The Brookhaven Medical Research Reactor

The first nuclear reactor designed specifically for medical research and therapy is described.

Lee E. Farr

A unique instrument, the medical research reactor, constitutes the heart of the equipment and machines of the new Medical Research Center of Brookhaven National Laboratory (Fig. 1). This is the only nuclear reactor which was conceived, designed, and built solely to add to knowledge of certain aspects of medicine. On 15 March 1959 this reactor became technically operative—that is, the core became "critical." While, since that time, the core has been operated at power levels up to 3 megawatts, it still must be described as only "technically operative," since a large battery of tests yet remain to be accomplished to establish the correctness of the design and materials used in the components surrounding the core, which are of prime importance in fulfilling the goals of this reactor design. In this regard, the core has been proved. The testing that remains is to determine the capacity of the instrument to deliver the neutrons or gamma fluxes at the point desired and in the purity required, without significant hazard to experimenters.

It is well at this point to define what is meant by a "medical research reactor." It is clear that at the present time all reactors which might be used in medicine are research in type. This reactor is therefore of a research type in this sense, but it is also "research" in two other senses. One is that ultimately, as an outgrowth of this experience, a true "medical reactor" may come to constitute one type of the presently growing family of nuclear reactors; the other is that for the immediate future, at least, it is a reactor the use of which will be limited to medical research. To encompass only the latter two senses, it is clear that two widely different reactor types may be used. The first is a general purpose or general research reactor wherein the primary usefulness for medicine is the generation of radioactive isotopes of medium term half-life. These radioactive isotopes can then be used for diagnosis, therapy, and studies in biochemistry, physiology, experimental pathology, and the like. In such a reactor no special medical devices are required, since the mechanical retrievers and access tubes are identical to those required for chemical, physics, or, in some instances, material-testing studies. It is clear that most biological fields can be served adequately by this type of reactor service.

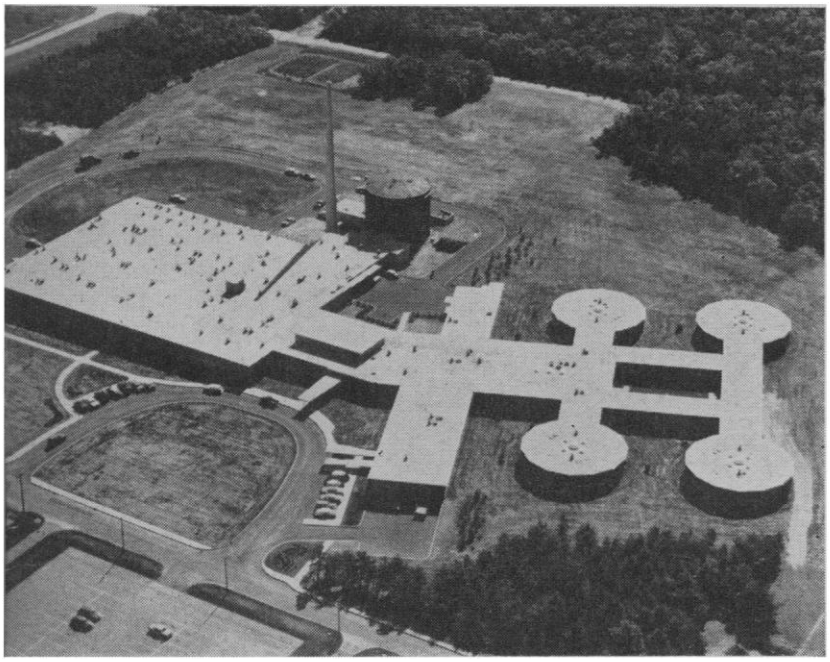
Therefore, it seems advisable to reserve the term *medical reactor* or *medical research reactor* for those devices wherein the reactor itself is used for therapy or diagnosis or studies leading to therapeutic or diagnostic goals which have required characteristic and different design criteria for core or operation. Such special design criteria involve (i) shielding and moderation of neutron energies to provide the massive, externalized stream of neutrons or the separation of core emanations into relatively pure components as gamma or neutron emissions; (ii) the continuous supply, during a stated period, of very short half-life radioactive isotopes required by therapeutic maneuvers; and (iii) those purposes when the patterns or schemes of reactor operations are entirely dictated by the therapeutic or diagnostic trials involved. By this definition the new reactor at Brookhaven is indeed a medical reactor or medical research reactor. It is clear that many components of such a medical reactor will be found in general reactors and in the devices comprising a medical unit or accommodation at a general research reactor, but in such reactors there has occurred no significant alteration in core design or operational schema dictated by the use to which the reactor or its products may be put. It is to be expected that the number of medical units at general reactors (*1*) will outnumber medical reactors until studies with especially designed units such as the Brookhaven medical reactor have demonstrated a clear need for and superiority of one or more major features and some reasonably widespread specific diagnostic or therapeutic usefulness.

