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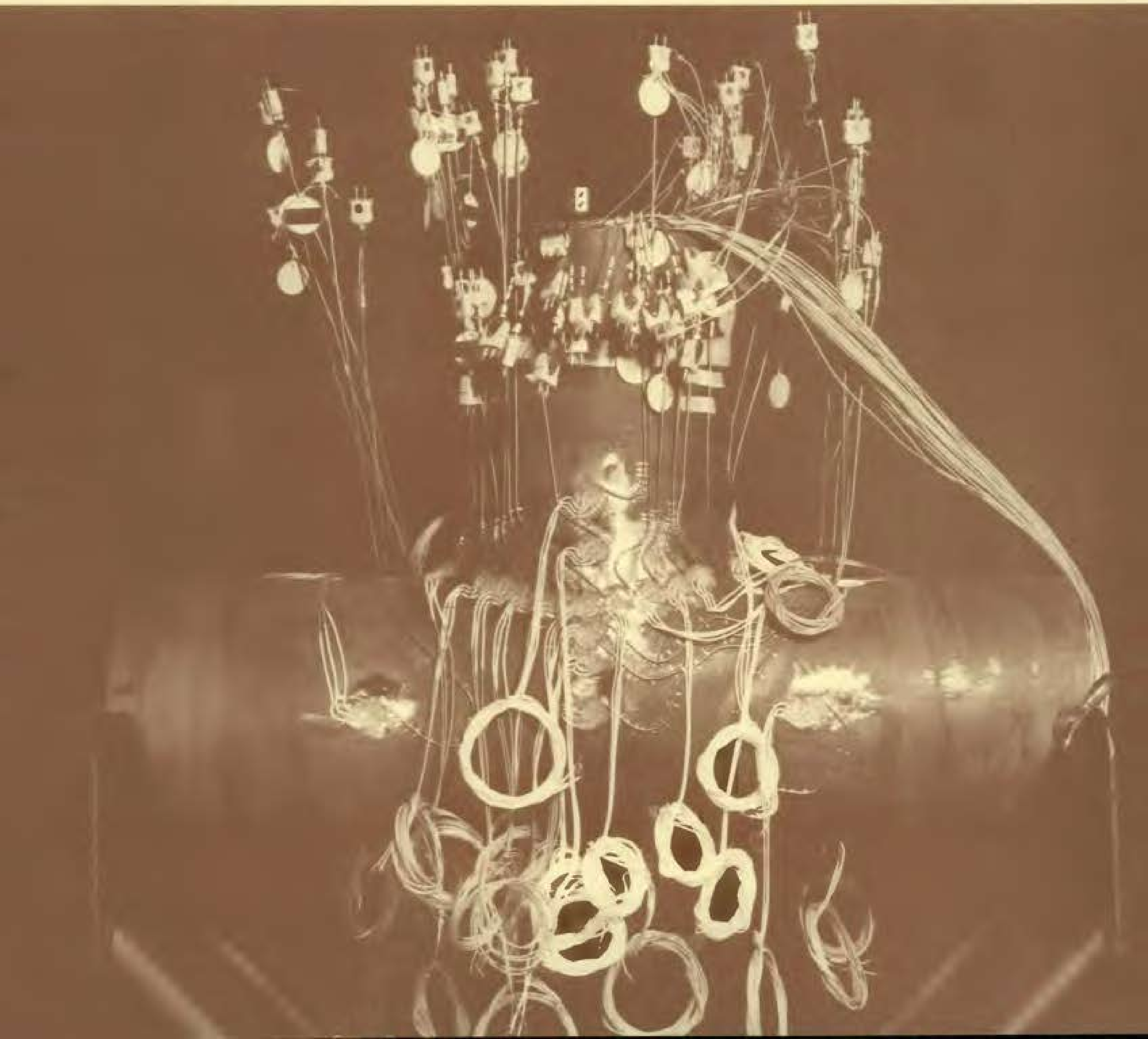
REVIEW

OAK RIDGE NATIONAL LABORATORY · WINTER 77



THE COVER: This forged piping tee, instrumented with strain gauges and thermocouples to help measure the response of nuclear reactor piping to thermal expansion loads, is one of the more splendidly bedecked test assemblies designed for ORNL experiments pertaining to LWR safety. For a comprehensive discussion of ten reactor safety projects under way at ORNL, see page 1. (Photo: Charles Tucker.)

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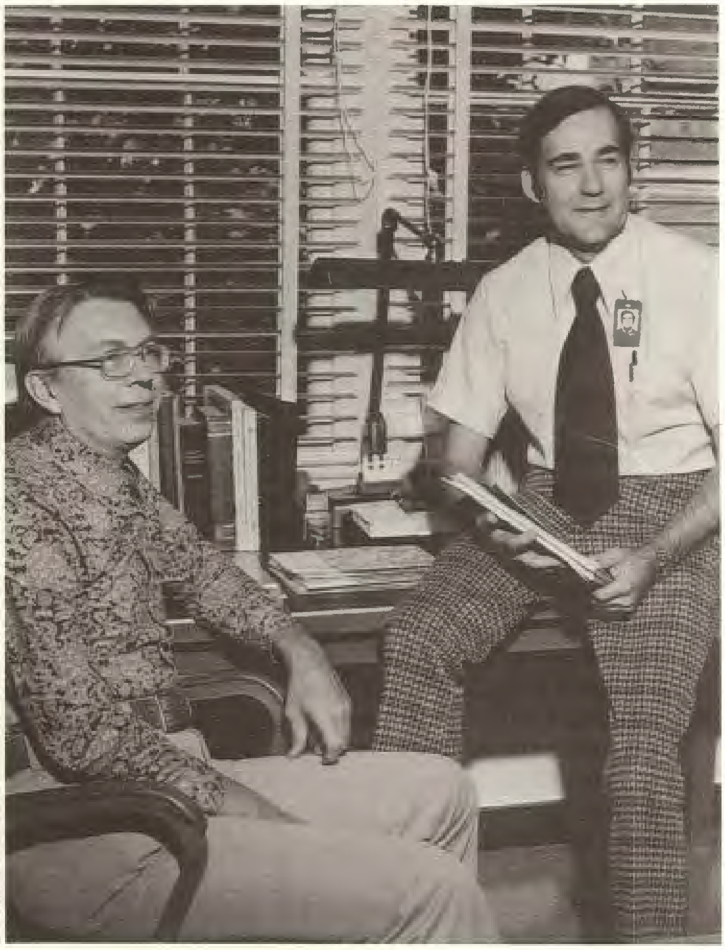
REVIEW

VOLUME 10, NUMBER 1 WINTER 1977

FEATURES

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION • FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION



CHARLES TUCKER

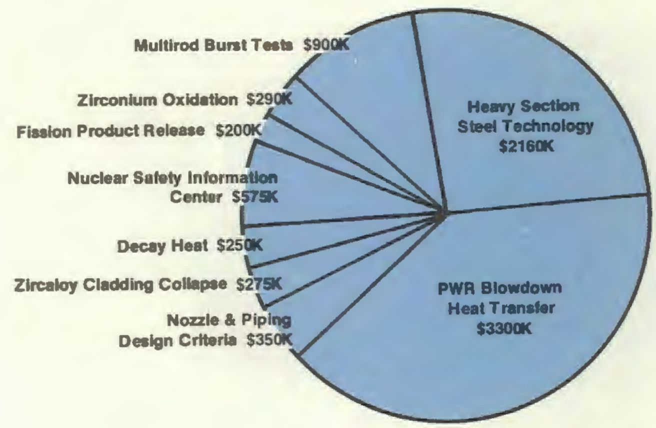
ORNL's Water Reactor Safety Research Program, sponsored by the U.S. Nuclear Regulatory Commission (NRC), encompasses ten experimental projects relating to the behavior of reactor systems under extended operation or accident conditions. These projects, discussed in the following article, are well known to Bill Cottrell, left, and Joel Buchanan (both of the Engineering Technology Division), who are involved in NRC-sponsored activities concerned with the dissemination of safety information. Cottrell is both editor of *Nuclear Safety* and director of the Nuclear Safety Information Center (NSIC), of which Buchanan is assistant director. Over the 18 years of *Nuclear Safety*'s bimonthly publication, it has evolved into a widely read, peer-reviewed journal of international acclaim. Primarily a review periodical, it provides information on the safe design, construction, and operation of facilities in the nuclear fuel cycle. The journal has received several awards from the various competitions sponsored by the Society for Technical Communication. NSIC is staffed by 15 technical experts who review all relevant safety literature bibliographic references, which are then stored in a computer file. Experts rely on the file to help them write state-of-the-art reports and bibliographies or to respond to information requests.

Water-Reactor Safety:
The ORNL Experiments

By CAROLYN KRAUSE

The scenario is familiar to nuclear safety experts and nuclear critics alike. A pressurized-water reactor (PWR) is operating routinely with the coolant water flowing through four large pipes into the reactor vessel at 2250 psi and 325°C. The coolant water, used both to prevent the fuel from overheating and melting and to carry away heat to make steam for generating electricity, is kept under pressure to prevent it from boiling. Suddenly, one of the coolant pipes breaks, and the water bursts forth. The pressure plummets. The coolant water flashes to steam. It is a loss-of-coolant accident (LOCA), an extremely unlikely event, but the prospect of which is everybody's nightmare. However, in less than 10 sec after the rupture, loss in pressure activates the emergency core cooling system (ECCS). To cool the core, water contained in gas-pressurized accumulators is injected from below into the vessel, and this function gradually is superseded by a slower-acting pumped-water system. The ECCS, like a fire hose turned on in time to douse a potentially destructive blaze, brings the overheating core under control and cools the fuel as the reactor is shut down. In the parlance of nuclear engineers, it is a successfully terminated LOCA. The emergency cooling successfully prevents the radioactive fuel and its fission products from melting

How $8.3 million of NRC funds are apportioned to the Laboratory's LWR safety projects for fiscal 1977 is shown in this chart.



through the fuel rod cladding, the primary pressure system, and the containment shell. Despite the accident, the neighboring public is protected; hazardous amounts of radioactivity are *not* dispersed to the environment, where they could damage property and increase the risk that members of the neighboring population might develop cancer and genetic diseases.

Even if the ECCS works as expected, there are still a number of questions that must be answered. Computer codes to describe the consequences of a hypothetical LOCA are still being refined; however, many of the inputs on which the codes are based have not been experimentally verified. This is where nuclear safety researchers at Oak Ridge National Laboratory and elsewhere enter the picture. The U.S. Nuclear Regulatory Commission (NRC) is sponsoring a number of light-water-reactor (LWR) safety research projects at ORNL at an annual cost of more than $8 million. The objective of many of these projects is to design experiments and gather data to determine the validity and conservatism inherent in the computer codes that are used to describe what happens during a LOCA and to provide the regulatory people with a basis for setting limits on reactor design and operation. As Tony Malinauskas of ORNL puts it, "A major goal at NRC is code validation."

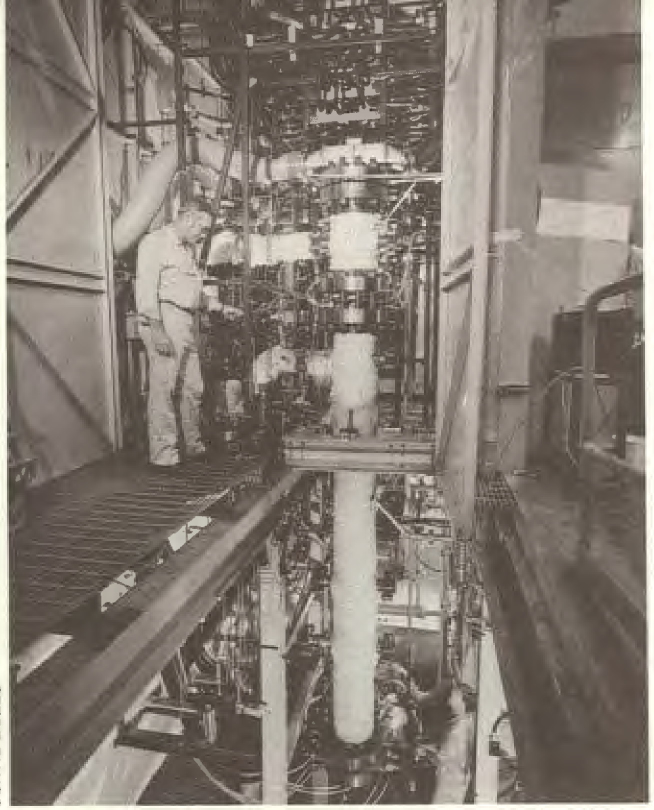
The codes and the ORNL experiments address a number of questions associated with a LOCA: How hot do the fuel rods actually get during the postulated LOCA? How long after the pipe break is the condition of critical heat flux, and when is reduced cooling attained? Will the steam oxidation of the Zircaloy fuel cladding make the cladding so brittle that it might shatter when the emergency cooling arrives? As the coolant pressure drops, will the fuel rods become so hot and the cladding so weak that the internal pressure will cause the rods to swell sufficiently to restrict or even block circulation of the emergency coolant through the bundle? If the fuel rods burst, to what extent and in what forms would the radioactive fission products be released? From a physicist's point of view, how much heat load (from the fission products decaying into stable isotopes) will the ECCS have to handle? Will a flawed reactor vessel operated at design temperatures be able to withstand the thermal shock of cold water from the ECCS?

The ORNL studies, concerned mostly with PWRs, are carried out in four divisions—Engineering Technology, Metals and Ceramics, Chemical Technology, and Neutron Physics—with assistance from the Analytical Chemistry and Instrumentation and Controls Divisions at ORNL and the General Engineering and Computer Sciences Divisions of Union Carbide Corporation-Nuclear Division. In addition to studies on avoiding significant public consequences from a LOCA, ORNL safety research also encompasses accident-prevention studies to determine the margin of safety inherent in fuel rods, pressure vessels, nozzles, and piping designed to withstand the cumulative stresses of normal and near-normal operation as well as of accident conditions.

"We view this as being a very important effort," says Don Trauger, associate director for nuclear and engineering technology. "It ranks high in our priorities for nuclear programs and is important for the overall solution of national energy problems."

PWR Blowdown Heat Transfer Studies

The most severe, hypothetical LOCA in a PWR, according to many scenarios, is characterized by the rupture of a major cooling water pipe and the consequent loss of pressure and water coolant as it flashes to steam—a phenomenon known as blowdown. The changes in the coolant's density and velocity that would result under blowdown conditions affect the rate of heat transfer from the fuel rods in the reactor core. The size and location of the hypothetical pipe rupture



CURTIS BOLES

This is an overview of the Thermal Hydraulic Test Facility, a nonnuclear pressurized-water loop having a bundle of 49 heater rods to simulate a small portion of a PWR fuel assembly. The THTF, located at Building 9201-2 at the Y-12 Plant, is used for studying PWR blowdown heat transfer separate effects.

influence such time-related functions as (1) flow direction within the fuel rod bundle and (2) time delay between the occurrence of the LOCA and the critical heat flux (which has a major effect on the highest temperature to which the rods are heated during a LOCA transient).

These and other separate effects of blowdown are being studied at the Thermal Hydraulic Test Facility (THTF), a nonnuclear pressurized-water loop serving as a mock-up of a portion of a nuclear core subassembly using a bundle of 49 electrically heated fuel pin simulators, or heater rods. Operated at pressures up to 2500 psi and temperatures up to 345°C, the THTF is used to simulate some of the conditions postulated to exist during a LOCA following a double-ended pipe rupture and thus permits researchers to determine the heat transfer coefficients of the heater rods during the first 20 sec of the LOCA, that is, before the ECCS water would be expected to reach the core.

Key features of the THTF which are similar to design characteristics of PWRs include heated rod length, integrated axial power profile, ratio of system volume to rod power, total rod power, test section inlet temperature, system pressure, channel temperature rises, and test section mass velocities. Because of the "separate effects" nature of the program, it was not necessary to model such features as downcomer volumes, multiple pumps, and steam generators. Among the most notable features of the THTF are its highly instrumented, 12-ft-heated-length electric heater rods.

These electrically heated rods, manufactured by the Watlow Electric Company in St. Louis, were developed in ORNL's Engineering Technology Division. Bob MacPherson, manager of the Division's Experimental Engineering Section (which built and operates the THTF under the supervision of R. E. Helms and B. G. Eads), states: "One of the major contributions of the Engineering Technology Division to nuclear safety studies is the development of electric heaters, or fuel pin simulators. The engineering challenge is to design and build a heater that simulates an actual nuclear fuel rod in power and temperature capability as well as temperature profile."

The ORNL-developed rods are used not only in the THTF but also in the Forced Convection Test Facility (supervised by Jim White), which tests fuel pin simulators singly in a blowdown environment to evaluate thermocouple reliability and survivability and to check two-phase instrumentation. Similar instrumentation is also tested at the Air–Water, Two-Phase Flow Facility (supervised by John Sheppard), which produces different flow regimes characterized by different densities and velocities of air–water mixtures. Such instrumentation helps researchers evaluate the effects of varying mass flow rates on heat transfer during the blowdown transient.

The 12-ft-long heater rods used in the THTF are each instrumented, with up to 5 center and 12 sheath thermocouples (a total of 454 in the 49 rods). At full power in the presence of the normal water coolant conditions, the heater rods achieve a surface temperature of 350°C and a center temperature of 595°C (compared to an actual nuclear fuel rod's 350°C at surface and 2200°C at center). According to David G. Thomas, manager of the PWR Blowdown Heat Transfer Separate Effects Program: "The rod bundle thermocouples and other process instrumentation (500 channels total) is scanned 20 times a second by the Data Acquisition System (DAS), yielding 6 million data points per test. To connect the THTF instrumentation to the DAS, over 8 miles of wire are strung between the sensors and the DAS."

