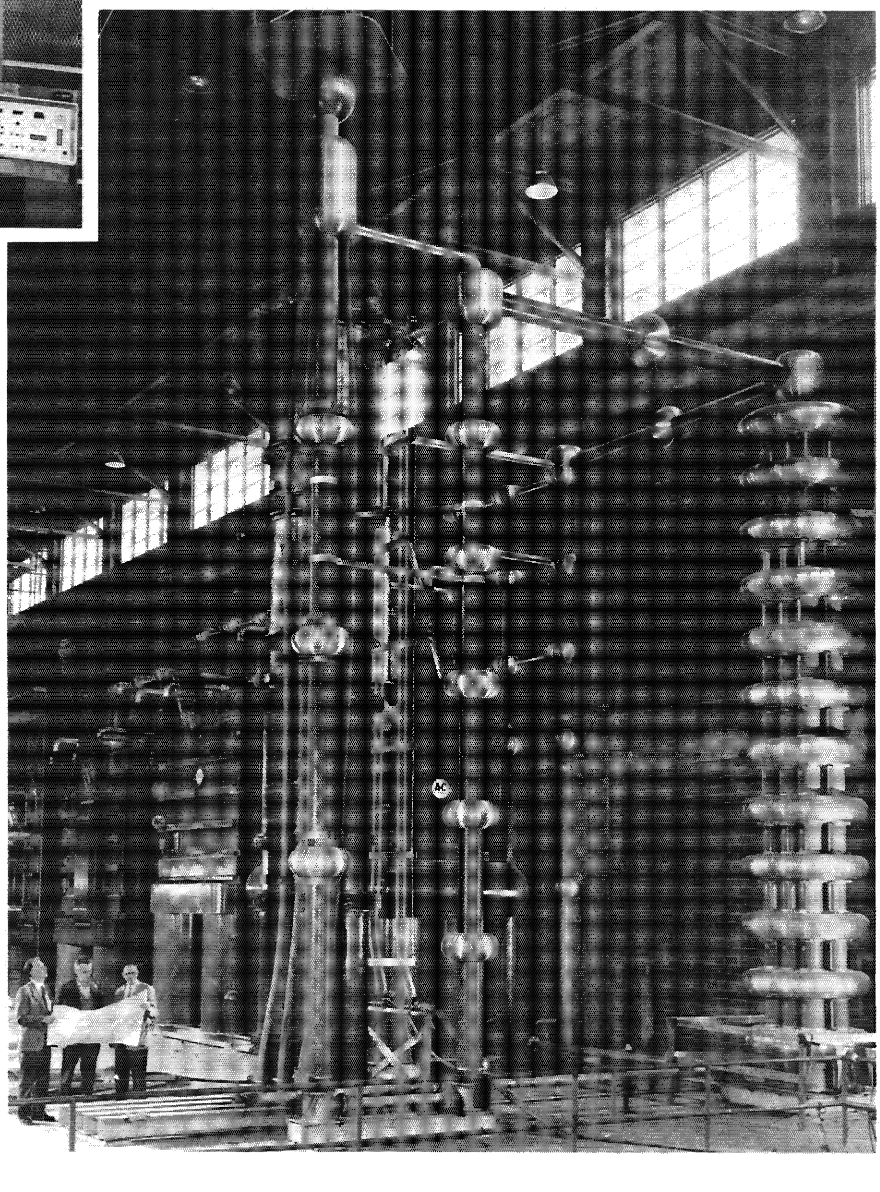
As regards the insulators, low-temperature dielectric investigations to date have been so limited in voltage, gap length, and test power that there are insufficient data and understanding for proper engineering design of either the cryogenic or the superconducting cables. Hence an important part of the work will be directed to this area. For dc dielectric breakdown tests we have available the large DCX-2 600-kV power supply; for ac work a new 700-kV (rms) power supply is being installed. First liquid helium and liquid nitrogen will be investigated; after that other liquid, solid, and gaseous insulators will come under scrutiny.

As regards the conductors, two investigations are in progress. One is directed to an understanding of ac loss mechanisms in high transition temperature superconductors such as pure niobium and the niobium-tin alloy Nb_3Sn. The other is centered around aluminum, because at low temperatures very pure aluminum ("six nines") may have an electrical resistance 30,000 times smaller than at room temperature. The softness of the pure aluminum is, however, a problem, and the Laboratory is studying methods to strengthen the aluminum while preserving the low resistivity.



New 700-kV ac power supply for use in dielectric studies of cryogenic power lines.

The old DCX-2 power supply, which will be used for dc dielectric studies for cryogenic power lines. Rated at 1 A and 600 kV, it gives a husky power backup for the breakdown tests.



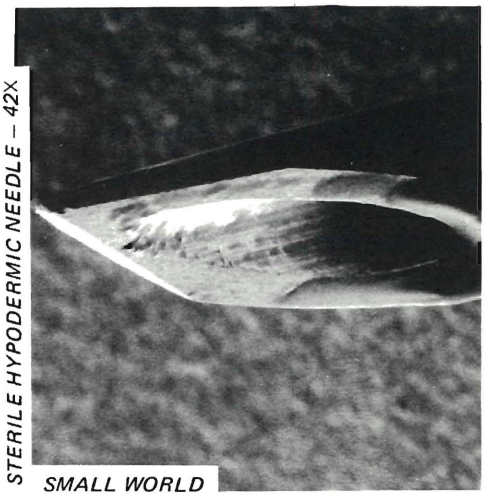
Environment

Impact Statements

The National Environmental Policy Act of 1969 (acronym NEPA) and its subsequent judicial interpretations have required the AEC to issue environmental impact statements to support any proposed licensing actions by the Commission. These statements must include detailed descriptions of the plants and independently assess the impact of their construction and operation on the community and the environment. In addition, they must provide an analysis of the benefits versus the costs of the plant and its possible alternatives. The preparation of such a comprehensive analysis requires contributions from varied disciplines: reactor engineering, hydraulic and meteorological modeling, environmental sciences, economics, and sociology.

A group has been established at ORNL, with participating staff from numerous functional divisions of the Laboratory, acting as an extension of the AEC Directorate of Licensing in the preparation of these statements. E. G. Struxness directs the local group. After issuance in draft form and review by many concerned public and private agencies, the final environmental statement forms a principal part of the evidence considered by the Licensing Board in its public hearings on the licensing of the particular nuclear plant involved. In many cases, members of the ORNL team which has prepared the statement serve as expert witnesses at these hearings.

During this past year, the Environmental Impact Statement Group has been responsible for providing draft or final statements for about 20 major nuclear power facilities. For 12 of these, the proceedings have progressed to the point where construction permits or operating licenses have been granted.



STERILE HYPODERMIC NEEDLE — 42X

Each plant has its own individual characteristics, and specific environmental conditions, so no two of the analyses are fully alike. During the past year, there have been several studies sufficiently unusual to merit particular comment.

At Indian Point, on the Hudson River 42 miles upstream from its mouth, a large 875-MW(e) PWR is approaching operation. The plant uses the Hudson River to cool its condensers, in a once-through cooling system. Ecological studies of the plant and its effect on the environment revealed that the plant happened to be located, inadvertently, at a position on the river where an important phase of the life cycle of the striped bass occurs.

The Hudson River at Indian Point is an estuary. Below the placid surface visible to the casual observer a complex hydrological system of fresh and salt water flows, driven by the river itself and by tides from the ocean at the river mouth. The estuary is a rich nursery environment for a variety of aquatic life. The striped bass is a major food and game fish off the whole middle Atlantic coast, and ecological studies at ORNL showed that the species spawns in the Hudson and spends a critical period of its larval and juvenile stage at a region of the estuary where the Indian Point station happens to be located.

The presently installed open-cycle heat rejection system passes Hudson River water through the condensers at 2650 cubic feet/second, about 13% of the average flow in the river. Many of the floating, sessile fish eggs and larvae which drift past the plant are entrained by this flow and pass through the condensers, where they are subjected to lethal thermal and mechanical shock. It is estimated that 30 to 50% of the striped bass larvae which migrate past Indian Point are likely to be killed by this entrainment. In addition, larger fish are killed by impingement against the intake structure screens. These combined effects lead to the conclusion that the open-cycle cooling system could reduce the striped bass fishery along the middle Atlantic coast by 30 to 50%.

This impact was deemed excessive if it were to continue indefinitely, and the analysis led to the requirement that a closed-cycle cooling system, which could be designed to withdraw only 125 cubic feet per second from the Hudson, must be installed prior to mid-1978 to avoid permanent damage to the species.

The Duke Power Company is proposing to build a 2000-MW(e) station on Lake Wylie, which is a dammed-off portion of the Catawba River, in northwestern South Carolina. The heat rejection system proposed is once-through flow. Under conditions of low river flow, our analyses showed that excessive lake water temperatures would occur. These could have adverse ecological impacts on fish species locally present, and on the relative population of various algal forms. A considerable portion of the lake could become too hot for satisfactory recreational use, but the greatest concern is associated with the resultant suitability of drinking water withdrawn from the Catawba River by two towns downstream from the Lake Wylie Dam.

An unusually intensive and original evaluation of alternative cooling systems was carried out for this plant by the Oak Ridge National Laboratory group. Engineering practicality, environmental impact, initial and operating cost penalties were assessed. The conclusion appears to be that cooling towers should be designed to replace the once-through system unless the applicant can conclusively show that another alternative is preferable.

Mendocino is a remote town of less than 500 people, located at one of the particularly scenic spots on the California coast about 150 miles north of San Francisco. The town sits astride California Highway 1, which hugs the rugged coastline for hundreds of miles, with only infrequent transverse access roads, one about 75 miles south, the other about 40 miles north of Mendocino.

A site on the Mendocino coast was being considered for the installation of a large nuclear power facility. As is the practice, after review of the applicant's environmental report, the ORNL team spent a week at the site reviewing the environmental and community circumstances existing there, in preparation for conducting the impact analysis.

In this case the plant location, the applicant's plan for treatment of the site terrain, the use of once-through cooling with water from the adjacent very vigorously mixed Pacific, all seemed to have acceptable environmental impacts.

However, substantial questions of social impact on a small remote community, and on the scenic character of Highway 1, arising from an extended period of heavy construction activities, were immediately apparent. These issues concern the impact of a 2000-man construction force on the schools, water and sanitation facilities, and social structure of a small isolated and hitherto rather dormant community. Much additional information turned out to be needed from the applicant on his construction schedules and means for coping with these potential issues. While these questions were being examined, the matter became moot because of the apparent unsuitability of the proposed site for seismic reasons. However, the preliminary investigation of such social issues by the ORNL staff was precedent-setting, and the Directorate of Licensing has asked us to prepare a summary document on this portion of the impact analysis.

These are three outstanding examples of the innovative work, in physical, biological, and social sciences, which has arisen during the preparation of impact statements on specific plants. In addition, there have been numerous general studies conducted to provide a generic base of information of utility in the analysis of many different plants. A series of conceptual design studies was carried out to identify the level of release of radioactive wastes, and the costs of various technologically feasible radwaste systems. This study was used to specify the criteria for the "as low as practicable" requirement of the AEC. Other studies have dealt with general fluid flow problems and computational methods for their solution, with chemical effects of chlorine and chlorine compounds on aquatic organisms, with the material resources used in the construction of nuclear plants. These general studies will serve to build up the "literature" of the environmental impact field.

Recently a new task was initiated which will grow in content and importance. This deals with the environmental impacts of off-shore floating nuclear power plants and will involve us in major new areas of marine engineering and ecology. The EIS program continues at a vigorous level at ORNL, and is dependent upon the variety of talents available at the Laboratory.

Nuclear Waste Management

The tentative plan for a Federal radioactive waste depository in an abandoned salt mine near Lyons, Kansas, has been placed in abeyance. The reasons were more political than technical, although it is to be noted that the citizens of Lyons itself strongly favored the project. Instead, the AEC has decided in favor of temporary surface storage of waste, under surveillance, while a long-range search is made for other underground sites.

The Laboratory's role has continued to be with the possibilities of the underground storage. A group under A. L. Boch, J. O. Blomeke, and W. C. McClain has been very active. In collaboration with the U.S. Geological Survey, a widespread study was made of possible alternative geologic formations and sites. The upshot of this has been a reaffirmation of the advantages of salt beds: they have been impermeable to water for millions of years; they occur in regions of low seismic activity; cracks and crevices repair themselves under plastic flow. The slightly elevated temperatures around the waste canisters would accelerate the plastic flow, and the wastes would be sealed in place, deep under ground. It is hard to imagine a place on earth that would require less surveillance.

Of a half-dozen salt regions in the U.S., a portion of the Permian basin in southeastern New Mexico appears to be most promising. It has advantages over the Kansas site in that there is less groundwater, there are fewer exploratory bore holes left by oil prospectors, no nearby mining operations, and the region is sparsely settled. It is likely that the Laboratory will accordingly recommend a bedded salt pilot plant repository, in which techniques and experience in waste disposal could be obtained over a period of perhaps ten years under conditions of full retrievability should difficulties be encountered. If the experience is favorable, this same region could then be developed into a full-scale repository. A depth of 2000 ft seems better for the New Mexico site than the 1000 ft chosen for the Lyons mine; this means that the mine design may be somewhat different, but much of the technology and the associated calculations (of the temperature distribution around the radioactive material, for example) that were made for the Lyons site are transferable to the new location.

Meanwhile there is the matter of plugging boreholes that may otherwise allow penetration of water. Slipshod methods won't do when you need tightness for periods of time measured on the geologic scale. Work is in progress to develop sophisticated methods of plugging these holes above, within, and below the salt formations. Initial tests have been made using various kinds of cement, water seepage under 100 psi of pressure being measured after the cements have hardened. One particular cement (type III Stress-Ex) was found to be quite impermeable. For good bonding to the borehole walls, the remnants of drilling mud must be removed.

Effects of Thermal Effluents

In order to answer many of the ecological questions that are raised about nuclear power plants, the AEC has constructed an Aquatic Ecology Building and six quarter-acre experimental ponds as part of the Oak Ridge National Laboratory. The building was completed and partially equipped in the fall of 1972. After about three months of equipment testing all installed facilities are now operating, and experiments are under way under the overall direction of C. C. Coutant.

The principal objective of the studies is to determine the biological limitations which can be used as design criteria for power plant siting, construction, and operation. The same scientific staff is assisting AEC Regulatory in preparation of environmental impact statements for power plant licensing under the National Environmental Policy Act. There is no better way to insure that the studies they conduct will be relevant to real problems.

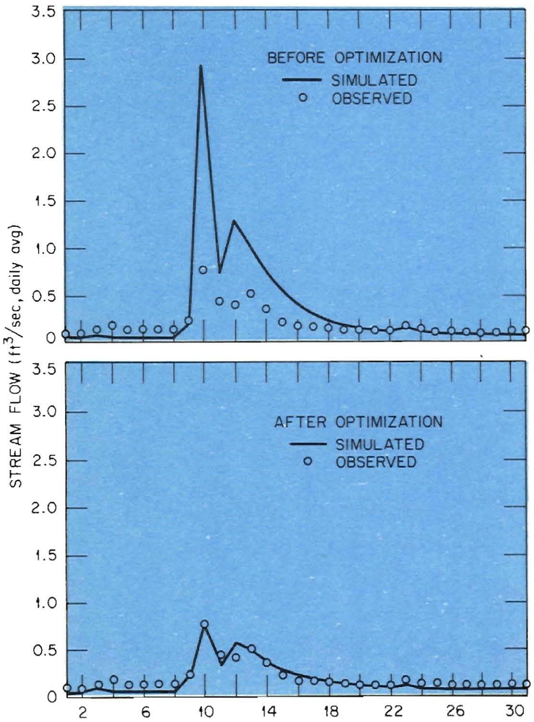
The laboratory experimentation conducted on aquatic life in this facility complements field studies being made at Bull Run and Kingston power plants. True predictability for environmental effects of power plants requires judicious application of data from both sources.

Some experiments now under way include determination of (1) survival of fish and other organisms at elevated temperatures, (2) growth rates of fish throughout the range of tolerable temperatures (studies that also determine the best temperatures for aquaculture in heated water), (3) predation rates on fish exposed to rapid rises or drops in temperature, (4) preferred temperatures as chosen by fish in the natural environment, using temperature-sensing fish tags developed by ORNL engineers, and (5) the mechanical deformation of fish eggs and larvae as they pass through pumps and piping of condenser cooling systems.

The latter studies illustrate redirection of scientific talents at ORNL once devoted to reactor development. Hydraulic engineers, using experimental facilities designed to study particles flowing in the molten salts of the molten salt reactor, are now doing similar studies to determine the physical design factors that will protect living "particles" as they pass through condensers.

Large circular tanks are used to study fish and other aquatic life at ORNL's Aquatic Ecology Laboratory. Experiments are being conducted at the AEL to determine thermal effects on aquatic organisms. The tanks hold up to 200 gal of water and have temperatures ranging from 5 to 43°C.

Comparison of simulated with observed stream flow for the Walker Branch Watershed. The simulation resulted from the application of the hydrological portion of the unified transport model, and the two curves show the comparison before and after optimization of the physical parameters in the model.



Ecology and Analysis of Trace Contaminants

This work is supported at the Laboratory by the National Science Foundation, Research Applied to National Needs Program, through an interagency agreement with the Atomic Energy Commission. The objective is to develop techniques and information which will be useful in assessing and solving environmental problems involving trace toxic pollutants. The work, which is being conducted by personnel from seven research divisions at the Laboratory, is divided into five interacting areas of research, which are: (1) the development of a unified transport model which would permit the realistic prediction of the movement in the environment of contaminants released from various sources using a minimum of experimental data; (2) ecological research concerning the biological availability of trace toxic metals from soil and sediment sinks, direct uptake from the water by aquatic organisms, aquatic food chain transfer, and aquatic and terrestrial cycling of trace elements; (3) development of improved analytical methods for trace contaminant measurements; (4) development of advanced abatement technology employing electrochemical and solvent extraction techniques to recover toxic elements from water waste streams or sludges; and (5) the development of a Toxic Materials Information Center to serve both information needs of the program as well as the needs of other organizations concerned with trace contaminants. As examples of progress over the past year, the work on the unified transport model and the work on a high-sensitivity quantitative monochromatic x-ray fluorescence method for multielement determinations are reviewed briefly.

The unified transport model (UTM)

The unified transport model is an attempt by M. R. Patterson and his colleagues to describe quantitatively the environmental transport of toxic contaminants by atmospheric and hydrologic processes. Biological and chemical exchange processes which are important in transport and in accumulation in various compartments of the ecosystem are also being incorporated into the model. The ultimate purpose of the UTM is to provide a predictive tool for estimating exposure of various biota including man to trace contaminants, given a particular source or mix of sources. If the effort is successful the model should be useful to regulatory agencies and to industrial and urban planners.

Although the UTM is being applied first to trace metal contaminants, it can be extended to include a large class of micro constituents, both toxic and nontoxic, such as nutrients, pesticide residues, and radioactive materials. The model is designed to simulate transport in a watershed. The watershed may be impacted by various types of air sources as well as by direct industrial or urban discharges into the streams or by surface contamination such as might occur due to agricultural practice. The types of air sources include point sources such as a stack, line sources such as a highway, or area sources such as a city or a stockpile of particulate mine wastes which may become windblown. The model attempts to account for the movement of a contaminant from any or all of these types of sources and to depict the transport of the contaminant with air and water in the watershed.

The model is being tested and evaluated first for the Walker Branch Watershed which is a highly instrumented ecological test area on the ORNL reservation. This watershed is near several large coal-burning steam plants. The atmospheric portion of the model, which starts from a Gaussian plume formulation and calculates both dry fall and washout-dominated wet fall deposition, is being used to estimate a spatial and temporal description of deposition on the watershed from the steam plants and from other sources in the area. Initial calculations show that most of the fly ash is not deposited in the immediate vicinity of these plants (more than 95% is deposited farther than 2000 meters distance from the stack) and that washout is a more important deposition mechanism than dry fallout.

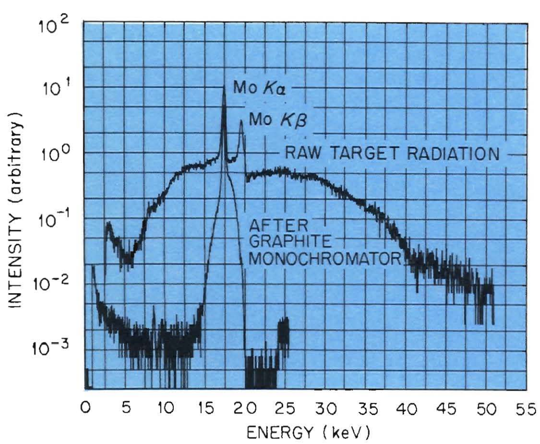
Deposition calculations such as this then provide input to the hydrological portion of the model. For this portion the Patterson group uses a modified version of a code developed at Stanford University and subsequently at the University of Wisconsin. The first task of the hydrologic portion of the model is to simulate accurately the flow of water in the watershed based on physical parameters. Some of these are difficult to determine experimentally, and they have incorporated an optimization procedure to determine the best value in a constrained range of physically possible values. Testing the optimization technique on simulated and observed stream flows in the Walker Branch Watershed showed a significant improvement in their agreement as a result of the optimization procedure.

Having modeled the water flows one can then calculate the consequential movement of dissolved contaminants or of contaminants adsorbed on suspended material including those introduced by erosion or by sediment resuspension during storm events. Of course, trace contaminants which enter a stream system can interact with the various compartments in the stream, such as sediment, suspended matter, biota, etc. A stream submodel has been developed to simulate these exchange processes for various trace contaminants from the point of injection into a stream. The initial version of this submodel was based on one developed at the University of Texas and was modified at ORNL to give a more realistic and complete treatment of the sorption-desorption mechanism.

