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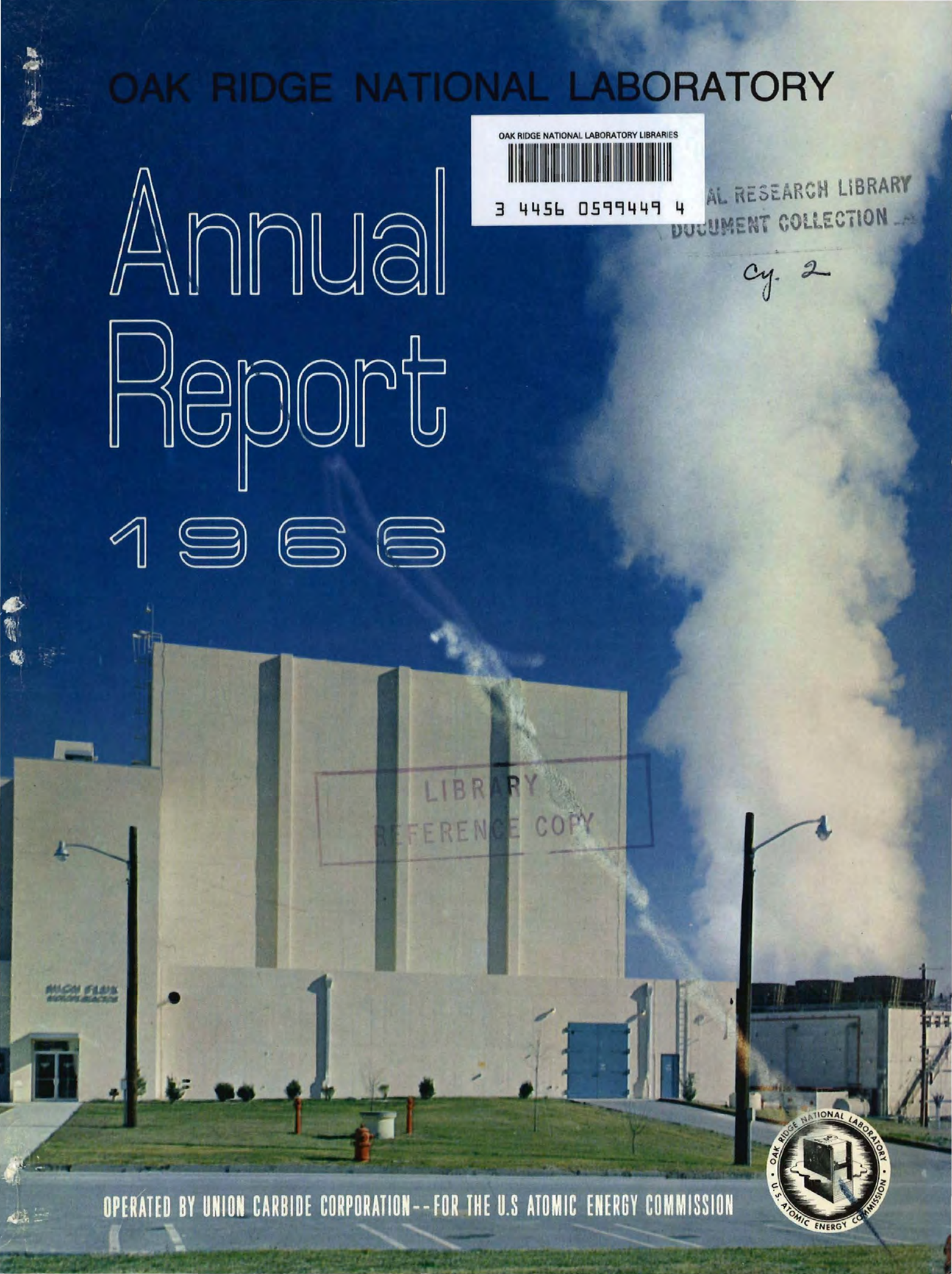

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Cover:

An immense vapor plume rises from the water cooling tower during operation of the High Flux Isotope Reactor at 100,000 kW.

Annual Report 1966

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION FOR THE U.S. ATOMIC ENERGY COMMISSION

INTRODUCTION

1966 has been one of ORNL's best years. The High Flux Isotope Reactor and the Molten Salt Reactor Experiment, upon which so much dedicated effort had been lavished for so long, came to full power uneventfully and then behaved beautifully – as well as the optimists had hoped, far better than the pessimists predicted. The transuranium reprocessing facility and the hydrofracturing waste disposal plant went into operation. And there were ever so many pretty, and often highly significant, discoveries in basic research – like the quantized energy loss of channeled heavy ions, or the evidence for possible incorporation of passenger viruses into the human genome.

It was also one of our best years because the successes of the Laboratory, set against developments in nuclear energy, as well as in other massive, socially oriented technologies, have reinforced the validity of the National Laboratory as a powerful instrument of technical, scientific, and social progress. These institutions are now more than 20 years old. They are a unique combination of mission-orientation and discipline-orientation: the two exist side by side in mutual symbiosis. In our Annual Report we present a sampling of the work of the Laboratory so as to stress this interaction between the basic and the applied.

Oak Ridge National Laboratory, in spite of its size and bewildering complexity, tries to maintain a kind of coherence. The problems that face society, and to whose solution nuclear energy may be a miraculous key, transcend divisional or disciplinary lines. These difficult problems will yield only to coherent attacks such as can be launched by coherent institutions. To emphasize this sense of unity, we usually do not indicate in our Annual Report in which division a piece of work originates, and indeed many of the researches described here involve several divisions.

The year 1966 is memorable for the Laboratory because this was the year during which our country and the world became sufficiently aware of the many great problems – such as lack of energy, pollution, shortages of food and water, urban disorganization – to begin to mobilize its resources to attack them seriously. And it became apparent that nuclear energy, as developed by Oak Ridge National Laboratory, or techniques developed here as a by-product of the Laboratory's long involvement in nuclear energy, could play an unexpected and possibly crucial role in resolving these problems.

How do the events at ORNL during 1966 suggest new ways of dealing with these urgent questions?

Perhaps the crucial event has been the success of the Molten Salt Reactor Experiment. This milestone reinforces our conviction that breeder reactors based on the molten-salt principle can, *in our lifetime*, produce power at phenomenally low cost – say, 1.5 mills/kWh with public financing. With energy this cheap, and available essentially to anyone, one begins to see better ways of producing ammonia fertilizer and other chemicals at attractive prices *anywhere in the world*. To this must be added the very encouraging results of our work in desalination, both in the design of better evaporators, and in the discovery of dynamic membranes and better heat transfer surfaces. Agricultural water from the sea must now be reckoned as a rational long-term goal, not a wildly impractical dream of the science fiction writer. In biology there is the continued development of the newer styles of large-scale and interdisciplinary research that have led to wide application of zonal centrifugation and better

understanding of aging, to mention only two examples. Inevitably the Laboratory finds itself called upon to apply its experience in the conduct of large-scale biological research to the difficult problems of pollution and carcinogenesis. In the course of our civil defense work we become involved in urban redevelopment, since utility and transport tunnels planned for redevelopment projects are obviously useful for civil defense. And there are many other such avenues – in isotope technology, space, atomic physics – too numerous to list here, but touched upon in our report where the Laboratory contributes both to science and to society.

Thus Oak Ridge National Laboratory, through its primary concern with nuclear energy, is drawn naturally, and to our country's advantage, into water, pollution (nuclear power is perhaps the most fundamental approach to cleaning our air of fossil fuel residues); fertilizer and thence food (via ammonia synthesis); civil defense, and thence the city; big biology and the broad problem of radiation and other insults to the biosphere. Of course the Laboratory is not equally involved in all of these things. Yet the extraordinary consequences of the development of a truly cheap, and ubiquitous, energy source seems compelling to all of us. The Laboratory, having laid the beginning of a technological foundation for a new attack on many of mankind's oldest social problems, is urgently wanting to get on with the task. To those who entered the nuclear energy enterprise during the war, 1966 carries back memories of 1943, when the job was so clearly seen by all, and when only the limits of human endurance could keep us from getting on with it.

But there is a difference. In 1943, Clinton Laboratories conducted little basic research. Today Oak Ridge National Laboratory carries on an enormous amount of basic research. And it seems clear that the Laboratory's capacity to do so many things, and to do them well, in no small measure depends upon maintaining our strength in the basic sciences. For the Laboratory's strong involvement, first hand, in the basic sciences gives a tone and quality to our applied endeavors that we could never manage if we did not nurture basic research so carefully. The pages that follow illustrate this: that applied research done in a basic atmosphere has a sophistication that is hard to duplicate in a less scientific environment; and that basic research done in an applied atmosphere has a kind of no-nonsense aggressiveness that is hard to duplicate when basic research is done entirely by itself.

A laboratory lives for years like 1966. Yet, with all these new vistas opening, it seems likely that there will be many more 1966's in ORNL's future. Certainly there is no lack of deeply important problems to which large-scale scientific technology can contribute. The multidisciplinary style of places like Oak Ridge National Laboratory – their coherence, their close contact with basic science, their flair for getting after very big and difficult matters – will surely continue to pay off. We look forward impatiently to recording these coming achievements in future Annual Reports.

Alvin M. Weinberg

March 1, 1967

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Transuranium Element Program

Among the outstanding events at Oak Ridge National Laboratory during 1966 were the full-power operation of the High Flux Isotope Reactor and the startup of the Transuranium Processing Plant. In November, to mark these events, the Laboratory held the Second International Transplutonium Symposium, which included invited reports on transplutonium element research by distinguished scientists from Denmark, England, France, Israel, the Netherlands, and West Germany and from AEC installations throughout the United States. The highlight of the symposium was the dedication of the High Flux Isotope Reactor (HFIR), the Transuranium Processing Plant (TRU), and the Transuranium Research Laboratory (TRL). This unique combination of three new facilities has been constructed at ORNL to make possible an exciting expansion of research in heavy elements by chemists and physicists from all over the world. The complex—used in conjunction with the extensive laboratories, accelerators, and sophisticated equipment of Oak Ridge National Laboratory—provides a means for greatly increasing our knowledge of heavy elements and the nature of matter.

Perhaps the significance of this newly acquired capability can best be conveyed by excerpts from the dedicatory remarks of Glenn T. Seaborg, Chairman of the U.S. Atomic Energy Commission and foremost pioneer in the discovery of transuranium elements:

The research complex we are dedicating here today will be used to produce and study the transuranium elements—elements available on earth only to the extent that they are recreated by man as a result of his scientific investigations and his technological ingenuity. This reactor, this processing plant, this laboratory, and the people who will be working with them will be making a major contribution to our understanding of these new elements, as well as to our overall knowledge of chemistry and physics.

* * *

The heavy isotopes produced by this reactor and this processing plant will be available for research here at Oak Ridge and at other laboratories engaged in transuranium research throughout the United States and other countries. The annual recovery of isotopes from HFIR is expected to amount to grams of californium, hundreds of milligrams of berkelium, tens of milligrams of einsteinium, and micrograms of fermium.

* * *

The knowledge gained from experiments on the transuranium elements will deepen our comprehension of nature by increasing our understanding of atomic and nuclear structure.

The High Flux Isotope Reactor, Transuranium Processing Plant, and Transuranium Research Laboratory were formally dedicated November 8, 1966, by Glenn T. Seaborg, Chairman of the USAEC. Participants in the dedication ceremonies included, from left to right, Alvin Weinberg, Director of ORNL; AEC Commissioner Wilfred Johnson; U.S. Senator Albert Gore; Chairman Seaborg; U.S. Representative John Duncan; and Clarence Larson, President of Union Carbide Nuclear Division.

HIGH FLUX ISOTOPE REACTOR

This high-performance reactor, which was specifically designed for production of transplutonium elements, utilizes a flux-trap fuel assembly to produce an intense flux of thermal neutrons. Initial testing, reactor startup, and operation at full design level have proceeded with essentially no difficulties.

The HFIR became critical and was operated at low power in 1965. During 1966 the power level was raised stepwise and reached the design level of 100,000 kW on September 9. Four full-power fuel cycles had been completed by the end of the year. Operation of the reactor during each fuel cycle was almost completely trouble-free, with all maintenance of components being accomplished during scheduled shutdowns. Since first reaching 100,000 kW the reactor has operated 75% of the time. The fuel cores have averaged an operating life of more than 22 days at 100,000 kW, which exceeds even the more optimistic predictions.

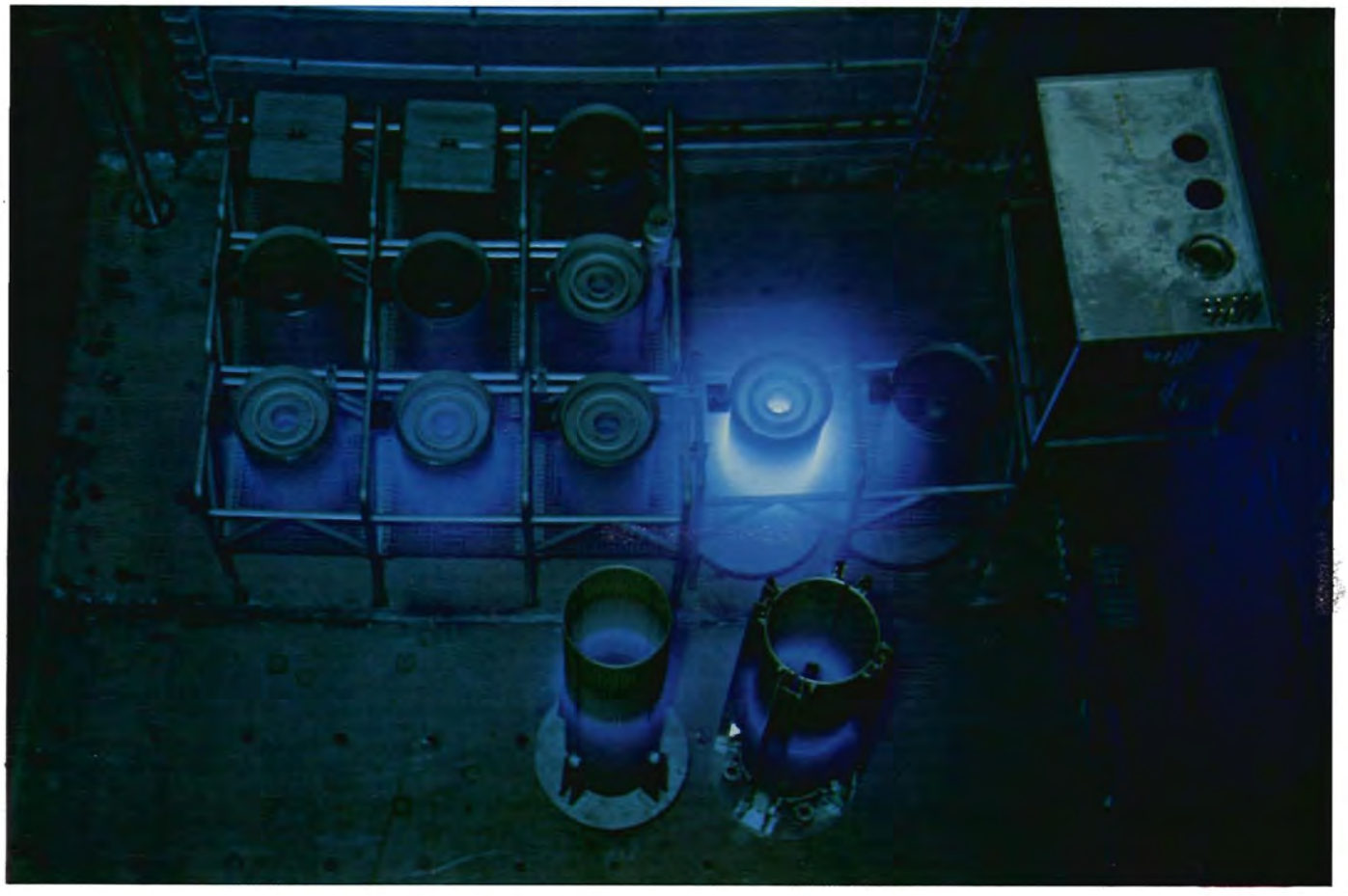
When the reactor is operating at 100,000 kW with no targets in the central water island, the peak thermal flux is 5.5×10^{15} neutrons cm^{-2} sec^{-1}. With a full target loading of 300 g of plutonium-242, the average thermal flux is 2.2×10^{15} neutrons cm^{-2} sec^{-1}.

Thirty HFIR targets, initially containing 262 g of plutonium-242, are now undergoing irradiation; seventeen of these are scheduled for processing in TRU during the summer of 1967.

Three neutron spectrometers for installation at the HFIR have been designed; they will be placed in position during the first part of 1967. These spectrometers will have access to thermal-neutron beam intensities of about 7×10^{9} neutrons cm^{-2} sec^{-1}, a factor of at least 4 above what has previously been available. Improved beam resolution and lower gamma-ray and neutron backgrounds are also expected.

An irradiation facility in which samples are inserted and removed hydraulically has been fabricated and is ready for installation in the flux trap of the reactor. In this facility, small specimens can be irradiated for times ranging from a few minutes to several days in a thermal-neutron flux of about 3×10^{15} neutrons cm^{-2} sec^{-1}, a factor of 10 higher than the maximum available in the Oak Ridge Research Reactor (ORR). Such a high thermal-neutron flux will substantially extend the range of research work concerned with short-lived radioisotopes.

Target rods containing plutonium-242 are inserted into the central core of the High Flux Isotope Reactor for irradiation. This photograph shows fuel elements and a target bundle just as they are assembled in the reactor. A fuel element contains 9.4 kg of uranium-235 in its 540 individual plates. A target bundle consists of 31 rods, each loaded with 8 to 10 g of plutonium-242.



The High Flux Isotope Reactor reached full design power of 100,000 kW on September 9, 1966. Spent fuel elements are stored under 20 ft of water in the HFIR clean pool. The brightest element had been operated at 100,000 kW for approximately 22 days and had been removed from the reactor only two days before this photograph was taken. The blue glow is Cerenkov radiation, which is caused by the intense radiation emitted by the fission products formed during reactor operation. The two cylinders in the foreground are reactor control plates.

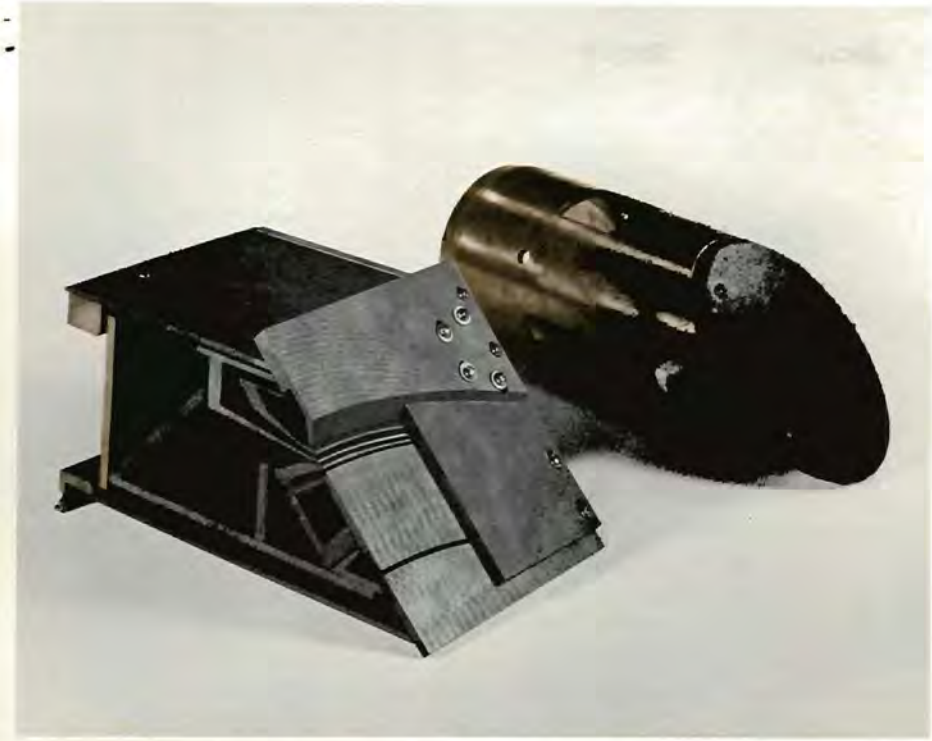
TRANSURANIUM PROCESSING PLANT

These instruments control the first operational production plant for the isolation of berkelium. The graphic panelboard, which depicts equipment and flow of process streams, is typical of the remote operating systems for the entire Transuranium Processing Plant.

Transuranium Processing Plant (TRU) operations with radioactive materials were started in August 1966 to recover transuranium elements from several prototype target rods that were irradiated during the Savannah River High Flux Demonstration Run. To simplify the startup of the plant, only selected parts of the equipment were operated during these runs, but the processing operations, followed by laboratory-scale cleanup and purification, have recovered 12 g of residual plutonium-242, 12 g of americium-243 plus curium-244, 20 μg of berkelium-249, and 130 μg of californium-252. The berkelium and californium will be used in research, the americium and curium will be recycled to the HFIR, and the plutonium, which contains about 0.5% plutonium-244, will be processed through electromagnetic isotope separators (calutrons) to isolate milligram amounts of plutonium-244. This isotope has previously been unavailable and is needed especially for measurements of the neutron cross section.

Californium-252 is often used as a yardstick for the production program because it is the heaviest isotope with an appreciable half-life that will be produced in gram quantities in the HFIR. Less than 1 mg of this isotope is currently available in the United States. An additional 2 mg will be recovered early in 1967 by the processing in TRU of eight plutonium-242 slugs that were irradiated in the reactors at Savannah River. The targets now being irradiated in the HFIR already contain about 1 mg of californium-252; this will increase to about 20 mg by late summer, when the targets are scheduled for processing. Thus the HFIR and TRU are expected to make a 20- to 30-fold increase in the nation's inventory of californium next year, and comparable increases will be made in the inventories of berkelium and einsteinium.

Operations during this startup period have been remarkably successful for such a complex plant. Some idea of its complexity can be obtained by comparing TRU with nuclear reactor fuel processing plants. When nuclear fuel is reprocessed, only one or two products are isolated; for example, slightly enriched uranium fuel is processed to recover plutonium and uranium. Only two or three processing cycles are needed, and the products, though toxic, can be handled with little or no shielding. The TRU facility is designed to isolate six transuranium elements: plutonium, americium, curium, berkelium, californium, and einsteinium. Since at least one processing cycle is required for each product, irradiated HFIR targets must be processed through five to seven cycles. Even though these are small-scale operations, with feed rates no greater than 500 to 1000 ml/h, the complexity of the equipment, instruments, and procedures is at least comparable with that for full-scale fuel reprocessing plants. In addi-



Enrichment of transuranium isotopes can be accomplished in electromagnetic separators. The assembly shown on the left is typical for collecting separated uranium and plutonium isotopes. This type of assembly is used when hundreds of grams of feed material are available and gram quantities of up to four isotopes are collected simultaneously. Such a collector must be disassembled to recover the separated isotopes. The smaller assembly, designed especially for separation of americium-242, permits withdrawal of the collector pocket through the front plate into a shielded carrier. This design was used to collect 5.4 g of 99.48% plutonium-238. By further miniaturization of the collector, transplutonium isotopes will be collected from milligram amounts of starting material.

Transuranium elements are intensely radioactive and must be handled in special facilities that provide adequate containment and shielding. This photograph of 15 g of curium-244 in 1800 ml of nitric acid solution was taken through a 4.5-ft-thick shielding window with only the intense radiation of the curium as the light source. Gram quantities of americium-243, curium-242, and curium-244 and microgram quantities of berkelium-249 and californium-252 have been distributed to scientists in the United States and in several foreign countries.

tion, special equipment is required for the final purification and handling of the products, which must be done behind shielding because of their penetrating gamma and neutron radiations.

Target dissolution, plutonium isolation, separation of transplutonium elements from fission products, and berkelium isolation have all been carried out in TRU process equipment, and these plant procedures are operational. The process for separating transplutonium elements from fission products has been used successfully in a pilot plant at activity levels exceeding those in HFIR target processing to prepare 25 g of curium-242 for use in isotopic heat sources.

Three of the TRU cells are equipped for remote fabrication of HFIR target rods containing recycle americium and curium. After the equipment had been satisfactorily tested, 17 target rods that had been irradiated at the Savannah River Plant were inspected and repaired in preparation for their insertion into the HFIR flux trap.

TRANSURANIUM RESEARCH LABORATORY

Although research on the transuranium elements is being conducted in many countries, the Transuranium Research Laboratory will provide unsurpassed facilities for chemical and physical research on these elements. Glove boxes and lead-shielded boxes will accommodate most of the work; a concrete shielded box will allow handling up to 10 mg of californium-252.

The relatively large quantities of transuranium elements produced by the HFIR will permit the chemist to apply more of the powerful techniques of inorganic and structural chemistry to the study of these elements. The purpose of the chemical program is to obtain fundamental information for the correlation of the chemical properties of actinide elements and other heavier elements, the role of *f* electrons in chemical bonding being of particular interest. To attain this objective, measurements may be made of the pertinent thermodynamic, structural, magnetic, and spectral characteristics of suitable chemical compounds of these elements.

The program also includes studies of the nuclear properties of the transuranium elements, of which there are now about 100 known isotopes. The HFIR, the Oak Ridge Isochronous Cyclotron, and the Tandem Van de Graaff accelerator can be used to produce additional isotopes for the study of induced and spontaneous fission and for decay-scheme and reaction studies. Since nuclei of the actinide elements are nonspherical, like those of the rare-earth elements, they are especially susceptible to study by Coulomb excitation, which excites nuclear oscillations (rotation and vibration). Information gained will aid both in the understanding of actinide nuclei and in the systematics of collective nuclear motion.

The Transuranium Research Laboratory contains the usual glove boxes needed to work with intensely active alpha-particle emitters. In addition, it will contain a concrete shielded box facility that has enough neutron shielding to allow a researcher to work with up to 10 mg of californium-252, which emits over 3×10^{10} neutrons/sec. Space is available in this facility for about 30 physicists and chemists to carry out research. About half the scientists will be permanent ORNL staff, and the others will be visitors from universities and other nuclear research establishments throughout the world.

Some of the Visitors at the Laboratory in 1966

(Right) Newly appointed USAEC Commissioner Samuel M. Nabrit is shown here on the right as he toured the Transuranium Processing Plant in September. With him, left to right, are D. E. Ferguson, ORNL, and Alvin M. Weinberg.

(Right) Gerhard Stoltenberg, Federal Minister for Scientific Research in West Germany, is shown here, fifth from the left, touring the High Flux Isotope Reactor in May. With him, left to right, are H. M. Roth, ORO-AEC; Max Meyer, German Federal Ministry for Scientific Research; A. L. Boch, ORNL; Joachim Pretsch, GFMSR; Stoltenberg; H. G. MacPherson, ORNL; Wolfgang Opfermann, First Secretary of the German Embassy; and W. W. Williams, U.S. State Department.

(Above) J. H. Hollomon, U.S. Assistant Secretary of Commerce for Science and Technology, spoke at ORNL in January.

(Left) Lins Memmel, Member of Parliament, West Germany, visited the Isotopes Development Center, guided by R. W. Schaich, ORNL, in June.

(Right) Governor of Brazil A. S. Nunes, second from left, is photographed while on tour of the Laboratory facilities. With him, left to right, are R. B. Davenport, ORNL, and Mauricio Prazeres, U.S. State Department.

(Left) The President of the Greek AEC, Admiral Jason J. Theophanidis, and Mrs. Theophanidis, third and fourth from left, toured ORNL in November. With them here, left to right, are E. A. Wende, AEC; and H. G. MacPherson and R. B. Briggs, both of ORNL.

(Below) U.S. Representatives John Anderson of Illinois, left, William Brock of Chattanooga, second from left, and John Duncan of Knoxville, second from right, toured the Molten Salt Reactor Experiment in March. With them, left to right, are H. G. MacPherson, ORNL; C. E. Larson, UCC; and S. R. Sapirie, ORO-AEC.

(Left) At the dedication of the Graphite Reactor in September, visitors Glenn T. Seaborg, USAEC Chairman, and Elbert Cox, Regional Director of the National Park Service, are shown here to the right and left with Alvin M. Weinberg.

(Below) A visitor at the State of the Laboratory talk in December was Dr. Albert B. Sabin, discoverer of oral polio vaccine. He is shown here at the social hour with, left to right, Alvin M. Weinberg, Alexander Hollaender, and N. G. Anderson, all of ORNL.

(Above) Senator-Elect Howard H. Baker, Jr., now junior U.S. Senator from Tennessee, visited ORNL in December. Shown here at the Molten Salt Reactor Experiment are H. G. MacPherson, ORNL; C. E. Larson, UCC; S. R. Sapirie, ORO-AEC; Sen. Baker; and Alvin M. Weinberg.

(Below) Ambassador Ousamane Diop of Senegal, second from left, visited the Laboratory in July. With him here are, left to right, Quentin Carrol, TVA; Franklin Pitcher, TVA; and W. A. Felknor, ORNL.

(Below) Thailand's Ambassador to Austria, Chatichai Choonhavan, is shown here between J. J. Pinajian, ORNL, left, and M. L. Nelson, ORNL, during his visit in April.

(Above) Ernst Stuhlinger, director of Research Projects Laboratory at NASA, lectured to a capacity audience at ORNL in February.

Power and Water

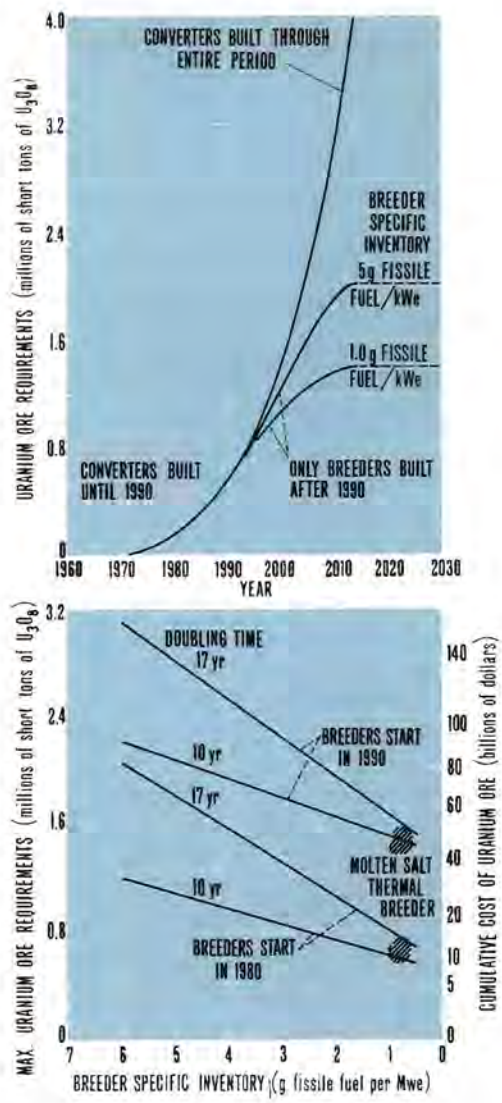
Development of advanced reactors such as the High Flux Isotope Reactor (HFIR) and the Molten Salt Reactor Experiment (MSRE), both of which demonstrated outstanding performance in 1966, continues to be the most striking contribution of the Oak Ridge National Laboratory in the area of reactor technology. But the Laboratory also seeks to advance the technology of nuclear reactors in a more general sense through work in reactor physics, design, component research and development, materials and structures, fuel utilization, instrumentation, safety, and waste treatment and disposal. Out of this work have come significant contributions which show promise of reducing the cost of nuclear energy. Low-cost energy is the key, for example, to desalination of seawater for agricultural use.

MOLTEN-SALT REACTOR DEVELOPMENT

The past year has seen the achievement of a major goal of the U.S. atomic energy program—the ability to produce economic electricity with nuclear energy in most parts of the United States. This was demonstrated in 1966 when orders placed for nuclear plant capacity exceeded those placed for fossil-fuel plants. The development of nuclear power plants must now be directed toward producing power at still lower costs and, in order to conserve our resources of low-cost uranium-235, toward breeding more fuel than is consumed. Today's light-water reactors extract energy from less than 1% of the uranium mined, whereas breeders could use nearly all the uranium or thorium mined and thus greatly reduce the ore requirements.

The Oak Ridge National Laboratory believes that both low power cost and fuel conservation can be achieved best in molten-salt thermal breeders which convert thorium into fissile uranium-233. Sixteen years of experience with molten fluorides, starting with the Aircraft Nuclear Propulsion program and including operation of the Aircraft Reactor Experiment in 1954, has given us confidence in molten-salt technology, and there is enough thorium available to produce low-cost energy with thermal breeders for thousands of years.

Because of our conviction that the molten-salt concept offers the best approach to cheap and virtually unlimited power, we have undertaken a major effort to develop a safe, reliable, and economic molten-salt thermal breeder reactor. The first step in this effort was to build and operate the Molten Salt Reactor Experiment, a reactor which was first brought to power in 1966 and which, as the year ended, was operating smoothly at its full power of 7500 kW.



Incentives for the development of thermal breeders. The upper figure shows the total amount of ore that will be required if the United States builds only light-water converters, and it reveals how the requirement is reduced by building breeders. The cases illustrated were simplified by assuming that we build only light-water converters until 1980 or 1990 and then begin to build only breeders. Just how effective particular breeders are in saving fuel depends on two of their characteristics: (1) the specific inventory, or the number of grams of fissile fuel in the reactor and its associated fuel fabrication and processing plants per kilowatt of electrical generating capacity; and (2) the doubling time, representing the compound interest rate at which fuel for new reactors can be accumulated from the capital investment of fuel in existing breeders.