Description of the Reactor

The conception and criteria for operation of the new medical research reactor were the outgrowth of pioneering studies on neutron capture therapy (*2*) made possible by the great flexibility of the large, general-purpose graphite reactor at Brookhaven which became operational in 1951. Within a year thereafter, the desirability of a new design to meet specific medical needs was clear, and during 1952 the first of the engineering and design studies was undertaken which was to lead ultimately to the present reactor. Now a total of 8 years' experience with the Brookhaven graphite reactor has laid a foundation for further penetration into an unexplored region of medical-nuclear research utilizing the Brookhaven medical research reactor. This reactor is housed in a circular steel building 60 feet in diameter and 54 feet high (Fig. 2), which is connected to the main building complex of the Medical Research Center by two sets of air locks. One set provides entrance into the general area about the reactor, whereas the other set directly connects the radiation operating room with the reactor treatment room. The floor plan of these regions is shown in Fig. 3.

The reactor core is contained in a cylindrical aluminum tank 24 inches in diameter and 7 feet 7 inches high in the region of the core. The tank has an 8-inch pipe to lead cooling water in at

The author is medical director of Brookhaven National Laboratory, Upton, N.Y.



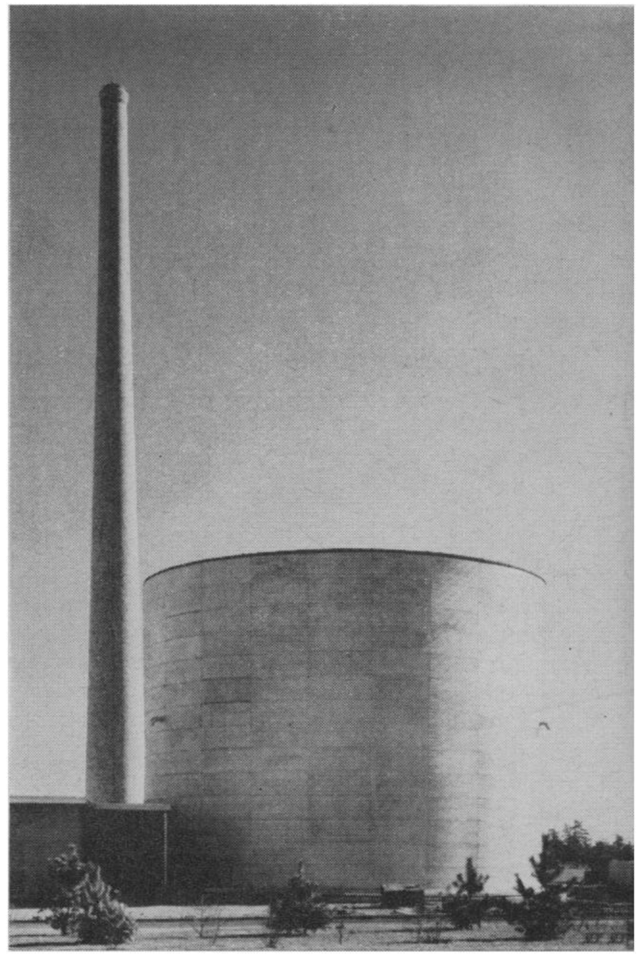
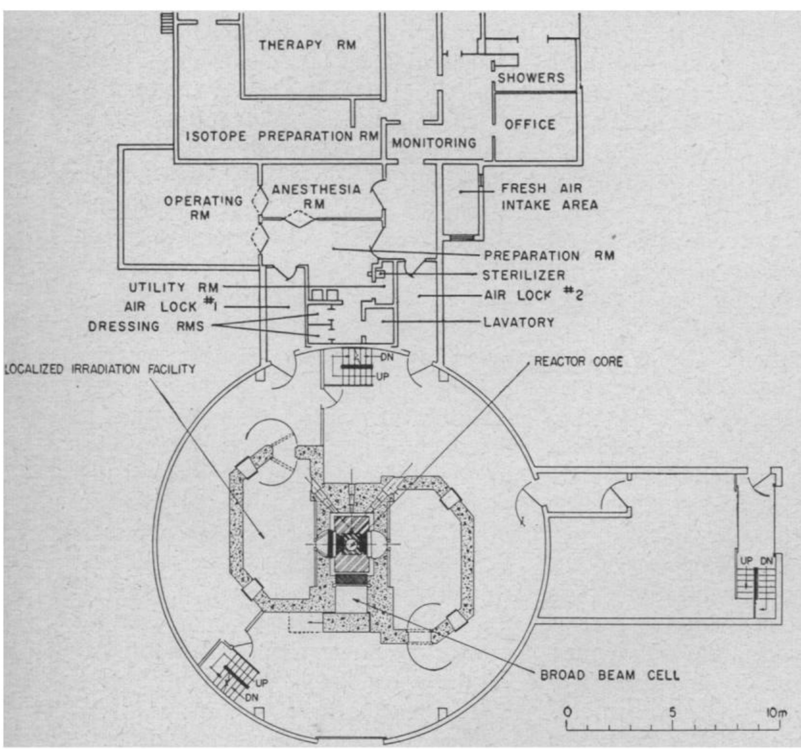


