THE USES AND POTENTIALITIES OF RESEARCH REACTORS

Herbert Kouts
Brookhaven National Laboratory
Upton, New York

1. Introduction

No radically different research reactors have been put into operation in the United States since the 1958 Geneva Conference. Two very high flux reactors of quite novel design are nearing completion, and substantial improvements have been made on designs of research reactors of types discussed in earlier papers [1,2]. The reduced rate of advance in research reactor design is caused partly by the continued interest in research problems that can be undertaken with existing machines, but it is more the effect of the greater costs of high performance reactors, and of the problems that arise when technology is pushed closer to its ultimate limits.

In this paper we shall consider a number of questions associated with the development of research reactors in the United States. These include the technical advances that have been made since previous reports at these international conferences, the trends in use of research reactors at different kinds of research centers, discussion of some areas in which expansion of research effort is to be expected, speculation on future advances in research reactor concepts, and views on the degree to which research reactors will continue to be important.

2. New Reactors

Two research reactors that in many ways present substantial progress over previous designs in the United States are in advanced states of construction. The High Flux Beam Reactor (HFBR) at Brookhaven National Laboratory will be completed this year (1964); critical loading is expected to take place in the late summer or early autumn. The High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory is expected to become critical about a year later. These reactors are discussed in detail in other papers presented to this conference [3,4].

These reactors are being built in response to specific research needs. Among the many physics and chemistry research groups using neutron beams at the Brookhaven Graphite Research Reactor, several required higher beam strengths than have been available to them. These higher intensities will in some cases provide greater neutron energy resolution needed in diffraction experiments to resolve ambiguities in the structure of certain interesting solid compounds. In other cases, higher intensities are needed to make possible experiments that cannot be done at lower neutron fluxes, or that are at present too lengthy. Two examples are studies of liquid state structure, and the diffraction of polarized neutrons from polarized arrays of nuclei.

The HFIR is being built to irradiate targets of transuranic elements, to convert them to higher atomic number species that will in turn be used as accelerator targets. Exposure in the accelerator will provide a variety of nuclear reactions that will improve knowledge of the high atomic number region of nuclides, and should lead to discovery of as yet unknown elements and isotopes.

The HFBR and HFIR illustrate a trend in the character of high flux reactors. Materials and configurations that are optimum for one kind of research will not be optimum for another kind. Thus the response to different kinds of demands has led to very different kinds of reactors. The HFBR will provide better neutron beams; the HFIR will be a much better irradiation tool.

To achieve high neutron flux in a large volume of the reflector, where beam tubes must be placed, the HFBR emphasizes neutron leakage outward from the core, with low neutron absorption in the reflector. To provide the highest possible flux per megawatt, HFIR design recognizes the need to concentrate neutrons in the small volume of a flux trap at the reactor center. These do not seem to be compatible goals in a single reactor design. Unperturbed thermal flux levels at HFBR isotope irradiation tubes will be slightly in excess of 10^{13} per megawatt, which can be classed as average performance. Unperturbed HFIR thermal neutron fluxes in the flux trap will be approximately 5×10^{13} per megawatt.

The advantage of HFBR over HFIR as a producer of neutron beams is more difficult to assess quantitatively at this time, because critical experiments at Oak Ridge have not explored this point. It is likely that beam tube fluxes per megawatt will be about a factor of two to three greater in HFBR than in HFIR, and that beam quality of the former will be superior.

The Argonne Advanced Research Reactor (AARR), which is now undergoing preliminary design, will provide high thermal neutron flux levels for isotope production, and will also have beam tubes as near optimum as possible for neutron beam research [5]. It is too early to know how this multipurpose design will compare with the other two specialized research reactors in properties that they emphasize. The AARR is expected to have a power level of 240 MW, which if achieved should provide a peak thermal neutron flux in the central flux trap of about 10^{16}. Power levels and flux intensities in this range in small volume research reactors require very high coolant velocities to remove the high heat density. The design assumes a coolant velocity of 45 ft/sec. Operation at moderately high pressure (800 psia) is needed, to provide an ample margin to burnout. The flow rates and fuel temperatures will preclude the use of aluminum fuel elements. Instead, stainless steel clad cermet will be used. The steel will also serve a useful function in the physics of the reactor. The fuel loading must be large to compensate for the neutron poisoning by the fuel element structural material, and so the core life will be reasonably long in spite of the high fuel burnup rate. Some very preliminary parameters of the AARR are given in Table I. Completion in 1969 is expected.

