Review

FALL 1968

OAK RIDGE NATIONAL LABORATORY

THE COVER: Jubilation and ceremony marked the startup, in October, of ORNL's Molten Salt Reactor using uranium-233, the first time this fuel has been used in any reactor. Director Alvin Weinberg points out a detail of the control panel to AEC Chairman Glenn Seaborg, co-discoverer of the uranium isotope, who brought the reactor to power.

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OAK RIDGE NATIONAL LABORATORY
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MSRE into MSBR?

The Hopes for ORNL's Molten Salt Reactor Program

By Murray W. Rosenthal

On June 1, 1965, the last capsule of fuel was added and the Molten Salt Reactor Experiment at ORNL went critical. The event created considerable excitement at the Laboratory, not just because it marked the completion of a complex undertaking, but because it also represented a significant step toward a major national goal: the achievement of the breeder reactor. We felt in 1965 that the molten salt reactor had great promise as a safe and economic breeder and that operation of the MSRE was a matter of national and world importance.

Now, three years later, we believe molten salt reactors look even more attractive, and our confidence in their prospects has increased. This confidence is based partly on our experience with the MSRE and partly on some very favorable developments that have occurred during the past year.

But first a brief review of the history of the molten salt program: During the 1950's when the United States was attempting to develop a nuclear powered airplane, one of the approaches explored was a reactor in which uranium as uranium tetrafluoride was dissolved in a molten salt which was a mixture of other fluorides. A reactor using UF_4 as fuel was operated at ORNL in 1954 as part of the Aircraft Nuclear Propulsion Program.

Several years before the aircraft program was terminated, the Laboratory had begun to realize that the molten salt technology might be applicable to civilian power plants. Studies between 1957 and 1960 indicated that molten salt reactors could be low cost power reactors and probably could evolve into very attractive thermal breeders. However, there would be important differences between these

Murray Wilford Rosenthal, director of ORNL's Molten Salt Reactor program, came to the Laboratory in 1953, the year he was awarded his doctorate in chemical engineering by Massachusetts Institute of Technology. His work at the Laboratory was for a time spent on reactor analysis and evaluation, including a period as leader of the Reactor Analysis Group for the Homogeneous Reactor Project. He has put in several stints as a teacher, both in the Oak Ridge School of Reactor Technology and as a Visiting Professor of Chemical Engineering at his alma mater for a term in 1961. In 1965 Rosenthal was U.S. delegate to an International Atomic Energy Agency panel in Vienna on the Utilization of Thorium in Power Reactors. He spent a year in Washington in 1965–66 as Technical Assistant to the Assistant General Manager for Reactors of the AEC, and subsequently was U.S. delegate to the Manila Conference on Problems and Prospects of Nuclear Power Applications in Developing Countries. Parts of the accompanying article are from a paper presented in Vienna this year at a second IAEA Thorium Utilization panel.

concepts and an aircraft power plant, and in 1960 it was concluded that another reactor was required to demonstrate that this technology is useful for civilian power. Construction of the Molten Salt Reactor Experiment therefore was begun in 1961.

The Design of the MSRE

The design features of the MSRE are given in Table 1. As noted, the fuel salt is a mixture of the fluorides of lithium-7, beryllium, zirconium and uranium. The vapor pressure is less than 0.1 mm of mercury at 1300°F, the viscosity at reactor operating conditions is similar to that of kerosene, and the volumetric heat capacity is about the same as that of room-temperature water. Since the salt melts at 813°F, all parts of the system that contain salt must be heated.

As shown in the table, the moderator is bare graphite. Unclad graphite can be used, since the salt does not wet graphite and will not penetrate into its pores if material having pores smaller than a micron is used.

The design of the MSRE is shown schematically in Figure 1. In the center is the reactor vessel. Fuel salt at about 1180°F enters the vessel near the top and flows down in an annulus around the outside. The salt then passes up through the graphite moderator, where the chain reaction occurs, heating it to about 1220°F. The salt flows from the reactor exit to the fuel circulating pump where it is pumped through the shell of the heat exchanger and back to the core.

In the heat exchanger, heat is transferred from the fuel salt to a coolant salt which flows through the tubes. The coolant salt is similar to the fuel salt but contains no uranium or zirconium. A lithium fluoride–beryllium fluoride salt was selected so that a small leak into the primary circuit would not make the fuel salt unusable. The coolant salt is pumped through an air-cooled radiator where the heat is discarded to the atmosphere.

When not in use, the molten reactor fuel salt is stored in one of the electrically heated tanks shown at the lower left in Figure 1. To fill the reactor, helium pressure is applied over the surface of the salt in the storage tank and the salt is forced up into the primary system. Salt is kept in the reactor by freezing a plug in the addition line. The "freeze valve" which accomplishes this is essentially a flattened section of pipe over which air is blown. To

drain the reactor, the air is cut off, the plug melts, and the salt flows by gravity back into the storage tank.

TABLE 1. MOLTEN SALT REACTOR EXPERIMENT DESIGN

Fuel	**Molten mixture of fluoride salts: 65%mole7LiF, 29%BeF_2, 5%ZrF_4, 0.2%UF_4**
Moderator	**Graphite (bare)**
Core size	**55" diameter × 64" height**
Vessel Material	**Hastelloy N**
Core temperatures	**Inlet, 1180°F; outlet, 1220°F**
Pressure	**5 psig**
Fuel flow rate	**1200 gallons /minute**
Power	**8000 kilowats thermal**

The reactor vessel (Figure 2) and all of the parts of the reactor that come in contact with salt are made of Hastelloy N, a metal especially developed at ORNL for use with molten fluorides. Hastelloy N is a nickel-base alloy containing molybdenum, chromium and iron. The Hastelloy N used in fabricating the MSRE was found to become embrittled by neutron irradiation, but in the last several years we have discovered that adding a small amount of titanium to the alloy greatly reduces the effect of radiation and produces a material which appears to be satisfactory for reactor use.

The reactor core is formed from 513 graphite elements that measure two inches on a side and 67 inches in length (Figure 3). Machined recesses in the elements form passages for the salt. The graphite moderator is a special material, designed for low permeability to gases as well as for small pore size. In the center of the core is space for three control rods and an assembly of graphite and metal specimens that can be removed to demonstrate the effect of salt and radiation on the materials.

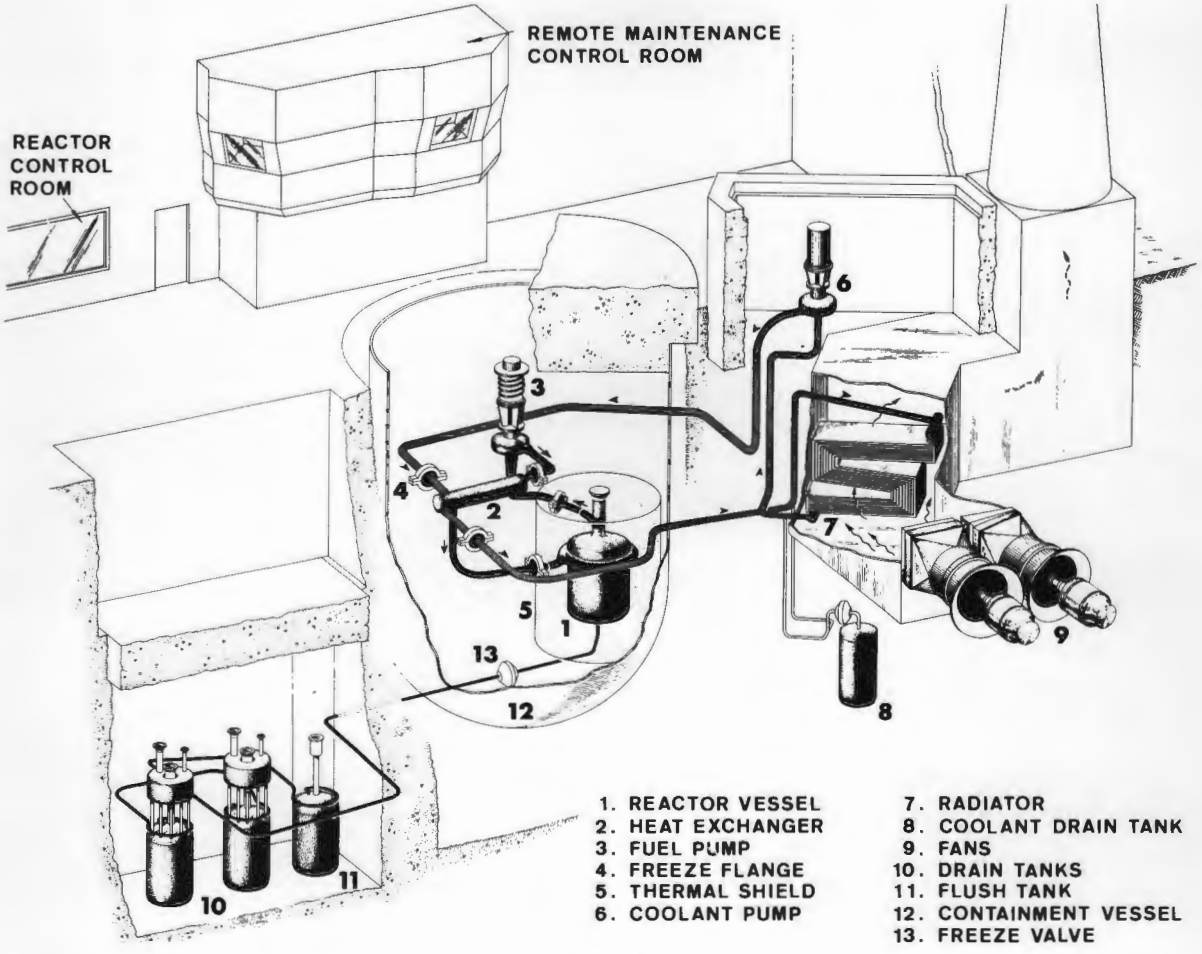


Figure 1

Figure 2

Figure 3

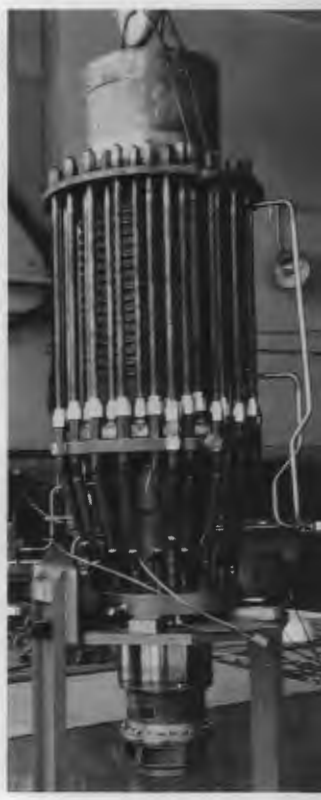


Figure 4

The vertical-shaft fuel pump (Figure 4) has an overhung impeller at the lower end. Above the impeller is a radiation shield that protects the motor and lubricant, and higher up are two oil-lubricated ball bearings in which the oil is retained by a rotating mechanical seal. A stream of helium enters at the lower end of the pump, flows upward to keep the oil vapors out of the pump bowl (Figure 5), and downward to keep the radioactive fission gases from getting to the lubricating oil.

The pump is the highest point in the fuel salt system and there is a gas space above the liquid surface in the pump bowl. The fission product that is the strongest neutron absorber, xenon-135, is a noble gas that is insoluble in the salt. This nuclear poison is removed by diverting 4% of the pump output to a spray ring in the upper part of the pump bowl and spraying it downward through the gas space. The technique has worked better than predicted, and five-sixths of the gas is removed and carried to offgas system by the helium purge.

More of the xenon was expected to diffuse into the graphite and capture neutrons before it could be removed. We now conclude that what makes the xenon removal system so effective is fine bubbles of helium carried into the salt by the spray. The bubbles circulate through the reactor, sweeping out the fission gases, and then are disengaged on returning to the pump bowl. Because this appears to work so well, on future reactors we intend to produce and remove the bubbles deliberately and hope to reduce the xenon poisoning further.

Uranium is added to the reactor and salt samples are removed using a "sampler-enricher" (Figure 6) that resembles a windlass and well bucket used for drawing well water. In this case the windlass is motor driven and the buckets are 0.75-in. dia. metal capsules (Figure 7); in all other respects the operation is identical: an empty capsule is lowered into the salt on the end of a cable and drawn up full. For adding uranium, the capsule contains solid salt which melts and drains when it enters the hot pump bowl. At the upper end of this facility is a small hot cell with a one-arm manipulator which hangs the capsules onto the cable. The sampler operated flawlessly for over two years, but in the past year we have twice dropped capsules down into the pump bowl.

Figure 5

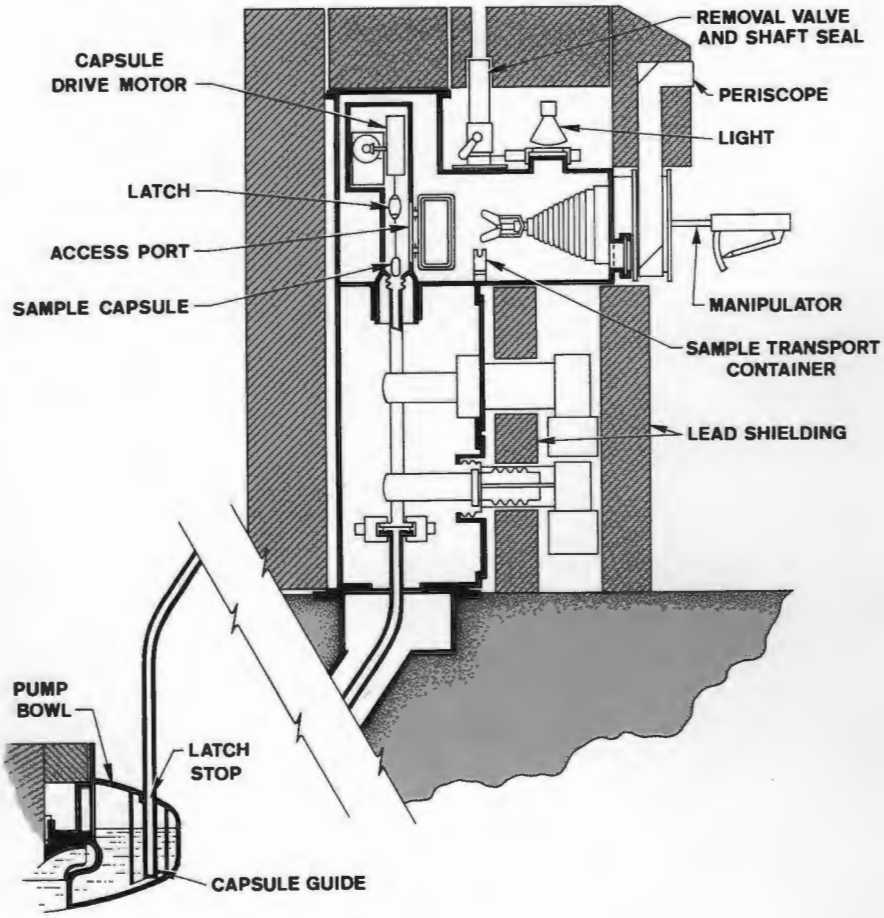


Figure 6

Figure 7

Maintenance

When necessary, maintenance is performed in the reactor cell by reaching down with long tools through a special work shield at the top of the cell (Figure 8). Each component of the reactor is designed so that all maintenance can be performed from the top. For example, the vertical rods that surround the pump are socket wrench extensions that make it easier to rotate the flange bolts if this assembly has to be removed from the pump bowl. So far none of the major equipment in the cell has required any maintenance, but we have replaced seals on the air lines that control the freeze valves, have removed and repaired two electric heaters, and have cleared constrictions and removed sections from a small offgas line leading from the pump bowl. We have also opened a flange at the top of the reactor several times to remove and add metal and graphite test specimens. One important conclusion from our maintenance experience is that there is very little spread of radioactivity when the system is opened.

Heat from the reactor is rejected to the air through a Z-shaped radiator consisting of two-thirds of a mile of tubing which glows bright red when the reactor is on (Figure 9, back cover).

Figure 8

MSRE Operating Experience and Its Significance

The MSRE has operated extremely well. As a demonstration of performance, it was filled with the fuel salt in September of 1967 and run for six months until shutdown on schedule last March. The only interruption in operation during this period was when the power was reduced to zero for a short time to allow repair of an electrical short.