In discussing the purposes of the THTF experiments, Thomas says: "In blowdown, you get

This is a scanning electron microscope photomicrograph (600× magnification) of a fracture section through a Zircaloy-4 PWR tube that was oxidized for 200 sec at 1300°C in steam. A highly brittle layer of zirconium oxide is shown at the top. The middle section (alpha phase) represents the portion of the Zircaloy into which oxygen has diffused and dissolved, rendering the metal brittle. The lower portion (beta phase) exhibits ductility because it has a comparatively lower concentration of oxygen. Tin particles can be seen running through the middle of the oxide layer.

a rapid pressure transient from 2200 psia to atmospheric pressure in 20 sec. Our objective is to develop a separate-effect data base over a wide range of operating conditions to permit an evaluation of the extent of conservatism built into the very large computer codes used by both the NRC and reactor vendors to assess the safety of PWRs."

Since May 27, 1976, a number of tests have been conducted at the THTF. Data have been collected on steady-state operation and on thermal-hydraulic effects during a simulated LOCA transient. The test sequence, according to Thomas, is this: "The analysis group, led by Bob Hedrick, must provide NRC with a pretest prediction based on the RELAP code three days before we do a test. Within 10 days after the test, the analysis group issues a Quick-Look Report that compares experimental data with pretest predictions."

What have been some of the preliminary results? According to Thomas: "We have found that RELAP models hydraulic behavior of the loop accurately. It correctly calculates the mass and momentum transport of water all around the loop. In the initial tests, the time from LOCA to the onset of critical heat flux (CHF) is 0.4 to 0.6 sec into the 20-sec transient.

"In some heater rods, we found that shortly after CHF the surface temperature rose from 350 to 650°C due to formation of a vapor blanket on the rod as a result of loss of coolant and an accompanying reduction in heat-transfer coefficient of 60,000-300 watts m^{-2} $°C^{-1}$. After about 4 sec of the transient, water returning to the simulated core segment increased the rate of cooling and started to cool the heater rods.

"A computer code is being developed by the analysis group to calculate heat-transfer characteristics of the THTF heater rods during a simulated LOCA. Preliminary results are very encouraging in that the initial calculations of surface temperature agree remarkably well with RELAP predictions throughout the 20-sec transient."

Cladding Studies

During a LOCA caused by a large pipe rupture in a PWR, the pressure drops precipitously and the remaining coolant water flashes to steam. An immediate problem arising from the presence of high-temperature steam is the possibility of oxidation of the fuel rods' Zircaloy cladding—an alloy of zirconium doped with small amounts of tin, iron, and nickel. During steam oxidation, a brittle oxide layer forms on the surface, and additional oxygen diffuses into and dissolves in the unoxidized portions of the Zircaloy, affecting the crystalline structure of the material and causing embrittlement. Furthermore, a Zircaloy-steam reaction is highly exothermic, and the heat released can increase the temperature of the cladding. This increases the heat load on the emergency cooling system. Weak, embrittled cladding could crack and break following a LOCA, allowing fission products to escape into the pressure vessel and containment shell.

In work done in 1972 in the Fuel Rod Failure Program, which was coordinated by Phil Rittenhouse, Dave Hobson observed that zirconium embrittles significantly even at temperatures below 2300°F (1260°C) if it is kept at such temperatures long enough. During the ECCS hearings (officially known as the Hearings on Acceptance Criteria for Emergency Core Cooling Systems for Light-Water-Cooled Nuclear Power Reactors) held by the Regulatory Branch of the U.S. Atomic Energy Commission (AEC) in 1972–1973, Rittenhouse and Hobson testified that the condition of the oxidized fuel element cladding after a LOCA is not a function of time or temperature alone but an integrated time–temperature effect.

Largely as a result of the Rittenhouse–Hobson testimony and subsequent testing done by Hobson, the AEC lowered the calculated maximum cladding temperature allowed during a hypothetical LOCA from 2300 to 2200°F (1260 to 1205°C). This peak temperature criterion may impose limits on the operating temperature of the core (thus limiting electrical output) and affects how efficient the ECCS has to be to ensure that the reactor core temperature during a LOCA is turned around before embrittlement of the cladding sets in. Another ECCS acceptance criterion resulting from the hearings requires that total oxygen consumption, expressed as the thickness of the corresponding zirconium oxide (ZrO_2) layer, shall not exceed 17% of the total clad thickness.

John Cathcart, Rodney McKee, Dick Pawel, Richard Perkins, Ray Druschel, Jack Campbell, and Dave McElroy of the Metals and Ceramics Division have been studying steam oxidation of Zircaloy in the temperature range of 900 to 1500°C. Their data on the oxidation kinetics of Zircaloy over a precisely controlled range of constant temperatures are being used to improve computer codes for predicting the oxidation characteristics of the cladding for any transient temperatures during a hypothetical LOCA. Their studies include measuring the heat generated during steam reactions with zirconium at different temperatures and examining microscopically the metallographic cross sections of steam-oxidized zirconium, which tends to be ductile where it is least oxidized and extremely brittle where it is most oxidized. The ORNL metallurgists have found that the zirconium oxide layers fracture along lines in which tin-rich particles abound.

The fuel rod experiments are carried out in flowing steam, but the temperatures desired are achieved by a radiant heating furnace. The tests are run for short time spans, from a minimum of 6 to 10 sec, and the temperatures of the cladding are measured by thermocouples.

"We have measured the isothermal rate of the steam–Zircaloy reaction and the diffusivity of oxygen in beta-Zircaloy at 50°C intervals from 900 to 1500°C," says Cathcart. "The diffusion coefficients for oxygen in Zircaloy oxide and oxygen-stabilized alpha-Zircaloy were determined from the oxidation data. Special care was exercised in the measurement of time and temperature.

"Transient temperature oxidation in this same temperature range was studied both experimentally and with computer codes developed to predict transient behavior. The sets of diffusion and oxidation parameters obtained can be used as a base data set for predictions of Zircaloy oxidation behavior under hypothetical LOCA conditions."

Adds Cathcart: "At 2200°F (the upper cladding temperature limit allowed by the NRC during a hypothetical LOCA), the parabolic oxidation rate constant derived from our new data is a factor of 2 smaller than that predicted by the correlation currently being used by the NRC in its reactor safety codes."

Fuel Rod Burst Tests

During reactor operation, gaseous fission products such as krypton and xenon accumulate in the void space (originally filled with argon and helium) within a fuel rod. Toward the end of a fuel rod's life, the internal gas pressure (at operating temperature) can approach the external pressure of the coolant, which is 2250 psi in a PWR. As the coolant pressure plummets during a LOCA, the pressure inside the fuel rod will exceed the external pressure. At the same time, the heat transfer rate decreases because of loss of coolant, causing the Zircaloy cladding to heat up rapidly with a further increase in gas pressure. As the Zircaloy's strength declines with increasing temperature and the fission gas pressure increases (while the counteracting external pressure drops), the fuel rod may swell, perhaps to the point of bursting. If a number of fuel rods in a bundle swell at the same axial position under these conditions, the coolant gaps could be reduced and restrict circulation of the emergency coolant.

A group in the Engineering Technology Division under Bob Chapman has completed tests of 38 single rods and is making preparations to start experiments on arrays of rods next summer in the Multirod Burst Test Facility. The goal is to compare the data from the single-rod tests with the results from the multirod tests in which researchers hope to learn how adjacent rods influence each other's behavior and how rods balloon and fail in relation to internal gas pressure. "One objective," says Bob Chapman, "is

CHARLES TUCKER

Bob Chapman, left, and Gunther Hofmann, seated before the Single Rod Test Facility in Building 9201-3 at the Y-12 Plant, discuss the results of experiments indicating that Zircaloy cladding does not swell as much when tested in superheated steam as it does in argon. The tube in the foreground was tested in steam, and the tube behind it was tested in argon. Both tubes were tested with the same heater and under the same pressure and temperature conditions.

to see whether we can predict the results of multirod arrays using information from single-rod tests, which we will continue to do since they can be instrumented and examined more easily and are relatively inexpensive. Another objective is to make as realistic and accurate as possible the data used in the computer programs that predict what happens to the fuel rod cladding during a hypothetical LOCA."

For single-rod tests, fuel pin simulators, consisting of an electrically heated fuel simulator inserted into a 5-ft-long Zircaloy tube, are pressurized with helium (to simulate the fission gas). Each rod is instrumented with thermocouples to monitor temperature changes on the rod's surface and a pressure transducer to indicate the pressure as a function of time. In the tests, which are conducted by technicians under the guidance of Jim Crowley, the temperature of the simulator is increased at a constant rate until the tube bursts.

Similar rods will be assembled into multirod test arrays and tested. Each array of electrically heated, instrumented rods will be placed in a pressure vessel, equilibrated to reactor conditions, using superheated steam at atmospheric pressure to simulate conditions postulated to exist in a LOCA.

One of the findings in the single-rod tests confirms the expected behavior about pressure changes in the rods as they are heated. Since the gas volume is very small (about 45 cm^3) and isolated from the pressurizing system during the test, the pressure in the simulator slowly increases due to the heating of the gas, attains a maximum value, then decreases at an increasing rate as swelling takes place. Even though the pressure decreases at an increasing rate near the end of the test, the strength of the Zircaloy decreases at a faster rate. When the pressure exceeds the load-carrying ability of the Zircaloy, the cladding fails.

Chapman's data on burst temperature as a function of burst pressure agree remarkably well with the results obtained by Dave Hobson of the Metals and Ceramics Division in tests done in the early 1970s. However, the findings on rupture strain as a function of temperature do not agree with the earlier studies. Hobson's tests, in which the tubes were tested in an argon atmosphere and uniformly heated in a furnace, showed dramatically that, at high temperatures, the rods in the bundle could swell to the point of touching each other and thus considerably restrict coolant circulation. Most of Chapman's rod experiments were conducted in a superheated steam environment, simulating LOCA conditions, and used electrically heated fuel simulators whose surface temperatures are nonuniform. (A few tests were conducted in an argon environment, and the results agreed reasonably well with Hobson's data.) These tests, although not yet complete, indicate that the cladding does not balloon as much in steam as it does in argon and that deformation is limited to localized hot spots, thus creating less of a coolant flow blockage problem than Hobson observed.

"We believe that the uniform temperature of the Zircaloy contributed greatly to the increased deformation of the rods," Chapman says concerning Hobson's results. "We simulate what you would expect in a reactor—large temperature differences in the Zircaloy cladding. We get large deformations on one side of the rod at localized hot spots. We find that cladding deformation is sensitive to small temperature variations."

Prior to assembly of the test simulator, the axial temperature profile in the heater is characterized by scanning the surface with an infrared camera. These scans can be used to pinpoint hot spots where rupture is most likely to occur. It has

Y-12 PHOTO

The region of maximum swelling in a 13-rod bundle tested in argon is shown here. Two ruptures are visible in the Zircaloy fuel cladding. These tests, run in 1971 by Phil Rittenhouse and Ralph Waddell, show dramatically that, under certain test conditions, severe coolant blockages can occur.

been shown that deformation in the Zircaloy tubes correlates with the infrared scans.

According to Chapman, another interesting finding of the current study relates to the change in heated length as a function of burst temperature. It was found that, below a certain temperature, the rods do shorten, but above temperatures around 950°C, the rods elongate. Chapman says, "We are not sure why, but we believe that this behavior is related to changes in the Zircaloy's structure."

A similar research program is under way at the Karlsruhe Nuclear Research Center in West Germany. Preliminary results from that program are in substantial agreement with the results of the ORNL study. To facilitate exchange of information, Gunther Hofmann of the Karlsruhe Nuclear Research Center is currently on assignment at ORNL to work in Chapman's group. Chapman states, "We find this exchange of information and personnel beneficial to both programs."

Fuel Rod Deformation and Collapse Studies

Fuel rods may fail by swelling and rupturing, as when the internal pressure exceeds the external coolant pressure during depressurization accidents. Bob Chapman and his colleagues are studying this phenomenon. Dave Hobson, however, is examining another way in which fuel rods can be damaged. The phenomenon is deformation of the cladding—sometimes to the point of collapse—caused by the compressive stresses of the coolant pressure following several thousand hours of normal or near-normal reactor operation.

"This non-accident study," Hobson says, "is of prime importance in determining the state of the heat transfer characteristics of the cladding and fuel-to-cladding gap. One must have this information to know the starting point for the blowdown phenomenon." Hobson and his colleagues in the Metals and Ceramics Division have completed collapse testing, whereby the temperature of the test Zircaloy-clad rods is kept constant and the external pressure is increased until collapse ensues. In this experiment, the test rods simulate fuel rods with pellet-to-pellet gaps—that is, there are unusual separation spaces between the fuel pellets inside the rods.

"As a function of temperature and pellet-to-pellet gaps," Hobson says, "we have determined what pressure is required for cladding to collapse. We have modeled the collapse pressures over a range of temperatures (315 to 425°C) for pellet-to-pellet gap simulation. We have determined the midwall hardness (a measure of the inherent strength of the cladding) at room temperature and plotted collapse pressure as a function of that hardness. All these collapse pressures are much higher than operating pressures of conventional reactors."

Currently, Hobson and his colleagues are obtaining data on creepdown—the rate at which cladding deforms under constant temperature and external pressure conditions that represent normal and near-normal operating conditions for the reactor. Hobson lists three reasons why it is important to know how rapidly the cladding is deforming.

- The rate of heat transfer from the fuel to the coolant will change proportionally to the amount of deformation.
- Additional stresses will be introduced where the cladding contacts the fuel, especially from expansion and contraction of the fuel due to power changes in the reactor.
- Data are needed to improve the various computer modeling codes that are used to predict fuel rod behavior.

"Reactor operating experience," Hobson says, "has shown that these stresses can force the cladding slowly into contact with the fuel, closing the helium heat-transfer gap. One needs to know how rapidly that gap is changing and at what time the cladding contacts the fuel.

"If a pellet-to-pellet gap exists in the fuel, cladding collapse becomes a possibility. A possible sequence involves a pellet-to-pellet gap and creep-down onto the fuel and into the fuel pellet gap. When the geometry produced by creepdown can no longer support the external pressure, the result is collapse, which is characterized by a time-independent yielding of the cladding."

Cladding deformation is monitored by sensitive electrical measurements of the test rods. This instrumentation, developed for this program by Caius Dodd and coworkers in the Nondestructive Testing Group of the Metals and Ceramics Division, can monitor tests to maximum conditions of 425°C and 4300 psi. "This is the first time that anyone has tried to measure the surface and geometry changes of a fuel rod continuously," Hobson says.

Next fall, Hobson's group will perform creep-down experiments at the RCN-Petten reactor in the Netherlands as a joint effort with Dutch researchers.

Fission Product Release Studies

To what extent and in what forms would volatile fission products be released if defected fuel rods burst during a successfully terminated LOCA or if spent fuel rods were ruptured during a spent fuel transportation accident? These questions have been tackled experimentally by Dick Lorenz, Jack Collins, and Oscar Kirkland of the Chemical Development Section (led by Tony Malinauskas) of the Chemical Technology Division. Since 1955, ORNL has been concerned with understanding fission product release from fuel elements under accident conditions. George Parker conducted the first studies of fission product release from irradiated nuclear fuel under simulated loss-of-coolant conditions. Parker obtained data on the relative amounts of nuclides released when the fuel was heated to the melting point. Lorenz's group is refining those measurements and is characterizing the physical and chemical forms of the released nuclides.

The tests involve heating simulated LWR fuel rods to temperatures characteristic of the accidents in question until the internal pressure causes

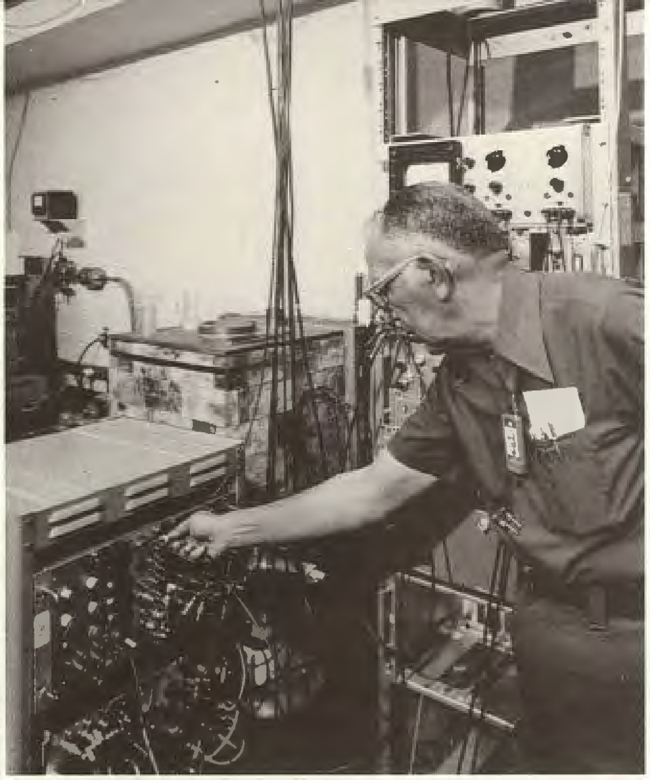
Temple Love adjusts equipment used to measure spectral distributions of beta and gamma rays emanating from fission products created by thermal-neutron fission of ^{235}U. The data obtained will be used to determine delayed energy release rates for studying hypothetical loss-of-coolant accidents in water-cooled reactors.

them to rupture. In the LOCA experiments, the rods are heated to 1200°C in flowing steam; in the spent fuel transportation accident tests, the rods are heated in dry air or steam to 700°C, the highest temperature that might occur should a truck or train overturn and the spent fuel cask rupture. The test rods consist of Zircaloy-4-clad fuel rod segments that contain unirradiated uranium oxide (UO_2) pellets coated with radioactively traced cesium hydroxide (CsOH), cesium iodide (CsI), and tellurium dioxide (TeO_2). The purpose of the study is to trace what happens to the volatile fission products—cesium, iodine, and tellurium—found in the gap between the fuel pellets and the cladding. As the rods are heated to the rupture point in a furnace, steam is passed through the furnace to sweep out the material released from the rod's gap. Released vapor then condenses out and deposits at different points along a gold foil lining a thermal gradient tube, which has different temperature zones ranging from 800°C at one end to 125°C at the other. Harris Dunn and Les Hulett of the Analytical Chemistry Division analyze and identify the deposited material.