The effects of these characteristics on ore requirements are shown in the lower figure, where the maximum amount of ore that must be mined was obtained from curves like those in the upper figure. The shaded areas to the right indicate the favorable performance we estimate can be achieved by molten-salt breeders as a consequence of their low specific inventory. The right-hand scale is the cumulative cost of mining the amount of ore that is required. This scale shows the billions of dollars in mining costs alone that can be saved by developing high-performance breeders and bringing them into early use.

Control room of the Molten Salt Reactor Experiment from the visitors' gallery. The operator sits at the console, which contains all the controls necessary for overriding the predominantly automatic operation of the reactor. In the background are seen the colored schematic diagrams of the various reactor circuits. The fuel circuit and components are in red to the right, while the coolant circuit is to the left in green. The reactor core is in the center panel, the fuel circulating pump at the top right, and the radiator to the left. Grouped around these diagrams at the appropriate points are instruments presenting information, lights to indicate the operating condition of valves or pumps, and switches to actuate any desired operation pertaining to that portion of the circuit. Locating the information and control functions by the picture of the circuit component makes it easier to train the operators and minimizes mistakes in interpretation.

Molten Salt Reactor Experiment

The MSRE was built to show that molten-salt reactor development would permit the materials and many of the design features of breeders to be embodied in an operable reactor. In the MSRE, a molten mixture of beryllium fluoride, lithium fluoride, zirconium fluoride, and uranium fluoride is pumped through a reactor vessel where, moderated by unclad graphite, the uranium forms a critical mass and generates energy by fissioning. The fuel is heated from 1168 to 1210°F as it passes through the core. At these temperatures the molten salt is quite fluid, with flow characteristics similar to those of kerosene at room temperature. After leaving the core, the fuel salt is pumped through a heat exchanger where heat is transferred to a coolant salt, which, in turn, is pumped through an air-cooled radiator where the energy is discharged to the atmosphere. (In a power reactor the coolant would pass through a boiler to generate steam.)

By the beginning of 1966 the MSRE equipment had been checked out, the reactor physics calculations had been confirmed by low-power experiments, and, finally, the containment had been sealed. The reactor was now ready for its ultimate test—operation at high power. Everything pointed to success, but since this unique reactor is an experiment, we recognized that some unforeseen problem could appear when heat, radiation, and fission products covering the whole spectrum of chemical reactivity began to be produced within the fluid fuel.

When the stepwise approach to full power was commenced in January, an unusual problem did, indeed, appear—the lines through which gases are vented from the fuel-salt system began to plug. Investigation disclosed that small quantities of intensely radioactive material were stopping up the small filter and the valves. Hot-cell examinations and analyses identified the material as a cross-linked organic polymer, laden with the daughters of volatile fission products. Evidently, oil vapors from a small leak in the shielding plug of the fuel pump had entered the off-gas line and had been polymerized by intense radiation from the very radioactive fission gases stripped from the fuel. The effect in a system designed for clean helium was inevitable. A spare pump with a slight modification that eliminated the oil leak was readied but was not used because larger valves and a new type of filter

reduced the problem to a manageable nuisance. The off-gas problem did not again seriously interfere with the operation of the reactor.

After this delay, power escalation was resumed, and in May the heat removal system reached its maximum capacity of 7500 kW. From then until the end of the year, periods of operation at high power alternated with shutdowns—some planned, others necessitated by failures in peripheral equipment, but none that resulted from a deficiency in the reactor concept.

The longest shutdown was for ten weeks, beginning late in July, after one of the radiator cooling blowers—left over from an earlier project—broke up from mechanical stress. While new blowers were being procured, an array of graphite and metal surveillance specimens was taken from the core to be inspected for corrosion or damage.

The end of 1966 found the MSRE in the middle of a run at full power that lasted for 30 days until terminated for a scheduled inspection of the new blowers. During 1966 the reactor was critical for 2766 h and produced 14,183,000 kWh of heat. Of more significance than these figures, however, was the favorable outlook for the molten-salt concept that emerged from the MSRE operation.

Chemical and Metallurgical Performance. Operation of a molten-salt reactor requires unusual compatibility of the reactor materials: molten salt, unclad graphite, and Hastelloy N (an alloy of nickel, molybdenum, chromium, and iron). Both analyses of the fuel salt, which was sampled frequently, and the reactivity behavior showed that, as expected, the salt was quite stable under all conditions. This was confirmed by the surveillance specimens removed from the core, which indicated that there was no significant deposition of uranium on the graphite—less than 1 g on all the graphite in the core.

Corrosion of the metal was practically nil—the change in corrosion product concentration corresponded to only about 0.0001 in. of generalized corrosion in the 18 months that the fuel had been in the system. Tests of the surveillance specimens showed no metallographic evidence of surface attack. Also, these specimens gave reassurance that the mechanical properties of Hastelloy N were more than adequate for the radiation exposure planned for the reactor vessel.

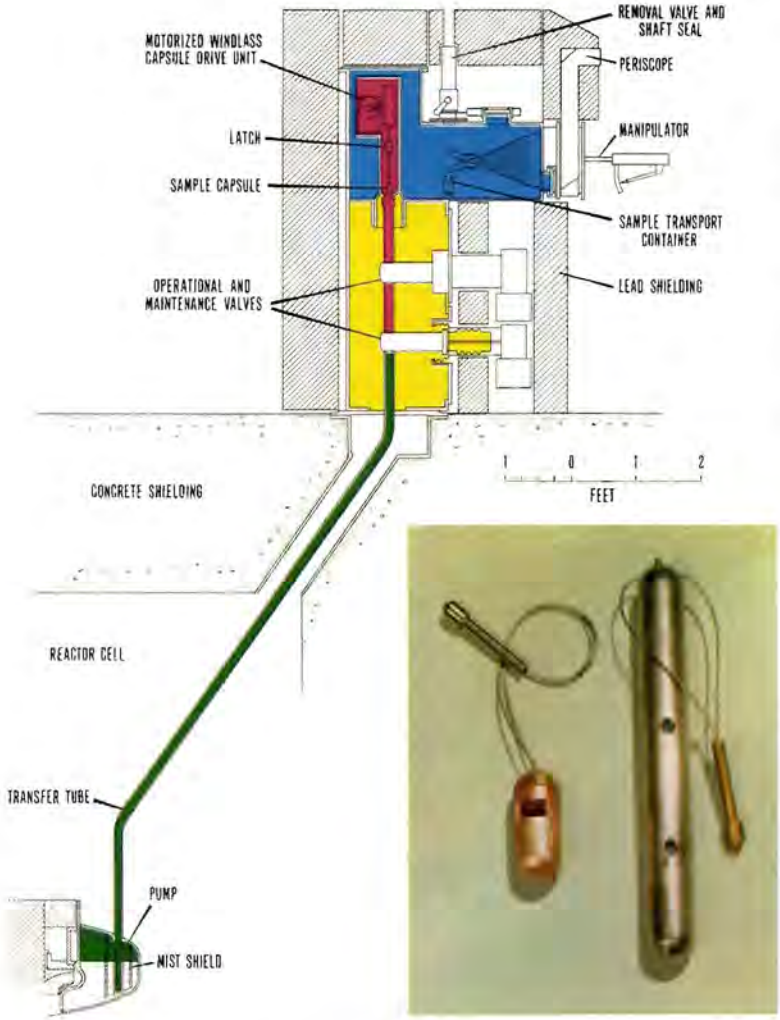
The surveillance specimens made it possible for the first time to measure the deposition of fission products from molten salt fuel during reactor operation. For these measurements, successive 0.01-in.-thick layers were milled from the graphite samples, and the concentrations of fission products in them were determined from the radiation emitted. Fission products having the noble gases xenon and krypton as precursors were present as expected, and their concentration gradients could be correlated with the half-lives and diffusion properties of the precursor gases. Also present, however, were molybdenum, tellurium, and ruthenium, which do not have gases as precursors. These same fission products were found on metallic wires exposed to the gas above the molten salt in the pump bowl, and we believe that they must exist as gaseous compounds. With respect to breeding performance, it is fortunate that they appear to deposit preferentially on metal surfaces.

The behavior of the important fission product xenon-135 has been more favorable than we had hoped. We find that this high-cross-section nuclide is stripped very efficiently from the fuel into the off-gas; the poisoning effect is reduced to one-sixth of what it would be if all the xenon remained in the fuel.

Nuclear Performance. Operation of the MSRE confirmed the adequacy of the basic nuclear data and the computational methods used for predicting reactor-physics characteristics. Low-power tests showed that the predictions of critical loading and control rod worth were quite accurate, and this success was repeated when the dynamic tests indicated that the reactor behaved as predicted and was stable at all power levels.

Mechanical Performance. The salt pumps, the mechanical components most essential for the molten-salt concept, ran flawlessly except for the small leakage of oil into the pump bowl. By the end of 1966 the fuel and coolant salt pumps had each passed 9000 h of trouble-free operation. The fuel sampler-enricher was used to take 88 samples in 1966, the only significant failure being an electrical short in a control cable. Otherwise, mechanical troubles were confined to peripheral equipment—the conventional machinery ancillary to the salt system. Maintenance proved quite feasible, even for a job such as replacing the off-gas filters, which had not been specifically planned in advance.

Significance of MSRE Operation. In its first year of operation, the MSRE has shown that a molten-fluoride reactor can be operated at temperatures above 1200°F without corrosive attack on either the metal or the graphite parts of the system, that reactor equipment can operate satisfactorily at these conditions, and that, when necessary, the radioactive equipment can be repaired or replaced.



The Molten Salt Reactor Experiment fuel sampling and fuel-enrichment system is a simple modification of the familiar windlass and bucket used for drawing well water. A windlass in the shielded cubicle lowers a bucket down the transfer tube and under the surface of the molten fuel salt in the sump bowl of the pump that circulates the fuel. The bends in the transfer tube prevent the escape of direct radiation. The bucket is withdrawn above the pump bowl, where the molten salt freezes, thus immobilizing the fission products in the salt. The windlass raises the bucket to the top of the transfer tube, where the operator can detach it with the use of the manipulator and a periscope. The bucket is finally withdrawn through the removal valve into a shielded carrier for transport to the analytical hot cells.

To replace burned-up fuel, the sampling procedure is reversed. A capsule containing the $LiF\text{-}UF_4$ eutectic of enriched uranium is inserted through the removal valve, attached to the windlass cable, and lowered into the pump bowl. Holes are drilled through the capsule wall just before use, exposing the frozen fuel concentrate. Contact with the molten fuel salt rapidly dissolves the eutectic to add approximately 90 g of uranium to the fuel system. The pump mixes the concentrate with the main body of circulating fuel rapidly and effectively.

Graphite cylinder brazed to molybdenum metal end caps. Graphite tubes are connected to metal piping in the assembly of the core of a molten-salt breeder reactor by brazing the graphite to molybdenum transition pieces, then brazing those in turn to Hastelloy N tubes. The thermal expansion coefficient of molybdenum is close to that of graphite. In order to show that a graphite-to-metal brazed joint is sound, we fabricated one from a graphite cylinder and flat molybdenum end caps – a much worse geometry than the overlapping concentric cylinders in the reactor. This assembly in the photograph was held in an incandescent furnace for over 500 h filled with salt at 150 psig; the assembly was not damaged.

Molten-Salt Breeder Reactor Design

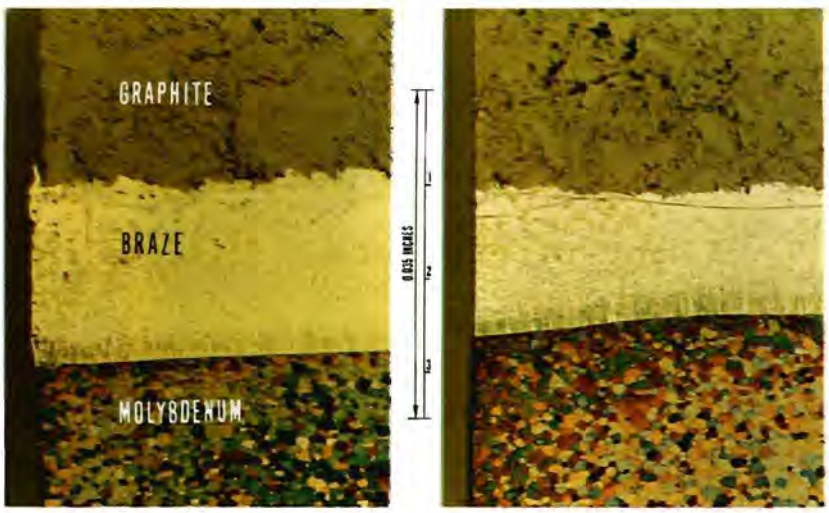
The feasibility of a molten-salt system having been demonstrated by the MSRE, we have begun to design a full-scale (1,000,000 kW) breeder reactor and to analyze its performance.

Two fluid streams would be used – a fuel salt, which would pass through the core in graphite tubes, and a blanket salt, containing thorium, which would surround the core and flow through the space between the tubes. Fuel salt would enter the reactor at 1000°F and leave at 1300°F. A secondary heat transfer loop containing an inexpensive low-melting salt, sodium fluoroborate, would isolate the steam boilers from the fuel circuit. When coupled to a turbogenerator operating on supercritical steam at 3500 psi and 1000°F, the thermal efficiency of the plant would be about 45% – higher than that of the most modern coal-fired power plant.

A reactor of this design would have a specific inventory of less than 1.0 g of fissile uranium per kilowatt of electrical generating capacity and

Molten-salt distillation – a key step in continuous reprocessing. One of the most important features of molten-salt reactors is that the fuel can be processed continuously and very cheaply to remove fission products as fast as they are formed. We are developing a simple low-pressure, high-temperature distillation process to separate the rare-earth fission products from the lithium fluoride and beryllium fluoride fuel components. This is a view into an equilibrium still used to determine the relative volatilities of rare-earth fluorides. It has been sectioned for sampling the salt after being operated at 1000°C and 1 mm Hg pressure. On the right is the still pot, which contains lithium fluoride colored with traces of cerium fluoride. To the left is the trap at the bottom of the condenser; in its center is the reflux overflow, which returns condensate to the still. The clear salt in the trap is condensed, purified lithium fluoride. The salt in the still pot is more than 2000 times as concentrated in cerium as the salt in the condenser trap.

a breeding ratio of around 1.07. As a result, it would produce uranium for starting up new reactors fast enough that our power generating capacity could double every ten years without requiring any newly mined uranium. The fuel cycle cost of this reactor is estimated to be only 0.4 mill/kWh and the total power cost about 2.7 mills/kWh under private ownership. This is to be compared with fuel cycle costs of about 1.5 mills/kWh and power costs of about 3.7 mills/kWh for the large light-water reactors that are being purchased today. With public financing the total cost has been estimated to be as low as 1.5 mills/kWh for a molten-salt breeder reactor.



Graphite-to-metal braze joint. Brazes for graphite, in addition to making a good joint, must resist corrosion by fluoride salts and be able to withstand neutron irradiation. This figure shows microstructures of a joint made by brazing graphite to molybdenum with an alloy of 60% palladium, 35% nickel, and 5% chromium. The right view is of an untested section. The left view is of a section that was exposed to a molten fluoride salt for over half a year at 700°C without attack. Longer exposure tests are in progress, and we are preparing to irradiate sample joints in a test reactor and in the Molten Salt Reactor Experiment.

The Next Step

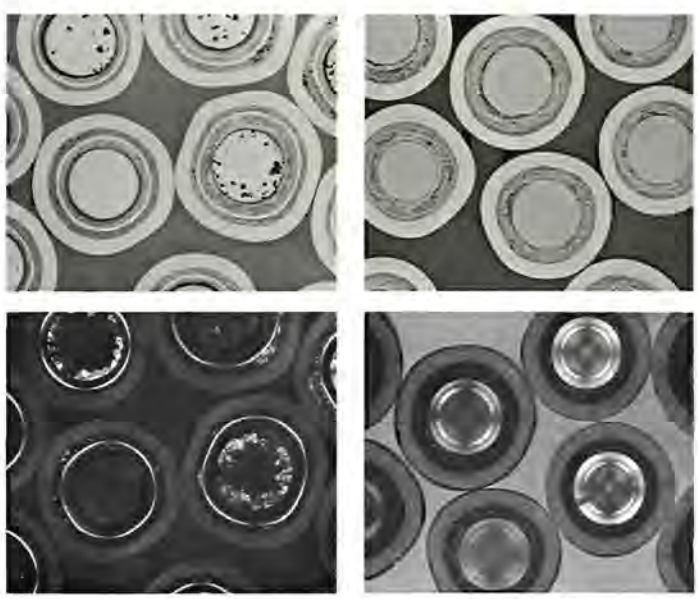
After we have completed the conceptual design of a 1,000,000-kW breeder and know more fully what its features will be, we plan to design a smaller breeder reactor to be known as the Molten Salt Breeder Experiment. A plant producing less than 100,000 kW could demonstrate all the basic features of the concept and bring us far enough along that only moderate scaleup and normal improvement in equipment and processes would be required for proceeding to a full-scale plant. The success of the MSRE makes us confident that the Molten Salt Breeder Experiment may be the last stepping stone toward the achievement of a virtually inexhaustible source of low-cost energy.

ADVANCED GAS-COOLED REACTOR RESEARCH

The high-temperature gas-cooled reactor (HTGR) promises economical power production, high thermal efficiency, and effective utilization of uranium reserves. A major Laboratory effort has been the development of HTGR fuels in the form of UC_2 or UO_2 particles coated with pyrolytic carbon to retain fission products. Emphasis has been placed on economical fuel production and on the establishment of serviceability as demonstrated by irradiation testing.

Sol-gel-derived oxide fuel particles with two-layer pyrolytic carbon coatings continue to show very good irradiation performance. For example, experiments were performed in 1966 in which burnup of uranium atoms to 50% was attained. These experiments revealed no significant change in structure beyond that observed in the 25% burnup tests carried out in 1965.

A recent study of the properties of coatings deposited from higher hydrocarbons indicates that the high-density isotropic type of outer coating required for good irradiation performance may be applied at much higher rates and lower temperatures than was previously thought possible. The economics of fuel fabrication should certainly be improved with the new technique. Tests of the rate of release of fission gases during irradiation indicate excellent performance thus far.



BRIGHT FIELD ILLUMINATION

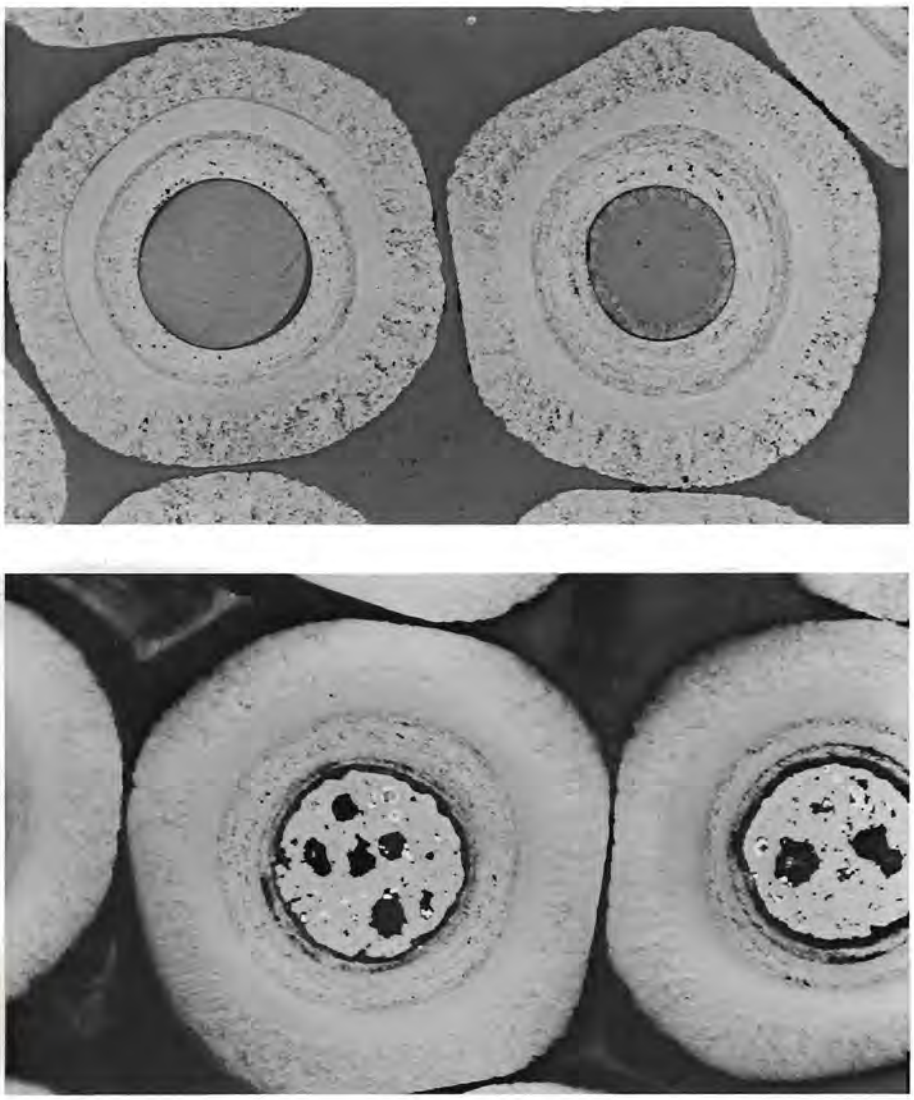
POLARIZED LIGHT

BATCH NUMBER	OR-502	100X, AS POLISHED
COATING TEMPERATURES	1050°C, 1150°C, 1050°C, 2000°C	
TOTAL DEPOSITION TIME	ONE HOUR	
OUTER COATING DENSITY	1.9 g/cm³	

	OR-526	100X, AS POLISHED
	1050°C, 1200°C	
	TEN MINUTES	
	2.0 g/cm³	

Structures of pyrolytic carbon coatings on thorium-uranium oxide particles. The coatings at the left were deposited from methane and require about 1 h at approximately 2000°C; the outer layer density is 1.9 g/cm³. The coatings at the right are deposited from propylene by the new ORNL method. An outer coating having a density of 2.0 g/cm³ was deposited in only 10 min at a maximum temperature of 1200°C. Note that the oxide particles coated at 2000°C developed large grains, which tended to break and pull out during metallographic preparation, whereas those coated at 1200°C could be polished without damage. Magnified 100×.

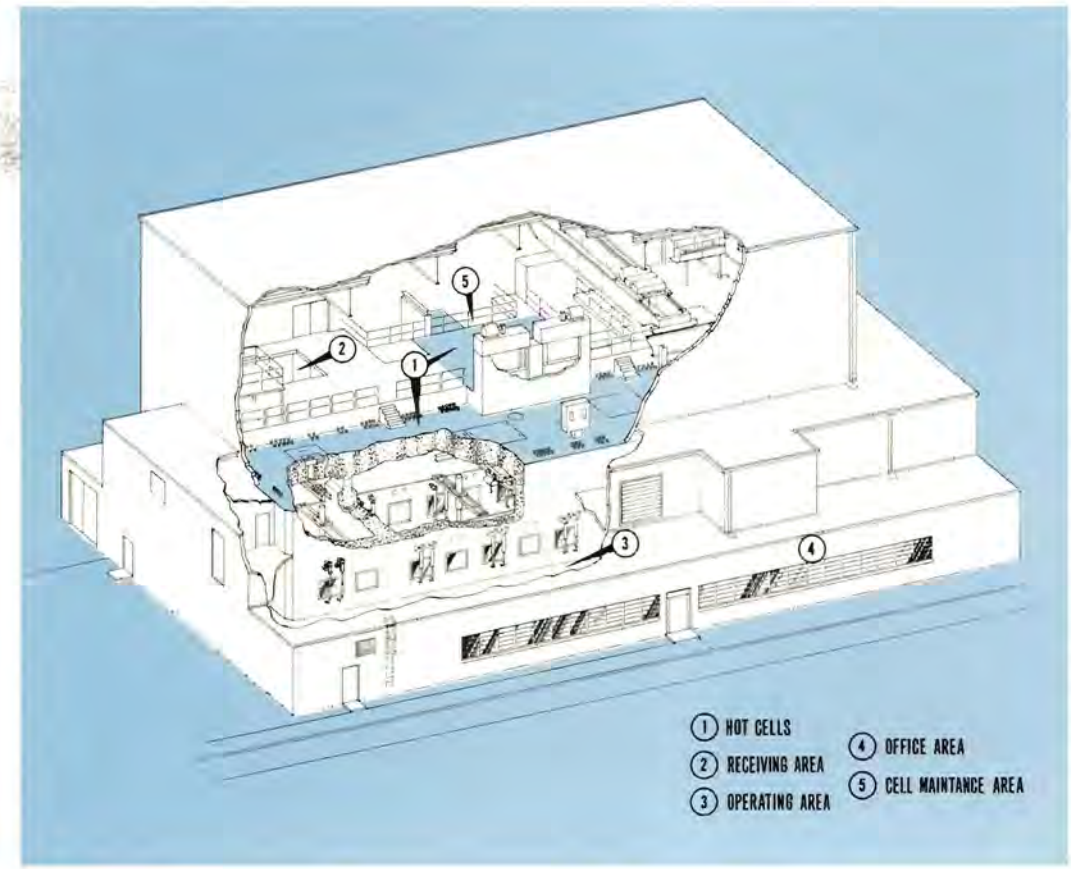
A mathematical model which was developed to predict the mechanical behavior of pyrolytic carbon coatings on fuel particles under irradiation has been tested by means of an irradiation experiment on ten different batches of coated UO_2 and UC_2 particles. Good correlation between predicted and actual behavior was observed, increasing confidence in the model and in the physical properties of the pyrolytic carbon coatings.



Typical pyrolytic-carbon-coated sol-gel UO_2 microspheres: unirradiated (left); irradiated for 260 days at temperatures of 1100 to 1350°C to approximately 50% burnup of the uranium atoms (right). These photomicrographs reveal the excellent stability of this type of fuel after high uranium burnup (twice that reported in the 1965 annual report). Note the metallic particles of a second phase and the porosity of the UO_2 as normally observed after appreciable burnup. The inner coating layer was slightly densified by swelling of the UO_2, but no damage to the outer coating layers is evident. Thus gaseous fission products were adequately retained.

THORIUM UTILIZATION PROGRAM

Thorium is one of the world's principal energy resources, existing in vast reserves in the United States and throughout the world. By irradiation in nuclear reactors, thorium-232 can be converted to uranium-233, a fissile isotope of uranium, in amounts that will meet the world's projected energy requirements for a very long period of time. The Thorium Utilization Program at the Oak Ridge National Laboratory is directed toward the prudent and economical exploitation of this resource, especially through the development of suitable fuel cycle technology for thorium-fueled reactors. In this fuel cycle, even after removal of all fission products, the uranium and thorium are made highly radioactive by growth of gamma-emitting daughter products from uranium-232, an isotope produced as a side reaction in the conversion of thorium to uranium-233. Consequently, processes and equipment must be developed so that the various recycle steps can be carried out in a shielded facility.



In the Thorium-Uranium Fuel Cycle Development Facility, four operating cells and two service cells are provided. The operating cells are to be used for (1) irradiated fuel processing, (2) chemical and mechanical operations for reconstitution of fissile and fertile materials into suitable forms, (3) fabrication of fissile and fertile materials into fuel elements, (4) inspection and assembly of finished fuel elements. The service cells are to be used for (1) decontamination of equipment to permit contact maintenance in a gloved maintenance room and (2) storage of contaminated equipment. Bridge-mounted mechanical arms, master-slave manipulators, and viewing windows are provided for in-cell operations.

A pilot plant for thorium fuel cycles is nearing completion at ORNL. This facility, the Thorium-Uranium Fuel Cycle Development Facility (TUFCDF), is a versatile, integrated hot-cell complex for development of all phases of thorium fuel cycle technology. It will provide the shielded and safely contained space in which to demonstrate the processes and provide economic information for all phases of remote recycle technology. Its size is sufficient to handle the full-size fuel elements used in high-temperature gas-cooled reactors.

The first fuel cycle to be studied in TUFCDF is that for high-temperature gas-cooled reactors. Typically, a recycle fuel element for an HTGR consists of a large block of graphite containing carbon-coated UO_2-ThO_2 microspheres that are bound together with nongraphitized carbon. Each of these fuel elements may include several different types of microspheres, each containing uranium-235, uranium-233, thorium, or various admixtures. Each of these types of particles bearing the different isotopes must be present in the fuel element in very precisely controlled amounts.

The fuel element is fabricated by the following steps: preparation of oxide microspheres, coating the oxide microspheres with carbon by pyrolysis of a hydrocarbon gas, blending the various types of particles in the desired ratios, cementing these together into a fuel stick by means of resin and carbon, and finally loading the stick into the graphite block and sealing the block. All this, as well as various inspections, must be done remotely.

During the past year, we have been successful in simplifying several of the more difficult steps and in using more economical materials. A solvent extraction process has been developed for preparing the mixed ThO_2-UO_2 sols necessary for microsphere preparation. This represents a simplification over the previous method, in which the UO_2 sol and ThO_2 sol were prepared separately and mixed.

Economic analyses have shown that the particle coating operation is the most expensive part of the refabrication process for HTGR fuel elements. During the past year, the use of propylene or propane in place of methane as the coating gas has allowed the use of much lower temperatures and much faster coating rates than had previously been possible (see section on Advanced Gas-Cooled Reactor Program).

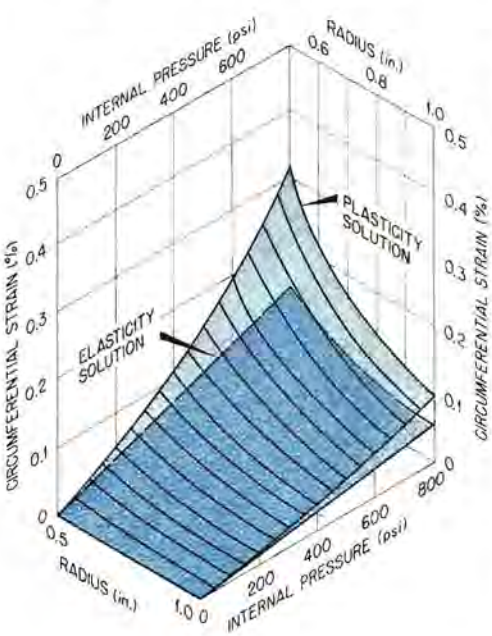
Vibrating capillary disperser. Formation of sol droplets of a specified uniform size is an important step in forming small, dense spheres. Extremely uniform droplets can be obtained by imposing a controlled vibration on a capillary from which sol is flowing. In the experimental device shown, four capillaries are vibrated at 90 cps by a loudspeaker cone to form 43,200 drops/min, each 950 μ in diameter. The sol consists of 75% thorium oxide and 25% uranium trioxide and was prepared by a solvent extraction process. Sol flow rate and vibration frequency control the drop size. The picture was made by a 2-sec exposure, using stroboscopic lighting; thus each "droplet" is really the superposition of 180 droplets.

ENGINEERING SCIENCE

In order to use structural materials efficiently in a nuclear reactor, unique problems must often be solved within rigid limits of safety and reliability. Therefore increasing attention is being focused on the detailed description of the manner in which structures and materials respond to different types of loadings.

Stresses and strains in structural elements are normally described with sufficient accuracy by the theory of elasticity. In many cases involving advanced reactor concepts, however, design formulas now available are either too conservative for efficient use of material or inadequate for describing the stresses in critical areas when the structure is loaded near its capacity. Stresses and strains can, however, be measured on suitably constructed scale models in the laboratory; more accurate design formulas can be solved by using high-speed computers; and better theory can be developed by studying the interrelationship between mathematical prediction and experimental observation. Several examples of the application of these techniques are discussed in this section.

Theoretical investigation of different stress-strain laws for graphite. Each of the two surfaces in this three-dimensional illustration represents the circumferential strain distribution $\epsilon_\theta(r, P)$ in the wall of a thick-walled tube of AGOT reactor-grade graphite as a function of radial position and internal pressure. Both of these solutions required the extension of theories of structural behavior commonly used in design in order to include mechanical properties peculiar to graphite. The lower surface is the result of using linear anisotropic elasticity, whereas the upper surface is the result of using an anisotropic theory of plasticity.



Graphite Mechanics

Graphite is being used as one of the main structural materials in several types of nuclear reactors, including molten-salt reactors, gas-cooled power reactors, and nuclear rockets, and it is being considered for use in future breeder reactors. In each of these applications the structural demands on the material are unique, covering a wide range of temperatures, irradiation intensities, environmental conditions, and stress levels. Furthermore, graphite is a low-strength material, which behaves only approximately like ordinary structural materials. In order to design graphite structures more efficiently, the Laboratory has for several years conducted an integrated theoretical and experimental program to develop stress-strain laws and failure theories specifically for graphite. Recent developments include the extension of plasticity theory, development of numerical techniques for computer solutions, and experimental test of the theories. Room-temperature, high-temperature, and transient thermal tests on simple and complex shapes are used to gather basic data as well as to test theoretical solutions.

