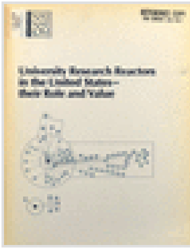

University Research Reactors in the United States: Their Role and Value (1988)

Pages
167

Size
8.5 x 10

ISBN
030931951X

Committee on University Research Reactors; Energy Engineering Board; Commission on Engineering and Technical Systems; National Research Council

University Research Reactors in the United States— their Role and Value

Prepared by the
Committee on University Research Reactors
Energy Engineering Board
Commission on Engineering and Technical Systems
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1988

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This is a report of work supported by Contract No. DE-AC01-86ER75241 between the U.S. Department of Energy and the National Academy of Sciences.

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PREFACE

This study was undertaken in response to a request to the National Research Council's Energy Engineering Board by the Office of Energy Research, U.S. Department of Energy (DOE) to evaluate the contributions of university-based research reactors (URRs) to research and education in nuclear science and engineering.

DOE wanted the evaluation to consider the fact that universities face increasing costs, decreasing enrollments and research in nuclear science and engineering programs, anticipated increases in regulation, and concerns about reactor safety and security. Indeed, some universities are simply closing their reactor facilities. These issues--viewed in light of national benefits-- are the focus of DOE's interest. Specifically, DOE is concerned with the future supply of workers for the nuclear-related professions as well as with the importance of URR research to U.S. technological standing worldwide.

The Energy Engineering Board established the Committee on University Research Reactors to conduct the study, with the following tasks:

- Review and evaluate existing university research reactors to determine their role in meeting the needs for education, training, research, and service in relevant fields of science and engineering
- Evaluate the specific mandates and interests represented by academic, government, and industry organizations with respect to university research reactors
- Review and evaluate the use and support of similar reactors elsewhere, in Western Europe, for example
- Review security and safeguard issues involving university research reactors
- Evaluate the role of university administrations and other entities in support of URR programs
- Evaluate the role of the federal government in support of URR programs

- Provide recommendations and/or options for federal and other support of university research reactors.

The above scope evolved from an initial study plan that included tasks on new nuclear fuels (i.e., low enriched uranium) and a review of reactors in Japan. The Committee emphasized tasks that would articulate the roles of the reactors and values to the user constituency and to the national interest. For example, a study of the Japanese experience was judged by the Committee to be of only minor relevance to the URR context in the U.S., while tasks on the federal role and support and on the role of university administrations were added as being of vital concern to the future of URRs.

In pursuing these tasks, the Committee organized a workshop (see Appendix A for the agenda) held in February 1987 at the Lawrence Berkeley Laboratory.

The Committee is grateful to members of the research reactor community who prepared presentations and attended the workshop (see Appendix B for the names of panel participants). The information and views presented were of great value. Additional workshop participants are listed in Appendix C. We appreciate the input of all who attended.

This study was sponsored by the Department of Energy's Office of Energy Research. The interest and support of Dr. Antoinette Grayson Joseph, Richard E. Stephens, Harry Young, and Keith Brown are gratefully acknowledged.

The Committee thanks Dr. Stephen Rattien, Deputy Executive Director of the Commission on Engineering and Technical Systems, for his attendance at the workshop and his valuable suggestions in preparing this report.

The Committee also thanks Archie L. Wood, Director of the Energy Engineering Board, for his invaluable insights and suggestions; Dennis Miller, former Director of the Energy Engineering Board, for initiation and overview of this study; Dr. Jack W. Beal, Technical Consultant, who assisted in preparing this report; and, particularly, Rosena Ricks for her help in organizing the workshop and other Committee meetings and in preparing this report. Finally, we are especially grateful to Frederic March, whose tireless efforts on behalf of the Chairman provided an extra dimension of staff support by the Energy Engineering Board, and added materially to the quality of the report.

David A. Shirley, Chairman
Committee on University
Research Reactors

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TABLES

EXECUTIVE SUMMARY

THE NATURE OF THE PROBLEM

Over the past two decades the number of nuclear reactors used for research and education on university campuses has declined from about 76 to 40. Moreover, while some universities continue to maintain and even upgrade their reactors, further reductions are expected. The reasons for this include competition for limited university funds, poor external funding prospects, lack of growth in the nuclear power industry, and, in some cases, prolonged hearings and litigation associated with licensing procedures. In effect a vicious circle has developed in which reduced support leads to lower faculty and student interest, which leads to under-utilization, which leads to lower motivation for continued support and so on.

It was a premise of this study that given the training, research, manpower development and other needs in the nuclear field, this trend should not be permitted to go too far. Policies that will limit closures and encourage modernization of a sustainable subset of existing reactors, sufficient in numbers and types to meet national and academic needs for research, education and service are clearly in the national interest.

To formulate such policies, the Committee addressed the following questions:

- What national interests (scientific, technical, medical and educational) are served by on-campus research reactors?
- What academic values derive from university reactors?
- Is federal financial support necessary or desirable to arrest current trends and assure the retention of an adequate population of university research reactors?
- What levels and types of federal support, if any, should be provided?
- What guidance can be offered to universities and to the federal government pursuant to reasonable and prudent licensing of university research reactors?

PRINCIPAL FINDINGS

Pursuant to the National Interest

The national interests served by university research reactors include:

- development of high-technology applications in fields such as materials sciences, fluid dynamics, and biomedical sciences, using reactors as sources of neutrons;
- research contributing to the future of nuclear power reactors, including the scientific basis for new concepts, for safeguards, and safety; and,
- education of personnel needed to operate, maintain and improve reactors and other facilities associated with national defense and nuclear power activities.

The Committee finds that the existing population of university research reactors, as a whole, does not adequately fulfill these national interests, particularly with respect to the use of neutrons in the development of high technology. Moreover, in several important research areas the U.S. is not currently on a par with Europe and Japan. Deficiencies at U.S. university research reactors, stemming in part from inadequate financial support, include inadequate peripheral research equipment such as spectrometers, cold sources, and radiographic equipment. The effects of these deficiencies would be reduced by better access for university-based researchers to major national facilities which are better equipped. But opportunities for such access are now inadequate.

The Committee is concerned that a failure to correct these deficiencies, coupled with a continuation of the trend in reactor closures, will serve to widen an existing gap of U.S. neutron science capabilities.

The Committee is also concerned that future national needs for nuclear engineers and scientists trained in the neutron sciences may not be met if the current negative trends continue.

However, selective reduction in the number of university research reactors will not of itself damage the national interest, provided that a healthy core of on-campus and off-campus research and educational reactor facilities is retained.

Pursuant to Academic Values

The Committee finds that on-campus research reactors contribute to academic values through research and education at the university, and through service to off-campus user constituencies:

Research: University research reactors are the focus of multi-disciplinary research with contributions to physics, chemistry, biology, medicine, epidemiology, environmental sciences, material sciences, fluid mechanics, geology, archaeology, paleontology, forensic sciences, and other fields in addition to nuclear engineering research and reactor physics. The three principal reactor research techniques are neutron activation analysis, neutron scattering, and neutron radiography. The latter two are largely confined to reactors of one megawatt and higher power. Research reactors in the United States constitute unique and essential research tools in several aspects: structural determinations of materials including superconductors and biologicals, ultrasensitive analysis for traces of elements, radiological display of physical phenomena, and introduction of radioisotopes for medical diagnostics and research (See Chapter 2).

Education: On-campus reactors have been a traditional focus of educational programs for nuclear engineers. In addition, on-campus reactors are increasingly used as laboratories by students in the non-nuclear fields listed above. Educational uses are made of even the smallest fractional watt on-campus reactors. Beneficiaries include graduate and undergraduate students, as well as nuclear power plant operators, secondary schools and the general public through outreach programs (See Chapter 3).