Lorenz et al. found that cesium release associated with the implanted cesium hydroxide appears to be limited by the formation of low volatility cesium uranate compounds. Experiments with cesium hydroxide and UO_2 in a Knudsen cell-mass spectrometer system confirmed this behavior. Explains Malinauskas: "Cesium release is controlled by the cesium uranate formed. Little elemental cesium is released when the material is blown out of the rods at rupture. The cesium uranates are less mobile than elemental cesium and will not volatilize themselves since the vapor pressure over them is many times lower than it is for cesium. Before this work was done, it was unclear whether a significant release of cesium to the environment could occur if spent fuel rods were ruptured during a transportation accident."

Other findings were

- Iodine release was observed primarily as cesium iodide but also as elemental iodine (iodine and cesium are among the most radiologically serious of the fission products).



GARY WELCH

- Tellurium release was markedly restricted by rapid reaction with the Zircaloy cladding.
- The tests in air yielded enhanced releases of cesium and iodine and considerable swelling of the oxidized UO_2.
- Measured release fractions were greater when the test rods were ruptured at temperature by internal pressure than when the cladding failures were machined in the rods prior to testing.

These findings on the physicochemical behavior of fission products in ruptured rods will be translated into specific accident behavior by means of computer models being developed for the NRC by the Battelle Columbus Laboratories in Ohio.

As for future work, Malinauskas says that they will try to verify their findings on simulated fuel by using irradiated fuel rods from the H. B. Robinson reactor in Hartsville, South Carolina. "Also," he adds, "we will do work on fission product behavior in the coolant and release during a depressurization phase of a LOCA. The main effort will be to provide input data and test computer codes developed at the Battelle Columbus Labs."

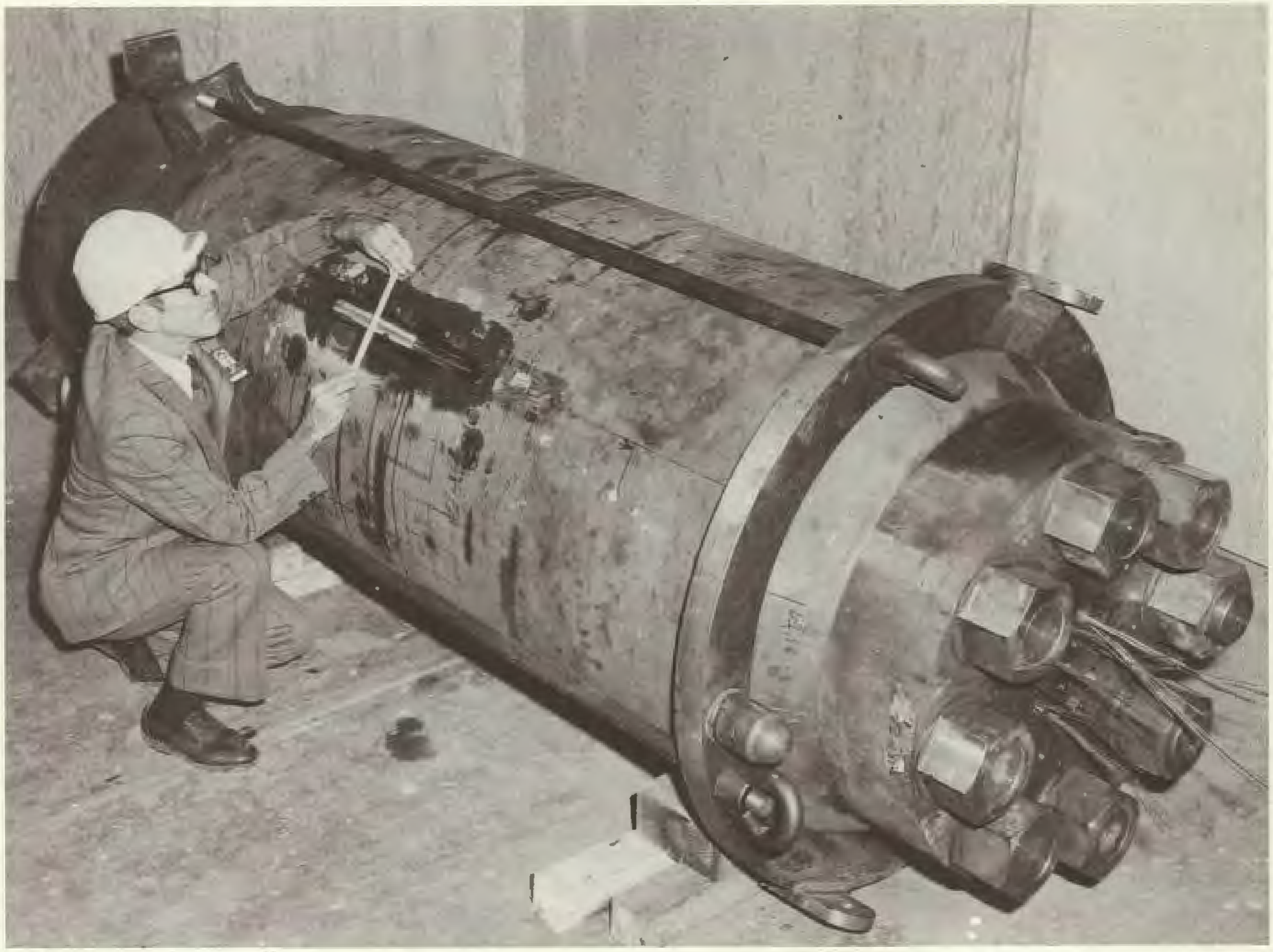
Decay Heat Studies

Light-water-reactor safety research today lies mostly in the engineer's domain, but physicists can make a contribution. One important area is the measurement of fission product decay heat—the amount of energy that is released as a function of time after fission of ^{235}U by its by-products as they decay into stable isotopes. In the late 1940s, the first significant work on decay heat was published in a classical paper coauthored by ORNL physicists Eugene Wigner and Kay Way. Currently, benchmark decay heat studies are under way at ORNL and other laboratories in an effort to ascertain precisely the heat load that must be handled by the ECCS after a LOCA.

At ORNL, Kirk Dickens, Temple Love, Jim McConnell, and Bob Peelle of the Neutron Physics Division, with assistance from J. F. Emery of the Analytical Chemistry Division, have been measuring the decay heat of ^{235}U fission products by beta- and gamma-ray spectrometry. Their approach has been to place about a microgram of uranium oxide (enriched with 93% ^{235}U) in a plastic "rabbit" and then irradiate it briefly in the Oak Ridge Research Reactor to induce fissions in the sample; blow the rabbit with compressed air down a tube to a spectrometry laboratory for measurements of beta- and gamma-ray emissions; and observe decay radiation spectra there as a function of time out to 10,000 sec. (The experiment is repeated with some 100 specimens.) Taking the observed spectra, they add up the heat energy released as a function of time to determine the heat load in a reactor following shutdown. Dickens et al. also count the number of fissions so that they can calculate watts per fission on an absolute basis.

According to Peelle, the problems with previous decay heat studies have been a deficiency of precise benchmark data and the lack of good radioactive decay information on each of the hundreds of nuclides involved. "Some radioactive species are very short-lived and hard to measure," he says. "For short times right after fission, the information has been sketchy. On the average, primary fission products decay three times before they become stable nuclei. Calculations on how much heat is produced based on physics data may be off by 30%." He adds that previous investigators now using the summation method have lumped in best estimates of the unknown with the known data to calculate decay heat at short times following fission.

Dickens says that the NRC requires precise decay heat measurements because (1) the licensing division needs an accurate decay heat curve for licensing purposes since it is difficult to prove that


K-25 PHOTO

the currently used curve is conservative, and (2) the NRC's research division desires as accurate a set of numbers as possible for use in computer codes describing the consequences of a hypothetical LOCA.

The currently used NRC curve, arrived at during ECCS hearings in 1972–1973, is based on a curve developed in 1961 by K. Shure at Westinghouse Electric Corporation and adopted in 1972 by the American Nuclear Society. The NRC added 20% to the Shure curve to cover uncertainty in the decay heat estimates.

Says Dickens about the NRC curve, "It is really very conservative in my estimation, but so far it is hard to prove." Still, the recent data gathered by Dickens' group and by a group at Los Alamos Scientific Laboratory using a calorimeter on irradiated fuel samples make it increasingly evident that the NRC curve allows for much more heat than is present as measured by the best American and European experimentalists in the field.

Thermal Shock Tests

One question of interest is this: Would there be any serious thermal shock effects on a vessel operating at design temperatures after a loss-of-coolant accident when cold water from the ECCS is introduced? The Heavy Section Steel Technology Program of the Engineering Technology Division has conducted three experiments simulating such a situation. Dick Cheverton, Grover Robinson, Jack Smith, and Sam Bolt performed these experiments in the Thermal Shock Test Facility, which consists of pumping equipment, a tank containing a solution of 35% methanol and 65% water capable of being chilled to -23°C, and a furnace for heating to 290°C a cylindrical vessel which is deliberately flawed on the inside. Each

CURTIS BOLES

Technician Dan Curtis (left) measures the growth of the machined-in flaw following testing of the intermediate-size pressure vessel. This vessel, pressurized hydraulically at the K-25 power house, leaked without fracturing after it was subjected to more than two times the design pressure. The original flaw was 18 in. long and 5⅜ in. deep in a wall 6 in. thick. Above, Robert K. Rice, electrician, prepares the same vessel, which had its old flaw repaired and a new flaw introduced, for retesting at the Naval Surface Weapons Center at Dahlgren, Virginia. The test was run June 18, 1976, using high-pressure nitrogen gas. The vessel failed by leaking after it was subjected to 2.2 times the design pressure.

test vessel was instrumented with thermocouples, strain gauges, and acoustic emission devices that detected sound waves as they emanated from the crack as it grew following the injection of the cold water–methanol solution into the cylinder.

One experiment was conducted to simulate a modern steel vessel having controlled residual elements and low susceptibility to irradiation damage, and two tests were performed on the equivalent of older vessels which have a higher susceptibility to irradiation damage. According to Grady Whitman, manager of the HSST Program, the results were these: "We found that cold shock is a nonexistent problem in modern steel vessels. We did two tests on vessels of the old variety which undergo a greater loss of toughness. In the tests of the old vessels, we found that the flaw will initiate and grow, and then it will arrest. We also found evidence of a self-healing or blunting of existing flaws by loading them at temperatures higher than critical so that its process may be self-limiting.

"We are interested in seeing what methods are applicable for predicting that the crack will initiate and then will arrest," Whitman explains. "We are also working with industry in its use of advanced methods of nondestructive inspection to detect the occurrence and extent of crack growth."

Pressure Vessel Tests

"If the pressure vessel, as well as the rest of the primary system, maintains its integrity at all times, no incident can present a serious hazard to the public," said Alvin M. Weinberg, former ORNL director, in his 1970 "State of the Laboratory" address. For ten years, ORNL engineers in the Heavy Section Steel Technology Program have been trying to determine the degree of safety of reactor vessels that are inadvertently flawed. Bob Bryan, Pete Holz, John Merkle, Grover Robinson, and Gordon Smith, who perform what the NRC calls accident-prevention studies, have completed tests of eight intermediate-size pressure vessels that were deliberately flawed and then intentionally pressurized until they failed, say, by leaking or bursting. In tests of eight 6-in.-thick vessels, it was found that the vessels failed only after being subjected to pressures 2½ to 3 times as great as the design pressure. According to Herbert J. C. Kouts, former director of NRC's Office of Nuclear Regulatory Research, "What was especially remarkable was ORNL's ability to predict at what loads the failure point would be."

Between June 30, 1972 and June 18, 1976, ORNL researchers tested eight vessels with machined-in flaws over a range of temperatures to simulate the material properties that would exist considering design and off-design operating conditions. Each vessel—costing $35,000 and fabricated by the Taylor Forge Division (Paola, Kansas) of Gulf and Western Products Company—was tested to determine the margin of safety in conventional PWR vessels (costing about $4.5 million apiece) designed according to the American Society of Mechanical Engineers (ASME) code. The eight vessels, having design pressures of 9700 psi, were hydraulically pressurized at the Oak Ridge Gaseous Diffusion Plant powerhouse. One vessel tested at 90°C failed by leaking only after the internal water pressurization attained 26,600 psi—almost three times the design stresses permitted by the ASME code. As the pressure level was raised, the sharp flaw in the nozzle corner grew in a stable manner until it penetrated the surface and leaked. Another vessel, tested at 90°C, had a sharp trapezoidal flaw 18 in. long and 5⅜ in. deep (in a wall 6 in. thick). The vessel leaked at 21,350 psi after the flaw grew in a stable manner. This vessel was retested after having its flaw repaired and a new flaw introduced by pressurizing pneumatically at the Naval Surface Weapons Center at Dahlgren, Virginia (which had pumping equipment and offered a safe place for testing a vessel with this high level of stored energy). The test, run June 18, 1976, used high-pressure nitrogen gas to more nearly simulate the more compliant loading of water-steam pressure in a PWR. Says Grady Whitman, manager of the HSST Program: "We wanted to try pneumatic loading because, if you get a leak, the load does not drop, whereas in hydraulic testing the load would collapse. We went to 2.2 times the design pressure, and the vessel failed by leaking. Pneumatic loading did not have any significant influence on the behavior of the structure."

Summarizing the results of the pressure vessel tests, Whitman said: "We have demonstrated that we can predict the pressures at which the failure would occur. We have evaluated several methods of prediction with our vessel experiments. We describe the experiment and properties and evaluate the accuracy and conservatism of these methods.

"We have demonstrated that very large flaws could be present without seriously affecting integrity. We found that vessels can endure very large defects without failure—defects that could not go undetected with normal inspection methods including nondestructive testing. Hence, less than detectable flaws would not have serious consequences under normal operating pressures.

"We also showed that the rate at which these flaws grow is so small that the flaws could not grow to the point of making the vessel fail between inspection periods. We tested various methods of inspection like ultrasonic techniques and provided opportunities for industry to participate in sharpening their analytical tools."

The HSST Program has developed data on fracture toughness, material properties, and methods of analysis that have influenced the ASME codes and standards for fabrication, inspection, and operation of reactor vessels.

Fracture Toughness in Irradiated Steels

Rey Berggren and Dom Canonico of the Metals and Ceramics Division are working on experiments to extend the knowledge of the effect of irradiation on the fracture toughness of the steels that are used in the fabrication of pressure vessels for LWRs. The immediate objectives of this study are to determine the fracture toughness of irradiated pressure vessel steels and to correlate the behavior of small specimens with large 4-in.-thick specimens which more nearly simulate the heavy pressure-vessel walls.

The term fracture toughness reflects a material's ability to withstand the propagation of a crack. In experimental conditions, a flaw (such as a sharpened crack) is produced across a specimen, and then the specimen is loaded to see how much toughness it exhibits before a crack propagates from the tip of that flaw. This material property is used in analytical predictions of vessel behavior such as that encountered in a thermal shock event or normal operating excursions when the vessel wall is subjected to significant thermal load at low temperatures.

Berggren and Canonico are currently working with a group of specimens that will be irradiated in the Bulk Shielding Reactor to a fluence equivalent to a significant portion of a reactor vessel design life, which is nominally 40 years. These specimens, ranging from 0.4 to 4 in. in thickness, are fabricated from weld material, and they will provide data on the maximum toughness that such material will exhibit after irradiation to a fast neutron fluence of 1×10^{19} neutrons/cm^2. In addition, correlations will be obtained to relate the behavior of small specimens to the larger specimens so that the data from small surveillance specimens in operating reactors can be used with greater confidence.

According to Grady Whitman, manager of the HSST Program for which this work is being done: "A longer-range goal of this study is to establish the minimum size and the geometry of specimens and listing methods to be used to monitor irradiation effects in operating reactors. The current irradiation project is the second in a planned series to obtain data to develop such information. The 4-in.-thick specimens used in these studies are the largest ever employed in such investigations, and the data obtained to date indicate that more than adequate levels of fracture toughness exist in highly irradiated pressure-vessel steels."

This is a cooperative program using testing facilities at ORNL, Westinghouse Electric Corporation, and Hanford Engineering Development Laboratory.

Nozzle and Piping Design Criteria

Among the nuclear-safety-related interests of the Engineering Technology Division's Solid Mechanics Section are the criteria used in designing pressure vessel openings and piping systems for nuclear power reactors. Sam Moore of that section manages a program that is investigating structural design criteria for such components as welded joints, elbows, tees, and inlets and outlets to pressure vessels. In operation, these pipes and components might undergo pressure loads, thermal expansion loads, mechanical loads imposed by the rest of the system, vibrations, fatigue, and potential disasters such as earthquakes. Nuclear power plant systems must be designed so that they will not fail under such duress, and therefore Moore's program is conducting an extended series of analytical and experimental tests of piping components to determine what stresses in-service nuclear systems might be subjected to.

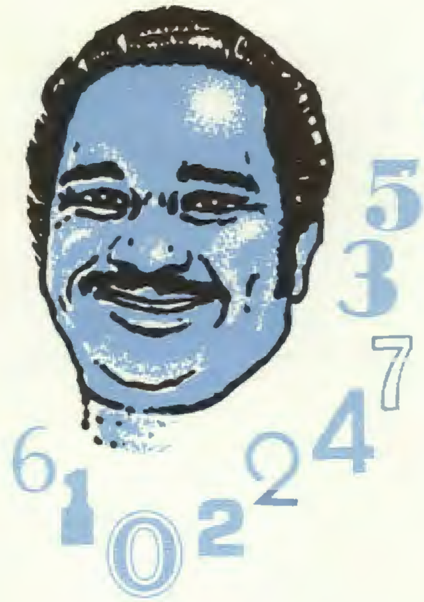
Computer codes have been developed by Bill Dodge and John Bryson of ORNL, Everett Rodabaugh of Battelle Columbus, Prof. G. H. Powell of the University of California, and others to predict the stresses in certain piping components and configurations under any of a wide range of hypothetical operating conditions. These computer programs are based on and checked against the results of experiments conducted here at the Laboratory and by subcontractors, such as Southwest Research Institute, Combustion Engineering, Auburn University, and The University of Tennessee. In these experiments, prototypic piping components and pressure vessel models that have been carefully forged or machined and painstakingly measured are extensively instrumented with strain gauges and thermocouples and subjected to pressure, thermal, and/or mechanical loads. The stresses throughout the body of the component are then measured, and a plot of the stress distribution is derived to document the component's response to that particular combination of loads. By conducting a number of such experiments under various loading conditions, enough data can be acquired to predict trends of stress production and to understand mechanisms of interaction between, say, pressure and thermal loads.