One particularly interesting experiment is the transient thermal stress rupture test, designed initially to screen different graphites for use in the Nerva nuclear rocket. High-temperature strength and resistance to thermal stress rupture were the primary considerations. Unirradiated graphite has such a high thermal conductivity that it is extremely difficult to create temperature gradients high enough to cause thermal stress failure. Steady-state thermal gradient tests which have been used to produce

A radial crack is created in a graphite disk by thermal stresses alone when the disk is heated rapidly with a Heliarc welder. This is the first successful thermal rupture test for graphite that does not require large amounts of power and coolant. Both the strains and the temperature distribution can be measured as a function of time, thus making it possible to obtain the data needed for developing a thermal stress failure theory.

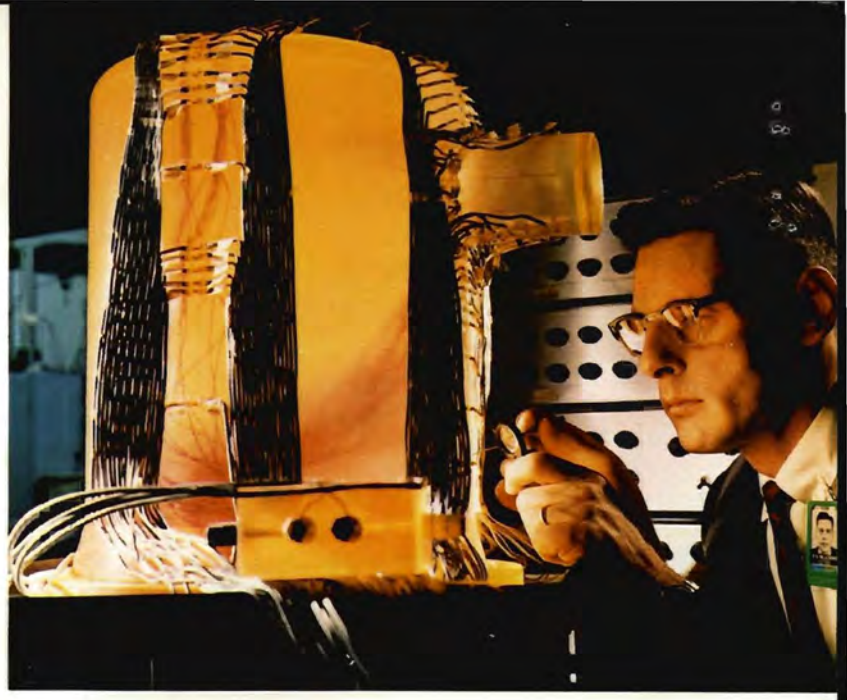
failure invariably require large amounts of power and coolant and are therefore complicated and expensive. A simple, inexpensive test was developed which uses a Heliarc welder as the power source and a water-cooled copper jacket as the thermal sink (see illustration).

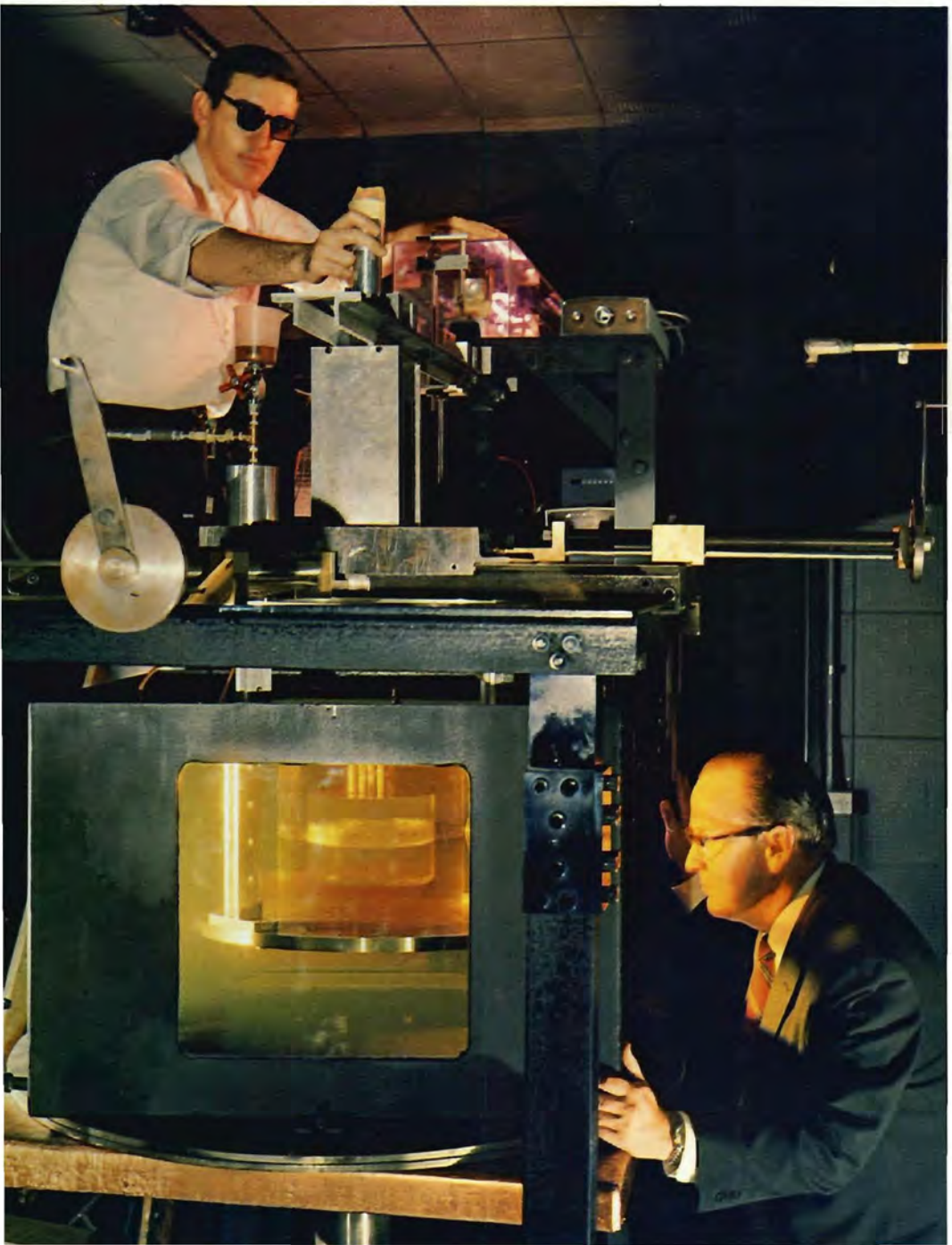
Nuclear Pressure Vessels

For several years the Laboratory has been contributing to the design and development of nuclear pressure vessels. In this work the Laboratory cooperates with the Pressure Vessel Research Council of the American Society of Mechanical Engineers, various universities, and foreign research establishments. Carefully machined steel and epoxy models are used experimentally to determine stress distributions in vessel configurations for which theoretical solutions are as yet unavailable. These data provide immediate design information and also serve as checks for comparison with theory.

A newly developed and powerful tool in the Experimental Stress Laboratory is a scattered-light polariscope that uses a continuous gas laser light source. A high-intensity beam of monochromatic light is passed through a birefringent epoxy model immersed in a bath of oil of a match-

Epoxy resin is often used for strain gage model tests in lieu of aluminum or other metals. The low modulus of elasticity provides high strains at relatively low applied loadings. The transparency of the material proves to be an advantage when placing outer surface strain gages opposite gages located on the inside of the vessel. Here a typical pressure vessel model is undergoing pneumatic testing.





A continuous-wave laser is utilized in this specially designed polariscope as a high-intensity monochromatic light source for determining stresses in birefringent models under applied loads. Scattered-light photoelastic analysis is a nondestructive method for experimentally determining the stresses at any point in a general three-dimensional stress field.

ing index of refraction. When the model is loaded, the intensity of the light scattered perpendicular to the beam is directly related to the stress. A pattern of light and dark bands is thereby formed, which can be photographed and analyzed to yield the local stress distribution.

The advantage of this polariscope lies in the fact that stresses can be determined in three-dimensional epoxy models without destroying the model. Previous methods required that stresses be frozen in and the model sliced into thin sections for viewing in a plane polariscope. This new polariscope is being used in the study of concrete pressure vessel design.

Noise Analysis for Reactor Diagnosis

A technique has been developed at the Laboratory to diagnose anomalies and to infer conditions inside the core of a nuclear reactor where no sensor can be inserted to make a direct measurement. The technique consists in measuring fluctuations of the neutron population and of the flow rate, temperature, and pressure of the coolant. These fluctuations, when analyzed with a computer, yield information related to the dynamic behavior of the reactor. Specific abnormalities are characterized by increased amplitude of the fluctuations occurring in a limited frequency range. Moreover, these various kinds of fluctuations can be cross-correlated with mechanical vibration of the core and acoustic noise to improve the degree of confidence in the diagnosis. The principal investigations cover the detection of local boiling of the coolant in the core, the subcritical reactivity of the reactor while shut down, the control rod burnup, and the mechanical integrity of the core components. As an example, excessive vibration of the control rods of the High Flux Isotope Reactor was discovered before visual inspection showed damaged rod bearings.

This method of analysis is supported by an extensive reactor dynamics model study intended to describe and explain the physical processes so that differentiation between the various sources of fluctuation and noise occurring in the reactor core is possible. Such knowledge is particularly important in devising safety and control mechanisms for large fast reactors.

DESALINATION

Water Research Program

The Office of Saline Water of the Department of the Interior supports a broad program of water research at Oak Ridge National Laboratory. In this program, emphasis is on studies of properties of multicomponent aqueous and water-organic mixtures; on phase relationships at high temperatures; on surface reactions and transport phenomena, including corrosion; and on separation processes, electrochemical methods, boundary-layer studies, and turbulence promotion. Separation process studies have involved fundamental investigations of many separation methods potentially applicable to the desalination of seawater. In recent years, the hyperfiltration, or reverse osmosis, method, and supporting research for it, have been emphasized. During the past year the program stressed the study of membranes that are dynamically formed on porous bodies when pressurized feeds containing suitable additives are circulated past the porous bodies. This class of membranes was mentioned in last year's annual report. The dynamic membranes frequently combine substantial salt rejection with high production rates, sometimes several hundred gallons per square foot per day.

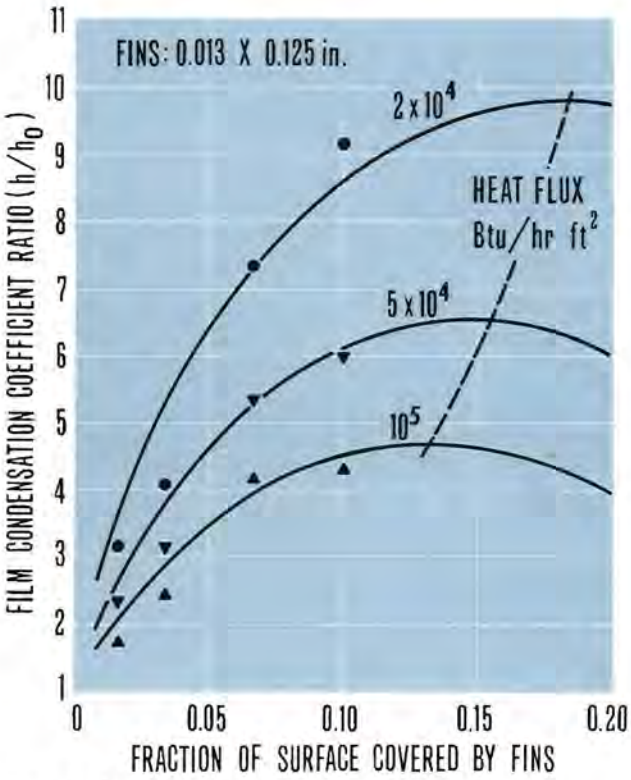
In the past year a wide variety of compounds were shown to be suitable as additives for the formation of membranes—for example, hydrolyzable ions, colloidal hydrous oxides, synthetic organic polyelectrolytes, and natural products such as humic acid and clays. The most interesting membranes so far achieved seem to reject salt primarily by an ion exclusion mechanism predicted for ion exchange materials, though there is no reason, in principle, why salt-rejecting membranes from neutral organic additives should not also be formed by this technique. Many porous bodies are suitable as substrates for membranes—porous metals, porcelain, sintered glass, and organic polymeric films, for example. Of particular interest for possible practical utility are porous carbon tubes.

Many dynamically formed membranes have been shown to reject organic solutes, as well as

Hyperfiltration apparatus. A porous carbon tube, coated on the inside with a salt-rejecting membrane, allows fresh water to seep through from the pressurized salt water inside the tube. In test apparatus of this sort, flows of several hundred gallons per square foot per day have been obtained with good salt removal.

electrolytes—an observation that suggests their possible application to pollution control.

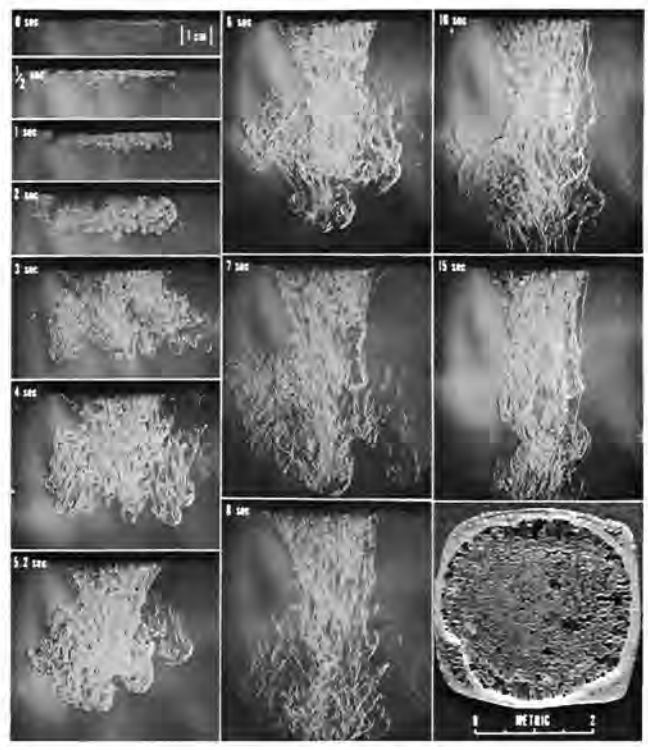
When high filtration rates are achieved with good salt rejection, concentration polarization at the surface of the membrane often occurs and reduces the efficiency of the process. In fact, polarization associated with the interface between a solid and a fluid reduces the efficiency of almost all desalination processes. Notable improvements in reducing polarization effects have been achieved by taking advantage of different mechanisms based on particular flow characteristics of various desalination processes. Significant increases in process efficiencies have been achieved through turbulence promotion caused by obstructions placed in flowing streams, through the thinning of condensate films by surface tension effects, and through natural convection in unstirred systems where density gradients occur.



On vertical condenser tubes, loosely attached fins improve heat transfer, evidently by providing "corners" into which surface tension draws most of the condensate running down the tube. With the condensate collected in rivulets next to the fins, the remaining tube surface has only a thin film of condensate and therefore exhibits better heat transfer performance.

In hyperfiltration tests, where concentration polarization is a serious problem at high production rates, salt rejection ratios and permeation rates have been increased by placing a wire spiral in the flowing stream on the membrane side of the tube but detached from the surface of the tube. A spiral wire in contact with the membrane surface had little effect on salt rejection. With dynamic membranes there is evidence that the turbulence promoters not only increase the turbulence in the fluid but also decrease the thickness of the rejecting layer and hence increase the production rates.

Greatly improved heat transfer has been achieved in vertical condenser tubes, where surface tension effects associated with small rivulets flowing down vertical fins loosely attached to the condenser tubes markedly reduce the thickness of the film between the fins, thereby permitting significant increases in the film condensation coefficient. In one series of tests as much as a ninefold increase in condensation coefficient was observed.



Schlieren photographs of salt dissolving from the 100 face of a potassium chloride single crystal into water. In the initial frames, streams of concentrated salt solution are falling in substantially parallel individual paths. After 3 sec a strong jet of solution develops and falls as a coherent lump of fluid. The inset shows an originally smooth crystal face after exposure to water. The dimples on the surface of the crystal are caused by the natural convective flow pattern.

Differences in the salt rejection by membranes have been observed in tests with unstirred (nonflowing) hyperfiltration solutions, depending on whether the membranes are placed above or below the feed solutions. Membranes placed above the solutions gave better salt rejection and showed fewer effects of concentration polarization. The marked difference in polarization was attributed to stirring caused by the density gradients formed near the interface where salt rejection occurs. Similar phenomena are being studied by placing single crystals of salt in contact with water at atmospheric pressure. This permits study of the flow patterns associated with the natural convection by schlieren techniques as well as by the etch patterns in the salt crystal.

Titanium is of interest as a material for the heater and condenser tubes in evaporator desalting plants. We found earlier that titanium suffers from crevice corrosion in seawater at elevated temperatures. Investigations of titanium alloys showed that initiation of the crevice attack occurs rarely at 100°C but occurs with rapidly increasing frequency at higher temperatures. The very high corrosion rates observed (0.4 to 1.5 in./year) and the greater resistance to crevice attack shown by alloys that are not attacked by dilute acids at 100°C suggested an active-passive cell mechanism. This mechanism involves formation of an acid environment in the confines of the crevice, due to consumption of oxygen and hydrolysis of the ions formed by the corrosion of the metal. Samples of solution from inside actively corroding crevices were found to be sufficiently acid (pH about 1) for activation of titanium in the absence of oxygen. Thus the corrosion behavior of titanium alloys in oxygen-free acid solutions can be used, at least qualitatively, as a basis for predicting their resistance to crevice corrosion.

On this basis the anodic polarization of a number of titanium alloys in 0.1 *M* HCl–0.9 *M* NaCl solution at 100°C was studied. All the commercially available alloys showed the same active-passive behavior as pure titanium and would therefore be expected to be similarly susceptible to crevice corrosion. However, the results also indicated that the addition of nickel or molybdenum to titanium should increase the resistance to crevice attack.

Nuclear Desalination Program

In addition to fundamental research, the Office of Saline Water supports a program of seawater evaporator development at the Laboratory. The Nuclear Desalination Program thus is in a unique position to study and develop large desalting plants that utilize nuclear reactor energy sources developed under the Atomic Energy Commission. Among the brightest technological opportunities to come clearly into focus this year is the possibility of developing a large industrial-agricultural-desalting complex. Huge nuclear reactors would produce electricity and process heat so cheaply that the cost of distilled water would be low enough for agricultural uses. Low-cost electricity and process heat could be used to clean up wastes of many kinds and convert them to useful products, to reclaim minerals from seawater, and to supply energy for manufacturing plants that would use these minerals, with other raw materials, for industrial production. Economic analyses of desalting plant concepts have clearly shown that large plants have the potential today for producing both water and electricity at costs that would be attractive in many areas. The multistage, multilevel flash evaporator plant reported last year was designed to produce 250,000,000 gal of water per day at an estimated cost of about 15¢ per 1000 gal.

This year, a feasibility study showed the interesting advantages of a 2,000,000-gal/day evaporator plant using a diesel engine as the energy source. The diesel would operate a vapor compressor across a two-effect vertical-tube evaporator, which would be coupled to a multistage flash evaporator. Waste heat recovered from the diesel engine would provide the energy for heating seawater in the evaporators. The plant would produce 27 lb of water for each 1000 Btu of energy used. This system appears attractive for small municipal water plants, since the water cost is estimated to be 50.4¢ per 1000 gal (on the basis of natural gas fuel for the diesel at a price of 32¢ per 1,000,000 Btu).

The Office of Saline Water has assigned the Laboratory primary responsibility for an expanded program to develop vertical-tube evaporators to the point where their potential can be assessed reliably.

A number of novel tube configurations have been found to perform two or three times as well as the tubes customarily used. The more promising types of evaporator tubing will be further tested in a five-effect vertical-tube pilot plant, now being assembled,

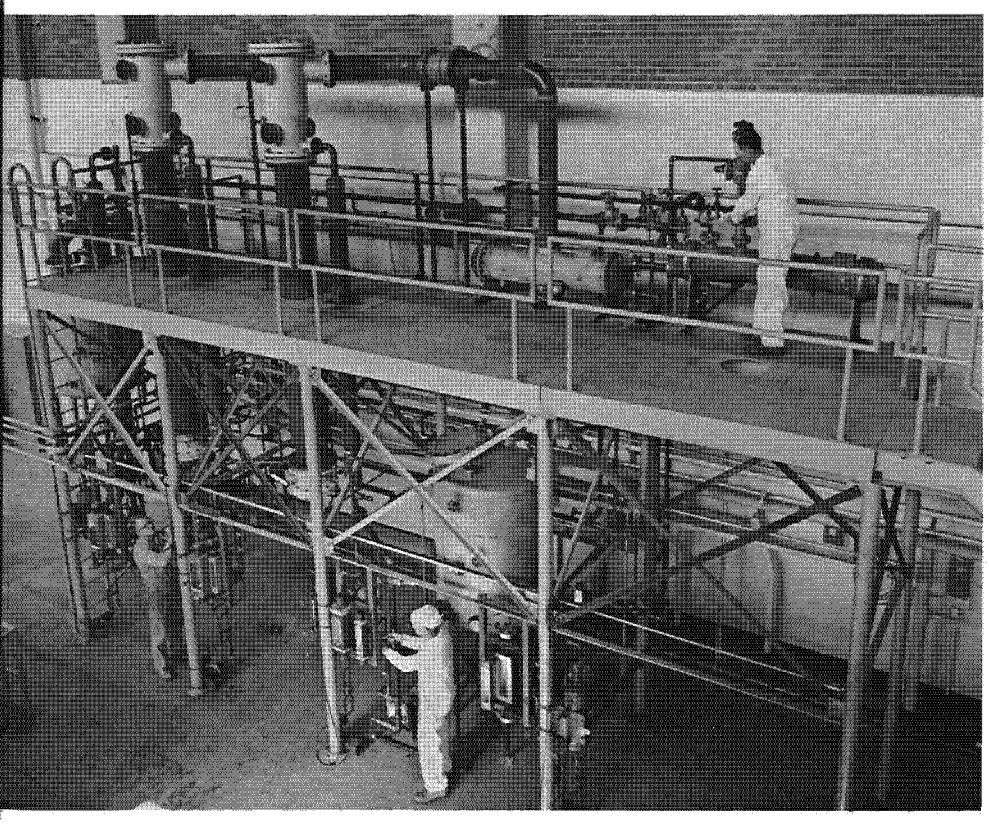
having a capacity of 20,000 gal/day. After operation in Oak Ridge, the pilot plant will be moved to an OSW station for tests with seawater.

The conceptual design of a 250,000,000-gal/day vertical-tube evaporator plant has been started, in order to provide a basis for evaluating the potential of this type of evaporator in comparison with others. Because of the high performance of the new vertical tubes, it is already clear that costs lower than for flash plants can be expected.

Major efforts in the multistage flash evaporator development program have been devoted to obtaining evaporator tubes at lower cost. Cooperative efforts have been undertaken with tubing manufacturers who will supply samples of tubes with surface shapes that will improve their heat transfer properties. Improved heat transfer was found in ORNL tests of horizontal condenser tubes grooved to improve the inside film coefficient and plated with nickel phosphide or gold to provide dropwise condensation.

Reactor size extrapolation studies, performed by subcontractors, have shown that several types of power reactors can probably be built to produce 3,000,000 to 10,000,000 kW of heat, the range of interest for large desalting plants. Preliminary estimates indicate that large versions of these reactors, which were selected because they are in the most advanced stages of development, can produce steam for costs in the vicinity of 10¢ per 1,000,000 Btu. Parametric studies of large desalting plants indicate that steam costs of about 4 to 5¢ per 1,000,000 Btu will be needed to achieve the production of fresh water from the sea at costs low enough for agricultural uses (about 10¢ per 1000 gal). It seems certain that water can be produced at costs low enough for U.S. municipal and industrial uses (about 30 to 40¢ per 1000 gal) even without further advances in technology.

Process application studies have disclosed several ways in which low-cost electricity from a large desalting plant could be used to manufacture other products, to reprocess sewage and other wastes, or to remove the scale-forming constituents of seawater. Such by-product uses for electricity may make dual-purpose plants attractive in areas where the present demand for additional electric power is small.



A five-effect vertical-tube evaporator pilot plant is being constructed at the Oak Ridge National Laboratory to demonstrate the performance of improved types of tubing in seven-tube bundles. The 20,000-gal/day pilot plant will be moved to a seacoast test site after trial runs and performance tests with ordinary water at Oak Ridge. In the photograph, the first two effects have been installed. Performance tests will be conducted in these effects before the three remaining effects are installed.

WASTE TREATMENT AND DISPOSAL

The earliest thoughts on using fission energy for power production were haunted by the specter of living with the ever-increasing quantities of hazardous wastes that would be produced. There were some who said that a safe solution to the problem would never be found, and if it were, the costs would be prohibitive. All agreed that past practices – tank storage for highly radioactive liquid wastes and dispersal to the environment for those less radioactive – would not be feasible at the time when nuclear energy had largely supplanted fossil fuels. The Oak Ridge National Laboratory's research program on waste treatment and disposal has long had the goal of solving such central problems as finding ways of converting highly radioactive liquid wastes to solids, which could then be stored safely; developing ways of disposing of the large volumes of intermediate-level wastes that would be produced in reactors and in plants for processing spent fuel; and inventing processes for removing radioactive material from low-level wastes before their disposal to the environment. This work has now progressed to the point that we may say, confidently, that radioactive wastes can be disposed of with complete safety and at a cost that contributes but little to the price of nuclear power.

The hydrofracture process for waste disposal has been under development for several years. In 1966 it was reduced to practice; and for the first time anywhere, intermediate-level radioactive waste was disposed of routinely and permanently. This was accomplished through two major changes in the waste system.

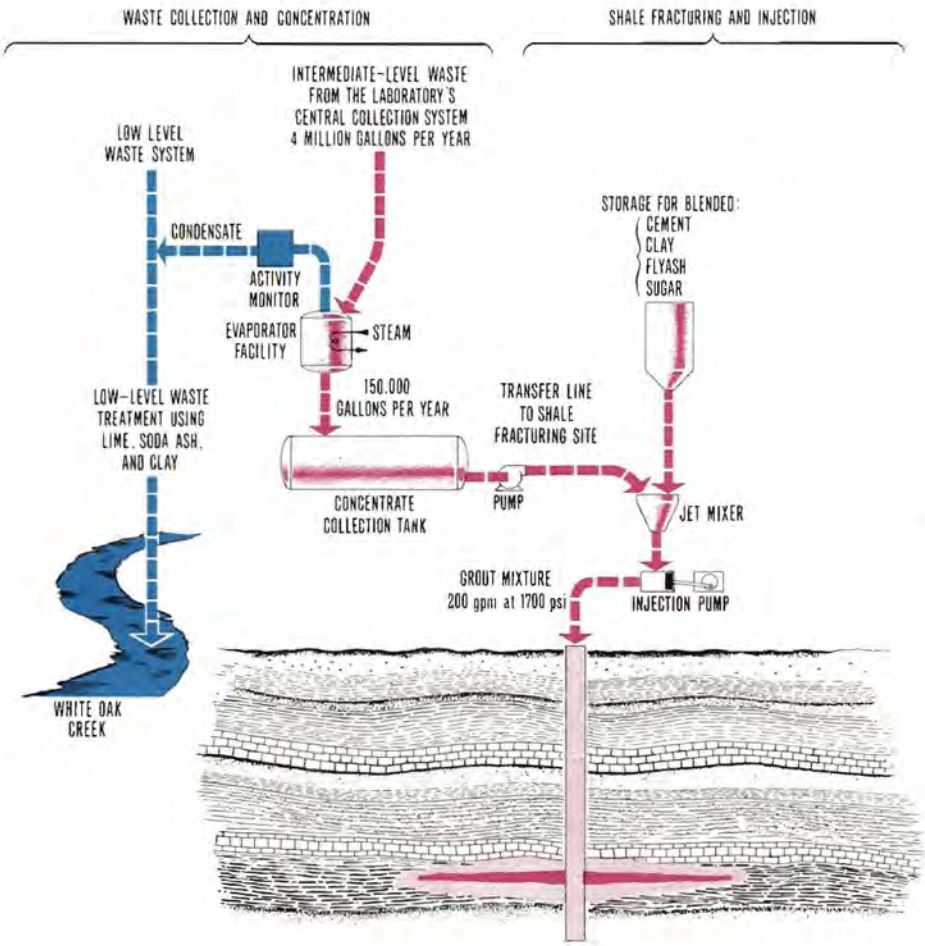
One was the addition of an evaporator to reduce the volume of waste. The evaporator is a steam-heated single-stage unit that has a maximum output of approximately 650 gal/h. At the maximum evaporation rate, its decontamination factor is 10^5. The waste condensate from the evaporator is sufficiently free of activity to permit its discharge to the environment with little further treatment. The evaporator is provided with automatic safety devices that make possible unattended operation three-fourths of the time. In the other change, the pilot plant used for experimental deep-well disposal of waste in hydraulically fractured shale was upgraded to permit its use for routine disposal of the evaporator-concentrated wastes.

The Laboratory generates about 4,000,000 gal/year of intermediate-level waste. The evaporator will reduce this volume to about 150,000 gal. The disposal of the concentrated waste into the deep shale will be made in 80,000-gal batches. By the end of 1966, 62,000 gal of concentrated waste containing 20,000 curies of activity, mainly cesium-137, had been disposed of permanently by the hydrofracture technique. A conservative estimate, based on an analysis of possible mechanisms of failure of the overlying rock, places the operating life of ORNL's first hydrofracture well at about

Demonstration of the disposal of highly radioactive solid wastes in a salt mine in Lyons, Kansas, continued during the past year. The radiation dose to the salt reached more than 5×10^8 rads with no indication of any direct radiation effects that would adversely affect a disposal operation. A shipping cask, containing about 1,500,000 curies of radioactivity in seven separate cans, is shown being placed in position at the waste-charging shaft. The cask was then tipped to a vertical position over the shaft, and the cans were lowered, one at a time, down to the mine level, 1000 ft below ground. This handling operation, which was carried out safely, showed that the disposal method is both safe and practical.

15 years. When the capacity of the old well is exhausted, a new well can be drilled beyond the outer edge of the grout-filled fractures and a new series of injections started.

The success of the hydrofracturing process has permitted the Laboratory to discontinue a 12-year-old practice of disposing of liquid waste in a series of seepage pits and trenches excavated in surface shale.



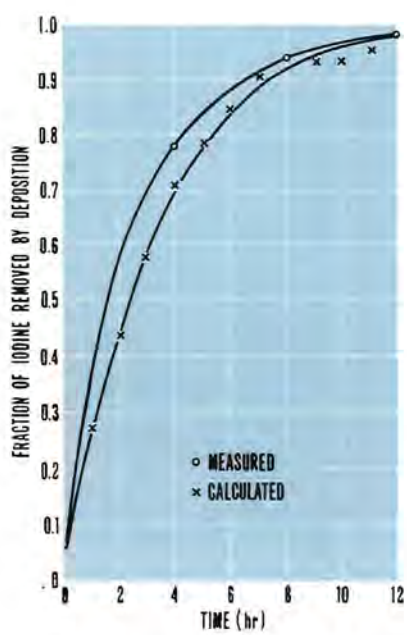
Disposal of intermediate-level wastes in hydrofractures at ORNL.

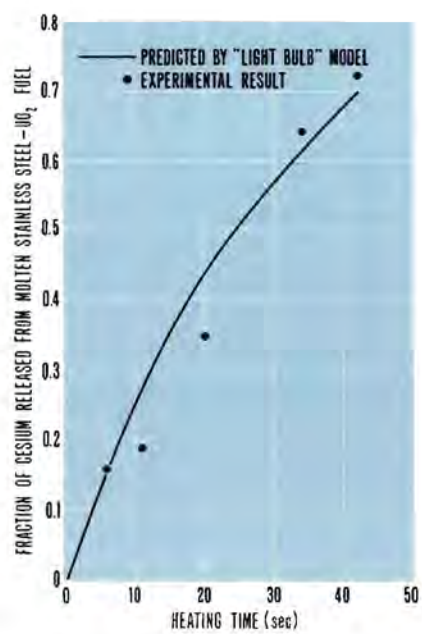
NUCLEAR SAFETY

In 1955 the Oak Ridge National Laboratory was asked to perform a few experiments to establish whether significant quantities of fission products would be released in the event that the coolant were lost from a nuclear reactor and the fuel became overheated. In the ensuing years, it became apparent that there are many processes by which fission products might be released from fuels: by diffusion on overheating, by vaporization on melting of the fuel, and by burning. The kind of fuel, cladding composition, atmosphere surrounding the fuel, and a host of other considerations are also important variables. In 1961, keeping pace with public concern on reactor siting and safety problems, the scope of the ORNL nuclear safety program was increased considerably, and since then it has grown rapidly. During 1966, about 100 people were engaged—full or part time— in nuclear safety research and development at the Laboratory. The research program may be described broadly as aiming to understand what happens if a nuclear reactor suffers an accident, assessing the consequences of the accident, and devising ways of ameliorating the consequences.

In the left drawing good agreement is shown between the calculated and measured amounts of iodine collected from the 1350-ft³ containment vessel in the Nuclear Safety Pilot Plant. In this case the gas phase contained steam; however, the model also applies in the absence of steam.

The "light bulb" model (right drawing) of fission product release gives good agreement between theory and experiment and permits the prediction of values that could only be obtained experimentally in the past.