Service: University reactors, particularly those of one megawatt and larger, serve a range of off-campus constituencies: the medical community, industrial organizations, and government agencies. These clients use irradiated materials, materials analysis, trace element detection, and radiographic analysis of objects and processes. By providing such services, managers of university research reactors establish beneficial links to off-campus users, expose faculty and students to commercial applications of the nuclear sciences, and earn revenues to help support reactor programs (See Chapter 4).

The Committee finds that U.S. university research reactor facilities must be upgraded and provided with modern equipment if they are to meet their intended objectives and become world-class research and educational facilities. Needs include modern instrumentation, low temperature irradiation facilities, cold neutron capabilities, modern spectrometers, radiographic equipment, increased power and neutron flux, and other enhancements.

University administrators, in weighing the future of on-campus reactor programs take into account the following factors:

- academic benefits in terms of research, education, and service;
- costs of achieving these benefits including the costs of safety and safeguards, as well as dealing with legal actions and protests;
- the availability of resources from federal and other sources to defray these costs; and

- competition from other on-campus research facilities for limited financial and other resources.

The academic benefits associated with university research reactor programs are summarized above and are discussed in detail in Chapters 2,3, and 4.

On-site reactors, clearly, enhance the educational and research missions of a university. Properly equipped and managed on-campus reactors offer unique advantages in terms of hands-on education and research experience in running small scale experiments which would not be practical at larger off-campus reactors. However, it cannot be concluded that every on-campus research reactor is essential to these missions. This depends on the particulars of the educational program, and on the the nature of access to off-campus research reactors.

Pursuant to Procedures for Safety and Safeguards

The Committee observes that the safety and safeguard records of on-campus reactors have been excellent. Nevertheless, a growing concern for reactor safety, as well as the potential for sabotage and for theft of nuclear materials, has led the Nuclear Regulatory Commission to upgrade the requirements for the protection of all reactors from the largest 3500 Mw (thermal) electric power facilities, down to the smallest university reactor. The Committee does not take issue with the Commission with respect to these concerns. However, the Committee finds that some of the procedures of the Nuclear Regulatory Commission associated with improving safety and safeguards at university reactors can result in costs out of proportion to the improvements achieved. A particular concern is that relicensing procedures associated with reactor safety and safeguard upgrades can in some cases unnecessarily expose the universities to costly hearings and litigation. The Committee is also concerned that existing rules and procedures for the licensing of university research reactors have at times lent themselves to abuse by intervenor groups who use the opportunity to assert their larger political opposition to nuclear power and defense activities (See Chapter 6).

PRINCIPAL RECOMMENDATIONS

The federal government, in partnership with the universities and the national laboratories, should develop and implement a national research reactor strategy, the elements of which should include:

- development of university and national laboratory centers of excellence in specific areas of the neutron sciences and reactor technology for world-class research as well as for education;
- anticipation that as some university reactors are upgraded and a user's network is created (see below), others are likely to close;
- mechanisms to assure that such closures do not go so far as to damage the national interest related to research and educational capabilities in the nuclear sciences and engineering; and

- development and support of a reactor network to provide enhanced utilization and productivity of U.S. research reactors involving researchers from universities with and without on-campus reactors, and from the national laboratories.

To implement the above strategy:

- a single federal agency should be designated to administer programs in support of the national research reactor programs; and,
- the federal government should create a standing advisory structure to advise on a continuing basis on all aspects of this program.

In pursuit of this strategy the Federal government should:

- adopt the goals of meeting U.S. research reactor needs, and regaining a position competitive with Europe and Japan in the neutron-based sciences;
- study, in detail, the approaches of other advanced countries to operating research reactor networks such as that of linking the major facility at Grenoble with smaller reactor research centers in Europe (see Chapter 5);
- establish and support such a network, adapted to U.S. needs;
- make up to $20 million available annually (as a preliminary estimate to be modified as improved data becomes available) to universities through the designated federal agency, specifically for operational support and facility upgrades of university research and educational reactors (see Chapter 7); and,
- create a peer review mechanism to assist the designated agency in making grants to universities.

The Nuclear Regulatory Commission should examine its current approach to the licensing and regulation of university research reactors in terms of the following issues:

- the small nuclear materials inventories and low power densities of university research reactors, which result in risk factors related to safety and safeguards considerably lower than commercial power reactors (see Chapter 6); and,
- avoiding unnecessary exposure of small university reactor operators to costly hearing and litigation procedures as a condition for licensing upgrades and improvements.

Finally, the Nuclear Regulatory Commission should consider grants of technical and financial assistance to help university reactor operators to comply with upgraded safety and safeguard requirements, including and continuing beyond the current program of assisting with the conversion to low-enriched fuels.

1

INTRODUCTION

PURPOSE OF THIS REPORT

This report explores the role of nuclear research reactors at U.S. universities. These reactors have a history of some 30 years, beginning with North Carolina State University whose reactor went critical on September 5, 1953. The Committee is concerned with the role of the university research reactors (URRs) through the end of this century and beyond.

Originally established for education and research related to nuclear science, technology, and radiochemistry, URRs have since become a multi-disciplinary tool involving physics, chemistry, biology, medicine, materials sciences, and other fields. They remain a vital component of research and education programs at many universities. In particular, research on the properties of nuclei and their transformations continues to be an important part of attempts to understand our world, its past and its future. Nuclear research will continue to have a profound effect on the development of science and technology. This report describes some of the research contributions to progress in several fields.

URRs also play a role in educating people for nuclear-related careers in the power industry, national defense, research and education, as illustrated in this report.

These 30 years have been a period of remarkeble growth in science and technology. Universities, in their efforts to provide constituencies with current state-of-the-art contributions to research and education, constantly evaluate new opportunities and set academic priorities. At the same time, programs perceived to be of less relative value to the university are terminated. Research reactor programs in particular have been adversely affected by these shifting priorities. Substantial changes in patterns of federal funding by the Department of Energy and the National Science Foundation have been a major contributing factor. Some further reduction in the population of URRs appears likely given current circumstances and trends.

The Committee is concerned that additional erosion of university reactor programs will reduce the nation's research and development capability and output in several important areas of science and technology. It may also adversely affect the supply of educated workers needed for a variety of essential scientific and engineering disciplines that benefit from programs at university reactor centers.

Accordingly, this report is primarily addressed to the people who make decisions affecting the levels of future university reactor programs: university administrators, department heads, federal policy makers, state and local policy makers, those in industry and government who depend upon a supply of nuclear-trained personnel, and those who are concerned with the future of the many sciences that benefit from the unique capabilities of nuclear-based techniques as well as from the nuclear sciences themselves.

The major thrust of this report is to illustrate the scientific and social benefits and contributions associated with well-managed and well-funded university reactor programs. Chapters 2, 3, and 4 discuss contributions of research and education on campus and service to users outside the university. The intent is to help a decision maker gain a perspective and appreciation of the scientific, academic, social, and technical values of URR programs.

The report also examines the role of university-like reactors in Europe, where a productive community of researchers is apparently served in an exemplary manner (see Chapter 5). In Chapter 6, the Committee assesses the security and safeguard needs at small reactors in a university setting in order to help gain a perspective on the potential hazards and relative risks involved. The last chapter discusses the kind of commitment and support needed if a significant population of URRs is to remain productive.