The reactor has been refueled twice at full power and the fuel salt has been sampled over 300 times. Three arrays of the metal and graphite specimens have been removed from the core and found to be completely undamaged by exposure to the salt. Examination of the metal specimens and analysis of salt samples show that the corrosion rate has been only 0.001 inch per year.

The MSRE has revealed some new and interesting things about fission product behavior. Perhaps most startling has been the behavior of molybdenum, niobium, ruthenium, tellurium and technetium, which are not reactive in the salt and remain as metals. If the specimens removed from the core are representative of the rest of the reactor, about 40% of these metals deposit on the Hastelloy N and about 10% on the graphite. What is surprising is that the remaining half appears to escape from the salt as a smoke of metallic particles and be swept from the reactor into the offgas system.

The MSRE has an on-line digital computer that, among its other functions, computes a "reactivity balance" every five minutes. From the present conditions and the operating history, the computer program estimates the effects of control rod position, xenon and other fission product poisons, fuel burnout, temperature, power level, etc., and compares the estimated reactivity with the known zero reactivity when the reactor is critical. This calculation has been surprisingly accurate (generally within .05%) and is a very sensitive indicator of the condition of the reactor.

There have been no malfunctions of the MSRE primary system. The salt pumps—the mechanical components most essential for operation of the reactor—have run flawlessly for over 15,000 hours, except for a small (and correctable) leakage of oil into the pump bowl. Maintenance of radioactive equipment has proved quite feasible, although time requirements in some cases have revealed need for design improvement.

Operation of the MSRE thus has shown that the molten fluoride fuel is stable to radiation and high temperature, that molten salt reactors can be operated at temperatures above 1200°F without corrosive attack on either the metal or graphite parts of the system, that reactor equipment can operate satisfactorily at these conditions, that xenon can be removed rapidly from molten salts and that, when necessary, the radioactive equipment can be repaired or replaced.

Completion of the six month run brought to a close the first phase of MSRE operation in which the objective was to demonstrate the attractive features and technical feasibility of these systems for civilian power reactors. The second phase of MSRE operation began this past summer when a small facility in the MSRE building was used to remove the 33% enriched ^{235}U that was initially in the fuel salt. This was accomplished by bubbling fluorine gas through the molten salt and converting the uranium to gaseous UF_6. The UF_6 was trapped on beds of sodium fluoride. Over 99% of the uranium—217 kg—was removed from the salt and caught on the sodium fluoride, and the decontamination was so good that the canisters containing the uranium could be safely handled without shielding. This on-site processing was a significant step in the demonstration of an integrated fuel cycle for molten salt reactors.

After the original uranium had been removed from the carrier salt, it was replaced with about 35 kg of ^{233}U. The ^{233}U, which does not exist naturally, was made in the Savannah River production reactors by irradiation of thorium. It was converted in ORNL's Thorium Uranium Recycle Facility (TURF) from an oxide to a high purity uranium fluoride–lithium fluoride mixture for addition to the reactor.

On October 8, Glenn T. Seaborg, chairman of the U. S. Atomic Energy Commission, operated the controls of the MSRE and brought it to a power level of 100 kw. The MSRE then became the world's first reactor to operate on ^{233}U. It was appropriate that Seaborg participate in this ceremony: ^{233}U was first made and identified by him 26 years ago using a cyclotron at the University of California. By his side at the startup of the MSRE was R. W. Stoughton, ORNL chemist, who had been his associate in this discovery in 1942.

After a period of operation with ^{233}U, we may try out a cheaper and lower melting coolant in the MSRE in place of the present intermediate salt. The Molten Salt Reactor Experiment possibly will then be shut down, having performed its function and arrived at a successful conclusion. We are considering other experiments, however, and may want to extend its operation.

The Attractive Features of Molten Salt Breeder Reactors

Now that the feasibility of molten salt reactors has been demonstrated, we are turning our attention to the development of a molten salt breeder reactor. The following basic characteristics of MSBRs make them very attractive systems for supplying the world's long-term needs for low cost energy:

Fuel Utilization

Fission products can be removed rapidly from molten salt reactors which makes it feasible to achieve a significant breeding gain in a thermal reactor. When combined with the low fuel inventory, this results in a very good fuel utilization. In addition, molten salt reactors can be started up economically on ^{233}U, ^{235}U, or Pu, and hence can use any of these fuels that is available.

Economics

The avoidance of fuel fabrication, the ease of processing and the low fissile inventory result in a very low fuel cycle cost of MSBRs. Capital cost should be favorable because of high thermal efficiency, low primary system pressure, and low pumping requirements. Remote maintenance requirements on parts of the plant should be offset by the higher availability resulting from on-stream refueling. MSBRs thus should have low power costs, and the attainment of low costs does not await the development of a large fuel cycle industry.

Safety

Molten salt reactors have important safety advantages: the salts do not undergo rapid chemical reactions with air or water; onstream refueling reduces the need for excess reactivity; fission products are removed continuously; the operating pressure is low; the reactors have favorable negative temperature coefficients; and iodine and strontium form stable, non-volatile compounds in the salts.

The Single-Fluid Breeder

The design of a molten salt breeder reactor that would have these advantages is shown schematically in Figure 10, and its characteristics are listed in Table 2. The fuel salt differs from that used in the MSRE in that it contains no zirconium fluoride, and does contain 12 mole % of thorium fluoride. Because of the thorium, the melting point is somewhat higher than that of the MSRE salt. As in the MSRE, the moderator is bare graphite.

The fuel salt enters the core at 1050°F and emerges at 1300°F. Heat is transferred in shell-and-tube heat exchangers to a secondary salt which we expect will be a mixture of sodium fluoroborate and sodium fluoride. This salt is much cheaper than a lithium fluoride–beryllium fluoride salt and melts at a lower temperature, near 720°F. If the fluoroborate continues to look good in tests that are now in progress, we will probably try it out in the MSRE.

TABLE 2. CHARACTERISTICS OF ONE-FLUID, TWO-REGION MOLTEN SALT BREEDER REACTORS

Fuel-fertile salt	72 mole% ^7LiF, 16% BeF_2, 12% ThF_4, 0.3% UF_4
	Melting point, 930°F
Moderator	Graphite (bare)
Salt volume fractions	Core, 15%; blanket, 40%
Core temperatures	Inlet, 1050°F; outlet, 1300°F
Reactor power	1000–2000 megawatt electrical
Steam system	3500 psia, 1000°F, 44% net cycle efficiency
Breeding ratio	1.05–1.07
Specific fissile fuel inventory	1.0–1.2 kilograms/megawatt electrical
Doubling time (compound interest)	13–20 years
Fuel cycle cost	0.3–0.5 mills/kilowatt hour

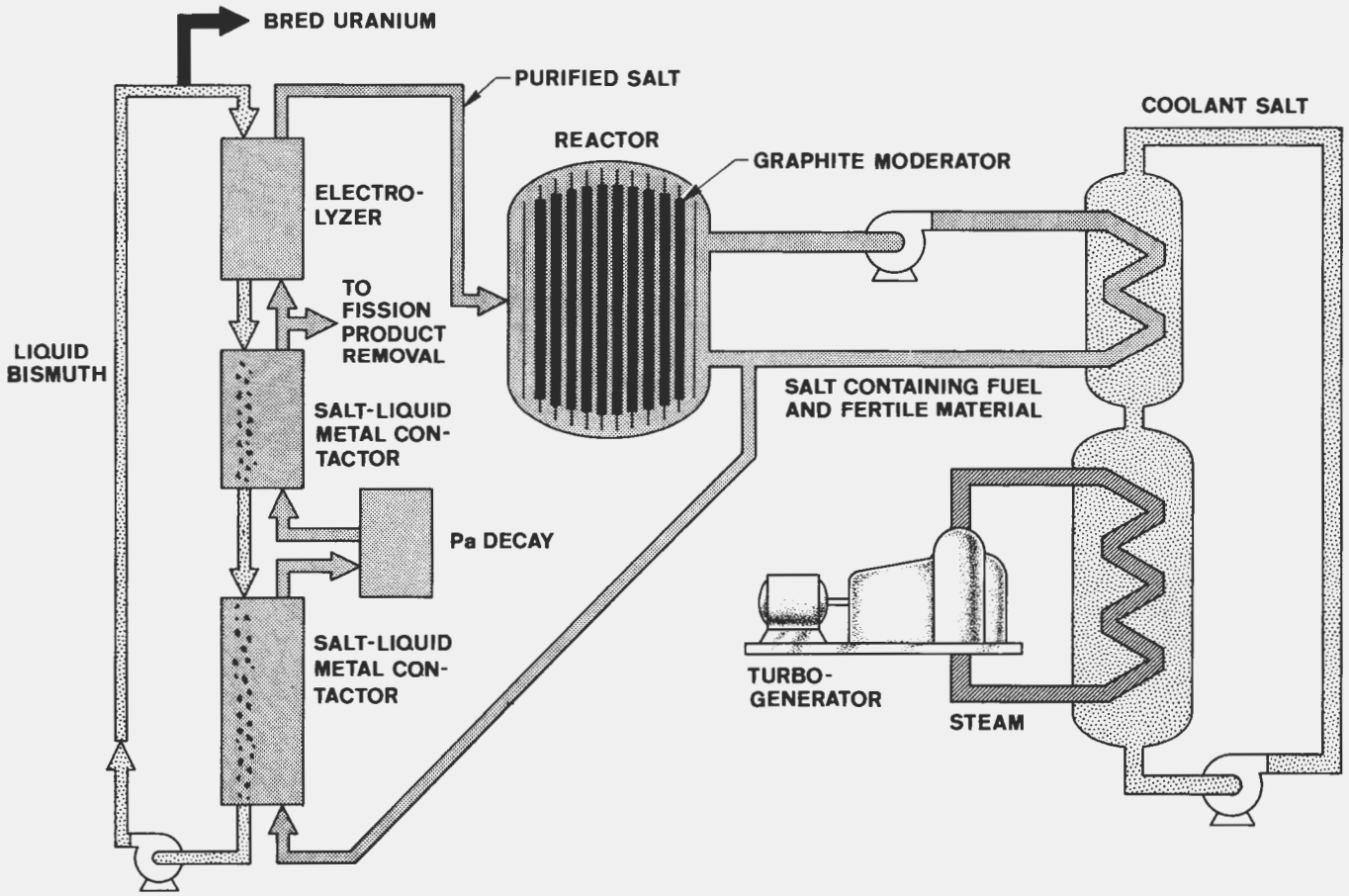


Figure 10

We have not studied the steam system extensively, but the conceptual designs are based on the generation of supercritical steam at 1000°F and 3500 psia. With a supercritical steam cycle, the net thermal efficiency of the plant would be over 44%.

Those who are familiar with our breeder design studies of the past several years will recognize that this concept represents an important change from our earlier views. This change is the use of a single salt that contains both uranium and thorium rather than separate fissile and fertile salts kept from mixing in the core by graphite pipes.

Use of separate fertile and fissile salts would be necessary for a high performance molten salt breeder if there were no process available for removing protactinium and keeping it out of the high flux region of the core. Protactinium-233 is an intermediate between thorium and uranium-233 that is formed when a neutron is captured by a thorium atom. It has a moderately high neutron capture cross section, and if not kept out of the neutron flux, some of it will capture neutrons and turn into ^{234}U, which has little value. With the thorium in a separate salt, the reactor can be designed so that most of this salt, and hence most of the protactinium, is outside the core.

The major disadvantage of the two-fluid system is that the graphite has to serve as a "plumbing" material in the core where it is exposed to very large neutron doses. Moreover, complexities in assembly of the core appear to require that the entire core be replaced when any graphite element reaches its radiation limit. As a consequence, a one-fluid breeder reactor in which the graphite serves only as a moderator has been a long-sought goal.

Two developments of the past year establish the feasibility of the one-fluid breeder. One is an advance in processing that makes the removal of protactinium possible, and the other is the recognition that a fertile blanket can be obtained with a salt that contains uranium as well as thorium. Both of these developments might properly be called inventions.

Processing of a Single-Fluid Breeder

The processing advance mentioned above consists of establishing the chemical steps in a liquid-liquid extraction process for the removal of protactinium and uranium from fluoride salts. The technique is that of exchanging a more reactive metal, dissolved in molten bismuth, for the constituents to be removed.

The theory on which the technique is based is that protactinium is intermediate in chemical potential between uranium and thorium. Thorium, for example, has a stronger tendency to become a fluoride than protactinium does, and the following reaction tends to occur:

$$Th + PaF_4 \rightarrow ThF_4 + Pa$$

If molten bismuth containing thorium metal is mixed with a $LiF\text{-}BeF_2\text{-}ThF_4$ salt containing some PaF_4, the thorium metal will form ThF_4 and enter the salt, and the Pa will be reduced to metal and dissolve in the bismuth. Protactinium metal in turn will reduce UF_4, so that Pa dissolved in bismuth will exchange for uranium in salt. We have demonstrated these reactions in the laboratory.

To reduce the protactinium loss in the reactor to a low level, all of the fuel salt would have to pass through the processing system every three to five days. Our calculations indicate that this could be achieved with extraction towers that are only about six inches in diameter and 12 feet tall. The flow rates of salt and bismuth would each be three gallons per minute.

It is possible that reductive extraction could also be used to remove rare earth fission products from the fuel salt. Unfortunately, the chemical reactivity of thorium is very close to the reactivities of the rare earths, and removing them from a single-fluid breeder salt without also removing thorium may be difficult. However, the rare earths only need to be removed on a 50 to 100 day cycle, and the method could be attractive even with small reactivity differences.

The chemical reactivities are not yet known well enough for us to be certain that liquid metal extraction will separate the rare earths from the thorium, but experiments now in progress should provide the answer. Because of the relatively long cycle times, other schemes will suffice for rare earth removal if the simple liquid-liquid process does not appear feasible. We have ideas for other systems and will try them if the liquid metal process does not work out.

The Core Design of the Single-Fluid Breeder

The second development that makes the one-fluid breeder feasible, i.e., creation of a fertile

blanket with the one-fluid salt, is accomplished by increasing the volume fraction of salt and reducing the volume fraction of graphite in the outer portion of the reactor's core. This makes the outer region undermoderated and increases the capture of neutrons by thorium before they are slowed down to energies at which uranium absorptions occur.

Consequently the region is subcritical, and the power generation falls off rapidly towards the outer part of the reactor. H. G. MacPherson suggested this several years ago. However, only recently, after finding that protactinium can be removed, did we complete optimization calculations showing that dimensions and volume fractions can be selected that will keep the inventory of uranium in the outer region from being excessive.

We now know that a single-fluid, two-region, molten salt breeder reactor can be built that has fuel utilization approaching that of our earlier, two-fluid designs, and probably lower power cost (Table 3).

TABLE 3. FUEL CYCLE COST BREAKDOWN FOR A SINGLE-FLUID MOLTEN SALT BREEDER REACTOR*

	mills/kwh
Fissile inventory	0.24
Thorium inventory	0.01
Carrier salt inventory	0.02
Thorium makeup	0.01
Carrier salt makeup	0.02
Processing plant fixed charges and operating cost	0.24
Total	0.54
Credit for sale of bred material	0.10
Net fuel cycle cost	0.44

*At 13.2%/yr inventory charge on material, 13.7%/yr fixed charge on processing plant, \$13/gm ^{233}U, \$11.2/gm ^{235}U, \$12/kg ThO_2, \$120/kg ^{7}Li, \$26/kg carrier salt (incl. ^{7}Li).