This stream exchange model has been partially validated using data which were obtained during a stream tagging experiment on the Walker Branch Watershed. Mercuric nitrate containing ^{197}Hg was added to the stream over a 19-minute time interval. Water samples were collected at five distances downstream, the last one being at 100 meters where only 35 percent of the activity remained in the water. In a comparison of the computer simulation with the experimental data, the agreement was good, particularly at the 70- and 100-meter positions.

X-Ray Fluorescence

Energy spectrum (upper curve) taken directly from the molybdenum target of an x-ray tube operated at 50 kV. The ratio of the integrated counts in the molybdenum Kα peak to the integrated background between 12 and 13 keV is 9 to 1. Any fluorescent x rays excited by the molybdenum Kα line must be registered above such a background, because the background at all energies is strongly scattered into the detector by the sample. The lower curve shows the effect of using a crystal of pyrolytic graphite to select the energy band.



X-ray fluorescent analysis (XRF) has been a widely used analytical technique since Moseley in 1913 stated the principle that each element when bombarded by particles of suitable energy will emit x rays of unique energies characteristic of that atomic number. Thus elements could be identified by their characteristic x rays, and their relative concentrations would be proportional to the intensity.

XRF has the desirable advantages of being nondestructive to the sample, requiring no prior chemical treatment, and detecting many elements from the same sample. These features become even more attractive when detecting trace quantities since any necessary handling for preparation or use of reagents always includes the possibility of contamination. Furthermore, XRF is both rapid and simple to use and is therefore one of the most economical analytical techniques available.

The obvious limitation to the sensitivity of the XRF technique has been the "noise" caused by use of direct radiation from x-ray targets for sample excitation. C. J. Sparks and J. C. Ogle attacked this by removing all the energy spectrum incident on the sample but for a narrow energy band selected to fluoresce most efficiently the elements of interest. They have chosen to use a highly efficient diffracting crystal of compression-annealed pyrolytic graphite to select the energy band. The radiation in the vicinity of the Mo $K\alpha$ line, diffracted from the (00·2) basal planes of the graphite monochromator, now gives an integrated peak-to-background ratio at 12 to 13 keV of 2000 to 1. After subtraction of detector background, the ratio is in excess of $10^4/9$, showing a reduction of 10^3 in the background radiation which would occur under the fluorescent energies of interest. As the graphite monochromators are doubly curved to intercept a large solid angle of radiation and to focus the x rays on the sample, the intensity is simultaneously more than 10^2 greater than obtained by using radioisotopes as monochromatic sources. Other techniques of producing monoenergetic sources of x rays such as transmission target x-ray tubes, secondary radiators, and filters produce beams of less spectral purity and less intensity on the sample.

An XRF system of this kind has been built as a development unit in our Metals and Ceramics Division and a similar system is being constructed with the Analytical Chemistry Division for application to trace element determinations in support of NSF environmental programs and for other Laboratory uses. Many elements are presently detectable to concentrations less than 1 part per million. An additional advantage of using monochromatic exciting radiation is the ease and precision with which the measured intensities can be converted to quantitative units thereby permitting calculations of concentrations without resort to standards.

Most of the remaining background is from degeneration of scattered radiation in the detector proper. A further improvement will involve replacement of the solid state detector with a second curved analyzing crystal for better energy resolution and removal of the detector background. This promises to increase the sensitivity to a few parts per billion.

Toxic Elements and the Coal-Burning Power Station — A Case Study

Some six hundred million tons of coal are burned per year in the United States, and 62 percent of this quantity is consumed in central-station power plants. There has been much concern about some of the more abundant chemical elements in their gaseous forms in the output of these plants (e.g. carbon and sulfur), but little information has been accumulated about the fate of other relatively abundant elements such as aluminum, calcium, iron, potassium, magnesium, sodium, titanium, and manganese, or of the minor elements such as arsenic, beryllium, cadmium, copper, nickel, lead, antimony, selenium, vanadium, and zinc which are of interest because of their toxicity.

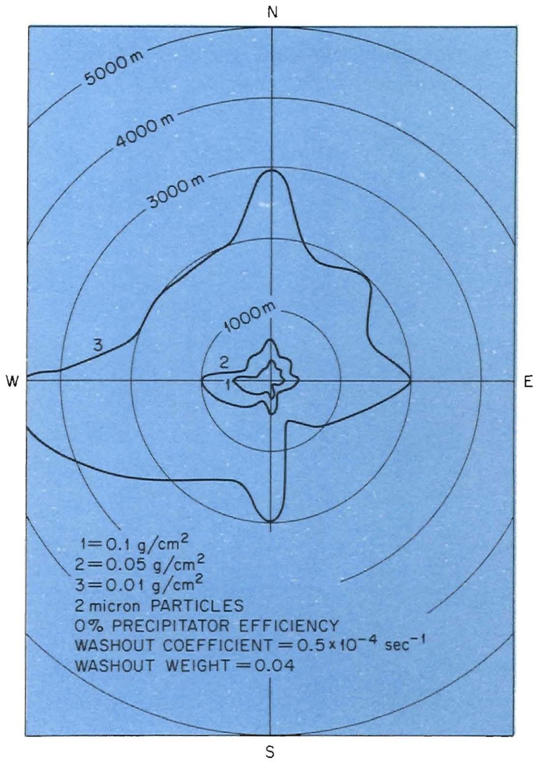
A team of ORNL industrial hygienists, ecologists, and analytical chemists under Newell Bolton have made a case study of these aspects of the TVA Allen Steam Plant in Memphis, Tennessee. This is an 870-MW(e) plant comprising three separate cyclone boiler generating units; it has been in operation since 1959. The electrostatic precipitators, however, are new (1972).

The studies were of two kinds. One, done in cooperation with the Tennessee Valley Authority, was in-plant and consisted of a materials balance to assess whether the chemical elements that go in with the coal can be individually accounted for between the bottom ash and the flue gas; this study included analyses of the flue gas particulates before and after the electrostatic precipitators, so that one could learn how effective the precipitators are, element for element. The other study was an environmental one; it was a search for any sign of accumulated toxic materials in the neighborhood of the plant. For this, soil samples were taken at distances up to 20 miles north and south of the plant (the direction of prevailing winds), and these were supplemented by water and sediment samples from the stream receiving the ash pond runoff.

Neutron activation analysis and spark source mass spectrometry were the principal analytical methods used; in general they gave coherent values.

Broadly speaking, the Allen Steam Plant study showed that:

1. For most of the elements measured, an approximate mass balance was obtained except that the results seemed to show a consistent negative imbalance (~20%). That is, the quantity of a particular element which was measured to flow into the plant with the coal was greater than the sum of the flows into slag tank residues



The results of calculations of fly-ash deposition patterns for the TVA Allen Steam Plant in Memphis. The calculated deposition isopleths are for the 14-year operating life of the plant and assumed a fly-ash particle size of 2 μm and zero percent precipitator efficiency. The actual deposition was probably a factor of 4 to 5 less due to an average precipitator efficiency over the years of 80 to 90%.

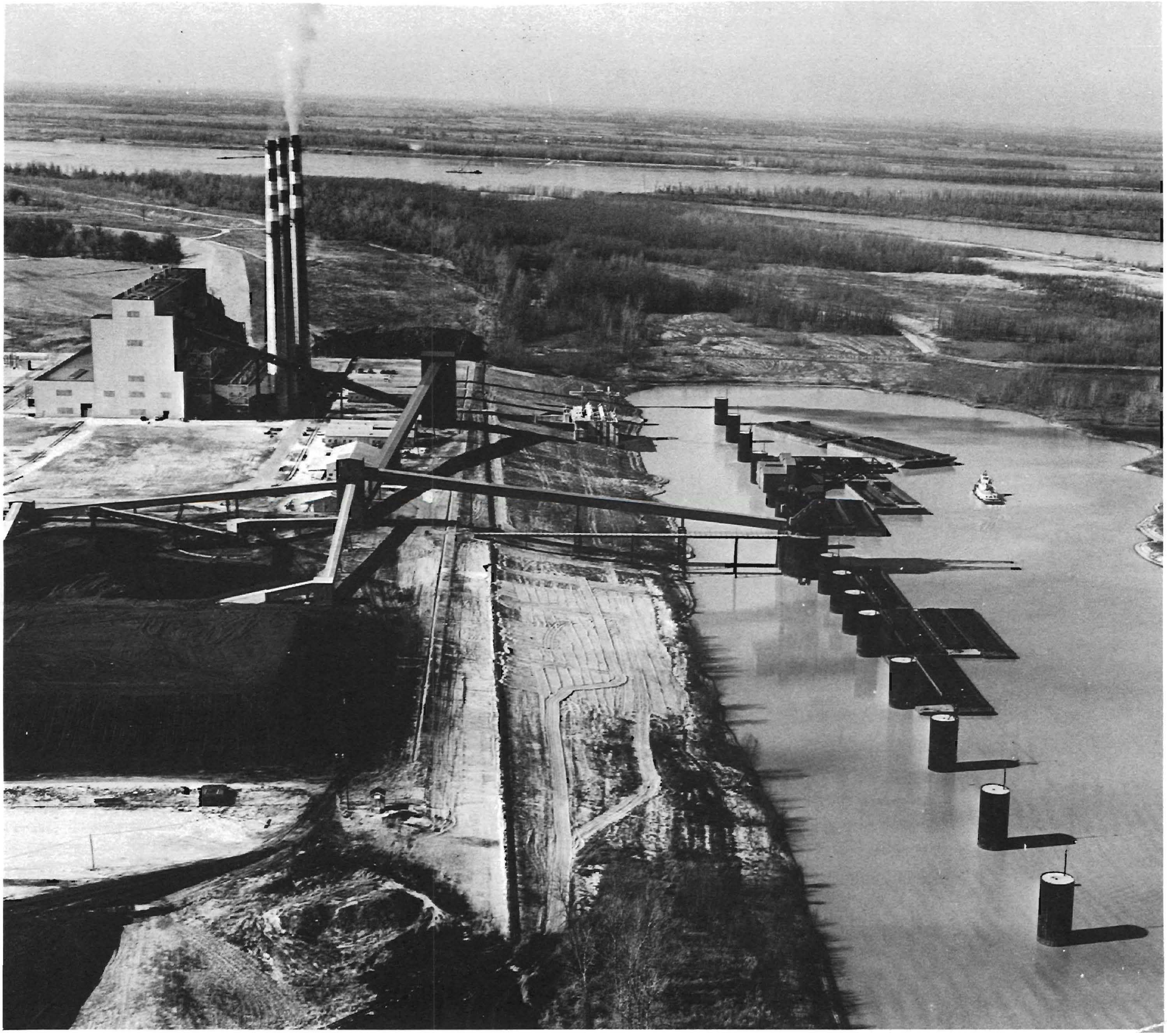
and into fly ash entering the precipitator. This may be due to the fact that air heater pneumatic cleaning and boiler soot blowing operations were not included in the sampling procedure.

2. Certain volatile elements (e.g., mercury and arsenic) were not fully accounted for since the air sampling methods essentially followed standard ASTM procedures for trapping only particulate matter.

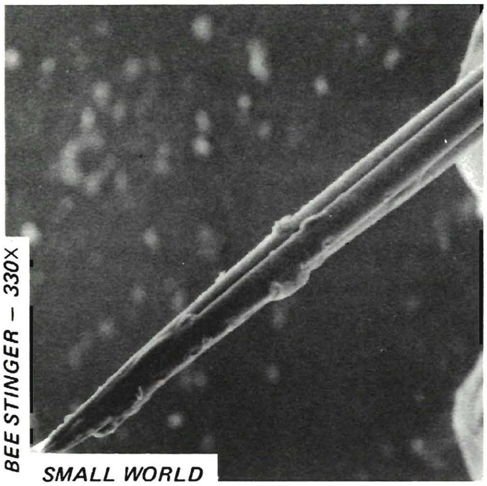
3. The electrostatic precipitators were 95 to 99% effective for most of the elements collected with the fly ash. A notable exception was selenium (7 to 60%).

4. The variations in the levels of trace elements observed in the soils around the plant could not be ascribed to fallout of fly ash from the plant.

The Allen Steam Plant at Memphis, Tennessee (photo courtesy of TVA).



Special Energy Studies



Econometric Models

In a study sponsored by the National Science Foundation, T. J. Tyrrell, L. D. Chapman, and T. D. Mount have developed empirical "models" to aid in the prognostication of the electrical energy demand situation in the United States during the next 20 or 30 years. Coefficients of the model are calculated by regression techniques from historical and current data. Future projections can then be based on plausible assumptions for the values of the explanatory variables. Once such a model has been established it can be applied in various ways; for example, by allowing for local variations from state to state, the national model can be modified so as to give predictions for New York or Idaho or Nebraska. Moreover, by calculating under various assumptions, one can get a feel for the sensitivity of the answer to variation of the input parameters.

In an application of such a model to the estimation of electrical demand in the United States, Tyrrell, Chapman, and Mount assumed that (1) the price of electricity would increase at 1% per year; (2) natural gas prices would increase at 6.7% per year; (3) incomes would increase at 2.9% per year; (4) appliance prices would decrease at 2% per year; (5) the population of the United States would be 270 million in 1990.

Most projections by others have been extrapolations of past experience, based on the implicit assumption that past trends will continue into the future. The present assumptions of increasing electricity and gas prices are sharply different from the past history of price reductions. As a result, the ORNL projections of electricity demand are appreciably lower than several other recent estimates. The figures were as follows:

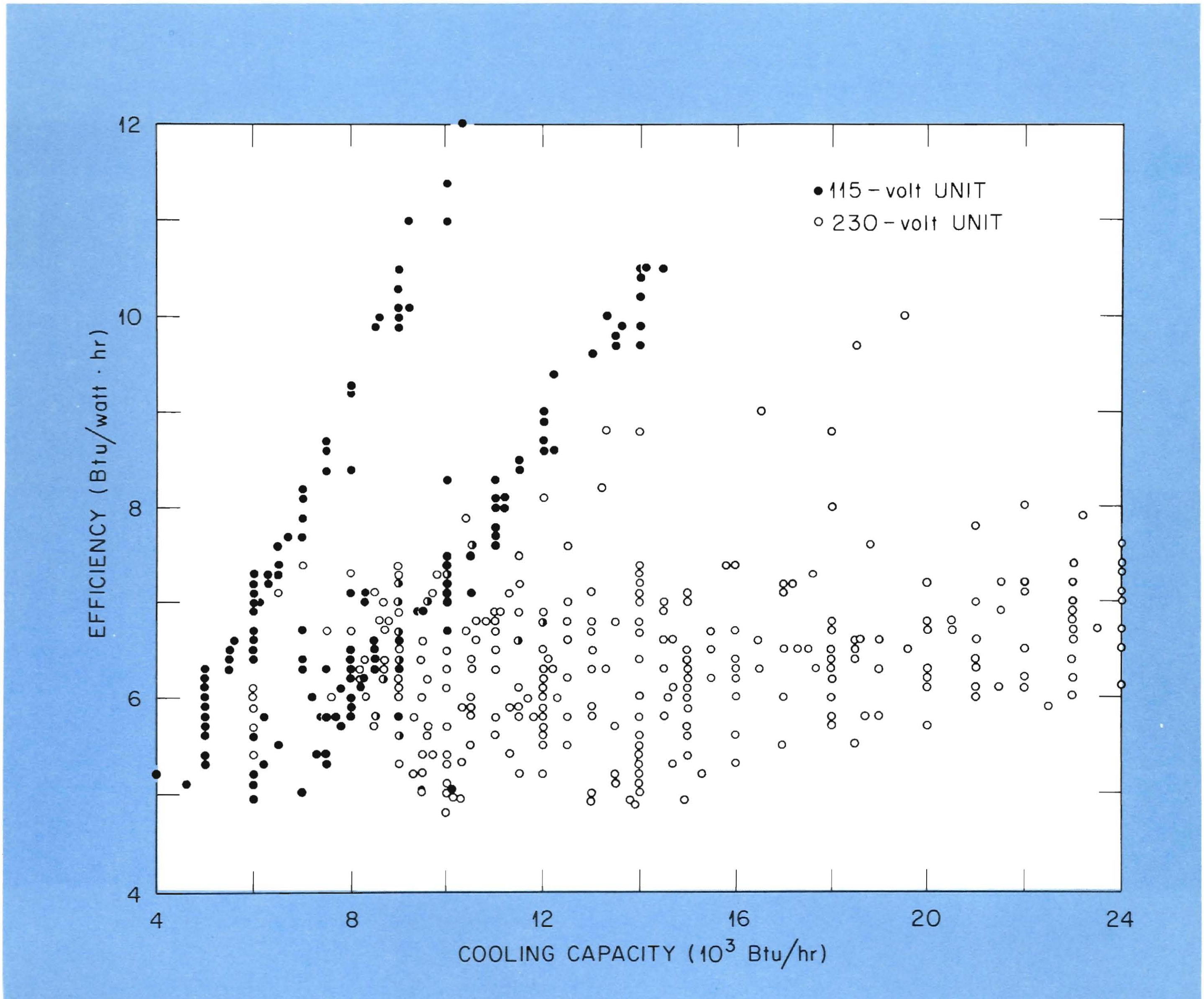
Electricity demands in the U.S. for 1990

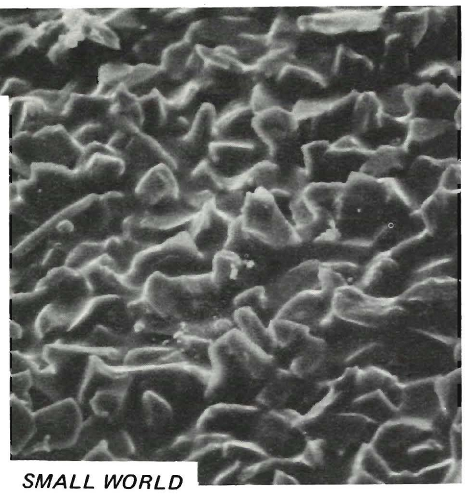
In trillions of kilowatt-hours

Source	Residential demand	Total generation
This study	0.97	2.93
Electrical World	1.70	5.91
Federal Power Commission	1.41	5.83
1970 experience	(0.45)	(1.52)

In spite of considerable uncertainties in the coefficients of the model and the future values of the explanatory variables, the study points up a potential for major changes in electricity demand growth.

In a study of residential energy consumption in the Laboratory's NSF-RANN work, J. C. Moyers assessed the efficiencies of 1972-model room air conditioners, with the results shown in this figure. The 115-V units are more efficient not because of technological advantages but because of marketing advantages. If the nation's air conditioners all had efficiencies of 10 Btu/Whr, we would use 15,800,000 kWhr of electricity less per year (at the time of peak summer demand), the connected load would be reduced by 17,800 MW, we would use 7,600,000 tons less of coal per year, and we would save 1500 acres of strip-mine land.





600 GRIT ABRASIVE PAPER — 250×

SMALL WORLD

Hydrogen

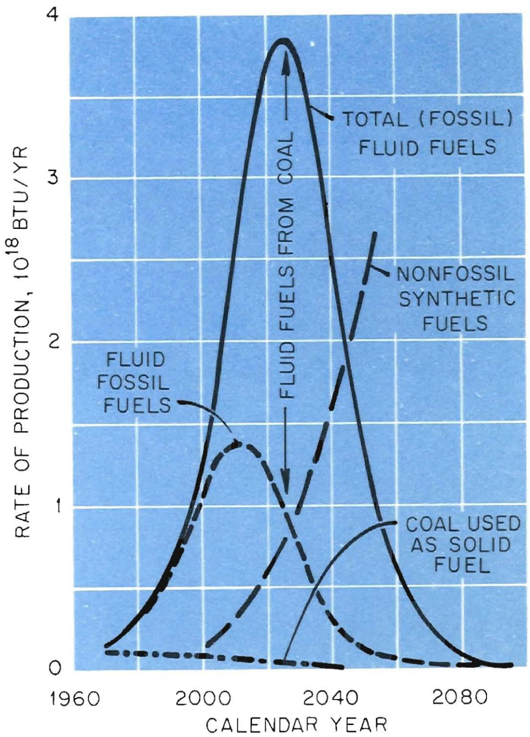
Under the sponsorship of the Federal Council on Science and Technology, a panel on Hydrogen and Other Synthetic Fuels was set up, with John Michel as the panel leader, to study the economics of synthetic fuels for power production. A number of ORNL staff members participated actively in the panel's study, the principal conclusions of which may be mentioned here.

The importance of fluid fuels is more pervasive than that of electricity, because of their indispensability to transportation. If one looks, as the panel did, at the coming demands for petroleum and natural gas one sees that in a mere dozen years the United States will be importing more than half of its petroleum and gas, and may be spending as much as $44 billion per year abroad to get it. The implications of this to the national welfare need not be stressed; one needs only to mention the balance of trade and national defense.

The time scale for this aspect of the energy crisis is indicated in the adjoining diagram taken from the panel's report. Here the production of fluid fossil fuels (petroleum and natural gas) is seen to peak in the year 2010 and fall off thereafter as the world supply is gradually exhausted. Meanwhile, it is anticipated that the larger available energy supply that resides in coal will be converted to the form of fluid fuels, but even this peaks in the year 2030, and thereafter declines. The panel considers various possibilities as to what this coal-derived fluid would be, and concludes that methanol and hydrogen are promising candidates. But that alone leaves the more distant future unprovided for, and new nonfossil fuels need to come in, starting about 1990, in order to meet the energy demand for the long term. The panel states that, by all odds, the best long-term synthetic fluid fuel will then be hydrogen generated from water.