HISTORY

Nearly 50 years have elapsed since the discovery of nuclear fission by Otto Hahn and Fritz Strassmann in 1938. Four years later, in 1942, Enrico Fermi and his co-workers demonstrated a self-sustaining nuclear chain reaction under Stagg Stadium at the University of Chicago, thereby initiating the nuclear reactor era. In the ensuing years, nuclear reactors have affected our economic life in many ways, through the direct production of energy as well as through secondary products such as radioisotopes and fissionable materials.

As the fiftieth anniversary approaches, nuclear reactor facilities are embedded in the milieu of a mature and somewhat troubled field, beset with several unresolved questions. The benefits of nuclear power are well-known, but so are the offsetting risks. There is no national consensus on the future development of nuclear power, and no viable process is in sight for developing a national strategy. Other nuclear issues relate to the use and proliferation of fissionable materials in weapons. The multiplicity of non-power and non-weapons uses of nuclear sciences, of high social value, such as that contributed by URRs, is generally not well understood by the public and many policy makers. Public attitudes on all things nuclear reflect ambivalence, uncertainty, and concern.

Against this backdrop, the Committee was charged with evaluating nuclear research reactors in the context of the U.S. university. This charge is complicated by at least three factors. First, the relation of a reactor facility to its university is often multi-faceted, with education, research, and service distributed throughout many academic disciplines. Second, over the past several years, the principal role of URRs has shifted from basic reactor physics and nuclear engineering to more applied research and technology in several disciplines. Further, public attitudes and concerns about nuclear reactors in the broader society often carry over to the university.

Research reactors at U.S. universities date from the mid-1950s. They were the landmark facilities of independent nuclear research first permitted by the Atomic Energy Act of 1954. This law ended the federal monopoly on operation of nuclear facilities and encouraged both universities and industry to begin developing peaceful uses of atomic energy. The federal government has historically provided funds to stimulate university research reactor programs. More recently, federal support has consisted mainly of supplying fuel elements.

The first URR at North Carolina State University began operations in 1953. Within five years, many other universities had some type of research reactor. They were either reactors of significant flux and power for that era, intended as general purpose research tools for university programs, or smaller, low power reactors intended primarily as teaching facilities for nuclear engineering.

The new discipline and curriculum of nuclear engineering had been generally defined by what was being taught at the Atomic Energy Commission's two programs of instruction in reactor science and technology: the Oak Ridge School of Reactor Technology and the International School of Nuclear Science and Engineering (ISNSE) at the Argonne National Laboratory. The first specification of nuclear engineering as a major field of academic study was at Iowa State University in the early 1950s; again, many other universities followed suit within a short time.

Selection of a particular reactor design for university use was influenced primarily by its expected use and by a faculty's familiarity with the various reactor types. However, universities interested in education and research tended to select the swimming pool reactor designs based on the bulk shielding research reactor at Oak Ridge. Universities interested in a tool for instruction and training tended to select either modifications of the Argonaut reactor, developed at Argonne for instructional use by the ISNSE, or the AGN-201, a low power, plastic moderated, homogenous reactor designed and built by Aerojet General Nucleonics.

Many other designs also appeared, ranging from liquid homogenous reactors all the way up to state-of-the-art research reactors such as CP-5, the choice of the Massachusetts Institute of Technology (MIT). When the TRIGA reactors, developed by GA Technologies Inc., became available in the early 1960s, their unique pulsing capability and improved safety aspects were so attractive that many universities ordered one initially or switched to a TRIGA.

As noted, reactor selection depended on expected use. Some universities aspired to the national laboratory pattern in which the primary use would be scientific research, education, and advanced engineering testing. Today, MIT with an upgraded reactor, the Georgia Institute of Technology, and the University of Missouri at Columbia all have high power ($\geq$5 Mw) research reactors that meet broad, multi-disciplinary research and education needs. At the other extreme, several universities acquired small reactors primarily as teaching facilities for nuclear engineering/nuclear science curricula and for student experiments. AGNs and low power ($\leq$100 kW) swimming pool reactors were selected. Many universities sought a compromise that would permit significant research use without creating conflicts between research and teaching. By and large, these institutions today have moderate power (100 kW-1 Mw) TRIGA and swimming pool reactors.

During the 1960s, nuclear energy as a whole, and university nuclear engineering/science departments in particular, prospered. This rapid growth in university research reactors and nuclear education and training was signaled by the 1961 International Atomic Energy Agency (IAEA) conference (IAEA, 1962). Represented at this conference were 31 countries with a total of 250 operating research reactors. Of this number, about 30 research reactors were operational at U.S. universities, and 16 more were under construction. Two early documents of retrospective importance are the proceedings of the (U.S.) University Reactor Conference held in 1960 and a 1960 National Science Foundation report. A more recent and equally significant symposium was held in 1983 at which U.S., European, and Japanese research contributions were presented (Harling, Clark, and von der Hardt, 1984).

The mood about nuclear research and nuclear energy in the 1960s was decidedly positive. Nuclear research, nuclear power, and nuclear education flourished and expanded rapidly. By 1970, about 70 university research reactors were operating. However, their work was changing. Research priorities in the physical sciences, particularly in fundamental nuclear physics at research reactors, were also changing. Nuclear engineering and development began to focus on applied technological problems that could be addressed at special purpose reactor facilities at the national laboratory centers. At this time, several service functions of university reactors came to the fore: irradiations for isotope production to be used in chemical and biological research, irradiations for neutron activation analysis, provision of neutrons for radiography, materials research, and neutron therapy, for example. Many university programs began to shift away from the more traditional nuclear science and engineering programs to a broad range of effort using reactor-produced materials and radiation in other disciplines.

In the 1970s and 1980s, public support for nuclear energy declined as the nuclear power industry experienced economic and technical difficulties. This loss of support was echoed by some university administrators who began to question the educational efficiency of on-campus research reactors. The shifts in research priorities noted above are of considerable importance to the future of URRs. Not all the universities were able to change their reactor use, and not all reactors could shed the images associated with a troublesome nuclear power industry and maintain institutional support; the reactor might not be able to support new types of work; or the faculty were simply not interested in moving into new areas of research. Additionally, enrollment in nuclear engineering programs dropped. During this period, many nuclear science and engineering programs at universities were simply abandoned or merged into other departments. Reactors were shut down and federal funding for nuclear education and research reduced or withdrawn altogether.

UNDERSTANDING THE PRESENT SITUATION

In order to focus the Committee's deliberations on the role of URRs in the present environment, the Committee held a three-day workshop at the Lawrence Berkeley Laboratory on February 2-4, 1987. It was designed to facilitate broad input by the scientific community interested in URRs. This goal was achieved through active participation of more than 70 attendees from the United States and several foreign countries (see the appendices). Views and conclusions expressed at the workshop provided valuable source material for the Committee. Though the conclusions and recommendations presented here are the Committee's own, they reflect the views of an informed segment of the science community.

One hundred power reactors and 115 research, training, test, and production reactors operate in the United States today. Within the latter group, 60 are research reactors, 40 of which are located at 36 university centers, 16 in federal laboratories, and 5 in industry. Among the more powerful research reactors (i.e., 2 Mw or above), 7 are in universities, 7 in federal laboratories, and 1 in industry. Table 1-1 lists the 40 URRs and their power levels. Table 1-2 lists the location and power levels of the 16 federal laboratory research reactors, and Table 1-3 lists the 5 industrial research reactors. It is noteworthy that, over the past decade, more than 20 URRs have been closed and decommissioned. A list of URRs known to have closed is provided on Table 1-4.

As Table 1-1 shows, URRs in the United States are heterogeneous. They range in power level from a high of 10 Mw to below 1 w. In addition, URR missions vary from mostly research for the higher power reactors to mostly education/training for the smaller ones. URRs also perform substantial service roles, such as providing isotopes and irradiating materials for research, medical, and other uses.