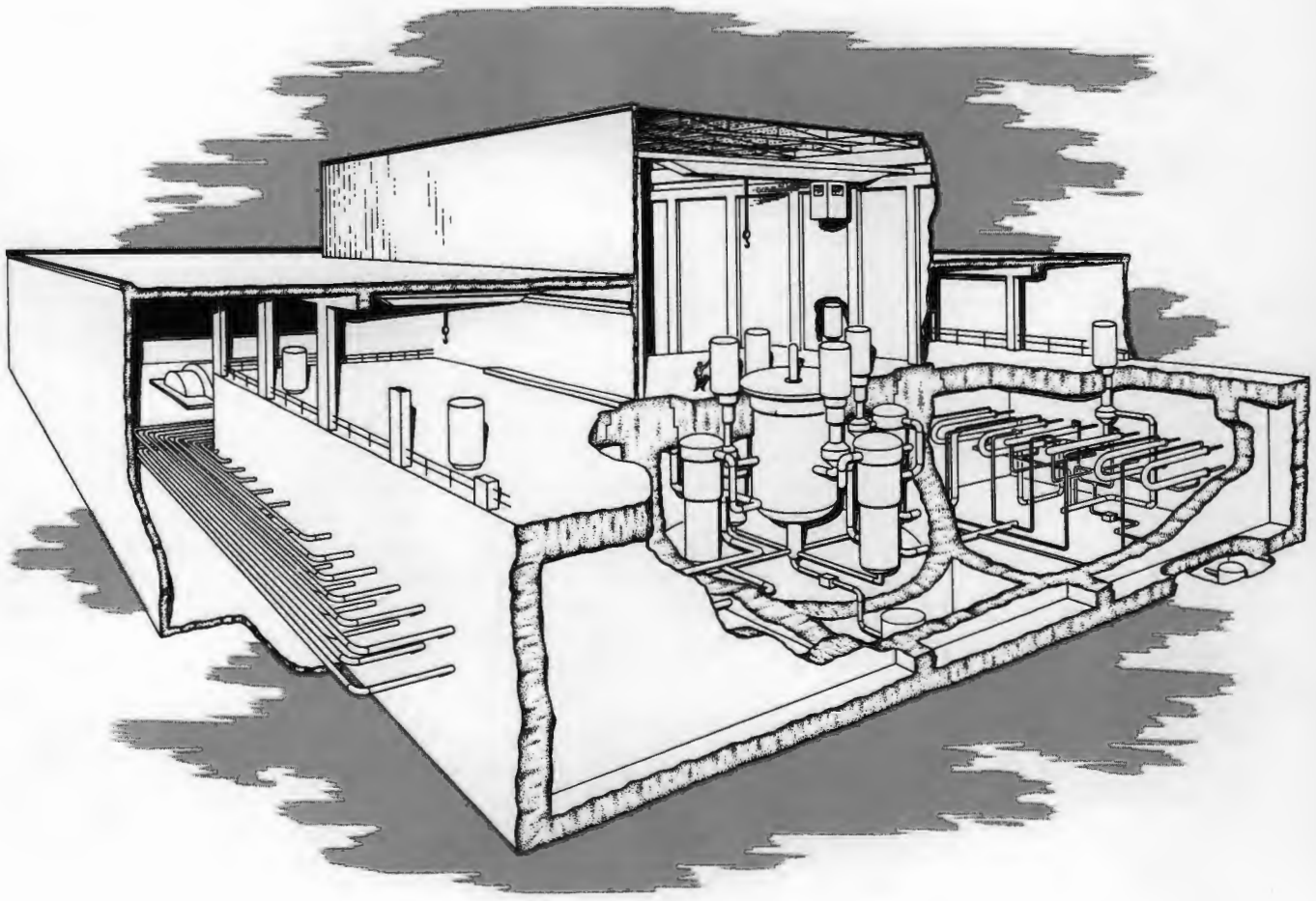


Figure 11

MSBR Plant Design

A fullscale one-fluid molten salt breeder reactor is illustrated conceptually in Figure 11. The reactor vessel would be around 19 feet in diameter for a plant generating 1000 Mwe and not much larger for a 2000 Mwe plant. Fuel salt pumps would be located at the top of the reactor vessel and intermediate fuel-salt-to-coolant-salt heat exchangers would be spaced around the sides. Four separate cells spaced about the reactor cell would contain the coolant pumps, steam generators, and reheaters. The pumps would be near the top of the cell so that part of the pump motors can be outside the upper shield, where they are protected from radiation and are accessible for maintenance. This also makes it easier to keep them cool, since for the MSBR we propose heating the entire cell rather than insulating and heating individual components as in the MSRE.

Graphite bars, shaped to provide coolant passages having the optimum volume fractions, form the central part of the core and the radial blanket (Figure 12). Graphite balls, which in random packing have about the right volume fraction for the blanket region, form the outer part of the core. The axial blankets are obtained by machining the upper and lower ends of the core pieces to increase the volume fraction.

To keep xenon poisoning in the breeder as low as we would like it, it will probably be necessary to reduce the gas permeability of the graphite even lower than it is in the MSRE. We want over 90% of the xenon removed, and a permeability to helium of a little as 10^{-8} cm^2/sec may be required. Such low values are difficult to achieve by repeated impregnations. We are, therefore, working on techniques of sealing the graphite surface with pyrolytic carbon or vapor-deposited metals in such a way that they penetrate into the pores and partially or fully plug them. The pyrolytic carbon process looks particularly promising, and samples having adequately low permeability are now being irradiated in a test reactor to see if they withstand high neutron doses.

Radiation damage to graphite by neutrons is a troublesome problem for MSBRs. At the temperatures which will exist in the core, irradiated graphite first contracts, then goes through a minimum volume and begins to expand. Until recently, we thought that isotropic graphite after passing through the minimum would expand slowly and that large exposures could be sustained before the expansion was very great. Data which became available this year on an isotropic graphite, particularly from

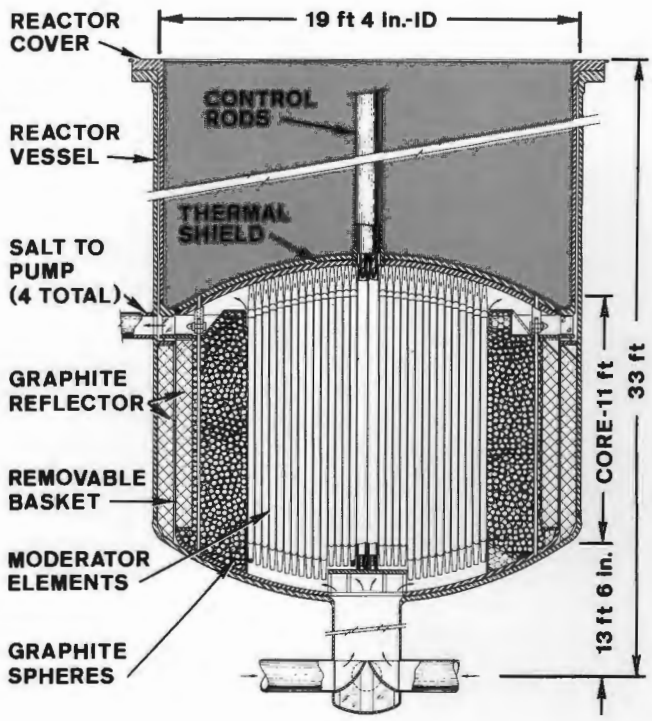


Figure 12

irradiations in the British Dounreay first reactor, showed that the expansion begins earlier than we had expected, and once the graphite has passed its original volume the expansion is very rapid. These data say that if we use graphite no more radiation-resistant than that irradiated at Dounreay, the material at the highest flux in our conceptual plant would expand back to its original volume in two to three years.

We recently completed an extensive review of all aspects of graphite behavior that affect its performance in a molten salt breeder reactor. Our conclusion is that a graphite can be developed that will withstand higher exposures before expanding greatly, and we are beginning a research and development program aimed at achieving this. One advantage in doing this at ORNL is that our graphite samples can be irradiated in the High Flux Isotope Reactor, where they will obtain in one year as high a radiation dose as any graphite has yet received. This affords us a way of determining in a reasonable time whether the approaches we try will work.

Having to replace some of the graphite every two years would raise power costs, but this increase will not be very great if the replacement can be done during other maintenance, such as turbine-generator overhaul. Whether or not improved graphite is attained, MSBRs will be designed so that the graphite can be replaced. The graphite pieces might be individually replaceable after the top of the vessel and a grid structure is removed, or the design might provide for removing large sectors of the core intact, or perhaps the entire core.

Several important auxiliary systems are required for the reactor, one of which is the fuel storage system. The storage tank is located below the level of the core in a separate cell, as in the MSRE. The conceptual design of the breeder storage tank, however, has a new safety feature: it is to be cooled by sodium fluoroborate, which would circulate by natural convection to a radiator that would dissipate the heat to the air. Our calculations indicate that a natural draft stack would provide adequate cooling for the radiator, which means that the heat rejection system would require no power or water and could operate indefinitely. Several parallel cooling circuits could be used to insure that the system would work even if one circuit ruptured.

A major part of the plant would be the system for removing xenon from the reactor and for handling the highly radioactive offgas. Very fine helium bubbles would be injected into the salt under more controlled conditions than exist in the MSRE. The bubbles would circulate through the system and then be removed from the salt by a centrifugal separator. This contaminated gas, containing xenon and krypton, and possibly the smoke of metallic fission products mentioned earlier, would then be passed through charcoal beds and other cleanup systems to remove the fission products, and the helium would be recycled to the reactor.

Provision for maintenance is a primary consideration in the design of the reactor. The reactor cell is to have very little in it besides the equipment illustrated in Figure 12. Most of the auxiliary devices will very likely be put in a separate chamber designed for ready access. Possibly this chamber will be provided with manipulators that will essentially make it a hot cell.

We have estimated the capital cost of 1000 Mwe molten salt reactor plants. The accuracy of the estimates is limited by the conceptual nature of the design, but our results indicate that the capital cost of a molten salt breeder reactor should be about the same as that of a light water reactor of the same capacity. Thus, since the fuel cycle cost should be well below that of LWRs, we can predict that power costs from molten salt breeder reactors will be comparatively low. Our estimates using present day uranium prices give costs about 0.9 mill/kwh less than the cost of power from light water reactors. The cost difference would become even more attractive as the cost of uranium goes up.

Fuel Utilization

Molten salt breeder reactors compete very well with other types of breeder reactors in conserving uranium ore. Fast breeders have higher breeding ratios, but this is offset by the lower fissile inventories of molten salt reactors. Counting the fuel in both the reactor and processing plant, MSBRs should have specific inventories not much above 1 kg of fissile fuel per electrical megawatt. The importance of this low inventory is illustrated in Figure 13, which shows the U.S. ore requirements if only light water reactors are built, compared with the ore requirements if breeders are introduced in the period 1986-98. The figure assumes that the nuclear power growth rate curve will pass through 140,000 Mwe in 1980 and 730,000 Mwe in 2000, which is typical of most projections made today. In such a rapidly growing nuclear power economy, a small fissile inventory is clearly a valuable asset.

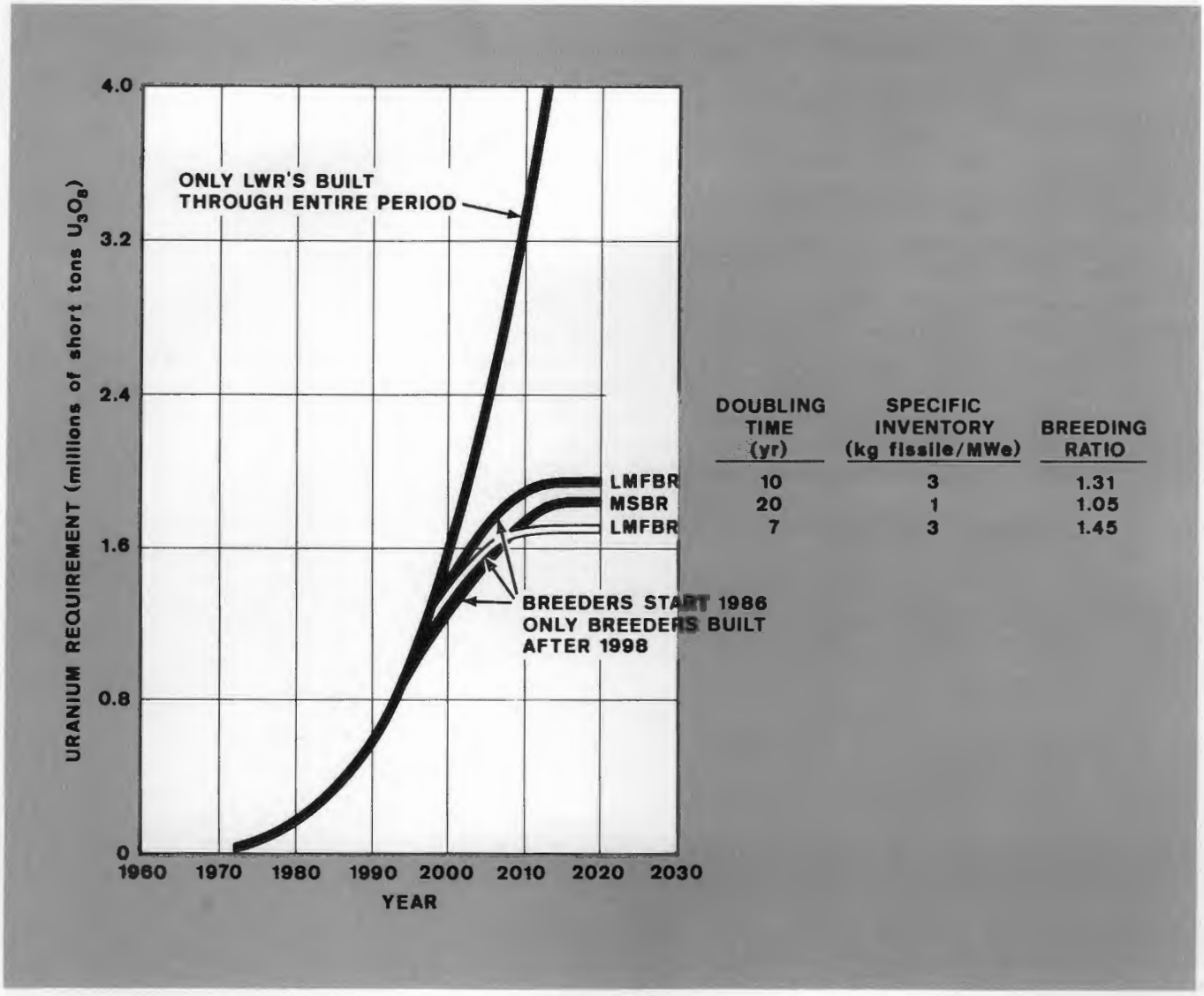


Figure 13

Where Do We Stand?

In conclusion, we believe that molten salt breeders have very favorable characteristics of fuel utilization, power cost and safety, and we are satisfied that all of the basic questions about the feasibility of the reactors have been answered. This does not mean that the problems associated with equipment and components for large reactors have been solved, but the fundamental questions involving the "science" of the reactor have been answered, as have many of the engineering problems. We cannot be as dogmatic about the new processing scheme, but we think that it will turn out to be workable and economic, since the concept is flexible and the equipment for the liquid-liquid extraction system appears to be small.

The major tasks that face us now, and on which work is in progress, are the engineering of a larger reactor and the development and demonstration of the reprocessing plant. From here we hope to go on to the construction of a breeder reactor experiment that we believe can be a stepping stone to an almost inexhaustible source of low cost energy.

The rich and motley career of Douglas A. Ross, B.Sc., M.Sc., Ph.D. (McGill), M.D. (Harvard), has carried him from his native Canada to Cambridge University, from McGill to the medical schools of Chicago, Harvard and Tennessee, engaging in study, research, instruction and development in an astonishing variety of subjects. As a physiologist, he investigated the hearing and balance mechanisms in fishes, frogs, cats and man, being introduced to electronic techniques while in England on a Royal Society of Canada traveling fellowship. As a medical doctor he conducted brain wave studies at Massachusetts General Hospital. As a physicist, he instructed Canadian Air Force trainees who would later be operating and servicing radar equipment, then joined the Harvard Psycho-Acoustic Laboratory staff to work on the testing and development of various speech-transmission devices used by the military. As an engineer, he worked for a time with a small firm of instrument manufacturers in Cambridge, Mass., doing developmental work on electronic devices for biological testing of many kinds. For his first encounter with radioactivity, he came to Oak Ridge in 1955 from the UT Medical School in Memphis, and spent the summer as research participant with the Oak Ridge Institute of Nuclear Studies. Attached to the Medical Division, he worked on the applications to nuclear medicine of ORNL's newly developed Medical Spectrometer. At the Medical Division's invitation, he joined their staff as "medical physicist," leaving Memphis for good in 1956. In 1963 he joined the group of which he writes here, and of which he is currently the leader.