Fig. 1 (left). Aerial view of the Brookhaven Medical Research Center, showing the relation of the reactor building, top center, to the laboratory areas on the left and the hospital area on the right. The four circular buildings are the nursing units providing 48 beds, of which 40 are available for research patients. Fig. 2 (right). Reactor building and stack for discharge of cooling air from reflector of Brookhaven Medical Research Reactor.



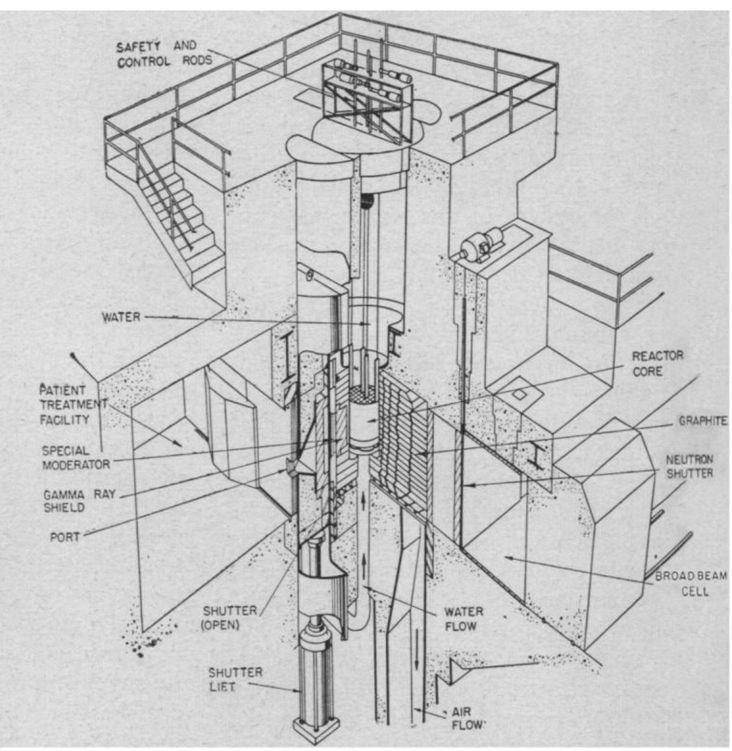
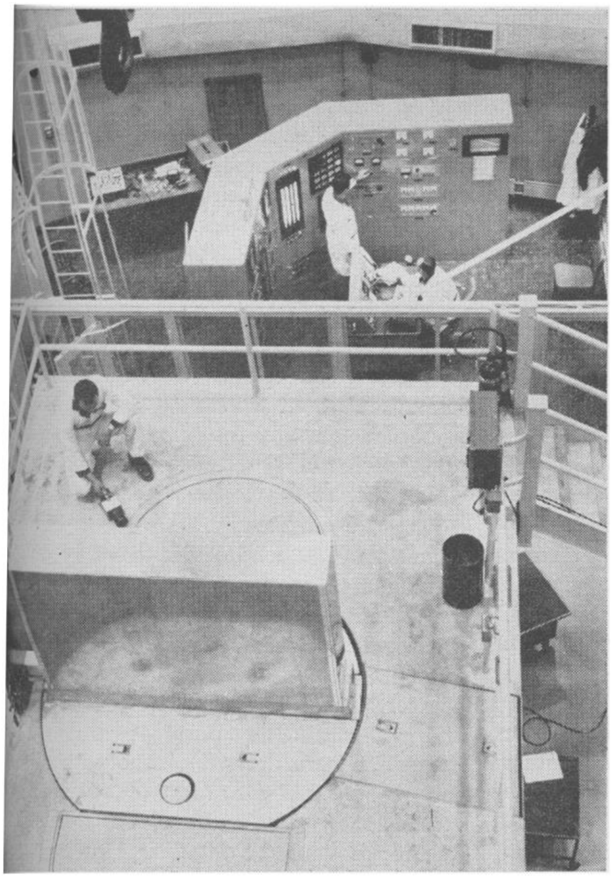