Let us first consider methanol. Methanol is most simply produced by heating (at 250° to 400°C) a "synthesis gas," which is a mixture of hydrogen, carbon monoxide, and carbon dioxide. A catalyst must be present. The synthesis gas in turn can be produced from coal using heat and steam. An estimate of the cost of methanol from a 20,000-ton-per-day plant comes to 8.5 cents per gallon. The

Projections of world fluid-fuel production show a dominating dependence upon coal derivatives in the first third of the next century. After that, nonfossil fuels will have to meet the world energy demand.



process has not yet been commercialized, but much work has been done on closely allied reactions designed to produce either hydrogen or methane from coal.

Methanol has a lower heating value than gasoline, so the automobile driver would get fewer miles per gallon. Precautions would have to be taken against its toxicity, but that need not be difficult. Its other features are attractive. It is a high-octane fuel, so engine performance would be good. It is noncorrosive, so it can be piped and tanked with ease. It is clean burning; without catalytic treatment of the exhaust it leaves $^1/_{20}$ as much fuel unburned as does gasoline, and it produces $^1/_{10}$ as much CO and about as much NO_x. With a catalytic exhaust reactor, bench tests at Stanford University gave the following results for a Gremlin engine:

Emissions in grams per equivalent mile of various exhausts from a Gremlin engine with exhaust treatment

	Unburned Hydrocarbons	CO	NO_x
Methanol	0.69	3.83	0.28
Gasoline	2.34	22.08	4.01
1975–76 Federal standards	0.41	3.4	0.40

Thus methanol shows promise in meeting Federal standards as a high-quality domestically produced replacement for gasoline, available so long as the coal supply lasts.

After the coal becomes rare, hydrogen generated from water has several advantages as a multipurpose fuel. The production process requires a lot of energy, and inasmuch as initial production will probably be an extension of present water-electrolysis methods, we are led to contemplate electrolytic plants supplied by nuclear power. Many plants may well sell electricity directly to residential and industrial customers in the conventional way, but produce hydrogen in off-peak hours. Other plants may be devoted solely to hydrogen production. The hydrogen would be transported by pipeline, and the consumer could burn it for heat, use it in internal-combustion engines, or use it to produce electricity directly if fuel cells can be successfully developed. It should be recognized that hydrogen production is compatible with all the proposed future primary energy sources: solar, geothermal, thermonuclear, etc. In fact, with some of these, hydrogen production may offer the best means to utilize a cyclical or remote primary energy source.

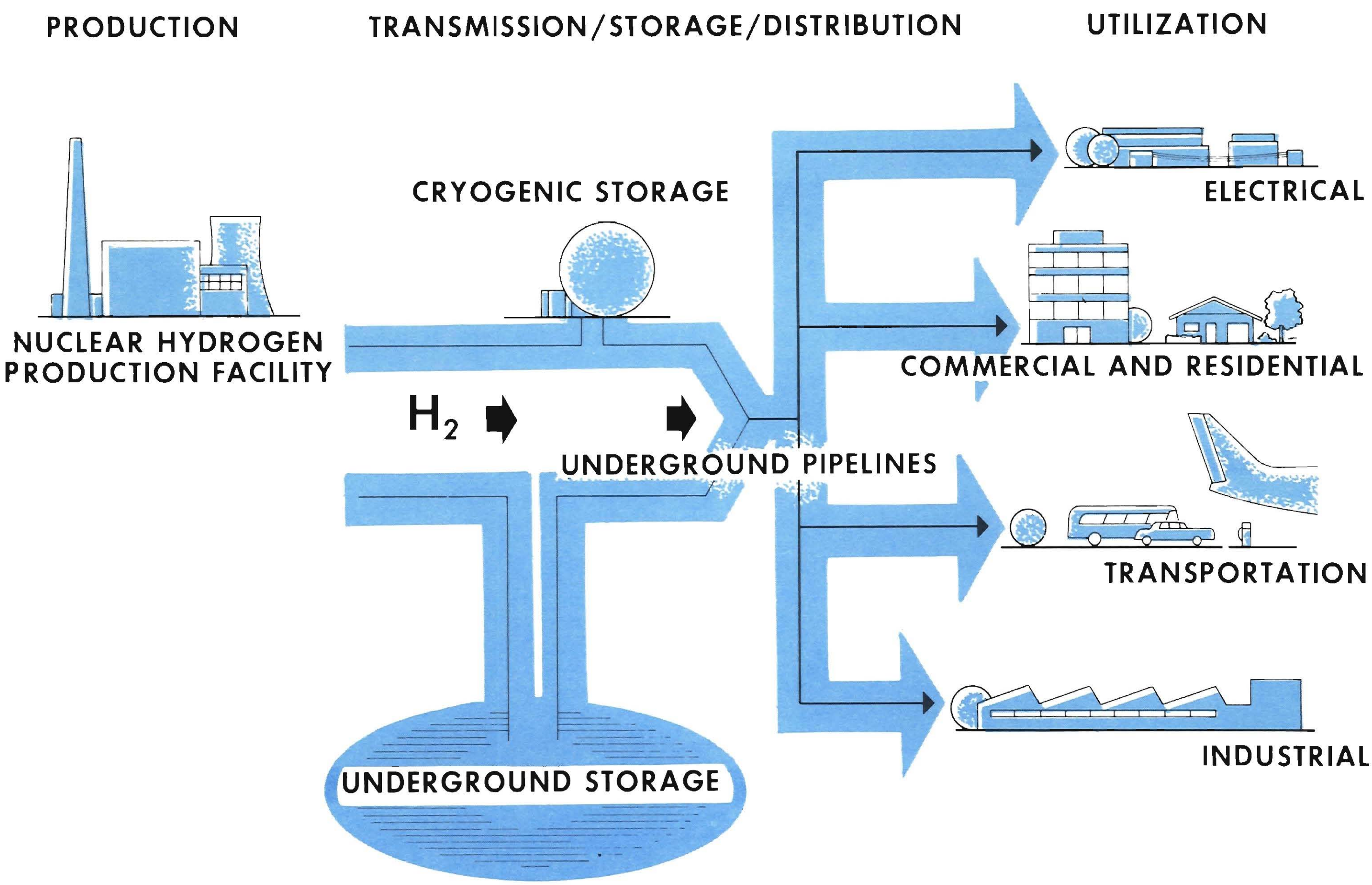
In spite of the high cost of generating hydrogen, the total picture looks economically favorable when one considers a large distribution system with underground pipe lines and storage facilities. The main reason for this is that for a given energy-carrying capacity, the pipelines are cheaper than overhead high-voltage electric transmission lines. In a summary of overall costs the panel suggests the following representative figures for a pure nuclear-electric system as compared with a nuclear-electric-hydrogen system.

Cost of energy delivered to residential consumers

In dollars per million Btu

Type of reactor — H_2 technology	Nuclear-electric system	Nuclear-hydrogen system
Light water — present	5.5–6.9	5.2
Liquid metal breeder	5.0–6.6	3.6
Residential mix (advanced); $^1/_5$ electric, $^4/_5$ H_2	4.4	

The elements of a hydrogen-based power economy.



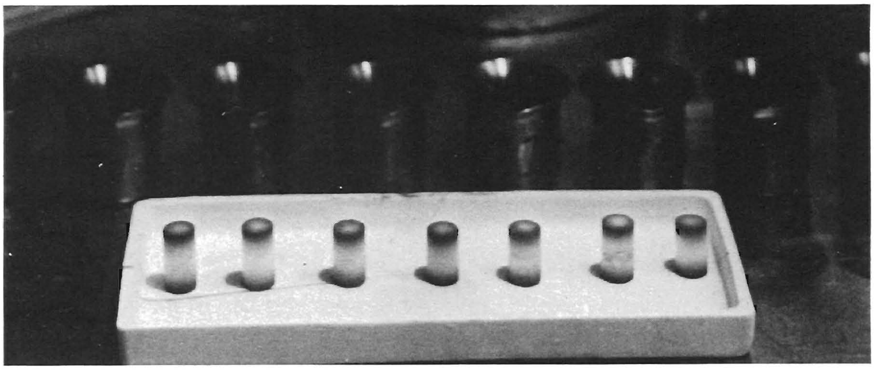
A number of ancillary advantages come with the concept of a hydrogen-based power economy, and also a few disadvantages. Some disadvantages are:

1. As an automotive fuel, hydrogen presents formidable storage problems. Liquefaction and small-scale cryogenic storage are expensive and still do not achieve the desirable space advantages. Storage as a reversible hydride or an easily dissociated compound may, however, become attractive possibilities.
2. Safety precautions would have to be worked out for each kind of use. An odorant would be added. The experience of NASA in handling large volumes of hydrogen for rocket propulsion adds some confidence that safety problems might be met, but fundamentally hydrogen will command more respect than the fuels to which we are accustomed.
3. Successful fuel cells have not yet been developed on a commercial basis. The picture would be much brightened if they were.

Now for some advantages:

1. Hydrogen is the cleanest burning fuel known — when burned in O_2, only water results; in air, only small amounts of NO_x may be obtained, although utilizing a catalytic, low-temperature process, even this may be eliminated.
2. As a fuel for aircraft, hydrogen offers an increase in payload, or in range, per unit of fuel carried.
3. A hydrogen pipeline distribution system would save the 12 acres per mile of real estate required for 345-kV electric power transmission lines, and save the beauty of the landscape.
4. Hydrogen as a reductant for iron ore appears to offer cost advantages over the conventional blast furnace, again with reduced environmental impact.
5. As a residential and commercial energy source, hydrogen appears to be cheaper than electricity for many uses, and more efficient than natural gas.
6. If oxygen is also available, hydrogen can be burned with the direct production of process steam, permitting cost and space savings and efficiency gains over conventional fuel-fired boilers.

Such is the approximate balance sheet, but be it as it may, the panel feels that we are likely to be forced to consider a hydrogen-based power economy within the next century. This will demand a great deal of nuclear power; if in the year 2000, one-fourth of the nation's needs for transportation alone were to be supplied by hydrogen from water, the equivalent of 150 of the Brown's Ferry nuclear complexes would be needed to generate the necessary electricity. Other forms of primary energy may also be used for its production; in fact, several cyclical or remote energy sources, for example, solar, ocean thermal gradient, winds, or even coal, may best be exploited by their conversion to hydrogen as a means of energy storage and transportation. Production by thermochemical means, making direct use of heat, is being developed in several laboratories both in the U.S. and in Europe. Work is also beginning at ORNL to harness solar energy via biological processes to produce hydrogen.



Seven pellets of curium-244 sesquioxide for use in an isotopic power supply for a communications satellite. Each pellet is about 1/2 in. in diameter, contains 32 g of Cm_2O_3, and generates 75 W of heat.

Curium

For the past year or more, the emphasis of ORNL development work on isotopic power sources has centered on ^{244}Cm mainly because of its adaptability to unmanned communication satellites.

Curium-244 is an alpha emitter with a half-life of 18.12 years — a convenient value for earth satellite missions of five-year duration. The associated specific power is high for isotopic sources — 2.3 watts per gram of curium sesquioxide. One of the attractive features of curium is its coming abundance as a by-product of the nuclear power economy; we will have lots of it. Its cost is forecast to be relatively low, at about $100 per watt (thermal), as compared with ^{238}Pu at about $600 per watt (thermal). These factors make ^{244}Cm attractive for space uses needing thousands of watts (thermal). Its principal disadvantage results from penetrating neutrons from spontaneous fission, but this radiation can be reduced to workable levels for satellite applications by the use of modest amounts of lithium hydride shielding.

A team at ORNL led by Eugene Lamb has been concerned with the curium fuel form and the capsule to contain it safely. They have fabricated curium into sesquioxide fuel pellets which they have studied for physical properties, compatibility with container materials, helium release, and dimensional and chemical stability. The knowledge gained in this program gives confidence that curium can be utilized in radioisotope power systems in which the heat source will be subjected to operating temperatures up to 1400°C and to short-duration excursions to higher temperatures upon reentry into the atmosphere. The goal will be to demonstrate beyond any doubt that the capsule provides safe containment of the curium under foreseeable conditions, normal or accidental.

The sesquioxide of curium (Cm_2O_3) is the chosen chemical form because of its thermal stability and compatibility with encapsulating materials. Curium sesquioxide is pressed into pellets which are then encapsulated in two or more concentric containers which may be fabricated of a superalloy, a refractory alloy, a noble-metal alloy, or a ceramic material. The encapsulated curium fuel will be used in power generating units designed to produce several hundred electrical watts.

Research

Once again we present a sampler of the ORNL research programs. It is patently impossible to describe a significant fraction of our research programs in the available space. Members of the research divisions in physical and biological sciences now publish about 500 papers a year. Why it is done is another matter. Much of it relates directly to nuclear technology, and more recently to energy technology in general. An important fraction is done here because it requires large-scale equipment. The remainder belongs to that exciting activity in science whose function it is to find new data and new kinds of order in nature. How can one hope to convey the flavor of such a vast intellectual enterprise? We have therefore selected a few areas where interesting things have happened in the past year; in the following pages we present examples of the kind of thing ORNL does in the way of basic science.

Heavy ion research not only forms the core of our nuclear physics and nuclear chemistry investigations; it has also branched out into an extremely interesting activity which deals with the physics of atoms that have lost all but one or two electrons upon passage through foils or gases. We are now obtaining interesting new results on radiation damage by using projectiles such as Al or Ni to bombard metals of the same elements. In another materials related research program we continue to exploit the country's highest flux reactor, as well as x-rays, to investigate structures and magnetic properties of solids and, more recently, certain liquids. Biologists continue their exceptionally broadly scoped research in various fields. The central theme is still radiation injury, but the topics on which we report here include cancer, genetics, molecular biology, and microbiology. We investigate very small systems and very large ones. Our new field emission electron microscope with superconducting optics is now operating and nearly ready for research problems in biology. On the other end of the scale we are modeling the ecology of the eastern deciduous forest as part of the International Biological Program.

Physical Sciences

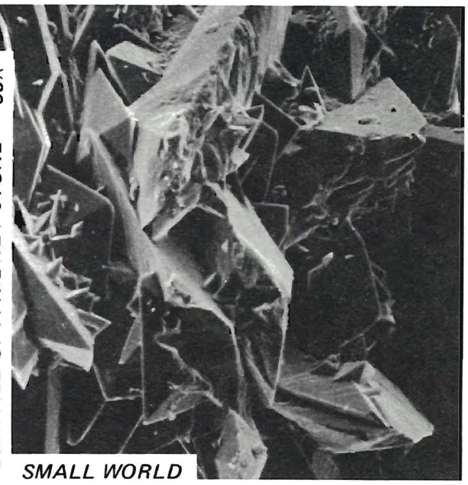
Heavy Ion Research

One of the more exciting fields in the physical sciences these days involves work with heavy ions. By "heavy ion" is traditionally meant accelerated particles heavier than helium nuclei. This excitement is manifest in the fact that, aside from installations that deal with high-energy elementary particle physics, all new accelerators that are either operating or in the process of being built, or proposed, are designed mainly for the production of energetic ions with large atomic numbers. The enthusiasm is worldwide; new heavy-ion facilities with vigorous research programs are in operation in the Soviet Union and other European countries as well as the U.S. The recent physics survey conducted by the National Academy of Sciences portrays a similar picture and goes a step beyond. The Academy's recommendation is that a new national heavy-ion facility be built in the U.S. with the capability of accelerating all elements up to uranium with energies of 10 MeV per nucleon. For uranium ions this means an energy of about two and a half billion electron volts. One can only speculate as to what startling new phenomena will be observed when such massive nuclei collide with one another at extremely high velocities.

ORNL has had a long tradition in the field of heavy-ion research. Indeed, it can be said that the field of heavy-ion physics per se had its inception at Oak Ridge in 1952 when a 63-inch cyclotron, designed to accelerate nitrogen-14 ions to an energy of 28 MeV, began operation. While this machine supported a broad research program, its main contribution was to enhance the understanding of nuclear reactions induced by heavy ions. After the cyclotron was shut down in 1961, heavy-ion research at ORNL was continued at the Tandem Van de Graaff accelerator. A recent impetus to the ORNL work came in 1968 when the Oak Ridge Isochronous Cyclotron (ORIC) achieved the acceleration of heavy ions to energies higher than those available at the Tandem, and today both the ORIC and the Tandem devote more than half of their operating time to heavy-ion research.

Heavy ions have three distinct and obvious advantages over light particles: they carry large electric charges, they have great masses, and they bring a large amount of spin into a nuclear collision. Until recently, heavy-ion beams, for most practical purposes, have been limited to the lighter elements with atomic numbers equal to 18 or less. The possibility of accelerating nuclei with five times the charge and six times the mass demonstrates that the field is relatively young, and that, up to now, only the surface has been scratched. Its richness and variety can be shown in a summary of the activities of ORNL staff members in heavy-ion research, covering the areas of nuclear

Experimental area of the UNISOR facility, with (l. to r.) R. L. Mlekodaj, E. H. Spejewski (UNISOR director), W. D. Schmidt-Ott, and H. K. Carter. The UNISOR consortium includes public and private universities, state and federal governments, and ORNL. Its objective is the study of nuclei far from the line of stability. To this end a commercially available electromagnetic isotope separator was installed at the Oak Ridge Isochronous Cyclotron (ORIC), a facility that is capable of accelerating a large variety of heavy ions that are useful to the production of extremely neutron-deficient nuclei. Because these nuclei are far removed from stability, their half-lives are short, which makes them hard to study. The separator not only sorts out nuclei whose weights differ by one atomic mass unit, but because it is "on line" with the ORIC, it provides a continuous source of whatever isotope is being studied. The ORIC beam impinges on its target just behind the wall on the left. The radioactive products are ionized, separated, and transported to a position (near Mlekodaj) that corresponds to the focal plane of the separator's magnet. At this location, nuclei arrive with masses differing by as much as 20 atomic mass units. These nuclei are transported still further from the radioactive background of the other isotopes by a 2.5-m beam extension tube provided with two focusing elements. The extracted nuclei penetrate the tape transport system in the foreground. Between the reels are four counting positions where detectors can be placed to examine the radioactive products.



SURFACE OF A KIDNEY STONE — 85X

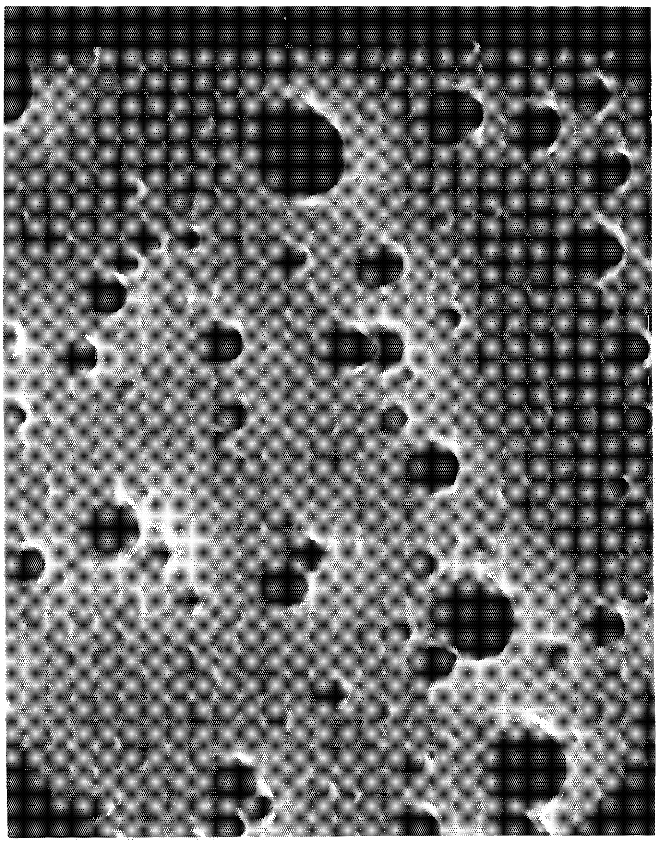
chemistry and physics, solid state physics, atomic collisions, and developments in accelerator technology.

The investigation and production of isotopes in the transuranium region are intimately connected with heavy ions. Light-ion bombardment requires targets of nuclides with atomic numbers (Z) close to the ones being sought. Adequate quantities of such target materials are unavailable due to the increasingly short half-lives of elements as they get higher in atomic number. With heavy ions, this problem is disregarded because a large amount of charge is transferred to a readily obtainable target nucleus. In fact, heavy-ion bombardments are the only way that isotopes of elements with Z = 102–105 have been synthesized. Usable quantities of elements with Z up to 98 are now available from the Oak Ridge High Flux Isotope Reactor. Because the ORIC is capable of producing intense beams of ions with Z as high as 10, this means that elements with atomic numbers up to 108 can be produced. An active program at the Transuranium Research Laboratory at ORNL is under way to develop techniques for the rapid separation and identification of short-lived isotopes produced essentially one atom at a time. In particular, very rapid gas chromatographic methods have been used, with some success, to try to separate zirconium from niobium and halfnium from tantalum (in the form of volatile bromides) as isotopes of these elements were being produced on line at the ORIC. Once the technique is perfected, it can then be applied to the study of the chemistry of elements 104 and 105, which, chemically, are expected to be the homologs of zirconium and hafnium on the one hand, and of niobium and tantalum on the other.