Since the last Geneva Conference, considerable improvements have been made in the research reactors that are offered commercially. The zirconium hydride fueled TRIGA series of reactors built by General Dynamics has profited by the development of an improved fuel element that permits operation at higher temperatures and more numerous pulses than previous elements allowed. Some TRIGA reactors now operate at a maximum steady state power of 1 MW, and a peak power in the pulse mode of 2000 MW. Similarly, a pressure tube element design by American Machine and Foundry is used by that company in research reactors of power levels to 40 MW. AMF reactors with ceramic fuel elements are proposed for operation in the pulsed mode.

In summary, the state of research reactor development at this time in the United States shows a steady improvement and increase in versatility of reactor concepts sponsored by industrial concerns, while the involved problems of recasting the designs to work near limits of technology are being pursued at national laboratories in response to specific research needs existing there.

3. The Question of Optimum Design

The problem of optimizing a research reactor for a particular kind of research can be formulated in several ways. These differ in the conditions that are imposed on the design. Limits may be set by technology, by initial cost or operating cost or some combination of the two, by a maximum power level set by heat sink capacity, or by other considerations. This question of optimum design has only recently become of high interest in the United States. Previously, the design of a research reactor was done as if the experimental facilities were only structural components. They were introduced in whatever ways the design of the reactor allowed. Recent developments recognize that, for instance, increasing the thermal neutron flux in an irradiation facility is equivalent in most instances to increasing the reactor power by the same factor.

Optimizing is, however, a question that is still only imperfectly formulated. It appears that in many cases the reactor, the experimental facility, and the experiment itself must be designed together if optimum performance is to be achieved. This aim is near achievement in the HFIR, for higher isotope production. For other reactors or other research, it is still a distant objective.

The usefulness of a research reactor for experiments based on irradiating samples with thermal neutrons is a direct function of the thermal neutron flux at the sample position. Generally, those reactors that can supply the larger flux levels are the most effective in this way. There are, however, subsidiary questions that sometimes can cloud the question of relative merit of different irradiation facilities. High fast neutron fluxes can cause undesirable nuclear reactions or radiation damage in samples that can reduce the effectiveness of a particular irradiation. High gamma-ray levels can cause excessive temperatures or can produce damage through ionization.

These effects are usually troublesome only in high flux reactors used for experiments that are either marginal or nearly so. The question of optimum design of an irradiation facility taking disturbing effects into account thus depends on the experiments to be done. It appears that no systematic studies have been done on improvement of the ratio of thermal neutrons to fast neutrons or gamma rays in facilities of this kind. For most reactors and for most thermal neutron irradiation experiments, such studies are of no benefit. There are, however, classes of problems for which optimization studies of this kind would have real value. Two examples are activation analysis for elements with low thermal neutron activation cross sections or low concentrations, and irradiations at high fluxes of sensitive material such as biological samples.

The optimum design for experiments done with neutron beams is much more difficult to define. Many kinds of experiment and experimental apparatus need to be considered. Some experiments use neutrons in a narrow band of energy near the thermal peak. Others use neutrons in the epithermal or the subthermal region. Most experiments are more difficult if background count rates are high; total counts for a datum point must be increased to provide the same statistical accuracy as could be reached with smaller total counts when the background is low. Some experiments are background limited. That is, the size of the region over which measurements can be done is set by the signal-to-noise ratio, rather than the total count rate.

Understanding of this question is limited, because insufficient measurements have been made on the amount and quality of the radiation emerging from facilities at existing reactors. When it is considered that the success of the experiments depends directly on the properties of the radiation supplied, this fact is astonishing.

Ideally, the kind of information useful in establishing the merit of a neutron beam facility is the neutron and gamma-ray flux per steradian, as a function of energy, at the place from which the radiation is extracted. This place is the inner end of a simple beam tube, or it is the surface of the scattering block in a through hole. If special features are added, such as lead or bismuth to reduce gamma-ray background, the effects of these on the radiation would be wanted.

In practice, this information is more detailed than can be used in an analysis of the worth of a beam facility for any given experiment. Any given experiment uses neutrons in a particular energy interval. Neutrons of other energies are only a source of background. Accounting for a given count rate by calculations starting from the source intensity requires the use of quite detailed information on the design of the experiment. A calculation of background counting rates starting from source intensities is an almost hopeless goal. The geometric problems of radiation scattering from collimators and shielding, and the multiple scattering from walls of the shielding about the experiment and from the experimental apparatus, seem too difficult to solve precisely.