To date, says Moore, the ORNL studies have helped to confirm or improve the design criteria used to assure the safe design and future operation of nuclear power plants. He adds that the ASME code for design and construction of such plants has recently been revised in a number of areas at the suggestion of ORNL. These revisions include improved rules for the design of pressure vessel openings; classification of stresses for elbows; rules for piping flexibility analyses; definitions of stress categories; and accepted stress indices for reducers, girth butt welds, tapered transition joints, socket-welding fittings, flanged joints, and support lugs welded onto pipes.

Pictured on the cover is a forged tee representing the standard design of the intersection of two nuclear service pipes that might carry fluids under pressure at different temperatures. This tee has been heavily instrumented and is now awaiting testing, in which the tee will be subjected to temperature gradients between the branch and run legs. The resulting stresses will be measured and compared with computer program predictions to provide a more complete understanding of the structural response of nuclear piping systems to thermal expansion loads.

Current Status

To minimize the possibility of a reactor accident resulting in significant public consequences, the NRC has set limits on reactor design and operation in accordance with computer codes modeling reactor behavior during hypothetical LOCAs. Results from ORNL experiments indicate that these codes are accurate and, in certain areas, conservative. (In a recent seminar at the Institute for Energy Analysis in Oak Ridge, Herbert Kouts, now at Brookhaven National Laboratory, said, "There is probably more conservatism built into the rules than we need.") The early findings suggest that the margin of safety for reactors is greater than was previously predicted. The research programs at ORNL and elsewhere are providing direct answers to various safety problems. These answers may help determine the future of nuclear power if they persuade an environmentally conscious public that nuclear power is a safe, acceptable option for meeting a substantial portion of the nation's energy needs.



Take A Number.....

BY V. R. R. UPPULURI

CAN ONE MULTIPLY FASTER?

If there are several algorithms to solve a problem on a computer, it is of interest to find the algorithm which takes the minimum of time (or work or storage). For example, the usual method to multiply two m-digit numbers takes m^2 elementary multiplications. For example,

```
   5678
  ×1234
  -----
  22712
 17034
11356
5678
-------
7006652
```

takes 16 elementary multiplications, and the question is whether we can do better. The answer is yes, and depends on the representation of the two numbers x and y which we wish to multiply. Let x and y both have $2m$ digits. One can write

$$x = 10^m x_1 + x_0 \text{ and } y = 10^m y_1 + y_0 ,$$

where x_0, x_1, y_0, and y_1 are m-digit numbers. Then,

$$xy = (10^m x_1 + x_0)(10^m y_1 + y_0)$$

$$= (10^{2m} + 10^m)x_1y_1 + 10^m(x_1 - x_0)(y_0 - y_1)$$

$$+ (10^m + 1)x_0y_0 .$$

This requires three multiplications of m-digit numbers plus some additions and shifts (multiplication by powers of 10). When this is applied to the above example with $x = 5678$ and $y = 1234$, we have $x_1 = 56$, $x_0 = 78$, $y = 12$, and $y_0 = 34$; and $x_1y_1 = 56 \times 12 = 672$, $(x_1 - x_0)(y_0 - y_1) = (-22) \times 22 = -484$ and $x_0y_0 = 78 \times 34 = 2652$. From these results, we have

```
xy =    6,720,000
           67,200
          -48,400
          265,200
            2,652
        ---------
        7,006,652
```

This procedure used only twelve elementary multiplications. Moreover, this procedure can be applied recursively; for example,

$$56 \times 12 = (10^2 + 10) \times 5 + 10 \times (-1)$$

$$\times (1) + (10 + 1) \times 12 .$$

One can show that, by the above procedure, the time required to multiply two n-digit numbers can be made proportional to $n^{\log_2 3} \times n^{1.57}$.

JIM RICHMOND

Chester R. Richmond was selected this year to present the Failla Memorial Lecture at the annual meeting of the Radiation Research Society in San Francisco. The lecture, in its entirety, will be published by the Society's journal, *Radiation Research*, in the near future. Herewith are excerpts from it selected by the author for the *Review* readership. Richmond, associate director for biomedical and environmental sciences, joined the Laboratory management staff from Los Alamos Scientific Laboratory in 1974. He holds the doctorate in biology-physiology from the University of New Mexico and was a recipient in 1974 of the E. O. Lawrence Memorial Award.

ENERGY, ENVIRONMENT, AND HEALTH

What Can We Learn from the Nuclear Experience?

By C. R. RICHMOND

We know that the fruits of scientific investigation can have significant impacts on other countries; for example, Hahn and Strassmann's work in the 1930s or the discovery of plutonium by Glenn Seaborg and his colleagues 35 years ago. Most of us are not too surprised to see how one nation can be affected, for better or worse, by a scientific achievement in another country. What is surprising to many of us is the effect of an economic event in one country on the scientific research and development in other countries. An important example of this is the world energy situation, especially with regard to its nonrenewable resources and the events that were triggered by the 1973 Arab oil embargo.

This particular event had a profound impact on the activities of many of us because it forced us to face the fact that we were indeed highly dependent on foreign sources for energy. The oil embargo and other energy-related events of recent years have focused greater attention on the health and environmental effects of the total fuel cycle of

". . . science and technology may be our strongest weapons against further environmental and health degradation . . . ."

the alternative methods of producing energy. This runs from extraction and transportation, through processing and use, to disposal and, in some cases, recycle of residuals.

Three-quarters of the total energy now consumed in the United States is derived from oil and natural gas, two of our scarcest nonrenewable fuel resources. The supply of these materials diminishes while the demand increases. One obvious result is the need to increase imports, and in 1975 our balance of payments outflow included $25 billion for these fuel imports. We are actually increasing our dependence on foreign fuel, although we have two plentiful domestic resources available for the near term, our lifetimes, in coal and uranium.

We must face reality and accept the fact that this country must rely on conservation practices and the burning of coal and uranium for at least the next generation to absorb the impact on electrical production of our declining oil and gas resources. During this critical time, we will not be saved by tides, geysers, windmills, biomass, garbage—which some euphemistically call "urban ore"—solar, or fusion. We cannot buy time, and it takes time to develop technology, some of which will be capable of satisfying only small amounts of our total energy requirements at best. In 1975, U.S. energy consumption was about 73 quads, or 73×10^{15} Btu. According to the Federal Energy Administration, the projected U.S. energy demand for 1985, based on a 2.8% growth rate and a $13 per barrel (1975 dollars) cost of oil, is about 100 quads. The historical growth rate for the 20 years prior to the 1973 oil embargo was about 3.6% per year.

Clearly, our real alternatives for the near future are coal-fired and nuclear power, although coal is also needed for production of commodities other than electric power. Conservation is very important and must be accepted as something to be practiced by each of us rather than by "the other guy."

We are all concerned about the effect on our health of exposure to low levels of pollutants, as well as about the attendant societal costs. Almost daily we hear or read about environmental impacts, accidents, and the importance of the environmental etiology of cancer. We know that acute exposure to high levels of pollutants is damaging and costly, but we are only beginning to better understand the situation as regards chronic exposure of the general public to lower levels of pollutants in our environment.

Whatever man does results in both good and bad changes in his surroundings. It also follows that the overall potential for increased environmental and health damage has increased as industrialization, urbanization, science and technology, and—perhaps most importantly—population increase. Some of these factors, such as science and technology, may be our strongest weapons against further environmental and human health degradation from chronic low-level exposure to pollutants.

Man has manipulated and exploited his environment in an attempt to increase his standard of living and decrease human misery and suffering, while his numbers have increased dramatically in apparent verification of the dark side of the Malthusian growth curve. We must now collectively act to put our house in order and learn how to strike a balance between the relative benefit and cost of exploiting our environment. Put simply, this means that we pay a price for everything we do and nothing of value is gotten free. As pointed out by Barry Commoner's Fourth Law of Ecology, "There ain't no free lunch." We are only now learning what we have actually been paying in health costs resulting from chronic low-level exposure to an ever-increasing number of pollutants.

The occupational record all too often has been the barometer that suggests to us that something may be going awry in the environment. It has been said that workers sometimes serve as "miners' canaries" for the public. Perhaps we must fine-tune this occupational record at an earlier stage so as to learn more about the potential effects of a material on the worker and, ultimately, the public.

Because no energy-producing technology is completely benign, we must be able to evaluate the impact of any proposed energy source and compare it with the impact of competing alternative sources. We may not be in a position to choose

"Of the . . . pollutants available to man, relatively few have been tested for carcinogenicity and . . . mutagenicity."

a single energy source; we may need to rely on a mix. We should be in a position, however, to know what the total societal costs are and, above all, not to allow ourselves to consider the health and environmental impacts of one energy-producing technology without considering those for the alternatives.

The wide variety of materials released to the air from coal plants include sulfur oxides, nitrogen oxides, hydrocarbons (some of which cause cancer), oxides of carbon, heavy metals, and radioactive material. Some of these products take part in chemical reactions that can produce other chemicals of concern to man, such as ozone. We know that excess ozone at ground level and insufficient ozone at high altitudes can both cause problems. Some fear that the carbon dioxide may cause widespread changes in the environment by changing the amount of sunlight that remains in the earth's atmosphere; this is the much-talked-about "greenhouse effect," which some people think could change the earth's temperature and global weather patterns.

Serious health effects in the form of cadmium-related *itai-itai* disease have been recorded in Toyama City, Japan. Exposure to cadmium dioxide or cadmium dust is known to produce acute pulmonary edema. Repeated inhalation exposure results in chronic emphysema and renal disturbance. However, in the Japanese incident, cadmium released from a smelter was concentrated by rice plants to levels much higher than levels in the general environment. The health effects differed from those observed in industrial exposures in that most of the affected were females over 50 years who had borne several children. The disease is characterized by bone and kidney damage that suggests severe disturbances of calcium metabolism. These data suggest that a segment of the population may be susceptible to adverse health effects of environmental levels of cadmium because of dietary deficiencies.

The list of materials now identified as environmental pollutants believed capable of producing such health effects as cancer includes benzo[*a*]pyrene, radioactive materials, asbestos, nickel, chromates, arsenic, vanadium, numerous polynuclear organic compounds to be found in smoke and smoked foods, coal products, exhaust gases from hydrocarbon combustion, aromatic amines, chlorinated hydrocarbons, and *n*-nitroso compounds. The lists grows daily.

Sulfur from mining and smelting activities has been released to the air we breathe for at least 5000 years. Early descriptions of Roman smelters by Strabo in 7 B.C. mention furnaces that have chimneys "so that the gas (sulfur dioxide) from the ore may be carried high into the air, for it is heavy and deadly." Currently, in the United States, about half of the sulfur dioxide released to the air appears to come from only about 10% of our land area. Concentrations tend to be higher in large, eastern, urban areas.

The carcinogenic effect of shale oil was recognized in 1876 when a British physician described a scrotal cancer in a Scottish shale oil worker. In 1910, another British physician prepared a dissertation on skin cancer, primarily scrotal, among mule skinners exposed to shale oil. We now know some of the carcinogenic components of shale oil: 3-ring aromatics and pyrenes, benzanthracenes, chrysenes, 4- and 5-ring compounds. Some of the chemical compounds produced from oil shale kerogen are also mutagenic in the fruit fly. These problems are generated as well by petroleum-derived oils.

The kinds and quantities of the carcinogenic chemical vary considerably with the production method and the ultimate refining or processing used for the raw shale oil.

Recent vital statistics from a National Cancer Institute (NCI) report on the distribution of various kinds of cancer by county throughout the United States suggest that increases in specific kinds of cancer in parts of the United States may be related to industrialization. We do not yet know what fractions of the total increases are related to nonoccupational exposure to given pollutants. These observations, however, do give us cause for concern regarding the probable importance of man-generated pollutants in producing so-called "naturally occurring" cancer.

According to a recent NCI press release, scientists have identified about 30 carcinogens through direct observations of human subjects. These include vinyl chloride, bis(chloromethyl)-

ether, and tobacco smoke. With the possible exception of arsenic, these materials also can produce cancer in experimental animals. This emphasizes the importance of using animal testing as a warning of potential hazards to people since the detection of carcinogens by epidemiologic means is difficult at best and cannot be done retrospectively for new materials entering the environment.

Some materials in polluted air are capable of producing mutagenic or carcinogenic effects in experimental animals, but generally the concentrations required are much higher than those normally found in the environment. Of the large number of pollutants available to man, relatively few have been tested for carcinogenicity and fewer still for mutagenicity.

The importance of protecting man from potential genetic hazards from pollutants and products of man's technologies is clearly stated in the 1969 "Report of the HEW Secretary's Commission on Pesticides and their Relationship to Environmental Health:"

> Surely one of the greatest responsibilities of our generation is our temporary custody of the genetic heritage received from our ancestors. We must make every reasonable effort to insure that this heritage is passed on to future generations undamaged. To do less, we believe, is grossly irresponsible.

Some chemicals can cause abnormal changes in the developing embryo which will produce an effect in that individual's subsequent offspring. In extreme cases, the conceptus or embryo may be killed. Short of this, contamination may result in various degrees of abnormal development, ranging up to gross structural or functional alteration of the embryo known as congenital malformations. Probably the most widely known example of a health effect from a teratogen is the large number of congenital malformations produced by the drug thalidomide.

Our knowledge about dose-response relations with respect to nonnuclear pollutants is primitive compared with that for nuclear pollutants. To compound the problem, we are faced with a staggering number of known and potential pollutants, many of which can act together additively, synergistically, or as promoters, or in ways that are not yet known. One view currently held by many researchers is that, although thresholds probably do not exist for carcinogens at the molecular or cellular level, there may be concentrations for even the most potent carcinogens that will *not* produce cancer in the intact animal or under natural exposure conditions.

We must not underestimate the complexity or magnitude of the problem for nonnuclear pollutants. We must endeavor to combine our total national resources, particularly in the important planning stages, to make sure of addressing the most important problems and using the most cost-effective approaches (e.g., screening tests for groups of related compounds using multiple biological testing systems). I personally hope that the government agencies charged with various health and safety responsibilities will increase their interactions both in planning and implementing national environmental health programs. The magnitude of the problem virtually demands this type of integrated approach, if only for qualitative understanding of the dose-response relations for chronic, low-level exposure to the more important nonnuclear pollutants. Nor should we delude ourselves into thinking that we will be able to measure quantitatively the dose-response relation and estimates of risk for very low exposure levels of a pollutant; a wealth of experience with radiation has taught us otherwise.

I would like to raise another question about establishing standards for environmental pollutants. Can and should they be set at some fraction of a naturally occurring background level for the material in question? This concept is becoming more popular and it might be worthwhile for us to consider several examples that have been given. The National Academy of Sciences-National Research Council report on "The Effect on Populations of Exposure to Low Levels of Ionizing Radiation in 1972" stated:

> Our first recommendation is that the natural background radiation be used as a standard for comparison. If the genetically significant exposure is kept well below this amount, we are assured that the additional consequences will neither differ in kind from those which we have experienced throughout human history nor exceed them in quantity.

Let us pause a moment to think about sensitivity and the question of dilution of one material in another. We are all familiar with measurements expressed in parts per million (ppm). Perhaps this concentration may be more meaningful if visualized as an ounce of vermouth in 7800 gal of gin—if not the world's driest, certainly the world's largest, martini.

Two specks of salt in one cup of sugar is also one part per million. One part per billion (ppb), however, becomes several specks of salt in 400 lb of sugar. We can now, as many of you know, measure some materials to concentrations of parts per billion, and we have the capability of detecting still others at the part-per-trillion (ppt) concentration. This is equivalent to several specks of salt in 200 tons of sugar.

The cost that society now pays for health effects produced by environmental pollutants is huge. Coal miners develop pneumoconiosis (black lung) and other lung disease. The annual cost to U.S. taxpayers for black lung payments to coal miners and their families is over a billion dollars. (Interestingly, black lung benefits are now linked by law to the same periodic adjustments accorded the pay of Federal employees.) I have no idea what the related cost is for lung disease suffered by the general population, except that it is huge.

Chronic bronchitis and emphysema, having doubled every five years since the 1940s, are among our fastest-growing diseases; they account for the second highest number of disabilities under social security. Respiratory diseases account for more days lost from work and school than all other diseases combined and cause more than one billion lost work days per year—an amount equivalent to 3.8 million man-years.

According to the Environmental Protection Agency, auto pollution is responsible for 4000 deaths and 4 million sick days per year. This is in addition to the acceptable risk (and cost) associated with the 40,000 or so deaths and many more injuries from auto accidents.

According to ERDA's 1975 Financial Report, the research and development (R&D) operating costs of the Environmental Health and Safety Program for the 10-year period, 1966 through 1975, amounted to $1.19 billion. This program has been reasonably successful and has been directed toward nuclear energy until recent years. Environmental Health and Safety R&D funding for other energy-producing technologies is more difficult to identify, but probably added at least $1 billion during the same period. However, the current annual cost of the black lung benefits program, not including medical payments, is of the same order as the entire 10-year ERDA funding of $1 billion. Black lung disease is but one adverse biological effect of one portion of one energy fuel cycle.

Perhaps the question of cost was discussed most eloquently and perceptively by Henry David Thoreau when he wrote, "The cost of a thing is the amount of what I will call life which is required to be exchanged for it, immediately or in the long run."