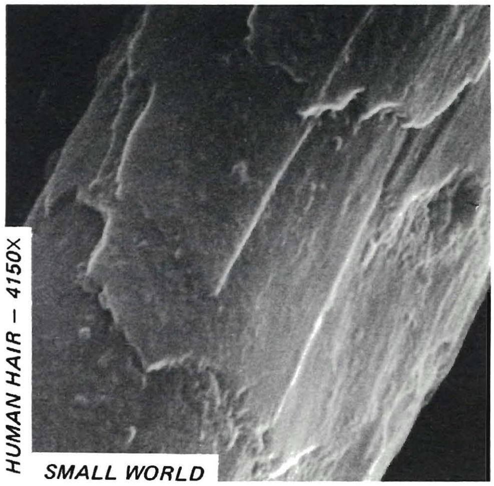
Another technique developed at ORNL provides for conclusive chemical identification of these short-lived transuranium elements. It is a well-known fact that no two elements have the same characteristic x-ray spectrum. C. E. Bemis, R. J. Silva, L. O. Keller, and colleagues have exploited this principle in a way that can be best illustrated by describing their recent experiments in the first undisputed determination of the Z number for a particular isotope of element 104. Three-tenths of a milligram of californium-249 (Z = 98) was bombarded with carbon (Z = 6) ions from the ORIC to produce the isotope number 257 of element 104. Products were collected for a period of twice the isotope's half-life (4.3 seconds) and then transferred rapidly to a location where alpha particles and x rays could be detected simultaneously. Since the production yield is extremely small, this bombardment and counting cycle was repeated 30,000 times. Alpha-particle emission decreases the Z number by 2. Then because the characteristic alpha particles of $^{257}104$ were correlated with the characteristic x rays of element 102, the experiment constituted a positive identification of element 104. This research team is planning similar experiments with element 105 and eventually with the unknown elements beyond.

A reversal in the trend of shorter half-lives with increasing atomic number has been predicted by theorists who postulate the existence of islands of stable nuclei situated beyond the known transuranics and clustered around Z = 114 and Z = 126. Do such superheavy nuclei live long enough so that their properties can be investigated? Unfortunately, estimates are critically dependent on the exact masses of these nuclei and predictions of half-lives range from a thousandth of a second to ten billion years. Their masses are calculated by the use of formulas which are designed to fit nuclei close to the line of stable isotopes; predictions, therefore, vary greatly for nuclei located far from stability. By obtaining decay energies (which can be correlated with masses) for nuclei far from stability, existing mass formulas can be improved and then be used with a better degree of confidence. Heavy ions are ideal for producing isotopes on the neutron-deficient side of the line of stability. This is because they bring in an equal number of neutrons and protons, while, as the atomic number increases, the line of stable isotopes bends more and more toward an excess of neutrons over protons. The ORIC's variety of heavy ions has been used successfully by K. S. Toth and R. L. Hahn to synthesize 17 previously unknown alpha-decaying nuclear species, some of which are located 20 mass numbers away from stability. The alpha-decay energies of these new nuclides are thus available for comparison with and improvement of existing mass formulas.

In heavy-ion interactions a great number of radioactive products are formed. In order to investigate their properties carefully, one must be able to focus on each one individually away from the contaminating presence of its neighbors. An instrument that performs this service is an isotope separator. In the past year, a separator of the required type has been placed on line at the ORIC and scientists are eagerly awaiting improved performance of this system. The isotope-separator project is known as UNISOR (from University Isotope Separator at Oak Ridge): a group of universities in the Southeast have purchased the separator and placed it at Oak Ridge.



This is a quartz wafer which has been used as a nuclear track detector in the measurement of reaction cross sections. The technique consists in exposing a target of interest, along with one of these quartz wafers, to a heavy-ion beam. Reaction products formed by the beam on the target impinge on the quartz wafer and leave tracks whose sizes can be correlated with the product masses. Etching in hydrofluoric acid reveals conical intrusions, which in the surface shown here are the result of a 10-min etch after exposure to products formed by a 150-MeV argon beam incident on a nickel target. The large holes indicate heavy particles (fusion events), while the smaller ones are indicative of lighter particles (fission events). This technique will be used to understand the dynamics of reactions induced by extremely heavy ions.



One question connected with the project is, how far from stability can we actually get? A program to measure production yields for nuclei in the krypton region ($Z = 36$) is in progress at the Tandem accelerator. These measurements have shown reasonable agreement with theoretical calculations. Further computations for nuclei in all parts of the periodic table should tell us where UNISOR can expect large enough yields, given the ORIC beams and suitable target materials, to pursue research for nuclei far from stability.

Attempts to synthesize superheavy nuclei will, by necessity, proceed by heavy-ion-induced reactions, two types of which have been proposed most often. The first, complete fusion, involves a combination of target and projectile that would lead to a product situated somewhere in the islands of stability. The second type, fission, involves the collision of two massive nuclei, for example, uranium on uranium; from this, it is hoped that a good percentage of the fission products will preferentially be the extra stable, superheavy nuclei. Unfortunately for the complete fusion reaction, calculations indicate that the large amount of rotational spin brought in by heavy ions overcomes the surface tension that holds the nuclei together. The probability for fission to occur then is so large that few, if any, products of the complete fusion type are left. Experimental investigations are under way with two goals in mind: one is to see how the yield of complete fusion products varies with projectile and target combinations, and the other is to understand the dynamics of heavy-ion fission. One group, consisting of E. E. Gross, A. Zucker, M. J. Saltmarsh, and H. G. Bingham, has studied systems formed by argon ions incident on nickel, iron, and titanium; while F. Plasil, F. Pleasonton, and R. L. Ferguson have looked at the system formed by neon on silver. Results from this second investigation indicate that fission and complete fusion do not account for all of the expected yield. It seems then that there are other, "missing," types of reactions. Clearly much work remains before the best method to approach the production of the superheavies is found.

One of the "missing" types of reactions involves trajectories in which nuclei are kept apart by the Coulomb field. Such reactions are termed transfer reactions because, as the nuclei travel on these Coulomb trajectories, protons and neutrons, singly and in clusters, can transfer between the two competing nuclei. Thus, only the nuclear surface is probed by this type of reactions since the bulk of the two nuclei never get close enough together to interact. Single neutron and proton transfer reactions induced by carbon and boron ions incident on a lead target have been systematically investigated by J. L. C. Ford, K. S. Toth, and J. B. Ball at the ORIC. The indications are that in many ways these reactions can be understood in terms of simple semiclassical concepts. Some subtle deviations do appear and efforts are now in progress to understand the reaction mechanism within more modern theoretical frameworks. It is, however, in the regime of cluster transfers that heavy ions hold great promise, because, as they are massive, the potential for transferring large quantities of nuclear matter is there. Such reactions can therefore be sensitive tools for the study of the nuclear surface. Does it, for example, consist of bumps or clusters of nucleons, or is it on the contrary quite smooth? This field is still in its infancy.

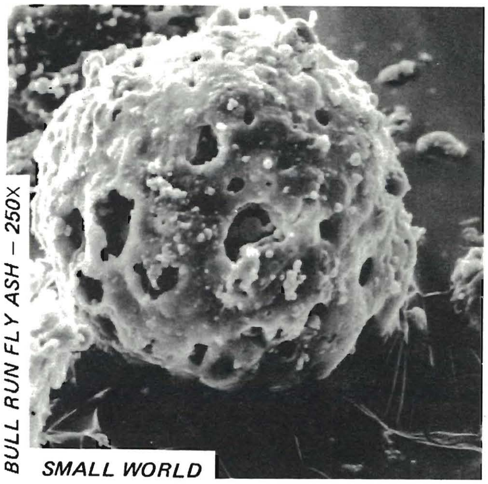
WOOD SPLIT ALONG THE GRAIN — 165×

SMALL WORLD

It has been known for some time that nuclei in certain regions of the periodic table are not spherical, but deformed into shapes that resemble footballs. The energy spacing for the excited levels in these nuclei can be explained if one assumes that they rotate about an axis through their centers. Because heavy ions bring in a large amount of spin, highly excited states of these rotational nuclei can be investigated by means of complete fusion reactions. An extremely interesting phenomenon, termed "backbending," has recently been observed. Up to a certain amount of excitation the level spacing can essentially be explained on the basis of the simple rotor model. Abruptly, however, the spacing of the levels decreases, indicating that the nucleus has suddenly become more rigid. This discontinuity has not been noted in all deformed nuclei; several conflicting theoretical explanations have been suggested. At Oak Ridge, P. H. Stelson, L. L. Riedinger, of the University of Tennessee, N. R. Johnson, Jr., and colleagues have been investigating the backbending effect with neon and argon ions in an effort to reach even higher levels to see if this trend in level spacing continues or not. In the course of these studies, a state in ^{165}Yb with $4\frac{1}{2}$ units of spin has been excited by ^{22}Ne ions incident on ^{148}Nd. This is the highest spin known up to now for a state in an odd-mass nucleus, that is, where the sum of the number of protons and neutrons is odd.

When the bombarding ion energy is kept so low that the projectile remains outside the range of the nuclear force of the target, then we are led into the rich field of Coulomb excitation. Here nuclear levels are excited only by the interaction of the positive charges of both target and projectile. With heavy ions one can once again excite nuclei to high energy levels. The hope is that with much heavier ions the energy of excitation will be high enough to get into the backbending region, and thus open up a new method of investigating this phenomenon. In the meantime, by Coulomb-exciting ^{232}Th and ^{238}U with argon ions, a group at the ORIC led by E. Eichler and Johnson was able to confirm some startling results obtained at the Tandem with helium ion Coulomb excitation. It turns out that deformed nuclei have a distinct bulge around the middle and look nothing like the streamlined football originally postulated.

The interaction of accelerated ions with solid matter has been investigated mainly at low energies and with light ions. But important recent experiments indicate that heavy ions offer not only the possibility of studying new and interesting phenomena, but also a means of obtaining valuable data for practical applications. Specifically, this has to do with radiation effects that will be encountered when fast fission breeder reactors, and eventually controlled thermonuclear fusion reactors, are used to meet the nation's energy needs. Materials in these reactors will be subjected to intense neutron fluxes. And yet, the required neutron sources for advance studies are unavailable, primarily because of the time element involved. It turns out, however, that it is the atoms (in effect, heavy ions) displaced by the neutrons that cause most of the damage. In fact, a few hours of heavy-ion irradiation produces damage equivalent to a year's worth of neutron bombardment. The ORNL single-stage Van de Graaff accelerator has now been modified to produce beams of heavy ions



to be used primarily for radiation damage studies. An elaborate selection system is set up to direct the accelerated ions into a reaction chamber whose temperature can be varied to simulate conditions that might be encountered in a reactor.

One extremely interesting phenomenon in solid state physics, called channeling, is being actively studied at the Tandem. If a near perfect single crystal is properly aligned with respect to the direction of a well-collimated ion beam, ions can move along a particular plane of the crystal and, therefore, suffer less energy loss than otherwise. In such trajectories the ions never come closer than one-billionth of a centimeter to the atoms in the crystal matrix. Channeling exists because of crystalline perfection and this makes it a sensitive tool for studying radiation damage. Some time ago light-ion investigations led to suspicions that some trajectories involved produce even less energy loss. It took, however, iodine ions accelerated at the Tandem to confirm the existence of "hyperchanneling" where ions are confined not just to one plane, but to a direction along one axis. During the past year, a group led by C. D. Moak, J. A. Biggerstaff, and Sheldon Datz, working at the Tandem, found that for single crystals of silver hyperchanneling differs in energy loss, depending on which crystalline axis the iodine ions are confined to in their traversal. Clearly the field of ion channeling is only now beginning to be thoroughly investigated.

The simplest atoms — those containing just a few electrons — are the most accurately understood objects of a size for which quantum effects are important. Our confidence in our knowledge of the most fundamental force in nature — electromagnetism — is based largely on the remarkably good agreement between theory and experiment as they relate to objects of atomic size. Only the lightest atoms, hydrogen, helium, and lithium, are susceptible to theoretical calculation of requisite exactitude. The complexities of heavier atoms, which contain more electrons, are not yet fully understood, even with the aid of modern high-speed computers. But heavier atoms that retain only a few electrons can be studied by stripping off all but a few of their electrons. Such ions are remarkably like their lighter brothers, except for the fact that the electrons in them move at speeds nearer the speed of light. The theory of relativity must then be merged with the quantum theory of electromagnetism to describe these elementary heavy ions properly.

Highly stripped heavy ions are terrestrially rare, but are not so rare in stars, or the sun. Thus the subject of energetic heavy-ion atomic physics is of significance to astrophysics where recognition of specific atomic spectral lines is the only way to know what elements are present in the stars. Stellar astronomers frequently study the light emitted by such ions to gain information about star surface temperatures and pressures, or the speed with which these stars travel through the universe. Analysis of the intensity of such light is a principal research tool in the characterization of the spectacular solar flares streaming out of areas of high solar activity.

Because stellar atoms are highly stripped, their spectra cannot be identified with conventional sources on earth. The one way that they can be studied in detail is to use heavy-ion beams. Once heavy ions are extracted from an accelerator, they can be passed through thin foils which then strip additional electrons off the ions. A strong research effort in beam-foil spectroscopy is under way at both the Tandem and the ORIC to understand the properties of such exotic ions. The people most directly involved are Ivan Sellin, David Pegg, and J. R. Mowat, professors at the University of Tennessee, and ORNL physicist P. M. Griffin. Some of their recent experiments have revealed interesting effects on the production of x rays when argon ions, foil-stripped of differing numbers of electrons, were passed through neon gas. Simple theories predict that x-ray production should have a quadratic dependence on the projectile charge. It was found, however, that the x-ray yield increased by a factor of 10 when the charge on the argon ions went from 6 to 14. More detailed studies are needed to understand this surprising result.

The same excitations of ions, which give rise to the emission of light as the ions "cool," frequently emit free electrons rather than photons of light. This type of cooling is frequently dominant, and is studied in the ORNL experiments also. Because only the photons from stellar emission processes reach the earth, the laboratory investigators provide information important for but inaccessible to solar astronomy experiments, like those aboard Skylab.

Continuous effort is going into the improvement of the heavy-ion capabilities of existing ORNL accelerators. The main thrusts have been in the direction of increased reliability of the machines themselves and in the development of ion sources to get a greater variety of beams with increased intensities. Mention has already been made of the adaptation of the single-stage Van de Graaff to radiation damage studies. At the ORIC improvements have been made in the vacuum of the accelerator itself and the beam transport lines. Good vacuum is important for heavy-ion beams which, because of the large masses involved, deteriorate in quality if residual gases are present to cause collisions. A computer control system has been installed which, among its other duties, will serve as a memory bank to store information necessary to accelerate the large variety of beams to whatever energies experimenters may desire. An ion-source test facility is being built which will free the ORIC from this function. The Tandem accelerator was shut down while four different types of ion sources were installed in conjunction with a new bending magnet which will allow a multileg configuration. Maintenance on each source can then be performed independently. A separate test facility is also being designed so that further ion source developments can be made without interrupting the Tandem schedule.

Finally, a promising concept is being examined by M. L. Mallory, E. D. Hudson, Lord, and Zucker that will allow the ORIC to accelerate heavier species of ions to higher energies and with greater intensities. The idea is to take a once-accelerated beam through a stripping foil and then reinject it for a second acceleration cycle. The main question is, can the two beams be kept separate? Computer studies of the beam orbits within the cyclotron have verified the theoretical feasibility of this concept, aptly named "recycle." By means of this technique, ions as heavy as krypton, with usable intensities, could be accelerated to an energy of about 500 MeV. The intensity for heavier ions drops off sharply. Nevertheless, the increase in the number of useful beams from the now available argon ($Z = 18$) to krypton ($Z = 36$) opens up new possibilities that researchers are eagerly awaiting.

Materials Structure

That structure is important to function is apparent everywhere in the visible world — consider an eel and an octopus, a lens and a prism, a pin and a needle. In the invisible, submicroscopic world of atoms and molecules it is natural to expect the same connection, and chemists indeed developed an enormously successful structural theory of organic chemistry even before direct physical evidence for discrete atomic particles was available. Such endeavors, and similar ones concerned with the properties of crystals, started with function — the chemical reactivity of various kinds of compounds, the external form of crystals — and deduced structure. The success of such structural theories in systematizing old and predicting new properties made it clear that structure on the molecular scale was a central concept in chemistry, and that a direct method of structure determination would be of the highest interest.

The discovery of x rays in 1895 provided such a direct method. It was not, unfortunately, quite so direct as simply looking at a crystal with some sort of x-ray microscope. X rays are bent too slightly by matter to allow the construction of practical lenses. The method relies instead on diffraction, the scattering of an x-ray beam by the separate atoms of a crystal and the formation of a diffraction pattern by the interference of the individual scattered waves. Where the separate waves from different scattering atoms are crest to crest and trough to trough the intensities of the waves add to give bright areas in the pattern; where they are trough to crest they give darkness. Such a pattern mapped on a plane or, better, on a spherical surface surrounding the scattering crystal can be traced back geometrically to reveal the structure producing the scattering.

The scattering of x rays by atoms is done by the electrons of those atoms, and the intensity of the scattering by a particular kind of atom depends on the number of electrons it contains. Since hydrogen contains only one electron it scatters very weakly; as a consequence hydrogen atoms in crystals with other kinds of atoms could not be located accurately by x-ray diffraction. A bit of bad luck, considering the importance of hydrogen in chemistry and biology. This difficulty was relieved by the discovery of the neutron and its partial wavelike character. Neutrons at around room temperature have a wavelength comparable to the spacings of atoms in crystals and molecules, and their wave nature causes them to be diffracted. However, they are scattered by nuclei and not by electrons, and it just happens that the nucleus of hydrogen (the

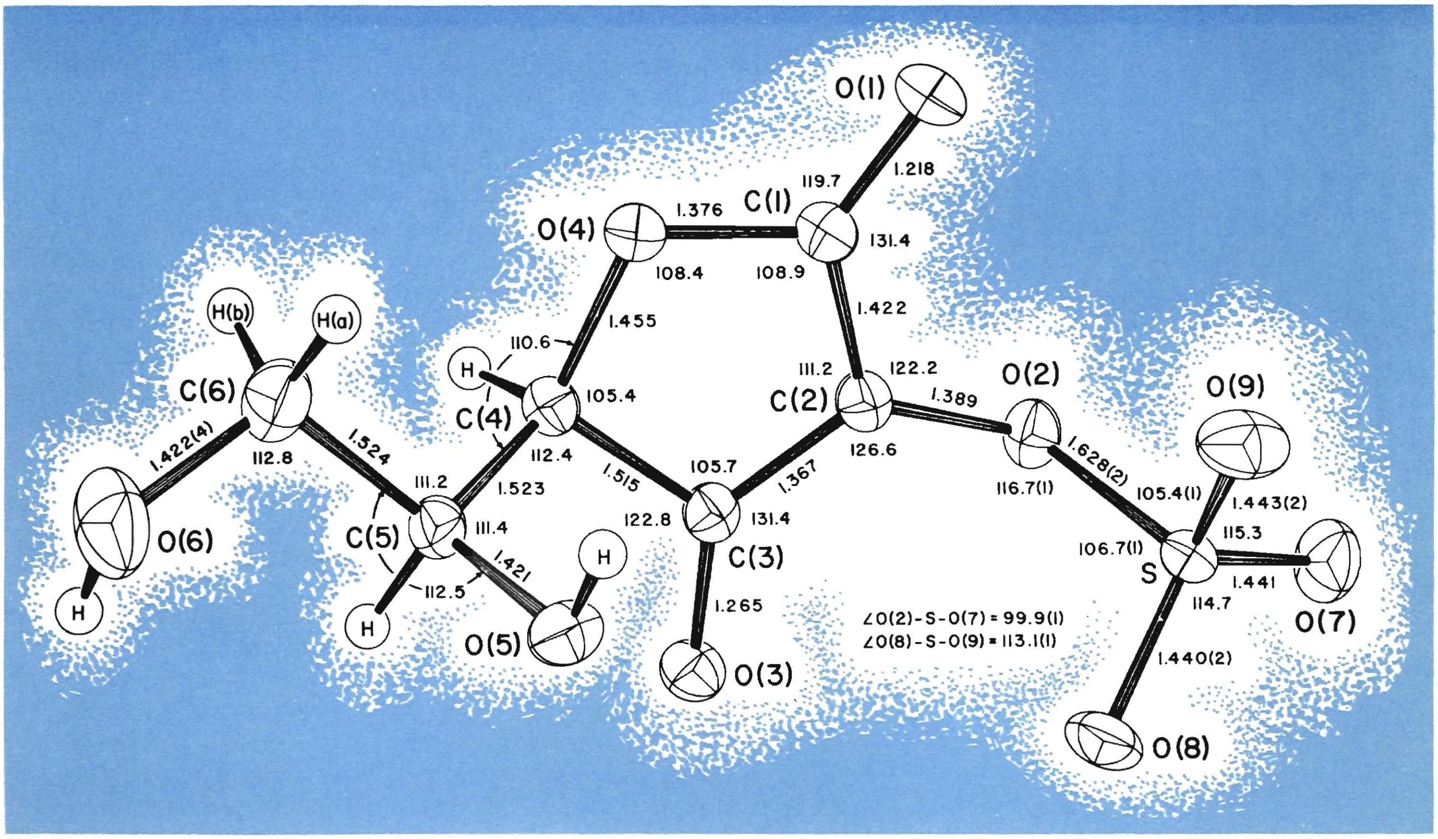
proton) is a strong scatterer as is the deuteron, the nucleus of deuterium (the heavy stable isotope of hydrogen). Hence the diffraction of neutrons can be used to locate hydrogen atoms in crystals.

Granted, then, that structure at the atomic level is interesting and possible to determine, what does ORNL do in this field? In chemistry and in biology it supports crystallographic groups which study compounds of interest to them and to their colleagues. What they do and why is probably best shown by some examples of recent work.