URRs vary widely in institutional setting, support structures, and clientele. Because of this diversity, the Committee's charge was organized under several general headings described in the following

Table 1-1. Research Reactors at U.S. Universities, May 1987

Owner	Designation	Power (Megawatts)
Missouri, University of (Columbia)	MURR	10
Georgia Institute of Technology	GTRR	5
Massachusetts Institute of Technology	MITR - II	4.9
Michigan, University of	FNR	2
Rhode Island Nuclear Science Center[a]	RINSC	2
New York, State University at Buffalo	SUNY	2
Virginia, University of	UVAR	2
Illinois, University of	UI-TRIGA	1.5
Lowell, University of	ULR	1
North Carolina State University	PULSTAR	1
Oregon State University	OSTR	1
Pennsylvania State University	PSBR	1
Texas A&M University	NSCR	1
Texas, University of (Austin)	UT-TRIGA	1
Washington State University	WSUR	1
Wisconsin, University of	UWNR	1
		(Kilowatts)
California, University of (Irvine)	UCI-TRIGA	250
Kansas State University	KSU-TRIGA	250
Maryland, University of	MUTR	250
Michigan State University	MiSU-TRIGA	250
Reed College	RRF	250

Table 1-1. Research Reactors at U.S. Universities, May 1987 (Continued)

Owner	Designation	Power (Kilowatts)
Missouri, University of (Rolla)	UMRR	200
Arizona, University of	UA-TRIGA	100
Cornell University	Cor U-TRIGA	100
Florida, University of	UFTR	100
Utah, University of	Utah-TRIGA	100
Washington, University of	UWNR	100
Iowa State University	ISU	10
Worcester Polytechnic Institute	WPI	10
Ohio State University	OSURR	10
Purdue University	PUR-1	1
		(Watts)
Cornell University	ZPR	100
Oklahoma, University of	AGN-211P	15
Idaho State University	AGN-201M	5
New Mexico, University of	AGN-201M	5
Texas A&M University	AGN-201M	5
Utah, University of	AGN-201	5
Illinois, University of	UI-LOPRA	1
Manhattan College	MCZPR	0.1
Rensselaer Polytechnic Institute	RPI	Critical

SOURCE: Burn, 1983, 1987.
[a]State operated.

Table 1-2. Research Reactors at U.S. Government Laboratories, May 1987

Owner	Designation	Power (Megawatts)
Oak Ridge National Laboratory	HFIR	100
Brookhaven National Laboratory	HFBR	60
Oak Ridge National Laboratory[a]	ORR	30
National Bureau of Standards	NBSR	20
Los Alamos National Laboratory	OWR	8
Brookhaven National Laboratory	BMRR	3
Oak Ridge National Laboratory	BSR	2
Oak Ridge National Laboratory	TSR II	1
U.S. Geological Survey (Denver, CO)	GSTR	1
		(Kilowatts)
Argonne National Laboratory	JANUS	200
Idaho National Engineering Laboratory	CFRMF	100
Veterans Administration (Omaha, NE)	TRIGA (VA)	18
Oak Ridge National Laboratory	HPRR	10
Oak Ridge National Laboratory	PCA	10
Idaho National Engineering Laboratory	ARMF	10
Argonne National Laboratory West	ZPPR	2

SOURCE: Burn, 1983, 1987; for Argonne, Argonne National Laboratory, 1986.
[a]Currently shut down.

Table 1-3. Research Reactors at U.S. Industrial Centers, May, 1987

Owner	Designation	Power (Megawatts)
Cintichem, Inc. (Hoffman-LaRoche), Tuxedo, NY	UNCR	5
GA Technologies Inc. San Diego, CA	GA TRIGA F	1.5
		(Kilowatts)
GA Technologies Inc. San Diego, CA	GA TRIGA I	250
Aerotest Operations, Inc. San Ramon, CA	ARRR	250
General Electric Company Pleasanton, CA	NTR	100

SOURCE: Burn, 1983, 1987.

Table 1-4 University Reactor Shutdowns Reported By the American Nuclear Society to 1983

CALIFORNIA POLYTECHNIC STATE UNIVERSITY
Aerojet General Nucleonics Reactor (AGN-201-100)
COLORADO STATE UNIVERSITY
Aerojet General Nucleonics Reactor (AGN-201-109)
ILLINOIS INSTITUTE OF TECHNOLOGY RESEARCH INSTITUTE
Armour Research Reactor (ARR(L-54))
NORTH CAROLINA STATE UNIVERSITY
North Carolina State College Reactor 1 (NCSCR-1)
North Carolina State College Reactor 2 (NCSCR-2)
North Carolina State College Reactor 4 (NCSCR-4)
North Carolina State University Research Reactor (R-63)
OREGON STATE UNIVERSITY
Aerojet General Nucleonics Reactor (AGN-201-114)
POLYTECHNIC INSTITUTE OF NEW YORK
Aerojet General Nucleonics Reactor (AGN-201M-105)
PUERTO RICO NUCLEAR CENTER
Puerto Rico L-77 Reactor (1-77)
Puerto Rico Nuclear Center TRIGA Flip Reactor (TRIGA)
RICE UNIVERSITY
Aerojet General Nucleonics Reactor (AGN-211-101)
STANFORD UNIVERSITY
Stanford Pool Reactor (SPR)
UNIVERSITY OF AKRON
Aerojet General Nucleonics Reactor (AGN-201-104)
UNIVERSITY OF CHICAGO
Chicago Pile (CP-1)
UNIVERSITY OF DELAWARE
Aerojet General Nucleonics Reactor (AGN-201-113)
UNIVERSITY OF ILLINOIS
University of Illinois TRIGA Mark I (UI-TRIGA-MK I)
UNIVERSITY OF WYOMING
University of Wyoming L-77 Reactor (L-77)

Table 1-4 University Reactor Shutdowns Reported By the American Nuclear Society to 1983 (Continued)

WEST VIRGINIA UNIVERSITY
Aerojet General Nucleonics Reactor (AGN-211-103)

ADDITIONAL CLOSURES REPORTED TO THE COMMITTEE

Brigham Young University	Stanford	University of Oklahoma
Catholic University	UCLA	University of Kansas
Columbia University	Berkeley	University of Utah
Northwestern	VPI	

SOURCE: Research, Training, Test and Production Reactor Directory American Nuclear Society, 1983.

section. This grouping is neither unique nor free of ambiguity, but it worked for the workshop, in the Committee deliberations, and in the organization of this report.

DEFINING THE ISSUES

Research, education, and service in the university setting are the three central missions of the university-based reactor. (They are the subjects, respectively, of Chapters 2, 3, and 4). The issue that takes precedence is:

- Do university research reactors serve the national interest now and in the future in U.S. science and technology?

Underlying this question is the widespread perception that reactor research, teaching, and service have drastically changed in the two to three decades since most university reactors were commissioned. Moreover, there is a trend in related scientific fields toward consolidation around a few large central facilities. The question can be answered satisfactorily by documentating the research, educational, and service activities at URR centers and by evaluating their scientific and academic values, as follows.

Research (see Chapter 2)

Research is the central activity and the most studied by this Committee.

- Which institutions, federal programs, and scientific disciplines benefit from university reactors?
- Does the present relationship of university research reactors to their scientific environment (i.e., users, sponsors, and national facilities) assure the United States a competitive position in reactor-based research?

