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Report of the Materials Irradiation Facilities Improvements Committee

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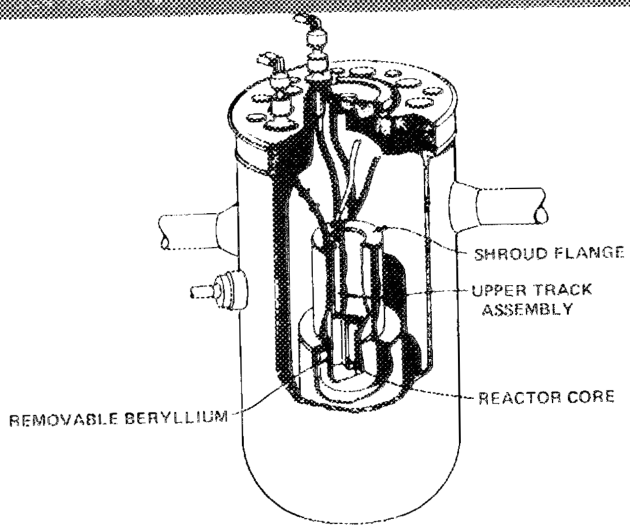

OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A04 Microfiche A01

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Date Published - October 1985

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. DE-AC05-84OR21400

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ABSTRACT

Engineering materials irradiations form a substantial program at Oak Ridge National Laboratory (ORNL), relying mainly on the High-Flux Isotope Reactor (HFIR) and the Oak Ridge Research Reactor (ORR). The HFIR neutron flux is high, but the reactor was not designed for materials irradiations; the lack of instrumented positions in the target region and the small size and limited number of positions in the high-flux region immediately outside the control plates pose particular disadvantages for this kind of research.

Relatively minor modifications to the HFIR, at a cost of less than $2 million, would give it a first-class materials irradiation capability, capable of undertaking most of the experiments now performed at the ORR in one-half to one-third the time.

The lack of comprehensive neutronics calculational capability at ORNL is a major drawback for experimenters and for the reactor operators, making it difficult to assess the feasibility of proposed new experiments or reactor improvements. The Operations Division should acquire the necessary computational capability, making use of new computational techniques and the newly available, more powerful computers as necessary.

As a long-term prospect, when the proposed Center for Neutron Research (CNR) is built and the HFIR is no longer needed for neutron-scattering work and isotope production, the HFIR core could be replaced by a general purpose materials testing reactor core; the result would be the world's finest materials testing facility for less than one-tenth the cost of a new reactor. The value of such a scheme will depend on the national need for materials irradiation testing and isotope production at the time that the CNR is commissioned.

1. BACKGROUND

Testing structural materials that can be used in a high-radiation environment and fuels or breeding materials for a variety of nuclear reactors is a substantial and long-term effort at the Oak Ridge National Laboratory (ORNL) and at other laboratories in the United States and Europe. The name "engineering materials irradiation" is given to such work, distinguishing it from the more basic investigations of irradiation effects carried out by, for example, solid-state physicists and biologists.

Generally speaking, most of the radiation damage to engineering materials is caused by neutrons. Fast neutrons cause damage primarily by striking atoms of the solid, displacing them from their regular positions in the crystalline lattice. Slow neutrons cause damage primarily by transmutations; new atomic species are created, a process that may be accompanied by the emission of an alpha particle or fully ionized helium atom. Upon neutralization, the helium atoms tend to congregate in clusters or bubbles in the lattice with consequent effects on the mechanical properties and dimensional stability of the host material. Likewise, protons from n-p reactions become neutralized to hydrogen atoms, which generally diffuse rather rapidly out of metals with little effect; however, hydrogen formation may be a significant factor in radiation damage to ceramics.

The scale of irradiation effects is generally unappreciated by those not directly involved in this field of study. The atomic displacements are not simply a few atoms knocked out of place: in the material of a fusion reactor vessel, for example, it is expected that each and every atom of the structure will have been struck by fast neutrons and displaced to a new position not just once but 100 times during the life of the reactor.

Most engineering materials irradiation experiments rely on neutrons from nuclear reactors, because isotopic sources are generally too weak to give interesting fluences (typically 10^{26} to 10^{27} neutrons/m^2) in a reasonable time. Accelerator sources may be used, and neutron radiation damage can be simulated in some cases by bombardment with charged particles, but the approach has limitations. General purpose materials reactors, such as the Oak Ridge Research Reactor (ORR), are designed so that experimental samples can be inserted into the core in place of a fuel element or reflector element. Larger samples can be placed close to an outside face of the core, as in the ORR poolside facility. Materials testing reactors are designed so that the fuel loading can be varied considerably to compensate for the effect of neutron-absorbing materials in the experimental specimens or to provide a locally increased (or decreased) flux to suit particular needs. Special purpose reactors such as the High-Flux Isotope Reactor (HFIR) lack such flexibility although they may offer other advantages.

Gamma radiation causes relatively little damage to structural materials, because the interaction is primarily with the electrons of the material, which are Compton-scattered by the incoming gamma photon. The kinetic energy of the scattered electron is soon randomized into thermal energy, heating the solid material. Once again, the scale of this effect is often surprising; in a recent irradiation of some very large steel specimens outside the core of the ORR, gamma photons alone deposited 0.25 MW of heat into the experimental assembly. The gamma flux is even greater in the HFIR, and a single 0.4T [10-mm-thick (0.4-in.)] standard compact tensile specimen in the target region would receive 2.5 kW of heating from gamma radiation. Except in fissile materials, the heat deposited by fast neutrons and from neutron-induced nuclear reactions is generally smaller.

For structural materials, usually steel or graphite, the experimenter's objective is to determine the change in mechanical properties such as tensile strength, toughness, and elastic moduli. Most of these properties must be determined by measurements on the (radioactive) specimens in postirradiation examination (PIE). In addition, dimensional changes are usually measured during PIE or by neutron radiography. Figure 1 presents a dramatic example of the difference in radiation swelling of two different steels. Creep is also affected by neutron irradiation, and some experiments have actually measured creep effects of specimens while they are in the reactor. Mechanical testing specimens

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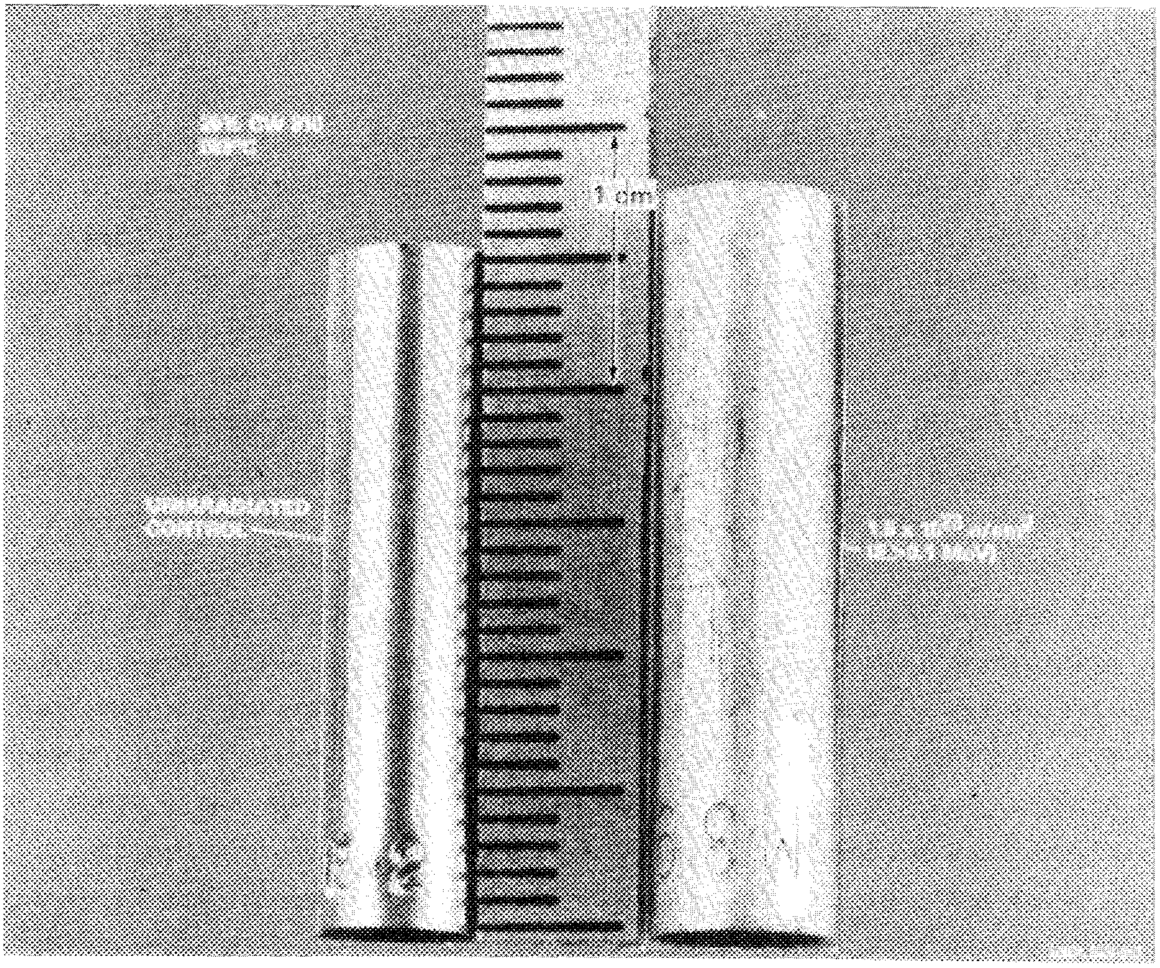

Fig. 1. Specimens of high- and low-swelling steels.

have ranged from the miniature specimens (e.g., the 0.25-mm-thick by 3.0-mm-diam transmission electron microscope samples) that have been developed by the magnetic fusion energy program to the massive 55-kg, 100-mm-thick (120-lb weight, 4-in.-thick) compact tension specimens of pressure-vessel steel tested for the light-water reactor (LWR) safety program.

In fuels testing, the usual objective is to determine the integrity of fuel cladding, the release and transport of fission products, and the mechanical changes in the fuel. Often, an inert sweep gas is passed over the fuel specimens during irradiation; the sweep gas is then analyzed for gaseous fission products. The same technique has been applied to investigations of breeder materials. Such on-line measurements are usually supplemented by PIE.

Fuel specimens have included 0.9-mm-diam TRISO spheres of high-temperature gas reactor (HTGR) fuel, 60-mm-diam pebble bed gas-cooled reactor (GCR) fuel, full-size research reactor fuel elements of low enriched uranium, and advanced fuels for space reactor applications.

In all cases, the experimenters need to know the specimen temperature; in most cases, they want to be able to control it. The simplest experiments are those carried out at the temperature of the reactor coolant on material compatible with the coolant; for example, austenitic stainless steels are irradiated at 70°C by immersion in the cooling water of the ORR. Small specimens irradiated in this way can be assumed to be at the reactor coolant temperature, and no further temperature control or measurement is needed. However, gamma heating can cause substantial temperature gradients within larger specimens; for example, the temperature difference between the center and the water-cooled outer surface of the 0.4T compact tension specimen mentioned earlier would be more than 300°C in the target region of the HFIR. For that reason, only very small specimens can normally be placed in such high gamma fields, a major limitation because the highest fast-neutron fluxes are almost inevitably associated with the highest gamma fluxes. Fortunately, the fusion energy program in particular has devoted much effort, with considerable success, to the development of miniature specimens and associated testing equipment.

For higher temperature irradiations, the specimens are partially insulated from the reactor coolant, usually by a narrow gas-filled gap, so that gamma heating, which may be supplemented by electrical heaters for fine control, raises the specimen temperature. The final temperature is determined largely by the thermal conductance of the gas gap, which depends on the composition of the gas. In the simplest experiments, a fixed-gas composition is sealed into the experimental capsule, but more sophisticated designs permit continuous control of the gas composition by combining streams of different gases (such as helium and argon) and allowing the resulting mixture to flow through the gap.

Where possible, the capsule or specimen temperatures are measured continuously by means of thermocouples; however, this requires access, which is not always available, for instrumentation leads. The HFIR, for example, has no penetrations of the reactor vessel that provide access to the target region during operation. If direct instrumentation is not possible, temperature estimates may be based purely on thermal-hydraulic calculations or measured by passive sensors, such as melt wires or silicon carbide monitors, that are examined during PIE. Neither approach is very satisfactory because the calculations are fraught with uncertainty, and the passive methods generally indicate only the maximum temperature reached or that a certain temperature was not exceeded. The gamma flux and, therefore, specimen temperature actually vary significantly during the reactor fuel cycle so that a knowledge of maximum temperature alone is not sufficient for many purposes.