Nature still supplies new compounds for the organic chemist to puzzle over as more and more plants, insects, or animal parts are searched for food, drugs, poisons, sex attractants, etc., or for clues as to how the plant or animal manages the business of living. Years ago such new compounds were studied by elemental analysis, functional group analysis, degradation, and the other tools of qualitative organic analysis, but, if the compound can be crystallized, crystal structure determination provides a shortcut through that maze of deduction. If the positions of all the atoms in the crystal are known, the molecular structure is obviously also known (even if more than one molecule constitutes the unit cell of the crystal, the repeating unit by which its structure is described, the atom-to-atom distances will show which atoms belong to which molecule). An example of this use of structure determination is the plant pigment methoxydalrubone, $C_{20}H_{20}O_5$. After several man-years of conventional effort had been expended on it without success, a crystal was sent here for study by diffraction. Some technical complications attended the solution of the structure, but they were surmounted by W. E. Thiessen and H. A. Levy and the structure was revealed. The chemist who had been working on the problem was moved to write: "Wow! I told you it was a crazy compound — ! We never would have gotten the structure in a hundred years."

The power of neutron diffraction to locate hydrogen (and deuterium) atoms was graphically demonstrated in another organic chemical problem. A compound with seven carbon atoms arranged in two rings was being followed through a reaction in which some of the hydrogen atoms attached to the carbons exchanged places. Deuterium had been substituted for hydrogen at some of these positions so one could tell whether or not those particular hydrogens had been involved in the exchanges. Since the compound crystallized well, it was examined by neutron diffraction by C. K. Johnson and T. C. Tesch. The large (and different) scattering by hydrogen and deuterium made it possible to determine the relative amounts of D and H at particular sites to good precision even when relatively small amounts of D were involved. With this information, some mechanistic details could be obtained that could not have been with conventional (NMR) methods of analysis for D at a particular site.

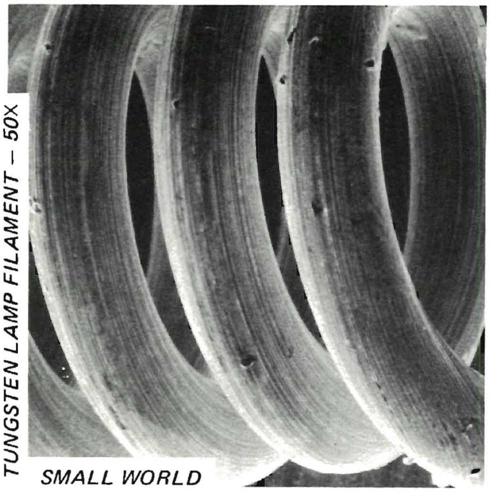
An area of intense chemical interest to the Laboratory is of course that of the transuranium elements, whose properties are particularly interesting because they are at the end of the list of known elements. Naturally, knowing the crystal structure of compounds of these elements is important, because sizes of the ions can be deduced from the interionic distances observed in the crystals, and these can be related to the electronic structures of the



Quantified configuration of an anion of vitamin C sulfate isolated from brine shrimp. The diffraction study has determined bond lengths and angles to a high degree of accuracy. Covalent bonds are shown as rods with lengths indicated in angstroms. The average thermal motion of each nonhydrogen atom is depicted by an ellipsoidal surface of constant probability density for the displacement of the atomic center from its equilibrium position. The dimensions of each ellipsoid are such that there is a 50% probability that the atomic center lies within it. Hydrogen atoms are shown as spheres of radius 0.1 Å.

constituent atoms. But the determination of structure sometimes serves a qualitative purpose, namely the description of just what entities are attached to the heavy atom in the particular compound. For instance, the exact nature of the heptavalent neptunium compound reported earlier by a Russian chemist was not at all clear. The report represented the first example of an actinide element with a valence of 7, and it was of great theoretical interest to know how the various groups attached to the neptunium were arranged. A heptavalent neptunium compound was prepared at ORNL and crystallized from solution. A diffraction study by J. H. Burns showed that the metal atom is surrounded by six oxygen atoms in the form of an elongated octahedron. It can be concluded (from this and from chemical analysis of the compound) that the neptunium in solution has the form of octahedral negative ions of the formula $NpO_4(OH)_2{}^{3-}$. This formula accounts for the valence of 7 but is different from the one suggested by the Russian workers, and gives a sound basis for understanding the chemical reactions in solution by which heptavalent neptunium is formed and destroyed.

Materials in the liquid state are important in all branches of science, and their atomic structures are equally interesting. Unlike crystalline solids, the positions of atoms and molecules in liquids do not have a highly ordered arrangement over large distances, but molecules retain a characteristic structure, and the positions of atoms and molecules over short distances do show a regularity. This regularity or ordering over near-neighbor distances is being explored by diffraction methods. For the first time, H. A. Levy, A. H. Narten, and F. Vaslow have studied an ionic solution extensively by both



TUNGSTEN LAMP FILAMENT — 50X

SMALL WORLD

x-ray and neutron diffraction. The solution chosen was lithium chloride (LiCl) in heavy water (D_2O) with concentrations ranging from dilute to saturated. With respect to the structure of the water molecules, this study shows it to be close to that of the molecules in the vapor. This is like the situation in pure liquid water but contrary to the example of ice where the water molecule is distorted. By combining the neutron and x-ray results a remarkably detailed insight is obtained for the structure of the liquid (the average arrangement of different molecules). In pure water at room temperature the water molecules are tetrahedrally coordinated with each pair of near neighbors being connected on the average by a straight hydrogen bond. As lithium chloride is dissolved in the water, the interactions of the ions with the water molecules alter the situation. The pure water structure diminishes gradually as LiCl is added, and the water structure disappears by the time the LiCl to D_2O ratio reaches 0.1 (this ratio is 0.3 at saturation). The structural features that replace those of pure water include octahedral coordination of the oxygen atoms of the D_2O about each Cl^- ion and tetrahedral coordination of water about each Li^+ ion. Structural effects of ions have been put forward in the past to explain thermodynamic properties of aqueous solutions; the present work gives direct evidence about such effects.

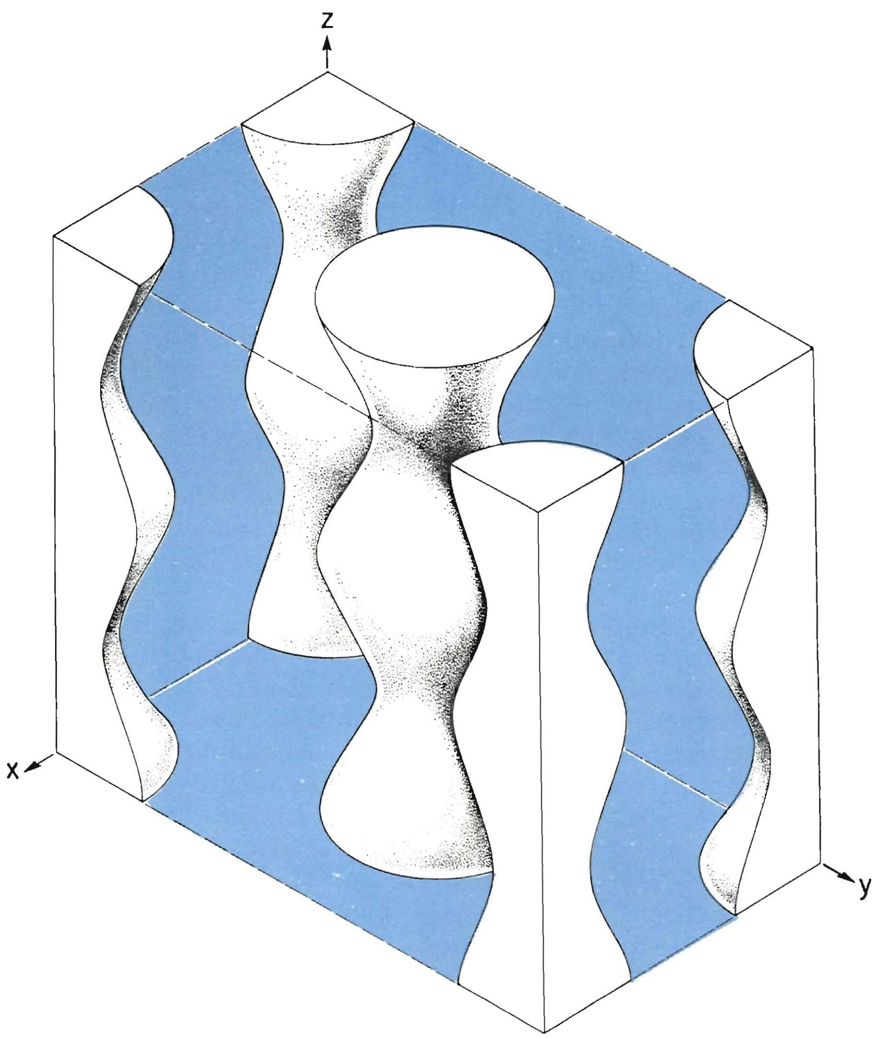
The x-ray diffraction group of the Biology Division is using single-crystal diffraction techniques to investigate molecular structures of biologically interesting molecules. Many of the molecules are "small" such as nucleosides, peptides, and carcinogens, while others are extremely large such as protein macromolecules.

Most of the small molecules studied come from within the Biology Division. Thus, this year B. W. McClelland and J. R. Einstein have completed the structure refinement of vitamin C sulfate, a compound isolated from brine shrimp cysts by C. G. Mead and F. J. Finamore and synthesized by A. D. Bond. Although the compound has been found to be widespread throughout the animal kingdom, its exact function is unknown as is that of its parent, vitamin C. An important point of dispute was the location of the sulfate group in the molecule. Earlier chemical studies of A. D. Bond indicated the sulfate to be at the 2 position of the molecule while others assumed it was at the 3 position. The x-ray results conclusively proved the 2 position to be the correct location. This particular structure is now known with great accuracy: the R index of discrepancy between observed and calculated data appears to be the lowest on record.

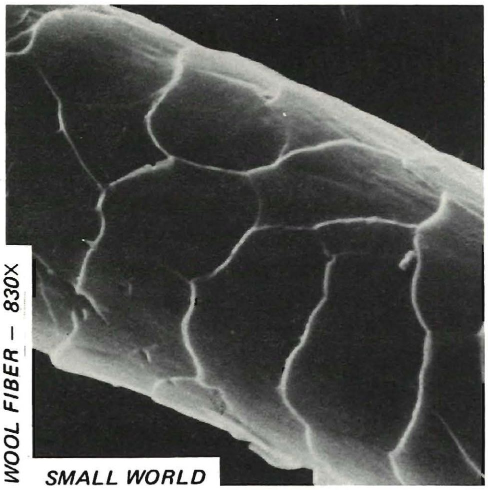
The study of large molecules involves solutions to several very difficult problems. Many thousands of diffraction maxima (reflections) must be measured, and the magnitude of such a task requires automated techniques. Before the work advances to this stage, however, there is the very difficult task of preparing single crystals of suitably purified materials. Work is now under way on four proteins and progress has been made in obtaining them suitably purified and in crystalline form. Paralleling this development, improved methods have evolved for computer-automated scanning of diffraction photographs, so as to achieve measurement rates greater by almost an order of magnitude than rates previously attained for such systems.

For chemical and biological purposes, neutron or x-ray diffraction has done its part when it has located all of the atoms in a unit cell (and in favorable cases provided an estimate of their thermal motions). For those physicists who study magnetism, neutron diffraction can provide one more kind of information, namely, the spatial arrangement of the elementary, atomic-scale magnets that are the source of the overall magnetism of a chunk of magnetized iron (for example). Neutrons can do this because they themselves are little magnets that are scattered by the elementary magnets in a crystal. This scattering is naturally superimposed on the nuclear scattering, so that the crystal structure and the magnetic structure together determine the resulting diffraction pattern.

In simple terms, there are three kinds of materials with respect to bulk magnetic properties: diamagnetic, paramagnetic, and ferromagnetic materials. Paramagnetic materials have atomic-scale elementary magnets in them and these are individually free to orient themselves in the presence of an external magnet. The whole piece of material thus becomes a magnet, and is attracted (rather weakly to be sure) to the magnet doing the aligning. When the external magnet is removed, the elementary magnets return, under the thermal jostling of the atoms of the solid, to their random orientation, and the piece is no longer magnetized.



Distribution of the diffuse component of magnetic moment density in gadolinium metal. The diffuse component is related to the distribution of conduction electrons in the metal.



Diamagnetic materials have no elementary magnets in them, and are outside the interest of this discussion.

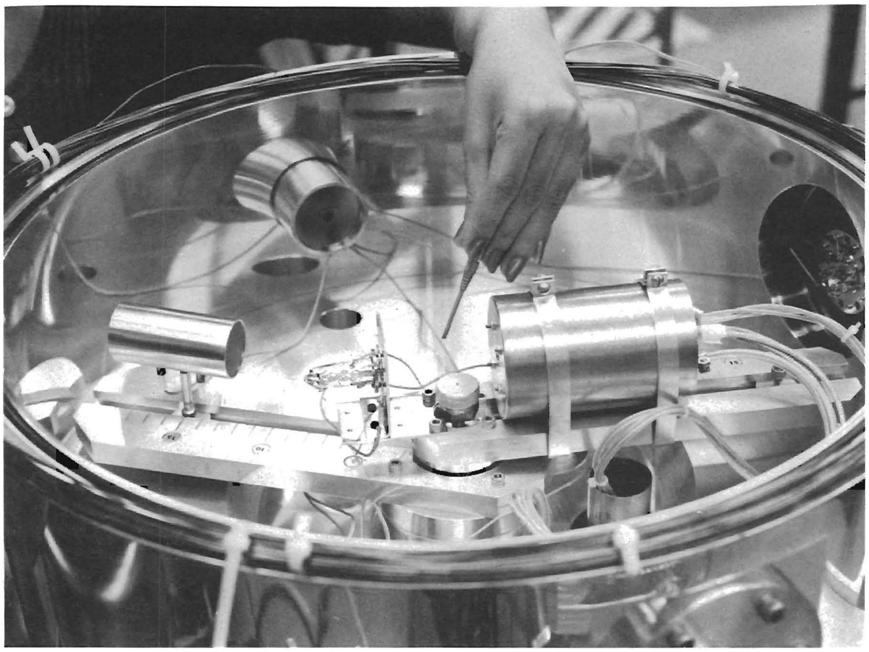
Ferromagnetic materials are similar to paramagnetic, except that electrical forces within the solid align the elementary magnets even in the absence of any external magnetic field. If you want to understand the nature of ferromagnetism, either for its own sake or for making better magnets, the important thing to know is how the elementary magnets are arranged, and this information can be supplied by neutron scattering.

Metals of the rare earth family of elements have been a particularly fruitful area of study. Like all metals, these materials are electrical conductors. In the case of the rare earths this conductivity arises from each atom giving up its outermost three electrons to the conduction band of the metal. The magnetic properties of the atoms arise from electrons that are more deeply buried in the atomic shell structure, the $4f$ electrons. Although these electrons may impart a strong magnetic moment to the individual atoms, they are sufficiently localized and isolated that the direct forces between atoms are too weak to give a cooperative alignment and ferromagnetic properties to the bulk material. There is, however, an indirect mechanism by which these electrons may strongly interact thereby causing the metal to become ferromagnetic. This indirect interaction is via the conduction electrons; the $4f$ electrons of one atom strongly interact with the conduction electrons which in turn interact with $4f$ electrons of other atoms. These interactions impart a small magnetic behavior to the conduction electrons. The experiment consists of preparing a neutron beam that is polarized; that is, the neutrons which themselves are tiny magnets are preponderantly oriented parallel to one another. This polarized beam is scattered from the metallic crystal. In these experiments carried out by W. C. Koehler, R. M. Moon, J. W. Cable, and H. R. Child of the Solid State Division, it is possible to distinguish between the nuclear scattering which gives information on the positions of atoms and the magnetic scattering from electrons. In the case of gadolinium, for example, the very strong magnetism centered at the atoms is observed. This is the magnetism from the $4f$ electrons. In addition, a weaker magnetic effect may be quantitatively mapped through the bulk of the crystal. This is the magnetic effect induced in the conduction electrons. Other rare earth metals that have recently been studied are samarium and promethium.

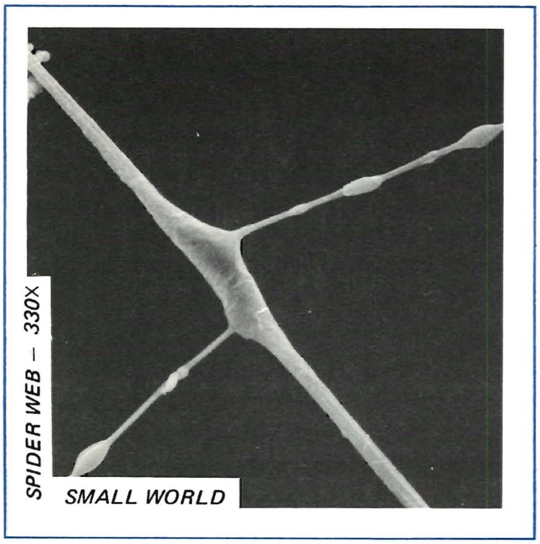
There are formidable experimental obstacles in carrying out magnetic scattering experiments. It is essential that nuclei present in the sample do not absorb neutrons too strongly. Unfortunately, naturally occurring gadolinium is not suitable, and it was necessary to use the separated isotope ^{160}Gd which has a manageably small neutron capture cross section. Single crystals of the metal prepared from this isotope were used in the experiments. Similarly, the separated isotope ^{154}Sm was used in the samarium experiments. Promethium is a man-made element, and a cylindrical rod of high purity metallic ^{147}Pm one inch long and one-quarter inch in diameter was used. The element is radioactive, and the self-heating of the metal due to the radiation was about 1.5 watts. Nevertheless, it was possible to cool the metal to 7.5°K in order to carry out the experiments.

Atomic and Molecular Physics

Research in Atomic and Molecular Physics at ORNL is spread out over several divisions; thus, the total effort is substantially larger than many staff members may be aware. One of these pockets of research is in the Health Physics Division. This research effort was started some twenty years ago in an attempt to devise a better proportional counter for neutron dosimetry. It has since expanded in many directions but is best known for its contributions in plasmon physics and in the study of negative ions. For many years, ORNL staff have studied the electronic energy levels in solids called plasmons. These are quantized collective oscillations of many electrons which can be excited by the passage of a charged particle. They may exist both in the volume of a target material and on the surface of the material. Our early work on energy losses to plasmon excitations for electron beams traversing metallic foils has been followed most recently by investigations of the interactions between photons and plasmons. As examples we have the decay of electron beam-generated plasmons by optical emission in the vacuum UV, the inverse process of photoelectric emission from plasmon decay, the generation of surface plasmon waves by photons, and the effects of surface plasmon production on the reflectance of mirrors. Aside from conceptual

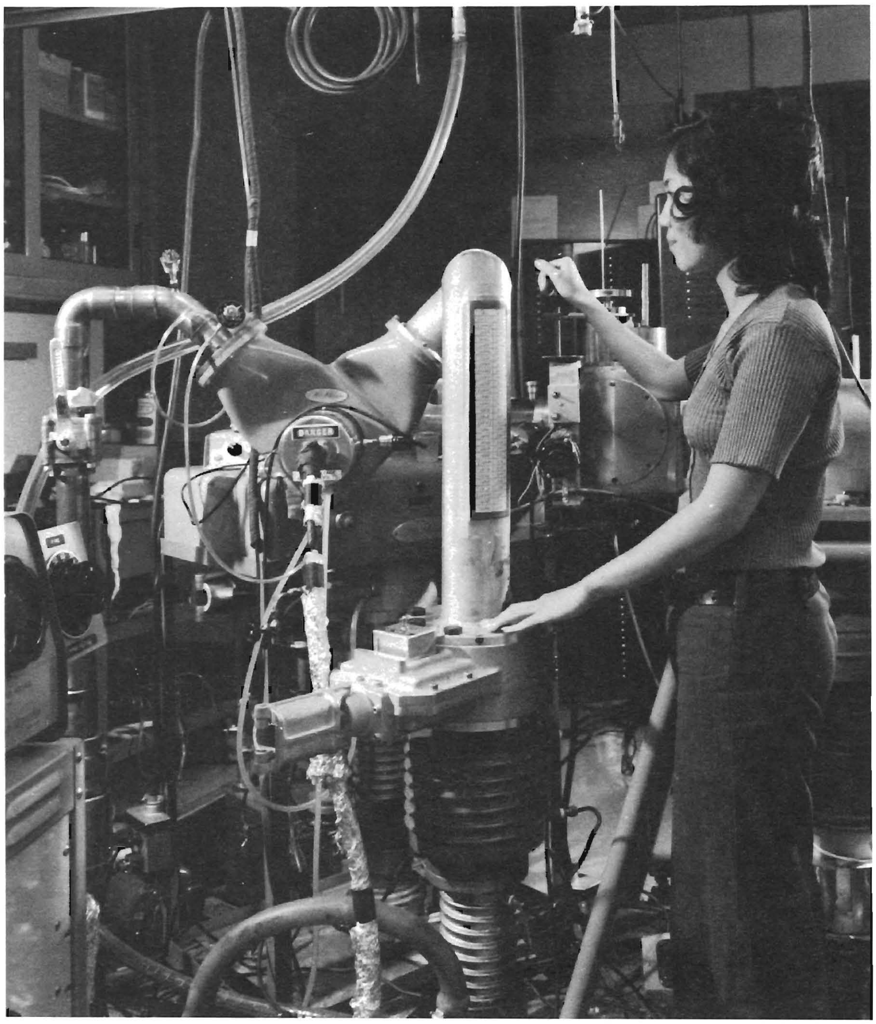


This is the interior of an apparatus used to study the kinetics of molecular dissociation. The large cylinder directly below the hand is attached to a movable arm and contains an electron gun that projects a horizontal pulsed electron beam of controlled energy. The beam intersects a vertical molecular gas beam emanating from an array of very fine parallel holes located beneath the flat knurled cap in the exact center of the chamber. The entrance to a quadrupole mass spectrometer, used to analyze the ionic and neutral products formed in the intersection of the electron and molecular beams, can be seen in the wall of the main vacuum chamber at approximately 3 o'clock. To the left, a second, independently rotatable arm supports a gridded tube used in quenching metastable atoms, and a shielded Channeltron detector, at near 12 o'clock, is used for obtaining ion time-of-flight spectra. The copper coil around the chamber rim is part of a Helmholtz coil system for reduction of the earth's magnetic field in the experimental region.