Education (see Chapter 3)

At issue here is the future of nuclear engineering and science education. The questions of concern to this Committee include:

- What are the educational roles of the various classes of university reactors?
- Are the university research reactors being used, and networked, effectively to serve the needs of all their constituencies?
- Is the university campus the most effective location for effecting reactor-related education and training?

Service (see Chapter 4)

Concomitant with the privilege of operating a research reactor is the responsibility to assist a range of worthy and needful clients for whom the reactor, viewed as a locally unique facility, provides special opportunities. Key issues here include:

- What is the nature of the services rendered?
- Who are the clients?
- What is the value of these services to the clients and to the university?
- Is service essential in medicine, industry, or elsewhere? If so, where?

Foreign Reactor Experience (see Chapter 5)

University class research reactors are operated in many countries. In Western Europe, research reactors are located at universities and research institutes as well as at large national and multinational facilities. Questions of interest include:

- What are the roles of research reactors at the various facilities in the overall Western European nuclear science and technology program?
- How is the research reactor program organized and administered to carry out its mission?
- Is the support available to reactor centers adequate to carry out their respective missions?
- Are the programs effective, and can the United States benefit from the Western European approach?

Safeguards and Security (see Chapter 6)

To some degree, URRs share some of the hazards of nuclear reactors in general. However, URRs differ from commercial power reactors in two important respects: both the fissile material inventory and the thermal power level are considerably smaller. The principal questions are:

- What are the real hazards associated with university facilities?
- What are the appropriate levels of safeguards and security for university research reactors?
- How can user access and flexibility be preserved while maintaining adequate safeguards and security control of material, access, and operating discipline?

Institutional and Federal Support (see Chapter 7)

The Committee examined the patterns of financial support at the university centers. The key questions are:

- What is the proper role of the federal government in supporting the use of university research reactors vis-a-vis other sources of support?
- Of what importance are URR programs?
- Is there national recognition of the importance of university reactor programs?
- What are the factors that work for and against on-campus institutional support?

These and other questions serve to define the issues the Committee studied through the workshop and its own deliberations. The following chapters describe what is important to those concerned with the future of university research reactors.

2

THE SPECTRUM OF RESEARCH AT UNIVERSITY REACTORS

INTRODUCTION

The Nature of the Research

The wide spectrum of research conducted at university research reactors (URRs) enables unique contributions to be made to science and technology in physics, chemistry, biology, medicine, geology, environmental sciences, archeology, and forensic studies as well as in nuclear and reactor engineering. It is important to note that URR programs now extend well beyond the nuclear engineering discipline for which many were originally conceived.

In this chapter, each major area of research carried out at URRs is reviewed. First, three basic reactor methods or tools are described and the range of applied research indicated. These methods are:

- Neutron activation analysis (NAA), an analytical chemical identification technique of extremely broad applicability
- Neutron scattering, an important technique in condensed matter and materials sciences that also has significant applications in biological research
- Neutron radiography, a procedure in which neutron beams are used to probe the internal constituents of otherwise opaque structures.

Second, three specific applied research areas using one or more of the three basic tools are described. They are:

- Biomedical uses, diagnostic and therapeutic applications
- Materials research, involving neutron irradiation of materials
- Nuclear reactor engineering and reactor physics, including future nuclear power safety and efficiency.

Each of these areas offers potential science and technology contributions to society in many ways. Figure 2-1 is a diagram of some of these diverse research topics.

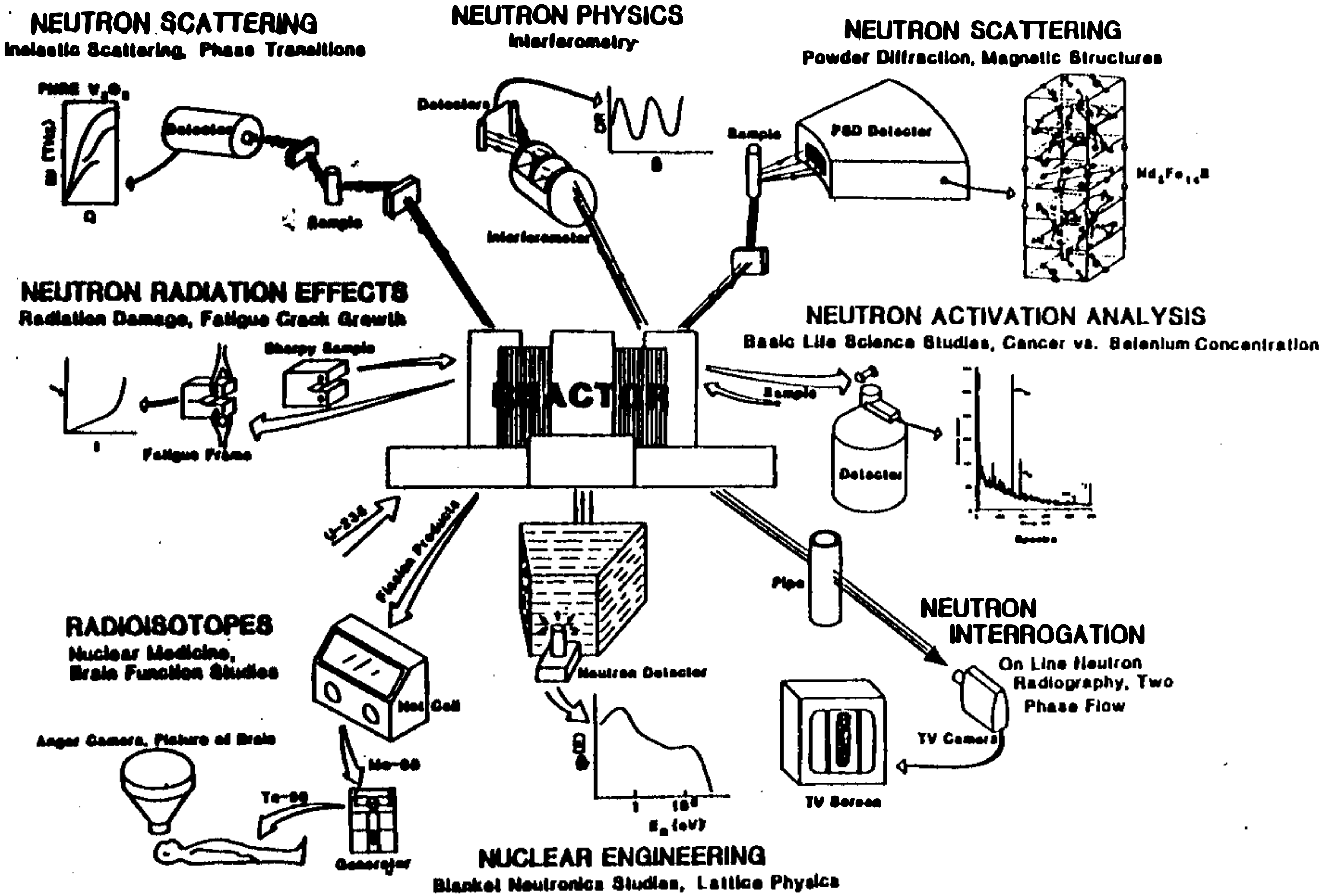

FIGURE 2-1. Examples of Research Activities Performed at University Resea. h Reactors.

Organization of This Chapter

This chapter is organized into six major subchapters, covering each topic indicated above. The intent in each case to illustrate the range of research endeavors, and to show, where appropriate, the academic and other values of the research. Each subchapter begins with a "Description" and ends with "Conclusions", in which the Committee's views of the importance of the research is stated. These subchapters are necessarily expository and technically detailed. For this reason, two additional subchapters precede the six expository subchapters:

- Summary description of URR Research
- Conclusions of Review of URR Research

The "Summary Description" provides a very short synopsis of the major features of each research area. The "conclusions" of the Committee's review of the research areas are then given.