Because fast and slow neutrons affect material properties in different ways, the neutron spectrum as well as the total fluence must be considered. For testing materials used in or near the core of a fast reactor, a "hard" spectrum with a high ratio of fast-to-slow neutrons is needed. The inner walls of a fusion reactor would also be exposed to a rather hard spectrum. Structural materials and fuels for thermal reactors, on the other hand, are generally exposed to a softer spectrum with a higher proportion of slow neutrons. The obvious way to undertake engineering materials irradiations in a hard spectrum is to conduct the experiment in a fast reactor such as the Fast Flux Test Facility (FFTF) or Experimental Breeder Reactor-II (EBR-II). Indeed, most work of this kind in the United States is done at those reactors. However, it is generally impractical to maintain the experimental specimens at any temperature lower than the reactor coolant, ~400°C for the liquid-metal-cooled fast reactors (LMFR). In most proposed designs for fusion reactors, the most heavily irradiated components are carefully maintained at rather low temperatures. Therefore, LMFR irradiations cannot simulate the anticipated service conditions.

The materials scientists and irradiation engineers have evolved a number of rather clever tricks for simulating in mixed-spectrum reactors, such as ORR or HFIR, the radiation effects expected in the harder spectrum of a fusion device. The simplest concept is "spectral tailoring," in which thermal-neutron absorbers are incorporated in or around the experimental capsule containing the test specimens. The absorber depresses the local slow-neutron flux more than the fast flux, thereby hardening the spectrum experienced by the specimens without substantially reducing the damage rate from fast neutrons. Materials testing reactors are well-suited to this type of work because the fuel loading flexibility makes it possible to accommodate and promote local variations in the flux and spectrum.

A second, very elegant, technique is called "isotopic tailoring." The fast-neutron damage, caused simply by transfer of kinetic energy in near-elastic scattering, is almost independent of the isotopic composition of the elements in the specimen. The slow-neutron damage is caused by nuclear reactions following inelastic scattering, the cross section for which is usually very different from one isotope to another of the same element. By suitably enriching the proportion of those isotopes with a low thermal-neutron cross section, the probability of thermal-neutron absorption is reduced, thus simulating the effect of a harder spectrum with no reduction in the fast-neutron-induced damage.

Using these and other techniques, it is possible to reproduce, simultaneously, several features of the fusion reactor environment. The isotopic tailoring approach may be applied in either LMFRs or mixed-spectrum reactors; however, the mixed spectrum reactors have the outstanding advantage over LMFRs of being able to cover the entire temperature range of interest to fusion.

Materials irradiation work is an important, in fact essential, part of all reactor technology programs including GCRs, LMFRs, and water-cooled power reactors; research reactors; fusion devices; and the proposed space reactor projects. Over the years, there have been major shifts every few years in the relative priorities of these different programs and in the balance between their needs (e.g., between structural materials and fuel testing). The nature of the work precludes rapid re-establishment of the necessary engineering and safety expertise after any major downturn. For a laboratory to maintain a strong presence over a long period, the facilities and capabilities must be available to provide the necessary help to any of the programs currently in need of materials irradiation work. Table 1 lists the present and presently foreseen needs in the major program areas. Table 2 summarizes the variables — such as flux, spectrum, temperature, and specimen types — that may be encountered in irradiation experiments.

Table 1. Present and projected needs of major programs

Reactor type	Need
Fusion	Miniature steel specimens Copper specimens Ceramic specimens Breeder blanket material tests
Gas-cooled reactor	Small fuel-sphere testing Fission-product release measurements Pebble-bed fuel testing (large spheres) Pebble-bed fuel testing (small spheres)
Water-cooled reactor	Small steel specimen irradiations (e.g., 0.4T compact tension) Very large specimen irradiations (4T compact tension)
Liquid-metal-cooled fast power reactor	Fuel and structural materials Out-of-core component tests
Space reactor (SP100 and SDI)	Fuel and structural materials Ceramics

Table 2. Characteristics of first-rate facilities for the major program areas

Characteristic	Fusion	Reactors		
		Water-cooled	Gas-cooled	Liquid-metal fast breeder[a]
High fast flux	Yes	Yes[b]	Yes	
Spectral tailoring	Yes	No	No	
Instrumentation	Yes	Yes	Yes	
Large-diameter specimen region[c]	No	Yes	Yes	
Large-diameter facility[d]	Yes	Yes	Yes	
Low-gamma heating[e]/ large specimens	No	Yes	No	

[a]Including space reactor. Tests for these programs are usually more appropriate to FFTF or EBR-II than to the ORNL reactors except for low-dosage, out-of-core component tests.

[b]For small specimens.

[c]25 mm in diameter.

[d]25 mm in diameter, including spectral tailoring shields.

[e]0.2 W/g (with shielding) for 2T specimens.

2. MATERIALS IRRADIATION TESTING AT OAK RIDGE NATIONAL LABORATORY

ORNL presently operates six reactors (Table 3) for various purposes, but most of the materials irradiation work is now carried out at the ORR and HFIR. Other reactors have been used on occasion for special purpose testing of materials [e.g., the Health Physics Research Reactor (HPRR) has a nearly naked core and so generates an almost unmoderated fission-like spectrum].

Table 3. Reactors operated by ORNL

Reactor	Power
HFIR	100 MW
ORR	30 MW
BSR[a]	2 MW
TSR-2[b]	1 MW
HPRR	10 kW[c]
PCA[d]	10 kW

[a]Bulk-shielding reactor.

[b]Tower-shielding facility reactor.

[c]Steady state; peak power of 50,000 MW available in a 60-s pulse.

[d]Pool critical assembly.

2.1 Oak Ridge Research Reactor

Other things being equal, the number of fissions and, therefore, the number of neutrons released are proportional to the reactor power. The ORR, a light-water-cooled and moderated 30-MW reactor, constituted a very powerful test reactor when it was new, but it is now exceeded by a number of facilities worldwide (see Sect. 3). The ORR has core positions into which experiments up to 74 mm in diameter can be inserted and also has a "poolside facility" that consists of a flat aluminum window in the reactor vessel close to one face of the core, which can accommodate experimental capsules of up to 600 by 600 mm. Figures 2 and 3 show the general layout of the ORR. Notice that access to the core positions is through sealed flanges in the vessel hatch. Most of the access ports are not placed directly above the core so that instrumentation leads and gas lines must be bent into an "S" shape inside the vessel. All such connections must be rigidly contained for protection from the high-speed cooling water flow, and each experimental capsule therefore fits only one combination of access flange and core position. Consequently, it is impossible during the course of an experiment to rotate a capsule or transfer it from one core position to another, which would be desirable for exposure to different spectrum, flux, or gamma heat conditions. Furthermore, the S-bend shape produces large bending moments from the coolant flow pressure-drop across the core, which adds to the difficulties of adjusting the vertical position of the experiment relative to the core; such an adjustment would make it possible to follow the neutron flux peak, which moves as the control rods are moved during the cycle.

2.2 High-Flux Isotope Reactor

The HFIR (Fig. 4) is a high-pressure, light-water-cooled, beryllium-reflected, 100-MW reactor that was designed for the production of isotopes, particularly transuranium isotopes, which respectively require high thermal- and epithermal-neutron fluxes; indeed, the HFIR target region inside the annular fuel assembly has the highest steady state thermal-neutron flux in the world. The high thermal flux also makes the reactor a good source of neutrons for scattering experiments, and there are a number of beam tubes for that purpose (Fig. 5). The fuel is constructed as two annular sets of involute plates; each set is made as a unit, and there is no flexibility for mixing heavy and light uranium loadings, which can be done in the ORR and other general purpose testing reactors.

Small (16-mm-diam) capsules can be accommodated in the target or central region inside the inner fuel element, but there are no pressure

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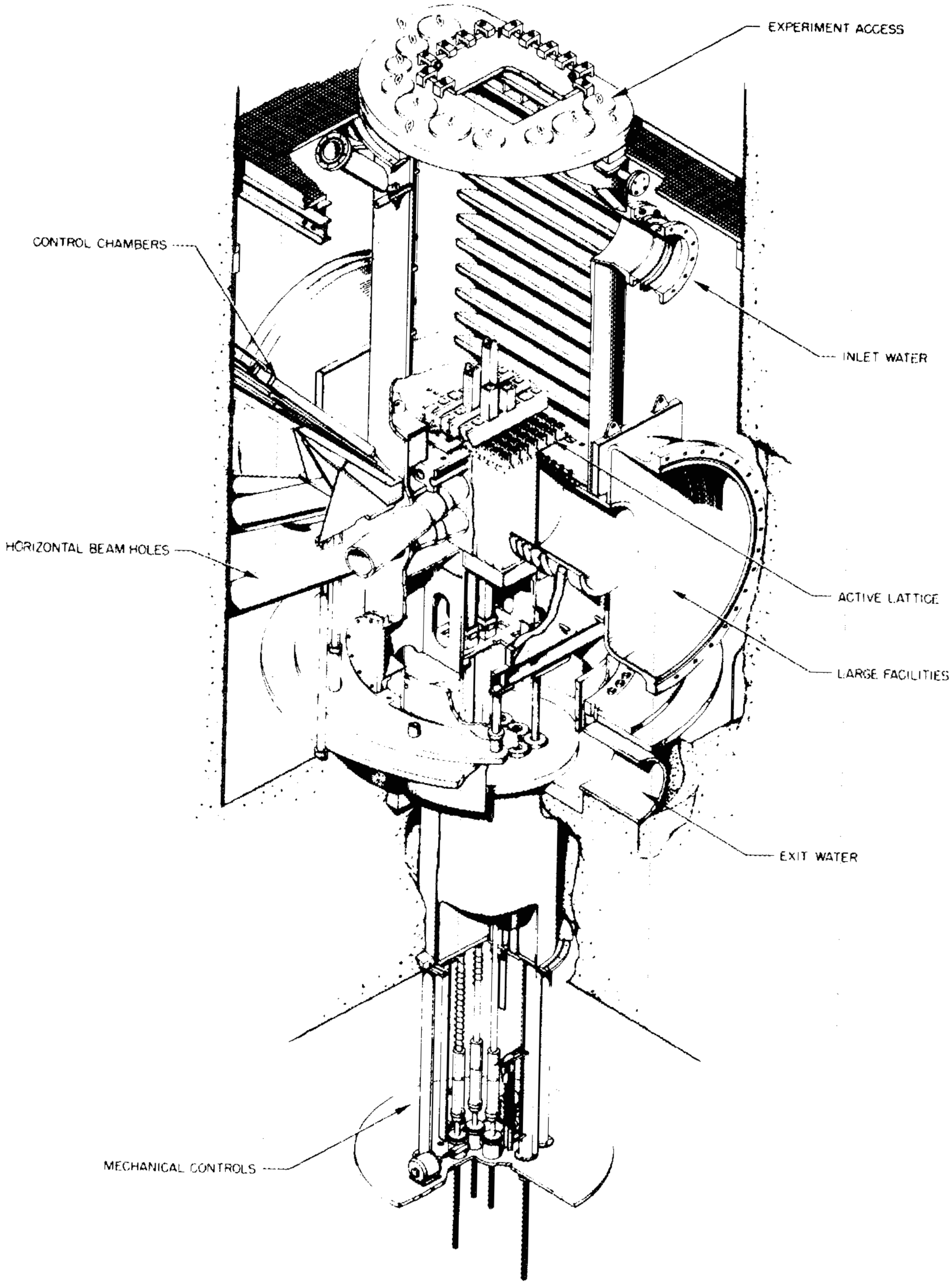

Fig. 2. ORR, showing access hatch.