Fission Product Release in Reactor Accidents

In water-cooled reactors, the kind most common at present in the United States, loss of coolant to the reactor core and eventual release of fission products from the overheated fuel is usually considered to be the most likely and serious potential accident. Until now all information on fission product release has been obtained experimentally, and no theory existed to explain it. The "light bulb" model of fission product release from overheated reactor fuel was developed to fill this gap. The theory, which is based on Raoult's and Henry's laws, takes its name from early work in the development of the incandescent lamp, in which the evaporation of the tungsten filament is described. It assumes the existence of a gas boundary layer surrounding the fuel and that the diffusion of the fission products through this boundary layer is the rate-limiting step in fission product release. The model describes the vaporization of fuel material, as well as fission products, and has been tested with data from several sources.

When fission products are released in an accident, it is important to know something of their behavior. How far do they travel? How do they behave physically and chemically? Many experimental programs are under way to answer these and other questions empirically, but there is still a need for basic understanding and prediction. Simple mathematical models have been derived to express the plateout behavior of iodine following a reactor accident. Two cases were considered: one assuming the presence of steam; the other, the absence of it. With no steam, relationships expressing the iodine concentration as a function of time were developed in terms of mass transfer coefficients, surface-to-volume ratios of containers, and surface characterization parameters describing the degree of iodine sorption on partially covered surfaces.

In the presence of condensing steam, there is bulk flow of steam toward the cooler walls. It was assumed that the iodine and the steam condense together, yielding a liquid of the same composition as the gas phase. Mathematical relationships were derived to express the concentration of iodine in the gas phase in a containment vessel as a function of time, surface-to-volume ratio, flux of condensing steam, and steam concentration.

The availability of these theoretical models of fission product release and transport will aid greatly in predicting the consequences of a loss-of-coolant accident and in correlating experimental data obtained in different facilities.

Ignition of Charcoal Adsorbers by Fission Product Decay Heat

Charcoal adsorbers are used in many current and proposed reactor safety systems for the removal of iodine from the containment system atmosphere. In the event of a nuclear accident in which fission products are released to the containment system, the adsorbers may be loaded with large quantities of short-lived fission products, as well as iodine. Most of the iodine and the other fission products will be retained near the entrance face of the charcoal adsorber, and the decay of these fission products will produce a large amount of heat. Irregularities in the adsorbing surface and in the fission product concentration in the inlet air stream to the charcoal trap could

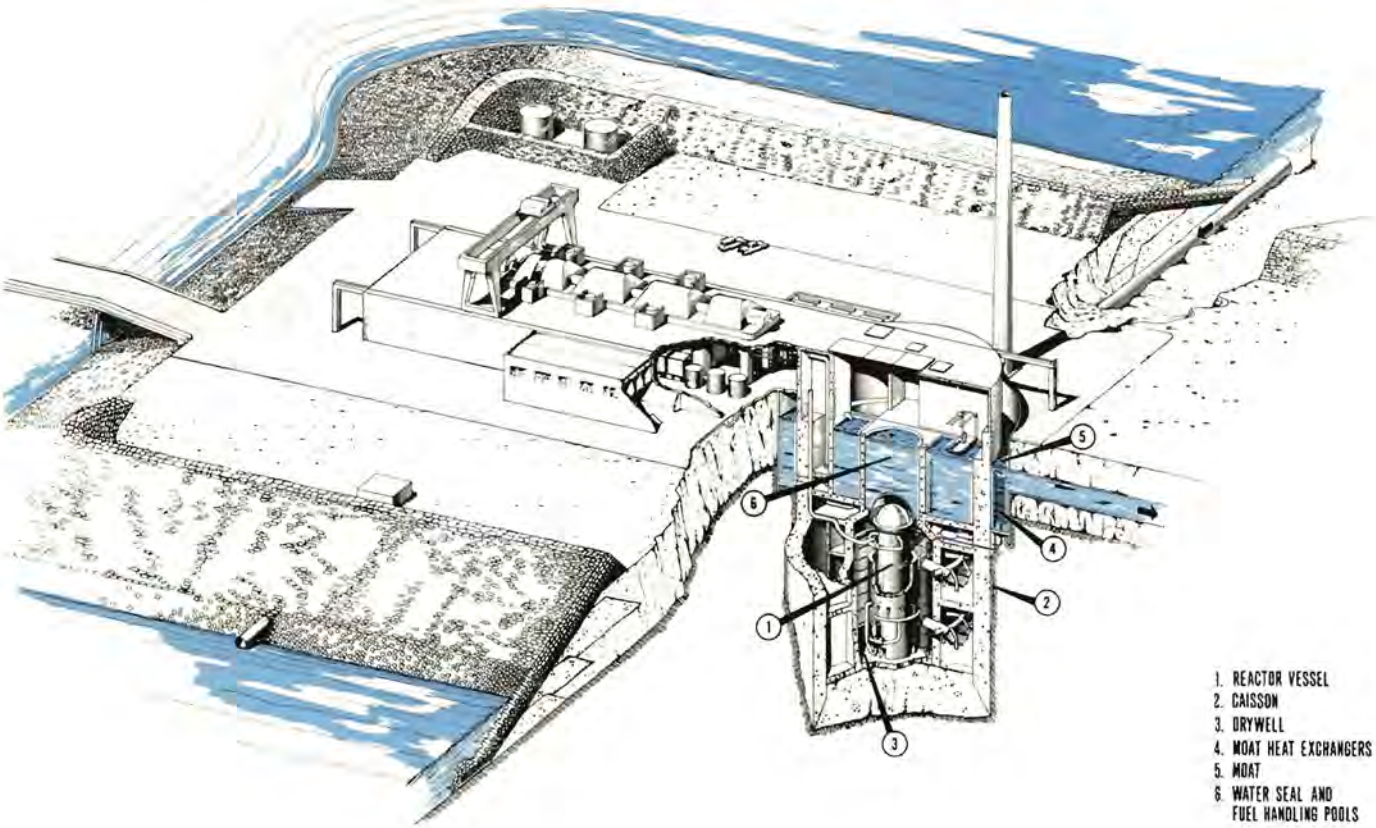
result in localized hot spots in the bed. Should this be the case, ignition of the charcoal bed could occur. In-pile experiments were performed to study hot-spot effects under conditions simulating those in a charcoal adsorber after a reactor accident. Although the charcoal adsorbers in these experiments were loaded with up to three times as much radioactive iodine per unit area of face as would be expected in the adsorbers for the High Flux Isotope Reactor or the New Production Reactor, there was no evidence of a hot-spot effect. In all cases the ignition temperature of the charcoal tested was increased by the presence of fission products.

Underwater Caisson Containment for Offshore Siting of Water-Cooled Power Reactors

A direct approach to the problem of locating power reactors near populated areas is the use of underwater caisson containment. This approach would assure greater safety and would entail less cost for power transmission. Underwater caisson containment is especially attractive for those cities which have available cooling water, are near bodies of water where offshore artificial islands could be constructed, or are faced with the presence of an obsolete power plant whose site could be used for an underwater nuclear installation.

The use of underwater caisson containment structures offers several safety advantages: an assured, positive external containment pressure; a virtually unlimited heat sink; and a potential for safe dispersion of radioactivity in the event of an accident.

In a design study, the caisson containing a Dresden unit II boiling water reactor was "sunk" in an artificial island, approximately 1/2 mile offshore in about 30 ft of water. If, during operation, the hydrostatic head should fall below a prescribed minimum, rupture disks would fail, allowing the ingress of seawater. It is estimated that this type of containment would have leak rates between 1/10 and 1/100 of those for a Dresden unit II with conventional containment.



Biological Sciences

Work in the biological sciences at the Laboratory is centered in the Biology and Health Physics Divisions. The work in the Biology Division has emphasized the action of radiation and, more recently, of chemicals on living things at various levels from the whole animal to the molecular. The investigations are designed not only to explore these specific problems but also to contribute basic knowledge in such fields as biophysics, biochemistry, genetics, immunology, experimental pathology, and developmental biology. Important recent developments are cooperative programs with the National Institutes of Health and the National Aeronautics and Space Administration. There has been an increasing trend for collaboration with the chemical technology and engineering specialists of the Laboratory in solving problems requiring large-scale isolations and containment.

The work in the Health Physics Division has as its purpose the protection of man and his environment from unwarranted radiation exposure. Because of this wide-ranging charter, the research activities extend from fundamental studies of the interaction of radiation with matter to dosimetry, to transport and accumulation of radioactivity, to effects on the biosphere, and to engineered systems to prevent the spread of radioactive materials.

Typical examples of these various kinds of work are presented, but they can give only an incomplete picture of the broad scope of the biological work at the Laboratory.

BIOLOGY

Studies on Plant Development

Systems in which cell growth and division can be separated are being used to study plant development in this Laboratory. Growth of higher plants involves concurrent expansion and division of cells. In lettuce at super-optimal temperatures, even though the embryo does not expand, the normal pattern of cell divisions can occur without cell growth. In a converse system, a chemical has been used to prevent nuclear division and cell division in wheat without preventing subsequent cell growth and root development. Cells that normally would have divided replicate their chromosomes and thus become "labeled" by their polyploidy; that is, they have a multiple of the initial chromosome number and can be recognized microscopically. Because of their form and location, certain groups of such cells represent the earliest detectable stages in the formation of a new branch root without the usually accompanying cell divisions. Thus in the initiation of new organs, the notion that development proceeds by means of the addition of cells as building blocks is untenable.

Genetic Control of Cell Division in Bacteria

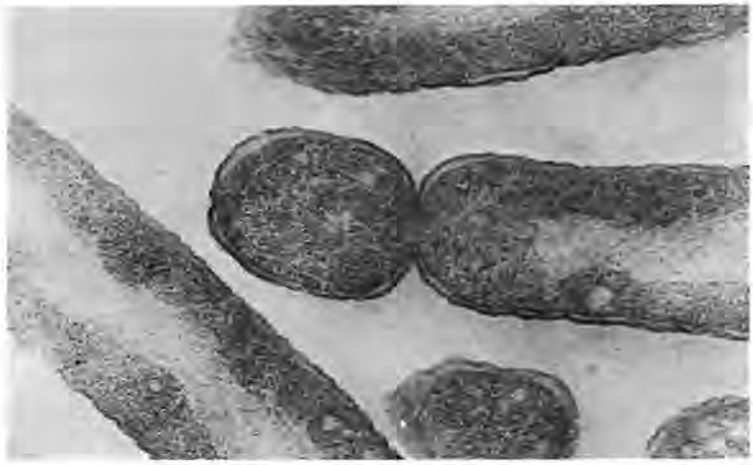
We have isolated and are studying some mutant strains of the bacterium *Escherichia coli* that have unusual patterns of growth and cell division. Experiments performed with these organisms are providing new insights into the genetic and physiological control mechanisms that play a role in normal cell growth and division.

Escherichia coli is a small, rod-shaped bacterium which divides by constriction someplace near the middle of the growing cell. In one mutant strain, the radiation sensitivity of the cell division process has been greatly increased. After exposure to low doses of radiation, cells of this mutant can no longer divide but continue growing in length for many hours. This results in the formation of very long, filamentous structures that may be 200 times the normal cell length. Unless they are treated in very special ways, these filaments continue growth, eventually lyse, and die. If, however, the growing filaments are treated with an extract of normal bacteria, they begin to divide again. Isolation and purification of the components in the cell extract responsible for the reinitiation of cell division is being undertaken. It is possible that these extracts contain some part of the normal cell division mechanism in this bacterium.

A second mutation, which seems to involve a gene in the same region of the chromosome, also affects the cell division process. Organisms con-

taining this mutant gene tend to undergo division very close to one pole of the rod-shaped cell. This abnormal placement of the division process results in the production of a very small cell that has unique properties. The small cell is metabolically active but cannot divide. It contains ribonucleic acid and protein but no detectable amounts of deoxyribonucleic acid. It may be considered to be a sampling of the cytoplasm of the bacterium without nuclear contamination. The misplaced cell division that gives rise to the small cells seems to be superimposed on the normal cell division mechanism. Both kinds of division go on simultaneously.

A third mutation of interest to us results in a culture that has lost the normal control of size and shape characteristic of the bacterium *Escherichia coli.* The cells of cultures containing this mutation appear in a variety of bizarre forms, very few of which resemble the rod-shaped wild-type organism. These bizarre forms can, however, undergo division, in spite of the fact that many of their internal structures have been put into novel geometric relationships. The study of these mutants by genetic and biochemical techniques is yielding valuable information regarding cell growth and division.



An electron micrograph of a mutant cell of the bacterium Escherichia coli *undergoing an abnormal division that yields one normal cell and one small cell lacking genetic material.*

The Photoreactivating Enzyme

When cells, viruses, or purified deoxyribonucleic acids (DNA) are irradiated with ultraviolet light, dimers are formed between adjacent pyrimidine bases in the DNA. These dimers may be lethal, unless they are repaired. One method of repair in cells, called photoreactivation, involves a light-dependent enzyme which does its job by converting the dimers back to the original pyrimidines, as shown by our earlier work. The photoreactivating enzyme has now been purified almost a millionfold, from about 1 ton of yeast, so that we may investigate details of its chemistry and mode of action. Photoreactivating enzyme has been found in a wide variety of biological material, including mold, sea urchin, frog, crab, insect, and bird. This enzyme occurs in many cells that in nature are never exposed to ultraviolet light, and thus it is probable that the enzyme has another function in the cell in addition to splitting pyrimidine dimers. An active search for this second function is being carried on.

Transfer Ribonucleic Acid

The large-scale biochemical separations program, a joint venture between biochemists, chemists, and engineers, has produced relatively large quantities of specific transfer ribonucleic acids (tRNA's). These tRNA's serve an important function in protein biosynthesis, especially since they accept specific amino acids from an activated complex bound to activating enzymes (aminoacyl-tRNA synthetases).

These separations have been made possible by the development of a reversed-phase chromatography system that fractionates the tRNA's into individual species of molecules. The availability of relatively large quantities of specific tRNA's and the utilization of reversed-phase fractionation as an analytical procedure have allowed experimentation on the mechanisms and control systems of protein biosynthesis.

One area of research concerns the identity and location of the synthetase "recognition site" in the tRNA molecule. The tRNA has been hydrolyzed to residues of smaller chain length that still contain the synthetase recognition site. A series of these residues have been obtained that allow us to approximate the position of the recognition site in the molecule. Future experiments will be directed toward identifying the chemical structure of the recognition site.

By using the reversed-phase columns to analyze bacterial RNA, we have established that when *Escherichia coli* (bacteria) are infected with a bacterial virus (bacteriophage), several new species of tRNA appear that were either not present or present in very small amounts in uninfected bacteria. These new species of tRNA appear to be involved in a late stage in the synthesis of the complete bacteriophage particle. These studies are basic to the question of how viruses multiply in infected living cells.

Virus Nucleic Acids as Carriers of Genetic Information for Mammalian Cells

Recent work of the Laboratory has indicated that functional genetic information may be introduced into mammals by the deoxyribonucleic acid (DNA) contained in passenger viruses. Passenger viruses are viruses which, upon infecting living organisms, including mammals, produce no detectable lethal or neoplastic effect upon the infected cells, though the cell "families" continue to have the genetic information contained in the virus nucleic acid. It was found that the Shope papilloma virus induces a unique enzyme in the skin of rabbits. This enzyme is an arginase that splits arginine into ornithine and urea; it is not present in the normal, non-virus-infected skin cells. In rabbit skin this enzyme is associated with the occurrence of a tumor. If, however, rabbits are inoculated in such a way as not to infect the skin (subcutaneous or intravenous injection), no tumors appear. That large numbers of other cell types are infected is demonstrated from the very low concentration of arginine in the blood of these animals.

Since the arginase indicates the presence of this virus, the levels of arginine in the blood of humans who were working or had worked with the virus were determined and compared with those of people who had had no known contact with it. About half the people who had had contact with the virus were found to have arginine levels low enough to be readily separated from the normals.

In addition, about three-quarters of the people who had had contact with the virus, like the rabbit, had antibodies in their sera against the enzyme. No discernible symptoms were associated with the low blood arginines in either rabbits or man.

It is thus apparent that the information carried by passenger viruses may be used to supplement the genome of rabbits and man. Such information will be of particular value in the therapy of genetic deficiency diseases such as phenylketonuria. In the future, it is possible that synthetic genetic information might be tied to virus nucleic acid and transferred to mammals using passenger viruses as vectors.

Hormonal Regulation of Enzyme Synthesis

Metabolism in a living cell must be rigidly controlled, and it is now apparent that the major method of control is through regulation of the activity of intracellular catalysts, or enzymes. In higher forms of life, this regulation is governed by the various hormones, which coordinate the activities of different tissues and organs to permit the proper functioning of the organism.

The mechanism by which hormones act to regulate the amount of key enzyme proteins in tissues is being studied by biochemists at the Laboratory. Several years ago we found that the adrenal steroid hormone hydrocortisone (the active form of the well-known cortisone) regulates metabolism in the liver by increasing the rate at which key enzymes are synthesized. Since enzymes are proteins, this result points toward a role for hormones in regulating the DNA-RNA-protein synthetic systems, which together form the "readout" of the genetic information passed from generation to generation. Further study of this effect of hydrocortisone has shown that the hormone is important in regulating the formation of RNA ("transcription") and that it may also play a role in the process by which the information in RNA is utilized to form the enzyme protein ("translation").

Recently we have found that other hormones also act to regulate the synthesis of the same key enzymes that are influenced by the adrenal steroids. For example, the pituitary hormone needed for normal growth (somatotropin or growth hormone) will completely stop or repress the synthesis of tyrosine transaminase, a liver enzyme whose synthesis is increased by hydrocortisone. When synthesis of the enzyme ceases, the amount available for catalysis of tyrosine metabolism drops to very low values, because the normal degradation of the enzyme is no longer matched by an equivalent rate of synthesis.

According to our current ideas about the action of hormones, the liver should contain a specific protein that combines with hydrocortisone to form a complex; this complex may be the active form of the hormone. We are developing a chromatographic procedure for isolating the binding protein, using hydrocortisone chemically bound to an inert support but with the significant portions of the hydrocortisone molecule free to react. When liver extracts are passed over this material, a small amount of protein is bound; it can then be eluted by detergents, which break the interaction between the hormone and the protein. This protein is being characterized, and its role in the hormonal regulation of enzyme synthesis will be studied.

Operation of a device in which rat livers are continuously bathed in circulating blood. Hormones are added to the blood, and their effects on enzyme synthesis in the liver are analyzed by biochemical techniques.

A new method of animal caging. A filter-top animal cage, originally invented by Elizabeth Kraft of Oak Ridge Associated Universities, has been investigated and put into use at the Laboratory as an important technique in raising and maintaining research animals. The filter top or cap allows free exchange of air between the cage and its surroundings but prevents the spread of microorganisms across the filter barrier. If a cage accidentally does become contaminated, the filter cap aids in the prevention of the spread of diseases from cage to cage. Three years' experience has been acquired with this method of caging. Extensive monitoring procedures for infectious agents, such as pathogenic bacteria, viruses, and parasites, have been carried out. Only one contamination has occurred, and it was quickly eliminated from the experiment by the removal of infected animals. The filter-top concept has been extended to larger research animals and constitutes a revolutionary development in laboratory animal medicine.

Radiation Response of the Human Testis

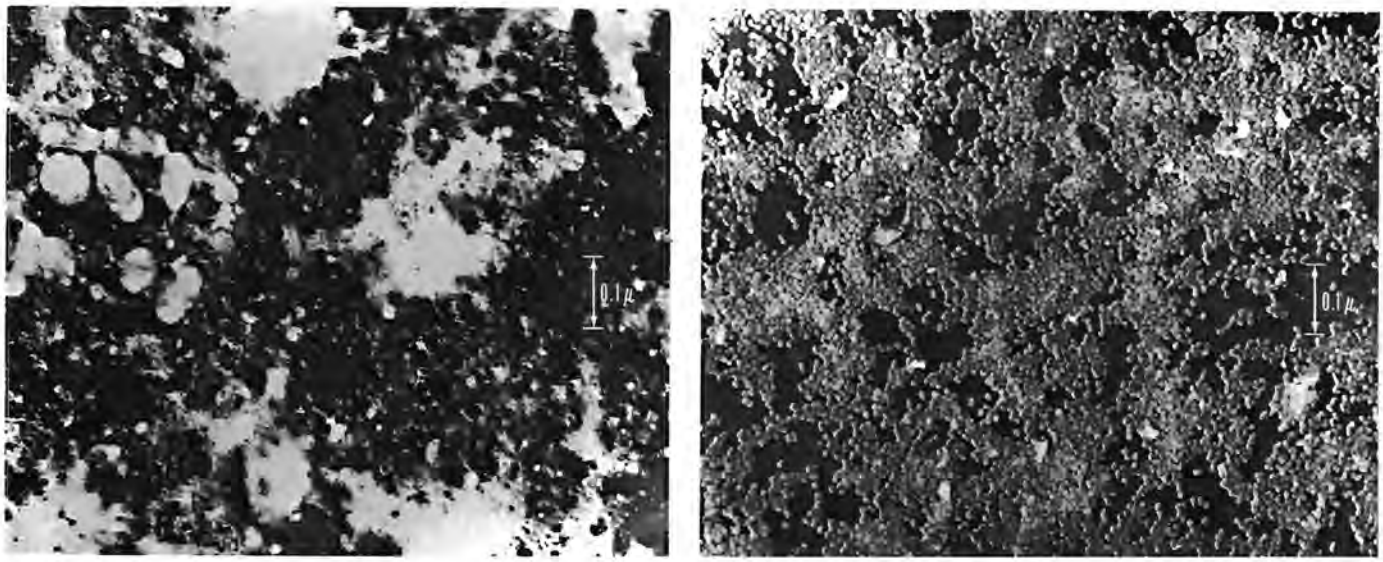
An intensive investigation of the radiation response of germ cells in mice has been under way in Oak Ridge for many years. A very high sensitivity, as measured by cell survival, has been demonstrated for certain stages in the development of both male and female germ cells. In contrast, late stages in the male and nearly mature eggs in the female show neither morphological changes nor reduction in number after high radiation exposures. Also, some of the earliest stages in the male are radiation resistant.

Recently an opportunity has arisen for making similar studies on irradiated human testes. Slides of biopsies from control and irradiated testes prepared in the Pacific Northwest Research Foundation have been evaluated by techniques developed at Oak Ridge.

As expected, the basic response in man is the same as in other animals, with high resistance of late stages and broadly distributed sensitivity of the earliest stages. Man appears to be more sensitive than mouse when the comparison is based on the earliest germ cells, the spermatogonia.

This comparison, however, must be evaluated in the context of differences observed between the two species. Depletion of spermatogonia in the mouse is primarily a function of cell killing, whereas in man other factors, and especially continued differentiation of the more primitive spermatogonia, also are important. Furthermore, differences in the requirements for spermatogonial differentiation appear to govern the rapid regeneration of the mouse testis as compared with the slow recovery in man. These difficulties emphasize both the caution that is required in extrapolating data on experimental animals and the need for more data on man.

Investigator operating equipment being used in the determination of three-dimensional structures of large molecules of biological importance.



Comparison of flu vaccine before and after purification by centrifugal techniques. Original vaccine shown at left; vaccine purified by use of the Oak Ridge B-IV rotor is shown at right. (Photographs by Dr. C. B. Reimer, Eli Lilly and Co.)

Many Aging Processes Unaffected by Germfree Environment

As medical science has applied its knowledge to the disease problems of man, especially infectious diseases, life expectancy has continually increased. In the development of cancer and other diseases associated with aging, however, the role played by environmental microbes remains largely unknown. One reason is that the investigation of this question requires animals in which the presence of microorganisms can be regulated at will.

To obtain microbially defined animals, full-term fetal mice were aseptically removed from the sterile uteri of their dams and raised in a sterile environment. These "germfree" mice are the most adequately defined animals available at present, from the standpoint of microbial flora. Germfree mice of several strains are being raised at the Laboratory and are being studied with respect to the long-term changes in irradiated and unirradiated individuals to determine whether such changes are influenced by the microbial environment.

Preliminary results with two mouse strains have shown that, on the average, germfree mice survived up to 200 days longer than their conventional counterparts. This difference in survival appears to be associated with the absence of infectious diseases in the germfree mice and tends to diminish in the last third of life, where senescent changes predominate. Thus, although the microbial flora and fauna may alter the form of the survival curve and may increase the mean survival time, they do not seem to increase the maximum survival time. The incidence of tumors does not seem to be different in germfree and conventional mice, except for radiation-induced myeloid leukemia, which is common in irradiated conventional mice of one strain but has not been seen in germfree irradiated mice of the same strain.

The greater number of germfree animals that live to "old age" and the control of their microbial environment, which prevents the infectious epidemic death of valuable aged animals, make the germfree animal an especially important tool for the study of aging processes.

HEALTH PHYSICS

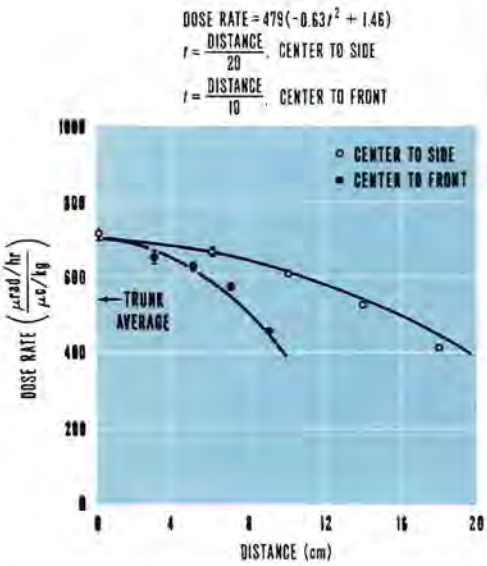
Capture and Scattering of Low-Energy Electrons in Gases

Knowledge of how low-energy electrons interact with atoms and molecules is very important in understanding radiation chemistry and radiation damage. This knowledge is also important in learning how to protect man from radiation injury. The several types of possible interactions are elastic collisions, inelastic collisions (which cause rotational, vibrational, or electronic excitation), and the formation of negative ions by electron capture. This capture process is thought to play an important role in biological processes such as carcinogenesis, energy transfer in mitochondria, and radiation toxicity.

Our experimental studies of elastic scattering and diffusion of electrons in gases have been compared with theoretical calculations; we found that the scattering by a polar molecule can be computed from its permanent dipole moment. We also found that processes involving electron capture may contribute substantially to the production of rotational and vibrational excitation.

A recently developed technique is being used to study the excitation of gas molecules by measuring the loss of energy by electrons that collide inelastically with the molecules. New and intense energy loss resonances at energies below the first excitation potential were discovered in benzene and several of its derivatives. The mechanism is apparently the capture of the electron to form an unstable negative ion.

A time-of-flight mass spectrometer has been modified for measuring the lifetimes of unstable negative ions formed when electrons are captured by gas molecules. For large polyatomic molecules the mean lifetime of the negative ion may be comparatively long—as much as several microseconds. It turns out that the product of the mean lifetime of the ion and the cross section for its formation by electron capture is correlated with the electron affinity of the parent molecule. Through this correlation, the electron affinities of a number of organic molecules have been estimated from the measured lifetimes and cross sections.



A newly developed computer code makes it possible to use a realistic geometric simulation of man's body and his organs and to ascertain how dose varies in different parts of the body from an internally deposited gamma emitter. Dimensions of the model may be adjusted to approximate any body size. Dose rates for any positions within the body are now obtainable. Average gamma dose rates from center to surface from uniformly distributed cesium-137 are shown.

Movement of Radioactive Cesium in a Plant and Animal Community

The variety of forest types and soils in the Oak Ridge Reservation provides favorable opportunities for controlled experiments on the movement of chemical elements in ecological systems. The Laboratory's experiments on the transfer of radioactive tracers between the various ecological compartments of forest systems—soil, vegetation, surface litter, animals, and microorganisms—are leading to a better understanding of the factors involved in maintaining forest productivity and also those involved in the spread of radioactive contamination.

In May 1962 the tulip poplar trees in a plot measuring 20 by 25 m were inoculated with radioactive cesium-137, introduced by means of chisel cuts through the bark. This area is typical of the deciduous forests of East Tennessee, in which the tulip poplar is one of the most abundant trees. Cesium-137, being produced in relatively high yield in uranium fission, is important in waste disposal and in fallout. Since most of the compounds of cesium are soluble in water, it moves fairly rapidly from one compartment of the ecological system to another; however, it is rather strongly adsorbed by certain components of soils.

The changes in the distribution of the cesium-137 in the forest from season to season and from year to year are being measured in great detail. At first the radiocesium moved rapidly into the forest canopy, but much of it was apparently withdrawn back into the tree trunks and into the roots before the leaves fell in the autumn. More radiocesium reaches the soil from the tree roots than through rain and fall of leaves. Removal of radiocesium from the plot appears to occur principally through leaves falling outside the area, rather than through movement of animals, since the total amount of radiocesium in the animals is small.

The interpretation of the results of the tracer experiment has been assisted by the development of mathematical models whereby the movement of the radiocesium can be simulated with a computer. The computations indicate that between the fifth and the tenth year of the experiment a nearly steady state is reached in which most of the radiocesium is held by the soil but a small percentage is continually recycled through the living parts of the ecological system.

Radioecologists from the Oak Ridge National Laboratory collecting leaf samples and insects in a forest inoculated with cesium-137. The lift truck and the tower visible in the left background help in sampling from tall tulip poplars—among the most productive trees in the eastern deciduous forest.

AWARDS

Everitt P. Blizard, Director of the Neutron Physics Division at the time of his death, received posthumously the Elliott Cresson Medal from the Franklin Institute of Philadelphia for his pioneering research in radiation shielding.

Alexander Hollaender was cited by the U.S. Atomic Energy Commission for outstanding service in America's atomic energy program, specifically for having created, in the ORNL Biology Laboratory, one of the world's major centers for research in radiobiology. Dr. Hollaender was Director of the Biology Division until his retirement at the end of the year. He is presently a Senior Research Advisor of the Division.

Alston S. Householder, Director of the Mathematics Division, was given the honorary degree of Doktor der Naturwissenschaften Ehrenhalber by the Technische Hochschule of Munich, in appreciation of his outstanding contributions to the development and promotion of numerical mathematics.

W. F. Gauster was awarded the Great Silver Insignia by the Federal Republic of Austria. Dr. Gauster is Director of the Engineering and Magnet Laboratory of the Thermonuclear Division.

H. W. Morgan received the honorary degree of Doctor of Science from Fisk University for his contribution in the field of chemical physics and the dedication of his talents to the advancement of Fisk University and of the Fisk Infrared Institute. Dr. Morgan is in the Atomic and Molecular Spectroscopy Department of the Physics Division.

G. H. Cartledge received the Willis Rodney Whitney Award, presented by the National Association of Corrosion Engineers, for his public contributions to the science of corrosion. Dr. Cartledge is a consultant in the Chemistry Division.

Physical Sciences

Advances in science will always depend on *individual* intellectual contributions, but our scientific society has passed beyond the stage at which the individual can contribute most effectively by working in isolation. The increasing complexity of the problems we are trying to solve, and the corresponding increases in the complexity of the mathematical, mechanical, and electronic tools we must use in solving them, tend to favor organizations in which many scientists, representing many disciplines, can work either alone or in groups as the problems dictate. In large research centers, the availability of extensive libraries, active information centers, up-to-date computing facilities, expensive instrumentation, and supporting services makes it possible for one man, or a team of men representing several disciplines, to test and develop new theories with a power and precision never before possible. The Oak Ridge National Laboratory, as a large national research center, contributes in such a way to the rapidly advancing field of physical science.

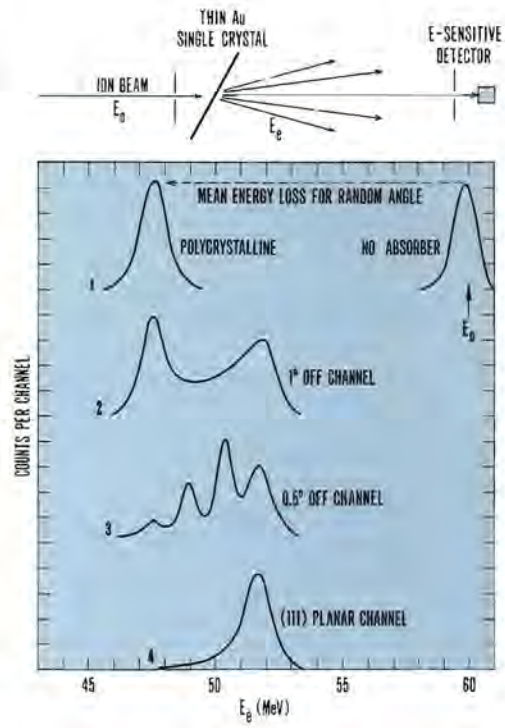
PHYSICS

The emphasis in physics research at the Laboratory is broad in scope but peaked on the interface between pure and applied. Fundamental physics research covers the gamut from elementary particles to nuclear structure to the structure of solids to stellar nucleosynthesis. The skills, tools, and interests represented are as diverse as those found in any laboratory, and the responsiveness of the members of the basic research groups to the needs of mission programs is a distinct and valuable asset.

An area of primary concern is nuclear structure. Our studies include nucleon-nucleon scattering, which directly relates to the nuclear force, and nucleon-nucleus interactions involving both simple and complex nuclei.

Also, and importantly, the new knowledge gained continues to illuminate other disciplines. As examples, studies of neutron capture reactions helped pinpoint the mechanisms by which the heavy elements in our solar system were formed; studies of the passage of energetic heavy ions through crystals have given an entirely new view of crystal structure. Although nuclear structure research, per se, is emphasized, it is by no means exclusive. For example, all classes of solids – metals, alloys, semi- and superconductors, crystals, ceramics, and organic polymers – are studied with a variety of experimental and theoretical techniques.