The reader may wish to first read these sections, and then move on to Chapters 3-7, returning to the main body of Chapter 2 for more detailed study.

The Nature of the Reactors

Operating research reactors are listed in Table 1-1. As mentioned in Chapter 1, reactor characteristics and power levels vary widely. The power level, other design features, and instrumentation determine what research is feasible. For example, neutron scattering research requires intense beams of neutrons and consequently can be pursued at only the most powerful reactor sources. Neutron activation analysis, on the other hand, can be done with less power.

Other design features determine research capabilities. Critical questions include:

- Can radiation beams of suitable size originating at suitable internal positions be brought through the necessary shielding for radiographic, scattering, and medical exposure studies?
- Are suitable internal facilities for transferring and irradiating samples available for neutron activation or radiation effects studies?
- Can the reactor be operated in a pulsed mode for real-time studies or other pulsed power research?
- Is there flexibility available in the insertion of facilities within the reactor or in the arrangement of components, diagnostics, and instrumentation outside the reactor?

The URR Research Community and Its Relation to National Reactor Laboratories

Research uses of URRs are determined by the interests of faculty and other researchers, including scientists of many disciplines whose work is enhanced by nuclear science studies. Interaction between scientists and technology specialists across a broad spectrum is characteristic of the university community, and the resulting collaborative research is possibly the most important aspect of the university environment.

The research pursued at URRs complements that performed at the higher power research reactors and neutron sources at the national laboratories: Brookhaven, Oak Ridge, Argonne, Los Alamos, Idaho, and the National Bureau of Standards. While these laboratories are dominant in neutron radiation, URRs make major contributions in selected areas (e.g., neutron activation analysis, interferometry, neutron radiography). Additionally, many new techniques and instruments developed at URRs have been incorporated into national laboratory programs.

Research programs at national laboratory high power reactors naturally reflect the priorities of the resident research staff and exploit the unique characteristics of each reactor. Though national reactor activities are mainly dictated by resident researchers, many university scientists draw upon the national laboratories' special facilities in collaborative work and are strongly encouraged by the national centers to do so.

Enhanced networking of research at URRs with the national high power reactors will increase research productivity. For example, a research program developed initially at a URR is then carried to the national laboratory for more complete execution. A university scientist studying the physical or chemical properties of a new material with non-reactor tools may complement the investigation with a determination of its phonon spectrum or state of aggregation at a URR of sufficient capability or a national laboratory reactor. Chapter 5 reviews the European research reactor network, in which work at small reactors is effectively linked to work at the world class Institut Laue-Langevin (ILL) reactor at Grenoble, France. URR researchers in the United States do not enjoy this kind of sharing.

Preliminary plans are under development at the Oak Ridge National Laboratory and the Idaho National Engineering Laboratory for construction of a new super-reactor, the advanced neutron source (ANS); at a cost of several hundred million dollars. It will supply neutron beams of unprecedented intensity. It will be a new national facility serving the needs of a large community of scientists throughout the country, and university scientists are participating in the planning. This situation represents an excellent opportunity for planning an enhanced network of reactor research to include URR researchers explicitly. Development of the ANS will produce maximum national benefits only by fully using all of the nation's research talent.

SUMMARY DESCRIPTION OF URR RESEARCH

To anyone not trained in basic nuclear sciences, the spectrum of research carried out on nuclear reactors seems arcane and remote from our ordinary economic and social concerns. Indeed, this work is highly technical and the vocabulary is highly specialized. URR research is at the same time extremely practical, and its results have great economic and social value through applications to industrial processes, quality control, new materials, medical diagnostics and therapy, environmental management, and other fields. These are in addition to their traditional contributions to nuclear engineering and reactor physics for power generation and defense technologies.

The topics that follow illustrate the major areas of URR research, emphasizing its interdisciplinary nature and applications to industry, medicine, and government. The first three, "Neutron Activation Analysis," "Neutron Scattering," and "Neutron Radiography," describe the fundamental reactor techniques used in chemistry, biology, medicine, physics, geology, and other fields.

"Biomedical Uses of Research Reactors" illustrates how a single field of research uses the above-mentioned reactor investigation techniques. "Materials Research Using Neutron Irradiation" provides another illustration of how reactor-based research helps industry. "Nuclear Reactor Engineering and Reactor Physics" describes continuing applied research to improve the efficiency and safety of nuclear power plants.

Neutron Activation Analysis

Neutron activation analysis (NAA) is a particularly productive technique that is a vital research tool. It has made possible the rapid and economic accumulation of the large amounts of data needed for analyses in many disciplines, and has been essential to many important scientific advances in the last 10-15 years.

In NAA a sample is irradiated within the reactor, resulting in activation of its constituent elements. Upon removing the sample, the researcher can analyze the gamma ray spectrum to identify the presence of elements at exceedingly low levels.

NAA has made important contributions to medicine, biology, archeology, environmental studies, forensic science, geology, paleontology, and other fields. It functions well at small reactors. The multi-disciplinary setting of a university makes NAA a particularly attractive area for research in these fields.

Neutron Scattering

Neutron scattering is a basic research technique that employs directed neutron beams to investigate the unique interaction characteristics of neutrons with many kinds of matter. By observing the changes in the direction and energy of neutrons as they exit or scatter from the impact material, neutron scattering provides valuable information on the fundamental structural properties of condensed matter such as chemical compounds, biological materials, polymers, and superconductor and semiconductor materials. Such structural information leads to new approaches for synthesizing new materials with advanced technological applications.

Neutron scattering can be used most effectively only at the larger URRs--2 Mw and higher. Neutron scattering research at European facilities is apparently more productive than at U.S. reactors, in part because of the superior collaboration between small and large reactor research facilities.

Neutron Radiography

Neutron radiography techniques using reactors provide an important research tool for examining the internal structure of an assembly, object, or organism. All radiations, including visible light, x-rays, gamma rays, and energetic particles such as neutrons, are attenuated by passing through material. The effects of attenuation can be displayed and measured. Radiography techniques based on the effects of attenuation have been extended to a degree of sensitivity and resolution and are increasingly important in visualizing physical, chemical, and biological phenomena. Neutron radiography is based on using reactor neutron beams whose attenuation reveals the presence of hydrogen and hydrogen compounds, enabling researchers to examine hydrocarbons, many organic substances, and almost all other types of hydrogenic compounds. Such compounds are typically almost completely transparent to X-rays. It can be used at small URRs, but the range of useful measurements increases with neutron flux and power.

This growing field of research has important practical applications in engineering and applied science. URRs, because of the university's multi-disciplinary setting and the flexibility in experimental configurations, have a clear advantage and can make further important contributions in this field. For example, university researchers have developed video techniques for neutron radiography in which real time examination of biological and fluid flow processes can be examined in great detail.

Nuclear magnetic resonance is another technique used to detect the presence of hydrogen in materials and to determine its location and the nature of its binding to compounds. For medical purposes, imaging and spectroscopy of hydrogen in vivo in patients and in specimens are an increasingly important technology. Due to the requirements of the intense magnetic field associated with magnetic resonance as well as to other geometrical constraints, and nuclear magnetic resonance has not been as competitive as neutron radiography with nuclear reactors for most applications.

The use of neutron radiographic techniques at URRs has led to many important and useful applications. Depending upon equipment availability, URRs will continue to play a direct and vital role in developing radiographic methods and techniques.