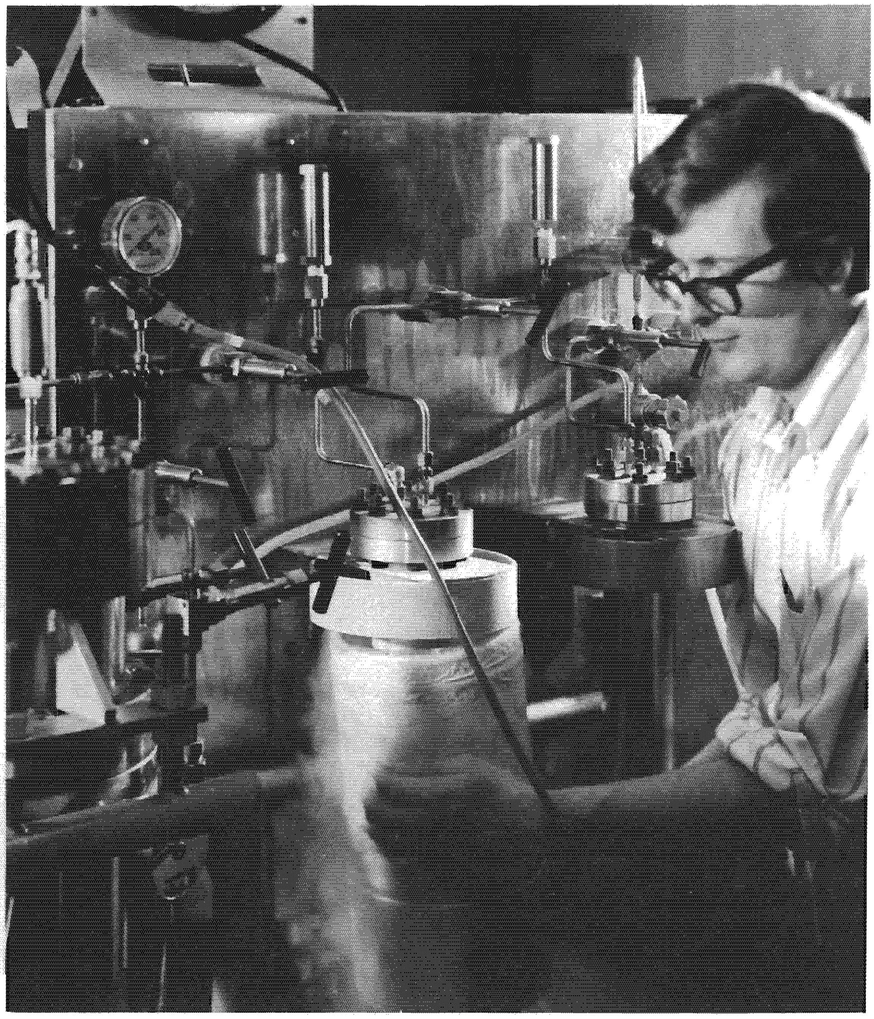


importance, applications to electro-optical control devices and improvement of high power ultraviolet lasers for thermonuclear fusion (by development of better mirrors) are immediate.

Studies of the electronic structures of liquids begun eight years ago at ORNL have just revealed the phenomenon of collective electronic excitation in water. Working at the University of Tennessee, Professor L. R. Painter, R. D. Birkhoff, and graduate student J. M. Heller have shown in addition that this plasmon generation is the principal mechanism by which ionizing radiation deposits its energy in water (and tissue). R. H. Ritchie and graduate student V. N. Neelavathi have made a theoretical calculation recently of the dielectric behavior of a dense collection of randomly located atoms which shows a strong plasmon effect, lending theoretical support for collective effects in liquids generally. Related in instrumentation to the above optical studies in the vacuum UV are observations of the optical absorption of chloroplasts and red blood cells, the latter in liquid suspension. Similarities in absorption structure are theoretically helpful and philosophically interesting. Also under investigation are the optical properties of the nucleic acid bases and DNA. A proper understanding of the optical behavior of the nucleic acids may be important in identifying the base sequence in DNA.



Physicist I-lan Tang, graduate student at the University of Tennessee, uses a Seya-Namioka-type vacuum ultraviolet monochromator to find the optical properties of some nucleic acids. The instrument enables examination of materials in the region of the electromagnetic spectrum between 500 and 6000 Å. Metals, liquids, insulators and semiconductors, and biological materials have been studied with this apparatus.

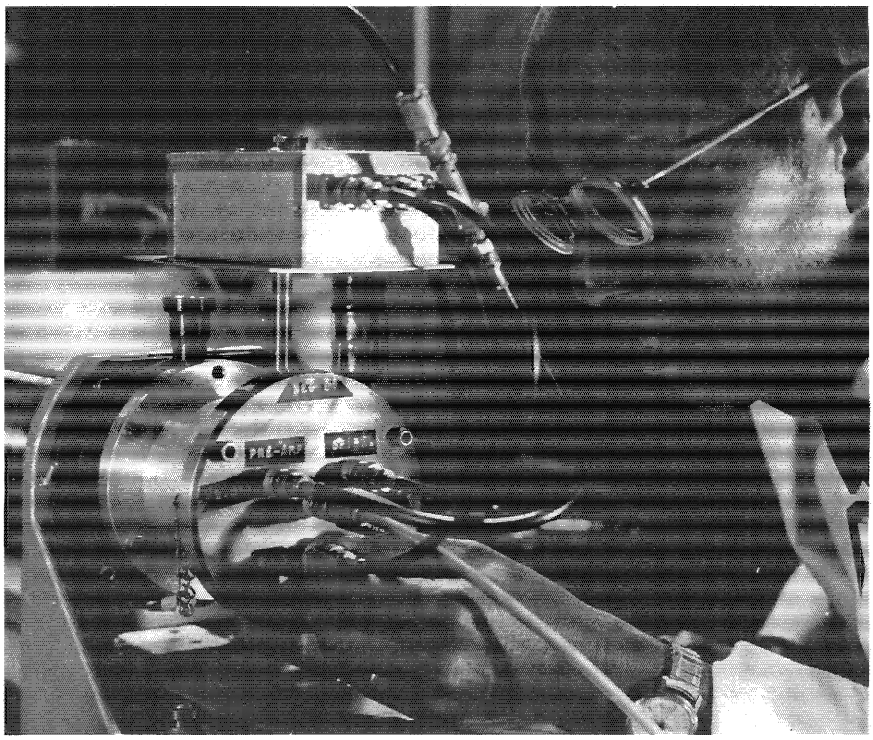


Ronald Goans, University of Tennessee graduate student, uses this high-pressure electron swarm chamber in the study of electron attachment to biomolecules in the very high-pressure gas phase. It is designed to probe electron-molecule interactions in experiments with total pressures up to 100 atm. These very high-pressure swarm experiments provide insight into the effects of the density and the nature of the environment in fundamental electron-molecule interactions. The device also affords an opportunity to study radiation processes over the entire pressure range from isolated molecules to the condensed phase. These experiments provide a picture of radiation interaction with matter in the density regions approaching those of biological interest.

In another research area L. G. Christophorou has been attempting to relate the often abundant knowledge of electronic properties of isolated molecules (low-pressure gases) to the properties of liquids and/or solids. To understand the roles of the physical and chemical properties of molecules in biological reactions, we must know how these isolated molecule properties change as the molecules are embedded in gradually denser and denser gaseous and finally liquid environments. In specially designed "swarm" experiments, for example, we have studied the process of the capture of slow electrons by O_2 when the O_2 molecule is embedded in a gaseous medium such as N_2, C_2H_4, or C_2H_6 at densities intermediate between low-pressure gas and a liquid. Drastic changes were observed in both the magnitude and the energy dependence of the capture cross section with increasing density demonstrating the gradual transition from "isolated molecule" to "condensed phase" behavior. From these studies it was possible to predict the "liquid state" behavior and to determine the autoionization lifetime of O_2^{-*} which was found to be equal to $\sim 2 \times 10^{-12}$ second.

The interaction of radiation with matter results in a complex array of electrons, photons, and charged and neutral atomic and molecular fragments. The electron-photon cascade is beginning to be

ORNL physicist Edward T. Arakawa makes final connections to a Bendix Spiraltron detector, a highly sensitive instrument capable of detecting photons, x rays, or charged particles such as electrons. Arakawa is using this detector with a grazing-incidence monochromator to measure the optical properties of nucleic acid bases in the soft-x-ray region of the electromagnetic spectrum. Here the photons have wavelengths of 500 to 100 Å, corresponding to photon energies from 25 to 125 eV. By using the photons as high-energy probes, information may be gained about the individual bases adenine, cytosine, guanine, and thymine, the fundamental components of genetic material.

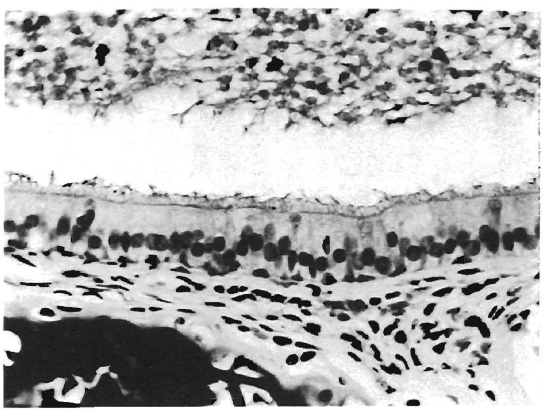


well understood, but there is very little information on the distributions (energy, angle, and type) of the charged and neutral fragments. R. N. Compton's work in this broad area is twofold: (1) determination of the cross sections for the production of slow secondary electrons upon electron impact ionization of the rare gases where comparison with the theoretical work of the Argonne group is possible, and (2) direct measurements of the energy and angular distributions of the fragments produced by dissociative ionization of molecules by electron impact. Energy distributions are determined from a time-of-flight analysis of ion pulses produced by a pulsed electron beam. The ion masses are determined with a quadrupole mass spectrometer. Energy and angular distributions have been recorded for O^+ from O_2, N^+ from N_2, H^+ from C_6H_6, and others.

In the few months since the announcement at San Diego in March 1973 of the high conductivity of TTF-TCNQ crystals, ORNL has mounted a substantial coordinated effort by a dozen staff members in six divisions. Results to date include growing large (1 cm) crystals, determination of the ionization potential of TTF and the negative ion states of TCNQ, and measurement of the conductivity of TTF-TCNQ as a function of temperature and crystal orientation. The conductivity found at ORNL exceeds all reported results except those for the three exceptionally good crystals of Heeger. That is, Heeger found crystals which at 60 degrees Kelvin had a conductivity similar to that of copper at room temperature, but no one has as yet been able to reproduce these data. It is not clear whether the conductivity found at ORNL and elsewhere is smaller than Heeger's because of imperfections in the very large crystals we have grown or impurities in them or whether in fact the tiny crystals measured by Heeger presented unusual experimental difficulties which made conductivity measurements less precise.

Biological Sciences

Section of normal tracheal mucosa composed chiefly of ciliated and mucous producing cells.



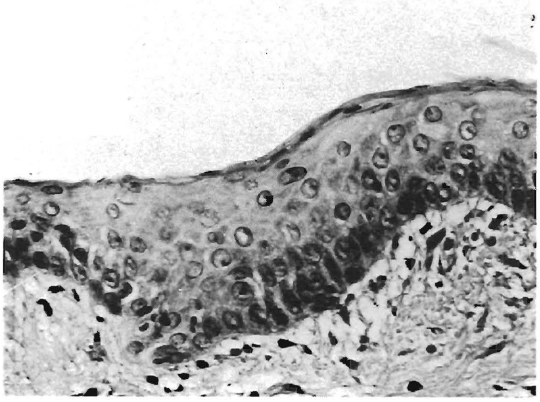
Thirty years of intensified investigation into the mechanisms involved in the effects of ionizing radiation on biological material have resulted in enormously advanced insights into a wide field of significant peripheral subjects. In examining ever more minutely the impact of x rays on genetic material, scientists in ORNL Biology Division have advanced the frontiers of knowledge in such corollary matters as cancer research, diseases of genetic origin, and virus management.

With the development of more and more sophisticated instruments for examining the structure of first the cell, then the nucleus, followed by the ability to single out the genes on the chromosome, and ultimately the order of the nucleotides in the polymer that is the DNA itself, what started out to be a single-goal research project has opened up a multidirectional network of discovery.

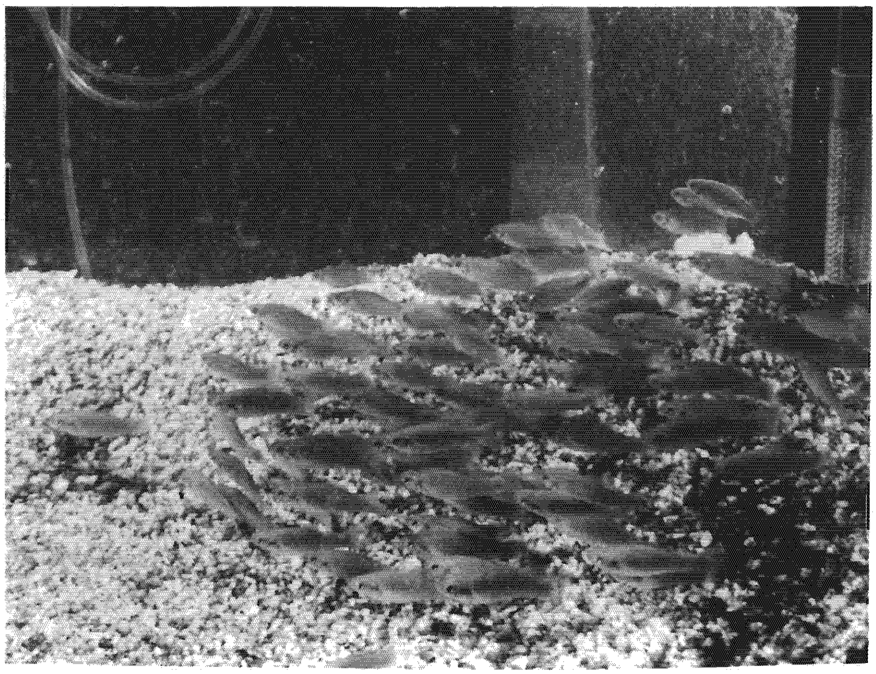
Basic to the entire work has been the insight derived from increasingly detailed knowledge of the biological material at the molecular level. It is here that the disclosures of how the virus acts, why the cancer lives or dies, what makes the chromosome repair itself, are now being observed.

Cancer Research

Section from trachea exposed for four weeks to the carcinogen benzo(a)pyrene. The normal mucociliary epithelium is replaced by multilayered squamous epithelium.



In research supported jointly by NCI and AEC, Virginia Cone and Paul Nettesheim have determined that certain levels of vitamin A have an inhibitory effect on the development of lung cancer in rats. Working with two groups of animals, one of which had received high doses of the vitamin in the form of retinyl acetate, the biologists delivered intratrachial injections of a known carcinogen to both. The development of cancerous tissue was significantly reduced in those that had been treated with the vitamin. It is known that vitamin A has an important function in the cellular differentiation of epithelial tissues. Vitamin A deficiency leads to abnormal cell differentiation and the appearance of squamous cells (which synthesize keratin, the protein of skin and hair) in the respiratory tract lining which is normally composed of columnar, mucus-producing, and ciliated cells. The cancers induced in the lungs of carcinogen-exposed rats are keratin-forming squamous cell carcinomas. Inhibition of squamous cell tumor development by excess vitamin A may be related to the vitamin's function in the control of differentiation of the cells lining the respiratory tract.



Clone of Poecelia formosa, *fish that reproduce nonsexually, used in tumor studies because their tissue is intercompatible.*

Understanding of cancer at the molecular level has also been enhanced by the research performed by R. E. Hart and R. B. Setlow on the tissue of the fish *Poecelia formosa.* Selected because it reproduces nonsexually, and hence results in a clone of individuals whose tissues are intercompatible, *P. formosa* contains as well the photoreactivating (PR) enzyme characteristic of all fish. This enzyme, not found in placental mammals, has the ability to use ordinary white light to repair specific damage inflicted on the DNA by certain frequencies of ultraviolet radiation. A known effect of uv radiation on the strand of nucleotides that make up the DNA is to form "dimers" by fusing two like molecules where they are adjacent. Photoreactivation of uv-affected systems results in enzymic monomerization of such dimers.

What Hart and Setlow did was take tissue samples from various organs of the fish, expose them to measured doses of uv radiation, and then inject the uv-irradiated tissues into a group from the same clone. They injected a second group of fish with unirradiated tissues, and a third group with irradiated tissue which had subsequently been exposed to ordinary light. They found that tumor incidence was less than 0.2% in the second group; of the ones injected with irradiated tissues, tumors were found in 15% of the fish; but if the tissue was exposed to PR light after uv exposure and before injection, tumor incidence was reduced in proportion to the length of photoreactivation time (0.5 to 30 min). The researchers' conclusion is that the presence in cells of pyrimidine dimers in DNA can cause malignant tumors. This is the first time that a known structural change in DNA has been implicated in the process of tumor formation.

In investigating the ability of a particular sarcoma virus to induce cancer in mice, John Yuhas and Nelson Pazmino have determined that the animals' susceptibility to such injections is closely dependent on their age. Working with mice whose ages range from birth to very old age (three years), they have found that newborn mice are

very sensitive to the virus, but as they approach young adulthood, they develop the ability to produce a specific antibody that protects them. However, after one year of age, sensitivity reappears, and increases with advancing age until it is as great as that of the newborn mouse. Since the serum antibody did not develop at all in the control mice, the inference is that it was a direct response to the injection of the virus. Apparently the ability to develop the antibody disappears with the decay of humoral immune capacity.

Long-range studies in the Biology Division, looking into the long-term effects of low doses of radiation (as little as 10 rads) on large mouse populations, are reaching a point where definitive conclusions can be drawn. The effects on mammals of different dose rates, ±1 rad/day, and the questions of whether there is evidence for a synergistic deleterious effect in the response to a combination of radiation with other known carcinogens, are still under study. Why neutron radiation effects, unlike those of gamma radiation, appear to be independent of rate is also still being investigated. All of these projects are expected to shed light on the environmental factors relevant to nuclear power plant siting. The results to date suggest the present standards for permissible exposure to ionizing radiation are conservative.

Molecular Biology

One of the mechanisms by which a cell repairs itself following chemical insult was studied by Gerald Vaughn, William Proctor, and John Cook by imposing a glycoside, ouabain, on a culture of human cells, and observing the chemical's interaction at the cell surface. The action of the chemical was to bind to and inhibit the activity of an enzyme in the cell's membrane, whose function was to maintain the balance of sodium and potassium in the cytoplasm. Such a balance is essential to the cell's ability to synthesize protein, to grow, and to maintain proper size and shape. When the entire surface of the cell was blocked, recovery did not occur; but partial blockage of the transport mechanisms resulted in a compensatory increase in the activity of the surviving sites for the length of time it took to regenerate the inhibited molecules, ultimately returning the cell to full normal function. Although the cell's growth and division cycle is about 24 hours, and there is thus a net synthesis from one whole cell membrane to two cell membranes in that time, the regeneration of inhibited molecules is complete in only 3 hours. Therefore the cell is capable of repairing its surface, which is its interface with the environment, much faster than would be expected from its normal growth rate alone.

The effect of heavy metal ions on the photochemical and luminescent properties of nucleic acids is being studied by R. O.

Rahn. Two of the metal ions studied, Ag^+ and Hg^{2+}, bind strongly to the bases in DNA and exert a "heavy atom effect" as manifested by a large enhancement in the intersystem crossing rate between the singlet and triplet manifolds. For the case of silver-complexed DNA, there is a 30-fold enhancement in both the rate of thymine dimerization and the intensity of the phosphorescence. These results implicate the thymine triplet as the precursor for the thymine dimer.

On the other hand, mercuric ions lower the triplet energy of adenine below that of thymine. Hence triplet energy transfer from thymine to adenine occurs in mercury-complexed DNA resulting in a tenfold quenching of both thymine dimerization and phosphorescence emission.

These observations indicate that heavy metal ion binding is a useful way of studying the energy pathways in DNA and show how the absorption of light by DNA leads to photodamage.