Underlying all of the research activities is a closely entwined program of development of new tools and techniques, for in physics, just as in so many fields, we cannot do tomorrow's jobs with yesterday's skills and tools. For the 1966 report, as in 1965, we do not attempt to review all of the research programs; instead we discuss several examples briefly.

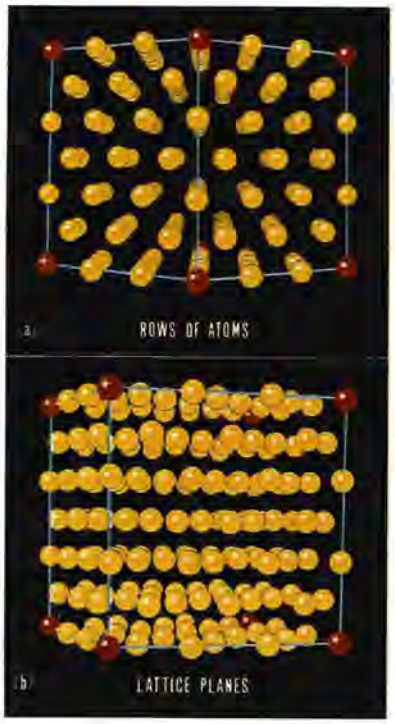


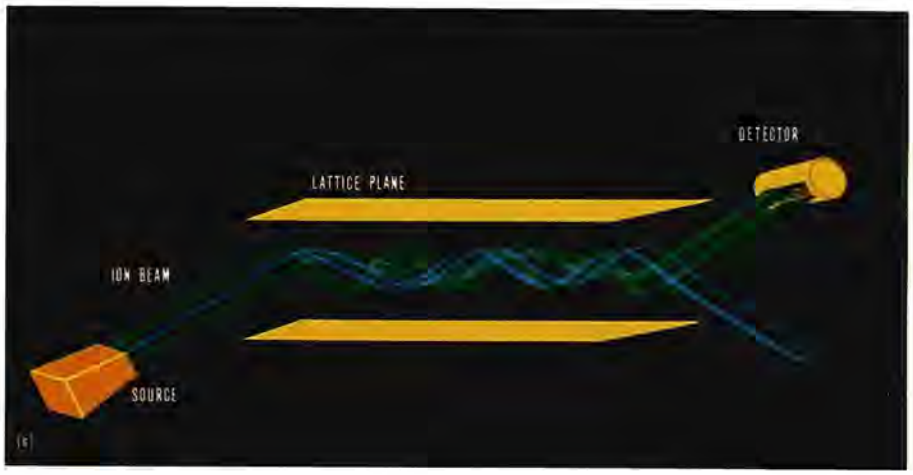
In the channeling experiment a highly directional beam of heavy ions passes through a thin single crystal of gold. The energy spectrum of the transmitted ions is measured with high resolution. When the crystal is oriented off axis (1) the transmitted ions have a simple spectrum. When the ion beam is directed precisely down a lattice plane the ions lose less energy (4) but still have a relatively simple spectrum. When the crystal axis is very slightly off line the transmitted beam becomes complex in energy (2 and 3). This complex spectrum yields fundamental information on interatomic potentials.

Channeling and the Structure of Crystals

In our annual report of 1965 we reported experiments in which it was noted that beams of heavy ions lose less energy and cause much less damage when they strike a thin crystal if they are directed exactly along "channels" of the crystal lattice. During 1966 the phenomenon of channeling was the subject of additional experiments that yielded some fascinating discoveries.

For several years energetic heavy ions – positively charged atoms of bromine or iodine, for example – have been produced in the Oak Ridge Tandem Van de Graaff accelerator for a variety of experiments. One such experiment was the measurement of their rate of energy loss in thin foils of materials. The principal energy loss mechanism is through collisions with electrons. Out of this work grew interest in comparing the energy loss produced when the ions travel parallel to channels or corridors between rows of atoms in a single crystal with the energy lost when they travel in a random direction. When traveling down a corridor the ions collide with





In a crystal lattice (a), rows of atoms form a lattice plane when rotated to a certain position (b). In (c) a parallel beam of ions from the source (left) enters the thin crystal at a slight angle to the lattice planes. The rows of atoms form an electric barrier and cause the ions to "rattle" down the lattice. Those that enter near the axis of the plane (lower green curve) feel a small restoring force and have a long period of motion. They emerge at the proper angle to be detected (right). Ions that enter farther off axis (blue curve) have a shorter period of motion due to stronger restoring forces and emerge from the crystal at a different angle, missing the detector. At still greater distances off axis the period is still shorter and the emerging ions again strike the detector. The latter ions lose more energy since they travel closer to the rows of atoms, encountering more electrons. Thus it is that the detector sees only those ions that enter the crystal at certain distances from the center of the lattice planes and the emerging ions have different energies, depending on the details of their trip through the crystal.

fewer electrons and nuclei and thus lose less energy over a given path length. By examining, at increasingly higher resolution, the energy distribution of the ions that pass through a uniformly thin gold crystal about 1000 atoms thick, the investigators found that, if the incident ion beam is almost but not quite parallel to certain lattice planes, the ions emerge in discrete bands of energy, implying that some mechanism acts to quantize the energy loss. The size of the newly discovered "quantum" energy loss is thousands of times the average energy lost in colliding with an electron.

Several suggested sources of this "quantization," such as effects due to fluctuations in the degree of ionization of the heavy projectiles, were investigated and found not to be the cause. One of the investigators suggested a basic mechanism that made the various observed effects all fall into a beautifully simple picture. His reasoning went as follows: The incoming ions and the detector are in line; thus in order to strike the detector the ions must emerge from the crystal *at the same angle that they enter.* Now if we plot trajectories of ions moving in an electric field (caused by the position-dependent density of electrons off the lattice axis) we see that there are certain restricted "zones" which, for a given angle of incidence, allow the ions to emerge parallel to their incident direction. With each zone there is a different average electron density encountered by the ion in passing through the crystal and consequently a different net energy loss. An important point is that the oscillation frequency is amplitude dependent, producing *anharmonic* motion, which in turn makes the observed energy spectrum of the transmitted ions sensitive to the details of the electric fields inside the crystal.

Thus we have, in a way, a new kind of supermicroscope that can reveal details of the distribution of electrons inside crystals. It is distinctly possible that this technique may be used to examine defects, thermal motions, and zero-point motions in some crystal lattice structures. In addition, we may gain a better understanding of how ions are slowed down in crystals, how radiation damage is produced, and the relative contributions of the nuclei and the electrons to the stopping power of crystals.

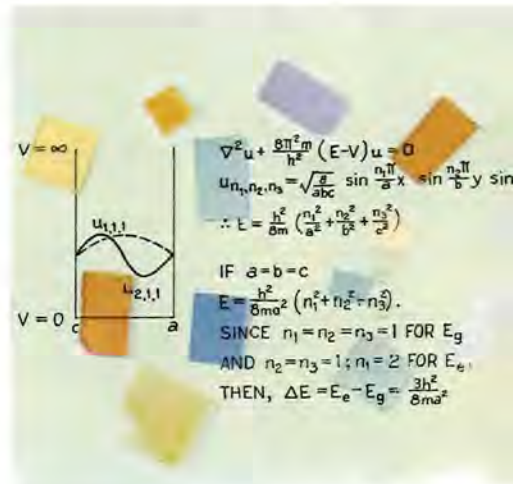
This series of experiments, which has resulted in the discovery of an entirely new phenomenon with broad implications, was made possible through the collaborative effort of specialists from different fields: nuclear physics, solid-state physics, metallurgy, and chemistry.

Color Centers and Lattice Defects in Ionic Crystals

Radiation-produced lattice imperfections in single crystals have been studied for many years. In transparent solids these defects absorb visible light, and this results in coloration of the crystals. The most prominent of these defects is the *F* center, an electron trapped at a negative ion vacancy. Investigations of *F* center production in alkali halide crystals, and hence our understanding of the radiation damage process, have been hindered by the lack of experimental reproducibility from one laboratory to another. Intensive research using high-purity potassium chloride crystals grown at the Laboratory has shown that the origin of this difficulty is trace impurities present in the specimens in uncontrolled amounts. For example, it has been found that as little as 6 ppm of lead nearly completely suppresses radiation coloration of potassium chloride by cobalt-60 gamma rays at room temperature. The absorption bands have been investigated theoretically, and the calculations are in agreement with measurements.

The study of defects, which has been so successful in irradiated alkali halides, is now being extended to the refractory oxides. It has already been found that fast electrons or reactor neutrons (energy above 1 MeV) are necessary to create *F* centers at a reasonable rate in magnesium oxide. The inability of x rays or gamma rays to produce defects and the much smaller yields obtained from high-energy electron bombardment indicate that the mechanism of radiation damage is quite different in these compounds from that in alkali halides. High-purity crystals will be needed to determine the influence of impurities, and steps have been taken to solve the difficult problems associated with purification and growth at ultrahigh temperatures (2800°C).

Some of the colors produced in normally transparent alkali halide crystals by gamma irradiation are shown below. The pretty colors result from defects produced in the crystals by the gamma rays. Studies of the coloration yield details about the defects. The equations in the background describe the effect and can be used to predict colors of different alkali halides after irradiation.



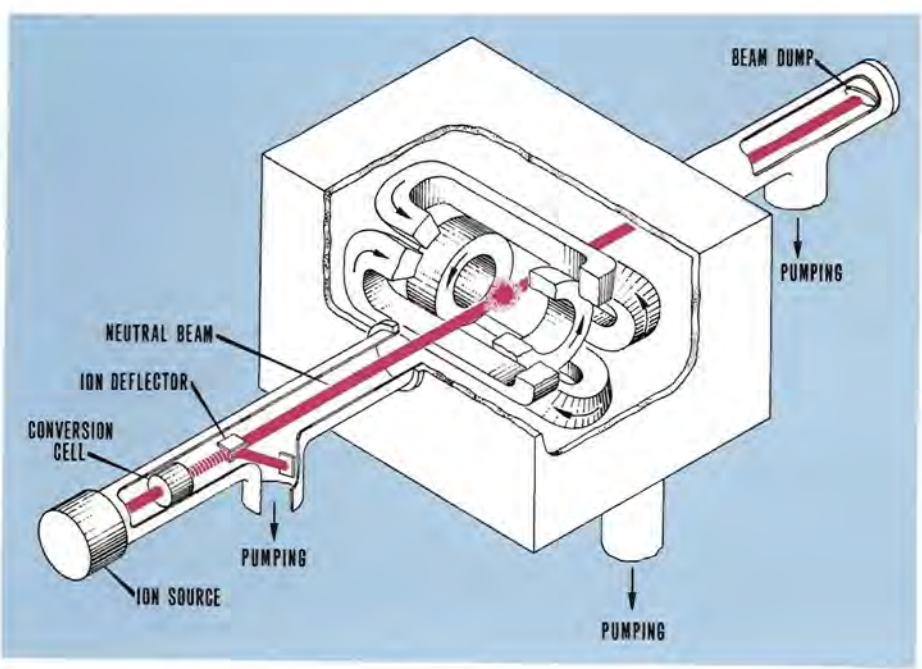


Diagram of new Oak Ridge experiment on the accumulation of a hot plasma in a "magnetic well" by use of a stabilizing target plasma. The ion source at left generates a steady current of H_2^+ ions, and these pass through a cell containing magnesium vapor. This converts most of the H_2^+ ions to hot neutral hydrogen atoms (H^0), and any particles that are not neutralized are swept aside. The H^0 beam penetrates the specially shaped magnetic field produced by a nest of coils bearing currents, as shown by the arrows, and strikes the target plasma in the center. Here some of the H^0 particles are caught, while the others pass on to the beam dump. The H^0 atoms that are caught are ionized by collisions in the target plasma and are held by the magnetic field so as to generate the desired experimental hot fusion plasma.

Generation of an intense collimated beam of 20-keV hydrogen atoms. A practically invisible beam of H_2^+ ions enters at the top and passes in the center of the picture through a cell containing magnesium vapor. As it enters it makes stray magnesium vapor glow with the blue light. On emerging below the cell, the atomic beam glows with the pink color of neutral hydrogen atoms. The beautifully collimated beam is about 3/4 in. in diameter, and its particle current is equivalent to about 1/5 A.

New Concepts in Overcoming Plasma Instabilities

In the field of controlled nuclear fusion, the main difficulty historically has been to hold in a magnetic field a body of deuterium that has a temperature of over 100,000,000° and almost paradoxically has a pressure of 100 atm even though surrounded by a vacuum. It is scarcely surprising that there are many known ways in which such a plasma can become unstable and disperse itself catastrophically. In 1966 a strong new concept for solving this basic plasma stability problem emerged from theoretical considerations that had been developing at Oak Ridge and elsewhere. The new concept is based fundamentally on an older Oak Ridge theoretical contribution, which suggested a shift of interest from the details of individual plasma instabilities to a more generalized interest in the energy sources that can drive them. Reduce the driving forces, the theory predicts, and whole classes of instabilities can never develop. The consequent simplification in the theoretical situation is tremendous: there are dozens of known plasma instabilities, and doubtless many more that have not yet been thought of, but the energy sources that can drive them can be identified as a mere half dozen. Our theoreticians have been able to pinpoint them and to set rough quantitative guidelines on what has to be done to minimize or remove them.

One experiment that emerges in answer to the theoretical situation comprises the injection of a beam of neutral atoms into a region in which

the magnetic field has its smallest strength at the center and increases in absolute value in all directions from the center. Such a field can be generated by a set of coils and currents; the use of such a "magnetic well" removes a whole class of particularly damaging instabilities. The trapping and the generation of the fusion plasma result from the interaction of neutral hydrogen atoms with a "target plasma" already established within the magnetic well by a method known as electron-cyclotron heating. This kind of target plasma serves a double purpose: it traps the particles because the neutral atoms, entering straight into the magnetic field, become ionized and therefore are caught into complex orbits, and it has a stabilizing effect by virtue of a phenomenon called Landau damping. Landau damping is a kind of a drag and dissipation upon the plasma waves that are associated with the growth of an instability. Such waves are difficult to suppress otherwise.

To remove another energy source known to drive severe instabilities, the beam of injected neutral atoms has to be dispersed in energy. The beam is generated initially from an ion source developed at the Laboratory for the production of an intense beam of hydrogen molecular ions at about 40 keV. This ion beam is made to pass through a windowless cell containing magnesium vapor, where the molecular ions are neutralized and dissociated so as to yield 20-keV neutral atoms. Energy spread is introduced by modulating the accelerating voltage applied to the molecular ions as they leave the ion source, while taking separate measures to preserve the beam focus. The techniques required for the generation, focusing, and energy spreading of the atoms and ions were all developed at the Laboratory.

Interactions Between Very Simple Nuclei

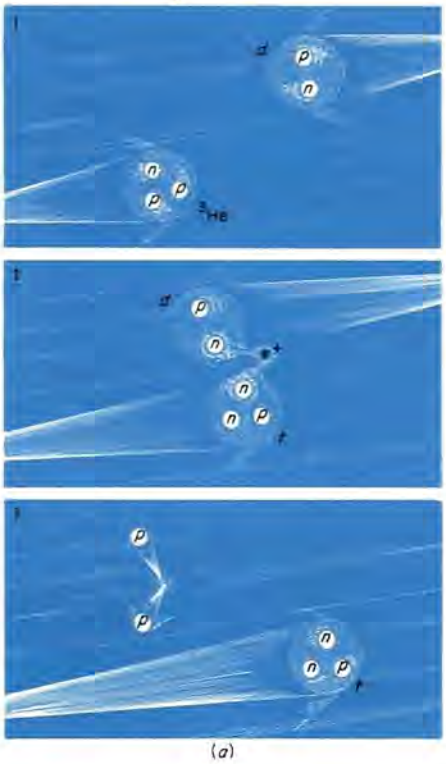
One of the primary goals of nuclear physics research is to characterize the fundamental nuclear force that acts between pairs of nucleons and to understand the structure of complex nuclei in terms of this force. The nature of this force is explored by studying collisions of simple nuclei from very low energy to extremely high energy, and by detailed studies of energy levels in complex nuclei. In the energy-level studies, deductions are made from fine details in the pattern of energy levels, and highly precise data must be obtained to see these details. The broad-range magnetic spectrograph that was installed at the Oak Ridge Isochronous Cyclotron during 1966 is a device for obtaining these data; it is capable of analyzing charged particles from reactions over the wide range of energy made possible by the cyclotron.

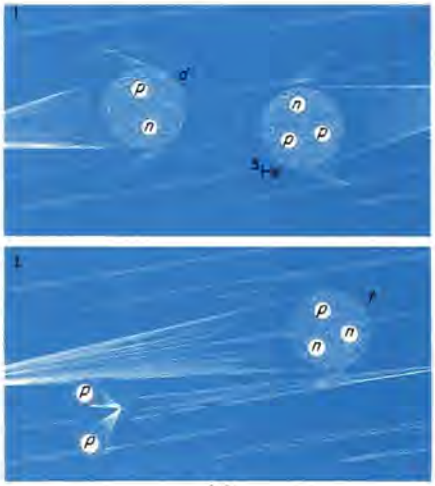
Broad-range spectrograph at ORNL. A precision magnetic spectrograph installed at the Oak Ridge Isochronous Cyclotron is used to analyze nuclear reaction products of various masses over a broad range of energies. The 60-ton magnet, one-fourth the weight of the cyclotron magnet itself, can be rotated readily from 10° to the left of the cyclotron beam to 160° to the right. With an energy resolution of 1 part in 2000 it is possible to investigate the basic elementary forces within nuclei.

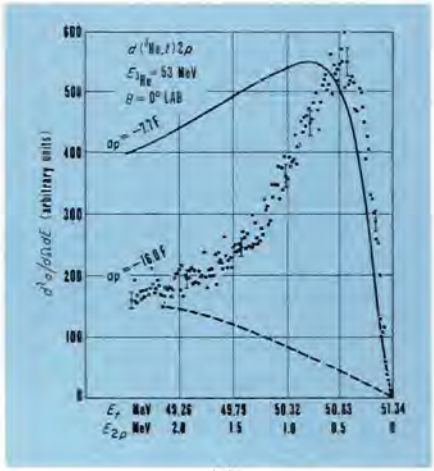
The capabilities of this research tool are being utilized to study the isotopes of strontium, yttrium, zirconium, niobium, and molybdenum; some of their energy levels are believed to differ only through the rearrangement of one pair, or at least very few pairs, of nucleons.

Another type of experiment that is making use of the broad-range magnetic spectrograph is the study of the interaction between two protons that are moving rather slowly with respect to each other. Normally, the proton-proton interaction is investigated by observing the scattering of proton beams from protons in a hydrogen target – a difficult experiment for proton energies less than a few hundred thousand electron volts because of Coulombic repulsion. For example, two protons with a relative energy of 100 keV cannot approach closer than 15×10^{-13} cm, a distance some ten times the range of nuclear forces. However, their interaction may be studied at low energy through reactions that create two free protons, as, for example, $^3He + d \rightarrow t + 2p$. Information about the proton-proton interaction can be inferred from the energy distribution of the tritons.

There are two different ways of viewing this reaction: charge exchange and pickup. The reaction was studied at the Berkeley 88-in. cyclotron by bombarding a helium-3 target with 30-MeV deuterons. The energy distribution of the resulting tritons in forward angles is explainable by a simple theory in which the two remaining protons are assumed to interact *outside* the nuclear force field of the triton. At the Oak Ridge Isochronous Cyclotron







(a) Sketch of a charge-exchange reaction. A proton in the helium-3 nucleus is changed into a neutron, converting the helium-3 nucleus into a triton, and the neutron in the deuterium nucleus is changed into a second proton.

(b) Sketch of a pickup reaction. A neutron is picked out of the helium-3 nucleus by the deuteron, converting it to a triton and leaving two protons behind.

(c) Forward-angle energy distribution of tritons from $^3He + d \rightarrow {}^3H + 2p$. The dotted curve was calculated assuming no nuclear interaction between the two protons or between the protons and the triton. The solid curve is the calculated triton distribution assuming that the two protons interact with each other outside the nuclear force field of the triton.

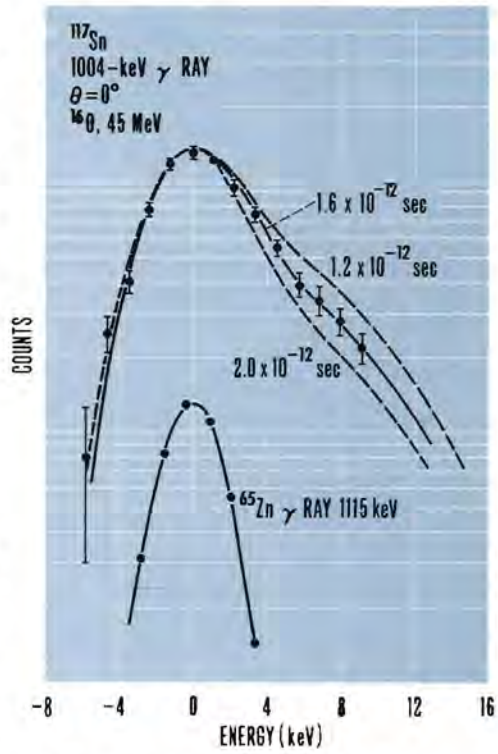
we have looked at the reaction using a 52-MeV helium-3 beam and a deuterium target, which give nearly the same center-of-mass energy as in the Berkeley experiment. High-energy tritons at small angles to the beam are thought to result from the charge-exchange process. Using the broad-range spectrograph both for energy analysis of the tritons and to bend the helium-3 beam out of the way, we were able to measure the high-energy triton spectrum at 0° (i.e., in the direction of the incident beam), an angle at which the effects of the two-proton interaction on the triton spectrum are most pronounced. If one observes the triton in the same direction as the incident helium-3 particle, as in the ORIC experiment, one can easily imagine that a charge exchange occurred, for if, instead, a neutron were deposited into the deuteron, the two protons rather than the triton would fly forward.

While the simple assumption of proton-proton interaction outside the nuclear force field of the triton appears to give a satisfactory description of the Berkeley data, it fails to fit the Oak Ridge data. The influence of the nearby triton on the two-proton system is evident. Interactions involving all five particles will have to be used to understand this seemingly simple experiment. These results reemphasize the importance of examining processes from several different vantage points.

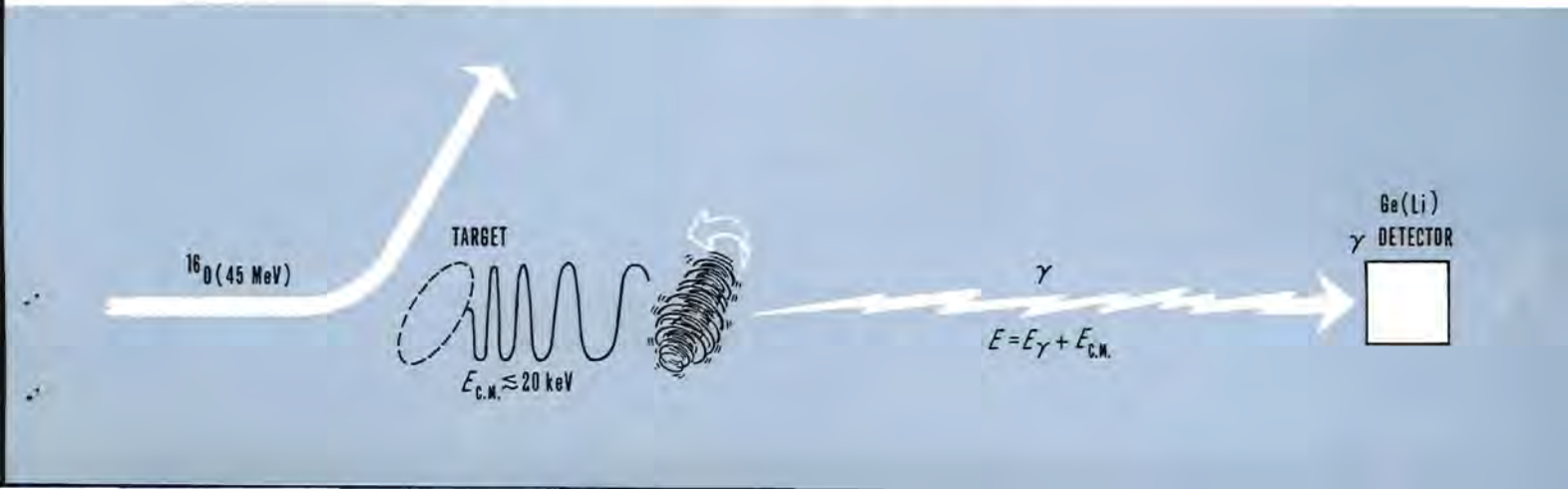
Measuring Nuclear Lifetimes in the Range from 10^{-11} to 10^{-13} sec

Nuclei generally exist in their excited states for a very short period of time. The characteristic lifetime of a given excited state is intimately related to possible nuclear configurations that describe the nature of the excited state. The limit of direct measurements of these lifetimes is about 10^{-11} sec, but many of the most interesting excited-state lifetimes are much shorter than this.

Recently a combination of several relatively new experimental techniques has allowed measurements of lifetimes from 10^{-11} sec down to 10^{-13} sec. The target of interest is bombarded with energetic heavy ions (e.g., oxygen-16 at 45 MeV). There are two important features of this interaction: First, the target nuclei recoil from the collision with a significant velocity. Second, the target nuclei are "kicked" into excited states by means of Coulomb excitation. The excited target nucleus then de-excites by emission of one or more gamma rays. The precise energy of the gamma rays is measured with a high-resolution lithium-drifted germanium detector. If the gamma ray is emitted *before* the recoiling nucleus has been stopped by atomic collisions in the target, then its energy will depend, according to the Doppler principle, on the velocity of the nucleus and the angle of emission of the gamma ray. Since the nucleus is slowed down by collisions with other nearby atoms, its velocity at the moment of gamma-ray emission



Nuclear lifetimes by recoil. If a collection of excited nuclei can be forced to decelerate while they are emitting their radiation, then a study of the Doppler shift of their gamma rays can be used to determine their lifetime. This trick was used to measure excited lifetimes in the range 10^{-11} to 10^{-13} sec by using heavy-ion Coulomb excitation both to excite the nuclear states and to accelerate the nuclei.



Digital computers have greatly enhanced our ability to perform increasingly complex and sophisticated experiments. One example is the study of molecular structure by x-ray diffraction techniques. A four-circle diffractometer is shown in the foreground, with the computer and associated electronics in the background. The computer performs all routine functions involved in data acquisition (including crystal positioning on four axes) and data processing, lessening technical manpower needs and enabling the scientist to spend his time more profitably in data analysis.

depends on how quickly the excited nucleus returns to its stable configuration. Thus the magnitude of the Doppler shift is directly related to the nuclear lifetime.

An example of a measurement is a level in tin-117, whose half-life was found to be 1.6×10^{-12} sec. These measurements would not have been possible without the recently developed high-resolution germanium gamma-ray detectors and techniques for producing energetic heavy ions in the ORNL Tandem Van de Graaff accelerator.

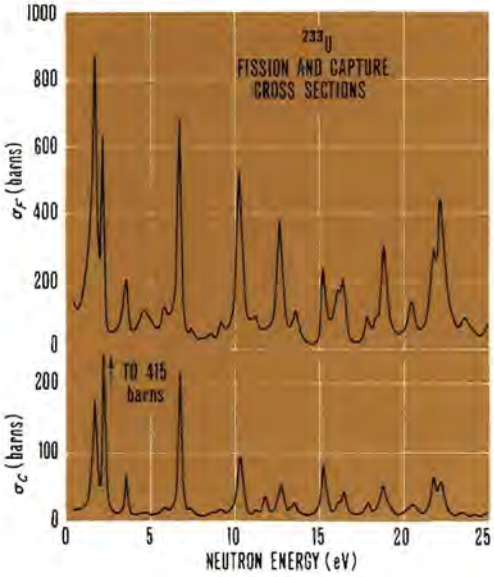
Simultaneous Measurements of Neutron Capture and Fission Cross Sections for the Fissile Isotopes

Capture and fission cross sections for the three principal reactor fuels—uranium-233, uranium-235, and plutonium-239—are needed in the design of all types of reactors. No technique has yet been developed or even envisaged for calculating these cross sections with the accuracy required, and the only recourse is to obtain them through careful measurements. In past years these experiments have emphasized uranium-235, principally because most present-day reactors utilize uranium-235 as the fuel. During 1966, emphasis was placed on the much more difficult uranium-233 measurements, which, along with plutonium-239 measurements, are very important for determining the economic feasibility of breeder reactors. Such reactors are possible only if the value of the parameter α, the ratio of the capture cross section to the fission cross section, is low (much less than 1).

A distinct advantage of the experimental technique used in this program is that the capture and fission cross sections for a specific isotope at a specific energy are measured simultaneously; thus α is much more accurately determined from the data, no corrections being necessary for the relatively large errors introduced by differences in two separate experiments.

In the uranium-233 experiments, pulsed neutrons were obtained from targets placed in the electron beam of the linear accelerator at Rensselaer Polytechnic Institute. Time-of-flight techniques were employed to measure neutron energy. The material to be studied was incorporated in a fission chamber, which was positioned in the center of a large liquid scintillator that was sensitive to the gamma rays emitted following either fission or capture events in the sample. Scintillator pulses with and

Neutron cross section results for capture and for fission in uranium-233. These data were obtained simultaneously, avoiding errors from such effects as relative flux determination.



without coincident fission chamber pulses denoted fission and capture events respectively.

One difficulty in performing the uranium-233 experiments stems from the fact that uranium-233 has a high specific activity of alpha particles, which create a severe background problem in the fission chamber. Thus while it was desirable to use a large sample in order to obtain a good signal-to-background ratio (a 6-g sample had been used for the uranium-235 measurements), the alpha background dictated the use of a very small sample. Not even a 1-g sample was tolerable in a fission chamber of standard design. It was necessary to modify the fission chamber so that it consisted of ten separate sections, each of which contained 100 mg of uranium-233 and each of which had its own amplifier.

A second difficulty in studying radiative capture in uranium-233 is the contamination from uranium-232, a prolific gamma emitter, which is usually present in uranium-233 samples. This problem was solved by electromagnetic isotopic separation of the material, reducing the uranium-232 to the manageable level of 0.7 ppb.

The uranium-233 experiments covered an energy range very important in the design of thorium-uranium breeders—from 0.5 to 100 eV—and resulted in the first direct measurements of uranium-233 capture cross sections. Earlier measurements by others indicated a relatively large value of α, in disagreement with integral measurement techniques, which gave a more promising low value of α. Our results, when averaged over energy, are in good agreement with the latter measurements. As a result of these studies it is now clear that the major remaining uncertainties in these cross sections are in the region below 1 eV.

Investigation of the Minima in the Total Neutron Cross Sections for Oxygen and Nitrogen

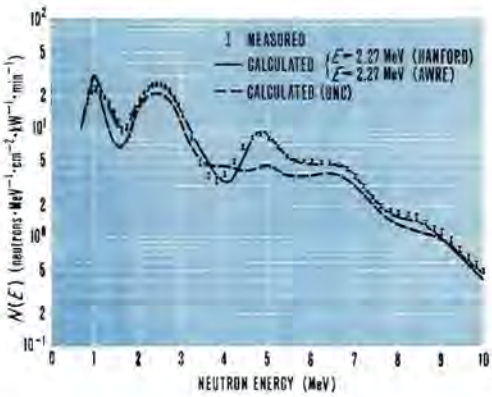
The importance of basic physical research to applied work is demonstrated by the need for neutron interaction cross sections in radiation shielding design. The recent rapid advancement of computing machinery has spawned the development of a large number of computer codes for calculating the transmission of radiation through shields, but the unavailability or unreliability of the cross sections required by the codes often precludes their use. Even when reliable cross sections are available, they have usually been obtained from measurements that emphasized the resonances, where the cross section is high, whereas it is the minima that must be known to solve the deep-penetration neutron transport problems encountered in shielding.

One shielding problem in which the accuracy of cross sections is insufficient is the calculation of the transport of neutrons through the atmosphere—for example, neutrons given off in the burst of a nuclear weapon. Widely differing results have been calculated by various organizations because of differences between the sets of cross sections used for oxygen and nitrogen.

In response to this problem a method for evaluating total cross section data was developed and applied at the Laboratory during the past year. It consists in measuring the spectra of fission neutrons transmitted through thick samples of liquid nitrogen and oxygen and comparing the results with spectra calculated using the various sets of measured cross sections. Thick samples were used to emphasize the effects due to minima

in the cross sections, and an experimental geometry was chosen that enabled a comparison between the measured spectra and the spectra computed from the total cross sections. The validity of the experimental technique was confirmed by comparing measurements and calculations for carbon and lead, for which the total cross sections are well known. It was found that certain sets of oxygen and nitrogen cross sections do exist which, when used in calculations, yield spectra that agree with the results of the thick-sample experiments. Calculations using other cross section data were not in agreement with the measured spectra.

An important aspect of these measurements was the availability of a neutron spectrometer having sufficiently high sensitivity. During the past several years a number of shielding projects have sponsored the development of a proton-recoil neutron spectrometer, but only recently has it progressed to the point that the instrument can be used in experiments involving large neutron attenuations. The spectrometer utilizes a 2- by 2-in. liquid organic scintillator and has an efficiency that ranges from 0.15 to 0.4 for neutrons in the MeV energy range. This allows it to be used in fluxes that are several orders of magnitude lower in intensity than those measurable with other spectrometers.



Spectra of neutrons transmitted through 24 in. of liquid nitrogen: comparison of measurements and calculations.