There is a set of information that could more readily be measured, and that would indicate the merit of beam tube design for most kinds of experiments. The following measures of radiation per steradian at the source would be valuable:

1) Absolute neutron flux per unit energy below the cadmium cutoff;

2) relative integral response of a 1/v detector to neutrons above and below the cadmium cutoff;

3) absolute neutron flux at particular energies as found by resonance detectors such as indium, gold, and cobalt; and

4) fast neutron flux as found by threshold detectors such as Th-232.

To make all this information useful, the count rates and signal-to-noise ratios found with simple and fairly standard experimental apparatus would be needed. A neutron monochromator would be useful for this purpose.

Optimum design of the beam facilities for their experiments and of experiments to match the features of the facilities is a clearly worthwhile goal. This optimizing is one of the outstanding problems of research reactor design. It is not sensible to build expensive research machines without trying to achieve best performance of the experimental facilities.

Ergen has investigated the maximum flux attainable in a reactor with fixed power level and realistic materials [6,7]. He has recently shown that the flux trap design achieves flux levels that are very near the theoretical maximum of any configuration, and that the HFIR is near optimum for maximum thermal flux for a light water moderated reactor of the design power level.

4. Research Applications at National Laboratories

The major research reactors at national laboratories in the United States are used primarily as sources of neutron beams. The experiments conducted are varied, and are mostly in fields of nuclear physics and solid state physics and chemistry. Most of these reactors are also used to some extent for irradiation experiments of various kinds.

At the Brookhaven Graphite Reactor, a large number of neutron crystal spectrometers are used in solid state structure experiments. These supplement x-ray diffraction experiments in measurement of crystallographic constants, and they also provide information on the magnetic alignment of the material used. A wide variety of intercrystalline compounds are studied. Cryogenic facilities are available at many of these spectrometers, so that measurements can be made both below and above the magnetic phase transition temperatures. These neutron diffraction methods are the most powerful available for studying magnetic properties of the solid state.

The nuclear physics studies with beams include slow chopper studies of low energy neutron inelastic scattering from solids and liquids, fast chopper measurements of resonance strength functions, measurements of capture gamma rays produced on thermal neutron capture, and studies of the scattering of polarized neutrons by targets whose nuclei are aligned at the temperature of liquid helium. In-pile experiments include radioisotope production and such applications of thermal neutron capture as radiation damage studies and some engineering loops. A slow neutron irradiation facility is used in studies of mutation and biological damage mechanisms. Apart from pneumatic tubes and other in-core irradiation facilities, forty experimental facilities are being used. Of these, thirty-six are beam tubes.

At the CP-5 reactor at Argonne National Laboratory, there are five crystal diffraction experiments, mostly for solid state structure studies. The neutron physics experiments include capture gamma-ray studies, slow chopper studies of low energy neutron inelastic scattering, fast chopper cross section measurements, studies of properties of neutron mirrors, and measurements of the ability of heavy ice to moderate slow neutrons. A biomedical experiment is concerned with the toxicity of gamma rays and neutrons, but this experiment is shortly to be transferred to the new JANUS reactor, which has been designed specifically for this research. Three irradiation facilities are used for measuring solid state damage and for testing reactor fuel.

Four beam tubes are currently in use at the MTR, at the National Reactor Testing Site in Idaho. A crystal spectrometer and a fast chopper are used in cross section studies. One beam facility uses a slow chopper followed by a crystal monochromator; another uses a double slow chopper. These permit precise and detailed information on low energy neutron inelastic scattering.

Of course, the MTR and ETR reactors are still used mostly for engineering studies such as those of reactor fuel performance and of radiation damage to nuclear reactor materials.

Four neutron beams are in use at the Omega West Reactor at Los Alamos Scientific Laboratory. Two use crystal spectrometers in solid state physics experiments. Two are capture gamma-ray experiments. In-pile experiments include radiation effects studies and research on direct conversion of fission heat to electricity.

At the ORR, at Oak Ridge National Laboratory, six neutron beams are in use. Two crystal diffraction experiments are studies of magnetic order scattering and of the structure of hydrogen-bearing materials. The fast chopper is being used in measurements of transmission cross sections of separated isotopes below about 1 kev, and of gamma-ray spectra from neutron capture in resonances. Nuclear physics experiments are performed on the systematics of fission, with a variety of studies of specific aspects of the process. In-pile experiments in the ORR include applications of activation analysis and radiation damage studies.