Thermonuclear's Stepchild

The Medical Instrumentation Group, and How It Grew

By Douglas A. Ross

ONE of the curious features of the Thermonuclear Division is that it includes a small group whose activities have nothing to do with controlled fusion. These people are instrument designers, yet are not in the Instrumentation and Controls Division. Their labors are biologically and medically oriented, but there is no official connection with ORNL's Biology Division or with the Medical Division of Oak Ridge Associated Universities. And in spite of negligible thermonuclear competence, they are housed, clothed, warmed, cooled, protected, encouraged and administered by the Thermonuclear Division. In the argot of contemporary biology they constitute a "heterotransplant, embedded in the thermonuclear body, amiably tolerated with few or no rejection symptoms."

This anomalous situation owes its origin chiefly to the interactions between two blithe spirits: Marshall Brucer in the medical field, and P. R. Bell in the field of instrumentational physics. Sometimes these interactions were abrasive and exothermic, but they were nearly always fruitful. In the early 1950's, Brucer was chairman of the Medical Division of ORAU, then called the Oak Ridge Institute of Nuclear Studies, while Bell was one of the leading lights in ORNL's Physics Division. Brucer

The author discusses a brain scan in his laboratory with P. R. Bell.

was interested in radiation therapy, among other things, and from time to time he would call up Bell and ask such questions as, "Why is scattering not the same in ice as in water?" and Bell would do his best to provide enlightenment. Gradually Bell came to realize that the medical people were beset with physical and instrumental problems, and their ignorance might better be dispelled than scoffed at. Further, it would be sound practice to give them a hand, since even a physicist may develop a backfiring thyroid gland, a brain tumor, or a large and lumpy liver. Compassion stirred.

ORNL's budding involvement presently received impetus from the ORINS Special Training Division. For some years ORINS had been offering courses to explain the virtues and vices of radioactive materials to interested students, many of whom were from the medical field. By and by enough people knew the rudiments of medical radioisotopery to make advisable a more advanced seminar, with emphasis on the problems of instrumentation. A member of Bell's group, C. C. Harris, had been working on the electronic circuits that count the gamma rays emitted by a radioactive source, and he was asked to speak to the seminar on these so-called scaling circuits. One of the participants took issue

The surgical probe in use. It is searching a patient's neck for secondary growths from a thyroid cancer.

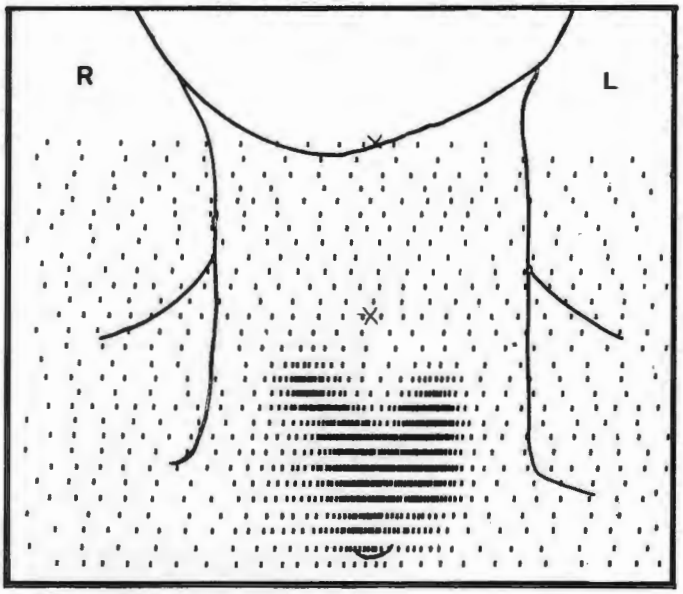
P. R. Bell models the ORNL research scanner developed by the Medical Instrument Group.

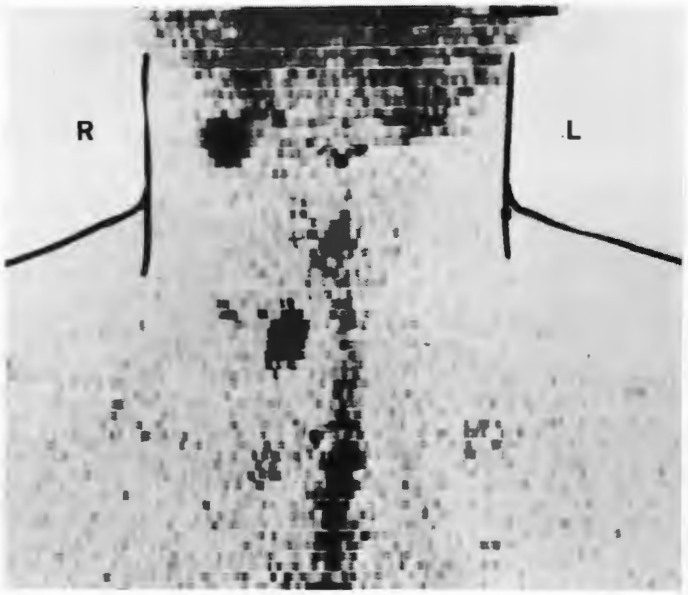
with him as to the value of scalers in medical work, contending that the direct-reading rate meters were preferable. The resulting brouhaha quickened the interest of Bell's group in nuclear-medical problems, and they decided it was time to put gamma-ray spectrometry into the hands of the doctors, who—whether they knew it or not—needed it. The outcome was the first of the clinically oriented pulse-height spectrometers, to which the group gave the name "medical spectrometer."

Streamlined Controls

Pulse-height spectrometers were, of course, well known to physicists and chemists, but the instruments were conglomerates, usually consisting of several chunks of equipment that had to be fitted together with proper consideration for line termination, stray capacitance, impedance matching, ground loops, and other unpleasantnesses that are the daily bread of the physicists and engineers but are a source of mystified helplessness to the doctors, let alone their technicians. The medical spectrometer of Francis, Bell and Harris put all the circuits beyond the detector on one chassis, and the controls were sufficiently simplified so that the doctors could learn to operate the instrument with a measure of understanding of what was going on. After some instruction, that is. Bell, Brucer and their colleagues supplied the instruction, and taught others to teach, and the new device caught on. Chief laborer in its design was J. E. Francis, Jr., still at ORNL. The other two contributed numerous ideas, Harris being especially concerned with the high-voltage supply, while Bell tossed in the expedient of counting the pulses by letting them charge up a condenser, thus replacing the then more bulky and expensive scaling circuits. A switch could throw in a leak across the condenser, converting it into a rate meter for anyone who would want it. The instrument was written up in *Nucleonics* for November 1955.

Included in the *Nucleonics* article was a description of a focused collimator. Bell's group had developed an incidental interest in the so-called "scintiscanners," devices that sweep back and forth across a patient, mapping out the areas of activity produced by a previously administered radionuclide. The detector's attention must be confined to the region directly below it, and the more primitive collimators did this poorly, with consequent loss of sharpness in the scans. It turned out that the late R. R.





DIFFERENCE BETWEEN THE OLD AND NEW INSTRUMENTATION: The scan on the left shows the neck region of a patient with thyroid cancer, before surgery (courtesy Medical Division, ORAU). A small dose of iodine-121 was used, and the scanner was one of mid-1950's vintage. When normal thyroid tissue is present, a cancer usually shows little uptake; here the growth, almost invisible, is on the right side, pushing the normal tissues toward the patient's left. The non-thyroid background is prominent, due largely to inadequate lateral shielding in the collimator; nevertheless the picture is highly informative. The scan on the right shows another thyroid-cancer patient, this one after surgery (ORAU Medical Division 1962). The ORNL Research Scanner was used, with a gold-tungsten detector and photographic recording. The surgeon sought to remove all thyroid tissue, normal and malignant, but this is difficult, and two small fragments on the right side were missed. The improved detector shows them plainly, but it also brings into view structures not seen with the earlier instruments: salivary glands, esophagus, and trachea—even a trace of the two collar bones. These new shadows caused some concern until their normal origin was established. Unlike the cancer spots, they disappear early. (The two threatening remnants were snuffed out with large doses of iodine-131, and today the patient is alive and well.)

The laboratory "scintiscanner" going to work on a lucite model in which sources of varying radioactivity are imbedded. On the table is the ORNL gold collimator made of gold on loan from Ft. Knox.

Newell and his colleagues, on the West Coast, had also invented the focused collimator, and the ORNL group learned about this just in time to add an acknowledging footnote in galley to the *Nucleonics* article. To this day the group has retained its interest in better detection and collimation, and the two-inch, focused collimator was only the first of many.

Electronic Bloodhound

The medical spectrometer was quickly followed by the surgical probe. Brucer's group at ORINS was intensely interested in the problems of thyroid cancer, including its possible treatment with iodine-131, with surgery, or with both. The problem with a cancer, of course, is to get it out of the patient before it can spread beyond repair, and for this reason the thyroid surgeon must search carefully for any secondary growths, or metastases, that may be present in addition to the primary tumor. The surgical probe helps him find them, for under the proper conditions the cancer can usually be persuaded to take up radioactive iodine, in which case the probe can sniff out the hidden metastases much as a terrier smells out a rat. The detecting unit consists of a small crystal at the end of a slender, four-inch light pipe leading to a photomultiplier tube, the whole assembly being encased in a watertight housing that permits it to be soaked in a sterilizing solution. The surgeon moves the sensitive tip around in the neck wound, listening to the note made by a "howler," the pitch of whose tone rises as the crystal approaches a radioactive spot. This method is considerably more effective than the conventional practice of simply feeling around with a gloved finger for little lumps that shouldn't be there—and that are easily missed. There can be no doubt that the surgeons, the surgical probe, and radioiodine, working together, have saved a number of otherwise forfeit lives. At least one of those thus rescued walks around in Oak Ridge today.

In June of 1956 the Society of Nuclear Medicine held its annual meeting in Salt Lake City, and the ORNL group attended. Interest in the instrumental aspects of the field was brisk, and one evening a group of physicists and physicians got into a bull session that lasted far into the night. A representative of AEC was there, and he urged the ORNL people to apply for direct AEC support. This they were subsequently granted, and although it was at first only partial, it permitted Bell and Co. to work on medical problems in legitimate time, instead of bootlegging man-hours from Physics Division projects.

Thus encouraged, the group proceeded with the development of better scanning detectors, setting its sights on one of the meanest of all scanning problems: that of detecting brain tumors, where the difference in uptake between the diseased and normal structures is far too small for comfort. Moreover there is the bony skull to block or deflect the radiation, and many skulls are thick. To provide better efficiency, the crystal diameter was increased from 2 inches to 3, and the best of the collimators used gold around the focusing holes, with mercury or tungsten for the lateral shield. If such a collimator becomes obsolete, the gold is returnable, undepreciated, to Fort Knox, but this didn't prevent the commercial boys from enjoying a loud, derisive laugh. The targets of the fun said nothing and sawed wood; they went on to show that the larger crystals, which presently became available, would permit the collimator to be longer, in which case lead would perform as well as gold for all but the higher energies in the band of medical interest. Today long lead collimators are available in commercial scanners.

Move to Y-12

In the late fifties the thermonuclear project was set up as a separate division, and it needed Bell's abilities. The site of operations was to be Building 9204-3 in the Y-12 area, which now houses a part of the Isotopes Division. But Bell found intolerable the thought of moving to Y-12 and leaving his medical-instrument colleagues six miles away at X-10, and after some table pounding it was decided that they should all go to Y-12 together. The medical work progressed slowly, for support was still on a part-time basis; Bell and Francis were both preoccupied with the thermonuclear project, while Harris had not only that to worry about but a bout with major surgery as well. Nevertheless work on an improved scanner continued: the gold-tungsten detecting head was mounted on a stronger and more reliable moving mechanism, and an improved recording system was developed. Thus the first ORNL Research Scanner was born. It was loaned out for clinical trial to ORINS Medical Division, where it performed so usefully that they kept it busy for seven years. By that time commercial enterprise had quit snickering at long-haired research, and had begun to produce passable scanners.

In 1959 the Thermonuclear Division moved into Y-12's Building 9201-2, which, apart from the

Marshall Brucer (1.) and the author test equipment for thyroid uptake measurements during Ross's employment at ORINS. (Photo courtesy of Medical Div., Oak Ridge Assoc. Univ.)

86-inch cyclotron in its west end, had been left largely unemployed when gaseous diffusion replaced the electromagnetic method for separating out uranium-235. Understandably, the medical project accompanied Thermonuclear, settling finally in an attractive laboratory. An old conflict remained, however: the competition, for research time and brainpower, between the medical and nonmedical programs. This was finally resolved in 1962, when the group was set up in its own right, funded from AEC's Division of Biology and Medicine. A horse trade was arranged whereby Francis devoted full time to thermonuclear matters, while Harris became group leader for the medical project, acting only as radiation safety officer for the Thermonuclear Division. Bell devoted most of his bounding energy to the thermonuclear project, but he remained available to the medical group as a welcome source of help in times of trouble.

This unorthodox arrangement has worked out well, although it has puzzled many people unaware of its history. The group has remained small but versatile, with its personnel drawn from several disciplines. In 1962 it acquired M. M. (Ted) Satterfield, an electronic engineer whose capabilities extend commendably into a number of related fields. In the following year I joined the group, contributing an engineer's acquaintance with biological and clinical problems, and assorted odds and ends of instrumental experience, some of it useful. In 1965 George Dyer, a physicist, was added: a character whose passion for gadgetry of all kinds is attested to by a basement workshop that has to be seen to be believed. Recently the group has been able to borrow, from K-25's Computing Technology Center, Bill McClain, an electrical engineer with specialized training in computer mathematics and programming problems. On the other side of the ledger, Harris has been lost to Duke University, and Bell is on leave of absence at the Manned Spacecraft Center near Houston.

Current activity centers around the application of computer techniques to the processing of scan data, in the hope of separating the "signal" from the "noise" and thus providing the clinician with a picture that gives him maximum information with a minimum of misinformation. Francis, attached to Thermonuclear's LINC-8 computer, is helping with this project. The group's activities, however, are by no means confined to the scanning field; any less-than-satisfactory instrument or procedure within the field of nuclear medicine is fair game. There is plenty to keep the boys out of mischief.

Macromolecular Separations

A Case History of Productive Collaboration

By G. David Novelli

THE events leading to the establishment of this collaborative program that involves the Chemical Technology, Analytical Chemistry and Biology Divisions of ORNL grew out of one of Alvin Weinberg's Advanced Technology Seminars and was born from my own feeling of frustration with cell-free systems that were being used to study reaction mechanisms during protein biosynthesis.

In 1960–61 Tadanori Kameyama, a visiting investigator from Japan, and I developed a cell-free system from the bacterium *Escherichia coli* that apparently brought about the synthesis of the enzyme protein β-galactosidase. The system was prepared by growing the bacteria in a nutrient solution, then harvesting the cells in the form of a thick paste by centrifuging them out of the nutrient solution. The cells then could be suspended in appropriate medium and broken open by forcing them through an orifice at 10,000 psi in an instrument called a French pressure cell. The extract was next separated into a particulate component (now called ribosomes or polyribosomes) and a soluble

Educated at the University of Massachusetts, Rutgers University, California's Scripps Institute of Oceanography, the Army of the United States, and Harvard, where he earned his doctorate in biochemistry, G. David Novelli came to ORNL in 1956 from Cleveland, O., where he was Associate Professor of Microbiology at Western Reserve University School of Medicine. Here he is Biology Division's principal biochemist, and leader of its Enzymology Group as well as of the Biological Macromolecular Separations Program described here. He is chairman of the AEC Committee on DNA, RNA and Proteins, and also of the American Cancer Society's Advisory Committee on Research on the Etiology of Cancer. He is a faculty member of the University of Tennessee, the University of Georgia, and the UT Graduate School of Biomedical Studies. His research interests include enzymology of biosynthetic reactions, molecular basis for genetic control of protein structure and synthesis, structure and function of transfer RNA, carcinogenesis, antibody synthesis, and microbial metabolism. The successful crystallization of tRNA reported recently in *Science*, enabling x-ray crystallography to determine its actual molecular structure, was done simultaneously at MIT and the University of Wisconsin with Oak Ridge-produced material.

component (containing enzymes and cofactors for the synthesis of protein). The particulate and soluble components were recombined and supplemented with certain "goodies" such as a source of energy and the 20 amino acids that are used by cells to make protein. When the system was prepared properly and supplemented properly we could observe, upon incubation of the system at 37°C, a rise in the amount of the enzyme β-galactosidase. The remarkable thing about the system was that when it was prepared from cells that had been irradiated with either ultraviolet light or x rays (both of which cause damage to the genetic material, DNA) the systems were totally inactive in synthesizing the enzyme. However, when these inactive systems were supplemented with DNA that contained the required structural gene (i.e., that gene which contains the information for the amino acid sequence for the β-galactosidase enzyme), synthesizing activity was restored. Jerry Eisenstadt, a postdoctoral fellow of the U.S. Public Health Service, also participated in these later studies. We were quite excited by them because it was the first time that a specific gene was observed to operate in a test tube, and we thought we had the system to uncover the details of the steps leading from DNA (gene) → RNA (messenger RNA) → protein (the specific enzyme). But this was not to be, hence the frustration I alluded to earlier, which was brought about by our inability to prepare active extracts on a routine basis. Our working time for a preparation extended almost continuously from 8 AM to about 1 AM before we could know whether we had a successful preparation. If it was active we could store it in liquid nitrogen and work with it for a month or two. But for each successful preparation we made there would be five or six unsuccessful ones. It was obvious that there were some variables in the system about which we were ignorant and therefore could not control.