Materials for Semiconductor Gamma-Ray Detectors

The advent of germanium semiconductor counters has revolutionized many experimental techniques in the study of nuclear structure, principally because of their greatly improved energy resolution. Only very pure germanium crystals can be used for producing these detectors, and even the purest available must be treated to compensate for impurities, which are about 1 ppb. The compensation process involves electrically forcing or "drifting" lithium ions into the crystal lattice. After this treatment the crystal must be always kept at a low temperature by cooling with solid carbon dioxide or other refrigeration to keep the lithium ions frozen into the crystal lattice. The compensation process consumes a variable amount of time, depending upon subtle differences in the raw material. Some crystals have been found to require up to 1000 times as long as others, making them useless for detector production. The cause of the slow drift rate was traced to an oxygen impurity at a level of 10 to 100 ppb. A lithium precipitation test five times as sensitive as the standard infrared absorption method for determining oxygen was developed as a result of this investigation.

Work is progressing on the production of purer germanium by vertical floating-zone remelting of the ingot. Oxygen impurity levels of 1/100 ppb were recently achieved. We estimate that if 1/5000 ppb (10^{10} impurity atoms/cc) can be reached, the tedious lithium drift compensation process could be eliminated entirely in detector production.

The world's first "swimming pool" reactor, called the Bulk Shielding Reactor, was built at the Laboratory in 1950. It served as a research tool for many years but was finally superseded by more advanced reactors. During 1966 the BSR was once again made an up-to-date facility, to be used mostly for solid-state research. The movable reactor core can now operate at 2000 kW at any location in the pool. Highly thermalized neutrons are produced in a tank filled with heavy water. Specimens can be irradiated at temperatures down to 3°K at thermal neutron fluxes of 2.5×10^{12} neutrons cm^{-2} sec^{-1}; this is made possible by a continuously operating closed-circuit helium refrigerator. In this photograph, an aura of Cerenkov radiation surrounds the reactor core. The flexible exit-water line at the left allows the reactor to be moved about the pool. The tank at the left of the reactor is filled with heavy water and serves as a "thermal column." A second tank of heavy water, at the right side of the reactor, transmits thermal neutrons to the helium-cooled cryostat.

In a Tower Shielding Facility experiment designed to evaluate various sets of total neutron cross sections for oxygen and nitrogen, measurements were made of the energy spectra of fission neutrons transmitted through thick liquid samples of the elements. The tank shown housed a 2- by 2-in. liquid organic scintillator, which, with its associated electronics and computer programs, constituted the spectrometer system. The scintillator was surrounded by a water and lead shield penetrated by an air-filled collimator extending from the front of the tank to the crystal.

MATHEMATICS

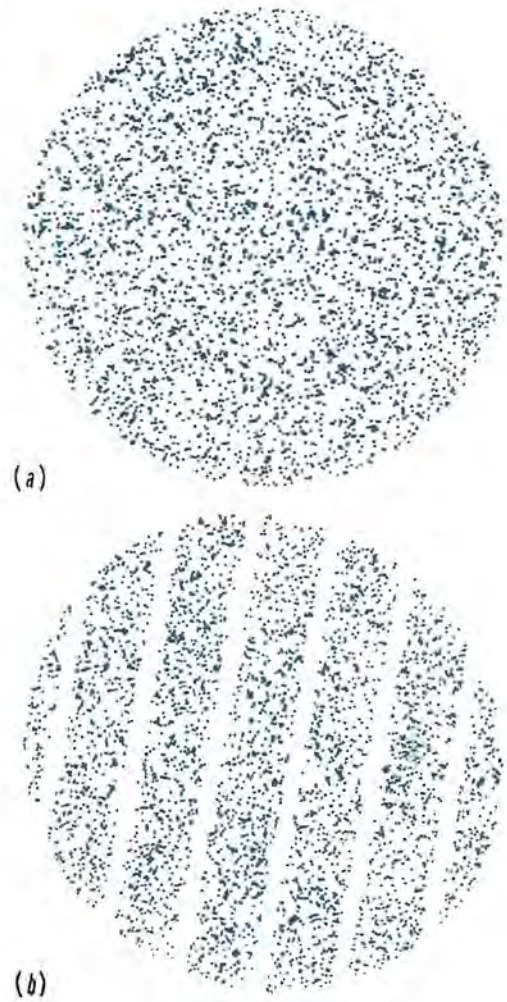
Some technical problems are best approached by the combined skills of research scientists, mathematicians, computer experts, and engineers. As an example, a team of mathematicians, physicists, and chemists worked with computer experts in developing the complex mathematical relationships to calculate relativistic electronic wave functions for atoms and ions and in preparing the computer program for the computations. Wave functions are the basic material for calculations of the electron shell characteristics of atoms, the transition rates for the changes in the electron shells that follow radioactive decay of the nucleus, and other quantities of interest in atomic physics. The amount of calculation involved in obtaining wave functions is so large that the characteristics of only the lightest atoms can be calculated without the use of a computer. The series of computer programs currently developed can be used for comprehensive studies of atomic structures, both for free atoms and for atoms bound in crystal lattices.

Mathematicians collaborate with scientists in all fields to develop the mathematical relationships of research data. Programmers contribute in the joint effort by planning the appropriate computer operations for data analysis and computations to yield the desired information.

Monte Carlo Calculations

In recent years, computer codes that use Monte Carlo techniques for a wide variety of calculations of physical processes, such as the depth of penetration of radiation in various media, have been widely applied. The Monte Carlo method uses computer programs to produce a computerized simulation of a physical experiment. Values of the parameters of the physical problem are determined by making repeated statistical trials of the experiment by means of the simulator. One of the most widely known Monte Carlo neutron transport codes was developed at the Laboratory and has been distributed to scientists all over the world. Among other things, it has been used to study the design and operating characteristics of nuclear reactors, to study the effectiveness of radiation shields of many kinds, and to study radiation effects on man and other animals. Since practically every step in the Monte Carlo calculations requires the generation of random numbers, there has naturally been considerable curiosity about which of the many available generators yields the best results. During 1966 mathematicians at ORNL developed a theory for testing random number generators and improving their performance.

Monte Carlo programs have recently been written at the Laboratory to do predesign studies of target and moderator configuration for the Oak Ridge Electron Linear Accelerator, a major experimental device now under construction. A program is under development to simulate a gamma-ray spectrometer that may be flown in an Apollo spacecraft and used to search for radioactivity in the remnants of a supernova (the Crab Nebula).



During 1966, mathematicians at ORNL developed a theory for testing random number generators which has shown not only that some of the well-known and commonly used generators are faulty (somewhat like playing with loaded dice) but also that the "improvements" that have been proposed in the past for certain generators have not been improvements at all! The figure shows that a poor random number generator, used in a code to randomly find points within a circle, can result in an uneven distribution of points, whereas a good generator produces an even distribution.

Computer Programming for Versatility in Scientific Applications

As an increasing number of scientists utilize the large general-purpose computers, mathematicians and computer experts have directed their attention to the problem of keeping up with the many demands made upon them. The difficulty can be circumvented if problems that require commonly used techniques are solved routinely by the use of standard computer programs. However, this approach involves a danger of using the computer in a stereotyped manner. In an attempt to minimize unimaginative use of standard programs, a system of computer programs is being developed to handle and analyze data by computer processes that can be arranged in any order. Since the system is designed with a collection of mathematical treatments programmed in "modules," complex calculations and analyses can be provided by putting the computer program modules together in the desired sequence. The system now contains a varied repertoire of computer programs to which additions will be made for greater versatility. A more elaborate system is under development. Ultimately the system will permit scientists and engineers to feed their research data directly into the computer and tell the computer how they want the data analyzed, evaluated, and used in computations.

Statistical Mathematics

The applications of statistical techniques to problems in the biological, physical, social, and engineering sciences increased during the year. In complex experiments where many interrelated factors must be considered, advance consultation with statisticians made it possible to design the experiment so as to draw the maximal amount of information from the data. Carefully designed experiments were performed on (1) the reduction in mortality from secondary disease of mice treated with bone marrow, (2) the uptake of radionuclides by tulip poplars, and (3) the effects of several factors on the efficiency of blending powders of uranium and aluminum. In addition, the sophisticated techniques of statistical analysis were applied to a wide assortment of problems in reactor chemistry, metals and ceramics, health physics, and biology. However, in connection with other types of highly complex research problems, mathematical research is needed to develop new techniques for the analysis and interpretation of research data.

During the past year several new approaches were proposed in the realm of stochastic (random) processes. Among these was a generalized stochastic model for the distribution of radioactive material in a system of connected compartments, such as might be encountered in plants or animals. The stochastic nature of this approach provides an alternative to the deterministic models, which consider the causes of the movements of materials among the compartments. This study also provided ancillary results involving random difference equations in single-compartment systems. Other research, both basic and developmental, involved problems in reliability theory, the design of experiments, nonlinear regression, and multivariate analysis.

CHEMICAL AND MATERIALS RESEARCH AND ENGINEERING

The application of any new theory or the implementation of any new concept requires that suitable materials be available. So it is necessary that our materials scientists—chemists, chemical engineers, ceramists, and metallurgists—continue their studies of processes and materials relevant both to the large-scale developmental programs of the Laboratory and to our understanding of the basic sciences that support these programs.

Our obligations as a supporting laboratory for the atomic energy program are reflected in the relatively great interest in the effects of radiation, the processing of irradiated materials, the chemistry of reactor fuels, and the development of improved reactor materials.

Paramagnetic Resonance Studies of Liquids During Photolysis

Many chemical reactions induced by radiation begin by fragmentation of the original molecule. Chemists and biologists are deeply interested in these fragments, even though only minute concentrations are available under most circumstances because they react so rapidly with their surroundings. One of the newer ways for studying such a fragment is through its paramagnetic resonance spectrum, which has its origin in the magnetic properties of the unpaired electron that such a fragment usually possesses. If the free radical (which the fragment is called if it does have an unpaired electron) also contains magnetic nuclei, the resonance spectrum is split into many component lines, which are very useful for identifying the radical and for learning something of its properties.

ORNL chemists have been studying the free radicals formed by irradiating liquids with flashes of ultraviolet light. Radicals in liquids generally give spectra consisting of sharp lines, which reveal the detail needed for fruitful studies. For the most part, low-molecular-weight radicals have been studied, and since their lifetimes are short, typically of the order of a millisecond, their spectra have been obtained during the exposure to the flash of light, rather than after. Initially, radicals derived from simple alcohols were studied; the list has now been extended to include radicals derived from other classes of compounds, notably ketones, nitriles, and amides.

The method most often used to form radicals has been to expose the system to ultraviolet light in the presence of a small amount of dissolved hydrogen peroxide. The hydrogen peroxide decomposes to the hydroxyl radical, which abstracts hydrogen from the substance of interest. Acetone may be used in place of hydrogen peroxide, since it is also capable of abstracting hydrogen, under excitation by light. This method is particularly advantageous in dilute solution and has allowed much work to be done in aqueous systems. For example, several percent each of acetone, $(CH_3)_2CO$, and methyl alcohol, CH_3OH, in water give a good yield of the radicals $(CH_3)_2\dot{C}OH$ and $\dot{C}H_2OH$. When acid is present in the solution, the spectra of these radicals are modified in an interesting way because of the reversible addition of hydrogen from the acid. This reversible addition of hydrogen is often called "exchange," because it provides a mechanism whereby the organic molecule or radical may give up some, though not necessarily all, of its hydrogen atoms in exchange for hydrogen atoms from the acid. In the radicals being studied here it is the hydrogen atom bonded to the oxygen atom, forming a hydroxyl group, that is readily exchanged with the hydrogen of the acid. The exchange is believed to occur by the reversible addition of the hydrogen of the acid to the oxygen atom—for example, in the case of the free radical formed from methyl alcohol,

$$\underset{\text{Neutral radical}}{\dot{C}H_2OH} + H^+ \rightleftharpoons \underset{\text{Radical ion}}{\dot{C}H_2OH_2^+}.$$

In the presence of enough acid the influence of the neutral radical on the paramagnetic resonance spectrum vanishes; the exchange becomes very fast, and the spectra become simpler. A study of this phenomenon has given measurements of the rate of exchange of the hydroxyl hydrogens.

The figures show the remarkable agreement between observed and calculated paramagnetic resonance spectra for the free radical $CH_3CO\dot{C}OHCH_3$. The top pair of curves shows the spectrum of 32 components under conditions of low acidity, where few protons are available for exchange. (Extra components in the observed spectrum are due to a small amount of another free radical.) In the middle pair the observed spectrum was altered by the addition of a moderate concentration of acid; the spectrum calculated with an exchange rate of 2.30×10^6 sec^{-1} gives a satisfactory match. In the limit of very rapid exchange (high acid concentration) a spectrum of seven lines is obtained, as shown in the bottom pair; the exchange rate for the calculated spectrum was 3.00×10^9 sec^{-1}.

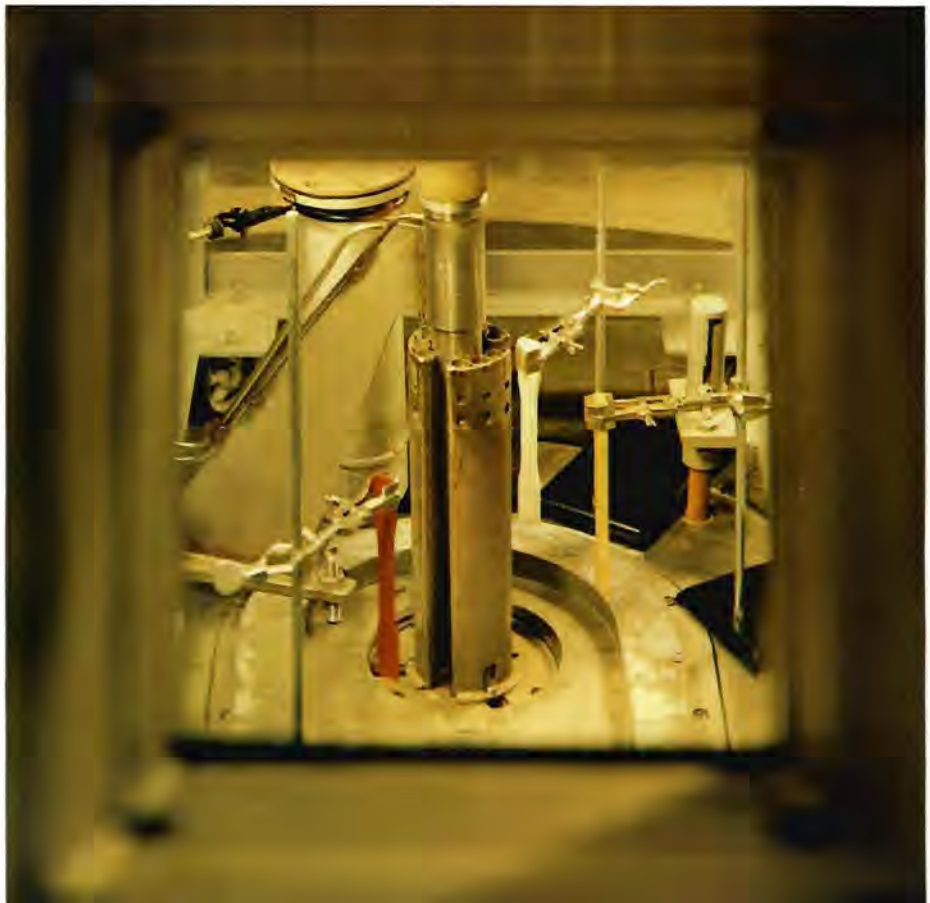
Other dynamic exchange effects have been observed. The most striking were from $CH_3CO\dot{C}OHCH_3$. This radical was prepared by photolyzing a solution of biacetyl, $CH_3COCOCH_3$, in isopropyl alcohol. The spectrum consists of 32 lines, arising from interactions of the unpaired electron with all the hydrogen atoms in the radical. Upon adding acid, exchange takes place, and the altered spectrum can be accounted for by the process

$$\underset{\text{Neutral radical}}{CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-\overset{\overset{\displaystyle OH}{|}}{\dot{C}}-CH_3} + H^+ \rightleftharpoons \underset{\text{Radical ion}}{\left[CH_3-\overset{\overset{\displaystyle OH}{|}}{C}-\overset{\overset{\displaystyle OH}{|}}{\dot{C}}-CH_3\right]^+},$$

for which the lifetime of the radical ion is negligible compared with that of the neutral species. In the limit of very fast exchange (high acid concentration), the protons of the two CH_3 groups appear to be equivalent. This leads to a simple spectrum of seven lines. At intermediate acid concentrations the spectra are very complex, but they can be computed for this process with parameters deduced from the initial spectrum of 32 lines and from a single rate constant. By adjusting the value of this rate constant, curves were calculated that give a very good match to the experimental spectra for a large range of acid concentrations.

Effects of Radiation on Organic Substances

The amount of radiation required to produce easily measurable chemical and physical changes in organic substances (plastics, pure liquids, solids, greases, oils) is so great that the irradiation experiments must be done remotely, behind heavy shielding. In order to permit experiments in which large specimens can be used, their temperature or the surrounding atmosphere controlled, and their mechanical properties measured during the experiment, chemists at the Laboratory have constructed a large shielded



Effects of radiation on organic substances. Red, white, and yellow tensile specimens of organic plastics being irradiated by 19,000 curies of cobalt-60. This picture was taken through the glass viewing port of our heavily shielded walk-in facility, in which the effects of irradiation can be determined over wide ranges of experimental parameters while the specimens are under mechanical stresses. The cobalt is contained, as encapsulated pellets, in the small tubes surrounding the central cooling thimble. At the conclusion of the irradiation, the split cylinder containing the cobalt is withdrawn into a shielded recess in the floor so that the experimenters can enter the cell.

room with a retractable radiation source containing 19,000 curies of cobalt-60 housed in the floor. Dose rates as high as 10^{19} eV per gram of material per minute can be delivered to a cylindrical region 2 in. in diameter and about 4 in. long, with lower dose rates outside the cylinder over larger regions.

The irradiation of polybutadiene has been of special interest. This relatively simple unsaturated hydrocarbon may be regarded as being the basic polymer backbone to which natural rubber and many of the synthetic rubbers can be structurally related. Different types of polybutadiene may contain a major fraction of the unsaturated groups in the *cis* configuration (as in natural rubber), the *trans* configuration (as in gutta-percha), or the side-vinyl configuration (as in cold rubber, and with a fair analogy to polystyrene). Irradiation of these various forms of polybutadiene has been found to cause very rapid conversion of their unsaturated groups into other structures. The G values (the number of unsaturated groups destroyed per 100 eV of energy absorbed) have been relatively high: 15, 19, and 40 respectively. Although the products of these conversions have not yet been identified, it has been established that only a small fraction of the reaction results in the production of cross-linkages. Whatever the mechanism, the high yields of these processes are significant in that they may ultimately offer possibilities for producing new materials.

Studies of Teflon (polytetrafluoroethylene) are also of special interest, since the material is comparatively resistant to corrosive liquids and gases and to high temperature. Unfortunately, however, when subjected to ionizing radiation, plastics of this structure are among the least stable, being rapidly degraded. Other workers have shown that the effect of radiation on thin films of Teflon is reduced if the material is in an inert atmosphere, rather than in air. Since much thicker stock is used in many applications and since air might be automatically excluded from the interior, the effects of radiation and environmental atmosphere on mechanical properties are being carefully studied; the tensile strength and the elongation at break are significant indicators of serviceability. As with the thin films, air accelerated the radiation degradation of the thicker stock; ten times as much radiation in vacuum was required to reduce the mechanical properties to half their original values as was required in the presence of air. Interestingly enough, low doses of radiation were found to *increase* the elongation at break; it is speculated that the initial damage produces crystal defects that permit intracrystalline slip under stress. Further study of the effects of radiation on the mechanical properties is expected to contribute to our knowledge of the molecular structure of Teflon and similar plastics.

Effects of Radiation in Chemical Analyses

Nowadays it is often necessary to analyze irradiated or radioactive materials. The effects of radiation during the analysis may be detrimental or useful, depending on the reactions involved. The nature of such effects in typical analyses is being studied by analytical chemists at ORNL. Ways to avoid or to exploit them, as the case may be, are being sought.

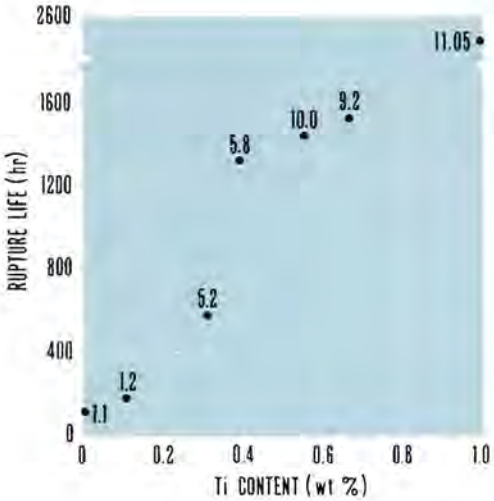
Alizarin red S (an anthraquinone dye) has been used for the spectrophotometric determination of various elements. Zirconium is one of the few elements that form colored complexes with alizarin red S in highly acid solutions. The color of the zirconium complex is very easily destroyed by radiation. There are, nevertheless, functional groups in the complex that are not readily affected by the radiation; a voltammetric method for the determination of zirconium has been developed that makes use of the chemical reactivity of such groups in the alizarin red S complex.

In some recent experiments several relatively inert metals were exposed to gamma rays while immersed in concentrated hydrochloric acid. The metals—gold, zirconium, tungsten, platinum, niobium, and tantalum—are among those commonly used to contain hydrochloric acid solutions or as electrode materials. Tantalum was attacked very slowly; of the metals tested, it appears to be the best for use in contact with highly radioactive solutions containing hydrochloric acid. The other five metals were dissolved at measurable rates; although the dissolution is slow, the amounts dissolved are large enough to interfere in analytical procedures. On the other hand, it is possible that irradiation under controlled conditions might be conveniently used to prepare dilute standard solutions of certain metallic elements.

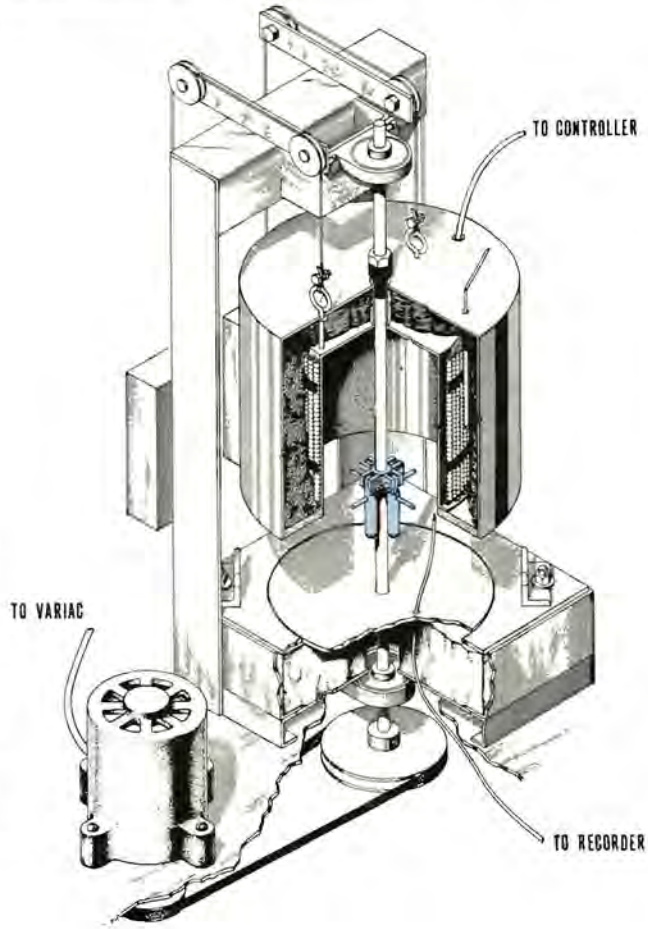
Modification of Hastelloy N for Radiation Stability

Hastelloy N is a nickel-base alloy developed at this Laboratory (under the name INOR-8) for corrosion resistance to molten fluorides. It is the structural alloy used for containing the fuel and coolant in the Molten Salt Reactor Experiment and is proposed for use in molten-salt breeder reactors and space reactors. Like other structural metals, on prolonged irradiation it becomes embrittled from inclusions of helium gas, produced principally by transmutation of boron impurity. When boron-10 captures a neutron it fissions into helium and lithium. Recently, metallurgists at ORNL, repeating their previous success with stainless steel, have shown that incorporation of titanium in a nickel-base alloy similar to Hastelloy N substantially improves its resistance to radiation damage. Alloys containing from 0.4 to 1.0% titanium irradiated to 2.5×10^{20} neutrons/cm^2 showed adequate ductility, and their rupture lives (which are shortened by radiation damage) at 650°C were longer than that of unirradiated Hastelloy N.

Several explanations of this behavior are possible. Titanium could combine with boron in such a way as to distribute the main source of helium where its damaging effects are minimized. Titanium could combine with other elements in the alloy to form insoluble particles that strengthen the grain boundaries. Also, titanium might alter the grain-boundary energy so that higher stresses would be required to form a crack. Future studies should identify the true mechanism.



Effect of titanium content on the creep of irradiated modified Hastelloy N. Nickel-base alloys containing 12% Mo, 7% Cr, 0.05% C, and the indicated titanium contents were annealed 1 h at 1177°C, irradiated at 650°C to a dose of 2.5×10^{20} neutrons/cm^2, and stressed at 650°C with 32,350 psi. The plot shows the time to failure; above each point is the percent elongation; this is the increase in length at failure and is a measure of the ability of the material to deform to accommodate in-service strains. Unirradiated normal Hastelloy N, similarly tested, has a rupture life of 800 h and an elongation of 12.5%.



High-temperature centrifuge constructed for the study of partial miscibility of liquids in molten salt systems. The small tubes attached to the central shaft (preloaded with the desired components) are maintained at temperatures as high as 1000°C by the surrounding furnace assembly. Rotation at 2400 rpm produces a force of over 500 times gravity. After equilibration, the rotating shaft is brought smoothly to rest, the furnace is quickly lifted, and the tubes are cooled with water, thus preventing any change in the compositions or relative proportions of the liquids at intermediate temperatures. A region of partial miscibility was discovered in the ternary system lithium fluoride–beryllium fluoride–zirconium fluoride, disappearing at an upper consolute temperature of 955°C and a composition of 25 mole % LiF, 55 mole % BeF_2, and 20 mole % ZrF_4. As far as we are aware, this is the first demonstration of incomplete miscibility of liquids in a ternary fluoride system.

Electroanalytical Chemistry of Molten Salts

Since molten fluorides are being used as the fuel for the Molten Salt Reactor Program, considerable research is being conducted to characterize this class of molten-salt systems. One important aspect of the work is the use of controlled-potential voltammetry to study the reactions that occur in an electrochemical cell with a molten salt electrolyte. In this technique the potential of the electrode is varied deliberately; the resulting changes in current are identified with the reduction or oxidation of ions or molecules in the solution.

Significant outcomes of the work thus far with molten fluorides are the identification of hydroxide and oxide impurities and also the characterization of the electrochemical behavior of uranium(IV) and the corrosion products iron(II), chromium(II), and nickel(II). Ways are now being studied to adapt electroanalytical methods to the continuous in-line determination of impurities and other electroactive materials in molten-salt reactor fuels.

Analytical Applications of Mass Spectrometry

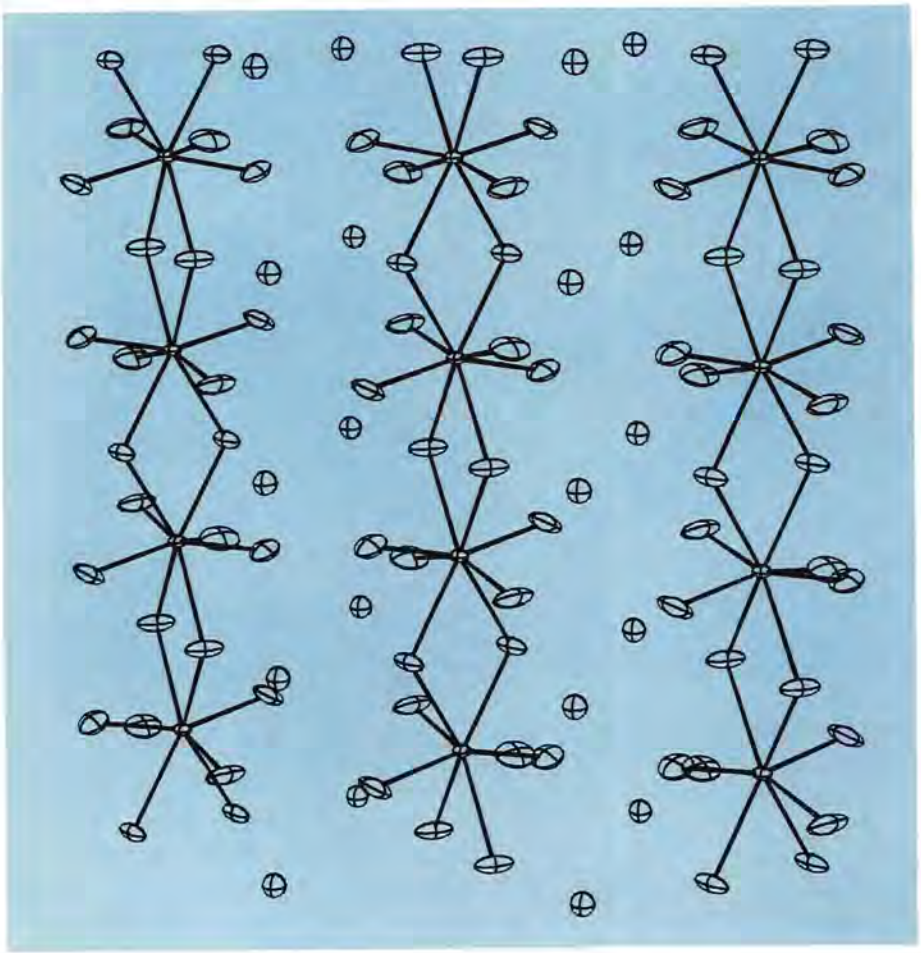
A mass spectrometer converts atoms or molecules into ions by heat or by electron impact, after which an electric or magnetic field separates the ions into a mass spectrum that can be collected and measured precisely. Analytical chemists are finding new applications of this technique in the fields of nuclear reactor and space sciences.

Recently, one of the ORNL mass spectrometers was used as a mass separator to obtain about 2×10^{10} atoms of californium-251, which has a half-life of 700 years. This batch is the purest californium-251 yet produced; it is being used to determine hitherto unknown properties of californium.

Another important application of the mass spectrometer is in the analysis of structural metals that may contain boron, a component undesirable for use in nuclear reactors because its less abundant isotope, boron-10, has a high neutron absorption cross section. With a mass spectrometer, less than 0.5 part of boron-10 per million parts of metal can be determined.

Crystal-Structure Analysis of a Compound of Protactinium

It is important in the study of any element to determine the crystal structures of representative compounds. Considerable insight into chemical behavior comes from knowing the size and location of ions in crystals. In the past, structures of crystals of highly radioactive heavy elements have not been known with the accuracy inherent in the best contemporary diffraction technique; sometimes the degree of inaccuracy has seriously affected the usefulness of the determination. One source of the trouble has been the difficulty imposed by the radioactivity on the growing of single crystals and their subsequent manipulation, so that many studies have been limited to interpreting powder diffraction patterns. The presence of one kind of atom much heavier than the others in a crystal adds



In this representation of the crystal structure of $RbPaF_6$, the atoms are depicted by ellipsoids showing the extent of their thermal motion along three axes. Each protactinium atom is bonded to eight fluorine atoms arranged in a dodecahedron. Four of the fluorine atoms of each PaF_8 group are shared between dodecahedra, forming a continuous chain. Each rubidium atom is bonded to six fluorine atoms of one chain and four of another; the rubidium atoms are shown (without bonds) between the chains. The thermal motions of the different atoms can be correlated with their environments and bonding.

another problem—a heavy atom contributes so much more to the x-ray diffraction pattern than a light one, by virtue of its greater scattering power, that extensive and precise measurements are necessary to locate the other atoms accurately.

Recently, however, the structure of a fairly complex crystal of a radioactive heavy element has been determined with the accuracy currently achieved with ordinary crystals. The compound studied was $RbPaF_6$. Inaccuracies in the determination that would arise from large, variable absorption of x rays by the crystal in different orientations were greatly reduced by grinding the sample to a sphere less than 0.1 mm in radius. To avoid ingestion or inhalation of protactinium, which is an alpha-particle emitter, this operation required the use of a microscope and a micromanipulator in a glove box. The diffraction measurements were made on the computer-controlled x-ray diffractometer developed at ORNL, and the ease with which large amounts of precise data can be obtained with this instrument contributed heavily to the quality of the final results.