It is interesting to note that several smaller reactors at national laboratories continue to be very actively used, even when machines of greater flux are available. The Neutron Source Reactor at Brookhaven and the Juggernaut Reactor at Argonne are primarily devoted to reactor physics experiments and are heavily used. The homogeneous reactor at Los Alamos, which was built during the last war and which is the oldest research reactor in existence, is still run often for such purposes as accurate activation analysis and tests of planned experiments. The original Swimming Pool Reactor at Oak Ridge continues to serve a number of interesting experiments, including, for instance, biological studies of thermal neutron induced mutation of bacteriophage, and thermal neutron induced damage to solids.

This continued use of smaller reactors is a result of their flexibility. A large number of interesting experiments do not require high neutron flux levels, but do call for an ability to change experimental conditions more or less at will. The low penalty attached to shutting down a small reactor for changes to experiments sometimes causes a real preference for using the smaller machines.

5. Uses at Universities and Other Centers

An increasing number of reactors are located at universities throughout the United States. These range in maximum power from a few watts to a few megawatts. The low powered homogeneous reactors of various designs are intended as aids in teaching. They are used for demonstration and for classroom-type experiments, such as demonstration of the kinetic behavior of chain-reacting systems. Since at 100 watts a nuclear reactor produces about as many excess neutrons as several hundred thousand curies of Ra-Be, these small reactors permit substantial improvement over experiments with neutron sources based on radioactive decay.

A wide variety of experiments based on the pioneering studies in neutron physics can be made standard parts of the nuclear physics laboratory curriculum.

Higher powered reactors, such as the pool reactors, the various models of TRIGA, and the heavy water tank-type reactors, are proving to be excellent research tools. Their role in supporting the graduate thesis program of universities has now become firmly established. The nuclear reactor is the only large research machine that can be used in common by nearly all of the experimental sciences, and it offers a unique opportunity for interaction of sci 'ists from different fields.

This potential is being realized in a growing number of universities. An excellent example is afforded by the group using the nuclear reactor at the Pennsylvania State University [8]. This pool reactor is one of the first installed at a university in the United States. It operates at a maximum power of 200 KW, with a central thermal neutron flux approaching 3×10^{12}. Laboratory courses in physics, nuclear engineering, chemistry, and chemical engineering make use of the facility in various essential ways. Nuclear engineering students conduct experiments directly with the reactor, learning about reactor operation, reactor safety, reactor physics, instrumentation, etc. In Modern Physics laboratories, students conduct similar experiments, and also learn techniques of measuring properties of radioactivity, with radioisotopes made in the reactor. Chemical engineering students learn activation analysis and tracer methods. In addition to its use as a teaching aid, the reactor is heavily employed in graduate and faculty research. In the one-year period from July 1, 1962 to June 30, 1963, ten doctors' thesis experiments and eighteen masters' thesis experiments were based on use of the Pennsylvania State University reactor. The integration of the reactor into the University program is indicated by the distribution of doctoral thesis problems: six were in physics, one was in chemistry, one was in agricultural biology, and two were in engineering.

While this is one of the better examples of acceptance of a research reactor into the university community, it is not unique, and it doubtless indicates a trend. The research done is relatively inexpensive. In fact, it includes no neutron beam experiments. It has been demonstrated that many disciplines can make use of the nuclear reactor as a tool in educating scientists to maturity. This demonstration should be of clear advantage to those nuclear centers throughout the world which have similar nuclear reactors. In most of these, the fundamental problem is to make the nuclear center a national asset. Drawing on the advantage to education and graduate student research is the surest and most desirable method.

A number of nuclear reactors have been installed at other centers. Some reactor manufacturers maintain facilities offering specialized services to industry and to research centers. The greatest use of these is for activation analysis, which is relied on as the most sensitive method available for analyzing for minute quantities of material.

A rapidly growing field of use of many reactors is the application to analysis for trace mineral content of blood and blood components, for medical diagnosis. These methods are being used at a number of laboratories. The TRIGA reactor at the Veterans Administration Hospital at Omaha, Nebraska is largely devoted to this problem.