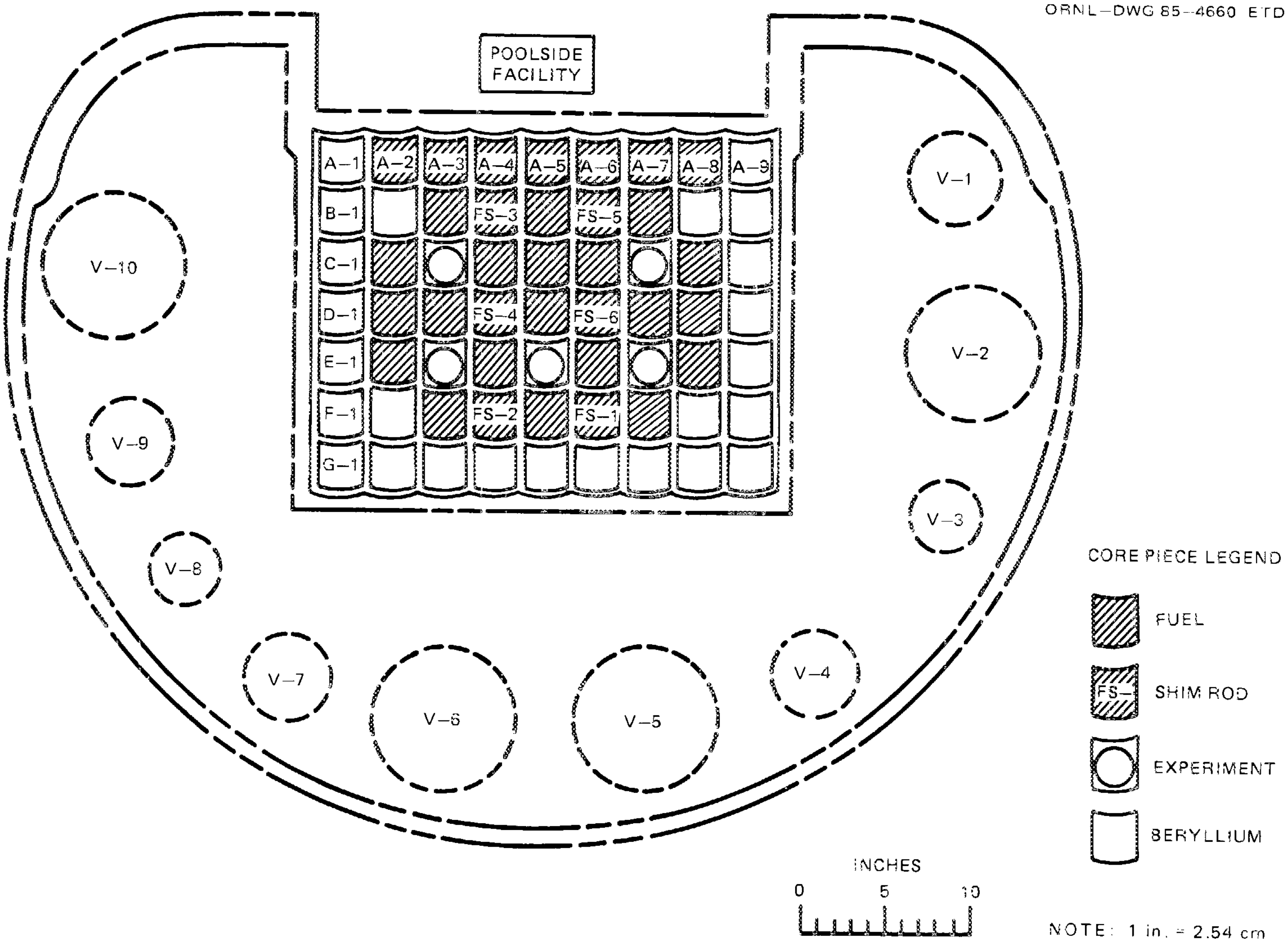

Fig. 3. Plan view of ORR.

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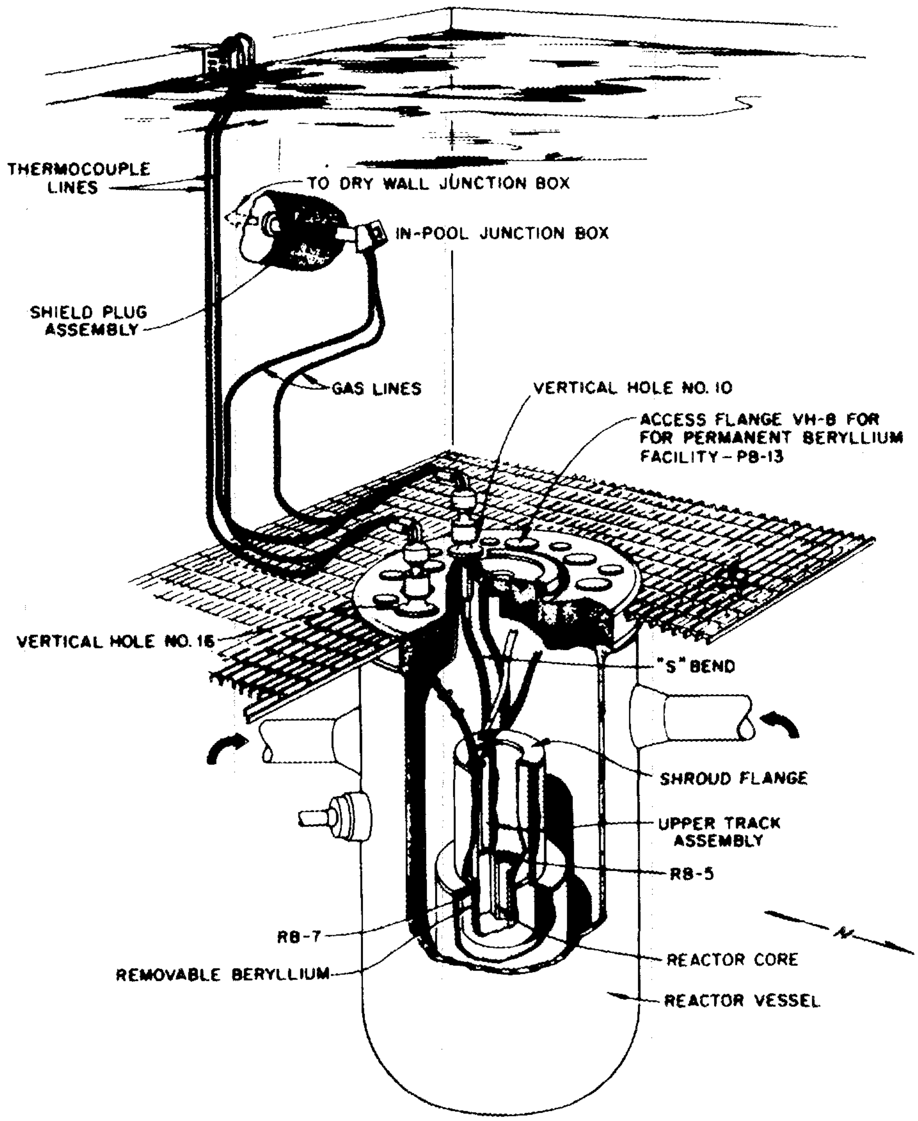

Fig. 4. HFIR, showing access hatch.

vessel penetrations providing access to that region so that experiments in the target cannot be instrumented. The total lack of instrumentation is unfortunate, because the very high fast- and thermal-neutron flux in the target region make it an extremely desirable facility for engineering materials irradiation. The very high gamma flux and, therefore, high heating rate limit the size and mass of specimens that can usefully be irradiated using present capsule designs.

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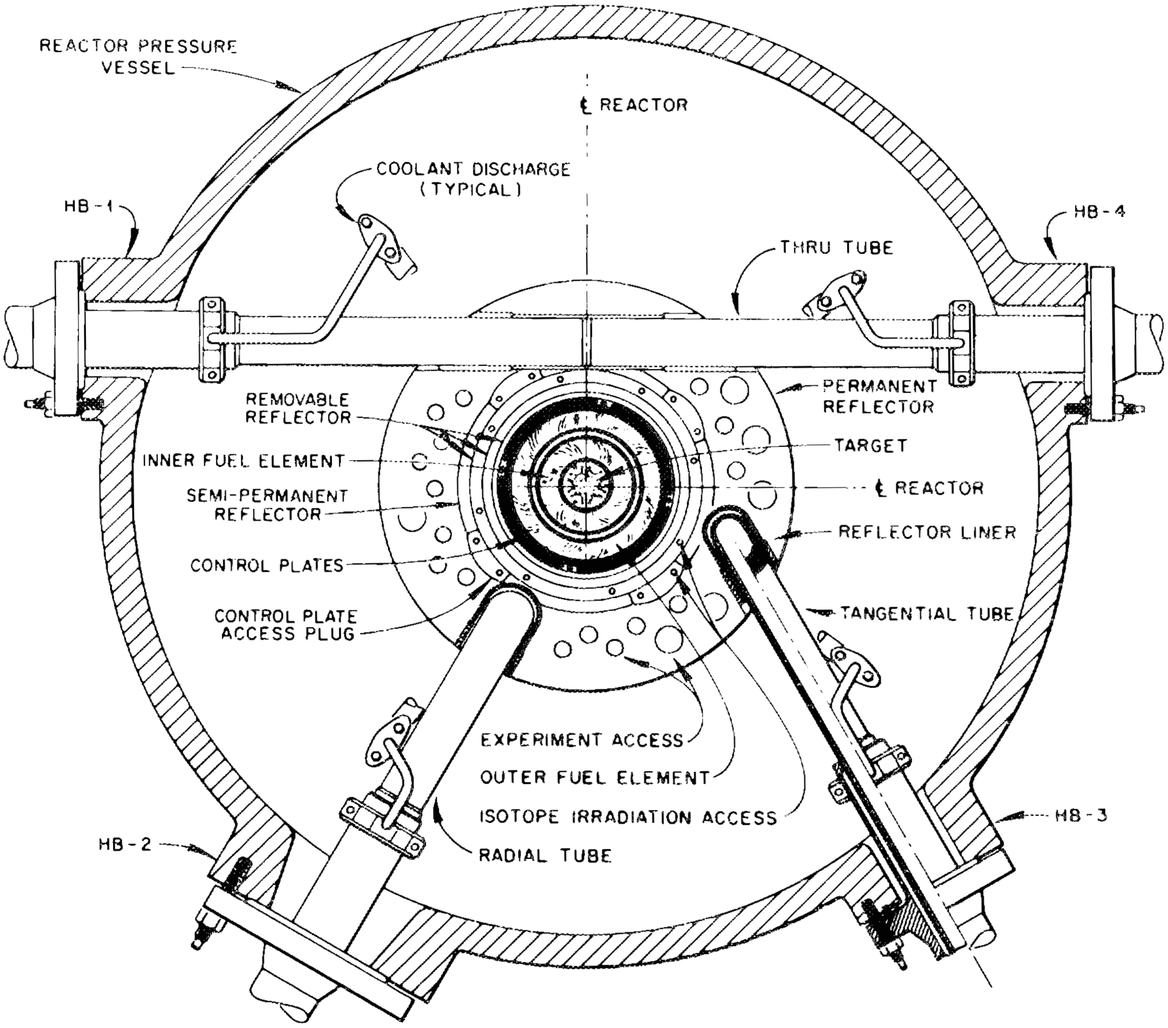

Fig. 5. Plan view of HFIR, showing beam tubes, target region, and reflector.

Larger (37-mm-diam) experiments can be irradiated in four positions in the removable beryllium (RB) surrounding the control plates outside the outer fuel element (Fig. 5). The neutron flux, although not as high as in the target region, is 2 to 3 times higher than that obtainable in the ORR, but so is the gamma heating. There is access for instrumentation, although S-bend lead tubes must be employed as in the ORR.

There are several other, less desirable positions for materials irradiation in the HFIR, but the majority of experiments are conducted in either the target region or the RB facilities.

2.3 Other Oak Ridge National Laboratory Reactors

Besides the HFIR and the ORR, ORNL operates four other reactors dedicated to research and development work as well as radioisotope production. These reactors are used by ORNL and qualified non-ORNL research and development groups. Much of the information describing these reactors is drawn from the *Oak Ridge National Laboratory Research Reactor Experimenters' Guide* by C. D. Cagle.[1]

2.3.1 Bulk-shielding reactor

The BSR is a 2-MW, open-pool-type, light-water-moderated and -cooled reactor that has ready access for the irradiation of large targets adjacent to any one of three of its sides. Originally, the BSR was used to measure radiation leakage through a variety of materials and configurations for reactor-shielding development studies. It has since been used for in-core and peripheral irradiations, including large specimens of pressure vessel steels and structural materials located adjacent to the reactor faces. The main role of the BSR at present is as the National Low-Temperature Neutron Irradiation Facility (NLTNIF), which consists of a cryogenically cooled irradiation capsule for basic physics experiments.

2.3.2 Pool critical assembly

The PCA is a light-water-moderated and -cooled pool-type reactor used for training, studying core configurations for the ORR, and pursuing various research projects in shielding, new instrumentation, and reactor physics. Located in the corner of the BSR pool, the PCA is administratively limited to a maximum power of 10 kW and is designed to duplicate the nuclear characteristics of the BSR and provide properties similar to the ORR when the latter is operated under conditions of low power and natural-convection water cooling.

In addition to the lack of complexity of this reactor system, one of the unique features of the PCA is the versatility of the core's design, which permits acceptance of either the BSR or ORR fuel elements. This is accomplished by means of "stacked" grid plates; the BSR-type grid plate, which has round holes to accommodate the BSR end boxes, may be aligned on top of the ORR-type grid plate, which has square holes to accommodate the ORR end boxes.

2.3.3 Tower-shielding facility reactor

The tower-shielding facility is a unique facility for shielding research and shield design confirmation. It centers on the TSR-2, a small, spherical, water-cooled reactor that can be operated in a stationary shield at ground level or can be supported between two towers at levels up to 60 m above the ground. Portable shields made of iron, water, and lead, may be designed to fit the reactor vessel snugly to modify the reactor neutron and gamma ray spectra. Both the reactor and shield can be lifted as long as the total weight does not exceed 55 tons.

2.3.4 Health physics research reactor

The HPRR is a small, unmoderated fast reactor that can be operated in the steady state or pulse mode. This device is the primary research tool at ORNL's Dosimetry Applications Research Facility.