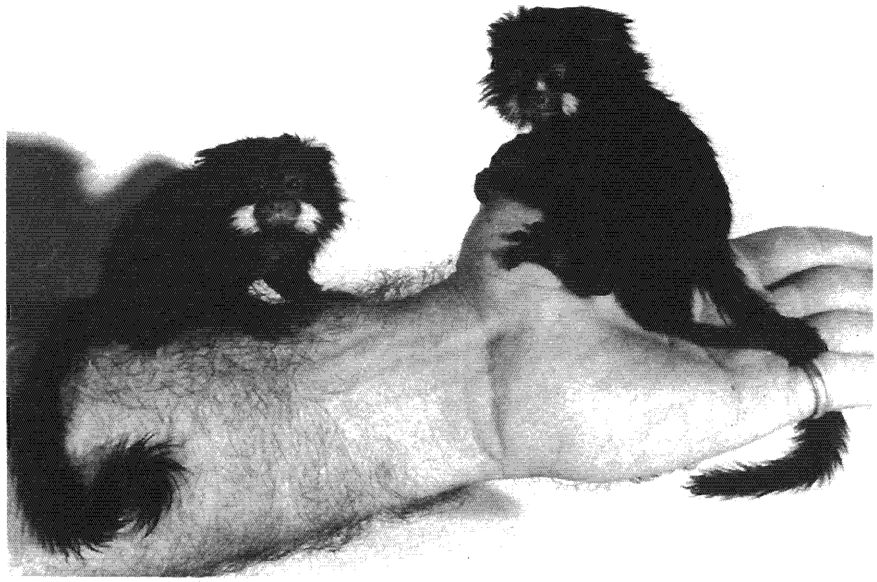
Genetics

Genetics — Somatic Cell Studies: Somatic Cell Mutagenesis

G. P. Hirsch and R. A. Popp have developed a technique which they hope will enable them to measure the frequency of base substitutions in mammalian somatic cells. Base substitution, a spontaneous phenomenon that occurs in all normal cells, is the principal mechanism by which genes evolve, both in somatic cells and in germ cells. In germ cells, this process can result in mutations or genetic errors such as sickle cell hemoglobin in man. Such activity in somatic cells may result in disease.

Given a method, however, for determining the exact rate of substitution taking place in somatic cells, both normally and in response to either radiation or chemical insult, a correlation of this response with the known response of germ cells to similar mutagenic assault could provide a test system of considerable value. The most attractive feature of the somatic cell mutagenesis test system is that only a single animal is required per test as compared with the large numbers needed to study the frequency of germ cell mutations.

Testing for base substitution mutations in somatic cells requires accurate measurements of the incorporation of trace amounts of a labeled amino acid, isoleucine, into highly purified hemoglobin of mammals selected for the absence of isoleucine occurring normally in their hemoglobin. These species include marmosets, sheep, and man. Chemical and physical insults in the form of mutagenic material and ionizing radiation that cause base substitutions in DNA can mutate by a single base substitution a codon such as GUU, which codes for



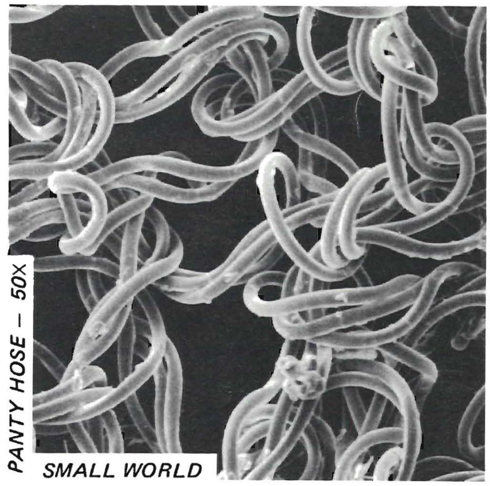
Two marmosets from the Oak Ridge Associated Universities colony. The similarity of this tiny primate's blood cells to those of man provides its contribution to the somatic cell studies of mutagenesis and chromosomal aberrations.

valine, into AUU, which codes for isoleucine. Base substitution mutagenesis is expected to increase the rate of substitution of isoleucine for other amino acids only when the nonisoleucine codons are mutable to isoleucine codons by a single base change. The sensitivity of the method is limited only by the frequency at which isoleucine is incorporated into hemoglobin through nongenetic errors at one or more of the many steps involved in producing the correct sequence of amino acids. The error frequency is estimated from the substitution frequency of isoleucine for amino acids such as alanine and glycine whose codons cannot mutate to isoleucine codons by a single base change. The normal error frequency of amino acid substitution in adult sheep hemoglobin has by this method been calculated to be 1 in 100,000, so that any agents that cause isoleucine to be substituted for other amino acids at a greater rate than this can be classified as mutagens.

Hirsch and Popp and their colleagues are now conducting experiments on marmosets to demonstrate that their substitution frequency can be elevated by feeding them chemical mutagens. When this has been established, the effect of radiation on base substitution mutations in somatic cells will be measured. So far no measurements of this kind have been made using mammalian somatic cells. Somatic cell mutagenesis is implicated in the induction of cancer, but the relative importance of base substitution mutagenesis versus other chromosomal alterations is still unknown.

This method will also be valuable to test one of the major theories of aging, the error theory. This theory proposes that the precision of cellular mechanisms, including protein synthesis, is largely controlled by proteins, and that proteins containing erroneous amino acid sequences are less precise than correct proteins; thus, infidelity is perpetuated at an increasing rate, eventually causing cell death.

Genetics — Somatic Cell Studies: Chromosomal Aberrations



One way of studying a direct effect of radiation on man's genetic material is to observe the changes it produces in the structure of human chromosomes. Thirteen years ago a technique was developed for observing the changes in the chromosomes of identical cells (immature leukocytes) that had been exposed to radiation. Since then, a large amount of data has been obtained on radiation-induced chromosome changes in human cells.

Two basic problems exist, however, in using these data to predict man's genetic hazard from radiation. First, the cells used in the experiments are somatic and unrelated to the genetically important germ cells. Second, the chromosome changes analyzed most easily are known to be cell and organism lethal, and hence would never be recovered in living future offspring if produced in germ cells. The chromosome changes, however, could be used as correlative indices of recoverable genetic damage if identical experiments could be done on the leukocytes of animals routinely used in genetic experiments.

J. G. Brewen and R. J. Preston have studied two types of chromosome damage in the leukocytes of various mammals, including man and mouse. The two types of chromosome changes they study are analogous to known genetically recoverable events that are produced in mammalian germ cells by radiation. These recoverable events are commonly known as reciprocal translocations (exchange of genetic material between chromosomes), and minute chromosome deletions that appear as mutations in subsequent generations. Although not all mutations are minute deletions, a significant number are.

Brewen and Preston have found that the chromosome change that is analogous to a reciprocal translocation occurs twice as frequently, per unit dose of radiation, in human leukocytes as it does in mouse leukocytes. The chromosome change that is analogous to minute deletions occurs at the same frequency, per unit dose of radiation, in both human and mouse leukocytes. These findings led Brewen and Preston to conclude that man was at least twice as sensitive as mouse to the production, by radiation, of genetically important reciprocal translocations; but they also conclude that both organisms are equally sensitive to mutation induction that results from minute deletions. These conclusions are of particular relevance as most of the available data on the frequency of mutations induced by radiation in a mammal have been obtained for the mouse, and in order to extrapolate to man, some point of comparison must be determined.

Brewen and Preston have now extended their observations on reciprocal translocations to include studies of the chromosome changes produced in both leukocytes and germ cells from animals exposed to the same radiation dose. They have found that for every chromosome translocation seen in the leukocytes 0.25 to 0.33 are seen in the meiotic germ cells of the male. This ratio is observed in the Chinese hamster, mouse, and marmoset, a primate with the same number of chromosomes as man and whose leukocytes are equal in sensitivity to man's. Other workers have shown that for every chromosome translocation seen in the meiotic germ cells of the mouse 0.125 are recovered in the next generation of offspring. From these data, Brewen and Preston conclude that the number of chromosome translocations seen in human leukocytes after radiation exposure can be corrected by multiplying by a factor of 0.03 to 0.04 to predict the number of translocation-bearing children in the next generation.

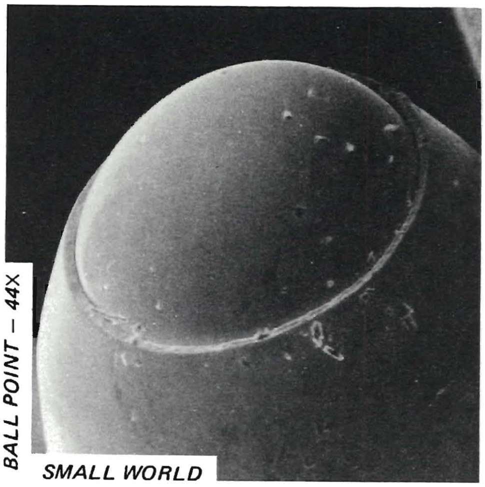
Such a study of reciprocal translocations is important when radiation effects on the population are considered. Carriers of reciprocal translocations may appear as normal individuals, and be fully fertile, but they have a fairly high probability of producing abnormal offspring; for example one type of mongolism arises in some of the children of mothers carrying a reciprocal translocation.

Brewen and Preston further conclude that the data on mutation induction in the mouse are directly extrapolable to man, employing no correction factors.

Further studies are now in progress to permit comparison of the frequencies of radiation-induced chromosome changes with known point mutations in mammalian cells grown in tissue culture. This will make it feasible to estimate the genetic hazard of radiation in terms of reciprocal translocations, minute-deletion-type mutations, and true point mutations to man.

Mammalian Genetics

The mutations that for years have served as an index for quantitative measurements of mutation rates in the mouse are now being employed in experiments that are yielding basic information with practical applications along several lines. The so-called specific-locus method, developed and extensively used by W. L. Russell and his group to measure the effects of physical and biological variables on mutation rate, leads to the detection of new genetic changes affecting any of seven loci "marked" by mutations that have occurred spontaneously in the past. Having done their job of providing a quantitative measure, these new mutations were maintained in breeding stocks; and, more recently, selected groups of them have been subjected by L. B. Russell to complementation mapping and other intensive genetic analyses. By these means she found that the genetic changes involving a given locus are far from a homogeneous group. Thus, the mutations at the *d* and/or *se* loci (dilute color and short ear) actually fall into 18 so-called complementation groups, and the mutations at the *c* (albino) locus comprise a minimum of five complementation groups. In addition, the complementation analysis has led to the identification of new "functional units" (perhaps genes) in the region of the marked loci, some of them being identified by viability effects, others by the production of biochemical changes. In the *d-se* region, for example, 7 to 8 such new units have been identified.



This type of analysis has had several practical applications. For example, it has been possible to estimate the number of "functional units" per crossover unit (crossover "distance" being a measure of the frequency with which given genes on the same chromosome segregate separately). Since the total crossover length for the entire chromosome complement of the mouse is roughly known, the total number of functional units could be estimated, and this figure was used in the latest report of the UN Committee on the Effects of Atomic Radiation to aid in calculations of genetic risks in humans.

Furthermore, since the new analyses have provided considerable additional information concerning the qualitative nature of the mutations produced at the specific loci by various treatments, we now know more about the relation of various biological and physical variables to the type of genetic change produced. For example, it was found that the mutations induced in spermatogonia by single or chronic doses of x or gamma radiation qualitatively resemble spontaneous mutations much more closely than do mutations induced in other germ cell stages or caused by other types or regimes of radiation.

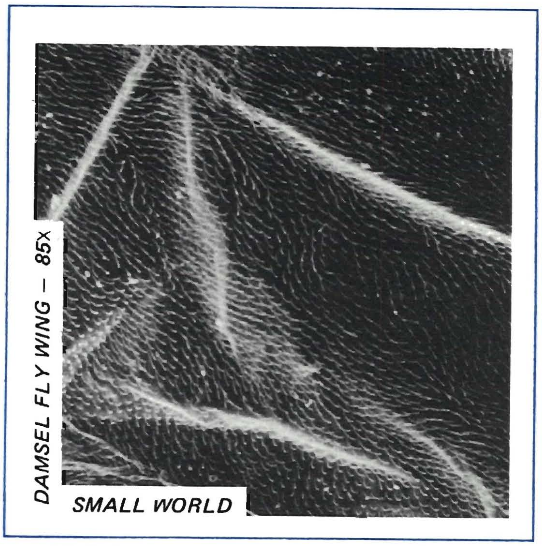
The qualitative characterization of individual specific-locus mutations is also providing tools for other types of investigation. One of these is the measurement of the effect of mutations. Since it is quite possible that induced mutations exert most of their effects on human populations while in the heterozygous state, the Russells feel that it is of paramount importance for the estimation of genetic risks of radiation to obtain — in addition to determinations of the *frequency* of mutations — their heterozygous effects. Past empirical experiments at other laboratories have led to equivocal conclusions. The well-characterized genetic material that is now available from specific-locus experiments has recently made it possible for L. B. Russell to initiate breeding programs for much more exact measurements of heterozygous effects.

Another by-product of the qualitative analysis of mutations has been the characterization of certain chromosomal deficiencies which are now, in turn, being used as tools to screen for new mutations in given chromosome segments, namely, those involved in these deficiencies. This method will yield new kinds of mutation-rate information, different from and complementary to rates obtained by other methods in the past.

Microbiology

Bacteriophages are viruses that attack bacteria in a parasitic way. Of a simple biochemical structure, essentially a protein coat enclosing nucleic acid, they attach themselves to the wall of the bacterium cell and inject their genetic material into the host. There the phage can either self-replicate until it destroys the cell (lytic situation), or its nucleic acid gets integrated into the bacterial genetic apparatus and remains dormant (lysogenic situation). The latter may become lytic when subjected to insults such as irradiation or certain chemicals. There also are cases where phages multiply within the bacteria without affecting the bacterial viability. The study of bacteriophages is basic to today's understanding of biological reproduction in molecular terms. So elementary is their composition that it is in the field of phage research that physicists, chemists, microbiologists, and geneticists all find themselves on common ground — a natural meeting place for interdisciplinary approach.

Phage work at ORNL has a long and notable history. Currently engaged in phage studies are these biochemists and microbiologists: Audrey Stevens: specific enzymes associated with phage infection; S. K. Niyogi: synthesis mechanisms for messenger RNA; R. K. Fugimura: DNA replication mechanisms in phage infection; S. Mitra: studies of M13 phage, a unique phage system that utilizes mostly host biochemical processes for its own synthesis; and Jane K. Setlow: transformation and recombination studies with a variety of phages.



Two of these studies may be described in further detail:

Stevens is studying the mechanism by which a bacteriophage, T4, infects *E. coli.* The intracellular multiplication of T4 in its host requires the production of at least 100 new proteins specified by the phage genome. These proteins are synthesized at different times during the infection cycle and can be classified roughly as "early" and "late" proteins. Stevens is looking at control mechanisms at the level of transcription (messenger RNA production) which lead to the production of "late" proteins and the cessation of "early" protein synthesis. DNA-dependent RNA polymerase of *E. coli,* the enzyme which catalyzes the transcription process, is modified in several ways after T4 phage infection. Stevens has observed that one modification of the enzyme involves its binding of four new small T4-specific proteins at a time in the phage infection cycle when "late" messenger RNA and "late" proteins are formed. The binding of the new small proteins leads to loss of the specificity of the enzyme for "early" messenger RNA production.

Mitra is working with a different kind of phage. M13, a small filamentous phage specific for male strains of *E. coli,* is a unique type of phage, in that it enters the host cell and multiplies there without killing it. It contains single-stranded circular DNA as the genetic material, which inside the host is converted into normal double-stranded DNA as an intermediate in the replication process. It offers a unique system for studying host-virus interaction. While the phage multiplies during productive infection, the host also continues to multiply at about a normal rate. Only a part of the host synthetic machinery is shunted off to make the phage-specific components. The only apparent aberrations in the host bacteria after infection are increased susceptibility to certain insults and a weakening of the cell wall. Since the phage does not appear to synthesize any new enzymes, Mitra is directing his inquiries to the following directions: Do any of the three known stages of phage DNA replication mimic precisely the host DNA replication? Are all the components necessary for host DNA replication also essential for phage DNA replication? Can the host enzymes be utilized directly for phage DNA replication and transcription of RNA or are these modified by phage-specific proteins? Partial answers to these questions have already been obtained. For example, it has been established that all the known functions necessary for host DNA replication are also essential in various stages of phage DNA synthesis. The replication of double-stranded circular phage DNA intermediate appears to occur in the same way as that of *E. coli* DNA. The transcription process of phage DNA, however, is not identical with that of the host.

International Biological Program

Oak Ridge National Laboratory, through its Environmental Sciences Division, is headquarters for the Eastern Deciduous Forest Biome study in the International Biological Program (IBP). The study is under the administration of the division's director, S. I. Auerbach. The IBP is an international attempt to relate the broad aspects of biological productivity to human welfare. Biological productivity involves the fixation, transfer, flow, and cycling of energy and materials through the complex of nonliving and biotic components of ecosystems. Although similar in process, productivity differs in organisms and environments in different parts of the world. This kind of productivity, including the production of food, fiber, building materials, and other sources of creature comforts, is important for man's physical needs, but portions of the earth's surface also furnish living space, scenic vistas, recreational areas, and wildlife habitats as well. These tangential features become more important to man's welfare as a burgeoning population places greater and greater pressures on society.

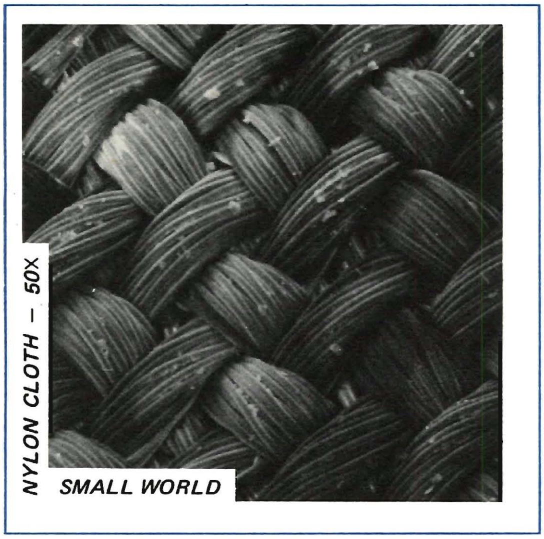
The great region of temperate deciduous forest in the eastern U.S. is an aggregate of aquatic and terrestrial ecosystems that collectively covers about a third of the country but at present supports about two-thirds of the people. At the interface of land and water systems, often referred to as a watershed, research is aimed at determining the uptake, transfer, and discharge rates and pathways of critical mineral elements, potential pollutants, and biological materials so that the whole dynamic system can be described mathematically. Such a description is termed a systems model, and can be implemented on a high-speed digital computer to simulate the mechanics of an ecological system. Thus, predictions can often be made of the eventual results of decisions under current consideration in resource management. The value of this approach to wise resource use is gaining wide recognition.

Auerbach's team at ORNL includes R. L. Burgess, Deputy Biome Director; R. V. O'Neill, Modeling Coordinator; and F. G. Goff, Biome and Regional Analysis Coordinator. The integrated program of research is carried out at five major sites. Besides using areas and facilities on the AEC-owned land in Oak Ridge, the sites include the Coweeta Hydrologic Laboratory of the U.S. Forest Service, and the Duke Forest near Research Triangle Park, both in North Carolina; Lake Wingra at Madison, Wisconsin; and Lake George, near Troy, New York. Since inception of the program in 1969, the Site Coordinator of the Oak Ridge site was D. E. Reichle. He has recently turned the office over to W. F. Harris.

Two working rafts used in the IBP study of 137-hectare (338-acre) Lake Wingra inside the city of Madison, Wisconsin. The lake, part of the Eastern Deciduous Forest Biome, is of interest because of its high degree of eutrophication.

The project is funded by the National Science Foundation, under an interagency agreement with the AEC. Biome management subcontracts research to be performed at the remote sites.

At the Oak Ridge site, the Walker Branch Watershed weirs are equipped to monitor water flow and chemistry on a continuous basis. The forests of the watershed have also undergone extensive analysis, particularly relating to mineral cycling and primary production. In the forest production analyses, year-to-year changes in biomass accumulation are characterized in terms of species composition, site climate, and stage of forest community development in order to estimate the accompanying mineral accumulation and subsequent recycling by vegetation. Increment core analysis of trees for a ten-year period, 1961—70, was used to reconstruct patterns of biomass accumulation. Samples included all major species representative of the area. From this study it was learned that average annual growth approached 2.5%, a figure independent of the degree of slope, or the direction in which the slope faced, for trees with mean diameters greater than 25.4 cm measured at breast height (dbh).



Three sampling series were also performed in the macrophyte (large aquatic plants) beds to determine patterns of spatial distribution and relative abundance of littoral zone plankton. Samples were collected both between plant fronds and from segments of plant stems. Preliminary analysis of the data indicates that standing crops of zooplankton in the littoral zone are about one-fifth of those of a comparable water volume in the limnetic zone. Comparisons of 1968–69 data indicated considerable disparity in both the seasonal timing and relative abundance of zooplankton population dynamics.

Aquatic insect studies included a benthic sampling program at twice-weekly intervals throughout the year. The littoral zone fauna is composed of a diverse assemblage of herbivorous, detritivorous, and carnivorous insects. The sublittoral community is dominated by two species of midges, representing about 75% of the benthic insect fauna. Most midge species in Lake Wingra produce two generations per year with major emergences during late May and July.

A fish exclusion cage was placed in the littoral zone for a preliminary experiment on predator-prey interactions. Macrophyte fronds and benthic samples were collected at biweekly intervals to determine numbers and biomass of insects both inside and outside the cage. Fish sampling was conducted at similar intervals in the same general area to determine relative levels of predation. The data indicate substantial fish predation on the midge populations inhabiting the littoral zone.

A major accomplishment was the derivation of a predator-prey biomass model for fishes, based on a series of equations that describe the processes of feeding, growth, egestion, excretion, respiration, reproduction, and predatory and nonpredatory mortalities. All parameters were implemented empirically, based on work at Lake Wingra as well as data available from literature sources.