I have pointed out that we have an obligation to understand and ameliorate the health and environmental costs attendant on the continuation of ongoing and the development of new energy-producing technologies. However, let us not forget something else in our zeal to get on with the job; that is, that the quality of life in general has come a long way, and much of this improvement is the direct result of technology.

At the turn of this century more than 13 of each 100 children born were destined to die before they reached one year of age. Infectious diseases like pneumonia, influenza, and tuberculosis claimed many lives. Life expectancy for those born in 1900 was significantly less than that for children born in 1976. We have retired many of the materials used earlier, such as carbolic acid, lead arsenate, Paris green, sulfites, formaldehyde, lead-based paints, lead chromate for food coloring, numerous addictive drugs, radioactive nostrums, just to name a few. We have also eliminated or brought under control many disease-carrying animals.

Not many people would want to return to the conditions that prevailed around the start of this century. However, we should not become complacent and sanguine. We must ask ourselves how much better we can make our environmental setting and not be completely satisfied with the progress we have made.

Technology has helped us along the road, and we must learn to use its power even more effectively as we proceed to meet the future and gain energy independence. We cannot delay too long, for planning without implementation is of no real value, and we cannot change the fact that today is tomorrow's yesterday.

We cannot afford to fear technology. It is but one more of mankind's tools. We must, however, guard against its misuse and strive to reduce its negative impacts on human health and man's environment to a socially acceptable minimum. We must be reasonable and worry about our total environment on this spaceship Earth.

Perhaps Max Born said it best in his book *My Life and Views*.

> Intellect distinguishes between the possible and the impossible; reason distinguishes between the sensible and the senseless. Even the possible can be senseless.

BOOKS

Grants: How to Find Out About Them and What to Do Next. *Virginia P. White. New York & London: Plenum Press. 1975. 354 pages. $19.50. Reviewed by Charles S. Shoup.*

THIS BOOK is a welcome aid for anyone who even begins to think about asking for research support as grant or contract money from government, foundations, charitable trusts, or private corporations. Here is a lively, well-written, and highly readable account of the history and nature of philanthropy and the meaning of grants and contracts and their varieties. We are told how to find out about granting agencies and the nature of their basic objectives, what to do before applying for a grant or contract, how to prepare an effective proposal, and how to properly reply to questions from proposed donors.

I can remember telephone conversations that we, as AEC regional contract research administrators in Oak Ridge Operations, had with our Washington counterparts. Often the calls pertained directly to the contents and purposes of this book. Frequently the conversations would be in this anguished mood: "Hey, you know Dr. Joe Doe down there in Blank University? Well, we have a contract proposal from him. I wish he had talked with us before his final preparation. His story on what he wants to do is incomplete. With the lack of detail on his procedures and background, I simply can't take the proposal to my committee. We would like to help him, and would be pleased to have a contract in his geographical area, but Joe simply has not followed our directions for preparation of research proposals. His objectives and the appropriateness of his research are not clearly set forth, and he does not indicate the facilities he has available. His budget calls for equipment that surely his univesity already possesses. He does not mention any safeguards for the virus work he has in mind, and his estimates of indirect costs are not in line with our knowledge of the policies of his university. I must send back the proposal for reworking. Can you phone him and soften the blow? This could set back his program for six months or a year. Why couldn't he look ahead and call us and get our advice and guidance first, and thus avoid this waste of time?"

This book is intended to prevent the above fiasco. The author tells how to obtain all needed information on grants. Some fifteen different Government money sources are identified, including the complex of Health, Education, and Welfare. There are nineteen sources of information on the hundreds of granting foundations, private and corporate. Hints and admonitions are offered. Sources included are not only the scientific areas but also those awarding the arts, social sciences, history, and education. Among the many granting organizations cited, the prospective grantee should surely find a comfortable niche.

About a third of this book is concerned with exploration prior to development of the proposal and the actual application. Pre-application discussions or letters, as recommended by our above phone conversation, are highlighted. The author then goes step by step and with considerable humor through the formal proposal, indicating everything important that must be done. Examples are presented with suggested outlines—the objectives, procedures, facilities, backing of the home institution, the institution's share of support, and then, of course, the all-important budget! Two budget samples are printed as guides: One is on-site and cost-sharing; the other is off-site and has no institutional sharing. Reference is made to numerous items that should not be forgotten in the budget to avoid future financial embarrassment. With the guidance found in this book, there should be no excuse for a beginner in grantsmanship to fail in preparing a reasonable budget.

After the proposal disappears into the mails come the anxiety and frustration of waiting! The author recognizes these agonies, and offers advice about differences in agencies in their responses, follow-up, and how to behave if the agency requests a site visit.

This book is needed by every library and every university grants officer. Unhappily, the cost of the book, reflecting present-day outlays for printing and paper, is just high enough to discourage individual buying unless the grantee can finagle the book into his new budget. The author, a former well-known Oak Ridger, is certainly to be congratulated on producing such a useful volume. It is truly a handbook and guide for every researcher who must ask for money. It is a pleasure to report that the book is dedicated to two other former Oak Ridgers, Henrietta and Alexander Hollaender. The book includes appendices, giving U.S. Federal Agency acronyms, HEW offices, PHS programs, Federal information centers, and a current U.S. listing of endangered animal species.

The Grass Roots Primer. *James Robertson, ed. San Francisco: Sierra Club Books. 1975. 287 pages. $7.95. Reviewed by Eric Hirst.*

THIS WONDERFUL BOOK features a collection of 18 stories that show how ordinary people are saving their environments: an urban neighborhood, a million-acre wilderness, a small pond, and citizen control over underground nuclear explosions. Although we often think of governments as the source of all things good (and bad!), this book shows how a few individuals truly can make a difference.

Although the book is aimed primarily at environmental activists, it is delightful reading for anyone interested in the political process and our physical environment. The first two-thirds of the book presents 18 stories that show how local groups in several states and Canada dealt with major local environmental problems. The issues covered in these examples range from protection of a small marsh near New York City to preservation of a large tract of Oregon wilderness; from opposition to coal strip mining in Montana to opposition to titanium strip mining in Tennessee; from citizen control of underground nuclear tests in Colorado to citizen control over the fate of the French Broad River in North Carolina. Four of the stories involve energy supplies—nuclear power in Oregon, coal strip mining in Montana, oil drilling in California, and a hydroelectric dam for Washington.

The second part of the book leads the reader through the key steps involved with planning and organizing a local environmental effort. This 50-page section, called "Steps to Power," includes information on the group, goals, action plans, publicity, and other elements of an environmental campaign. For example,

> The Goal: Decide exactly what you want to achieve, and exactly what you will settle for; then forget what you will settle for and go after what you want.

I was struck by the general applicability of the issues and suggestions offered here. I recently took the Union Carbide Management Course, and—surprise!—many of the same elements of organizations are discussed in both places.

The third part of the *Grass Roots Primer* summarizes important Federal and state environmental legislation. Much of this discussion focuses on the National Environmental Policy Act, a piece of legislation well-known at ORNL.

The writing in this book is generally quite good—informal, clear, concise. I enjoyed reading all 18 of the grass roots environmental action stories. It is heartening to see how individuals can group together and successfully challenge unacceptable practices of large corporations and indifferent government agencies. The book shows that, if we want it, we can have Power to the People.

Staff quote:

"An interesting program carried out by Dr. Berne Neidhardt in Darmstadt (Germany) is on the activation analysis of wines. A 100-ml sample of each wine is freeze-dried and heated to remove organics; then a 0.1-mg powder sample is irradiated with a known number of neutrons. After a decay period of a few days, the sample is analyzed by germanium-detector gamma spectrometry and the data is stored in a computer. Neidhardt has found that each wine (of a given year, vineyard, type of grape, etc.) has a definite pattern, much like an individual's fingerprint. The ratios for elements such as sodium, silver, calcium, iron, and potassium are constant for a given wine and can be used to detect adulterated or falsely labeled products."—**Charles E. Haynes,** reporting on a recent European trip.

Ray Wymer, associate director of the Chemical Technology Division, has had many years of experience in the nuclear fuel cycle. Because of this experience and his current involvement in several major fuel recycle programs, he is qualified to comment on the fuel cycle and its current status. The *Review* is pleased to present to its readers this article by Wymer on the nuclear fuel cycle, which is a critically important part of the solutions to the nation's energy problems. Wymer came to the Laboratory in 1953 from Vanderbilt University, where he had just earned his doctorate in chemistry. With a few years' absence to serve on the faculty of Georgia Tech and later in private industry, he has been on the ORNL staff since then.

JON THOMPSON

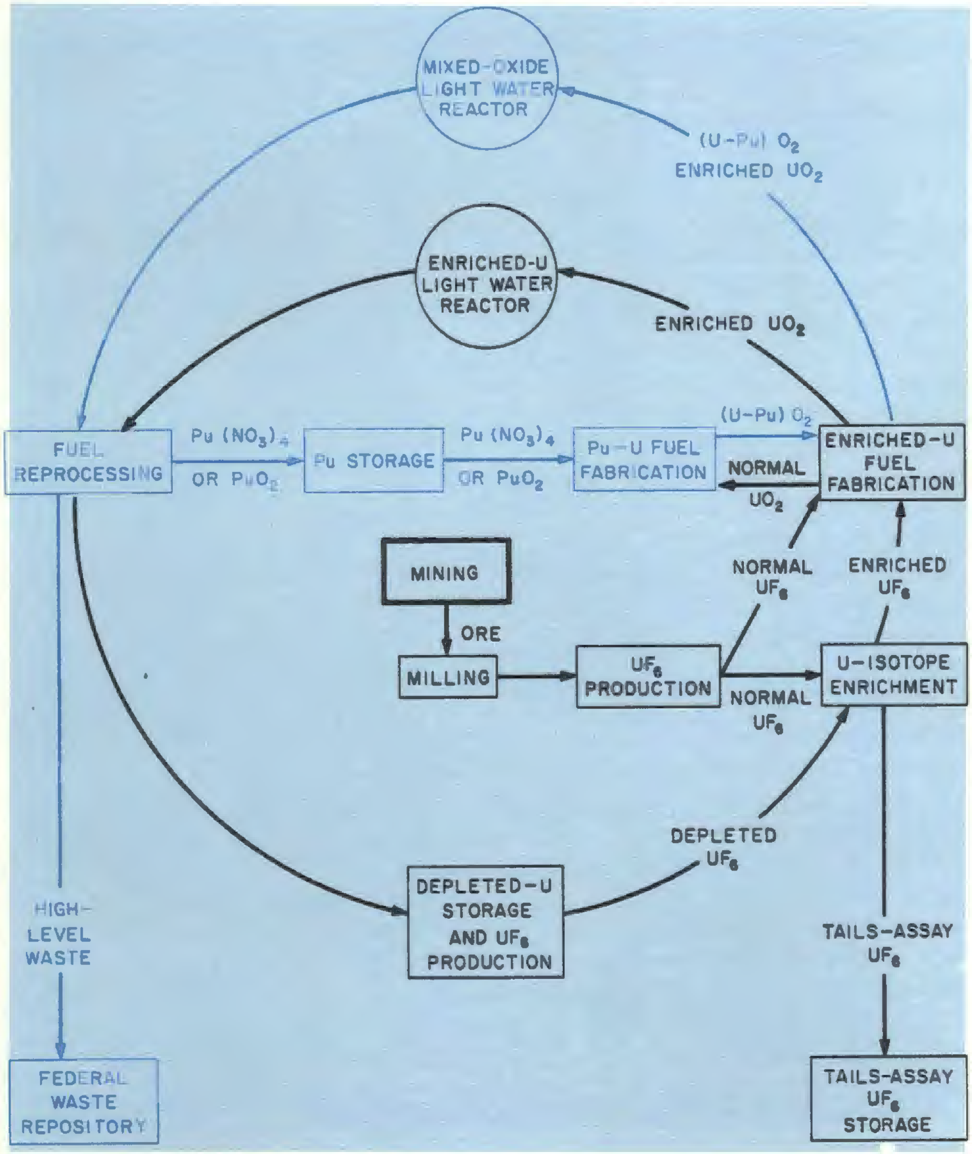
What About the Nuclear Fuel Cycle—

Where Do We Stand?

By R. G. WYMER

The term "nuclear fuel cycle" is generally given to those operations necessary to prepare fuel for nuclear reactors. The operations include recycle of uranium and plutonium from spent fuel and management of the wastes produced. At present, not all the fuel cycle operations are being carried out—at least, not in the United States; however, all the operations necessary to make possible the production of electrical power from light-water nuclear reactors are being performed in this country, where more than 55 power reactors are operating.

In this article, I want to discuss the fuel cycle and offer answers to some questions that



The nuclear fuel cycle, both as it is now and as it will be when the breeders are operating, and when the cycle is complete. The routes in blue are not now in operation.

concerned people are asking as the situation regarding the nuclear fuel cycle becomes more critical.

What Are the Fuel Cycle Operations?

On this page is one of many ways of schematically showing the fuel cycle. It shows the flow of those materials which do, in fact, cycle, as well as those which do not. The fuel cycle operations, as may be seen from the figure, are uranium mining, milling, purification (refining), conversion (UF_6 preparation) and enrichment, fuel fabrication and reprocessing, storage of divers materials, and waste disposal. Not shown explicitly, but implicit in all parts of the fuel cycle, are the necessary shipping operations. Those fuel cycle operations not now performed commercially in the United States are fuel reprocessing, all operations involving plutonium, and disposal of the radioactive wastes in a Federal repository. Although uranium enrichment is not performed commercially, the Federal government makes available a uranium enrichment service. The figure also shows a light-water reactor operating with uranium-plutonium (mixed-oxide) fuel; although there are some LWR test fuel elements containing uranium and plutonium being irradiated in several reactors in the United States, there is at present no reactor operating entirely with this mix. Such reactors will be essential if we are to have an optimized nuclear fuel cycle.

An important fact to keep in mind in any discussion of the nuclear fuel cycle is that the operations are extensively interrelated. The amount of ore that must be mined is related to the uranium enrichment plant capacity through the degree of enrichment and the uranium-235 content of the enrichment plant waste stream; it is also related to whether uranium and plutonium are recovered from spent fuel and put back into the fuel cycle. The shipping requirements of such important materials as spent fuel from the reactors to the reprocessing plants, plutonium from the reprocessing plants to the fuel fabrication plant, and high-level radioactive wastes from reprocessing plants to waste repositories are determined by the geographical locations of the various operations. This geographical interrelation is so important that it may have a decisive influence on the location of some of the fuel cycle operations.

Uranium mining and milling are closely related and are usually operated in conjunction. The amounts of uranium recovered by surface mining and by deep mining are approximately equal, and the ores are largely sandstone. Because the ore now being mined averages only about 0.17% U_3O_8, it is desirable not to ship it very far before recovering and concentrating the uranium. The recovery and concentration operations, called milling, produce an impure concentrate dubbed "yellowcake." The residue left after milling, which is the bulk of what was mined, is put into piles called tailings piles. These tailings piles, which contain most of the decay chain daughters from the uranium isotopes originally present in the ore, constitute an important and troublesome fuel cycle waste. About 11,600 tons of U_3O_8 were produced in 1975 in the United States; the present milling capacity could produce 17,000 tons of U_3O_8 per year. Thus, at present, capacity exceeds production.

Uranium purification (refining) is carried out on the U_3O_8 concentrate to remove impurities to make the uranium suitable for use in reactor fuel fabrication. A high degree of purification is required, especially with regard to those materials which are parasitic with respect to neutron absorption and which would cause problems in the isotope separation gaseous diffusion plants. The purification and conversion (to UF_6) operations can be performed together because they are so


W. N. TILLERY

Underground salt domes still offer the greatest security for nuclear waste repositories, having been demonstrably free of circulating water for hundreds of millions of years.

closely related. In the early days, the U_3O_8 concentrate was dissolved in nitric acid, and the uranium was purified by solvent extraction and conversion to UF_6 by a series of chemical reactions. Now about half the uranium destined for commercial use is refined by a process that does not use acid or solvent extraction and that produces a UF_6 product which has been purified by fractional distillation. Present plans are to convert the uranium recovered during fuel reprocessing to UF_6 at the reprocessing plant. Conversion capacity is adequate for today's needs for UF_6.

Uranium enrichment is performed by the Federal government in the gaseous diffusion plants at Oak Ridge, Paducah, Kentucky; and Portsmouth, Ohio. The UF_6 is enriched as a service for a contracted price, or "toll." At present, only these plants are producing enriched uranium for commercial power reactor use in the United States; however, a substantial development program is under way on gas centrifuge isotope separation. Both separation processes rely on mass differences between $^{235}UF_6$ and $^{238}UF_6$ molecules to effect isotope separation. The advantages of the gaseous diffusion process are its proven reliability and low-maintenance operation; its disadvantages are the enormous size of the plant required to achieve the needed enrichment and the high energy consumption. The gas centrifuge process not only requires less space but consumes about 10% of the energy used in gaseous diffusion; its disadvantages are its lack of demonstrated reliability (and so the greater risk of investment in building and operating a plant) and the possibility of higher maintenance costs.

Enrichment capacity is measured in separative work units (SWU), a term used for the amount of work (energy and, hence, cost) of enriching UF_6. It is a complicated function of the uranium-235 concentration of the feed, the product, and the tails, or waste stream, of the isotope separation plant. At present, U.S. capacity is somewhat in excess of 17 million SWU per year and is to be increased to over 27 million by improving and upgrading the three existing plants. This increased capacity is expected to meet enrichment needs until the mid-1980s.

Fuel fabrication brings together the skills of the ceramist to produce pellets of UO_2 or PuO_2-UO_2, the metallurgist to produce the Zircaloy tubes which contain the pellets, and such other craftsmen as experts in nondestructive testing and quality assurance, inspections, and assays for fissionable materials and measurements of plant emissions. Fuel fabrication for LWRs, which use uranium enriched to around 3% uranium-235, is a mature industry. The same cannot be said for fabrication of fuels containing plutonium. Institution of industrial capability for plutonium fuels must await Nuclear Regulatory Commission (NRC) decisions on plutonium recycle.