Fig. 3 (left). Floor plan sketch of Brookhaven Medical Research Reactor, showing the heavy shielding about treatment rooms and the adjacent operational and experimental units. Fig. 4 (right). Semidiagrammatic sketch of the Brookhaven Medical Research Reactor, showing general relations of its component parts. Instrumentation parts and units for specimen irradiation and activation are not shown. The 20-ton shutter can be opened and closed in 3 to 5 seconds.



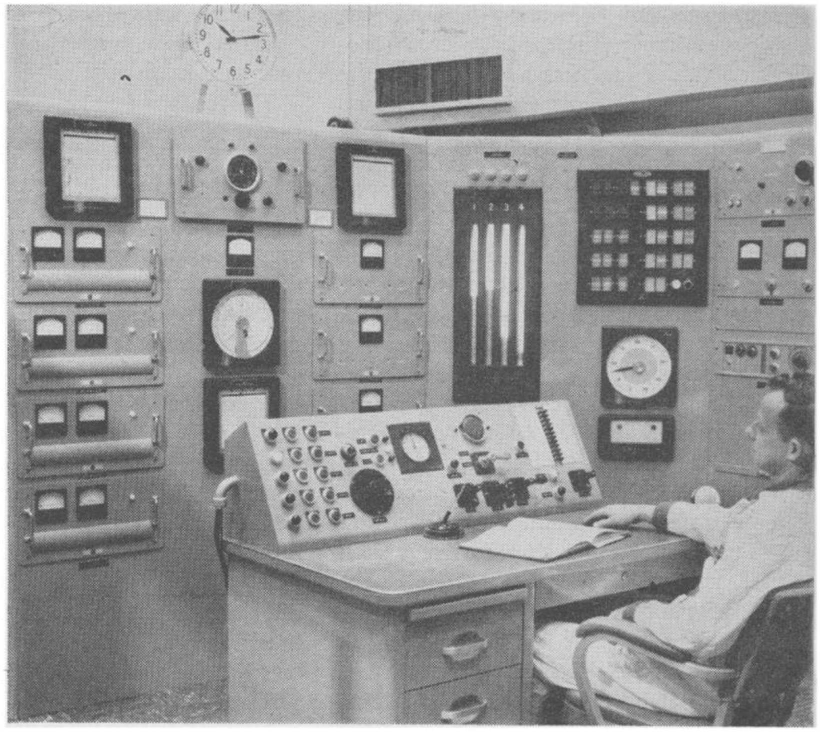
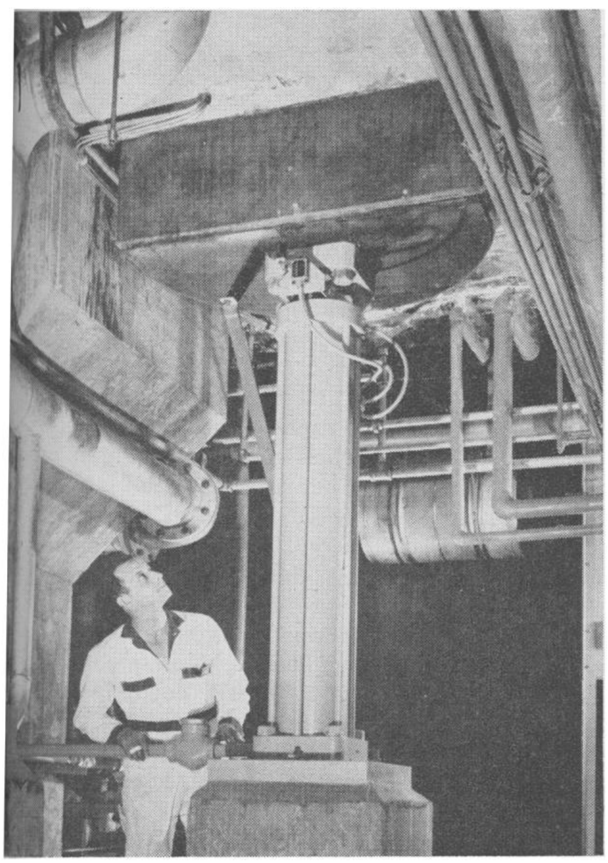