On August 1, 1961, through the effort of Stan Carson (S. F. Carson, now deputy director of Biology Division), I was given the opportunity to speak at ORNL's Fifteenth Advanced Technologies Seminar on the subject, "The study of gene action in the absence of living cells, and the problem of the isolation and characterization of the active components." As I recall the meeting, I detailed the events given above, but really stressed the biochemists' ignorance of methodologies for the handling of biologically active macromolecules in such a way as to maintain their activity.

Two benefits resulted from this seminar. We had two problems in the preparation of microbial extracts with the French pressure cell. One of these was our inability to maintain the pressure constant

at 10,000 psi, largely because we pumped the hydraulic jack by hand. The other was that the maximum capacity of the French pressure cell was only 40 ml, and we wanted to make as much as a liter of extract at a time. With the setup we had, it required a mighty strong back to repeat the operation ten or 20 times. The first of these problems was solved by a visit to my laboratory by Beecher Briggs, then in the Reactor Division, who, after examining our setup, told us about a hydraulic pump that was used in Metals and Ceramics Division that might be suitable for our purpose. He proved to be right; the electrically operated pump we use now has a very fast relaxation time and it is no longer a chore to operate the French pressure cell. Many scientists who have visited our laboratory have equipped their systems with this pump and now its use is widespread in biochemical and microbiological laboratories throughout the country – to the everlasting gratitude of many graduate students. The irony of this development is that we had had this problem ever since I came to Oak Ridge, and Beecher Briggs had been my next door neighbor all this time, but it took an Advanced Technology Seminar to bring the problem to the man who could find the solution.

The other problem, that of scaleup, took longer to solve, but it was solved eventually by Dick Lyon (R. N. Lyon, also in the Reactor Division). Dick came to see me regarding a possible design for scaling up the French pressure cell capacity to around half a liter. We discussed the problem and its specifics and he left to disappear wherever it is engineers go to do their thinking. I heard nothing further for several months and assumed that the minor problem of a biologist had been forgotten. One day Dick appeared at my office and told me, "Sure, we can build a scaled up version of the pressure cell for you, but I don't know what you can use to apply the pressure."

That seemed to close that issue, but a few days later I received a phone call from Dick who told me he had been looking through a catalog which listed engineering equipment and had seen an instrument, designed to homogenize paint, that might be useful for our purpose. He sent the catalog to me and it looked promising so we ordered the homogenizer, on a trial basis. It proved to be an efficient replacement for the French pressure cell, plus having the desired capacity to make a full liter of extract per minute. Here again this development was picked up by visiting biologists, and its use is now widespread in this country and abroad for making extracts from microbial, plant and animal tissue whenever large amounts of extract are required.

Enter Chem Tech

In spite of these technical improvements our ability to make reproducibly active preparations that would synthesize β-galactosidase did not improve and I was forced to conclude that the then current methods for the preparation of the macromolecular components of the protein synthesizing systems were inadequate and did not permit the preservation of unknown but critical components (possibly structural elements) of the protein-synthesizing apparatus. In informal discussions with Alvin Weinberg, who always maintained an interest in this work, I proposed the notion that progress in the understanding of the mechanism of the large macromolecules was being hampered by the lack of good methodology for their production in sufficiently large quantities and high state of purity. He reminded me that the Chemical Technology Division of ORNL was abundantly blessed with a wide variety of experience in all types of chemical separations technology and suggested that I talk with some people in that division to see if there would be any interest in our problems.

Our contact with them was ultimately expedited by Alex Hollaender (then director of Biology Division) and came about through the following sequence of events. At the Symposium on Solvent Extraction Chemistry at Gatlinburg in October 1962, Floyd Culler (then director of Chemical Technology Division) said in his opening remarks that solvent extraction technology had moved forward from the use of diethyl ether for separating uranium from contaminating metals to being a much more versatile technique for the separation of closely related compounds in a variety of media. He said that he could foresee the time when its use for separations of biological substances would be greatly extended. Hollaender seized upon this remark to set up a series of luncheon meetings between interested biologists and technical personnel from other divisions. As a result of these luncheon meetings a group from the Chemical Technology Division came to visit those of us in the Biology Division who had separation problems. Among this group were Culler (now a deputy director of ORNL), Don Ferguson (present division director), Keith Brown and several others. They discussed separations problems with

". . . here again the development was picked up by visiting biologists, and its use is now widespread in this country and abroad . . ."

me, Dick Setlow, Fred Bollum, Ken Volkin and others in the Biology Division and left in a high state of confusion. It was clear that they had a genuine interest and desire to help us, but were put off by the fact that each individual with whom they spoke had a different class of compound that needed separation and purification. After stewing over these conversations for a few weeks, Floyd Culler telephoned me to say they were indeed interested in trying something, but they wanted to discuss specifics this time. Another discussion was arranged and we tried to decide in which area Chemical Technology should make its first effort.

By this time my group had temporarily given up attempts to improve the cell-free protein synthesizing system, and had instead returned to re-examine the first step in protein synthesis, namely the activation of the amino acids.

The Remarkable Code

All proteins are made up of 20 building blocks, the 20 naturally occurring amino acids. A protein of average molecular weight, say 100,000, will be made up of about 1000 amino acids, so it is obvious that each of the 20 amino acids will be used several times in constructing a given protein. Each different protein will have a unique sequence of amino acids in its structure and the biological activity of a protein is determined by this sequence. This is best illustrated by considering sickle cell anemia.

In the red blood cells is found a protein, hemoglobin, whose function it is to carry oxygen to the tissues. Individuals with this hereditary anemia contain in their blood cells a hemoglobin that is very inefficient in carrying oxygen. By a careful comparison of the amino acid sequence in normal hemoglobin with that of hemoglobin from patients with sickle cell anemia, it can be seen that sickle cell hemoglobin differs *in only one* of its long chain of 600 amino acid building blocks. This is all the more remarkable when we consider the fact that as you are reading this article each of you is losing, on the average, about five million red blood cells per second. If these red blood cells were not being replaced at the same rate at which they are being lost we would all soon become anemic. However, our blood forming tissues are, in fact, producing new red blood cells at the same rate that they are being lost. There are approximately 200 million molecules of hemoglobin in each red cell, so the machinery that makes hemoglobin does it at the rate of 10^{15} molecules per second. (This number is one million times the national debt.) The assembly of the 600 amino acids in the hemoglobin molecule is taking place at this fantastic rate without making a mistake in the sequence This is truly a remarkable machine. Similar calculations can be made for other proteins, since most protein molecules are turning over constantly.

How then is this exquisite fidelity for a given amino acid sequence maintained? The instructions for a particular amino acid sequence (the cell makes hundreds of different proteins, all with different amino acid sequences) is contained in the nucleic acid, DNA.

DNA does not participate directly in the construction of a protein but its information is first transcribed onto another nucleic acid called messenger RNA by a coupling process not unlike modern printing technology. Messenger RNA is synthesized in the nucleus. It is transported from there to the cytoplasm where it associates with an RNA-containing particle called the ribosome. This association with one or more ribosomes constitutes the protein

synthesizing apparatus. To get the whole process of protein synthesis started, it is necessary to "activate" the amino acid. This activation process is mediated through an enzyme and there is a separate enzyme for each of the 20 amino acids of the genetic code. Each enzyme recognizes only the amino acid for which it is specific. The activated amino acid, now attached to its specific enzyme, is highly reactive and unstable and subject to undesirable side reactions before it reaches the protein synthesizing apparatus. Nature, always on the lookout to avoid such disasters, has developed an almost fool-proof transport system using still another kind of smaller RNA called transfer RNA (tRNA) that transports the activated amino acid to the protein synthesizing apparatus.

If there is a slipup *during* the activation process, however, the inevitable result will be the insertion of an incorrect amino acid into the protein. And once an amino acid is attached to a molecule of tRNA, it has relinquished its ability to determine where it will appear in a peptide chain.

The final recognition mechanism in protein synthesis is between two nucleic acids. We know something about the chemical "ground rules" that make possible a specific recognition between two nucleic acids, but we know nothing about the chemical rules that permit the specific recognition of a nucleic acid by an enzyme protein. This is the reason that we returned, some years ago, to a more detailed study of the first step in protein synthesis, namely the activation of an amino acid by a specific enzyme and the attachment of the amino acid to its specific carrier transfer RNA. In order that there be no mistake in the subsequent steps in protein synthesis, it is necessary that the activating enzyme recognize both the amino acid and its cognate tRNA with extreme fidelity. In order to understand the chemical basis for this extreme specificity we must study the activation reaction with both pure enzyme and pure specific tRNA.

Separating the tRNA's

Well, we were at this stage in our studies when we had our second major discussion with our friends in the Chemical Technology Division, who wanted to get down to specifics in the area in which they would try to help us. After they had become acquainted with the details of our problem, we all agreed that a good place for the chemical technologists to start would be in devising new methods for the separation of individual amino-acid-specific tRNA's.

It is known that for most amino acids there are more than one different carrier tRNA's, so the number of individual species is greater than 20. They all have about the same molecular weight, and consist of single chains of about 75-80 nucleotides in length. The separation of these very similar molecules represented a real challenge for the chemists and chemical engineers. They addressed themselves to the task of developing new biological macromolecular separation technology.

To initiate the program, Don Kelmers of Chemical Technology was assigned to work in the Enzymology Group of the Biology Division in November 1963. Biology and biochemical disciplines were completely new to Don, and his first job was to acquaint himself with the jargon of the field and learn a few fundamental principles of nucleic acid chemistry. This he did in short order, tutored by Mel Stulberg of the Enzymology Group with whom he was to work. Shortly before this Holley (1968 Nobel Laureate) and his group at Cornell had made the first isolation of an almost pure species of transfer RNA using a liquid-liquid extraction technique.

It was our intention to develop a system for the isolation of a specific tRNA that could be scaled up to produce the pure compound in gram quantities, and so we decided to stick to column chromatographic procedures, since all that is needed to scale up a column procedure is a bigger pipe! But we wanted also to exploit the separation capabilities of the liquid-liquid extraction procedure. We knew, from the work of Zachau in Germany and ORNL's Joe Khym, that some nucleotides and tRNA's had been partially separated from each other by distribution in a liquid-liquid system consisting of a quaternary ammonium compound in an organic phase and an aqueous salt solution. Kelmers obtained a series of long chain quaternary ammonium compounds from commercial sources and proceeded with experiments in liquid-liquid extraction, using various organic phases and extracting the tRNA into aqueous salt solutions. He was helped by useful discussions with Khym.

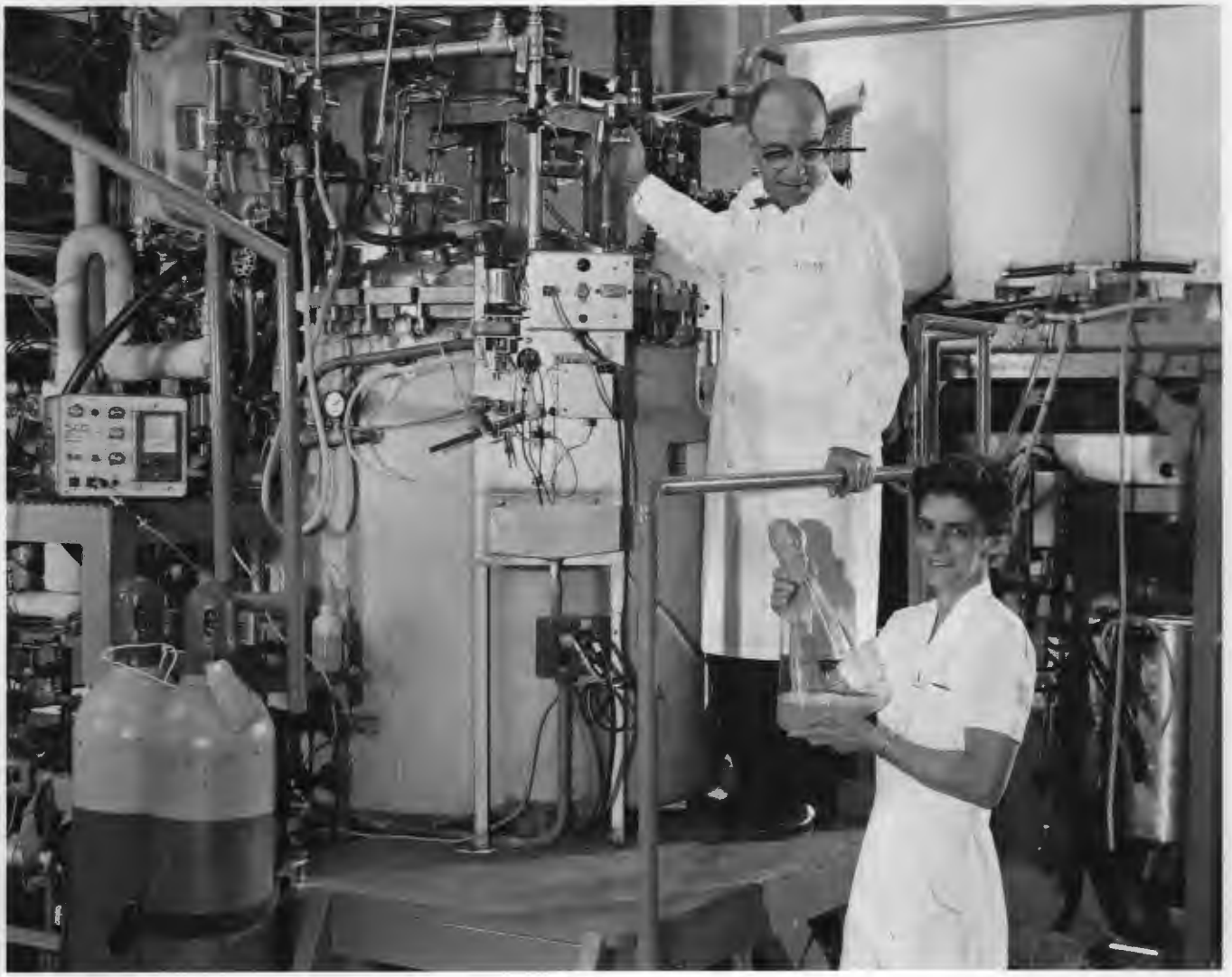
It is interesting to note here that both Kelmers and Khym had earlier gained experience in the use of quaternary ammonium compounds in liquid-liquid extraction in the Chemical Technology Division program on the separation of mineralogical raw materials.

In the beginning we focused attention on phenylalanine tRNA, primarily because Stulberg had already isolated the pure activating enzyme, and studies on the recognition mechanism could begin as soon as some pure phenylalanine tRNA became available.

After a large number of tests with the liquid-liquid extraction experiments, the particular organic phase was found from which phenylalanine tRNA could be extracted with salt water. It even promised some success with other tRNA's. When the organic phase was successfully immobilized on a solid support, we were ready to convert to column chromatography. These systems are called "reversed-phase chromatography" (RPC). From this beginning, a technology was developed which eventually produced almost completely pure samples of the desired specific tRNA.

". . . On a Rather Large Scale . . ."