The reactor core is a right circular cylinder (20-cm diam and 23 cm high) containing enriched ^{235}U fuel alloyed with molybdenum. During steady state operation, power levels between 0.1 and 10^4 W can be maintained for several hours. The maximum allowed nominal yield during pulse operation is 10^{17} fissions, which corresponds to a peak power of ~50,000 MW and a pulse half-width of 60 μs. Neutron dose rates can be varied over 15 orders of magnitude (10^{-6} to 10^9 rads/h) depending on the location of the experiment relative to the core, the type of operation, and reactor power levels.

2.4 Support Facilities

Reactors alone are not enough to support a viable, much less a high-quality, materials irradiation program. There must be hot cells for postirradiation examinations and for loading radioactive specimens into test capsules. Dosimetry measurements must be taken to characterize the flux and spectrum to which specimens have been exposed and to predict the exposure of planned experiments. Similarly, there should be a computational capability that can predict or assess in detail the neutronics of the reactor and experiments; surprisingly, after almost 30 years of research reactor operation, no such capability is routinely available at ORNL even for the ORR.

2.4.1 Hot cells

The ORNL hot cells used for materials PIE are decrepit, outdated, and unreliable. Management recognition of the inadequacy of those facilities led to the formation of a committee, chaired by M. Feldman, which recently produced a plan[2] (M. J. Feldman et al., *Report of the ORNL Ad Hoc Hot Cells Improvement Advisory Committee, July 29, 1983*) designed to remedy the situation. The plan called for refurbishment of the more important hot cells and presented a detailed set of recommendations for doing so. Although the plan was accepted in principle by ORNL management, the necessary funding has not yet been made available. The Materials Irradiation Facility Improvements Committee endorses the plan and wishes to emphasize that the state of the hot cells poses a significant problem for materials irradiation experimenters. Further details will be found in the Feldman committee report.

2.4.2 Dosimetry

At present, there is no centralized method for having neutron dosimetry work performed at ORNL. In the recent past, it has been the responsibility of the individual experimenters and/or programs to seek out their own sources of expertise and then solicit and provide funding for services required.

The fusion program has designated a national "dosimetry coordinator" for all fusion program irradiation experiments except those carried out at Hanford Engineering Development Laboratory (HEDL). Larry Greenwood at Argonne National Laboratory (ANL) presently serves the fusion program in this capacity, providing all of the dosimeter sets for fusion program experiments conducted in ORNL reactors. Following completion of each experiment, the dosimeter sets are shipped to ANL for analysis and reporting of the data.

A problem associated with performing dosimetry at ORNL is that, as presently organized, several different parts of the Laboratory (Operations

Division, Analytical Chemistry Division, etc.) must usually be separately coordinated. Not only is this time-consuming, but it sometimes leads to quality control problems. There have been cases of samples or data being lost in "the system."

The Materials Irradiation Facilities Improvement Committee suggests that the Operations Division consider designating a "dosimetry coordinator" to whom any experimenter could go to secure dosimetry, either for characterization of facilities or for long-term use to determine fluence levels in actual experiments. This coordinator could be provided with the tools (counting facilities, computer codes, characterized materials, etc.) necessary to provide dosimetry service consistent with internationally accepted standards. The service would not only meet the needs of experimenters, but would allow the Operations Division to characterize all ORNL reactors more fully and to determine quickly the effects of core changes.

2.4.3 Neutronics calculations

As is the case with dosimetry, there is no centralized method of having neutronics calculations performed at ORNL. The technical capability exists primarily in the Engineering Physics Division, but personnel in other ORNL divisions (Engineering Technology Division and Operations Division) also have the expertise and knowledge to work with some or all of the neutronics analysis codes available.

Several sophisticated computer codes developed by ORNL and/or Computing and Telecommunications Division personnel are available to perform the complex calculations. The AMPX-II code is a collection of modules or programs used to prepare the libraries of cross sections necessary as input to the large analysis codes. Each of the modules used to make up AMPX-II can be run independently to obtain a wide variety of information. As an example, the XSDRN-PM module, which is a one-dimensional transport-theory code, can be used to estimate gamma-heating rates in various materials.

The two primary, large analysis codes (which make use of the data generated by AMPX-II) are (1) VENTURE — a multiregion, multienergy group, one-, two-, or three-dimensional, diffusion-theory code and (2) DOT-III — a two-dimensional discrete ordinates transport-theory code.

For all of the codes, models must be developed for the specific reactor in which an irradiation experiment might be performed. Models have been prepared for both the ORR and the HFIR, but these were developed and are supported by several different people in either the Engineering Physics or Operations Divisions. Additional models have been proposed for the CNR reactor concept, which at present looks very similar to the HFIR.

At the HFR facility at Petten in Holland, a small support group in the Reactor Department performs routine neutronics analysis for any experiment proposed for installation in the reactor. The same group also provides routine information, such as expected fluxes and gamma-heating rates in all of the experimental positions of the HFR, to experimenters. Thus, potential experimenters can readily determine which experiment position would best suit their needs without expensive dosimetry and prototype experiments. Another result of this type of organization is that all of the neutronics analysis expertise and people knowledgeable in the core behavior are concentrated in one group. Should a more difficult analysis problem arise that requires a more sophisticated solution, a second, small group of people are available in the Physics Department to aid the support group.

The Committee recommends that the Operations Division acquire the necessary neutronics calculational capability, which should then be readily accessible to both experimenters and reactor operators. This capability should make use of the latest computational techniques available as well as the newest and most powerful computers, such as the recently installed Cray. It should be concentrated in a small group and be familiar with and able to serve the needs of all of the operating reactors at ORNL.

2.4.4 Capsule assembly

In the past, most of the components for irradiation capsules have been fabricated at outside machine shops, but assembled at ORNL; the assembly step is generally the more time consuming and costly of the two.

There is a capsule assembly area in the Engineering Technology Division facilities at Y-12 and another in the division's laboratory at X-10. In both cases, Martin Marietta Energy Systems, Inc., craftworkers are heavily involved, either from the Y-12 Maintenance Division or from ORNL Plant and Equipment Division. The assembly area in Building 9201-3 at Y-12 has a room where plutonium and other fuel specimens can be assembled and loaded into the capsules.

Recently, a comparison has been made of the construction (i.e., parts fabrication and assembly) of identical capsules in the 9201-3 assembly area and at an outside subcontractor. The capsules at the outside shop were assembled under the supervision, and with the help, of an ORNL technician. ORNL Quality Assurance staff monitored the process, at the contractor's premises, to ensure conformance. Both sets of capsules were satisfactory, meeting the necessarily stringent quality requirements for this kind of work. It is likely that in the future, in-house craft support will be sought for capsule assembly in special cases, for example, for fuel-bearing or radioactive specimens or for experimental designs where the design may need to be changed during construction and cannot be specified closely enough in advance for subcontract bidding to be practically feasible. For more routine capsules, the option of outside manufacture will be considered and evaluated.

2.5 Experimental Techniques

A wide variety of experimental techniques are presently employed at ORNL to satisfy the irradiation conditions specified by the materials scientist customers for particular projects. By far the most important single parameter considered during the design of irradiation experiments is the temperature of test specimens during irradiation. Consequently, a significant effort goes into the techniques used to control test-specimen temperatures.

The most primitive form of temperature control, more accurately described as temperature setting, utilizes as the thermal resistance element a fixed-gas composition in a gas gap. This technique requires a reasonably detailed heat transfer analysis to fix both the gap size and the gas composition, because it is impossible to change the gas composition during irradiation. Obviously, this is the technique that must be employed in uninstrumented experiments such as those presently conducted in the target region of the HFIR. A significant drawback of this technique is that it does not allow control of temperature while the gamma-heating rate is changing because of movement of the reactor control rods. It can also be a very poor method of achieving desired temperatures if one of the materials making up the gap suffers from severe dimensional changes during irradiation.

A much better method of achieving and controlling temperatures with gas gaps is the use of a variable-gas composition; this can be done only if gas lines can be run from instrumentation facilities to the capsule. The same range of temperature available to the designer with the fixed-gas technique is available with the variable-gas technique, with the added feature of being able to change the composition and, therefore, the thermal conductivity of the gas gap during operation. Typically, helium is used with either neon or argon added to provide a wide range of lower thermal conductivities. The size of the gas gap is determined through a heat transfer analysis based on the midrange of thermal conductivities available from the mixed gases. Gas gaps as small as 0.05 mm and as large as 3.00 mm have been used with this technique. If the gas gap is large because high temperatures are sought, the controllability is reduced because heat transfer by radiation becomes a higher percentage of the heat transferred across the gap. This limitation can be minimized by the addition of radiation barriers or the use of carbon- or ceramic-fiber gap filler materials. If small gas gaps are required because of either high heat fluxes or low temperatures, the range of controllability is reduced because the amount of temperature drop across the gap becomes a smaller percentage of the drop through the fixed-conductance materials of the capsule.

Another temperature-control technique used quite successfully in a variety of experiment designs involves the use of electric heaters. These are typically small-diameter (1.5-mm) stainless-steel-sheathed, mineral-insulated, single conductor heaters. In most designs the heaters are used in conjunction with a gas gap. The heaters are located strategically to reduce the spatial temperature variations caused by nonuniform heat generation or end-effect heat losses. A very good feature of electric heaters is the ease with which they can be controlled by a computer, providing continuous and very accurate temperature control. A limiting condition for the use of heaters exists in high-temperature capsules. High temperatures, especially in the heating element, can lead to early failures. Low-temperature operation, on the other hand, can result in a very high degree of reliability. One recent program, where electric heaters operated at about 300°C, experienced only two failures in 324 heaters. Like the variable-gas composition temperature control method, the use of heaters requires instrumentation access to the capsule during operation.

Two possible new temperature control techniques presently under investigation are the use of heat pipes and the design of capsules relying on the temperature gradients in solid materials. An analysis and proposed design of a HFIR target capsule utilizing an annular heat pipe was completed by M. V. Davis of Georgia Tech while on assignment at ORNL as a summer faculty research assistant. This design uses water as the working fluid and should be capable of removing 4 kW of heat, while maintaining specimen temperatures at about 250°C. The heat pipe design provides a rather uniform axial temperature profile even though the gamma-heating rate gradients are quite steep.

The use of temperature gradients in solid materials is presently being investigated in the design of an experiment that will irradiate small copper specimens at 100, 250, and 400°C in the HFIR RB positions. By placing the specimens strategically in a material with relatively low thermal conductivity and a high gamma heat generation rate, such as stainless steel, all temperature requirements should be met in one solid capsule.

While all the techniques can be used to control specimen surface temperatures, quite often gamma heating rates are so high that unacceptable temperature gradients can result within the specimen itself. Two solutions to this problem are shielding from gamma rays and miniaturization of the test specimens. The former technique has been used successfully in the ORR poolside facility where 100-mm-thick steel specimens are being irradiated behind a shield of stainless steel that is almost 100 mm (4 in.) thick. By using the shield, the gamma-heating rate was reduced by about 80% with no significant reduction in the damage flux. The resultant temperature variation across the specimen of ±10°C is quite acceptable and much lower than the ±50°C gradient that would exist without the shield. In the HFIR target region where space is limited, the materials scientists have developed miniature specimens in which gamma heating rates as high as 55 W/g can be accommodated without experiencing unacceptable gradients.

Specimen temperatures are usually measured with thermocouples. At low temperatures (up to 1100°C), Chromel/Alumel thermocouples have proven to be highly reliable. Between 1100 and 1400°C tungsten-rhenium alloy thermocouples have met with some success, but transmutation effects cause significant decalibration, especially for long-duration experiments. A potentially better platinum-molybdenum alloy thermocouple has been tried in the 1100 to 1400°C range, but further development is needed on this combination. Other, more exotic measurement devices such as the Johnson Noise thermometers and ultrasonic thermometers have met with only partial success. In uninstrumented experiments it is necessary to use passive sensors such as silicon carbide, melt wires, and thermal-expansion devices; a major drawback of these devices is that they can only provide information about the maximum temperature during irradiation and do not give a history of real-time temperatures.

The creep rates of Zircaloy fuel cladding were successfully measured with eddy-current displacement measuring devices in one series of irradiation experiments in which the tubing was subjected to a continuous external pressure loading of up to 18.6 MPa (2700 psig). The resolution of the measuring devices was determined to be better than 10 μm during the entire irradiation period.

The determination of release-to-birth rate ratios (R/B) of candidate HTGR fuels is routinely accomplished by taking samples of the sweep gas, which is passed over the fuel particles. These samples are then analyzed on a gamma-ray spectrometer for various fission products.

2.6 Dollar Values and Programs

The various engineering materials irradiation programs form a substantial activity at ORNL, as shown by Table 4. Research costs include the work of the experimenters in preparing their specimens, testing them, and analyzing the results, as well as the design, construction, and operation of the irradiation capsule. In 1984, these costs amounted to some $5.5 million. Reactor charges came to over $3 million, and the charges for use of the hot cells were almost $1 million. The total expenditure in 1984 of almost $10 million represents perhaps one-fifth of all the materials research and development at ORNL.