Biomedical Applications

Biomedical research using URRs has involved the collaboration of nuclear physicists with medical scientists in many successful efforts to identify and treat society's significant health problems. Though the most widely applied nuclear medicine procedures use radioactive tracers for diagnosing diseases and monitoring treatment, radionuclides produced by reactors are also important in therapy and research. The development of new radionuclides, including radiopharmaceuticals, is an important research area involving URRs.

University reactors, though small, are used collaboratively with medical research faculties on and off campus. Nearly all reactor-produced biomedical radionuclides have originated with university faculty who collaborated with university or government reactor staff. This arrangement has been a powerful factor in much of the development of new and innovative procedures in nuclear medicine. URRs provide a flexible, informal working atmosphere in which medical researchers can collaborate with physicists creatively. Moreover, the synergism between URR centers and medical schools and their associated teaching hospitals contributes to the training of students and researchers.

Materials Research Using Neutron Irradiation

Interaction between materials and the neutron flux can alter the electrical, mechanical, chemical, optical, and magnetic properties of the material itself. These alterations allow researchers to alter materials selectively to achieve special effects and properties useful in many engineering and scientific applications. Examples include semiconductor electronics, contributions to metallurgy, and studies of superconductivity. Characterization of embrittlement and fatigue properties of various steels exposed to neutron irradiation has application to the nuclear power industry and to defense uses of nuclear materials.

Significant work in materials sciences requires the combination of a low temperature irradiation facility (in the 4-5^{o} K range) and a high neutron flux. None of the higher flux URRs in the United States is so equipped. As a result, URRs are under-utilized for materials science work, particularly for low temperature irradiation. By contrast, low temperature irradiation programs are supported at several European centers. There are important opportunities in the coming decade for U.S. based URRs to participate more actively in the revolutionary gains in materials science, with emphasis on low temperature capabilities.

Nuclear Reactor Engineering

URRs continue to be used for developing and testing new techniques for more efficient and safer operation of nuclear powerplants. These techniques include computer control of reactor operations using closed-loop control algorithms and expert systems, neutronic calculation and testing of fuel enrichment configurations, and evaluation and calibration of radiation monitoring systems. Future research contributions relating to several areas of reactor physics and engineering include nuclear pumped laser states, improved neutron cancer therapy beams, and in-pile coolant loop research. URRs can make significant contributions to these areas, depending upon their size, configuration, and availability.

CONCLUSIONS OF REVIEW OF URR RESEARCH

URR research is highly multi-disciplinary, involving applications to physics, chemistry, biology, medicine, geology, environmental sciences, archeology, and forensic studies as well as nuclear and reactor engineering. University research reactors have made and continue to make significant research contributions in the areas of:

- Neutron activation analysis
- Neutron scattering
- Neutron radiography
- Medical diagnostics and therapy
- Radiation effects in materials
- Nuclear engineering and reactor physics.

URRs are significant producers of applied research with broad benefits to society. Yet, because of under-funding, the full potential is not being realized.

In each of the fields addressed herein, the research contributions can be enhanced by enlarging the base of financial support to URRs. Support is needed to upgrade reactors, modernize the instrumentation, and purchase support equipment. (Recommendations relating to support are given in Chapter 7.)

For URRs, the research role is closely linked to the educational role in that much of the research is performed by graduate students under faculty supervision (see Chapter 3 for discussion of the educational roles of URRs).

Nuclear sciences research in the United States would benefit by introducing a reactor user network concept in which investigators at small URR centers would be linked to major reactor centers (see Chapter 5 for discussion of the European model).

NEUTRON ACTIVATION ANALYSIS AT UNIVERSITY RESEARCH REACTORS

Description

NAA is a technique of elemental analysis based on the production of characteristic nuclear radiations when a sample is exposed to neutrons. It is a special example of more general analytical techniques that use interacting particles to produce characteristic nuclear radiations. The technique was first used by Hevesy and Levy (1936) to determine the amount of dysprosium in samples of yttrium. In 1938, Seaborg and Livingood determined the amount of gallium in iron using protons as irradiating particles.

Because reactors are copious producers of neutrons, neutron activation analysis use has expanded greatly since the 1940s. Most analyses use neutrons in the lower energy range ($E_n < 1$ KeV), however, special application neutrons with energies up to about 1 MeV and beyond can be used. In most NAA experiments, gamma ray emissions from the radioactive decay of the products of neutron capture are used more frequently than other radiations such as beta particles. Alternatively, gamma rays from the neutron capture process itself are measured.

In a typical NAA procedure, a sample is placed in a container and inserted into the reactor where it is irradiated for a prescribed time. After irradiation, the sample is removed from the reactor and examined by a scintillation counter or Ge(Li) solid-state detector. The resultant gamma ray spectrum is compared to that from a standard sample (or to catalog spectra from individual elements) in order to identify the elements and the amounts present in the sample. Figure 2-2 is a diagram of NAA.

A principal advantage of NAA is its extreme sensitivity to approximately 80 percent of the naturally occurring elements. Figure 2-3, a portion of the periodic table of elements, identifies a broad range of elements whose presence can be determined by NAA. NAA techniques are also used to analyze trace elements, in some cases as small a few picograms (1×10^{-12} gram).

Other advantages of NAA include the potential for simultaneous determination of numerous elements in a sample. Specific isotopes can be measured, allowing for experimentation with altered isotope ratios.

NAA may also be used in experiments with chemical processing between the sample irradiation and radiation measurement steps. This use is unique to NAA, one that is important in analytical procedures attempting to extend the range of sensitivity and selectivity to their limits.

Further, classical NAA is a non-destructive analysis technique in which the sample remains intact. This point is particularly important to objects that cannot be "sampled," such as technical equipment, art objects, etc. These fundamental differences are the major reasons for using NAA, in many cases as the reference method for further comparison.

Comparison of NAA with Other Spectroscopy Methods

Two other analytical techniques for elemental analysis and trace element detection are important: atomic and mass spectroscopy. Each has particular advantages and disadvantages that make it suitable (or unsuitable) for a given application. The choice also depends on availability of technique to the researcher and the familiarity of the researcher with it.

The major advantage of atomic spectroscopy methods with respect to NAA is the relative availability of required equipment. No research reactor is required. The major disadvantage of atomic spectroscopy compared with NAA concerns sample requirements. Atomic spectroscopy normally requires solubilization of samples, which may lead to both contamination and volatilization problems well beyond these normally encountered in routine NAA procedures.