This is just an example of one kind of ecosystem analysis research that is under way as a part of the Biome program, augmenting our knowledge of ecosystem processes and landscape dynamics. Indeed, the extent to which the work is valued is seen in the fact that, although the International Biological Program will terminate in the spring of 1974, the Biome program is to continue its research into ecosystem analyses.

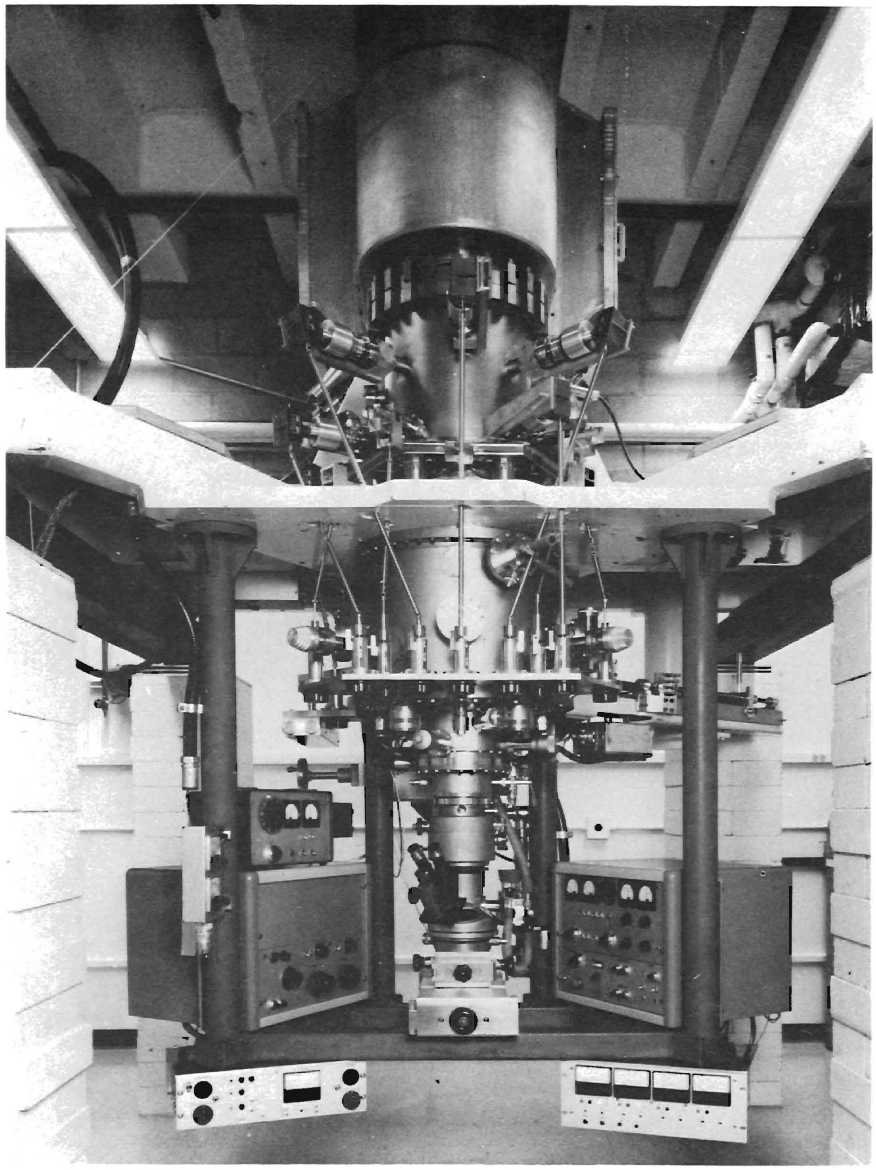
In the case of smaller-diameter classes, that is, less than 15 cm dbh, growth is sensitive not only to size but also to site variables; however, improved accuracy in predictions appears feasible with improved analysis of site influences. Detailed analysis of relative biomass accumulation offers a simplified method of enhancing the precision of forest production estimates in watershed models.

At the Lake Wingra Site, a small, shallow lake lying entirely within urban Madison, Wisconsin, research has focused on several aspects of aquatic ecosystems. Among these, studies of zooplankton production included a vertical sampling series collected from the limnetic zone at weekly intervals throughout the year. Standard population data on major species also included numbers of females bearing eggs or embryos and clutch sizes as a data base for calculations of birth rates. Length-frequency distributions and length-weight relations were determined by species to establish more accurate estimates of biomass.

Instrument Development

High Resolution Electron Microscope

The specific meaning of the term "high resolution electron microscopy" continues to be a function of time. Currently, high resolution refers to the general region of 5 Å, and below for amorphous materials. With the best commercial microscopes and suitable specimens, a good microscopist can achieve 3 Å routinely. With modified commercial instruments values approaching 2 Å have



The high-coherence electron microscope at ORNL uses a field-emission source to obtain a transverse coherence length at the specimen greater than 1000 Å. The ultrahigh-vacuum tank for the gun is at the top of the column, while the power supplies associated with the gun are located in the high-voltage terminal to the rear and above. The 150-kV operating voltage is brought in from a separate supply. The tank below the support frame contains the liquid helium cryostat, the superconducting objective lens, the specimen stage, and the objective aperture.

been achieved. Already, a number of experimenters using specially prepared specimens containing a few heavy atoms like uranium or mercury spaced 10 to 15 Å apart have strong evidence for the detection of these individual atoms. The instruments used were capable of resolving 3 to 5 Å.

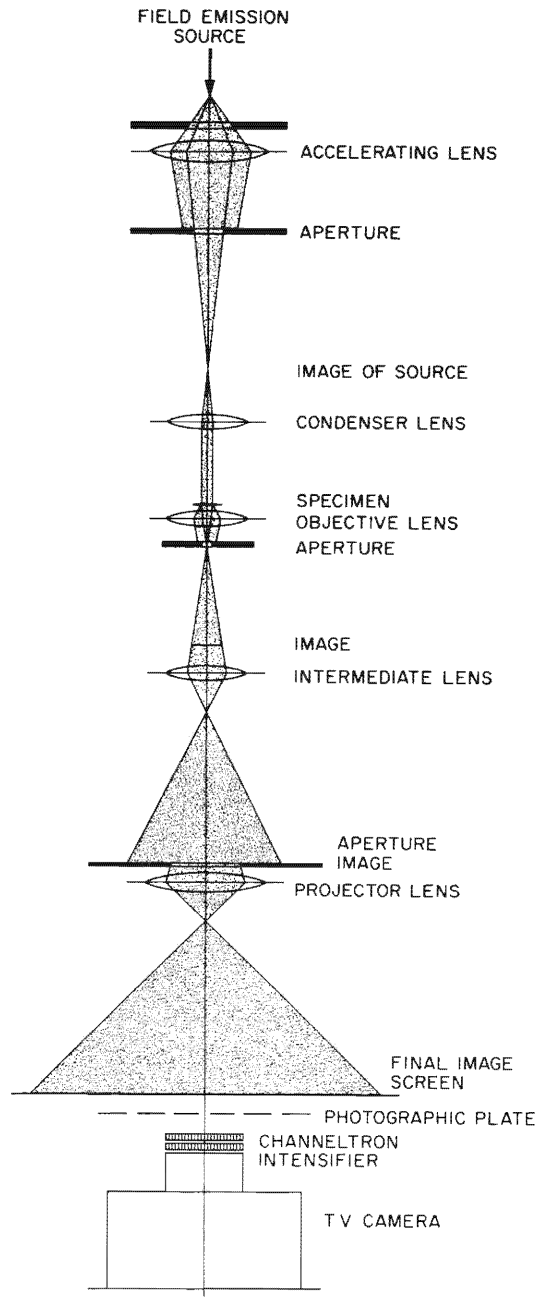
A great need exists, however, for what is the major leap, down to the 1-Å region, and for improved contrast for lighter atoms. This resolution enabling one to literally "see" heavy atoms for Z greater than around 35, which is bromine, is theoretically possible, and appears to be well within practical reach. However, several major modifications are required in the instrument as it is currently constructed and used.

The resolving power of a microscope is limited fundamentally to a value that is approximately equal to the wavelength of the radiation used. In an optical microscope, detail may be seen down to about half a micron corresponding to about 5000 atomic diameters. With an x-ray microscope, the resolving power could theoretically get down to the 1-Å region. Neutron or gamma-ray microscopes could have even smaller resolving powers, but unfortunately no way has been found to construct lenses that would make these instruments possible.

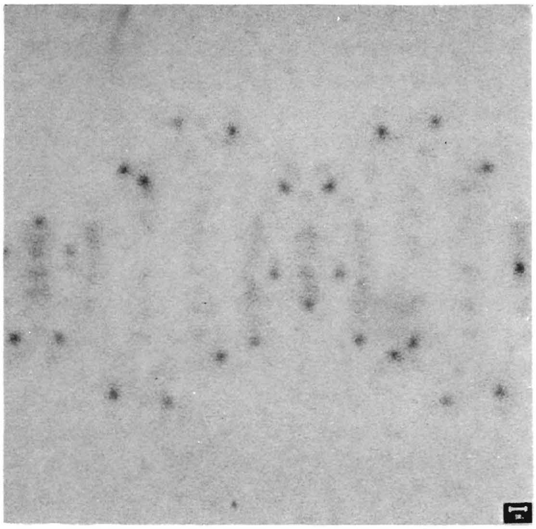
With the confirmation of the wave nature of the electron by Davisson and Germer in 1927 and the demonstration by Busch in 1926 that electric and magnetic fields can act as lenses for electron beams, the possibility arose for a microscope with a resolving power well under 1 Å. About five years later Knoll and Ruska completed the first one. This instrument immediately showed a resolving power superior to optical microscopes. The first commercial instrument was produced in Germany in 1938.

However, even today resolution in the electron microscope remains far short of the value early workers dreamed of. Electrons at 100 kV have a wavelength of 0.037 Å; however, the best resolution achieved is about 2 to 3 Å. Compared with optical lenses, the performance of electron lenses is quite poor. This situation is forced by the natural limitations on the shaping of electric and magnetic fields that may be used for electron lenses and not by the limitations of technology.

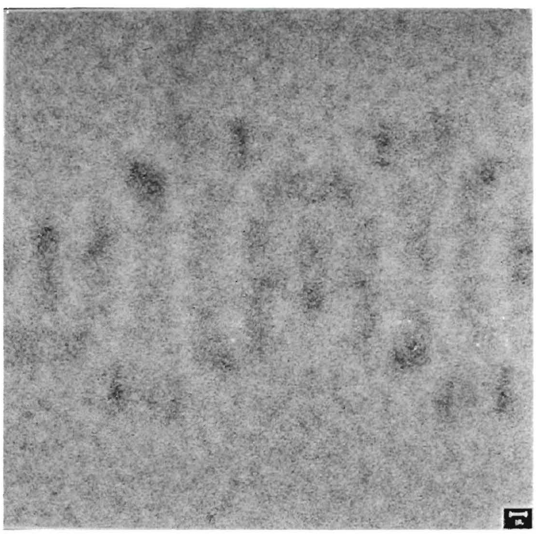
Ernst Abbe, working just over a century ago, developed the diffraction theory of microscope optics. He showed that the formation of the image is a two-step process. The radiation (light, x rays, electron waves) falling on the object is scattered in all directions, forming a diffraction pattern. This pattern exists where the waves scattered from different parts of the object are either in or



The field-emission source uses a needle point about 1000 Å in diameter. This tungsten needle, which has a (111) crystal orientation, leads to an effective source size less than 100 Å. With acceleration, the electrons are focused above the condenser lens, which turns the rays nearly parallel for illumination of the specimen. A magnification greater than 500,000× is possible to make all image detail well above the photographic grain size. For operation at minimum beam current during alignment of the column and to reduce radiation damage to the specimen, a Channeltron TV image intensifier may be inserted.



The upper micrograph is a computer-generated image of what a section of a DNA molecule would look like made in the high-coherence microscope. The base sequence is shown. Thallium atoms were assumed chemically attached to the phosphate groups of the backbone. Excessive phase shift at the higher spatial frequencies caused by the spherical aberration of the objective lens limits the apparent resolution, although with highly coherent illumination the information is still present. The lower picture is a simulated micrograph showing what can be done by the application of a Wiener filter to correct the phase shifts, unscrambling the information. The position of the heavier thallium atoms is now clearly defined.



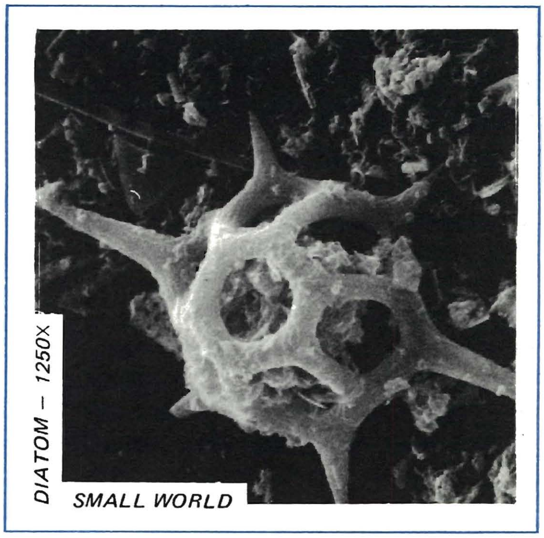
out of phase: in step or out of step. If a suitable detector such as a photographic film or phosphor screen were placed at the plane of the diffraction pattern, bright regions would be found where the waves were in phase, that is, where they interfere constructively, while dark regions would indicate out-of-phase waves, or destructive interference.

For single crystalline objects, the diffraction pattern consists of a pattern of bright spots with each spot corresponding to a particular set of parallel planes in the crystal. The closer the spacing of the planes, the larger the radius out to the spot from the instrument axis. Amorphous objects show a more or less continuous pattern with rings of increased intensity corresponding to more common spacings in the object. In the second part of the image formation process, the objective lens of the microscope directs the diffracted waves to a plane where recombination occurs to form the image of the object. The characteristics of the image depend critically on the amount of the diffraction pattern used in its formation.

For single crystalline objects, the x-ray diffraction camera and "fly's eye" neutron diffractometer developed at ORNL may be regarded as microscopes, although no lenses exist. In the first part, the diffraction pattern is formed and, here, recorded. The image may, then, be calculated from these data. However, a loss of the knowledge of the phase relationships among the various diffracted waves would prevent the calculation of the image unambiguously. A trial-and-error technique, a technique useful only for small crystals, was used originally. Image formation was made possible for complex molecules by the discovery by Perutz in 1953 of the method of "isomorphous replacement," which solved the phase problem. The most notable achievements of this method were the detailed atomic structure of the myoglobin molecule by Kendrew and the hemoglobin molecule by Perutz.

The electron microscope offers the tremendous advantage that structure may be determined in amorphous objects. Therefore, a single crystal of the object need not be grown and the object may, in many cases, be observed in a more nearly natural state. However, all of the information must come from an individual molecule in the object, whereas the single crystal object may consist of some 10^{12} identical molecules. Thus the number of electrons per atom required to get sufficient information to determine the position of each atom would be much greater for the amorphous material, making radiation damage a very serious problem.

Now: what can be done to improve resolution in the electron microscope? The principal limiting factor, as noted, is the low quality of the objective lens, compared with optical lenses. Consider a microscope that is perfect except for its objective lens. The electrons illuminating the object would come from a perfect point source. The electron waves would all be in phase; such a source is called highly coherent. Further, the electrons would all have the same energy. With the imperfect objective lens, the electron waves scattered in the object to larger angles — corresponding to the information at larger radii in the diffraction pattern — are delayed, or get out of step, with the waves at smaller radii. This delay goes up as the fourth power of the scattering angle. This defect is termed spherical aberration, or *Öffnungsfehler*, as the Germans so appropriately call it, the "opening error." When the waves scattered at the larger angles recombine with the unscattered wave to form the image, their being out of the proper phase reduces the contrast of the detail in the image. In fact, if the waves were completely (i.e., 180°) out of phase, the contrast would be reversed: black would be white and white, black. For the waves shifted 90° the information would be lost; contrast would be zero. Suppose a circular aperture were located at the diffraction plane and its radius could be adjusted. If it were made very small, then only the waves corresponding to broad spacings in the object would be allowed to form the image. There would be no contrast reversal, but sharp edges would be rounded. If the aperture radius were increased to include more information from the finer details in the object, waves increasingly out of step would contribute to the image, which would, naturally, show more and more detail. But, because of the contrast reversals, the shape of the finer details would not be clear. The interpretation of the details in such a micrograph would be extremely difficult (what's real and what's artifact?) and, in addition, the varying phase would cause a reduction in contrast and hence a loss in resolution. This method of obtaining contrast — the only method usable for high resolution — is known as phase contrast.



Thus it appears that there can be more information in an electron micrograph than is readily usable. T. A. Welton of the Physics Division has devised a method for exploiting the maximum amount of this information. The micrograph, converted to digital form in a microdensitometer, is fed into an IBM 360/91 computer. A diffraction pattern is calculated, and from its shape, plus the radii and intensity corresponding to the different phase shifts, it is possible to compute all the operating values of the microscope. Then, the excessive phase shifts of the diffracted waves introduced by the objective lens can be corrected to approach their true value with the fitting of an optimum filter to the data much as is done in electrical communication problems. A new image may then be calculated from this corrected diffraction pattern that, theoretically, allows an improvement in resolution of about four times.

There is another approach to the solution of this problem that is theoretically possible, and is, logically, an alternate method and/or the next step after the method described above. Involved is the direct reduction of the spherical aberration. A complex system of at least four quadrupole and three octopole lenses following the round objective is the minimum requirement. This method could lead to improved resolution and contrast directly in the micrograph; and when combined with the methods of filtering mentioned above it could lead to a resolution of about 0.4 to 0.5 Å with, most important, improved contrast for lighter atoms.

To summarize: a microscope with highly coherent illumination that is completely free of all disturbances that would affect the resolution at the 1-Å level is needed. Welton has shown, theoretically, that the transverse coherence length of the illuminating wave should be about 1000 Å. A typical value for a good commercial microscope would be about 25 to 100 Å, at best. Further, he has shown that resolution is not a sensitive function of energy, allowing the microscope designer to choose a value based on practical considerations.

A thermionic gun could produce the highly coherent beam required, with proper aperturing to define the beam down to a point source. However, the time required to collect enough electrons to form the image would be excessive, since the remaining source current would be so small. The field emission gun developed by A. V. Crewe at Argonne and the University of Chicago for the scanning microscope appears to be well suited here. The brightness (number of electrons per square centimeter per steradian) of a field emission gun can exceed that of a thermionic gun by a factor of at least 1000, which provides enough electrons to give good statistical information in the image at the 1-Å level with exposure times of about ten seconds. The gun developed at ORNL is basically similar to Crewe's although for a slightly higher operating voltage. The illuminating system — gun, condenser, pre-field of objective — is quite different, however, since the scanning mode is not used.

Chromatic aberration must be made negligible by closely defining the energy of the electrons. The sources of energy spread are the field emission tip noise (about 0.2 V) and the accelerating voltage noise and ripple. At 150 kV, the maximum operating voltage selected, source noise would lead to 0.1—0.2 Å degradation, a negligible value. The 150-kV supply was developed with an even lower noise; it operates routinely with about one-fourth to one-third of a part in 10^6 peak-to-peak noise.

In an attempt to reduce radiation damage, it was decided to operate the specimen at liquid helium temperature. There is evidence based on observation of electron diffraction patterns from organic crystals to show that an increase in dose by about a factor of 5 can be tolerated in certain crystals if they have been cooled to liquid helium temperature. Since mechanical stability of the specimen is of very great concern at high resolution, the entire system of stage, objective aperture, and objective lens were made into one rugged structure attached to the liquid helium cryostat. Naturally, the objective lens was made superconducting. It can run in the persistent mode with a stability of about one part in 10^{10}, much more than is needed. Because of the long time constant for a superconducting lens, focusing is accomplished by varying the accelerating voltage.

All of this hardware was designed, developed, and tested by a team of engineers: R. E. Worsham, J. E. Mann, N. F. Ziegler, and Everett Richardson of the Physics Division. Fabrication was done entirely in the ORNL shops. Construction is now finished, and the testing of the components and of the complete system is in progress.

Beyond the efforts to achieve full operation of the microscope and the studies in image analysis that are under way, there remain problems associated with specimen preparation, mounting, and interpretation. Experiments are being mounted to develop the techniques for making very thin substrates to support the specimens and in some cases to eliminate the substrate altogether. The techniques for solving real problems at the highest resolution are, of course, new and untried. For example, the development of heavy metal stains that would be specific for each of the bases that occur in DNA is needed to unravel the base sequence in DNA. This is the kind of collaborative work that has historically been performed most successfully at multidisciplinary laboratories like ORNL.

Meetings:

Oak Ridge National Laboratory
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Symposium on Advanced Analytical Methods in the Clinical Laboratory	March 15–16
Chairman: C. D. Scott, ORNL	
Annual Biology Research Conference	April 9–12
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First Annual NSF Trace Contaminants Conference	August 8–10
Chairman: W. Fulkerson, ORNL	
Symposium on Superconductivity and Lattice Instabilities	September 10–12
Chairman: H. G. Smith, ORNL	
Health Physics Instrumentation Information Exchange	September 18–19
Chairman: E. D. Gupton, ORNL	
International Conference on Atomic Collisions in Solids	September 24–28
Chairman: S. Datz, ORNL	
17th Conference on Analytical Chemistry in Nuclear Technology	October 23–25
Chairman: L. J. Brady, ORNL	
Third Conference and Workshop on Embryonic and Fetal Antigens in Cancer	November 5–7
Chairman: N. G. Anderson, ORNL	
Conference on Interaction of Radiation with Noble Gases	November 9–10
Chairman: G. S. Hurst, ORNL	