Fuel reprocessing is that part of the fuel cycle in which the fission products and other materials are separated from uranium and plutonium present in spent reactor fuel and in which the uranium and plutonium are separated from each other. The waste product is prepared for storage in a repository, and the uranium and plutonium are prepared for recycle. A commercial fuel reprocessing plant (the Allied-General Nuclear Services Plant) is nearly completed in Barnwell, South Carolina, but it may not start operation until the NRC decides what may be (or must be) done with the recovered plutonium. Also, decisions must be made on the form and packaging of the plant's radioactive wastes. The capacity of the Barnwell plant is nominally 1500 metric tons of uranium and plutonium per year, but by the time the plant could be on stream, the rate of fuel discharge from the operating U.S. power reactors will exceed the plant's capacity. Another plant of comparable size (the Exxon Nuclear Fuel Recovery Recycling Center), possibly to be located near Oak Ridge, is under design and in early licensing stages, but it will not be operational before the mid-1980s. Two other commercial fuel reprocessing plants have been built in the United States, but neither is operating, and it appears doubtful that they will operate. One of these, General Electric Company's Midwest Fuel Reprocessing Plant in Illinois, although constructed, never started operation because of deficiencies in its basic design; the

Staff quote:

"The majority of those patients who had suffered from mild or modest degrees of intoxication improved greatly; however, it could not be ascertained whether this improvement reflected the patient's learning to compensate for residual neurological defects; the need for vigorous rehabilitation programs was stressed repeatedly.

"Prenatally exposed infants, on the contrary, showed no appreciable improvement; at two years after exposure, manifestations of methylmercury poisoning became evident in many infants who previously had been classed as healthy."—**James E. Huff,** *reporting on a conference, supported by the Swedish International Development Authority, on "Intoxication Due to Alkylmercury-Treated Seed" in Baghdad, Iraq, in 1974.*

other, the Nuclear Fuel Services Plant near Buffalo, New York, operated for a number of years and then was shut down for modifications. Now it appears it will not be put back into service.

Storage of the various materials, most of them exotic, in the nuclear fuel cycle is not usually included in discussions of fuel cycle operations. However, a number of important storage operations are involved. The current delays in fuel reprocessing plant operation make it imperative to store spent fuel until it can be reprocessed. Until a Federal waste repository is established, the accumulated fission product wastes may be stored in solution in tanks at the reprocessing plant, pending solidification and packaging for shipping. Also, consideration is still being given to temporary, or interim, storage of solidified high-level waste in repositories from which it could be retrieved at a later date if desirable.

Radioactive waste disposal problems arise throughout the fuel cycle. The most significant wastes appear to be the tailings piles from the mills and the high-level wastes from the reprocessing plants. The tailings piles are low-level in radioactivity but extensive, and they are consequently difficult to contain. The high-level wastes will be produced in a relatively small volume, but they constitute far and away the most radioactivity in the entire fuel cycle. Other wastes include fuel fabrication plant wastes, which are composed of alpha emitters; isotope separation plant wastes, constituting depleted uranium in the form of UF_6 (a material that, because it could prove to have value in the future, might be considered either a storage or a waste problem); reactor wastes, which include a variety of radioactive materials, mostly those removed from the water that moderates and cools the core; and a spectrum of miscellaneous wastes from the fuel reprocessing plant. Most wastes will be stored in one of several types of proposed Federal repositories throughout the United States. In general, these repositories will be in stable geological formations such as salt beds, clay-bearing shales, and crystalline rocks. The first of these may be ready to receive high-level wastes in the mid-1980s on a demonstration basis. The tailings piles can be dealt with through use of appropriate coverings and stabilizing vegetation.

Why Do We Need a Fuel Cycle?

It is possible to have nuclear power for a limited time without a completed nuclear fuel cycle by continuing to use the uranium ore present in the earth's crust. The nuclear fuel cycle, however, will extend the time available before the uranium is totally used up and will also reduce the cost of nuclear power by permitting substitution of recovered plutonium for part of the uranium. Recovering and recycling the unused uranium from the spent fuel will also reduce uranium enrichment requirements. Recycle to LWRs of just the uranium alone could reduce the cumulative uranium ore requirement by about 13% by the year 2000. On the same basis, if plutonium is recycled as well, the cumulative ore requirement can be reduced by as much as 21% by the year 2000. When the cost of uranium (which will increase as uranium ore gets more scarce and as available ore becomes poorer in grade) is considered, these reductions in ore requirements are found to be very significant.

Notwithstanding the above benefits, the really important long-term benefit to derive from fuel recycle is in its potential to supply plutonium for use in liquid-metal fast breeder reactors (LMFBRs). These breeders hold the promise of effectively eliminating the present reliance on availability of uranium ore. Once a sufficient number of LMFBRs are in operation, the plutonium needed to fuel additional ones may come from the breeders themselves (that, of course, is the reason they are called breeders), and the LWRs may be phased out. However, it is not simple to switch from LWRs to LMFBRs. The breeder reactors must be built quickly to meet the country's power needs before the useful uranium ores are exhausted; and the plutonium to fuel the first LMFBRs must come from the LWR fuel cycle.

What Is Being Done?

The Energy Research and Development Administration (ERDA) and private industry are taking steps to see that the LWR and LMFBR nuclear fuel cycles are completed in a timely manner. Union Carbide Corporation-Nuclear Division (UCC-ND) plays major roles in the ERDA fuel cycle programs, which include ORNL studies on reprocessing fuels from both LMFBRs and LWRs. The Laboratory also has prime technical responsibility for the LMFBR fuel reprocessing program, now housed in the former EGCR building, and an important supporting role in the LWR fuel recycle program, for which Savannah River Laboratory has prime responsibility. The UCC-ND also has prime technical responsibility for developing and demonstrating methods for disposing of high-level radioactive wastes in stable geologic formations such as salt deposits. This program, now located in the UCC-ND Office of Waste Isolation (OWI), is of central importance to fuel recycle and to acceptance of nuclear power in the United States. The OWI technical personnel is largely made up of former ORNL staff members. Other important LWR fuel reprocessing and waste disposal problems are being addressed in ERDA facilities across the country. The UCC-ND, operating two of the nation's three uranium enrichment plants for ERDA, is responsible for the gaseous diffusion plant uprating and cascade improvement programs, which will increase the total capacity of the plants by almost 60% when they are completed. The central problem of availability of uranium ore is being better defined through an ERDA program called National Uranium Resources Exploration, in which UCC-ND has responsibility for a ten-state regional survey of the United States for new sources of uranium ore and other materials.

Private industry, through private investment and participation in ERDA-supported fuel cycle programs, is also contributing to completion of the nuclear fuel cycle. The Allied-General Nuclear Services plant attests to the current involvement of industry in fuel reprocessing. Private investment in development of processes for PuO_2-UO_2 fuel fabrication shows substantial support for this part of the fuel cycle. Continuing industry reviews of and comments on standards and on various government rule-making proposals and proposed changes in regulations indicate the broad interest and participation of industry in all aspects of the fuel cycle. Finally, industry's proposals for major investment in the building and operating of isotope separation plants demonstrate its commitment to fill this gap in the fuel cycle.

What Are the Impediments?

Difficult technical problems have yet to be solved to complete the fuel cycle. Beyond these, and more serious, are impediments which are social and political in nature. A most urgent problem is that, despite the fact that the currently operating power reactors are continuing to discharge spent fuel, there is no commercial fuel reprocessing plant in operation to recover the uranium and plutonium from that fuel and to treat the radioactive wastes in anticipation of final disposal. Storage of the accumulating spent fuel pending its shipment to the reprocessing plant is rapidly becoming a serious problem. The storage pools at the reactors are being modified to accept the additional burden, and some fuel is being stored in the pools at the Midwest Fuels Reprocessing Plant and the Nuclear Fuel Services Reprocessing Plant, both of which are licensed to store fuel, but neither of which is licensed to reprocess it. Several entrepreneurial groups have indicated a willingness to provide interim fuel storage capacity, which might be necessary if delays continue in fuel reprocessing, but such storage is at best a stopgap measure.

It is also important to recognize that, even if enough uranium ore is found to support the projected nuclear power growth, the rate of exploration and expansion of the mining industries must be great to keep pace with the projected growth rate. For example, the milling capacity may have to be doubled by 1980–1981 and certainly must be tripled by 1985. The wastes produced from the uranium mills contain most of the daughters in the decay chains of the natural uranium isotopes, as well as unrecovered uranium. Treatment of the tailings piles from mills already abandoned and of the piles continuing to be produced remains a significant fuel cycle problem.

Processes for remotely fabricating plutonium-containing fuel, as well as processes for reprocessing these fuels and others (which will contain much higher fission product concentrations than fuels reprocessed commercially heretofore) must be developed and demonstrated.

Although these and other technological problems remain to be solved, there do not appear to be any that are incapable of solution. The more troublesome problems are the political and sociological ones. The political problems are both national and international. Key fuel cycle problems of this nature currently under discussion are those relating to the delay or prohibition of recycle of plutonium pending the NRC decision. Related to these are the concerns about (1) plutonium safeguards and toxicity and (2) the potential proliferation of nuclear weapons production capability by nations not presently in the "club" in the event that fuel recycle capability is developed in those nations. A recent addition to the list of problems is the ruling that inhibits reactor construction until the related implications of fuel reprocessing, waste disposal, and alternatives to nuclear power, such as conservation and other power sources, have been addressed.

Finally, acceptance must be obtained for storage of radioactive wastes in Federal repositories located in a number of states across the country.

What Are the Prospects?

The prospects for having private industrial involvement in the entire nuclear fuel cycle in the immediate future are dim. Delays connected with the NRC decision on recycle of plutonium are seriously affecting the onset of fuel reprocessing. The enormous investments required in all parts of the fuel cycle and the great uncertainties that exist today with respect to regulations, licensing, and safeguards make private industry reluctant, and perhaps unwilling, to provide the necessary capital to fill in all the fuel cycle gaps. The Federal waste repositories will be operated only as demonstration facilities until they have been used satisfactorily for a number of years, although the plan is that they be ready to receive wastes and store them in retrievable form by the time the wastes arrive from the reprocessing plants.

It appears that we will be well into the 1980s before a commercial LWR fuel cycle can be complete and certainly into the 1990s before the fuel fabrication and reprocessing operations for LMFBR fuel can be incorporated into the cycle. In the meantime, any decision to substantially increase the role of nuclear power in the United States depends greatly on the perceived ability or inability of other available sources of power to meet the power needs in a timely way and on the availability of sufficient enrichment capacity to extend the uranium ore supply. (It is a feature of the interconnectedness of the fuel cycle that enrichment capacity can be traded off for ore requirements.)

Notwithstanding the difficulties that must be surmounted, those of us working close to the nuclear fuel cycle are sustained by the conviction that nuclear power is in fact essential to the economy of the nation and therefore must be available when it is needed.

Staff quote:

"The Mexicans are also very proud of their ability to design 'earthquake-proof' structures by using the floating foundation concept. In the soft clay soil of the Mexico City area, the floating foundation spreads out the load of large heavy structures over larger areas and prevents the buildings from slowly sinking in the soft clay. During the small earthquakes which frequently hit the area, the foundations keep the buildings from undergoing large motions; therefore, very little damage results. A small earthquake hit the Mexico City area during the conference and measured 3.5 on the Richter scale. No noticeable damage was seen in the city."—**Richard C. Gwaltney,** *reporting on his attendance at the International Joint Petroleum Mechanical Engineering and Pressure Vessels and Piping Conference, Mexico City.*

R&D sequels

This will introduce a new feature to appear from time to time, its intent being to provide updated information concerning articles that have appeared in previous issues of the *Review*. This issue's Sequels report on subsequent events relevant to the ACES concept, ANFLOW, and the Poster Sessions.

ACES, Anyone?

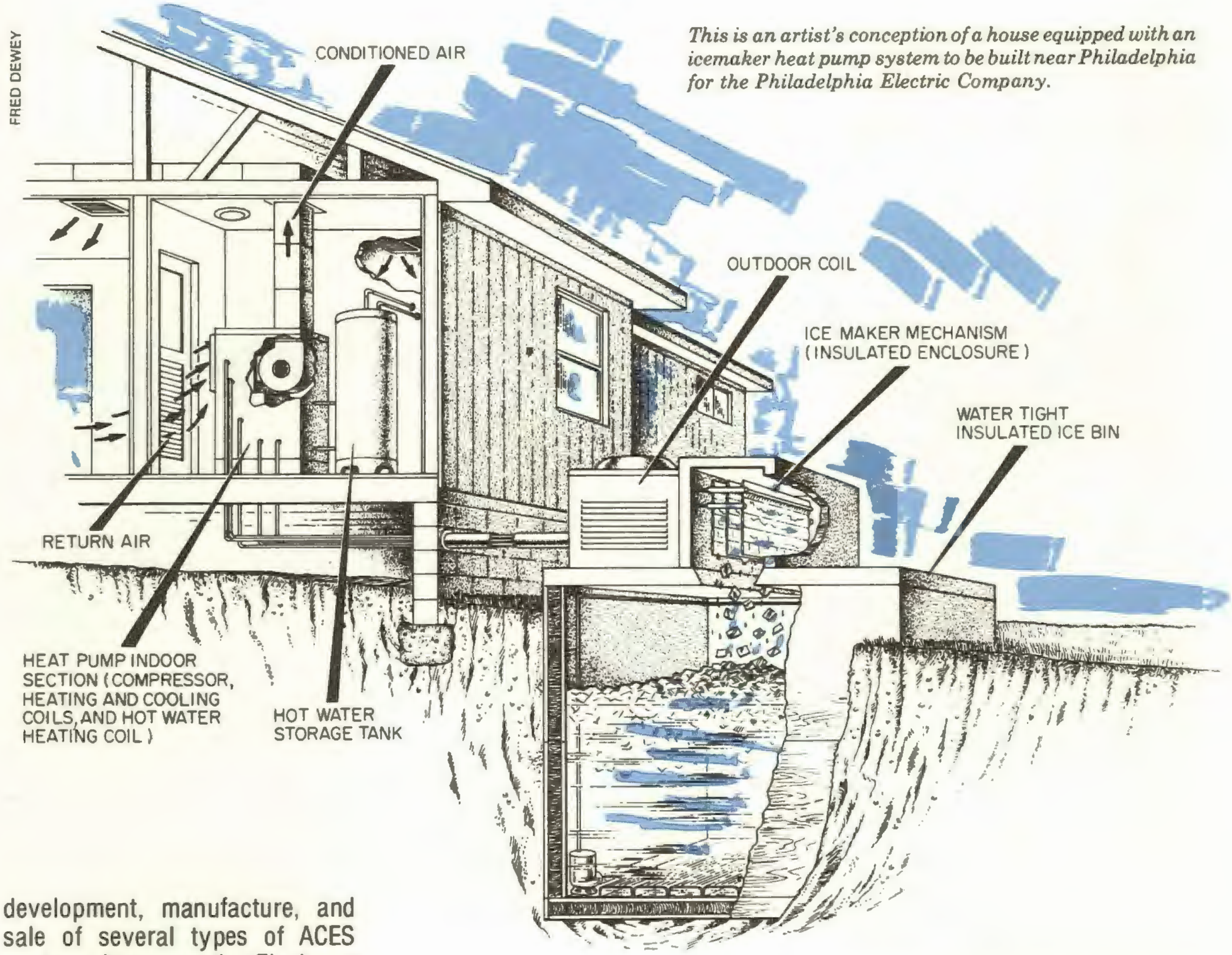
What's in the cards for ACES—the Annual Cycle Energy System scheme in which a heat pump extracts energy for wintertime heating from a large, insulated tank of water, gradually making ice that could be used to keep air-conditioning costs down in the summertime? Indications are that the ice bin continues to be one of the hottest technological developments in energy conservation. According to Harry C. Fischer, ORNL consultant who developed the system for economically providing hot water and space heating and cooling for homes and commercial buildings, there have been many developments in the past year.

- The local ACES house, funded by ERDA and by the U.S. Department of Housing and Urban Development, was completed and put into operation July 1, alongside the solar energy demonstration house sponsored by the University of Tennessee and the Tennessee Valley Authority. The two houses, along with a third house having a conventional electric heating and cooling system, all located on Alcoa Highway between Knoxville and the McGhee-Tyson Airport, are being studied to determine how energy-efficient the novel heating systems are.
- An icemaker heat pump system has been developed. According to Fischer, this second generation ACES, which accumulates sheets of ice on aluminum freezer plates and then shucks off ice slabs into the bin below, is easier and less expensive to manufacture and more cost-effective to operate than the first-generation ACES, the system used at the local ACES house in which a block of ice accumulates around coils through which an alcohol-water solution circulates.
- The Philadelphia Electric Company has contracted with a leading builder to construct near Philadelphia a house to be heated and cooled by an icemaker heat pump system. The house, whose ACES system is to go into operation March 1, 1977, will be tested for 18 months and then sold.
- Several private industries are manufacturing ACES-type equipment. These include Refrigeration Systems, Newburgh, Indiana; Remcor Products, Inc., Chicago; Turbo-Refrigerating, Inc., Denton, Texas; and Scotsman, Queen Products Division of King Sealy Thermos, Albert Lea, Minnesota.
- The Veterans Administration Hospital's 60-bed nursing home in Wilmington, Delaware, which includes an ACES heating and cooling system, is now under construction.
- This past November a private company was to have completed a demonstration ACES house in Richmond, Virginia.
- There is growing foreign interest in the ACES concept. "This system," Fischer says, "may be even more applicable in Europe because the energy costs there are higher."

Fischer, who believes that "it is no sin to sell a good idea," is promoting the icemaker heat pump system especially for home-owners buying power from the 19 private electric utilities offering time-of-day rates—that is, lower electric rates for the hours when demand is down.

"The icemaker heat pump is a natural," Fischer has written. "The ice can be made at night, on weekends, or on cool days. Then, when traditional peak loads occur on hot weekday afternoons, buildings can be air-conditioned from ice inventory without compressor operation, thus reducing utility peak demand and giving the building owner more economical air conditioning because of lower off-peak rates. With some of the time-of-day rates now being tried, the icemaker heat pump equipment will pay for itself in one to three years."