Table 4. Approximate FY 1984 costs
(dollars in thousands)

Program	Research costs	Reactor charges	Hot cell costs	Total
MFE	2900	2050	300	5250
HSST	1720	270	150	2140
GCR	560		140	700
RERTR	270	830	210	1310
Other	80		800	80
Total	$5530	$3150	$800	$9480

The balance of the work between different programs varies markedly from year to year, as revealed by Fig. 6. Plotted in Fig. 6 are the costs of designing and fabricating irradiation capsules for the various programs involved in these studies — which is a better measure of the level of activity than the total costs would be because it takes a snapshot of all work at the same stage. The total costs for each program include reactor or hot cell costs associated with experiments that were

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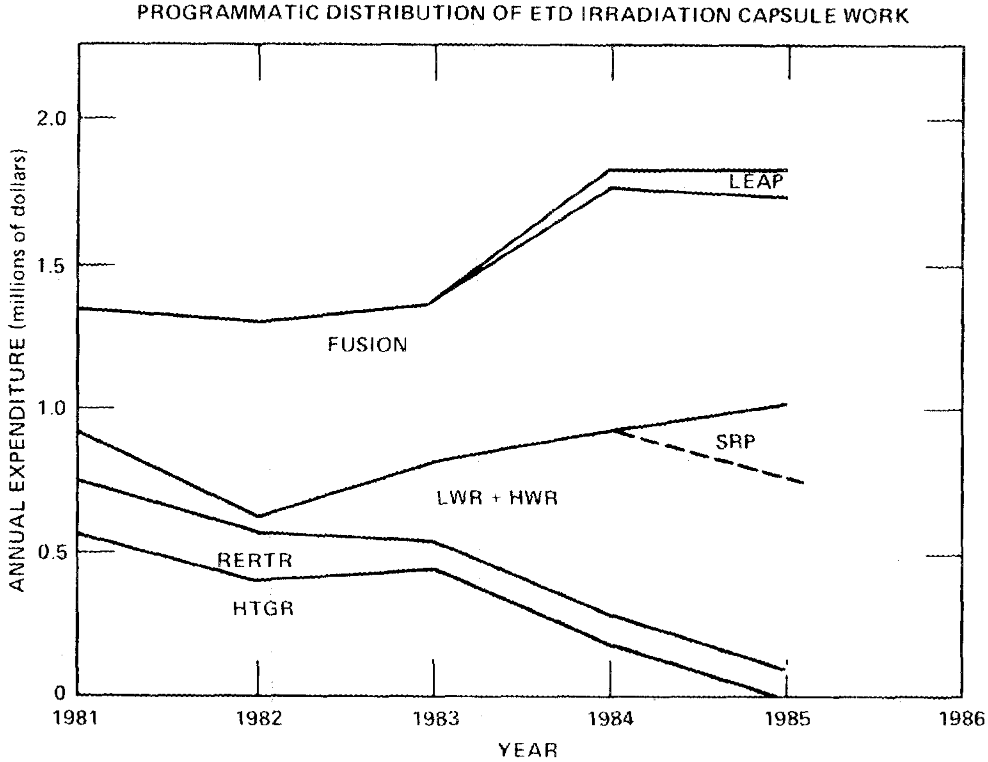

Fig. 6. History of ETD irradiation work from 1981 to 1985.

committed years before, as well as efforts toward planning experiments that may be some years away from operation.

Overall, the amount of work has been relatively constant over the last 5 years, but there have been substantial changes in the nature of the experiments and in the sponsorship. Without the flexibility to meet the needs of different programs — a flexibility that requires a range of facilities as well as a design capability — there would be very large variations in the level of activity, variations that would probably make it impossible to maintain the essential Quality and Safety Assurance for this rather specialized field.

3. COMPARISON WITH OTHER U.S. AND OVERSEAS FACILITIES

Table 5 compares the ORNL reactors used for engineering materials irradiations with other reactors around the world [Belgian Reactor 2 (BR-2) is in Belgium and the High-Flux Reactor (HFR) is in the Netherlands]. The ORR is generally inferior in all significant respects, whereas the HFIR, while lacking in certain aspects, offers outstanding neutronic characteristics.

Table 5. Characteristics of some leading materials high-flux testing facilities and the HFIR

Characteristics	FFTF[a]	General purpose reactors			HFIR	
		BR-2	HFR	ORR	RB	Target
Fast flux,[b] 10^{14} neutrons/cm^2/s	40	7	5	3	7	14
Displacements per atom per year, S.S.	40	10	8	4	10	30
Thermal flux, 10^{14} neutrons/cm^2/s	<1	10	2	2	15	28
Gamma heating, W/g S.S.	3	15	10	8	17	55
Typical capsule diameter, mm	28	52[c]	74	74	35	16
Number of positions	60	35[d]	17	12	4[e]	14[f]
Instrumentation	Yes	Yes	Yes	Yes	Yes	No
Neutron radiography	No[g]	Yes	Yes	No	No	No

[a]MOTA — Materials Open Test Assembly facility.

[b]>0.1 MeV.

[c]There are also two cadmium-shielded positions of 200-mm diam.

[d]Plus two 200-mm-diam positions, cadmium shielded for low thermal flux.

[e]Plus four smaller positions, ~12-mm diam.

[f]Including six peripheral target positions.

[g]Available at another reactor on the same site.

For materials irradiation work, the most important single characteristic is the damage rate, which is usually expressed in terms of displacements per atom per year. The damage rate depends on the fast flux, the spectrum, and the material being irradiated. In addition, the diameter of the irradiation capsule that can be accommodated and the gamma heating rate both tend to place an upper limit on the size of the specimens that can be irradiated. As explained earlier, temperature-measuring instrumentation is important and, in some cases, essential. Neutron radiography, by providing a direct view of the interior of the capsule with a high resolution between even low-density materials, facilitates certain experiments.

The FFTF is an excellent facility in many of these respects, but it is a liquid-metal-cooled reactor. Because the minimum temperature at which capsules can be operated is ~400°C, many experiments of interest to the magnetic fusion energy program are excluded. In principle experiments could be refrigerated, but in practice this has not been considered feasible or economical.

In considering the future of materials irradiation work at ORNL, it is crucial to understand the importance of maintaining and improving the experimental facilities. To illustrate this, Table 6 compares the ORR, as it was 20 years ago and still is today, with the European Economic Community's (EEC) HFR reactor at Petten in Holland. Based on the ORR design, the Petten reactor is almost a sister to the ORR. When commissioned in 1966, the HFR was in most respects somewhat inferior to the ORR, which at the time was one of the world's leading facilities. Since that time, the Europeans have committed themselves to, and pursued, an explicit policy of upgrading and improving the HFR and its associated support facilities. The United States has made no such improvements to the ORR, which has, in fact, declined in certain respects. The result, not only predictable but predicted, is that the Petten reactor is now greatly superior in every significant respect to the ORR.

The present difference between the two reactors results from the formal objective of the Petten facility "to develop new methods and equipment for future tasks" and the provision of funds for meeting that

Table 6. Comparison of the ORR with the corresponding facility in Europe

Characteristic	1984 ORR	HFR Petten	
		1966	1984
Reactor power, MW	30	20	45
Burnable poison	No	No	Yes
Fuel cycle, d	20	14	26
Time operating, %	83		75[a]
Instrumented core positions	12	12	17[b]
Neutron radiograph facilities	None[c]	None	2
Vertical access to core positions	No	No	Yes

[a]1983 figure, reactor shutdown in 1984 for vessel replacement.

[b]Increasing to 27 in 1985.

[c]There actually *was* a neutron radiograph camera at the ORR, but it was removed several years ago to make room for an experiment at the window and never replaced.

objective. The Petten Laboratory spends ~$0.8 million/year on new experimental equipment and ~$1.2 million/year on reactor modifications and development. Since the HFR began to operate, more than $50 million (1985 dollars) has been spent on improvements and upgrades. The figure may be taken as a rough measure of the sum that would be necessary to take the ORR not to superiority, but at least to rough equality with competing facilities.

The following lists some upgrading and developments at the Petten reactor that took place during 1966–1984: (1) power increases from 20 to 30 MW and from 30 to 45 MW; (2) introduction of burnable poison fuel; (3) several major changes to the core; (4) complete replacement of instrumentation, both for the reactor and for experiments; (5) new in-tank experiment penetrations; (6) several improvements to major plant systems; (7) in-house computer code developments; (8) new reactor and experiment data loggers; (9) new dismantling cell-transfer system; (10) second neutron radiography facility; (11) enlarged computing facilities; (12) replacement of reactor vessel; and (13) preparation for possible upgrade to 60 MW.

Table 7 shows, as a single measure of the effort devoted elsewhere to facility improvements, the power upgrades of European research reactors. Out of the 14 European reactors, 12 have been substantially upgraded; almost half have been upgraded twice or more since the ORR began operation at 30 MW. (The ORR first operated in 1958 at a power of 20 MW. Three years later, larger cooling towers were fitted, and the power was raised to 30 MW.)

Table 7. Some thermal test reactors (>5 MW) in Europe

Reactor	Country	Power upgrades (MW)	First operated
BR-2	Belgium	50 to 125	1961
DIDO	Great Britain	10 to 15 to 22 to 25	1956
PLUTO	Great Britain	10 to 15 to 22 to 25	1957
DR3	Denmark		1960
MELUSINE	France	? to 8	1958
TRITON	France	1.2 to 6.5	1959[a]
SILOE	France	15 to 30 to 35	1963
OSIRIS	France	50 to 70	1966
FR-2	Germany	12 to 44	1961[b]
FRJ-1	Germany	5 to 10	1962
FRJ-2	Germany	10 to 15 to 23	1962
FRG-2	Germany		1963
HFR	Holland	20 to 30 to 45	1961
R2	Sweden	30 to 50	1960

[a]Shut down in 1981.

[b]Shut down in 1982.

4. NONREACTOR IRRADIATION FACILITIES

The development of materials for fusion and fission reactors requires two parallel experimental approaches to irradiation studies (i.e., scoping experiments and basic mechanistic experiments). Scoping irradiation experiments must be carried out to determine the property changes produced by the temperature, neutron fluence, and spectrum parameters characteristic of the intended reactor application; these experiments test the response of new materials and help develop a design data base. However, it is equally important to pursue well-controlled irradiation experiments designed to explore the basic physical mechanisms involved in displacement damage and the resulting property changes.

In the light-water and breeder reactor materials programs, scoping experiments in existing reactors have been admirably supplemented by mechanistic studies using various types of particle accelerators. However, the fusion reactor materials program faces a unique situation because no fusion reactor materials irradiation facility exists. Consequently, every available irradiation facility must be evaluated and full advantage taken of its ability to reproduce some characteristic of the expected fusion reactor radiation environment.

Heavy-ion accelerators are not well suited to the scoping type of materials irradiation. They typically produce displacement damage rates that are $\sim 10^3$ times greater than those expected in a fusion reactor. For engineering materials, this high damage rate confounds the prediction of in-reactor behavior from heavy-ion data because the important segregation and precipitation phenomena are both temperature and damage rate dependent. In addition, other factors must be taken into account, including the effects of surface proximity, diffusional spreading, and injection interstitials.

In contrast, because of their well-defined temperature and fluence conditions, accelerators producing 4- to 5-MeV beams of heavy ions are widely used to investigate the physics of high-temperature phenomena related to the annihilation of point defects at internal sinks (e.g., cavity nucleation and growth, dislocation evolution, segregation, and precipitation phenomena). A second accelerator may be used to simultaneously inject helium into the material being irradiated with heavy ions to simulate in-reactor helium production from (n,α) reactions. It is possible to investigate very high damage levels (>100 dpa) with these techniques. Such facilities are also frequently equipped with nuclear microanalysis capabilities for determining the distribution of injected species and Auger equipment for surface segregation measurements. Heavy-ion accelerators play a vital role in the pursuit of underlying basic studies that are essential to the success of material development programs.

A second type of machine that is being used for basic studies is the accelerator-based neutron source. The most powerful machine of this type, RTNS-II, is located at Lawrence Livermore National Laboratory. In this machine, a beam of 400-keV deuterons strikes a rotating copper target coated with titanium nitride; the resulting T(d,n) reaction produces a beam of monochromatic 14.1-MeV neutrons. The beam flux is several orders of magnitude too low for scoping irradiation experiments on engineering materials. As far as the fusion materials program is concerned, the machine is used primarily to study the basic physics of 14-MeV neutron displacement damage and defect clustering in a wide range of metals and alloys. Specimen miniaturization techniques have been developed that allow the study of the effects of low levels of displacement damage on the fundamental and mechanical behavior of metals and alloys.