Only a sketch of the distribution and use of American reactors can be given here. The general situation can be summarized by observing that while the existing machines are in most cases heavily engaged, the potential in many cases is only beginning to be realized. The number and usage of research reactors will continue to grow for some time.

6. Future Developments

Mention has been made above of the anticipated continued growth of use in teaching, graduate research, and in support of industry and general technology. The uses of activation analysis in particular have yet to be developed and explored to the degree needed. The sensitivity and accuracy that activation techniques allow make this tool extremely powerful. Applications to criminology, biology, metallurgy, and other fields are already growing rapidly. Two other possible applications should be mentioned, because they have not yet received the attention they deserve. These are assay in mineral exploration and mining, and the analysis for trace minerals in soils and botanical specimens. The development of these fields will supply a host of useful research problems, and the results of the research will have high economic value. These problems require exploring in reactor centers both in developed and developing countries.

The uses of active isotopes in medicine, both for diagnosis and therapy, are firmly established. Growth in number of kinds of techniques and of their application must be expected to continue. Similar remarks apply to the use of tracer techniques in biology and chemistry.

Certain fields in physics require special mention, because of probable growth induced by recent technological advances. The development of lithium drifted germanium detectors is expected to have a profound effect on gamma-ray spectroscopy. The excellent resolution of these detectors should open new fields in capture gamma-ray spectroscopy and the study of nuclear systematics. (The sensitivity of activation analysis techniques should be affected as well.) It is anticipated that many new capture gamma-ray experiments will be brought into operation in the next few years, and that many previously measured radioactive decay schemes will be investigated again.

The development of cryogenic techniques in solid state experiments increases the amount still to be done in a field which, though very active, will continue to support much significant new research for a long time.

Some other research reactor applications that should continue to expand are: the study of slow neutron induced biological mutations, the study of slow neutron induced damage to organic and inorganic solids, and the applications of pulsed reactor techniques to phenomena with short characteristic relaxation times.

On the other hand, the measurement of neutron cross sections with reactor neutron beams is already decreasing, because of the striking advantages afforded by pulsed accelerators. Unless new techniques advantageous to reactor-based research are found, this decline will continue.

The development of high flux reactors will continue to be of interest, because of the new kinds of research they will support. But it is difficult to see how the technology can be strained to exceed the expected AARR performance by a sizable factor. It is believed that further advances in high flux reactor development will come from more efficient design and use of the experimental facilities. Other reactor concepts are being explored actively so as to increase the potential for certain kinds of experiments. Two concepts being actively pursued are: fast neutron research reactors, and high average power pulsed reactors.

References

[1] HUFFMAN, J.R., and WEINBERG, A.M., in Progress in Nuclear Energy, Reactors (II), Vol. I (CHARPIE, R.A., HUGHES, D.J., LITTLER, D.J., and TROCHERIS, M., eds.) Pergamon Press, London and New York (1956) 49-110.

[2] Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy in Geneva, 10, United Nations, Geneva, 1958. Various papers by American authors.

[3] HENDRIE, J.M., report to this Conference on the HFBR.

[4] SWARTOUT, J.A., report to this Conference on the HFIR.

[5] FROMM, L.W., private communication.

[6] ERGEN, W.K., The Highest Thermal Neutron Fluxes Obtainable from Fission Reactors, in Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy in Geneva, 10, United Nations, Geneva, 181-184.

[7] ERGEN, W.K., private communication.

[8] REMICK, F.J., Eighth Annual Progress Report of the Pennsylvania State University Nuclear Reactor Facility, June, 1963.

TABLE I

AARR Core Thermal and Nuclear Characteristics

Power, MW	100	240
Coolant		
Flow rate, lb/hr	7×10^6	8×10^6
Velocity, ft/sec	40	45
Inlet temp, °F	135	< 135
Outlet temp, °F	183	215
Inlet pressure, psia	800	
Heat Flux, 10^6 BTU/hr-ft^2		
Average	0.56	1.34
Nominal maximum[a]	1.36	3.27
Hot spot	1.77	4.25
Power Density, MW/liter		
Core average	1.30	3.11
Nominal maximum	3.2	7.6
Hot spot	4.2	10.0
Fuel Loading, kg U^{235}	60	
Core Volume, liters	77	
Core Lifetime at Full Power, days	90	37
Core Lifetime at Full Power with Full Xenon Override Capability, days	75	27
k_{eff} Cold, Clean	1.22	

[a] With power flattening by radial variation of fuel loading.