Fig. 5 (left). A view from above the Brookhaven Medical Research Reactor, showing the reactor control area on the mezzanine. Fig. 6 (right) A close-up of the control console of the Brookhaven Medical Research Reactor.



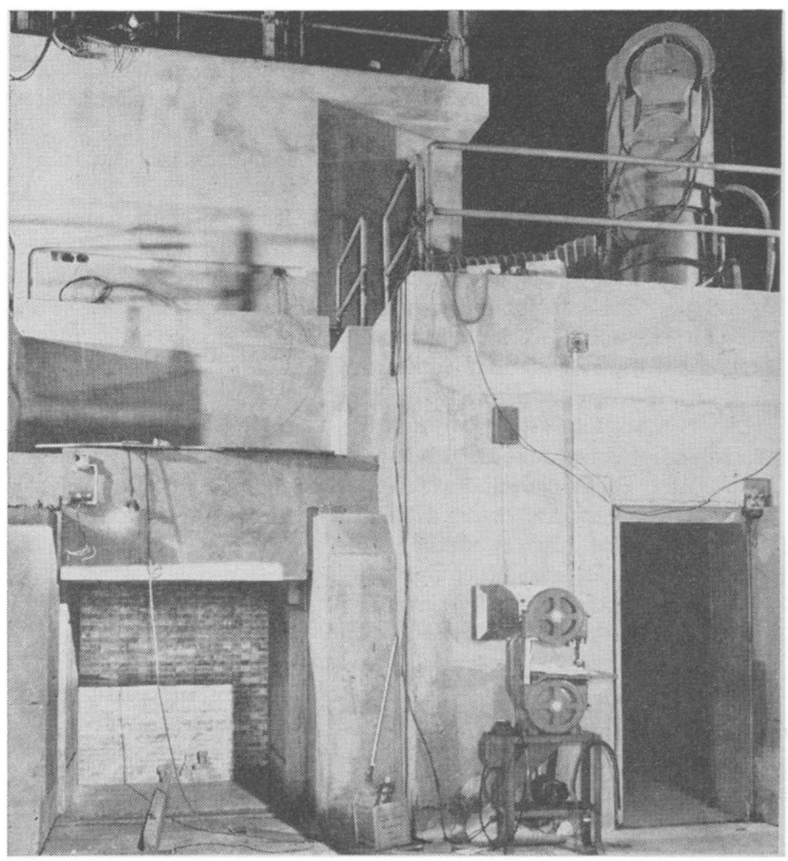


Fig. 7 (left). A view from beneath the Brookhaven Medical Research Reactor, showing the piping leading from pumps to the reactor tank. Fig. 8 (right). The broad-beam cell, showing the bare graphite reflector in the cell. Adacent is an entry door to an experimental room. This photograph was taken during construction.

the bottom. The tank is 60 inches in diameter and 12 feet high in the widened upper part, which thereby provides at the junction a circumferential shelf inside the tank which can be used as a temporary fuel storage area and as a decay tank. A schematic diagram is shown in Fig. 4. The reactor core is of the MTR (Materials Testing Reactor) general type, with BSF (Bulk Shielding Facility) type fuel elements. No experimental devices penetrate the core. With its configuration obtained with graphite reflectors about the core, a critical mass was produced with 2.249 kilograms of uranium-235 in 17, 140-gram fuel elements, each of 18 plates. The fuel is uranium-235 of over 90 percent enrichment, rolled into aluminum-clad plates.