To provide the international materials community with a high flux of 14-MeV neutrons, the DOE's Office of Fusion Energy initiated the construction of the Fusion Materials Irradiation Test Facility (FMIT) at Hanford. Some $100 million was spent on the project until it was shelved in 1985 because of the inability of the three partners (United States, Europe, and Japan) to agree to commit the $120 million required for completion. The design is based upon a linear accelerator producing a beam of 35-MeV deuterons, which strikes a target stream of liquid lithium. The d(Li,p)n reaction produces a high flux of neutrons with energies ranging from 2 to 45 MeV, which produce a peak of displacement rate at about 14 MeV. As with all other irradiation facilities, it cannot wholly reproduce the fusion neutron spectrum; it possesses known advantages and disadvantages, and several areas of uncertainty. Its major advantage lies in the high energy spectrum, which ensures that the transmutations produced by threshold reactions in a fusion device will be reproduced. Of particular importance, the hydrogen and helium generation rates typical of a fusion environment will be generated in materials of any composition. A disadvantage is that the irradiation volume within which the displacement rates are similar to those of a fusion reactor is very small (~10 cm^3). This factor will necessitate some major innovations in miniaturization of mechanical testing techniques if the facility is to yield data suitable for design predictions. Areas of uncertainty are (1) the effect on materials behavior of the substantial fraction of neutrons with energies in the range 14 to 45 MeV and (2) the availability factor of such a complex accelerator-based facility.

Several other proposals for 14-MeV neutron machines are being formulated in the United States, Japan, and Europe. It is essential that one of these machines be built as an international project. However, it is difficult to envisage such a facility being operational within the next decade. Until that time the fission reactors, such as HFIR and FFTF, must remain the major engineering materials irradiation facilities supplemented by more fundamental studies using heavy-ion accelerator facilities.

5. SUPPORT AND FUNDING MECHANISMS

5.1 Funding Techniques

Three broad categories of funding arrangements are appropriate to describe financing of work at research reactor facilities.

1. Experimenter pays complete cost

This is the funding technique used at the ORR and HFIR. Costs for all aspects of an experiment and for running the reactor must be paid from the operating budgets of the sponsoring programs. It has been found that support commitment is generally unreliable, and it is not unusual for a program to reduce or completely terminate its support with no advance notice.

Initially, the HFIR was funded completely by the Division of Physical Research via the Transuranium Program. However, as funds became less available, other programs were encouraged to use the reactor and share the cost of its operation. A system of allocating charges was developed. This system is based upon irradiation units (IU) defined as 1×10^{20} nvt/in.^{3}. Each reactor user, in theory, would be charged on the basis of the number of IUs used per experiment. The cost per IU is determined by dividing the gross annual operating budget by the total number of units in use. This system has been used mostly as a guide in estimating what reactor charges should be because few users actually pay the full cost based on IU used; rather, the KC (Basic Energy Sciences) Program provides direct support for the operation of the reactor, which makes up the difference between user support and actual operating cost.

The ORR was supported during its early years of operation by charging each of the many experimenters in proportion to use of reactor space (core), building space, and vessel access ports while also taking into account other considerations such as unusual flux perturbations or unusual utility demands. The system used to establish the relative importance of these considerations was somewhat arbitrary but fair. This method was gradually phased out as the number of experimenters diminished, and it became necessary to fund part of the ORR cost from Laboratory overhead with the remaining operating costs shared by the programs that continued to use the reactor. Funding of the ORR deficit from overhead was terminated in 1975, and in 1977, the reactor was operated only ~25% of the year.

In 1978, however, the Magnetic Fusion Energy (MFE) Program provided a substantial (~40%) portion of the operating funds for the ORR after it was chosen as the best available facility for MFE irradiations. Subsequently, the ORR has been supported principally by the DOE's Energy Research Division through the MFE Program. Supplemental support during this latter period of operation has come from the Work-for-Others Program (HSST irradiations and RERTR).

In planning the overall operation of the HFIR and ORR, support commitment is generally unreliable; it is not unusual for a program to reduce or completely terminate its support with no advance notice. This unreliability forces cost projections to be conservatively high to minimize the likelihood of cost overruns.

Even with uncertainties in funding and changes in the various experimental programs, it has been possible to maintain a high degree of continuity in reactor operations. The experimenters' needs have usually been met with a minimum of inconvenience, because at least one reactor usually has been well funded even when others were not. Because all the reactors are operated by a single department, it has been possible to shift some people and costs to accommodate shortages.

2. No cost to experimenter

This approach is used by the RRT Division of DOE in funding EBR-II. RRT also funds the operations of the hot-cell facility in which EBR-II irradiation experiments are examined. The only costs that experimenters must pay out of their operating budgets are (1) disposal after postirradiation examination, (2) design work and materials costs associated with nonstandard irradiation capsule design, (3) preparation of design documents and SARs, and (4) site coordination. Usually, large-scale experiments (such as those associated with fuel development or cladding development) will have several engineers located permanently at the EBR-II site to follow the progress of the experiments.

3. Partial payment by experimenter

The best example of the application of this method of funding is the HFR Petten. This reactor is located at the Joint Research Center (JRC) — Petten Establishment, Petten, North Holland. Funding for the reactor operation staff (~70 people), research and administrative staff (~80 people), supporting laboratories, and general-purpose control equipment for experiments comes from the European Community (Euratom). Under this system a number of large research projects declare their long-term technical needs for irradiation services and motivate the governments of Euratom countries to grant funding for several years. This funding includes operating expenses and improvements in both the reactor and general-purpose irradiation equipment. Research programs from within the Euratom countries are provided IU and certain other services from JRC personnel without charge. Experimenters must pay for external services, capsule materials and fabrication, and other consumable materials. The facilities of JRC are also available to experimenters from outside Euratom on a space-available basis. Such experimenters must pay a prorated share for IU and service work within the JRC. Other European test reactors operate on the same general principle, although the mix of government-sponsored and experimenter-sponsored services varies.

5.2 Funding Experience at HFR Petten

At present, the HFR Petten is a model test reactor. The irradiation space in this reactor is used as fully as is practical. A well-trained, competent technical staff is in place at the facility. Research programs are running smoothly, and a long-term plan (~20 years into the future) has been identified for the reactor. Upgrading of the physical plant and support facilities has taken place over the past decade so that this facility is one of the best in the world.

The comparison between ORR and HFR Petten is a particularly interesting one because the latter is essentially a carbon copy of the former. The HFR Petten started operation in 1963 (compared with 1958 for the ORR) and operated quite successfully until about 1973 when "... it appeared that there was insufficient 'European' interest in the continued joint operation and utilization of the reactor."[3] The reactor was funded by experimental programs during this period (prior to 1973), as described under the "experimenter pays complete cost" method.

In 1973, a funding arrangement was introduced at HFR Petten "... whereby only two Euratom countries (i.e., the German Federal Republic and the Netherlands) took over the financial burden of HFR exploitation. Included in the arrangement was, however, that both countries could make both the irradiation space and the irradiation services (The HFR Petten infrastructure includes an irradiation technology service, maintained by Euratom-Petten) at Petten available to their national research institutes and their nuclear industry without charging any users either irradiation or man-power costs. The possibility for 'free-of-charge' utilization of the reactor has over the past years gradually led to the satisfactory reactor loading .... In particular, the German utilization of the reactor has contributed to this situation.[3]

The ORR, in contrast to the HFR Petten, has for the last decade been supported on a bare subsistence basis, with no provision being made for upgrading or modernization of the physical facility or supporting activities. Reactor use has fallen at times to such a low level that shutdown of the facility has been barely averted; only the decision by the DOE Fusion Energy Program to provide massive support to the ORR prevented its shutdown after FY 1976.

Until 1973, when the funding policy for the HFR Petten reactor required users to pay the complete costs of reactor operation, the fiscal instability of the HFR Petten and the ORR were comparable. Since that time, when the financial burden of the HFR Petten exploitation was assumed by the German Federal Republic and the Netherlands, a major disparity between the HFR Petten and the ORR with respect to use and upgrading has occurred with the ORR disadvantaged in comparison.

6. PROPOSALS FOR MATERIALS IRRADIATION FACILITIES IMPROVEMENTS

In seeking to reestablish ORNL's position as a world leader in irradiation experiments, it is clear that the HFIR, already an outstanding facility in many respects, is a better starting point than the ORR, which is surpassed in all respects by a number of other reactors.

6.1 High-Flux Isotope Reactor

The basic improvements needed at the HFIR are clearly evident in Table 5. The highest flux positions in the target or flux trap region cannot be instrumented and are very small. The removable beryllium (RB) positions are few and much smaller than those in the general purpose reactors. The proposed reactor modifications address these issues.

Figure 7 is a diagrammatic side view of the HFIR fuel elements and target region. A structure known as the target tower extends upward from the target region almost 2.5 m (8 ft) to the quick-access hatch, a removable plug in the center of the reactor pressure vessel lid. The quick-access hatch is pierced in the center to admit a hydraulic rabbit tube. The committee proposes that a new quick-access hatch be made, pierced with three access holes on an equilateral triangle. Two of the three penetrations, to be provided with suitable flanges, seals, and hold-down clamps, will provide access to the target region for instrumentation ducts. The third penetration will be for the existing hydraulic tube facility. Because the rather complicated target tower assembly provides support and guidance for the hydraulic tube, it too must be redesigned and rebuilt.

With these modifications, at least two small target capsules of 16-mm diam may be instrumented. By occupying up to seven target positions, capsules up to 25-mm diam could be accommodated (Fig. 8). If desired, it would also be possible to incorporate a shield (e.g., of tungsten) to reduce the gamma heating rate in the capsule and permit the irradiation of larger specimens while maintaining acceptable temperature gradients within the samples. Alternatively, it would be possible to selectively

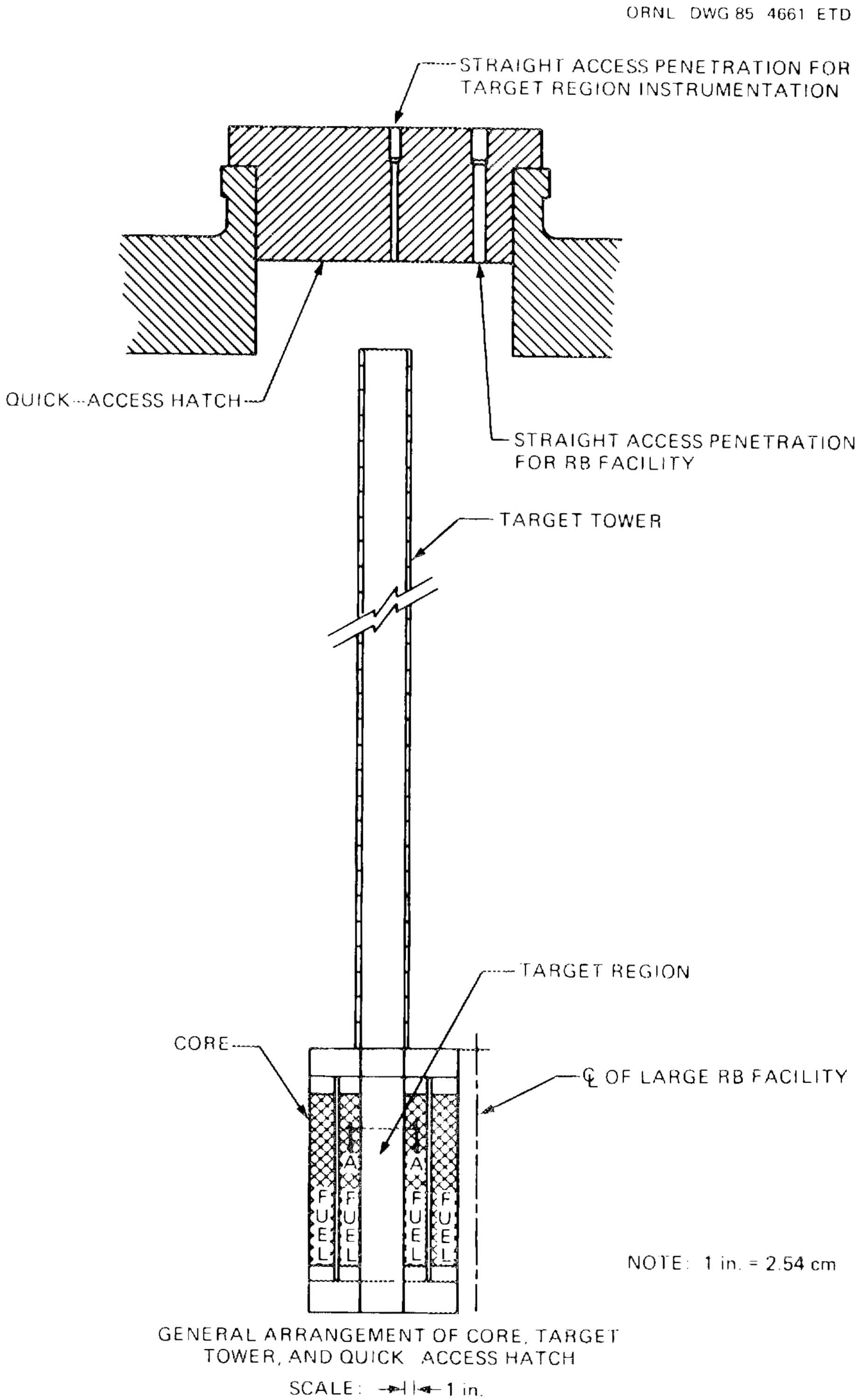

Fig. 7. Side view of HFIR core.