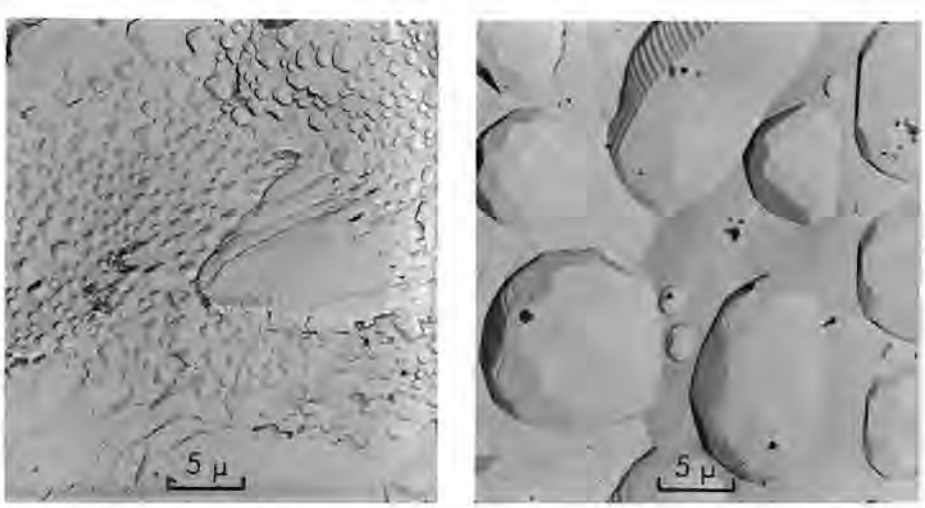
This determination of the crystal structure of a compound of protactinium points to the possible use of this technique in studying the chemistry of transplutonium elements.

Fabrication and Study of Refractory Metals

More economical fabrication methods are resulting from the studies at this Laboratory on refractory metals (niobium, molybdenum, tantalum, and tungsten) and their alloys. The principal advances have been in the extension of conventional techniques to higher temperatures and in the chemical vapor deposition of metals.

Several improvements center around the previously developed self-lubricating extrusion technique, in which tungsten and molybdenum are lubricated during extrusion by a film of molten oxide, which later evaporates. This method was extended to alloys that oxidize too slowly for self-lubrication and to niobium and tantalum, which do not form suitable oxides; for such materials a thin chemical vapor deposited coating of pure tungsten or molybdenum is applied to the billet before extrusion.

Chemical vapor deposition is a very economical, convenient way of preparing tubing and other shapes from refractory metals. It involves the deposition of a metal from one of its volatile compounds as a result of a chemical reaction between gases flowing past a heated surface. For example, metallic tungsten can be prepared by passing a mixture of tungsten hexafluoride vapor and hydrogen through a copper tube heated to about 600°C. At this temperature the two gases react, forming hydrogen fluoride, and metallic tungsten is deposited on the inside surface of the copper tube. Methods have been developed at Oak Ridge National Laboratory for depositing many complex shapes that cannot be formed by conventional techniques. In comparing chemical vapor deposited and conventional tungsten it was found that the deposited tungsten has a characteristic columnar structure that could not be removed by annealing at temperatures up to 2500°C. This structure might be detrimental for some applications, because of its adverse effect on strength, ductility, and fabricability. However, the texture of chemical vapor deposited tungsten became the same as that of conventional wrought tungsten after rolling to one-fifth of its original thickness. Also, the chemical vapor deposited tungsten could be rolled at temperatures as low as 400°C, which compares very favorably with conventional material.



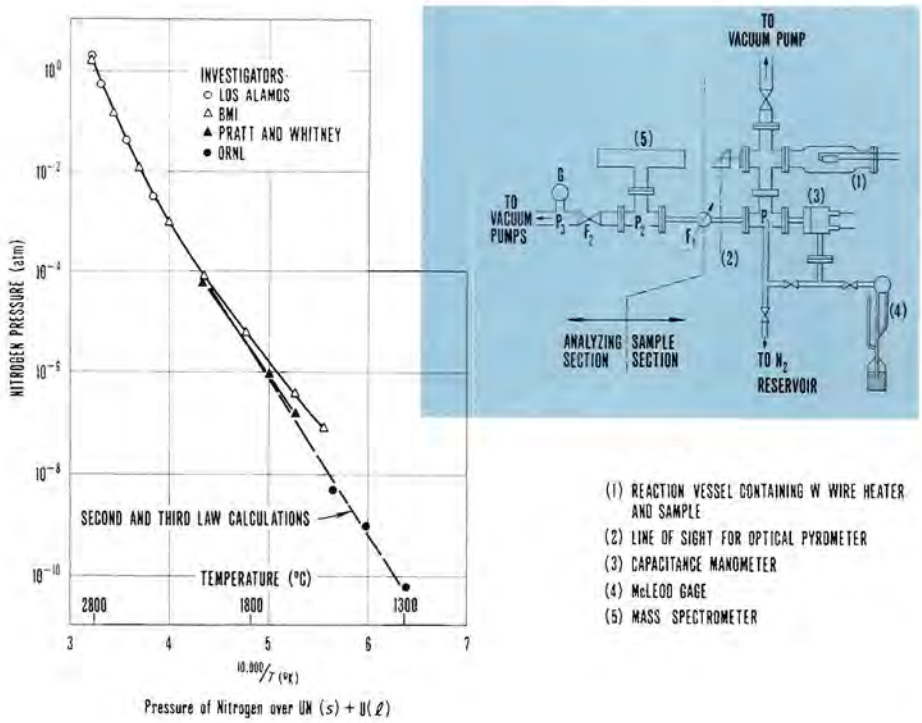
Electron micrographs showing gas bubbles along grain boundaries in chemical vapor deposited tungsten. Such bubbles develop on heating if 1 to 30 ppm of fluorine is present. They inhibit grain growth and may affect mechanical properties. Bubbles on the left developed in 2 h at 2500°C; those on the right in 5 h. Their polyhedral shape is a result of surface diffusion of tungsten to balance the internal gas pressure and the surface tensions of the low-index crystallographic planes. Therefore one can relate the surface energy of tungsten to crystallographic orientation.

Loading tungsten billet into extrusion press at 2000°C. The white-hot billet, during transfer from the furnace to the press, reacts with air to form a molten oxide layer, which lubricates the extrusion.

Uranium Mononitride, a New Nuclear Fuel

Uranium nitride shows many useful properties as a nuclear fuel, particularly for fast breeder reactors and for compact reactors to be used in outer space. It has much better dimensional stability than uranium metal, higher uranium density and thermal conductivity than uranium dioxide, and better stability to water and air than uranium carbides. A study program has been undertaken at Oak Ridge National Laboratory in order to fully evaluate the potential of this material.

The first, and necessary, accomplishment has been the development of a method to produce pure UN, which had not previously been available. Pure uranium powder from decomposition of the hydride was converted to U_2N_3 by reaction with purified nitrogen. This, in turn, was heated in high vacuum to 1500°C to make pure UN powder, which was then sintered at 2000°C in nitrogen to decrease the reactivity associated with a high



Dissociation pressure of uranium mononitride. The ORNL measurements at very low pressures have extended the range of data by three orders of magnitude. Also shown are thermodynamically predicted values. The apparatus can measure differences in gas volume of 10^{-9} std cm³ under equilibrium conditions and can detect gas flows of 10^{-11} std cm³/sec under transient conditions. A mass spectrometer measures total pressure and individual gas pressures down to 10^{-12} atm at temperatures up to 1800°C. The technique is useful for studying many gas-solid interactions; one application has been the study of the solubility and rate of solution of nitrogen in refractory metals and alloys.

specific surface. Material produced in this way contains only about 200 ppm each of oxygen and carbon, the only significant impurities.

Using a unique and highly sensitive technique for measuring gas-solid interactions in a high vacuum (see illustration), values have been obtained for the stability of high-purity UN at the operating temperatures of high-temperature power reactors. Heated in a vacuum, UN decomposes by the reaction

$$2\,\mathrm{UN}\ (\mathrm{solid}) \rightleftharpoons 2\,\mathrm{U}\ (\mathrm{liquid}) + \mathrm{N_2}\ (\mathrm{gas}).$$

ORNL measurements at 1300 to 1500°C gave results that are in excellent agreement with thermodynamic calculations and include dissociation pressures down to below 10^{-10} atm. For comparison, material containing 1300 ppm of carbon and 400 ppm of oxygen has 1000 times the dissociation pressure of the high-purity material.

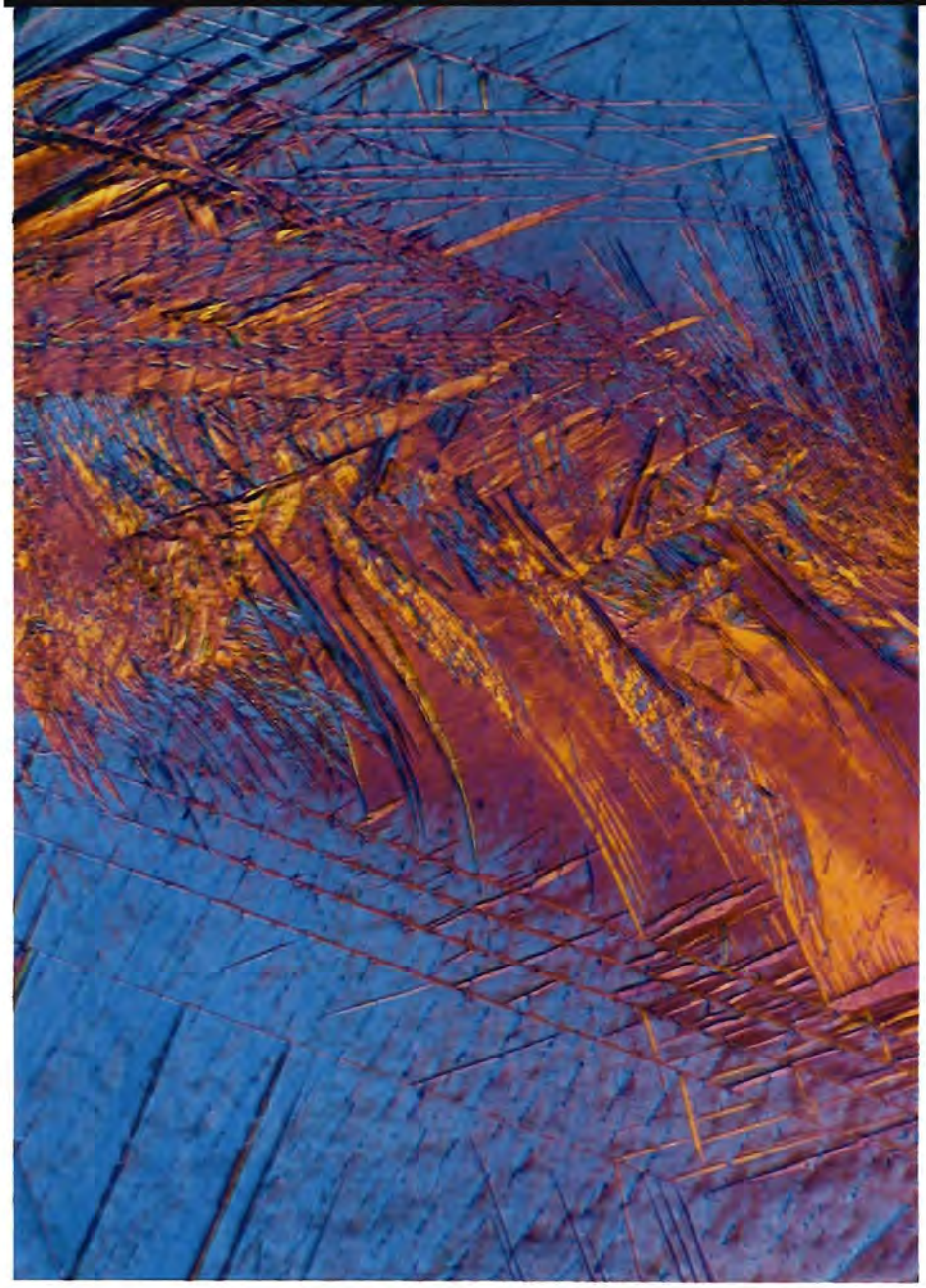
Sintered Aluminum Products

Sintered aluminum products material (SAP) is the leading candidate for the construction material of the Heavy-Water Organic-Cooled Reactor. This material is fabricated from partially oxidized aluminum powder; the dispersed oxide strengthens the aluminum and extends its usefulness to higher temperatures. Many previous preparations and examinations of SAP have shown considerable variation in process yield, structural homogeneity, resistance to gas fissuring and blistering, resistance to fracture, anisotropy, and creep ductility. Consequently, studies were undertaken at Oak Ridge National Laboratory to devise a dependable process for consistent production of material suitable for reactor use.

The result has been the laboratory-scale development of a satisfactory process which involves hot pressing of fine aluminum flake combined with vacuum annealing at a high temperature. The product is both uniform and reproducible, but the mechanical properties were found to be very sensitive to the testing conditions. Much of the previously reported variation in these properties could be traced to differences in testing procedures.

Deformation in Zirconium

The plastic deformability of metals permits them to assume desired shapes during fabrication and to absorb strains that occur in service. For metals to deform, the individual crystals or grains must change shape; this happens in two ways. The usual mechanism is *slip*, in which planes of atoms move past each other. When suitable directions for slip are unavailable, *twinning* occurs, in which portions of the grain deform by shifting into an atomic arrangement that is the mirror image of the rest of the grain. The ability of ORNL metallurgists to prepare high-quality single crystals of zirconium is proving to be a powerful tool for studying deformation in this metal, which is used so widely in the nuclear industry. Single crystals can be oriented so as to force deformation to occur on certain planes in specified directions. When a zirconium crystal is aligned so that slip is difficult and then is forced to deform, unusually high degrees of twinning occur. The results of these and other studies of the deformation behavior of zirconium will lead to improved fabrication and utilization of zirconium alloys.



Shear zone of a single-crystal zirconium specimen sheared in a $\langle 11\bar{2}3 \rangle$ direction on a type $\{10\bar{1}1\}$ plane. The abrupt change in crystal orientation at a twin boundary causes the sharp color changes under polarized light and sensitive tint. Slip is revealed by gradual color changes; in this case it is more prominent near twin boundaries. The colors and orientations of the markings allow complete identification of the deformation systems and hence lead to a greater understanding of texture (or preferred orientation) development in polycrystalline zirconium and zirconium-base alloys. Such textures have a profound influence on the effective strength of the material. Magnified 100×.

Schlieren System for Study of Ultrasonic Phenomena

In regions of abrupt density changes in transparent media, light is diffracted just as it is by objects of size comparable with the wavelength. This phenomenon is used, for example, in aerodynamics research, in the schlieren optical technique for observing shock waves. ORNL test engineers have adapted the technique to study the transmission of ultrasonic waves through various media. The schlieren pattern reveals the path of a pulse of ultrasonic energy through a tank of water; the change of the pattern when a solid object, such as a piece of tubing, is placed in the tank shows the nature of the interaction of ultrasound with the solid object. Flaws in the solid object should change the schlieren pattern. The knowledge obtained from this work will improve the interpretation of ultrasonic test results and open possibilities for new nondestructive inspection methods.

Ultrasonic pulse revealed by schlieren technique. A pulse of light is diffracted by the density variations in water transmitting the ultrasound. The left photo shows the complex patterns of reflection, refraction, and diffraction arising from interaction with a section of tubing. The right photo shows how ultrasound can be focused by a curved surface.

New Applications of the So

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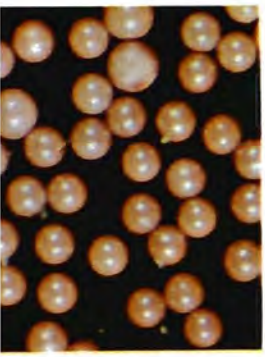

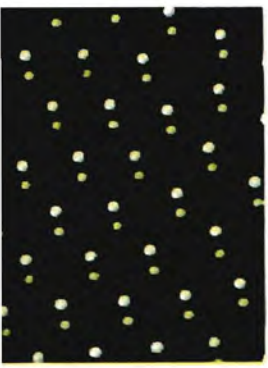

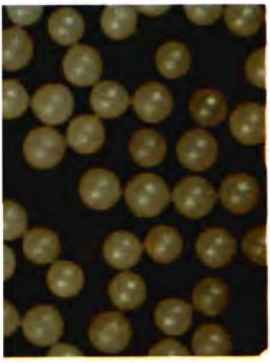

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Isotopes Development Center

The Isotopes Development Center has production and development programs in three principal areas: radioisotopes, stable isotopes, and special research materials. Isotopes are used in every field of science and technology, from medical diagnosis and therapy to isotopic power in space. One of the most interesting of the current applications is the use of thousands of curies of pure radioisotopes, fabricated into safe, usable, compact sources of heat for the generation of electricity. Only a few of the many Isotopes Development Center activities are mentioned here.

Loading of the SNAP-11 generator in the lunar simulation chamber.

Curium-242 Thermoelectric Generator (SNAP-11)

A significant forward step in the achievement of practical isotopic power was taken in the successful completion of the fabrication and testing of the SNAP-11 curium-242 thermoelectric generator, the backup power source for the lunar Surveyor vehicle. The generator produced electrical power by the thermoelectric conversion of heat provided by 7.5 g (25,000 curies) of curium-242, a transuranium isotope until recently considered a laboratory curiosity. The test showed that isotopic power is a contender for use (in the watt-to-kilowatt range) for space applications.

The SNAP-11 program at the Laboratory extended over a four-year period. Production of the curium-242 involved the preparation of americium oxide targets containing 77.4 g of americium-241, their irradiation in the ORR and the MTR, separation of the curium-242 fraction from fission products by solvent extraction, fabrication of the curium oxide into pellets, and sealing the pellets within a container consisting of five concentric capsules made of five different refractory materials. The 20 g of purified curium-242, the largest amount ever processed at one time, was heated to incandescence by its own radioactivity, and completely new techniques had to be developed to handle the hot material and fabricate it into a source. For example, the heat generated by the isotope and by welding operations required the handling of the inner capsule components in a highly purified argon atmosphere to prevent oxidation of the refractory material.

The thermoelectric generator was tested under simulated lunar conditions in a large vacuum chamber. The test consisted of five days at lunar night temperature (−235°F), 80 days lunar day (+235°F), and then five more days at −235°F. The electrical output was 23 W during lunar night conditions and 18 W under lunar day conditions. The power output decreased exactly with the 163-day half-life of the isotope decay, being 20 W at the end of the 90-day test, during which 36,275 Wh of electrical energy was generated, equivalent to the output of about 60 ordinary automobile batteries.

Parent-Daughter Radioisotope Production Systems

Radioisotope generators are useful for supplying short-lived radionuclides on location, as, for example, at a hospital. A short-lived daughter radioisotope is separated (e.g., by elution from an ion exchange column on which the long-lived parent radioisotope is sorbed) to provide a ready supply of short-lived radioisotope. After the short-lived isotope is removed, the daughter isotope again builds up, and further separations are possible for a period of time, depending upon the half-lives of the radioisotopes involved.

A radioisotope generator of this kind was developed for the tungsten-188–rhenium-188 system. Tungsten-188 (half-life, 70 days) is sorbed on an inorganic ion exchanger, and after reaching equilibrium with the parent, carrier-free rhenium-188 (17-h daughter) is very simply eluted with normal saline solution.

Rhenium-188 as the perrhenate ion behaves like iodide and pertechnetate ions in that it is strongly sorbed by the thyroid gland. Rhenium-188 is especially useful in thyroid scanning. Several rhenium-188 generators have been supplied to medical researchers in cooperative programs to evaluate the usefulness of this radioisotope in medical applications.

The production of tungsten-188 itself is interesting and illustrates the type of complex procedures now being used to produce unusual nuclides in the reactor.

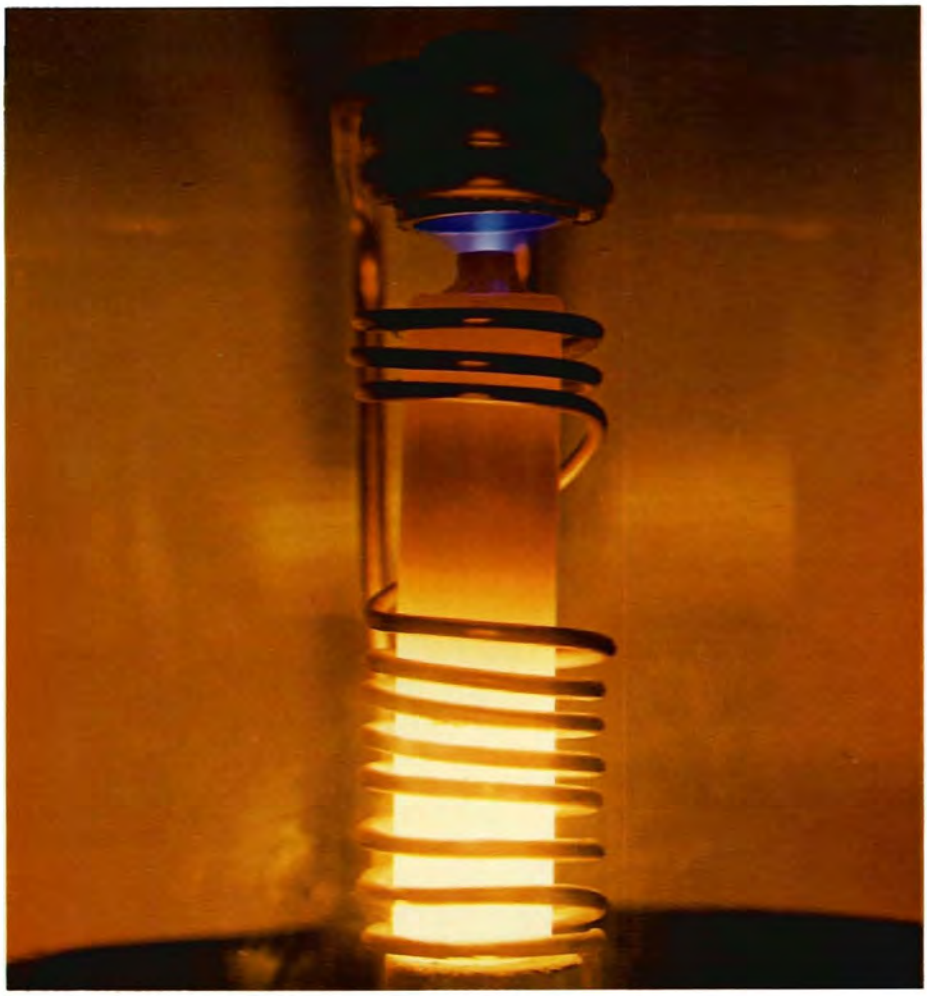
The method used involves two successive neutron captures in an enriched tungsten-186 target. The first, or intermediate, product is 24-h tungsten-187, which captures a neutron to finally produce 70-day tungsten-188. When favorable neutron cross sections occur, practical production by successive neutron captures is possible, especially when enriched target materials and very high fluxes are used.

Iodine-123 for Improved Medical Diagnosis

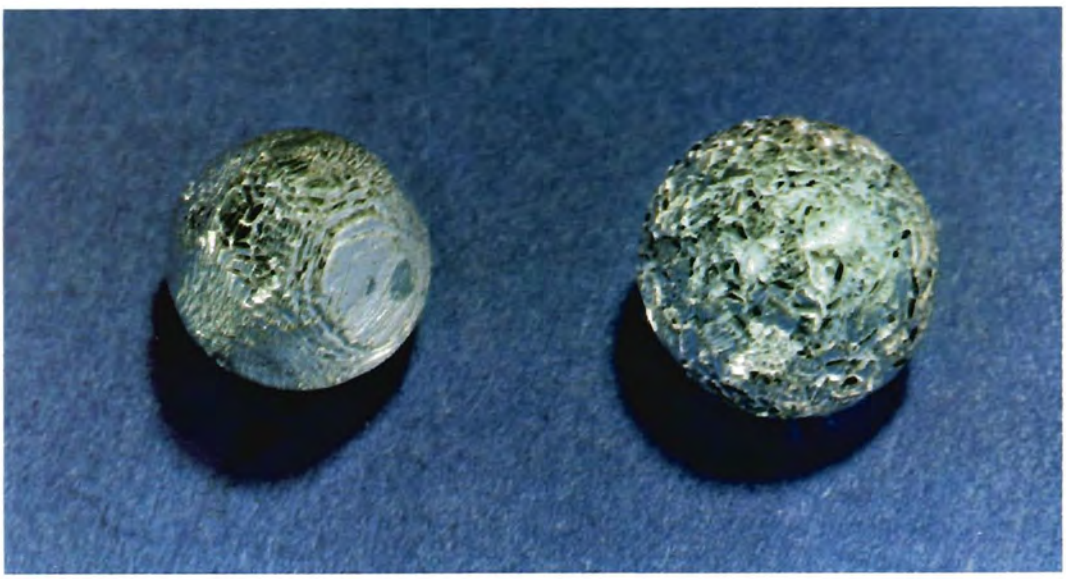
Iodine-123 closely approaches the ideal radionuclide for use in medical diagnostic procedures because of its short half-life (13 h), single low-energy gamma ray, and absence of beta radiation. The internal radiation exposure to the patient from iodine-123 is only 3% of that from an equivalent dose of iodine-131 and 10% of that from an equivalent dose of iodine-125.

Small quantities of iodine-123 were prepared for research purposes by the $^{123}Te(p,n)^{123}I$ reaction in the ORNL 86-Inch Cyclotron. The yield from four bombardments of 230 to 270 mg of 79.2%-enriched elemental tellurium-123 was about 80 mc of iodine-123 per beam hour at 185 μA beam current. Concurrent production of iodine-124, iodine-125, and iodine-126 by (p,n) reactions on the tellurium target was less than 1.5% of the iodine-123 activity at termination of bombardment. The iodine was separated from the target by distillation; 95% of the valuable enriched tellurium target was recovered in a form suitable for another bombardment.

Enthusiastic reports have been received from the investigators at several U.S. medical centers to whom we sent iodine-123 in a cooperative evaluation program.



Reduction-distillation of isotopically separated calcium-40 in an induction-heated tantalum column. Differential heating of the column allows purification by fractional distillation. Ionized calcium metal vapors are issuing from the top of the column.



Magnesium-26.

Reduction-Distillation of Chemically Reactive Metals

Isotopically enriched specimens of many of the more chemically reactive elements, including magnesium, calcium, strontium, barium, neodymium, promethium, samarium, europium, dysprosium, erbium, ytterbium, neptunium, and americium, were prepared as metals for the first time in forms suitable for cross section determinations and solid-state physics experiments.

The process developed for the preparation of reactive metals was the high-temperature reduction of the metal oxide or carbonate and subsequent high-vacuum distillation of the metal, using a reducing agent of sufficiently low vapor pressure to prevent contamination of the condensed product metal. The choice of the reducing element depends not only upon the vapor pressure but also upon the thermodynamic stability of the oxides, the melting point, and availability; typical reductants include aluminum, zirconium, lanthanum, tantalum, and thorium. By using the best combination of reductant and oxide in pelletized form, overall yields of pure metal from 60 to 95% were obtained. Development of special crucibles for use in ultrahigh vacuum distillation and condensation techniques permitted these metals to be formed directly into thin films, "flowers" of polycrystalline material, and even single crystals. In all cases, total chemical impurity levels as low as 10 to 300 ppm were achieved, which makes these isotopically enriched metals comparable with the best available nonenriched material.

Because of the limited availability and great value of separated isotopes, the process was designed to use small quantities of starting material; as little as 10 mg was used efficiently in some cases.

All the metals produced by this technique were sufficiently pure to be cold rolled into extremely thin target foils, between 0.001 and 0.00005 in. thick. Several large elliptical plates of europium-151 and europium-153 were formed this way; each plate contained 10 g of metal prepared by the reduction-distillation technique. The largest quantity of any isotope converted to metal was 65 g of very high purity calcium-40.

Electromagnetic Separation of Isotopes

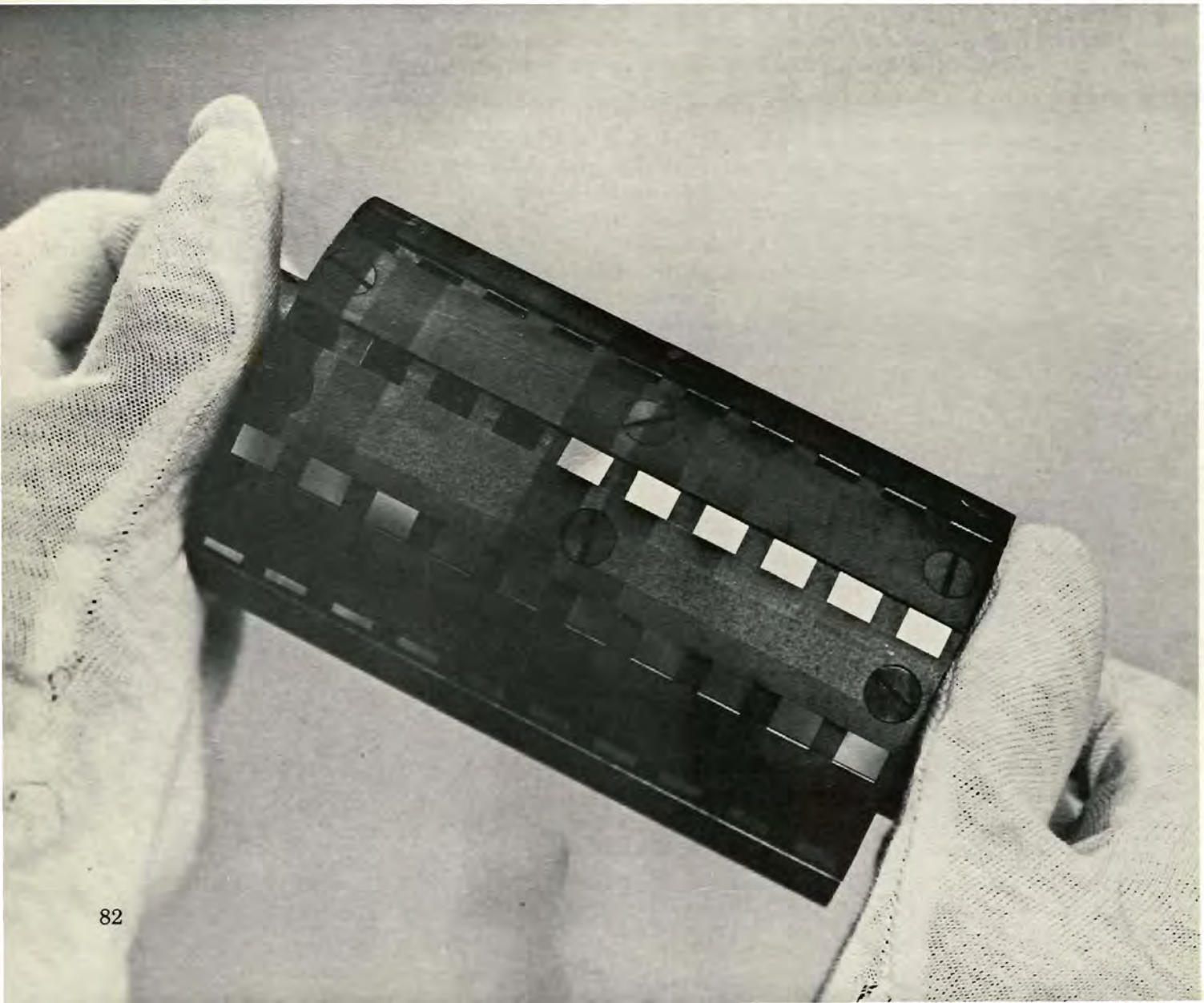
The electromagnetic isotope separators (calutrons) at ORNL were originally designed for processing relatively large quantities of materials. Over the years, changes in source design have reduced the quantity of input material needed for a satisfactory separation to about 1 g. Separation of the isotopes of the transuranium elements in milligram quantities will be needed in the near future. In anticipation of this need we have demonstrated that the calutron can be used to process 1 to 10 mg of feed material with reasonable efficiency. As little as 1 mg of uranium feed used in short (2-h) runs yielded 30- to 100-μA currents of U^+ ions. Extraordinary beam resolution was achieved, and in one run in which the enriched isotope was collected and assayed, the 0.7% uranium-235 in normal uranium was enriched to 94.3% uranium-235 in a single pass.

Ion Implantation

Ion implantation of small amounts of certain elements into substrates in the calutron is a service performed for research organizations interested in the development of new semiconductors and related electronic devices. A modified calutron provides for substrate bombardment with any stable or suitable radioactive ion species within the energy range of 200 to 160,000 eV. Rates of ion deposition can be varied from fractions of a microampere to hundreds of microamperes per square centimeter, and doses well below saturation are controlled accurately. Rotating target holders (see figure) permit the implantation of ions into 100 substrates at a single loading; individual rows of substrates (ten rows of ten substrates each) permit a wide latitude in choice of services performed (e.g., change in energy, ion species, dosage, or dosage rate).

Within the past year, many substrates, ranging from aluminum to quartz, were bombarded with many kinds of ions at densities up to 5×10^{16} ions/cm^2 and energies ranging from 2.5 to 40 keV. A typical calutron implantation of ions into a group of 700 substrates requires about 30 h of operating time.