Furthermore, the core design is such that, according to analyses made, the unit will not explode or vaporize in the event of instantaneous removal of all control rods. A dry, graphite reflector, approximately 3 feet thick, is placed around the core. The graphite reflector is cooled by filtered air that is blown through cooling passages provided. This exhaust air, and all air exhausted from the building, is passed through absolute-type filters and discharged from a stack 150 feet high. The core temperature is maintained by circulating natural water at 600 gallons per minute. To improve neutron economy the grid spaces about the fuel elements are filled with dummy units of graphite. All experimental channels through the shielding and graphite terminate in the graphite reactor. The operating conditions are controlled by three centrally located safety rods and one more peripherally placed regulating rod (Figs. 5 and 6). The control and regulating rod entrance tubes are located between fuel elements, rather than within fuel elements. This permits removal of fuel elements and reinsertion without disturbing the control rods. The water pumps, heat exchanger, and water treatment equipment are located in the basement of the reactor building (Fig. 7). The water treatment equipment is a standard, commercially available, mono-bed, ion-exchange column. The assumed duty cycle at present is 8 hours on and 16 off.

Since this reactor was designed specifically for use in the Brookhaven medical research program, it provides two shielded rooms, on either side of the reactor, primarily to further studies on neutron effects with particular reference to development of neutron capture therapy (*3*). Vertically moving shutters weighing 20 tons are provided to control neutron and other radiation emission through special ports into these rooms.

The construction differs on the four faces between the core tank and the exit ports or external shielding, as the case may be. Between the core tank and the broad-beam cell there is only graphite. Similarly, only graphite fills the space between the core tank and the external face shield where the instrumentation and activation ports lie. However, between the core tank and the exit ports of the two treatment rooms there exists a complex of reflector, moderator, screen, and filter, so that appropriate and requisite purity of emitted radiation can be attained. Approximately ¼ inch from the core tank is a wall of graphite 6 inches thick. From the center to the periphery, there are a ½-inch air gap and a 2-inch bismuth gamma shield encased in a spray coat of pure magnesium 1/30,000 inch in thickness. Then there is another ½-inch air gap, followed by another magnesium-encased bismuth gamma shield 5½ inches thick. This, in turn, is followed by another air gap, a thin magnesium window of AZ-31 alloy, another air gap, and then the tanks made of pure aluminum. The outside dimensions of the three tanks as one unit are 30½ inches wide and 31½ inches high, with each tank approximately 1½ inches thick. Then there is another air gap of approximately ⅜ inch, and another magnesium window which bounds the reactor fixed ports from the shutter mechanism. At present, in the shutter itself, there are 13 inches of graphite and then a final gamma shield of 4 inches of bismuth, with an air gap to the plastic wall in the shutter opening. Of the highest import is not only the purity of materials in these various components but also the geometry and the relationship of the components to one another. It is planned to fill one or more of the tanks with heavy water, which, it is believed, will provide very effective moderation and permit the selection, at will, of several average energy values of emergent neutron streams. Under maximum moderating conditions, it is believed the exit neutrons will be largely of thermal energies with a slow-to-fast ratio of 10^4. Thus it can be seen that by appropriate selection of moderating liquid, screen, filter, and shields, a variety of effects can be achieved. This system has not been tested, and it is hoped that these tests can be completed this fall.

It must be pointed out that the construction design is such that the entire system of moderators and shields leading to the exit ports in the treatment rooms can be removed as desired for alteration, substitution, or elimination of any given component part. Structurally, this is the system which markedly sets this reactor apart as a medical reactor. It is in the area of extensive exploration into the effects of configuration and materials on neutron number and quality that fields of medicine and engineering have a maximum joint problem in technology, since it is presumed that any future type of operating core can be fitted to the system which will be developed here.

The exit port can be varied in size from 10 by 10 centimeters to 40 by 40 centimeters, presumably with a relatively uniform neutron field over the mouth. Test runs have thus far shown a maximum flux of 2.4×10^{10} thermal neutrons per square centimeter over a 40-by-10-centimeter port. A thermal neutron is here defined as one with an energy of 0.025 electron volt. This is approximately one-tenth of the flux it was hoped would be obtained. However, by the time present tests are completed, it is believed the desired flux will be reached.