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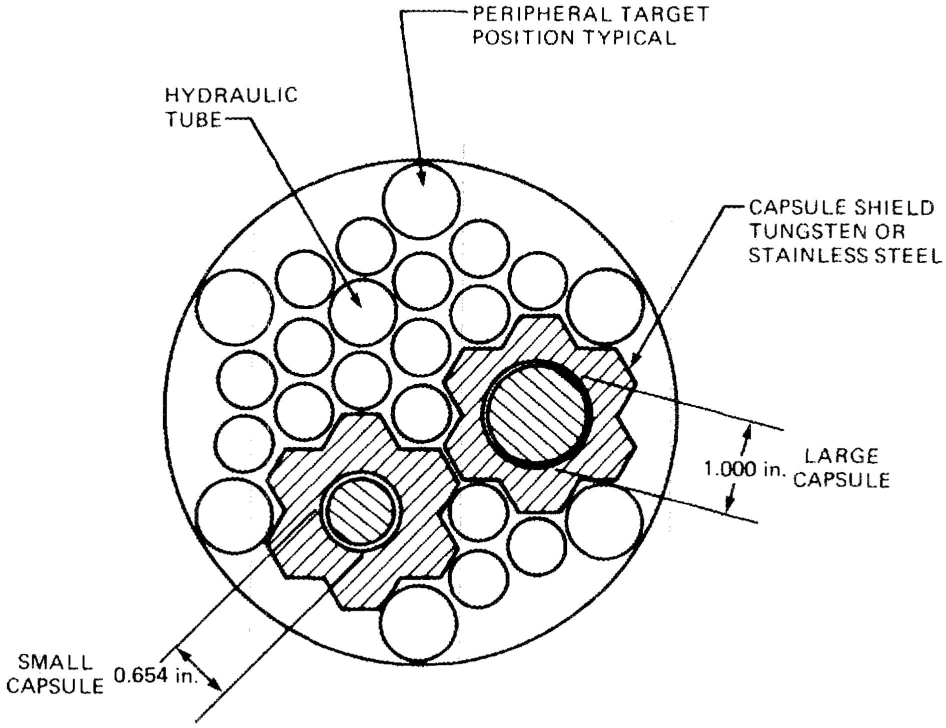

Fig. 8. The HFIR target region with two capsules.

absorb thermal neutrons (by using, e.g., a cadmium or hafnium shield) to provide spectral tailoring, but the effect of the shields on core life and on other uses of the reactor has yet to be fully assessed.

There are presently four 37-mm-diam irradiation positions in the RB region of the reactor [Fig. 9(*a*)]. The committee proposes that the four be replaced by eight larger holes capable of accepting 48-mm-diam capsules [Fig. 9(*b*)]. The change would increase the total experimental volume available within irradiation capsules at these positions by a factor of 3 to 4. The new positions are referred to later as the RB Star (RB*) facilities, and they could accommodate most of the work presently accomplished in the ORR core with a twofold to threefold increase in neutron flux.

To provide straight-line instrumentation access to the RB* facilities, other components of the HFIR, mounted above the RB and the core, must also be redesigned and rebuilt. Specifically, the upper-track assembly and the shroud flange (which are part of the control plate

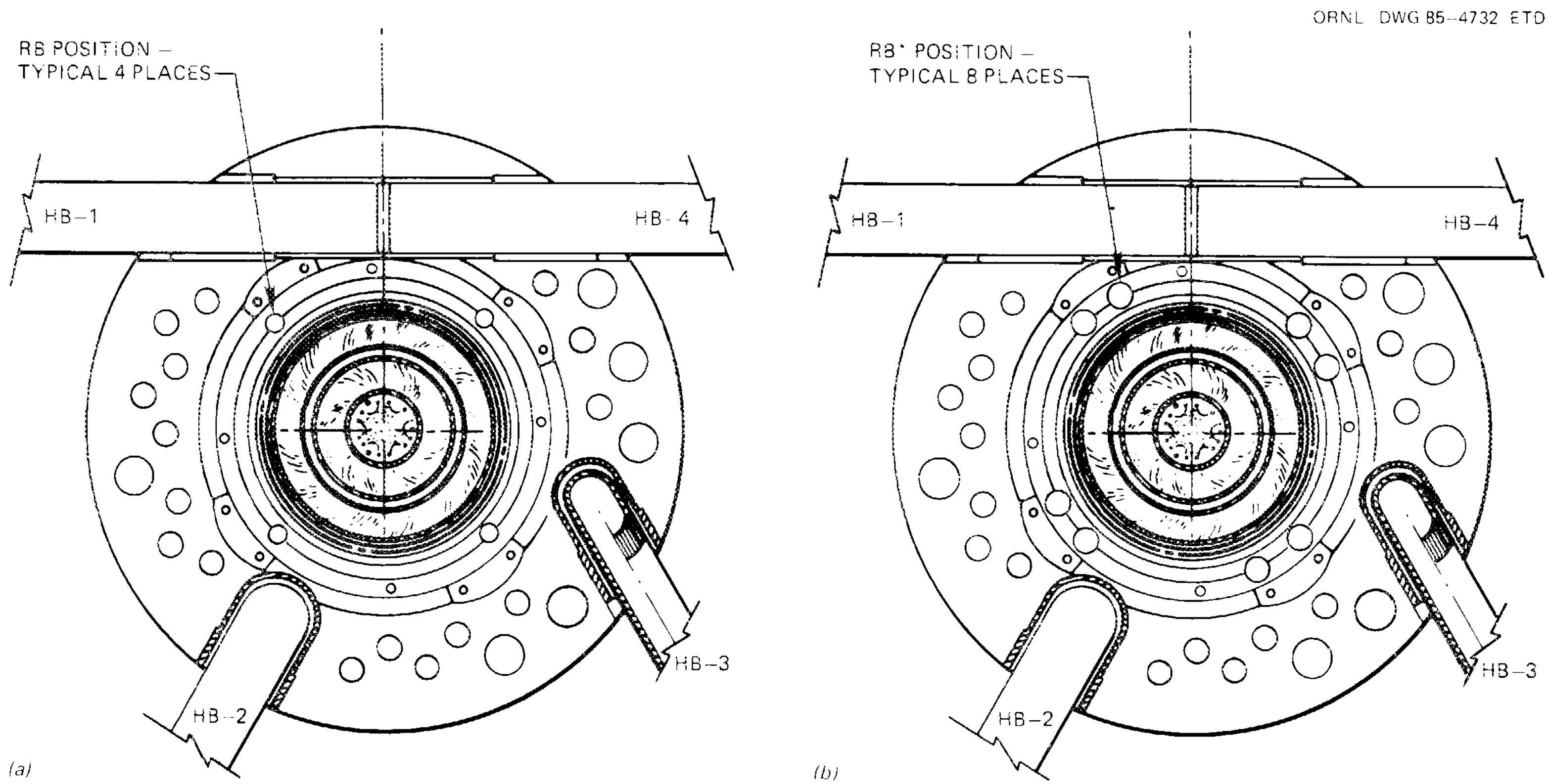

Fig. 9. The RB and RB* positions.

location and drive system) must be modified. It is also proposed that additional penetrations be made in the quick-access hatch to provide straight-line access to the RB* positions for instrumentation. The straight-line access will also permit rotation and vertical relocation of capsules during the course of an experiment, as well as making experiments interchangeable.

It is expected that some experimenters will wish to include spectral tailoring shields in their RB* capsules, and it is very important to understand the effects of such neutron absorbers on the core life, beam tube flux, and isotope production capability. Some preliminary and not totally convincing calculations have been carried out, but the question is not yet settled. It is clear from these efforts that the reactor operators and experimenters do not have available any satisfactory way of calculating and predicting the effects of loading new materials into the vicinity of the core. The committee believes that such a capability is essential if a well-organized program of research is to be carried out at the modified HFIR and that the provision of such a capability (perhaps through the Experiment Coordinator's office) is as important as the provision of the physical facilities.

The proposed modifications address directly most of the major limitations of the HFIR for materials testing and will again provide ORNL with world-class capability in this area (Table 8). The modifications do not, of course, change the fact that the fixed-fuel configuration of the HFIR cannot provide the same flexibility as the variable core loading that is possible in a true general purpose test reactor. It is, therefore, very important that ORNL establish an appropriate mechanism for mediating and prioritizing the needs, which may sometimes conflict, of different users of the modified HFIR.

As explained, the effects of neutron absorbers in the RB* positions have not been ascertained in detail. Preliminary calculations indicate that at least two hafnium shielded experiments could be inserted without shortening the fuel cycle more than 15 to 20% even if no action were taken to counter the effect. Furthermore, a number of actions can, in principle, be undertaken to reduce the shortening of the fuel cycle.

Table 8. Proposed irradiation facility upgrade — comparison with existing instrumented facilities

Characteristics	Existing facilities					New proposals	
	FFTF[a]	BR-2	HFR	ORR	HFIR/ RB	HFIR/ RB*	HFIR/ target
Displacements per atom per year	30	10	8	4	12	10	30
Maximum capsule diameter, mm	28	52	74	74	33	48	25[b]
Number of test positions	60	35[c]	17[d]	10	4	8	14/8[b]

[a]MOTA facility: minimum temperature 380°C.

[b]At least two target facilities will be instrumented. There may be 2 large (25-mm) and 6 small (13-mm) positions or 14 small positions; these figures include the 6 existing small PTP positions.

[c]Plus two 200-mm-diam positions, cadmium shielded for low thermal flux.

[d]In 1985, test positions will be increased to 27, of which perhaps 17 can be used at one time. The capability of moving capsules from one core position to another provides spectral tailoring without the need for thermal-neutron absorption shields.

Among these are an increase in the uranium content of the fuel (shown to be possible by recent work on the reduced enrichment fuel program) or removal of the spectral tailoring experiment (or at least the shielding material) for the last few days of each fuel cycle. In any case, more detailed calculations and a dosimetry experiment with hafnium in the RB positions will be carried out in the next few months.

Preliminary estimates of the HFIR modification costs have been made and are shown in Table 9. Note that the figures are expressed in 1985 dollars and assume the overhead rates appropriate to operating funds. Table 10 shows a breakdown of the cost estimates, along with a schedule that meets the commitments of present irradiation programs and the RB replacement that is already scheduled for 1987.

6.2 The Oak Ridge Research Reactor and the Bulk-Shielding Reactor

With the availability of the RB* facilities, it is expected that the need for in-core experiments at the ORR will decline considerably, and continued operation of that reactor will be difficult to justify. The committee, therefore, proposes no major expenditure for ORR improvements as long as either the HFIR or its planned successor, the CNR, seem likely to be available and suitable for materials irradiation experiments. However, neither the HFIR nor the CNR has facilities equivalent to the ORR poolside facility for the irradiation of large (600- by 600-mm) capsules. Other reactors in the United States, such as the Union Carbide reactor in Sterling Forest, New York, can carry out such experiments. If, for some reason, a large irradiation facility is needed at ORNL, the BSR can be used again although the neutron flux is only about one-third of that at the ORR window. The recent installation of the National Low Temperature Neutron Irradiation Facility (NLTNIF) in one face of the BSR means that modifications to the reactor support structure at another face would be necessary to accommodate large irradiation capsules. However, there seems no doubt that appropriate modifications would be possible and that experiments could be designed and scheduled to avoid seriously compromising the NLTNIF experiments.

Table 9. Cost estimates for HFIR modifications

Item	Estimate (thousands of 1985 dollars)	Base for estimate
	Reactor facilities	
Design		
Conceptual	33	5 mm of HFIR Engineering Support Group
Detailed	200	4800 h [replace 80 drawings at 60 h/drawing at $40/h + miscellaneous reviews (e.g., PVRC)]
Fabrication		
Hatch and target tower	140	Plant and engineering estimate based on existing design drawings
Track assemblies	198	Cost $125,000 in 1980 — updated for inflation plus small contingency
Shroud flange	83	Cost $50,000 in 1980 — updated for inflation plus small contingency
Outer shroud	100	Last made in 1963 — used same hours with present rate
Removable beryllium	275[a]	Cost $200,000 in 1984 — added inflation plus $50,000 allowance for additional machining
Installation	50[b]	Allowance for modification of existing tools
Subtotal reactor facilities	$1,079	
	Neutronics analysis	
Feasibility	25	Estimate from Operations Division
Detailed	50	Pure estimate by Engineering Technology
Subtotal neutronic analysis	$75	
	Experimental facilities	
New target capsule design	75	Half of $130,000 spent on design of larger, two-temperature-zone ORR capsule for Japan plus 15% contingency
New RB capsule design	150	$130,000 spent on design of similar ORR capsule for Japan plus 15% contingency
Instrumentation facility	150	Based on recent installations at ORR
Subtotal experimental facilities	375	
ETD supervision	126	One man-year at present rates
Total	$1,655	
Additional contingency	165	10% of total
Grand total	$1,820	

[a]Does not allow for spare beryllium assembly.