From this continuous-flow fermenter, starting with a colony no larger than that which research assistant Mary Long is holding, as much as six kilograms per hour of E. coli *can be produced for an extended period of time.*



No Longer a Chore . . .

Mel Stulberg demonstrates the ease with which the French pressure cell can now be operated, with the heavy work done by the electrically powered hydraulic pump on the right.

Another Division Joins Forces

At this stage in the development, the number of samples that had to be analyzed was severely limiting our progress, so Ira Rubin of the Analytical Chemistry Division was assigned to the project to help with the analyses, and Charles Horton, also from Analytical Chemistry, started an attempt to automate the analytical procedure.

In the spring of 1964 this project was set up as a collaborative effort between the three ORNL divisions, and remodeling of laboratories to accommodate this type of work was begun in the Chemical Development C section and Unit Operations sections of the Chemical Technology Division. The Analytical Chemistry Division organized a bio-analytical group to support this project.

We purchased, from General Biochemicals Corporation, 20 grams (at $100 per gram) of mixed crude tRNA that had been prepared from *E. coli* bacteria. From this material, Kelmers prepared 100 mg of pure phenylalanine tRNA and 100 mg of highly purified leucine tRNA. This was accomplished by seven or eight runs on 1 cm × 240 cm jacketed columns.

W. E. Cohn and M. Uziel of the Biology Division immediately started nucleotide sequence work on

the pure material, and Stulberg started studies with it and his pure phenylalanine activating to determine the recognition site. It was obvious that much more of the pure material would be needed to complete these projects. Unit operations then prepared to scale up the process to produce a gram or more of pure phenylalanine tRNA. But when we turned to General Biochemicals Corp. with a request for 500 grams of mixed *E. coli* tRNA, they informed us that they could not provide us with the quantities we wanted. We then had no recourse but to make the starting material ourselves. This would require growing the bacteria on a very large scale. Although we have in the Biology Division a 300-liter fermentor, trying to grow large amounts of cells in batches would take a long time. Here again the engineers in the Chemical Technology Division came to our aid. They built for us a continuous-flow sterilizer that permitted us to grow cells on an uninterrupted basis. For example, in one operation in which Conny Chester (C. V. Chester, now with Civil Defense Research Project) participated enthusiastically, we grew cells continuously over an 80 hour period at the rate of 100 liters per hour. From this came 500 kilograms of cells (about half a ton), from which approximately 500 grams of mixed *E. coli* tRNA was prepared. This took place during the summer of 1965.

In April that year, Kelmers had presented the first public report of the development of the new column chromatographic system and its success in isolating 100 mg of pure phenylalanine tRNA, at the annual meeting of the American Society of Biological Chemists in Atlantic City. As a result, the National Institute of General Medical Sciences (NIGMS) sent representatives to ORNL, expressing an interest in supporting work on the development of macromolecular separations technology. We complied promptly with a proposal, whose longterm goal was the development of improved methods for the separation, purification and large scale production of pure, biologically important macromolecules; and whose immediate goal was the development of methods for the separation of the individual amino acid specific tRNA's from *E. coli*. Such laboratory studies were to be carried out to prove the feasibility of scaleup to pilot plant quantities. The Analytical Division was to provide the necessary analytical support, as well as conducting research and development studies of new or improved analytical methods to support the project.

The wheels of government agencies grinding as slowly as they do, it was a full year before an interagency contract was negotiated between AEC and NIGMS. We received our first funds in May 1966, but the program had continued in the interim, so that by the time NIGMS support was available the overall procedure had been comparatively streamlined.

With the new support, we set about growing another large batch of *E. coli* cells. Four weeks of intermittent, three-shift operations produced 400 kg. From this, 500 grams of crude mixed tRNA was prepared, which was then fractionated on reversed-phase columns for the recovery of phenylalanine tRNA. Two sets of coupled columns were used, each set consisting of a 2-inch by 8-foot column feeding a 1-inch by 8-foot column. In a typical run, approximately 20 grams of crude tRNA was loaded on the first column and was fractionated with a 50-liter linear gradient of sodium chloride. In all, 20 runs were required to process the mixed tRNA. The phenylalanine-tRNA-rich fractions were further processed to yield 1.5 grams of approximately 70% phenylalanine tRNA. The remaining tRNA's were precipitated with alcohol and saved for further processing. One gram of the purified phenylalanine tRNA was turned over to NIGMS for distribution to the scientific community. An announcement of the availability of this material was made in the Letters pages of *Science*, July 7, 1967. Applicants for the tRNA were approved by NIGMS, and received their shipments from ORNL. As of this writing the original 1.0 gram of phenylalanine tRNA has been completely distributed, generally in five to ten mg amounts. The material has been shipped all over the world to such countries as England, Spain, Norway, Russia, Poland and Japan, although the greatest amount has gone to U.S. scientists.

The Systems Proliferate

As we gained experience with the separation of tRNA it became evident that a single chromatographic system would not be capable of separating all of the many tRNA's. While C. Hancher and H. Weeren were producing the material in the Unit Operations section, Kelmers, Weiss, Pearson and their colleagues were developing additional systems with different properties that might be useful in the program. At this writing five chromatographic systems for the separation of tRNA have been developed. Four of these are reversed-phase systems (RPC-1 to RPC-4), each employing a quaternary ammonium compound adsorbed to

hydrophobic diatomaceous earth (chromosorb W or G) with or without an organic solvent, as the stationary phase and the tRNA is fractionally eluted with a sodium chloride gradient. The fifth system has hydroxylapatite (a form of calcium phosphate) as the solid support and the tRNA is eluted with a sodium phosphate gradient.

During the past six months the tRNA from which the phenylalanine tRNA had been taken has been reprocessed to yield about one gram of pure formylmethionine tRNA and 90% pure valine tRNA. These have now been turned over to NIGMS for distribution to the scientific community and their availability will soon be announced. Our general feeling now is that with the separation methods developed at ORNL together with several other methods already described in the literature we can isolate in a highly purified form any tRNA we desire. The Unit Operations section will continue to improve on the large-scale operation and will systematically isolate each and every tRNA that may be of interest. Meanwhile, Chemical Technology's Research and Development group will turn its attention to the development of methods for the separation of ribosomal RNA, messenger RNA and, hopefully, to the eventual separation of individual genes.

Extra Dividend

An unexpected bit of "spin-off" has emerged from this program that may turn out to be more important than the production of pure species of tRNA. That is the analytical use of the column chromatographic methods to detect modifications, alterations or changes in individual tRNA's during the course of metabolism, differentiation, development, virus infection, etc. As mentioned earlier, proteins are made from 20 amino acids, and each amino acid has its own specific enzyme for its activation. But each amino acid is carried by, not one, but several transfer RNA's. How many there are for a given amino acid is not yet fully known, owing to the previous lack of good separation methods, but we know that there are at least five different tRNA's to carry the amino acid leucine, also five for arginine, etc. These are called "isoaccepting species."

At first the multiplicity of isoaccepting species of tRNA's was ascribed to the "degeneracy of the code" through the course of evolution. More recently, however, many of us have begun to think that there may be a more profound reason for this multiplicity. The idea, reinforced by some circumstantial evidence, is that in addition to their normal role in protein synthesis, certain of the transfer RNA's may also be involved in the process of control and regulation of metabolism. That is, the appearance or disappearance of a given tRNA molecule may regulate the turning on or off of the synthesis of certain proteins at certain stages in development and thereby be important factors in the control of many metabolic reactions. If indeed some of the tRNA's perform such a function, there should be fluctuations in the amount of certain species of tRNA's during changes in metabolism of cells. Several investigators have suggested that such changes may indeed occur. Biology Division's Larry Waters was the first to apply the new RPC systems to this problem. He set out to repeat an observation reported by Sueoka of Illinois that, six minutes after infection of *E. coli* cells by a bacteriophage, rather specific change of leucine transfer RNA took place. Using RPC-1 system, Waters not only confirmed the six-minute change, but discovered that shortly before completion of the viral cycle, two new species of leucine tRNA appeared.

At the moment we are trying to determine the physiological significance of this change. The methods developed in this program are being used at ORNL to observe changes in tRNA during liver carcinogenesis in the rat, in the development of the brine shrimp, and in mouse cells in normal vs. cancer tissue growth. Other workers in the field are applying these methods in similar studies.

In the past year, over 50 scientists have visited the laboratory for from two days to a week in order to learn this methodology so they can apply it to similar problems. Recently NIGMS has asked us to set up a workshop for a detailed discussion of methods for the separation of biologically active macromolecules in general. This workshop is in the planning stage and will include about 20–25 scientists who are leaders in this field.

In recounting the history of this trans-Laboratory program, I hope to have shown the remarkable productivity that can be accomplished when the considerable talents of scientists and engineers in widely diverse fields are pooled in a common effort. Only at a vast, complex research laboratory such as we have at Oak Ridge could the Macromolecular Separations Technology program have been set into motion to arrive ultimately at techniques which may prove to revolutionize a large segment of biological research.

Alert to the earth's every microrumble is the author of this article, who writes from the vantage point of having headed up ORNL's two years of earthquake studies. Richard Norton Lyon joined the Manhattan Project at the University of Chicago, his undergraduate alma mater, in the spring of 1942, interrupting his graduate studies in chemical engineering at the University of Michigan to do so. Moving to Oak Ridge in 1945, he completed requirements for his doctorate as soon as the war ended, using for his dissertation the work on heat transfer he had done in the course of his wartime employment on the Project. He is currently Associate Director of the Reactor Division. His participation in earthquake studies dates from the Laboratory's involvement in 1966 which began with a state-of-the-art investigation for the AEC by T. F. Lomenick of the Health Physics Division and C. G. Bell of the Reactor Division. Shortly after the start of that study, Lyon was asked to draw up a program plan on earthquake engineering for the AEC Division of Reactor Development and Technology, and to place and coordinate a number of subcontracts on specific studies. These have included design studies for earthquake resistant nuclear power plants, studies on the application of models and shaking tables, and recently, actual shaking of the EGCR. Others working on the program are J. Foster, W. K. Sartory, J. G. Merkle, and R. H. Bryan of the Reactor Division and W. C. McClain of the Health Physics Division.

Earthquakes and Nuclear Power

By Richard N. Lyon

Of the thirteen nuclear power plants now operable in the U.S., five range in electrical capacity from 175 to 460 megawatts (Mwe). Thirty-one nuclear power plants are now being built that range from 420 to 1065 Mwe. Forty more have been committed by contract to start up by 1975, 33 of which will have electrical capacities between 765 and 1125 Mwe. Undoubtedly at least one large nuclear power plant now operating, in construction, or planned will be shaken by a strong earthquake.

Unless we design that nuclear plant correctly, locate it wisely, build it well, and operate it properly, the earthquake will threaten containment of the radioactive fission products that are formed in the core at the rate of about three kilograms per 1000 megawatt-days of electricity produced. Earthquakes are the most probable and most permeating of major potential external hazards to nuclear power plants.

Recorded earthquakes in the U.S. have occurred most frequently along the Pacific Coast, but the

According to Maori legend, the god of volcanoes and earthquakes is Ruaumoko, one of the children of the Earth Mother. He is said to have had the misfortune to be accidentally pressed into the earth when his mother, who had been feeding him, turned over face downwards. He has apparently since been expressing himself in a series of growls and eruptions from his position of entombment.

greatest earthquakes in U.S. history have shaken the East: three were centered at New Madrid, Mo. in 1811-12 and felt from the Atlantic Coast to the Rockies; and one in 1886, centered near Charleston, S.C., was felt in Boston and on the Mississippi River.

Obviously, some earthquake protection should be provided for all nuclear reactors, and to some extent it is provided. As we build more and larger nuclear power plants, however, the hazard increases and greater precautions must be taken. To do that we must learn more about earthquakes and their possible effects on reactors.

Earthquake Phenomena

Shaking in the ground, by definition, is the universal characteristic of an earthquake. But in addition a deformation of the earth's crust called a tectonic displacement usually accompanies a large earthquake. Frequently a giant water wave, or tsunami, may be formed, sweeping across the ocean at over 500 miles per hour, and causing spectacular damage.

Seiches, a bathtub type of sloshing wave in a lake, river, or partially confined body of water, may result from an earthquake on the opposite side of the earth, even though there may be no other perceptible indication of the distant earthquake. For example, the uniquely powerful earthquake in Assam (northeast India) in 1897 caused a recognizable seiche in Loch Lomond.

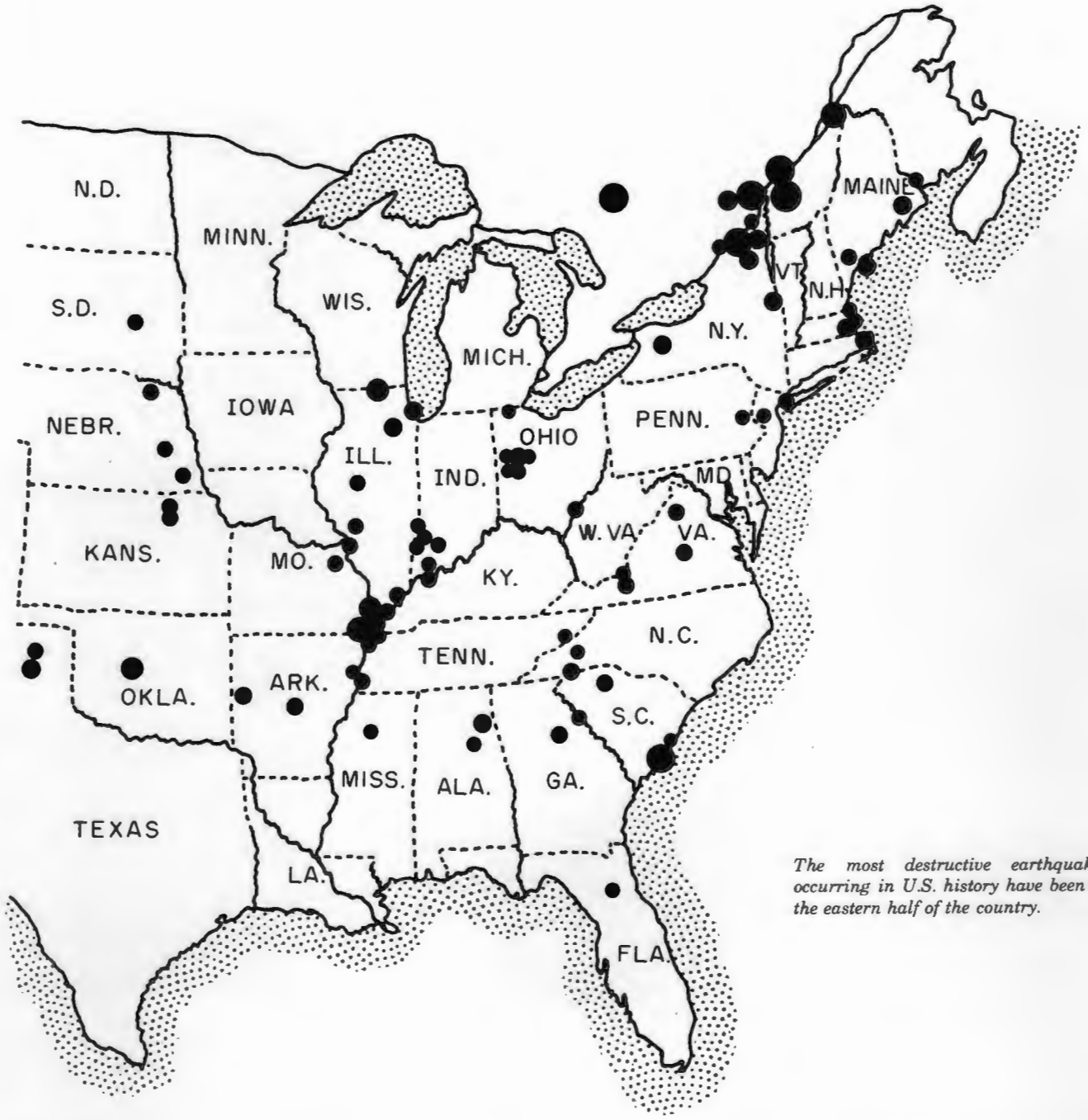
Soil failures due to shaking cause the most serious secondary effects of earthquakes. Both landslides and soil liquefaction are common. In 1964 at Niigata, Japan, the soil under a row of apartment buildings liquified during a strong earthquake, and one of the buildings tilted 80 degrees without collapsing. (The inhabitants escaped by walking down the wall of the building, after climbing up to the windows.)