In "The Ice Bin Cometh," an article about ACES in the Fall 1975 issue of the *Review*, Fischer was quoted as saying that he and his colleagues were making an effort "to get the system commercial by 1976." The effort has led to an expansion of the ACES group, which has five full-time researchers—Fischer, Eugene Hise, Allen Holman, Grimes Slaughter, and Ed Nephew. With the entry of several private firms into the



This is an artist's conception of a house equipped with an icemaker heat pump system to be built near Philadelphia for the Philadelphia Electric Company.

development, manufacture, and sale of several types of ACES systems, it appears that Fischer et al. are on their way to attaining their goal. Says Fischer: "I'm just commercializing old technology, selling it now when the time is right. [A patent on the ice bin heat pump was first obtained by C. E. Schutt in August 1934.] By next year, I may have worked myself out of a job."

Fischer, who came out of retirement to develop ACES at ORNL in 1974, does not seem to mind the prospect of retiring again, this time in Florida, where he can resume his love affair with an energy-conserving form of recreation—sailing in the sun.
—C.K.

M&C's Circus

Last year, two divisions introduced an innovative format to their information meetings (ORNL *Review*, Spring 1975). Both Metals and Ceramics and Thermonuclear Divisions devoted a portion of their meetings to the so-called "poster sessions," in which each area of research was described in picture, graph, and hardware, much like a museum display. Manning each exhibit was one or more of the authors of the work, who were available to provide a demonstration, a talk, or answers to visitors' questions. Both divisions declared the experiment a great improvement over the auditorium method of paper-reading with slides.

This year the same divisions repeated the format. Thermonuclear, now the Fusion Energy Division, stayed largely with the same program as last year. But M&C let the world know of their year's achievements by erecting a full-size tent in the parking lot of the flagpole entrance to Building 4500. Inside, two double aisles of three- and four-panel exhibits stood on tables that held a variety of hardware, mock-ups, and models. For two-and-a-half days the division staff held court while advisory committee members, colleagues, and Laboratory staff members milled through the tent, learning about the year's M&C work. On the first day an exclusive showing was accorded the six-member advisory committee, who, undistracted by other visitors, absorbed the information in the exhibits; each member was assigned to a specific, limited area for his attention and comment. Subsequently, the committee met in an evaluation meeting for discussions of the work.

Instead of offering the customary 12 to 18 speakers in a string of auditorium presentations, the large exhibit enabled 60 pieces of research and development to be aired, with the added advantage of optional one-to-one, in-depth discussion available to interested visitors. Jim Weir, division director, expressed deep satisfaction with the new format, as did all six members of his advisory committee.—B. L.

This is what the M&C Division's information meeting looked like to the daring young cameraman on the flying trapeze this year. The tent accommodated about four times as many research projects in the division as could have been disclosed in two days of auditorium sessions.

J. W. NAVE

ANFLOW

In the Fall 1975 issue of the *Review*, we reported that ORNL researchers Alicia Compere and William Griffith hoped to obtain funds from ERDA and industry to build an ANFLOW pilot plant at Oak Ridge's East End Sewage Treatment Plant to demonstrate the biological treatment of sewage and the production of methane. In September 1976, it was announced that a pilot plant to demonstrate the ANFLOW process would be built as a cooperative project by ERDA, the City of Oak Ridge, and the Norton Company, headquartered in Worcester, Massachusetts. The Norton Company's Chemical Process Products Division in Akron, Ohio, manufactures ceramic packing materials for the ANFLOW pilot plant and built the plant's tower.

Also in September, Compere, Griffith, John Googin of the Nuclear Division Engineering Development staff at Y-12, and Stanley Smith of the Norton Company received an IR-100 award for the novel ANFLOW technique. The magazine *Industrial Research* presents IR-100 awards for the 100 most significant new technical products in a given year.

The ANFLOW system consists of cylindrical columns packed with special ceramic materials to which anaerobic microorganisms are anchored (these materials were developed by Googin and Smith). The organisms feed on the stream to be processed, breaking it down to smaller molecules, producing a cleaner waste stream, and converting pollutants into useful products such as organic chemicals and fuel gas.

lab anecdote

THE BETATRON

As all who were here at the time well know, the years 1946–1948 marked a time of great uncertainty and travail at the (then) Clinton Laboratories. What was our future? Nobody knew, but one thing was clear—the future of the Lab would depend largely on us. In the Physics Division we sought some advanced, timely, and absorbing course of action to serve as a theme for new research in nuclear physics. One such field was the relatively newly discovered "mesotrons" (later called mesons)—particles having a mass about 200 times as heavy as that of the electron and whose role in the nature of things was not clear.

In 1945 the General Electric Company developed and placed on the market a betatron that would accelerate electrons to 100 MeV. Think of it—*100 MeV*! Far larger than previous betatrons, the magnet pole had a diameter of 76 in. (For further details, consult the *Journal of Applied Physics* for 1945.) Anyway, electrons and x rays of this energy could now be bought in tremendous intensity for laboratory research.

The main interest, however, came from the observation by M. Schein, A. J. Hartzler, and G. S. Klaiber at the GE Laboratories of cloud-chamber tracks taken adjacent to their betatron. In the applied magnetic field, some of these tracks showed a curvature that corresponded to a mass 200 times as great as the mass of the electron (*Physical Review*, September 1946). Looking at it again, I see that their statement was cautious; they avoided mentioning mesotrons, but the implication was there. However, the observations seemed good, and at the least, there was something intriguing about the situation. It seemed possible, then, that some of the new cosmic ray particles might be produced in abundance in the laboratory, or at least that some novel puzzle was at hand. Henry Newson and I were group leaders in the Physics Division at the time, and we persuaded Laboratory Director Martin Whitaker and Research Director Dick Doan to order a GE betatron. Perhaps we could build a timely and dynamic research program around it.

We were not alone; the University of Chicago also ordered one of the betatrons, and the third was the one at the GE research laboratories.

But a few months after the note by Schein, Hartzler, and Klaiber, H. A. Bethe published a paper (*Physical Review*, 1946) in which he showed that multiple scattering of particles in the cloud-chamber gas could account for the tracks. Poof! went the mesotron interest in the betatron, so we had to fall back on other, less glamorous researches if the betatron were to serve as a basis for a program.

The betatron arrived in due course and was stored in Oak Ridge because we did not have a shielded building for it. Meanwhile there were big changes. Whitaker and Doan left, and the Monsanto year started. Lothar Nordheim had left as Director of the Physics Division, and his place had been taken by Alvin Weinberg. Then Henry Newson left for distant parts, and I was left holding the bag—containing 130 tons of betatron.

I worried about it in 1947–1948, feeling that it would be better for the Lab to have a positive-ion accelerator than an electron accelerator if we were to build a future in nuclear physics. One thought occurred to me, however, and that was that, if you used the magnet as a basis for one of those newly invented electron synchrotrons instead of a betatron, you could almost double the particle energy. This is because the magnetic system of the betatron has to obey certain "betatron conditions" that limit the field strength at the orbit of the particles; the synchrotron is free of these conditions.

I traveled to Schenectady to talk with Westendorp and other engineers who had designed the betatron. They agreed that conversion to a synchrotron was possible, but this still left me unsatisfied that it would be a desirable course for ORNL.

In 1949 there was little interest in the Physics Division for the betatron. On the contrary, Bill Good, Dick Lamphere, and Charlie Moak had found the parts of a 2-MV Van de Graaff accelerator in the Chemistry Division and had begun to make a positive-ion source and accelerating tube to go into it. They also were planning a 300-kV Cockcroft–Walton set, to get monoenergetic fast neutrons using the DD or $T(p,n)He^3$ reactions. At about the same time, quite independently, Bob Livingston and his colleagues were assembling the 86-in. cyclotron, using bits and pieces of the big stuff that was lying around at Y-12.

So the course of the Lab swung to the positive ions. As new director of the Physics Division, I elected not to proceed with a building for the betatron, but to opt for a Van de Graaff building instead. In effect, I handed the betatron bag to Alvin Weinberg and Clarence Larson, to their considerable embarrassment. However, they stood behind the Physics Division. The NEPA Van de Graaff came along with a strong staff including Joe Bair, Francis Green, and Conway Snyder (1951). The Van de Graaff building was built for double the amount of money allotted to it, but here again Weinberg and Larson backed us. It had a big empty target room that could be used for fast-neutron cross-section measurements (an important challenge at the time) without much back-scatter of neutrons from walls and floor. Bernard Kern was helpful in its design. Meanwhile, the Electronuclear Division had taken shape, and a few years later their efforts culminated in ORIC. Thus, Van de Graaff technology and cyclotron technology developed in parallel, and we now see the linking of the two in our new Heavy-Ion Accelerator.

The betatrons? Ours presumably went on Government surplus; at any rate, it was picked up by the National Bureau of Standards, converted to a synchrotron at 180 MeV, and used to good effect in their program. The betatron at Chicago, however, was completely overshadowed in importance and research usefulness by the 450-MeV cyclotron they had in the same building. One rumor had it that they eventually donated it to an institution in South America. The GE betatron was, and continued to be, beyond my ken.—Arthur H. Snell

Notable quote:

"Even accepting that intentional bias has sometimes led to good results, attention needs to be directed towards evaluating such bias for three reasons. First, it is unsatisfactory that no data at all exists on its incidence. Second, intentional bias in an experiment is at present more or less impossible to detect, and no real safeguards against it exist. Third, pressures on researchers to obtain positive results are very strong and need to be taken into account.

"Although scientists in general are very critical of untested assumptions,the assumption of scientific impartiality is almost completely untested. Where information which bears on the question is available, it is far from reassuring. When L. Wolins (Amer. Psychologist, *vol. 17, p. 657*) *wrote to 37 authors asking for the raw data on which they had based recent journal articles, he found that, of the 32 who replied, 21 reported their data to be either misplaced, lost, or inadvertently destroyed. He was able to analyse only seven sets of data supplied by nine of the original 37 authors. Of these, three had errors gross enough to invalidate the author's conclusions."*—**Dr. Ian St. James-Roberts,** "Are Researchers Trustworthy?", *New Scientist* 71: 481.

JIM RICHMOND

Bill Rodgers, a member of the Experimental Engineering Section of ORNL's Chemical Technology Division since 1974, is a native of Fitzgerald, Georgia (which is "75 miles southeast of Plains," he now says). After earning his B.S. and M.S. in chemical engineering from the University of Florida at Gainesville, Bill worked at Shell Development (the research arm of Shell Oil Company) for five years at three locations: Emeryville, California; Wood River, Illinois; and Houston. In 1972, he moved to Tennessee, taking a research position with the Keene Corporation's Fluid Handling Division in Cookeville. When he came here two years ago, he brought to ORNL's Coal Technology Program his experience in petroleum residue, asphalts, and filtration—the kind of experience that lends itself to solving problems related to converting coal to clean liquid fuels. At left, Bill reads a digimetric weighing scale and records the filtrate weight at frequent time intervals during filtration of SRC liquids. The tube at left is a long-tube batch settling device for determining settling rates of particles in coal liquids.

COAL LIQUEFACTION—

Removing The Bottleneck

By BILL RODGERS

In 1900, nearly 70% of the energy consumed in the United States came from coal, which we burned to power our steamboats and locomotives and to heat our homes and factories. However, with the discovery of abundant quantities of oil and gas (which by nature are easier to develop and use), coal has been relegated to a lesser role over the last half century, even though it is our most abundant resource, making up about 80% of our energy reserves. Today, 76% of our energy comes from oil and gas, which constitute only 8% of our reserves.

With an impending domestic shortage of oil and gas, we are becoming increasingly dependent on foreign sources for these fossil fuels. This means that we have to face the possibility that our lives could be drastically changed by others who do not have our interests in mind; we could be plunged into an economic crisis that would rival the Great Depression. The obvious solution is to develop our own energy resources so that we will be much less dependent on the resources of others. Fortunately, we have a disproportionate share of the world's coal reserves. North America has about 50% of the world's coal, and the United States has about one-third. At 1973 energy usage rates, our coal reserves could supply all our energy needs for nearly 900 years. Clearly, increased exploitation of our coal reserves would help stave off a serious energy crisis.

The U.S. Energy Research and Development Administration (ERDA) plans to diminish the energy gap by developing an improved coal liquefaction technology for converting domestic coal into clean boiler fuel, distillate heating oil, gasoline, and chemical feedstocks. There are three liquefaction schemes under study—carbonization or hydrocarbonization, solvation, and catalytic hydroliquefaction. The first involves heat and pressure with or without hydrogen to convert coal in fixed or fluid beds to gas, liquid, and solid (char) products. Char often constitutes more than 50% of the final carbonization product; an example is the COED (Char–Oil–Energy Development) process developed by the FMC Corporation, which has operated an ERDA pilot plant in Princeton, New Jersey. Solvation involves slurrying the coal with a mixture of process-derived "donor solvent," usually in the presence of hydrogen. The solvent actually dissolves the coal under conditions of temperature and pressure and transfers hydrogen to break up the heavier molecules; an example is the SRC (Solvent-Refined Coal) process developed by Spencer Chemicals and currently tested by Pittsburgh and Midway Coal Mining Company. Catalytic hydroliquefaction, as the name implies, involves the use of a catalyst to aid hydrogenation of the coal molecules. An example is the Synthoil process developed by the U.S. Bureau of Mines and tested by ERDA's Pittsburgh Energy Research Center.

The Problem

A major problem in burning coal and its liquid products stems from the undesirable constituents of the fossil fuel. The coal seams in the eastern half of the United States, formed from decomposing algae, fungi, leafless plants, and ferns about 350 million years ago in the Paleozoic (ancient life) era, contain large concentrations of pyritic sulfur. The coals in the West, developed during the Cretaceous and Tertiary periods about 30 to 130 million years ago, are low in sulfur but have large amounts of non-energy-producing inorganics, which generate unusable residue or airborne pollutants when converted to usable energy.

When coal is burned to produce steam for generating electricity, sulfur dioxide and fly ash go up the stack, polluting the air and posing a hazard to public health. Hence, several years ago, when the U.S. Environmental Protection Agency (EPA) imposed emissions standards on coal-fired steam power plants to protect public health, a number of utilities were forced to switch from coal to less abundant, increasingly expensive oil.

The liquid fuel products yielded in ERDA's coal-conversion pilot plants do not consistently meet EPA guidelines for sulfur and ash. The liquid products contain fine, suspended, solid particles, which must be removed to reduce the ash and sulfur emissions of liquid fuel burned in power plant boilers to meet EPA requirements and to make the product suitable for further refining into synthetic oil products such as gasoline.

ERDA's coal research and development programs to date have emphasized the coal conversion step for producing gases and liquids; other process steps that have received little attention include development of a solids separation technology for removing most of the sulfur and ash from the liquid products of coal-conversion plants. Nevertheless, a small group in ORNL's Chemical Technology Division has looked at this difficult technical problem of solids separation and has begun to shed some light on how best to remove this bottleneck.

Some Solutions

The solid particles that contain sulfur and ash are difficult to remove from coal liquids because of their small size (50% are less than two microns). Most conventional separations techniques cannot be applied to particles this small.

Sid Katz, Phil Westmoreland, Dave McWhirter, and I have taken two novel approaches to methods of removing these solid particles from coal conversion liquids—improved precoat filtration techniques and agglomeration (making the particles stick together so that they are heavy enough to settle rapidly). We first

This is a coal precoat deposited on a 3-in. filter screen showing the accumulation of the solids on the precoat surface.

searched for processes which deviate from the standard type of precoat filtration. In precoat filtration, a diatomaceous earth is deposited on a porous membrane, such as a screen, before the filtration begins. The small, effective pore openings in the bed of diatomaceous earth allow the liquids to pass through, but hold the solids back. The solids "bridge" the pores until the tightly packed solids themselves become the filtering surface. We have found that a powder made of coal-derived materials is superior to diatomaceous earth for precoat filtration because it is one-tenth as costly and because the coal precoat and collected solids can be fed to a coal gasifier for recovery of energy values.