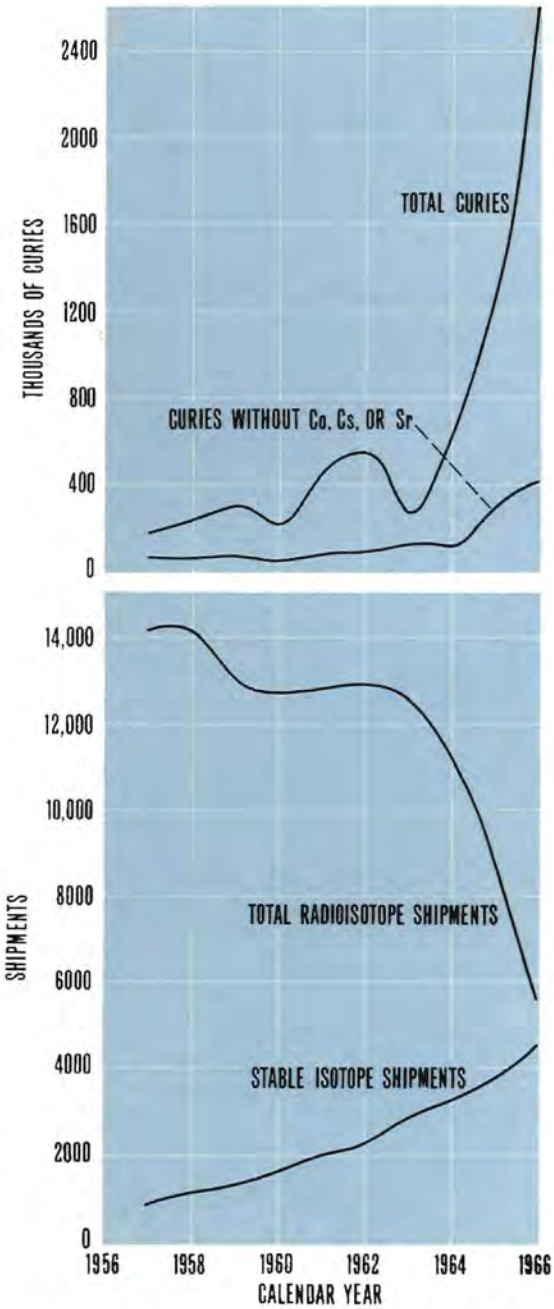
Target holder for use in multisubstrate implantation of calutron-produced ions. Rotation of the holder aids in the attainment of a uniform deposit, while the various rows of substrates allow different kinds of material to be processed at one time.

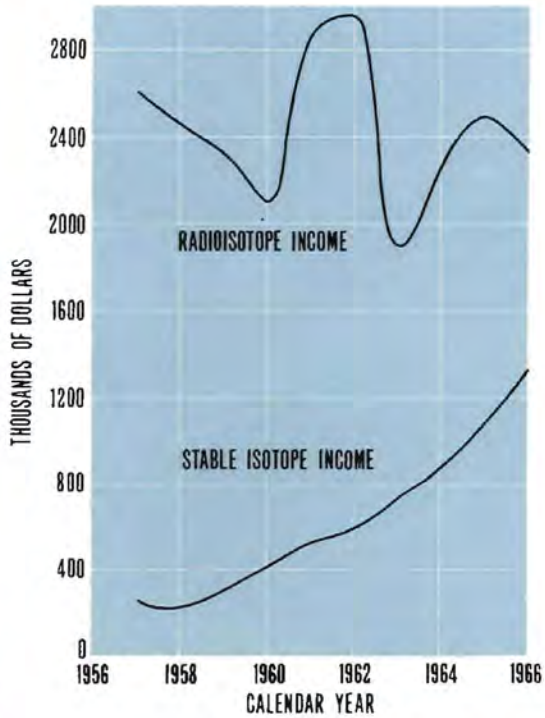


Isotope Production

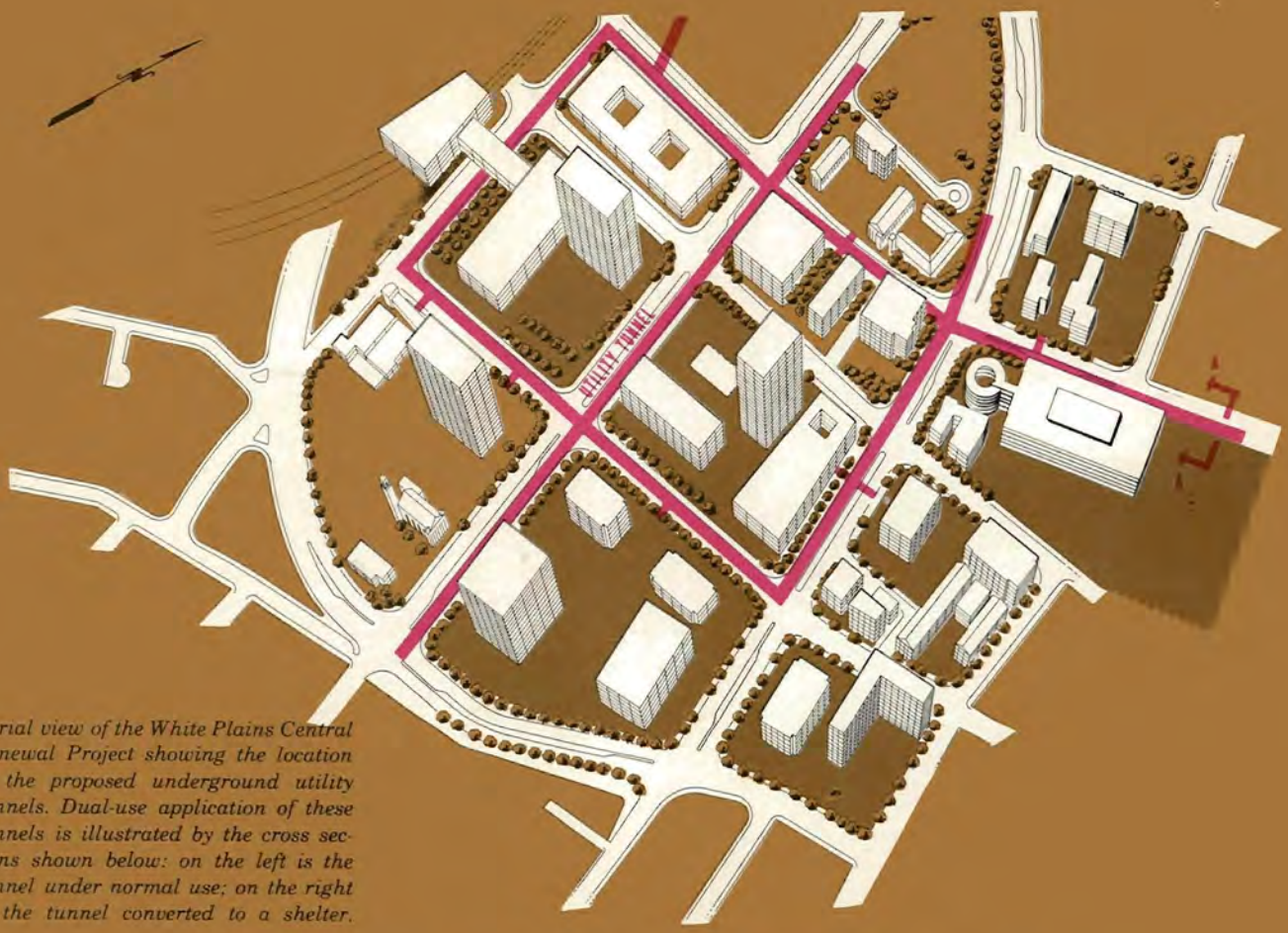
The withdrawal of ORNL from routine radioisotope production in favor of commercial radioisotope producers continued in 1966. Thirty-four isotopes now have been withdrawn from ORNL production and distribution.

During the year, 5319 shipments totaling 2,608,000 curies were made. The gross income was $2.33 million, a decrease of about 6% compared with 1965. Sales of stable isotopes and other special research materials climbed 115% in 1966, to a total of $2.02 million. The trends during the past decade are shown in the accompanying graphs.





Civil Defense



Aerial view of the White Plains Central Renewal Project showing the location of the proposed underground utility tunnels. Dual-use application of these tunnels is illustrated by the cross sections shown below: on the left is the tunnel under normal use; on the right is the tunnel converted to a shelter.

SECTION A–A

The Civil Defense Research Project, with its diversified staff of physical scientists, engineers, and social scientists, is attempting to develop and evaluate alternative systems to protect the population from the moment that a nuclear attack becomes likely through the recovery period when people have emerged from their shelters and are starting to resume a near-normal existence.

Areas of research include the technical and economic feasibility of sheltering urban populations from the blast overpressures from nuclear explosions, combinations of shelters and anti-ballistic missiles that would most effectively limit damage, attitudes of citizens and their leaders toward various defense systems, the vulnerability of U.S. food supplies and critical industries (e.g., petroleum), the thermal threat from nuclear weapons, emergency salvage of livestock, and the feasibility of dual use of protective shelters.

Major interest continues to center around the protected-city concept, with emphasis on the dual-purpose approach for using existing or planned underground interconnected installations as shelters. The original concept of a possible tunnel-grid system of underground traffic tubes in Manhattan has been extended to such below-the-street structures as a rapid-transit system in Washington, D.C., and a truck route and pedestrian walkway in Dallas. Drawings and cost estimates have been produced for the emergency use of these structures as shelters.

The most recent dual-use application is the urban utility tunnel. Such a walk-through tunnel that could include all utilities (fuel gas, water, electricity, telephone, hot and cold water lines for air conditioning and heating, etc.) has been designed for possible use in a White Plains, New York, urban renewal project. Studies are now in progress to compare the cost of this tunnel system with the cost of the traditional system of burying utility lines in the ground and to determine the costs (both incremental and deferred) of strengthening the tunnel to afford blast protection. Two other functions being considered for utility tunnels are the movement of solid wastes and the transfer of goods to and from businesses. Performing these services below the ground would increase the spaciousness and the beauty of the surface for man.

The possible use of utility tunnels as shelters underscores the social aspects of civil defense by linking it with urban renewal and new-city planning. The union of civilian emergency protection with convenience and aesthetics can be accomplished if, for example, city planning and defense planning go hand in hand. There appears to be little evidence of such coordination. But before such coordination could take place, we need a national decision to improve strategic defense and an organizational framework to improve the ability of local, state, and federal officials to work together on this common problem.

Meanwhile, technical efforts to improve interconnected shelter systems continue. Knowledge of the behavior of shock waves in tunnels, for example, is very important, since the blast effects of weapons are most important, especially in cities. There is reason to believe that the protection afforded by a tunnel shelter can be improved by devices such as baffles and blast doors, which hinder the entrance of shock waves into the tunnels or attenuate them once they have entered. We have built an explosively driven shock tube to study the effectiveness of different kinds of such devices. The shock tube serves two purposes in these studies: one part acts as a "gun" to produce shock waves, while the rest acts as a model of the protective tunnel.

It is increasingly apparent that the problem of achieving an effective system of protection of the United States against nuclear attack is one of the most complex problems we have ever faced. The achievement of such continental protection rests not only on an increased understanding of the social, political, and technical aspects involved but also on the interdependence of all three of these.

Information, Education, and Industrial Cooperation

The areas of technical information, education, and industrial cooperation in Oak Ridge National Laboratory are all concerned with the basic purposes of a research laboratory, namely, the gain and use of new knowledge. The Laboratory's success in these objectives is shown, in part, by its technical reports, its published books and papers, its papers at meetings of technical societies, and the theses written by those doing graduate study. In a typical year our technical staff averages, per man, about one technical paper published in the journals or given at meetings. These total over 1500 papers. Most of the staff contribute to the 500 or so Laboratory reports, which are primarily for other government laboratories and for intralaboratory communication. About 100 members of the Laboratory's technical staff are doing part-time graduate study; they produce about 50 theses a year which lead to advanced degrees.

TECHNICAL INFORMATION

The libraries, with the participation of the Mathematics Division, are adopting computer techniques wherever they prove useful and economical.

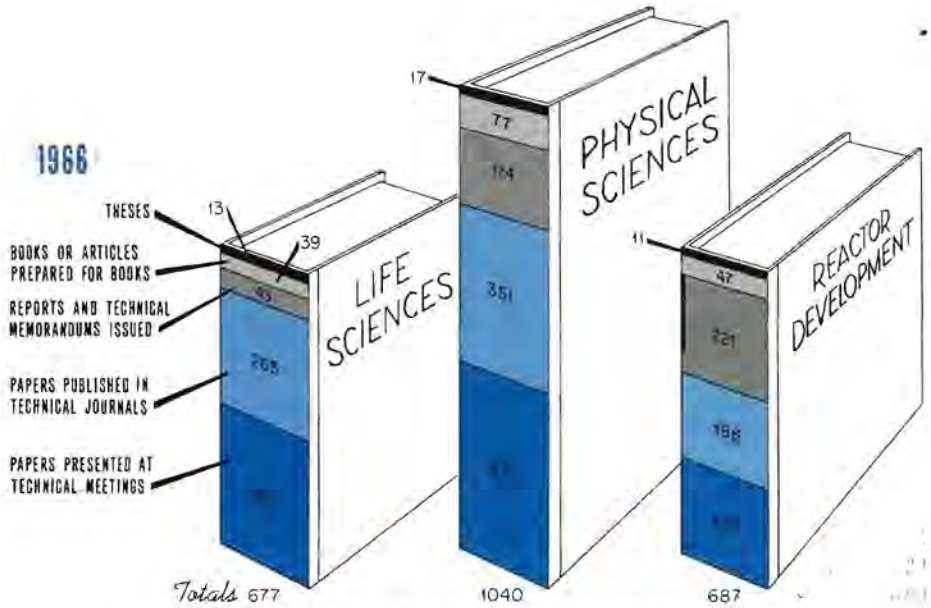
The computerized indexing system called KWIC (key word in context) provides a subject index to Laboratory reports. The basic program runs in machine language on an IBM 7090 computer. It has been extended to the annual listing of publications and speeches by staff members, the annual cumulative index for the *ORNL Master Analytical Manual*, the journal *Nuclear Safety*, bibliographies, and several information center files.

The computerized circulation system provides information on about 6000 books. The program runs on an IBM 360. The input includes shelflist information on books and identification information on library users. At the time a loan transaction takes place, the book information and the user information are merged in an IBM 357 system, which becomes the input to the IBM 360. The output is a daily updated list of books on loan arranged by book call number and by user badge number. The listing includes due dates, and the computer prints out overdue notices. The computer is also programmed to keep statistics on book loans and provides an inventory of missing books and books out on long loan.

The shelflist information, keypunched for the circulation system, is also used as input for the book catalog programs. These programs are written in COBOL for the IBM 360. The output is an author catalog, a subject catalog, and an authority file showing the author and subject entries.

The library has initiated a two-phase computer program for handling records on serials (journals). The first phase became operational in July 1966 and handles financial information. The second phase includes holdings information and will begin operation during 1967. The programs are in COBOL and are currently run on the IBM 7090. Approximately 4600 different journals are included in these detailed programs.

This chart shows the open-literature publications in the calendar year 1966. The total of all publications for 1966 is about the same as for 1965.



NUMBER OF CONTRIBUTIONS FROM ORNL MADE AVAILABLE TO GENERAL PUBLIC

INDUSTRIAL COOPERATION

The Office of Industrial Cooperation is the branch of the Laboratory whose principal responsibility is to encourage the dissemination of new technical information to industry. It seeks to identify the developments that will be most useful to industry and to supplement the traditional reporting channels by such means as the general news release and the Industrial Cooperation Conference. Firms interested in the application of new technology in their own operations may obtain more detailed information from the Laboratory. Arrangements for such assistance are handled through the Office of Industrial Cooperation.

During 1966, more than 1500 industrial visitors came to the Laboratory for individual technical conferences with members of the staff. Many more attended scheduled seminars, conferences, and meetings. To others, technical information was sent by mail in response to specific requests. There were 28 news releases from the Laboratory containing technical information related to new developments. One of these concerned a new self-repairing filter membrane. Another described a new rescanning technique to increase the accuracy in locating diseased tissue or tumors in patients examined by radioactivity scanning methods. Eight persons from industry were assigned to work with Laboratory personnel for various periods of time during the year to gain information or on-the-job experience for their parent firms.

Members of the Laboratory staff provided consulting services to industry throughout the year. These services included assistance in the

commercial adaptation of centrifuge equipment, help in the design of commercial equipment for handling radioisotopes, advice used for the design of radioisotopic sources for various commercial applications, and help in the modification of a commercial model of a meter developed at the Laboratory for the identification of metals. The metal identification meter was about to be marketed in volume at the end of the year.

The country's first privately owned plant for processing nuclear fuel began routine operation during 1966 at West Valley, New York. The facility is based on technology developed, for the most part, at the Oak Ridge National Laboratory. Technical assistance purchased from the Laboratory during the planning, construction, and startup of the plant totaled 266 man-days, including consulting and on-site assistance during design, installation, and testing of many of the process steps and in the training of operators.

INFORMATION CENTERS

The Laboratory's 13 information centers, with one exception, were established about three years ago. The centers have developed publication and communication methods suited to their purpose and to the technical area in which they function.

The activities of the *Radiation Shielding Information Center* have become increasingly international. Through participation in seminar-workshops held at the European Nuclear Energy Agency's Computer Programme Library at Ispra, Italy, and visits by staff members to European nuclear installations, a regular scheme was developed for exchanging computer codes in shielding with European scientists.

The *Nuclear Safety Information Center* greatly expanded its selective dissemination of information (SDI) program. The computer-printed cards, containing information selected on the basis of the participant's "interest profile," now reach about 700 members of the nuclear community. During 1966 the Center issued ten reports describing the state of the art in special areas such as secondary shutdown systems for nuclear power plants, filters, sorbents, and air-cleaning systems used as engineering safeguards in nuclear installations. The scope of the Center includes earthquake considerations for nuclear plant design.

The *Research Materials Information Center* experienced a marked increase in the number of queries received during the past year; the current number of nine questions per day is nearly twice the average number for 1965. Several bibliographies were prepared. The collection of coded microfilm was provided with a suitable index.

The *Isotopes Information Center* observed the twentieth anniversary of the first commercial isotope shipment from Oak Ridge. This culmination of 50 years of work by scientists from all parts of the world was commemorated by a special issue of *Isotopes and Radiation Technology* on the history of isotopes and radiation, both before and after the Manhattan Project.

During the past year the *Atomic and Molecular Processes Information Center* (AMPIC) has been fully operational, with the writing of an IBM 7090 program for the tabulation and retrieval of pertinent critical data. The Center has entered into a formal contract agreement with John Wiley and Sons, who will publish selected evaluations and reviews in monograph form.

The publication of nuclear information developed by the *Nuclear Data Project* in *Nuclear Data*, a journal devoted to compilations and evaluations of experimental and theoretical results in nuclear physics, by Academic Press has been very successful. Section A presents contributed papers by authors anywhere; Section B is limited to the Nuclear Data Sheets prepared by the ORNL Nuclear Data Group. Subscription prices are $15.00 per volume of 600 pages. The number of subscribers to Section B exceeds those to the old Sheets published by the National Academy of Sciences, and those to Section A, a completely new venture, are only slightly less.

In order to reach a broader audience, the *Charged-Particle Cross Section Data Center* started to use the journal *Nuclear Data* as its outlet. During the past year two compilations were published, covering the nuclear cross sections for charged-particle-induced reactions in lithium, beryllium, boron, and carbon.

EDUCATION AND UNIVERSITY RELATIONS

A primary responsibility of the Office of Education and University Relations is the extensive program of education and university cooperation at the Laboratory. There are a number of programs conducted in cooperation with the Oak Ridge Associated Universities.

The Research Participation Program, which is conducted jointly with the ORAU, has been in effect at the Laboratory for 16 years. About 50 faculty members of colleges and universities, selected from applicants on the basis of anticipated benefit to the applicant and his home institution, are at the Laboratory each summer; a total of 1000 appointments had been made through 1966. In addition to the Research Participants, between 25 and 30 other summer appointments are arranged annually for university faculty. A total of 80 staff members of colleges and universities were at the Laboratory in the summer of 1966.

The Traveling Lecture Program, also conducted in cooperation with the ORAU for the past 16 years, provides lectures to degree-granting institutions throughout the United States. Because of budgetary and other limitations, only half of the some 500 requests received annually can be filled. During the 1965–66 academic year, 84 members of the Laboratory staff presented 257 lectures at 117 institutions.

The summer program for technical students was continued; 174 students were appointed in 1966. Of these, 24 were graduate students, 86 were undergraduates who had completed at least two years of college, and 64 were third-year students assigned at the Laboratory under the ORAU Summer Trainee Program.

Other students spend from one to three years at the Laboratory engaged in thesis research. During 1966 there were 50 Oak Ridge Graduate Fellows at ORNL; in addition to these, 53 candidates for the M.S. degree and 58 candidates for the Ph.D. were engaged in thesis work at the Laboratory. The Oak Ridge Graduate Fellowship Program is administered by the ORAU. Since 1950, when the program was first established, 127 Fellows have received degrees following completion of their thesis work at the Laboratory.

The first AEC postdoctoral Fellow under the program administered by the Oak Ridge Associated Universities was assigned at the Laboratory in 1965. Nine of these Fellows were engaged in postdoctoral research at the Laboratory during 1966. In addition to them, there were at the Laboratory 60 young scientists who either held formal postdoctoral appointments, such as those granted by the U.S. Public Health Service, the National Institutes of Health, and the National Science Foundation, or held temporary appointments to the Laboratory's staff of the kind that is commonly regarded as postdoctoral.

In September 1966, the Massachusetts Institute of Technology established a school of chemical engineering practice at the Laboratory; ten students were enrolled in the first of four sessions scheduled during the academic year. The school provides practical experience, under supervision of Laboratory staff, for young engineers who are earning a master's degree at the Institute. Two members of the Institute's faculty spend full time as director and assistant director of the school.

Under a special arrangement with the University of Tennessee, 30 members of the Laboratory's senior staff are permanent members of the University faculty on a part-time basis.

A formal program in Health Physics continues with Vanderbilt University. From 15 to 20 students spend the summer quarter at the Laboratory under the Atomic Energy Commission Special Health Physics Fellowships, and staff members of the Laboratory's Health Physics Division are part-time professors at Vanderbilt.

The University of Tennessee Oak Ridge Graduate School of Biomedical Sciences is undergoing its developmental year. R. C. Fuller became its director on September 1, 1966. The design of a building, to be erected on a plot of six acres that is adjacent to the Biology Division and which the Atomic Energy Commission has deeded to the University, is progressing. The building is expected to be completed in late 1969. Meanwhile, space within the Biology Division is being adapted for use by the School.

John Cook, a physiologist, has been appointed Professor of Biomedical Sciences, effective July 1, 1967, and Donald Olins, a biophysicist, will become Assistant Professor of Biomedical Sciences. Several members of the Oak Ridge National Laboratory's staff will join the faculty on a part-time basis.

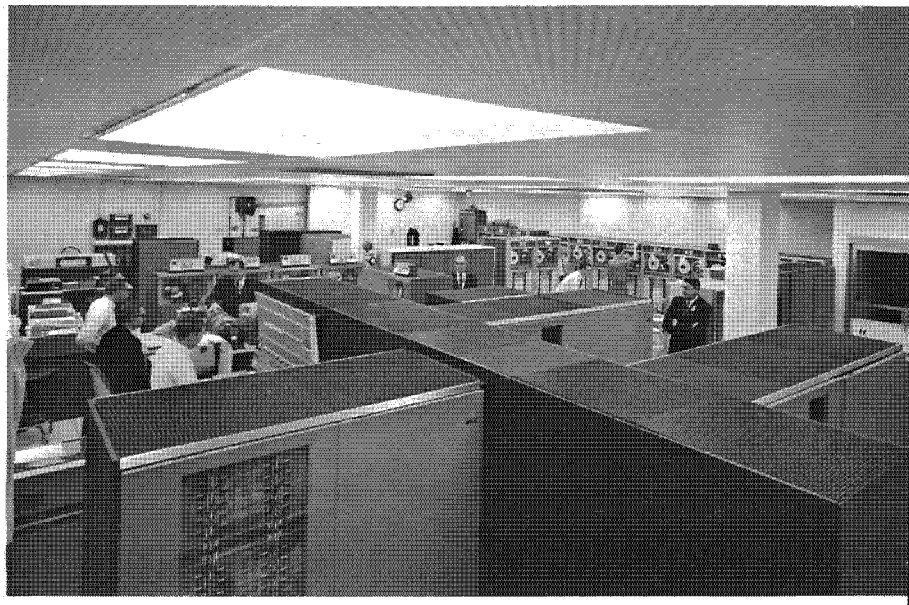
The University has purchased eight apartment buildings in Oak Ridge for housing students and for the development of a student center. The Union Carbide Corporation has contributed $100,000 for student facilities exclusive of housing. Alexander Hollaender, the School's first Professor of Biomedical Sciences, has given his entire collection of scientific journals to what is expected to become an excellent library.

From more than 150 applications that have been made, about a dozen students will be selected for the first class, which will begin in the fall of 1967.

Operations and Services

The Oak Ridge National Laboratory provides assistance to its professional staff with skilled specialists, technicians, and craftsmen, who operate one of the world's most advanced physical plants for research and development. Research workers may devote most of their attention to scientific work, while auxiliary needs are handled by the services staff. Sixteen divisions, departments, and staff offices devote their efforts primarily to service and operations work; four research and development divisions also provide special services; many services are also available from other Union Carbide Nuclear Division units.

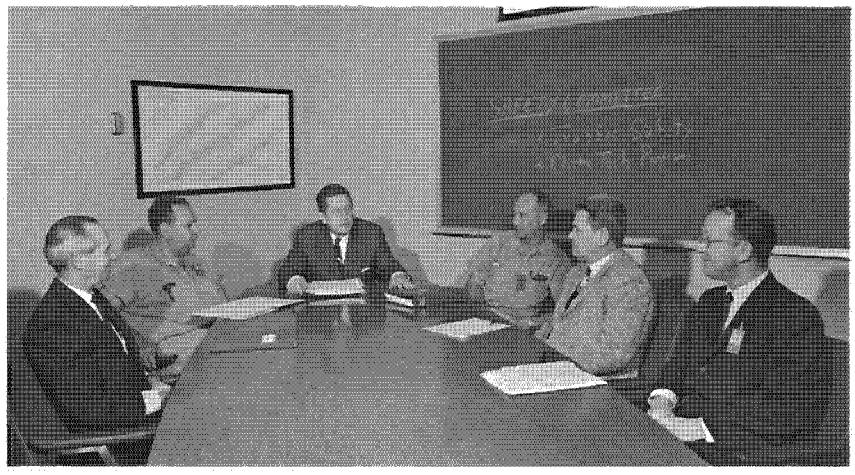
1. The ORNL Computing Center includes an IBM 360/75, shown in the foreground, and a CDC 1604-A, in the left rear. Many problems of great complexity, often types that are completely intractable without the use of such computers, are handled in this center.



1

2. The General Safety Committee, shown here in one of its regular meetings, was organized in 1966. The Laboratory received the Union Carbide Corporation's highest recognition, the Award for Distinguished Safety Performance, in 1966, achieving the lowest disabling injury frequency rate, 0.51, in ORNL's history.

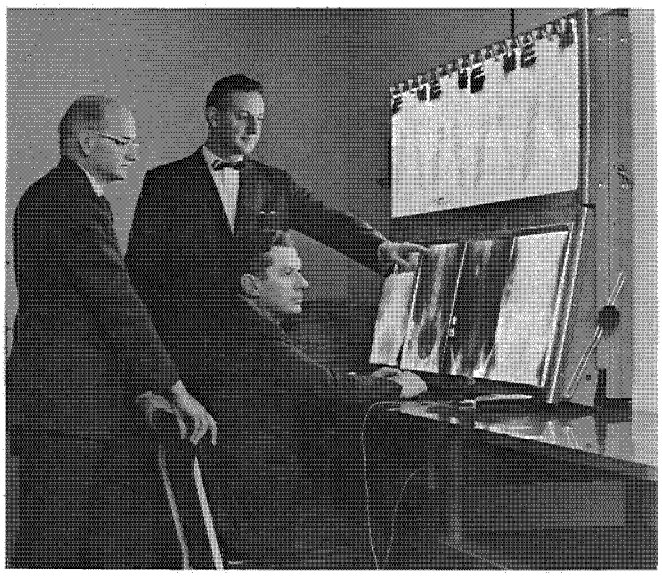
3. Two physicians of the Health Division consult with a radiologist on a difficult diagnostic problem.



2

4. Very complete analytical services are available at ORNL. A spectrographer is determining the purity of a separated stable isotope on a double optical spectrograph. With this arrangement, a spectral range is covered that ordinarily would require two exposures.

5. Workers changing one of the 1840 filters used in Laboratory exhaust systems. More than 1,000,000 ft³ of potentially contaminated air is filtered each minute. The filters remove particles down to 0.3 μ size with 99.95% efficiency.



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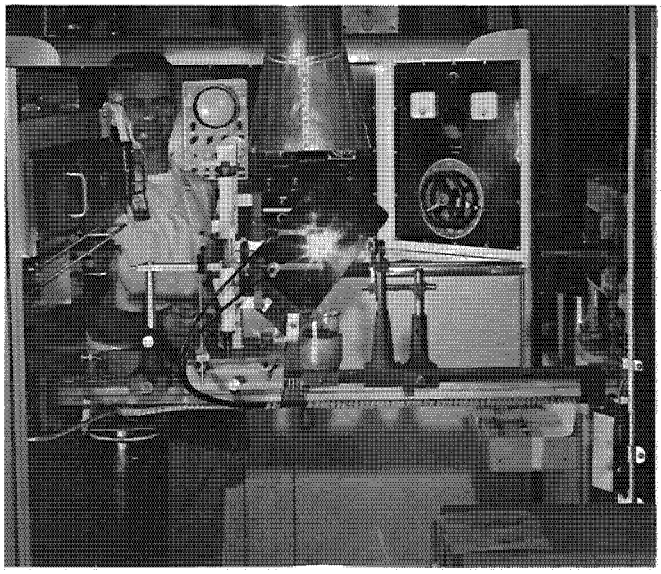

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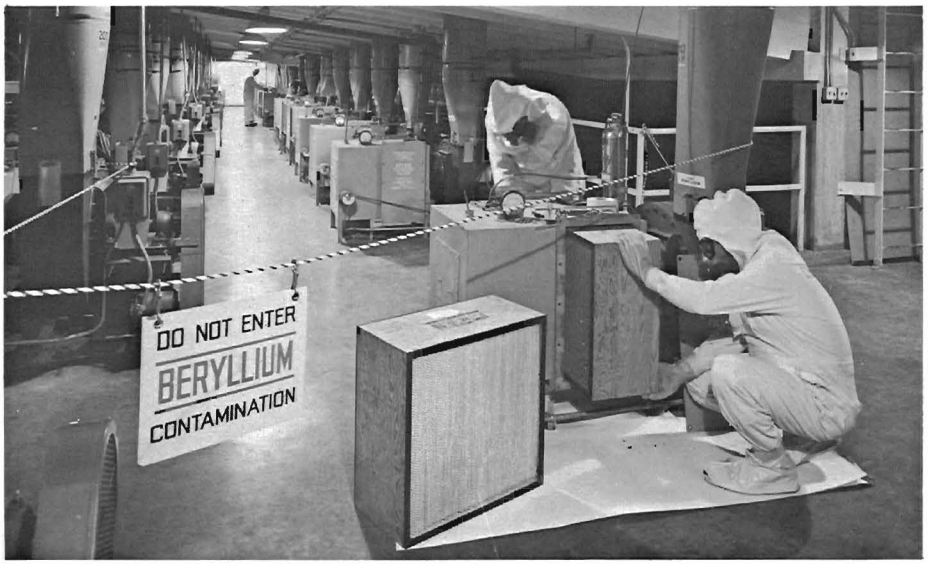
The ORR operating at 30,000 kW, the LITR at 3000 kW, and the BSR at 2000 kW provide a wide range of irradiation and experimental facilities for the Laboratory's research programs. All three reactors are routinely operated from a single control room.

LOW—INTENSITY TEST REACTOR

REACTOR CENTRAL CONTROL

OAK RIDGE RESEARCH REACTOR

BULK SHIELDING REACTOR



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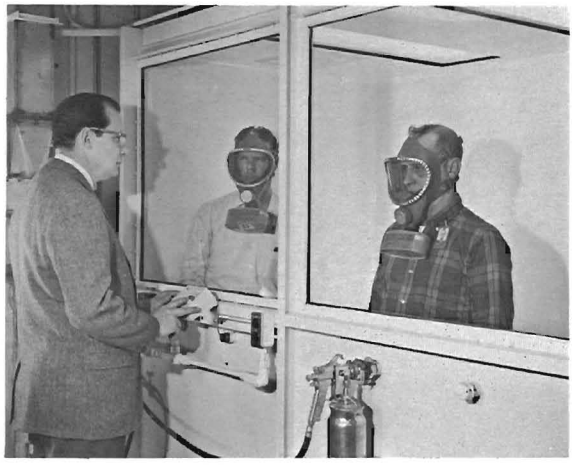
6. Custom fitting of full-face respirators in test chamber. Tests are made to determine the type of equipment for the worker's facial contours to give him maximum protection and comfort. About 150 pieces of respiratory equipment are issued to employees each day.

7. Apprentice training includes classroom work in addition to direct instruction in craft work.

8. An automatic camera for printing full-size copy from microfiche film—a 13-fold enlargement. A 4 × 6 in. title microfiche can contain up to 58 pages and a trailer microfiche up to 70 pages of a book or report; this is convenient for storage and handling. This camera was designed by Graphic Arts personnel and built in Plant and Equipment shops.



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9. Approximately 25 apprentices are trained each year in ORNL shops. Many of the finest craftsmen at the Laboratory received their training in this apprentice school. Here an apprentice is being instructed in the use of optical equipment for checking the accuracy of a rotary table.

10. Apprentices and instructors are using a milling machine in fabricating one section of a High Flux Isotope Reactor shielding plug.

11. The Laboratory shift supervisor represents the Laboratory Director on off shifts, holidays, and weekends in maintaining continuity of operations, controlling emergency services, and providing necessary services in the absence of regular Laboratory forces.

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