Earthquakes are not usually accompanied by volcanic activity. Also there appears to be no relationship between the weather and the occurrence of an earthquake, although many reliable witnesses have reported seeing lightning flashes during strong earthquakes.

The Hazard

A large nuclear reactor power plant is, by far, the most dangerous assembly of structures that can be threatened by an earthquake. The hazards are worth reviewing.

After only a few weeks of operation, modern large reactors will contain hundreds of pounds of radioactive fission products—over a ton in less than a year. Some of this material will be released from the fuel if loss of cooling water, malfunction of a cooling system, or a power surge in the reactors ruptures or melts the fuel cladding. If clad rupture occurs in connection with previous, simultaneous, or subsequent rupture of the primary cooling system and outer containment structure due to vibration, tearing out of an umbilical, or melting from the heat of the radioactive material itself, a large fraction of the fission products may be released to the atmosphere and to the ground water. Such release near a large city would threaten all the lives in the city and could make wide areas lethal, possibly for years. It could contaminate a river and all its downstream confluences—both directly and by contaminating watershed runoff.



The most destructive earthquakes occurring in U.S. history have been in the eastern half of the country.

The responses to earthquakes may vary for different reactors, but the potential hazard of major releases of radioactive material is the principal danger in all of them.

Today's nuclear power plant is not a single structure. Large nuclear power plants are combinations of separate buildings. The reactor building is itself a large emergency pressure vessel, and it contains only those systems and components that must be near the reactor. The turbine, for example, is outside the outer containment vessel, and in current designs is on a separate foundation. More important, emergency-power diesel generators, their fuel, the cooling-water pumps, and the control building are also on separate foundations. Any severe earth-shaking or differential shifting would threaten essential connections with the main reactor building.

A number of safety systems are provided in large nuclear power plants. Among these is the automatic control system that shuts down the reactor when operating conditions reach proscribed limits. No large reactor plant being built today, however, is provided with a "seismic scram" to shut down the reactor in the event of a strong earthquake. Later we will discuss some of the pros and cons of a seismic scram.

The emergency core-cooling systems (usually more than one) are a very important set of safety systems in a water-cooled power reactor. They are intended to cool the fuel if the primary cooling water is lost through a pipe rupture. After shutdown, partially consumed fuel will continue to generate heat; the heat-generating radioactivity will take centuries to die out. In a 1000 Mwe reactor this heating can still amount to 30,000 kw after one hour—about one-third the output of Norris Dam.

Even if the emergency cooling system works properly following a sudden cooling-water loss through a rupture of the primary cooling system, it will not necessarily prevent escape of fission products from the fuel rods. In the large water-cooled reactors being built today, the cladding on up to 90% of the fuel rods may be ruptured in spite of the emergency core cooling system, because the clad will reach the temperature (about 1200°F) where it is too weak to contain the pressure of gaseous fission products inside, against the reduced pressure in the cooling system. The clad may even reach a temperature (over 2000°F) where it reacts appreciably with the steam that surrounds it. With such a break in the primary cooling system causing a partial radioactive release, it is essential that the outer containment vessel remain intact. It is the last resort.

If the emergency cooling is delayed, the clad temperature may reach the point (about 2800°F) where the reaction between the Zircaloy cladding and steam can only be prevented by complete immersion of the fuel rods. At 3400°F the Zircaloy melts, with substantially greater release of the more volatile fission products.

In the extreme case, the fuel will reach its melting point of 4800°F. Any sizable collection of molten fuel in the bottom of the reactor vessel will quickly melt through the steel, and, if uncontrolled, through the building foundations into the ground. Facetiously, it will not stop until it reaches China. The possibility of the "China Syndrome" is recognized, and some reactors have "catchers" that are intended to intercept the molten fuel.

The above considerations are particularly important in discussing earthquakes. In an earthquake all components and systems will be shaken; soil movements and fault slips can rupture essential umbilicals, jeopardize the outer containment, and tilt the entire reactor; and changes in relative water level caused by tectonic movement or landslides may flood the plant or remove its source of cooling water. No other conceivable natural assault on a reactor is potentially as complete and all pervading.

The State of the Art

Earthquake engineering is a particularly frustrating endeavor. We already have the basic knowledge to protect a nuclear power plant against almost any conceivable level of shaking and horizontal fault slip and against a considerable amount of vertical fault slip. It is more difficult to decide the level of shaking and amount of fault slip on which to base the design. Excess caution penalizes the owner; insufficient caution threatens the public. And if we have chosen well, we will never have empirical evidence of how overconservative we have been; the design-basis earthquake will never come.

Knowledge to help us predict when and where an earthquake will occur, what level of shaking to expect, and what tectonic displacement will take place will come very slowly. We will probably first reduce the cost of earthquake protection by improving the design itself rather than by being able to reduce the design requirements.

". . . if we have chosen well, we will never have empirical evidence of how overconservative we have been; the design-basis earthquake will never come."

The Vibration Response of Structures

Because of its application in many areas of engineering, vibration theory for simple structures is well developed. Several useful concepts can be understood by considering a simple inverted pendulum that consists of a flexible, weightless column surmounted by a ball of known mass. It is found that very often a more complex structure can be approximated by an interconnected system of such "lumped" masses and springs.

We all know that, neglecting any effect of gravity, if the mass in our "single mode" system is pushed to one side and released, it will swing back and forth across dead center. The number of complete cycles it makes per second is called the "natural frequency." In any real system, the vibrations tend to die down as a result of friction in the spring. This damping may be so extreme that the mass does not cross dead center, but rather approaches it asymptotically. The minimum damping that prevents the mass from crossing the center is called the "critical" damping and is used as a base for comparison with other amounts of damping. Many of the structures in reactor systems for example have only a few percent of critical damping, and will shake long after the initiating action is stopped.

Damping is particularly important because it limits the shaking response of vibrating systems. The frequency of shaking at which our inverted pendulum can reach the greatest response when its base is shaken is the "resonant" frequency. If the base is shaken continuously at the resonant frequency, the pendulum reaches an amplitude that is inversely proportional to the damping – fifty times the base amplitude for 1% of critical damping.

Since lightly damped resonating systems press back against the base, heavy, undamped, stiff structures will tend to reduce the input motions from soft ground to the structures at their resonant frequencies.

A lightweight system may vibrate with much greater amplitude than a heavy system of the same resonant frequency through which the vibration is being transmitted. In a recent shaking of the Experimental Gas-Cooled Reactor by a group from the University of California at Los Angeles, under subcontract to ORNL, the outlet steam pipe from the steam generator could be made to shake at its resonant frequency with 120 times the amplitude applied to the floor above using two 5000-lb. (force) shaking machines.

Thus an essential component may be forced to withstand many times the input ground motion to a reactor plant, because of its location on a particularly responsive part of the structure. An input of only 0.1 g acceleration could result in response acceleration of 10 or more g.

The Nature and Classification of Earthquakes

Earthquakes are apparently due to some mechanical adjustment of rock in the crust or the mantle of the earth. The crust is a thin (roughly 20 to 40 miles thick) layer of relatively low-density rock that lies on top of the denser mantle. The mantle is considerably thicker, about 1800 miles. Below the mantle are concentric layers of a liquid core.

Any sizable earthquake causes the earth to quiver over its whole surface. People are conscious of it only nearby, but the teleseisms (recordings of distant earthquakes) show up on seismometers around the world.

In California it appears that most earthquakes are "shallow" and are caused by sudden slip along known faults or cracks in the crust. In 1906, the San Andreas fault slipped horizontally on the surface along a length of over 200 miles, and, north of San Francisco, differential displacement reached 21 feet.

In Alaska there is ample evidence of tectonic movement during the 1964 earthquake; for example, one side of Montague Island was lifted permanently up to 33 feet, but there is little evidence of primary fault slip on the surface. Seismographic evidence

implies a deep subsurface fault slip over a length of about 450 miles.

As the vibration waves move out, they are initially of two forms, compression or "P" waves and shear or "S" waves. P waves move at about three to eight miles per second; S about half as fast, their velocity increasing with depth.

It is mnemonically helpful to think of P and S as abbreviations for "pressure" and "shear." In fact, however, they stand for the Latin phrases *undae primae* and *undae secundae,* referring to the order of their arrival. Teleseisms indicate a wide variety of waves, some of which travel along the surface of the ground, some in the ocean, and some almost directly through the earth. Thus, the farther away an earthquake is, the longer the shaking lasts.

One approach for grading or classifying earthquakes is in terms of the area affected and the physical effects produced by the earthquake. The Modified Mercalli Scale is the most widely used scale of intensities. The MM Scale ranges from I to XII based on the reactions of people, animals, trees, and structures: it is not easily applied in poorly populated areas.

From a seismologist's point of view, the most reproducible, quantitative measurement of an earthquake is the amplitude of the recording it makes on a standard seismometer at a standard distance from the epicenter. Readings on other types of seismometers at other distances can be used to predict the amplitude a recording would have shown on a standard instrument at the standard distance. The universally accepted measure, based on these facts, is the "Richter Magnitude." It is defined as the base-10 logarithm of the maximum amplitude, in microns, recorded on a Wood-Anderson torsion seismometer having a natural period of 0.8 seconds, an amplification of 2800, and a damping coefficient of 0.8 critical located 100 kilometers from epicenter.

In 1940, earthquake engineers got a bit of a break. For the first time, a moderately strong earthquake was recorded on strong-motion instruments. Today the El Centro 1940 north-south strong-motion spectrum is still the most widely used for computing the response of a given structure to an earthquake.

The availability of large digital computers now makes possible the analysis of very complex structures, using actual recorded ground motion data like those from the El Centro earthquake. Most of the calculations today use complex, lumped-mass spring models, but the finite element approach is rapidly gaining favor.

We still have no quantitative idea of the shaking during any "great" earthquake. The really strong shaking at El Centro (magnitude 7.1) was over in about ten seconds. The massive Turnagain Heights landslide at Anchorage didn't begin until the strong shaking had been going on for about $1\frac{1}{2}$ minutes during the 1964 Alaska earthquake of 8.4 magnitude (30 times as big). No strong-motion instruments were there.

A unique little 5.2 magnitude earthquake occurred in 1966 along the San Andreas fault between Parkfield and Cholame in middle California. During the earthquake, a series of instruments recorded the maximum accelerations at their locations with a maximum of 0.5 g very near the fault. The earth moved over and back about eight inches during that pulse, and moved perpendicular to the fault rather than parallel as predicted by the fault slip or "elastic rebound" theory. Because there was only one really strong pulse, it did little damage.

One final word on the ground shaking. A single recording cannot tell the story. A mild earthquake in San Francisco in 1957 produced records in many types of soil and at different distances from the epicenter. The amplitude, duration, and predominant frequencies varied remarkably.

On July 29, 1967, Caracas, Venezuela, was struck by an earthquake that collapsed twelve-story buildings at locations where fourteen-story and eight-story buildings survived. At other areas, twelve-story buildings survived but other buildings collapsed. These peculiar results appear to be due to the resonance of the layers of soil on which the buildings were built. Those buildings with resonant frequencies similar to the ground resonance collapsed while others resisted the earthquake. Microearthquakes, dynamite blasts, mechanical shakers, and underground nuclear test shots, as well as mathematical predictions based on soil depth and properties, are all being used at present to develop methods for predicting the resonant ground frequencies at potential reactor sites.

Tectonic Displacement

Primary fault slip reaches to the earth's surface in most of the large earthquakes in California and Nevada. It is still very difficult to predict the amount of slip that can occur along a given fault. Geologic history at the fault and the general seismicity of the area are the primary bases used today for establishing the amount and type of slip expected. The San

Andreas fault has slipped horizontally over most of its history. Some geologists believe it has slipped a total of over 100 miles. The Dixie Valley-Fairview Peak fault in Nevada slipped 12 feet horizontally and 12 feet vertically during the 1954 earthquake. Geologic evidence has been found that suggests much greater slips along both these and other faults.

It is unlikely that anyone would propose siting a nuclear plant directly on top of the San Andreas fault, or any other major fault that is known to have slipped in historic times. (Many types of structures are not sited so carefully, however. One interesting example is the University of California Stadium at Berkeley which is built directly on top of the major active branch of the San Andreas fault called the Haywards fault.) It is not as easy to avoid minor short faults. They are often hard to detect, and having found them it is not easy to tell if and how much they may be able to slip. So far the most certain method is to cut trenches through the overburden and into the rock. If faults or cracks are found, examination and dating of the overburden may show how recently the crack slipped.

We are now finding evidence that earthquakes and other major ground shocks can trigger secondary fault slips. The Borrego Mountain earthquake of April 8, 1968, in Southern California was entered on the Coyote Creek fault, which slipped over a length of about 27 miles with a maximum of 1 foot 3 inches horizontal differential displacement. A few days later, slips on three other faults were found—located between 28 and 43 miles away from the Coyote Creek fault. Most geologists believe all four breaks are closely related and formed almost simultaneously. Thus, proximity to a major fault may increase the probability of fault slip on a secondary fault.

As with fault slip, net tectonic rise or subsidence is difficult to predict. A barnacle-covered Indian artifact was reported found 50 feet above sea level near the mouth of the Colorado River at the Gulf California. This implies strongly that a reactor in that area should be designed and built to withstand rather drastic changes in water line. Perhaps the most glamorous tectonic subsidence in modern history was the sinking of Port Royal, Jamaica, beneath the waters of the Caribbean during the earthquake of 1692. Port Royal at that time was one of the largest cities in the Americas, and one of the richest in the world, since it was headquarters for most of the pirates on the Spanish Main. Many people at the time attributed the immersion to a cleansing act of God.

History shows little vertical tectonic displacement along the California coast, but as already indicated such displacement may be very important in Baja California (where a large nuclear desalting plant has been proposed), and in Alaska.

Soil Failure

The shear strength of a soil derives from two phenomena: (1) cohesion between particles of soils and (2) dilatancy, i.e., the necessity to expand when shearing. The first phenomenon occurs principally in clays; that is, in soils with particles that are small enough (less than around five microns) to respond to Van der Wall and chemisorptive forces. Some clays expand and contract as a function of water content, but others are dense, impervious shales that make excellent underpinning for heavy earthquake-proof structures, provided they do not contain layers of weaker material.

Some wet clays and muds tend to yield slowly under moderate loads. They may also lose shear strength when being sheared rapidly and may not regain their original shear strength until some time after the shearing has ceased, a phenomenon called "thixotropy."

Silts, sands, and gravels are cohensionless but are usually dilatant, which means that their shear strength will increase with compressive load on the plane of shear and, hence, with depth. But many cohesionless materials are not well compacted, and under the influence of man-made or earthquake vibration they tend to compact further.

When the connected interstices between the particles of an uncompacted cohesionless soil are filled with water (saturated), compaction of the particles displaces water from the interstices. If the cohesionless soil is in a layer between two impervious layers of clay, the water accumulates on top of the sand layer, and the sand becomes temporarily suspended in the water. The combination forms a low-friction film on which the upper clay layer can slide. This is what caused the drastic landslides in Anchorage in 1964.

If the cohesionless soil bed is thick and extends to the surface, the expelled water moves up through the bed and fluidizes it. This type of liquefaction occurred at Niigata, Japan, in 1964 and in Chile in 1960.

Several approaches have been used in countering soil weakness. One is to use piles that penetrate to

rock or to a stronger soil. Another is to substitute a stronger soil, usually by compacting the existing soil or by adding hardening materials to it. Where instability is due to water in the soil, a third approach may be to remove the water by drainage or with drywells. All these approaches need development effort.

The most important problems are the detection of thin layers of potentially unstable soil, the determination of the shear strength and thixotropy in clays, and the degree of compaction in cohesionless soils.

Tsunamis and Seiches

A plausible, though not proven, mechanism for the formation of a tsunami is a sudden vertical displacement of a large section of the ocean bottom. The wave length may be several hundred miles, so that even in the deepest ocean such waves behave as shallow water waves; and since the velocity of a shallow wave is proportional to the square root of the water depth, tsunamis move across the ocean at velocities as high as 500 miles per hour.

Their amplitude is only a few feet in deep ocean so they are not detectable by ships at sea, but on nearing a shore the height of the wave increases. When concentrated at the end of an inlet (as at Hilo, Hawaii, several times; or Crescent City in 1964), the water rolls up onto shore as a step change in water level that is headed by a tumbling bore.