[b]In addition to regular RB installation costs.

Table 10. First estimates of HFIR facility costs and schedule (total costs in thousands of FY 1985 dollars)

	FY 1985				FY 1986				FY 1987			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Target instrumentation												
Design			125									
Fabrication and installation						245						
New capsule design						75						
RB*												
Beryllium reflector design						75						
Other design (including neutronics)			25			100						
Beryllium procurement[a]							50					
Other procurement and assembly							250		250			
Installation										50		
Instrumentation facility							75		75			
New capsule design									150			
Beryllium changeout already scheduled												

[a]Plus standard cost of semipermanent and RB replacement.

The NLTNIF is an interesting facility, using the space created by removing a fuel element from one face of the reactor. Provided suitable scheduling arrangements could be worked out, the NLTNIF location would be an excellent place for short-term experiments involving reactor power ramping or physical movement of the capsules. Experiments of that kind, involving 60-mm fuel balls (too large to be accommodated at any of the high fast flux positions in the HFIR), are presently under consideration in the GCR program.

The BSR and the ORR are located in adjacent buildings. They are operated by the same crew, housed in the ORR building, and staff costs are a major part of the operating expense. If major cost savings are to result from a shutdown of the ORR, the BSR must be operated by the HFIR crew, either by long-distance remote control or perhaps by physically moving the BSR into the HFIR pool. In any case, this is a serious question, involving safety issues as well as economic and personnel considerations; a plan for the operation of the BSR after the closedown of the ORR should be completed and agreed upon within the next year.

6.3 Support Facilities

As indicated previously, the hot cells are a major problem. This committee endorses previous findings and recommendations for the improvement of certain key cells and equipment that are important to the execution of the programs considered in this report.

The lack of an adequate and credible capability for predicting the behavior of ORNL reactors under different loading conditions, especially for the HFIR, has been as severe a drawback for this committee as it has been for researchers proposing new types of experiments. The knowledge and the basis for computer codes to provide this capability already exist at ORNL and are being further extended as part of the effort to design the reactor for the proposed CNR. The necessary capability should be available in the Operations Division, perhaps through the Reactor Experiment Coordinator — an office that will, in any case, need to be strengthened when the modifications to the HFIR widen both the range of possible experiments and the possibility of conflicting requirements between different users of the reactor.

Most organizations involved in engineering materials irradiation have direct access to, and make use of, neutron radiography facilities. Neutron radiography is invaluable in the examination of failed or failing capsules. It is also a means of carrying out direct observations and measurements on specimens during the course of irradiation, making possible experiments on the time-dependent mechanical behavior of, in particular, fuel specimens that are not easily carried out any other way. The committee recommends that a study be made of the feasibility and cost of providing a neutron radiography capability at the HFIR, either with an isotopic (californium) neutron source or with neutrons from the reactor.

7. SUMMARY AND RECOMMENDATIONS

The following summarizes the findings of the committee:

1. The HFIR has outstanding neutronics characteristics for materials irradiation, but some relatively minor aspects of its mechanical design severely limit its usefulness for that purpose.
2. The ORR, with its relatively low flux and inconvenient access ports, is no longer competitive for most types of materials irradiation experiments.
3. The BSR, as modified for the NLTNIF, has some capabilities that would be well suited to large sample irradiations and power ramping experiments.
4. The Operations Division and the reactor experimenters are handicapped by the lack of neutronic computational capability to calculate the effect on the reactor and on other experiments of introducing neutron absorbers, especially spectral tailoring shields.
5. The irradiation capsule operators and experiment designers could carry out new types of experiments and could greatly benefit from the availability of a neutron radiography facility.

The committee makes two major recommendations. Neither is expensive, but together they would very greatly enhance ORNL's position in the field of engineering materials irradiation, providing a unique capability for most of the areas in which we are now working. From a currently inferior position, ORNL would acquire first-rate facilities if these recommendations are followed.

1. Modify the HFIR quick-access hatch and target tower to provide access for instrumentation in the target region: approximate cost — $370,000.
2. Modify the HFIR quick-access hatch, removable beryllium, shroud flange, and upper track assembly to provide eight materials irradiation experimental positions, each capable of accepting 48-mm-diam capsules and each having straight-line instrumentation access: approximate cost — $920,000.

These estimates do not include the design of new capsules to make use of the enhanced facilities or the cost of the beryllium scheduled for replacement in 1987. In addition, the committee makes four other recommendations.

3. Establish the means for making detailed calculations of core and experiment neutronics on demand from the Operations Division.
4. Study the feasibility and cost of establishing a neutron radiography capability at the HFIR.
5. Consider using the BSR as an alternative to the ORR for large- and medium-scale irradiations, provided that the NLTNIF work is not thereby disrupted. The cost of any necessary modifications or additions to the core support structure would be covered by the program sponsoring the irradiation.
6. Plan for the economical operation of the BSR if the ORR is closed down.

The first three items are all aspects of the committee's first priority recommendation, which is the enhancement of the HFIR's capabilities for materials irradiation. Items 4 and 5 are important for improving the Laboratory's materials irradiation facilities but are lower priority. The sixth and final item is not a recommendation for such an improvement but is an action necessitated by the decline in usage of the ORR for irradiation experiments.

REFERENCES

1. C. D. Cagle, *Oak Ridge National Laboratory Research Reactor Experimenters' Guide*, ORNL/TM-8308/R1, October 1982.

2. M. J. Feldman et al., *Report of the ORNL Ad Hoc Hot Cells Improvement Advisory Committee*, July 29, 1983.

3. Letter from R. J. Swanenburg de Veye, Reactor Centrum Nederland, to D. B. Trauger, Oak Ridge National Laboratory, October 9, 1975.

Appendix A

MATERIALS IRRADIATION FACILITIES IMPROVEMENTS COMMITTEE

A.1 Membership

C. W. Alexander	Chemical Technology
J. A. Conlin*	Engineering Technology
S. S. Hurt, III	Operations
R. M. Moon, Jr.	Solid State
E. Newman, Jr.†	Operations
A. F. Rowcliffe	Metals & Ceramics
K. R. Thoms‡	Engineering Technology
C. D. West (Chairman)	Engineering Technology

*Retired in December 1984.

†Joined the Committee in September 1984.

‡Joined the Committee in February 1985.

Exhibit A.1

August 17, 1984

TO: C. D. West

FROM: F. R. Mynatt, R. S. Wiltshire

SUBJECT: Materials Irradiation Facilities Improvement Committee

We request that you chair a Laboratory-wide ad hoc group to consider and recommend changes and improvements to the Laboratory's facilities for materials irradiation testing — chiefly, but not limited to, the HFIR and ORR reactors.

The ad hoc group has been selected to include not only materials irradiation workers but also other major ORNL users of the reactors so that the effect of any proposed changes on our other programs can be evaluated. The members of the committee are:

C. W. Alexander	Chemical Technology
J. A. Conlin	Engineering Technology
S. S. Hurt, III	Operations
R. M. Moon, Jr.	Solid State
A. F. Rowcliffe	Metals & Ceramics
C. D. West (Chairman)	Engineering Technology

We are asking the committee to carry out a number of specific tasks which are listed on the attachment. The tasks include a consideration of the extent to which the type of materials testing work currently undertaken at the ORR could be carried out at other ORNL facilities if, as is presently planned, the ORR is closed when the fuel currently on hand and under contract is exhausted in about 1988. The committee is also required to ensure that, as far as possible, proposed changes in experimental methods, techniques, and facilities for the HFIR are compatible with the proposed HFIR-II reactor.

The Executive Committee expects to receive a progress report and be given the opportunity to discuss the interim findings of the Committee after four months, and a draft report should be presented for Executive

Exhibit A.1 (continued)

Committee review three months after that. It is expected that the Committee findings will eventually be published as an ORNL report.

Research Committee members are asked to provide assistance to the ad hoc committee members in their assignment, which is expected to have a major influence on some very important programs and facilities of the Laboratory.

FRM:RSW:CDW:bdb

Attachment

cc/att. R. E. MacPherson
Materials Irradiation Facilities Improvement Committee
Research Committee

Exhibit A.2

Materials Irradiation Facilities Improvement Committee Charter

- To compare the present reactor facilities for materials irradiation testing at ORNL with those available elsewhere
- To identify likely changes in the technical requirements of irradiation experimenters over the next several years
- To identify feasible improvements to the HFIR and ORR irradiation facilities, operational techniques, and supporting activities that would provide the Laboratory with competitive or, preferably, unique capabilities for both in-house and outside users
- To identify feasible changes or modifications to the HFIR and other reactors at the Laboratory that would allow them, in conjunction with new experimental techniques if necessary, to accommodate materials irradiation needs currently met by the ORR
- To evaluate the effects of proposed changes on other uses of the reactors, particularly isotope production and neutron-beam experiments
- To recommend priorities, or sets of priorities dependent upon external events, for the suggested modifications

Appendix B

THE WORLD'S BEST MATERIALS TESTING REACTOR — A POSSIBILITY FOR THE 1990s

The recommendations for modification of the HFIR will give ORNL a unique facility for many types of engineering materials irradiation experiments. However, the HFIR will always, because of its core construction, lack the flexibility of a general purpose reactor. There is apparently no present need to build such a reactor at a cost, presumably, in excess of $100 million or even to upgrade the ORR at a cost of perhaps $50 million.

In the middle of the next decade, there is a potential opportunity to establish at ORNL the best general purpose test reactor in the world for a cost of perhaps $20 million.

If the CNR is built, along with its new reactor, the HFIR will no longer be needed for neutron scattering or for isotope production. S. S. Hurt has proposed that under those circumstances (assuming there is a need at that time for a general purpose test reactor), the HFIR core and inner reflector could be replaced with the ORR core or a similar one (Fig. B.1). The modifications involved would be modest, and most of the more expensive components of a reactor — the cooling system, control room, pool, containment building, and office space — would already be in place. With the HFIR cooling system, a materials testing reactor core like that of the ORR or Petten could run at 75 to 100 MW, which is higher than the HFR in Petten. The result would be an unmatched facility for general purpose materials testing at perhaps one-tenth the cost of building a completely new reactor.

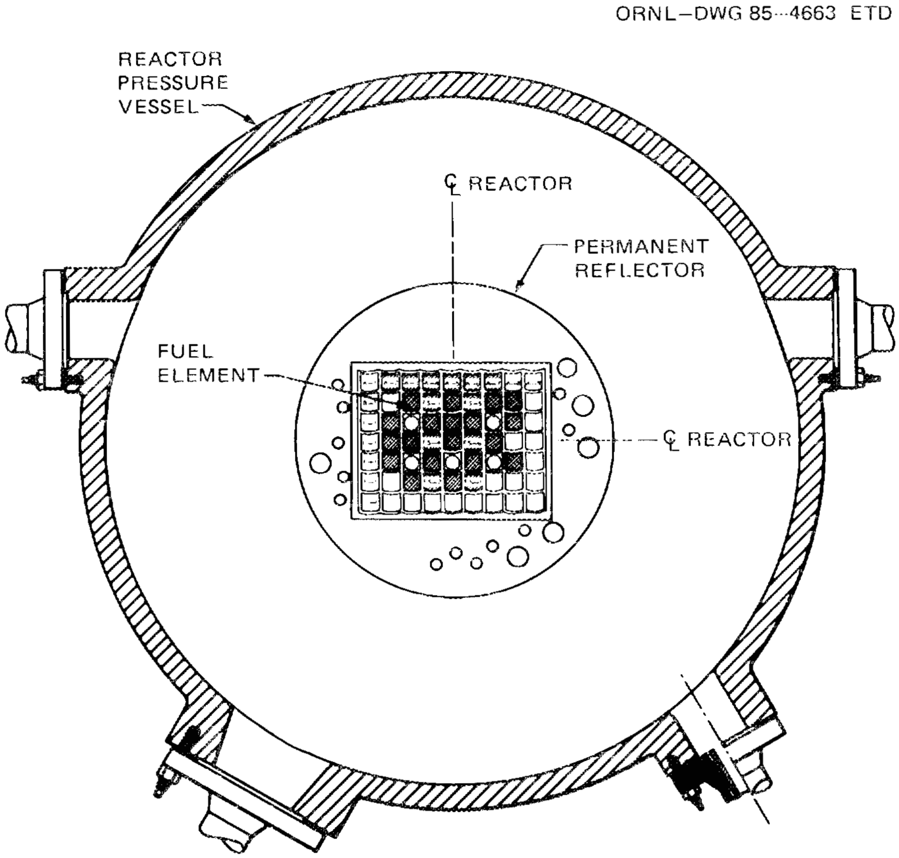

Fig. B.1. A materials testing reactor core compared with present HFIR core.

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