One face of the reactor has been left essentially bare except for graphite. This broad-beam cell (Fig. 8) is designed to permit various studies of shielding effectiveness in a "sea" of neutrons as well as to permit a wide variety of mammalian exposure studies. Tubes deep in the graphite reflector and ending tangent to the core tank are provided for production of radioactive isotopes of short half-life, as for therapeutic and diagnostic use.

The reactor will permit not only exploration of the practical application of neutron capture therapy, but also intricate studies of the mechanism of energy transfer to biological systems from neutrons of epithermal and intermediate energy. Studies in progress indicate that the effects upon cytological structures of the central nervous system of thermal neutrons are far below what might have been predicted. The reaction tubes will be utilized in studies of activation analysis, but these will by no means be limited to materials or specimens. In-vivo activation occurs during neutron capture therapy. The extent and nature of the activation are being studied by gamma spectroscopy as a first step. This is the first procedure which has been developed which permits one to make any significant measurement of effective integrated thermal neutron infiltration.

In developing these and other studies the operational routine of the reactor will be markedly varied. It is hoped that it may be used for very large neutron burst pulses as well as more usual continuous operation. Thus far the maximum power level reached is 3 megawatts; the reactor design permits continuous operation at this power.

Brookhaven National Laboratory

While the reactor has been described largely in terms of its development of Brookhaven's medical program, it must be made clear that it is one dramatic representative product of the interplay between various scientific and engineering disciplines represented on Brookhaven's staff. In this environment the staff of the Medical Research Center is composed not only of medical department members but also of colleagues working daily within their own specialties, who come from the reactor operations, nuclear engineering, chemistry, physics, instrumentation, and health physics departments of the laboratory.

Brookhaven National Laboratory is a civilian academic establishment, operated under the guidance of nine major private universities of the Northeast area. They supervise its administration through a corporate entity, Associated Universities, Inc., chartered under the education laws of New York State. Supporting funds are obtained by the corporation from the U.S. Atomic Energy Commission under terms of a specific contract (*4*).

References and Notes

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X-ray Emission from Television Sets

The gonad dose to the population is evaluated on the basis of laboratory and field measurements.

Carl B. Braestrup and Richard T. Mooney

It has long been realized that any electronic tube operating at a potential above a few thousand volts may be a source of x-radiation. The need for eliminating any resulting hazards received official recognition by the American Standards Association in 1946 (*1*). It was specified that the radiation level at any accessible region "shall not exceed 12.5 mr/hr"—that is, 100 milliroentgens per 8 hour day, the then-prevailing maximum permissible dose (MPD). The purpose of this requirement was to prevent radiation injury to the individual; no consideration was given to genetic effects at that time. The maximum permissible dose has since been progressively reduced; the present limit for radiation workers is an average of 100 mr per week.

Since the publication of the reports of the International Commission on Radiological Protection (*2*), the National Academy of Sciences (*3*), and the British Medical Research Council (*4*), attention has been focused on the genetic effects of ionizing radiation. It is now agreed that the dose to the gonads should be kept as low as possible without sacrificing the many benefits associated with the use of radiation. For this reason, a further reduction has been made in the maximum permissible dose for persons not occupationally exposed. For individuals in the environs of radiation areas, the National Committee on Radiation Protection (*5*) has set the maximum permissible dose at 0.5 rem per year. An additional limit has been recommended for the exposure of large population groups. The National Academy of Sciences has proposed that the average exposure of the population's reproductive cells to radiation above the natural background, but including the contribution from medical exposure, should be limited to 10 r from conception to age 30. The International Commission on Radiological Protection has recommended that the genetic dose to the whole population from all sources, additional to the natural background, should not exceed 5 rems plus the lowest practicable contribution from medical exposure (*6*). Consequently, even sources of minute radiation are of interest if they affect a large percentage of the population. Yet there have been very few scientific publications concerning sources of nonuseful x-rays such as cathode-ray tubes, oscillographs, electron microscopes, and television and other electron tubes (*7*). Of these, home television is of particular genetic interest because a high percentage of the population is involved.

The present study includes an estimate of the average per capita dose to the gonads from home television sets, based on radiation measurements on representative types of television tubes and the results of laboratory depth dose measurements required to determine the actual dose to the gonads.

Instrumentation

Highly sensitive instruments are required to measure the low level of radiation. Scintillation and thin-window Geiger-Müller counters have the required sensitivity (*8*) but are quite dependent on wavelength. For quantita-

The authors are on the staff of the Physics Laboratory, Francis Delafield Hospital, New York.