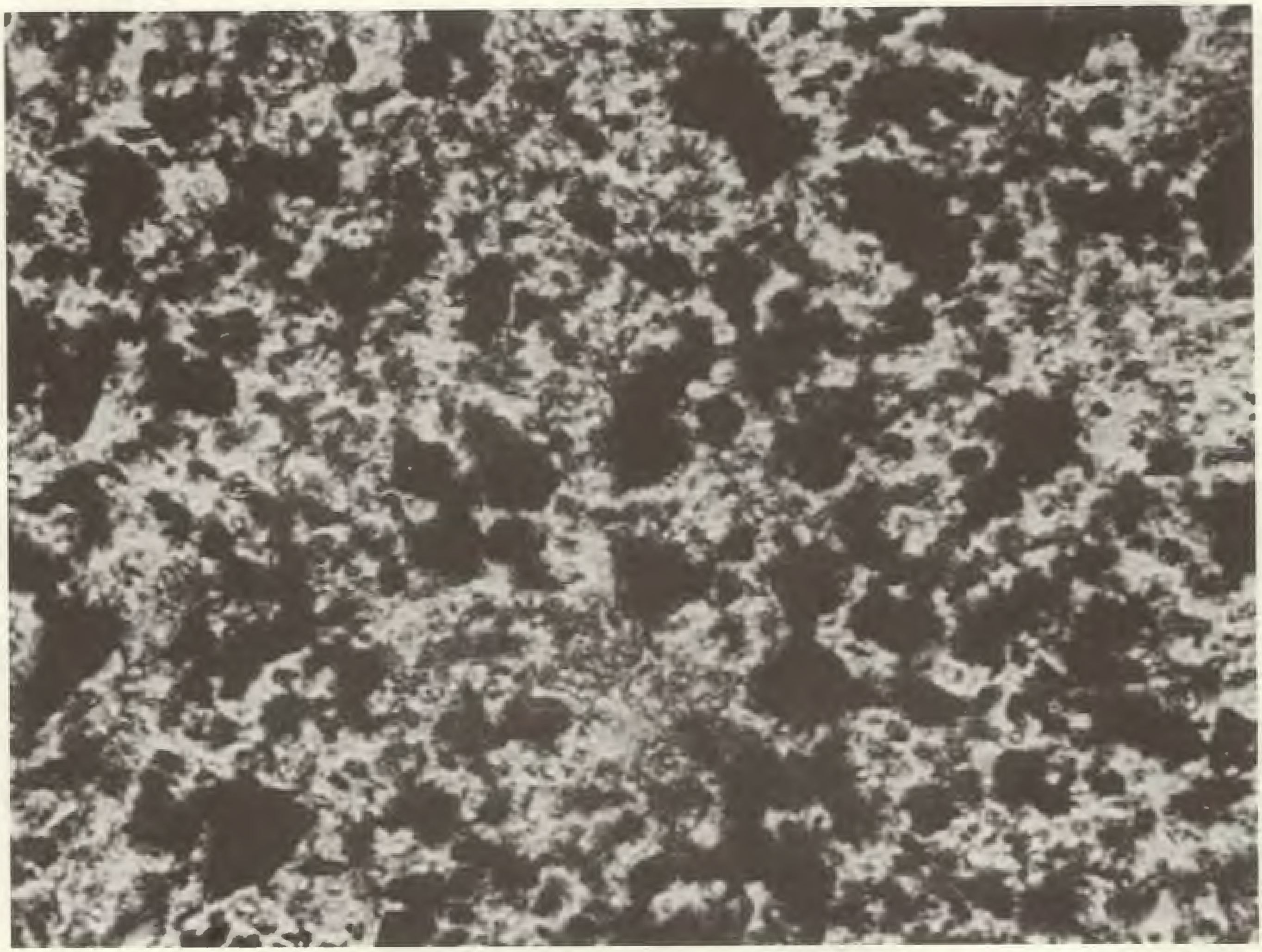
We have also found that certain solvents like toluene will produce particle aggregation and reduce viscosity of the slurry, thus increasing filtration rates by as much as four times. We have also found that low concentrations of certain additives can produce agglomeration. The aggregates of particles thus produced settle out of the product liquid, a desirable alternative to filtration because it avoids the mechanical problems of rotary drum filters. The products from separations performed in the laboratory have met all EPA requirements.

Precoat Filtration

Two major problems with precoat filtration of coal conversion streams are the large consumption of diatomaceous earth and the accompanying contamination of potentially valuable solids. We at ORNL believe we have developed a potential solution to these problems. In 1975 we proposed that pulverized coal could be used as a precoat, since the coal mesh size can be varied over a wide range and still provide increased filtration rates as compared with a standard diatomaceous earth precoat. We found that the filtrates from these tests meet EPA requirements. Obviously, ground bituminous coal would not be satisfactory for a precoat at very high temperatures because of softening and subsequent plugging of the bed. Recent studies indicate that this upper temperature limit is near 230°C. Most coal-liquefaction process filtrations can be carried out at or below this temperature, however; for those that require higher process temperatures, an anthracite or a devolatilized coal could be used.

One of the most significant advantages of using ground coal as a precoat is that it allows the use of very thin (essentially zero-thickness) filter cakes. Reducing the filter cake thickness from ¼ to ⅛ in. more than doubles filtration rates, and ultrathin cakes produce rates nearly ten times as great as those obtained with ¼-in.-thick cakes. In practice, ultrathin cakes can be maintained by setting the "doctor blade" on a rotary-drum filter to advance at a rate equal to or greater than the thickness of solids which accumulate during a revolution of the drum and increasing the speed of the drum. Of course, some precoat would be

Optical micrograph of COED (Char-Oil-Energy Development) unfiltered oil. 750×.



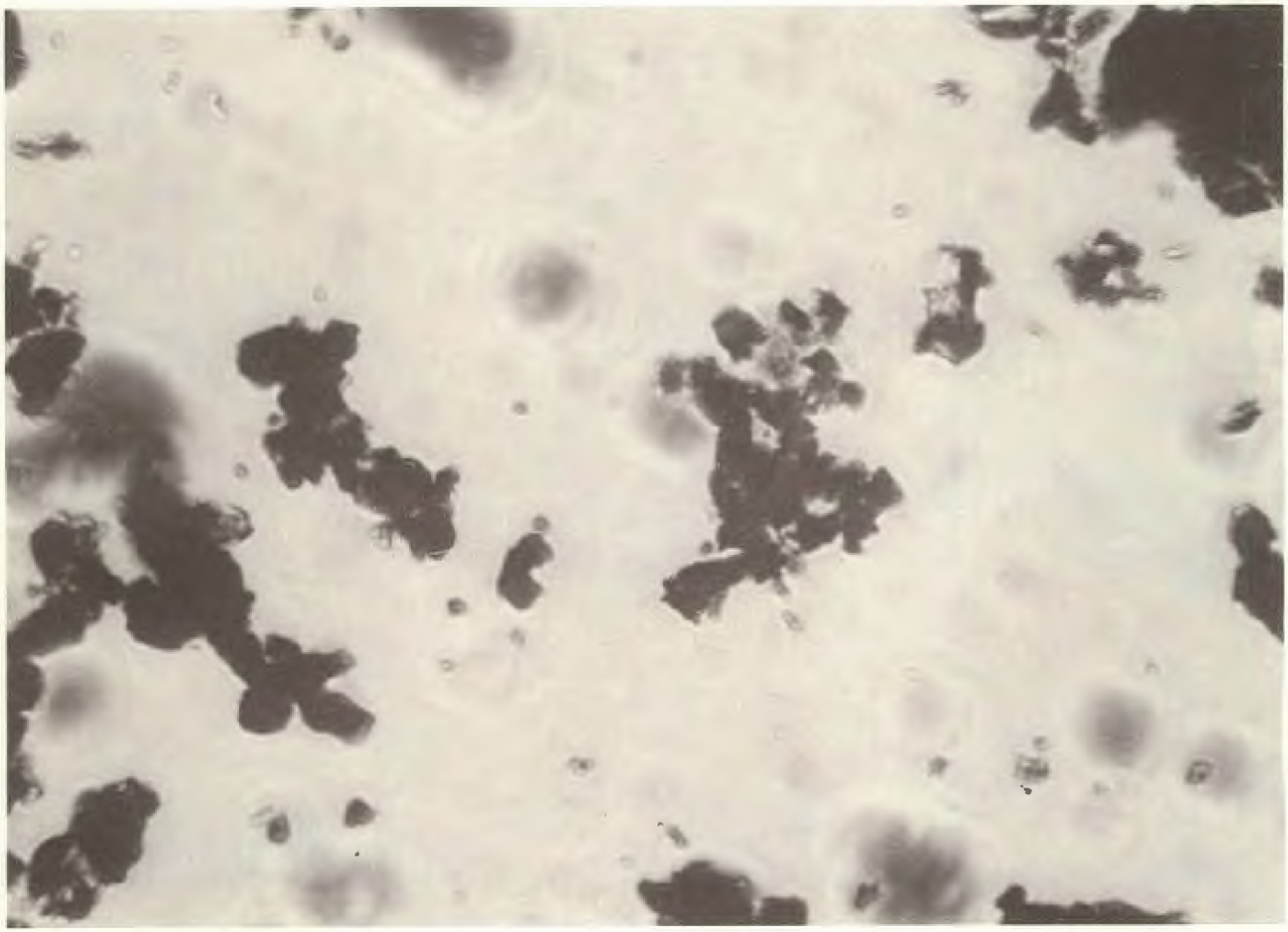
collected with the filtered solids. This ground coal precoat, added to the approximately 30 to 60% organic material already in the solids, enhances the value of the collected material as a gasifier feed to produce hydrogen or methane for the process. The gasifier would then reject only the mineral matter for disposal. As mentioned previously, typical inorganic precoats collected with the solids yield a contaminated product and reduce the usefulness of this material for downstream processing to recover the hydrocarbon content. In cases of excessive contamination, a waste product may be generated. Additionally, it was found that ground coal added to the process stream as a body feed prior to filtration provides a small increase in filtration rates. Coupled with coal precoat, such a body feed could also be used as a parameter to adjust the carbon content of the gasifier feed.

Agglomeration

Another method that has been found to increase filtration rates involves agglomeration to increase the effective particle size. Agglomeration is accomplished by use of aromatic solvents, paraffinic solvents, and process-derived solvents. At 100°C and 50 psi, the average initial filtration rate of a 5% toluene mixture is three-and-one-half times as fast as the average filtration rate without the addition of toluene. Addition of 30% process solvent will approximately double the filtration rate. Settling, followed by filtration of the upper fraction, produced filtration rate increases up to ten times as great as those of the unsettled values.

For long settling times at elevated temperatures, a completely clarified upper fraction could be

Optical micrograph showing agglomerates in COED unfiltered oil after toluene has been added. 1000X.



obtained, leading to the discovery that sedimentation, especially with materials added to enhance agglomeration, was an effective separations method. This was surprising since the calculated settling rate based on particle size distributions was only 0.008 in./hr. The observed settling rates at elevated temperatures were as high as 8 in./hr, a factor one thousand times as large. Apparently, a significant amount of agglomeration occurred at the higher temperatures, possibly due to surface melting of a heavy organic layer surrounding the inorganic particles. Solvents and additives could also be used to increase settling rates, indicating that particle surface modifications were taking place.

What Now?

At ORNL we have made significant improvements in filtration technology. Even though filtration economics have been improved, it is still a borderline process, owing to expensive equipment and mechanical unreliability. However, existing coal-liquefaction plants can make immediate use of the developed technology to improve their flow rates on existing equipment. A number have expressed interest in doing so. But more importantly, a much improved process, which should speed the development of coal-liquefaction technology, has been identified. The first separations section employing sedimentation within a coal liquefaction process is planned for the H-Coal plant to be built near Catlettsburg, Kentucky. This process was developed by Lummus Corporation and employs a paraffinic "de-ashing" solvent prior to a continuous settler. It is a step in the right direction, but much more development work is needed on some basics, such as treatment of settler underflows, before the process can realize its full potential.

Awards and Appointments

William R. Martin and **Gerald M. Slaughter** have been named Fellows in the American Society for Metals.

The American Society for Testing and Materials has appointed **Larry T. Corbin** chairman of Committee C-26 on Fuel, Control, and Moderator Materials for Nuclear Reactor Applications.

J. R. McGuffey, formerly head of the Inspection Engineering Department, has been appointed to head the newly created Department of Quality Assurance and Inspection.

Arthur P. Fraas and **G. Raymond Satchler** have been named Union Carbide Corporate Fellows.

Newell E. Bolton has been elected to the Board of Directors of the American Industrial Hygiene Association for a three-year term.

The Division of Nuclear Chemistry and Technology of the American Chemical Society has chosen **G. D. O'Kelley** for a two-year term as Alternate Councilor. O'Kelley has also been named a Fellow in the American Physical Society.

Donald G. Jacobs has been appointed manager of the newly established Environmental Policy Analysis Program at ORNL.

C. R. Richmond was named this year's Gioacchino Failla Memorial Lecturer by the Radiation Research Society. His lecture, delivered at the annual meeting in San Francisco, is excerpted in this issue.

Three accomplishments at Oak Ridge National Laboratory were selected this year for the IR-100 Award, bestowed by **Industrial Research**: a method for fabricating ceramic wire into highly accurate, low-cost dosimeters for nuclear reactors, devised by **Edward H. Kobisk** and **Thomas C. Quinby**; development of a novel, laboratory-generated, composite metallic crystal, characterized by superior mechanical and physical properties, for use in many advanced types of electronic devices, by **G. Wayne Clark** and **Alan T. Chapman** (on assignment from Georgia Tech); and ANFLOW, an energy-saving method of biologically treating liquid wastes to recover usable products, developed by **Alicia Compere** and **William Griffith.**

David E. Reichle was awarded the International Union of Forestry Research Organization's 1976 Scientific Achievement Award for his work at ORNL in setting up the cesium forest for analysis of total ecosystem nutrient cycling.

George H. Job received the Distinguished Society-Service Award of the Instrument Society of America.

Elected to the Board of Directors of the American Nuclear Society for three-year terms from ORNL are **Jack Cunningham** and **Herman Postma.** Other staff members holding offices in the ANS are **Don Steiner**, vice chairman-chairman-elect, Controlled Nuclear Fusion Division; **Elliott Whitesides**, vice chairman-chairman-elect, Nuclear Criticality Safety Division; **Raymond G. Wymer**, secretary-treasurer, Nuclear Reactor Safety Division; **Fred R. Mynatt**, chairman, Radiation Protection and Shielding Division; and **James L. Scott,** chairman, and **J. A. Horak,** secretary-treasurer, of the Materials Science and Technology Division.

William L. Russell became the first member of the Union Carbide Corporation Nuclear Division to be named Senior Research Fellow of the Corporation, the highest honor UCC can bestow on a member of its research personnel.

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Letter from a reader

Dear Dr. Steiner:

Your recent article on fusion published in the Oak Ridge National Laboratory Review *(Spring 1976) represents one of the best summaries of the realistic aspects of fusion that I have had an opportunity to read. It serves a very useful purpose in providing perspective for the non-specialist.*

Sincerely yours,
Chauncey Starr
President, Electric Power Research Institute

awards and appointments . . .

Anna Tai Li, an ORNL-UT Biomedical Graduate Student, has won the George Cameron Award, bestowed by the Kentucky-Tennessee branch of the American Society for Microbiology, for the second consecutive year. Her award this year was in recognition of her work on virus-induced birth defects.

Two statisticians in the Mathematics and Statistics Research Department of the Computer Sciences Division, **Kimiko O. Bowman** and **David G. Gosslee**, were named Fellows of the American Statistical Association at this year's annual meeting of the association.

The American Society for Nondestructive Testing and Materials bestowed its Achievement Award on **Caius V. Dodd** and **James H. Smith** for their paper, "Optimization of Eddy Current Measurements of Coil to Conductor Spacing." The Society also named Dodd a Fellow.

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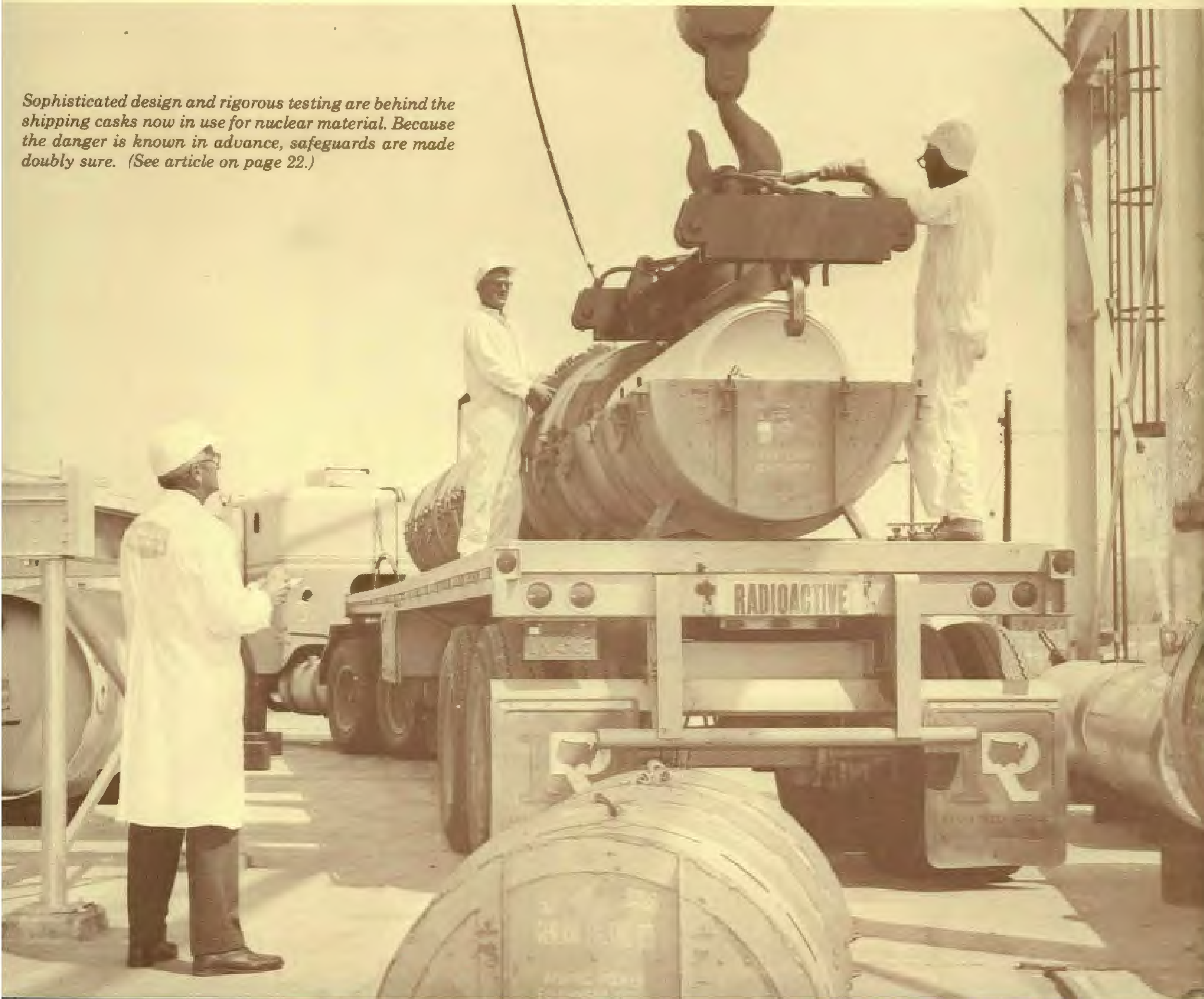

Sophisticated design and rigorous testing are behind the shipping casks now in use for nuclear material. Because the danger is known in advance, safeguards are made doubly sure. *(See article on page 22.)*