At Hilo in 1960 the velocity of the bore in the streets was estimated at 25 to 40 feet per second where the height ranged from 8 to 12 feet. Much greater heights have been experienced. In 1946, a tsunami over 100 feet high demolished a well-built lighthouse 45 feet above sea level at Unimak Island in the Aleutians, and produced up to 55-foot waves on Hawaii and Molokai. One hundred and fifty-nine people were killed and 488 homes destroyed. This same tsunami rose 12 feet on the California coast at Santa Cruze. The depredations prompted the establishment of a tsunami-warning system that saved many lives in the 1960 Hilo tsunami.

The possibility of tsunami intensification near a nuclear site can be examined analytically with some success, but if a danger is still suspected, it may be desirable to perform model tests, as has been done by the U.S. Army Engineers for Hilo at their Vicksburg, Miss., station.

Seiches are sometimes formed by far-distant earthquakes, although they are also initiated by winds and other causes. They consist of a standing wave between two shores. They may form in channels, wide rivers, or lakes. At any site near such a body of water, the possibility of a seiche must be considered.

Protection against seiches and tsunamis in general consists of modifications in the water to minimize intensification, as is being carried out now at Hilo, or erection of a protecting wall, as at the San Onofre nuclear power station, south of Los Angeles.

The following description of a tsunami was taken from a paper by Eaton, Richter and Ault on the Hilo tsunami of May 26, 1960:

"At first there was only the sound, a dull rumble like a distant train, that came from the darkness far out toward the mouth of the bay. By 1:02 a.m. all could hear the loudening roar as it came closer through the night. As our eyes searched for the source of the ominous noise, a pale wall of tumbling water, the broken crest of the third wave, was caught in the dim light thrown across the water by the lights of Hilo. It advanced southward nearly parallel to the coast north of Hilo and seemed to grow in height as it moved steadily toward the bayshore heart of the city.

"At 1:04 a.m. the 20-foot-high, nearly vertical front of the inrushing bore churned past our lookout, and we ran a few hundred feet toward safer ground. Turning around, we saw a flood of water pouring up the estuary. The top of the incoming current caught in the steel-grid roadway of the south half of the bridge and sent a spray of water high into the air. Seconds later, brilliant blue-white electrical flashes from the north end of Kamehameha Avenue a few hundred yards south of where we waited signalled that the wave had crossed the sea wall and buffer zone and was washing into the town with crushing force. Flashes from electrical short circuits marked the impact of the wave as it moved swiftly southeastward along Kamehameha Avenue. Dull grating sounds from buildings ground together by the waves and sharp reports from snapped-off power poles emerged from the flooded city now left in darkness behind the destroying wavefront. At 1:05 a.m. the wave reached the power plant at the south end of the bay, and after a brief greenish electrical arc that lit up the sky above the plant, Hilo and most of the Island of Hawaii was plunged into darkness."

An example of soil failure. The resulting landslide completely severed this schoolhouse in the 1962 Good Friday earthquake in Anchorage.

Earthquake Prediction

The Good Friday Earthquake in Alaska on March 27, 1964, focused attention, at least temporarily, on how little we know about earthquakes. While the earthquake was still fresh in their minds, the Office of Science and Technology appointed a committee, headed by Prof. Frank Press of Massachusetts Institute of Technology, to recommend ways by which we might learn to predict earthquakes. The committee concluded that although a variety of geophysical phenomena are known to occur at the time of an earthquake, insufficient data had been collected to provide predictive correlations.

They recommended that $137 million be spent in establishing clusters of instruments, some of whose recorded readings might correlate with the subsequent occurrence of an earthquake. The phemena that would be monitored include microearthquakes, tilting, rock strains, magnetic field, gravitational field strength, heat flow, and thermal anomolies. Twelve clusters would be located in California, three in Nevada, and nine in Alaska. In addition, a few "superclusters" would be located in California and Alaska, and portable clusters would be moved from place to place.

The Press Committee plan has never been started, but the Japanese are making a similar series of measurements in their Matsushiro District which is subject to a continuing series of earthquakes. They claim some success in predicting the occurrence of particularly strong shocks, largely from measurements of tilting in the earth. In some but not all cases, strong shocks are preceded also by a reduction in the number of microearthquakes recorded. This last phenomenon has also been observed on a few occasions in the United States.

Recently, evidence has accumulated that man's own activities may cause at least microearthquakes. Earthquakes up to 5.5 magnitude have occurred in Denver which never had an earthquake before the Army pumped large quantities of liquid waste into the bedrock. The microearthquake activity in Nevada has increased since Lake Mead (Hoover or Boulder Dam) was built. Seismologists report increases in microearthquake activity following underground nuclear bomb tests. Perhaps these bits of evidence can help in devising our prediction method.

Evidence is also accumulating that the root of seismic disturbances may lie in the liquid core of the earth. A young graduate student at the Colorado School of Mines has discovered that most seismic belts form circles on the surface of the earth that are the traces of planes tangent to the liquid core. Near the surface the faults themselves appear to have the directions of those planes. Also, it has been observed that the earth wobbles slightly on its axis a few weeks before a large earthquake.

Antiseismic Design

As long as we cannot predict the exact shaking and fault slip to which a given nuclear power plant will be subjected at a given site, the choice of design conditions must be arbitrary. Unfortunately, arbitrary judgment too often reflects the fears or the foolhardiness, the interests or the unconcern of the judger. Some guidelines are beginning to emerge, however.

Intuition and records show that strong earthquakes are less frequent than weak ones. With that hypothesis, nuclear power-plant designers and regulatory groups consider two possible earthquakes:

An *operating-basis earthquake* for the site, with probability so low that it is impractical to design the plant to operate normally through either greater shaking or greater net tectonic movement.

A *design-basis earthquake* for the site, with probability so low that it is impractical to consider greater shaking or greater net tectonic movement in designing the systems for safe shutdown and maintenance of a safe shutdown condition.

The nuclear submarines and the NS *Savannah* are examples of our ability to design reactors that can accommodate shaking and tilting. There seems little reason to doubt that reactors can be built to withstand fault slip as well. To test that belief for water-cooled reactors, ORNL let four subcontracts to engineering firms last year for investi-

"There seems little reason to doubt that reactors can be built to withstand fault slip . . ."

gation of four different approaches to shaking and fault-slip protection in a 1000 Mwe nuclear power plant costing, unprotected, about $140 million.

Homes and Narver in their study of this question estimate an increased cost of about $1.3 million to strengthen the wall to resist shaking and three feet or more of displacement when imbedded about 50 feet in a firm, cohesionless soil. They suggest, as an alternative, that the foundation pad be extended out from the vessel and be used also to support an expendable retaining wall.

Such a modification would increase the cost of a 1000 Mwe pressurized-water reactor plant by an estimated $2.2 million above that of an unprotected plant.

Kaiser Engineers found that they could avoid the interconnection problem by bringing all essential services into a single strong building. The cost was increased above that for an unprotected plant by about $5 million for a unitized plant on reasonably firm soil and about $5.6 million for such a plant on rock. Stored water and diesel fuel in the reactor building permit the reactor to remain safely shutdown for four days without outside support.

An advantage of floating a reactor plant is that shear waves cannot be transmitted through a liquid. Donald W. Douglas Laboratories, subcontractor to *Daniel, Mann, Johnson, and Mendenhall,* in their design study of a barge-supported plant, also proposed a honeycomb of air cushions on the bottom of the four-acre barge to protect against vertical pressure waves. The result would be that no further protection against either fault slip or shaking would be needed. Such provisions would increase the cost to about $18 million more than that for an unprotected plant. This includes the cost of a rock breakwater, but not the cost of the causeway to land. It takes no credit for the saving in cost of land and site preparation on shore. The cost would be only $7 to $9 million more than for an unprotected plant on an artificial island such as that proposed for the Bolsa Island power and desalting complex. There appear to be no serious development problems in this concept. Excavation on shore to form a pond would involve approximately one-half million cubic yards for a cavity about 550 feet square and about 40 feet deep. In some way the pond should be connected directly with an irremovable source of water.

The most serious problem in using a slurry or mud to support the vital parts of a nuclear power plant is in finding an appropriate material. *Burns and Roe* in their study of this concept found that approximately $5.3 million was required to supply equipment and ingredients to form and maintain the fluidity of the aqueous bentonite-$BaSo_4$ slurry they chose. Further, about 33,000-hp pumping power was needed to circulate the suspension and maintain its fluidity. The caisson basin for floating the reactor was estimated to cost about $6.8 million and the total increase in cost above that of the reference plant (Brown's Ferry type) was $15.3 million. The non-Newtonian properties of the suspension offer the advantage for a land-based plant that a crack in the basin wall need not result in complete, or even appreciable, loss of fluid.

Trends and the Future

For most of us, earthquakes are things that happen to someone else. Even the great Alaskan earthquake not five years ago has largely faded from public consciousness. It is not surprising therefore that designers, operators, and many individuals in regulatory positions have been slow to recognize the unusual hazard of earthquakes for reactors.

Earthquake engineers are usually conditioned to consider the integrity of structures, not the malfunction of operating systems. Thus in the past, designers and builders of nuclear power stations in known seismic regions have provided damping devices for heat exchangers and piping, but usually little attention has been paid to possible malfunction of transducers, electronic equipment, nonmanual valves, mercury switches, and other components that may "fail" in nonstructural ways when shaken.

The reactor core itself may malfunction because of changes in nuclear reactivity as shaking varies the relative positions of the fuel rods. This effect is probably minor, if observable at all, in current

Multifarious are the possible effects of an earthquake on a nuclear power plant, but the grave danger is in the ultimate release of fission products to the environment.

PW and BW reactors. It may, however, be very important in fast reactors such as the Liquid Metal Fast Breeder.

Earthquake hazards for nuclear power plants are now becoming more widely recognized. The owners of the San Onofre station are installing, at their own expense, one strong-motion seismometer outside the reactor building and three at carefully chosen points inside. Not only can these instruments provide useful data on earthquake spectra, should an earthquake occur nearby, but the records will give important information on the response of the building structures and help determine the need to look closely for hidden structural and component damage. Other plant owners are now being encouraged to install strong-motion recorders in their nuclear power stations. Unfortunately the instruments being considered will not record above 1 g, while the structures may respond at 5, 10 or more g.

At least one engineering firm is considering a shaking test of a 783 Mwe PWR that it now has under construction.

Seismic scrams are being studied, and in the long run they probably will be installed in all large nuclear power plants. The preliminary safety analysis report for the Oconee PWR power plant points out that if the primary cooling system is broken while the reactor is operating, power will be generated for one to two seconds following the break, and the clad on 70% of the fuel rods will rise in temperature beyond the point where it can contain the fission gases in the fuel. As a result, some fission products will be released into the ruptured coolant system in spite of the emergency core cooling system.

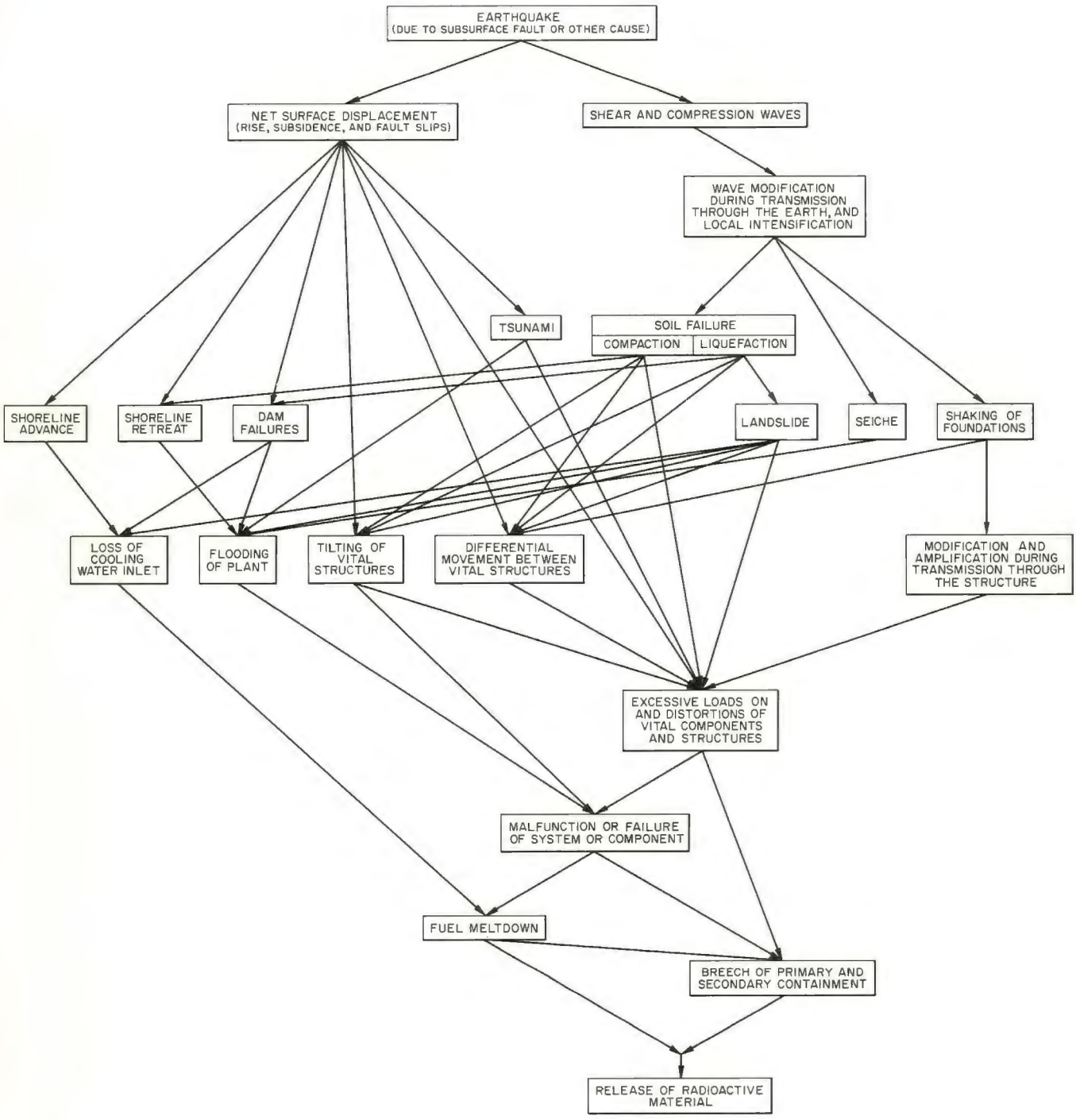
If shutdown is initiated only one and one-half seconds before the primary system rupture, and if the emergency core cooling system comes on in 18 seconds after a pipe rupture as it is designed to do, *none* of the rod cladding will be ruptured. We would thus retain two tandem barriers against fission product release instead of having to rely entirely on the outer containment vessel.

The seismic scrams, like all nuclear controls, must be extremely reliable, not only to protect the reactor but to prevent costly false scrams. Too many false scrams may induce operators to disconnect the offending safety device. For this reason, and perhaps because of an intuitive distrust of automatic equipment, some individuals have suggested a seismic warning system instead of an automatic scram. This would leave the decision to scram up to the operator. It is hard to imagine a condition under which a reactor operator would be less likely to show good judgment than in the middle of a violent earthquake. Since, as we have seen, a few seconds might make the difference in maintaining the integrity of the cladding on the fuel, it seems probable that seismic scrams, rather than warning systems, will be installed in reactors.

It appears that for a considerable time to come, reliance will have to be placed largely on engineering and on conservative siting requirements rather than on better understanding of earthquakes. The latter will come slowly, barring unexpected fortuitous discoveries.

Most important of all, the magnitude and limits of the nuclear-seismic hazards will be recognized and dealt with realistically by nuclear designers and operators, as a whole. Already many individuals of the staffs of reactor manufacturing concerns, engineering firms, and power companies are aware, competent, and eager to face the earthquake problem in a practical fashion. Their managements are beginning to get the message.

It may not be too late.



BACK COVER: The radiator of the Molten Salt Reactor at ORNL glows a spectacular cherry red when in operation. Over 2,000 feet of three-quarter-inch pipes circulate the coolant salt at temperatures above 1000°F.