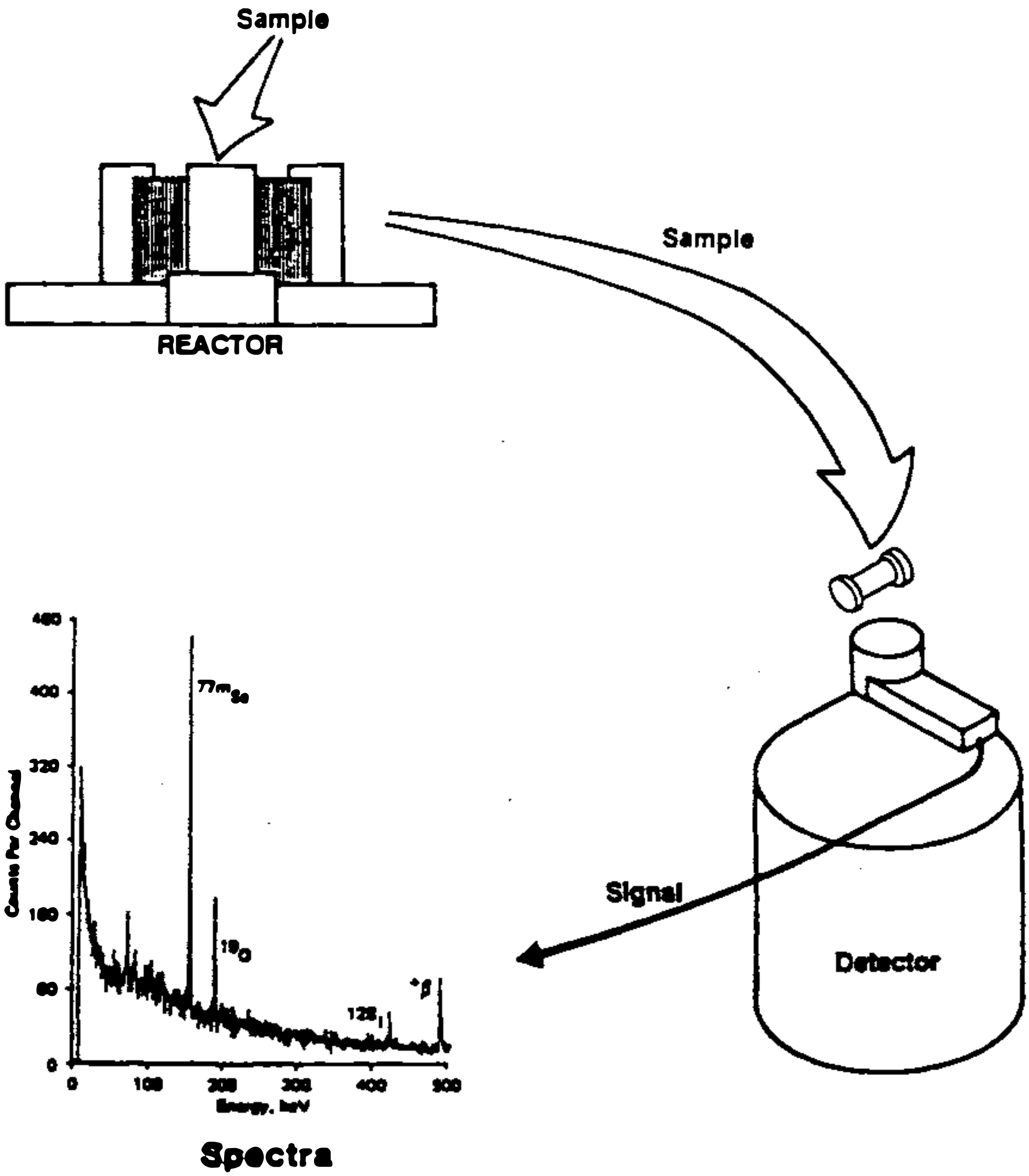

Figure 2-2. Neutron Activation Analysis

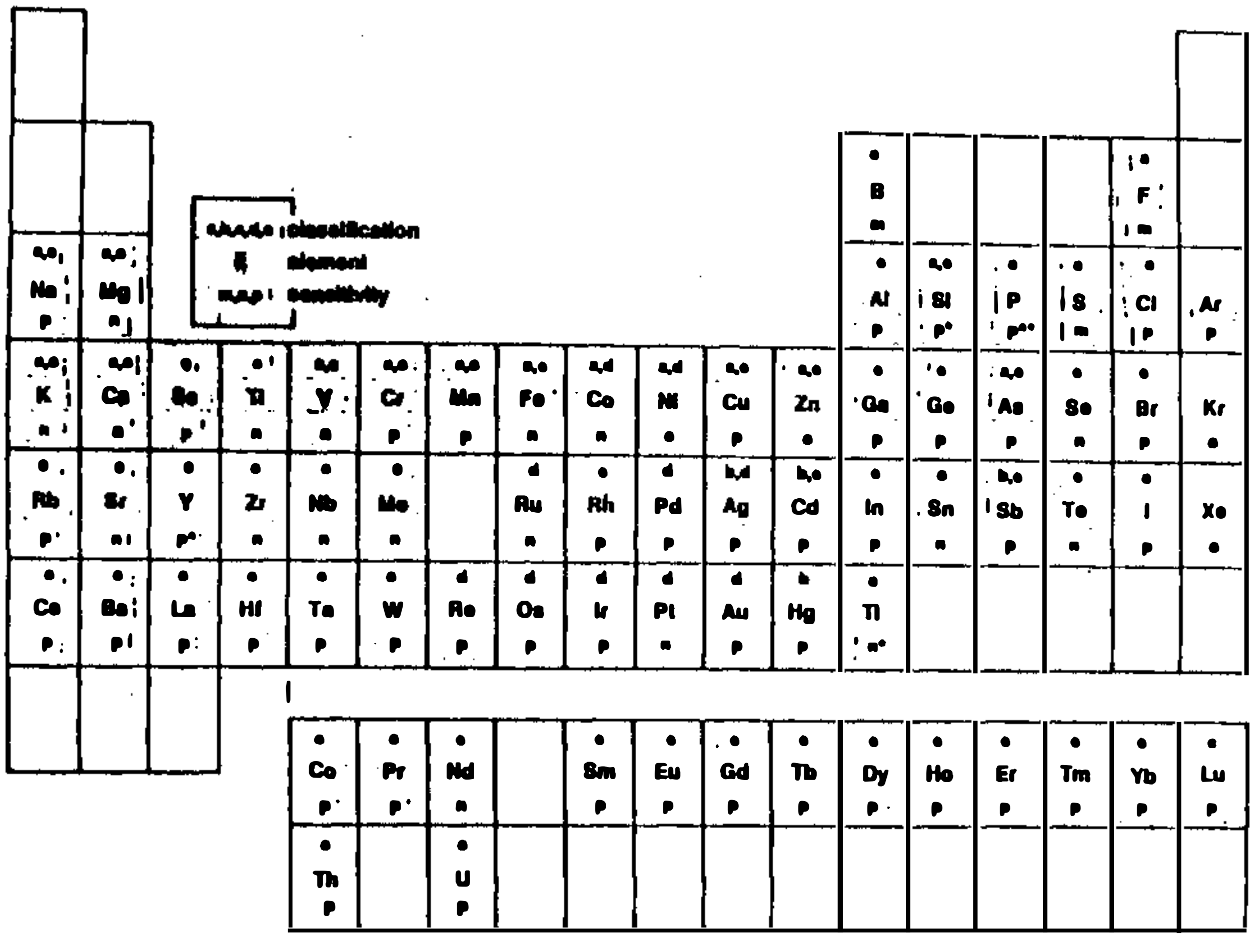

FIGURE 2-3. Classification of the Elements Determined by Neutron Activation Analysis*

*The classification above the element symbol describes a routine application for that element. Elements classified as "a" are essential for life, "b" are toxic to living organisms, "c" are often used by geologists in petrogenetic modeling, "d" can be used to identify meteorites, and "e" are of broad general interest. These classifications illustrate the scope of NAA applications. A strong advantage of NAA is its excellent sensitivity for most elements. A sensitivity category is shown below the symbolas m, n, or p for microgram, nanogram, and picogram, respectively.
**Elements determined by beta counting.

Mass spectroscopy procedures are the more conventional means by which isotopic ratios are measured. In general, the advantages and disadvantages given above also apply to comparing mass spectroscopy methods and NAA, with one difference. Mass spectroscopy techniques have a wider range of isotope ratio applications than does NAA.

It should be noted that though these three techniques may be viewed as competitive, they are more profitably considered complementary. Of particular significance is the fact neither atomic nor mass spectroscopy can completely replace neutron activation analysis; NAA is unique in several important aspects.

A discussion of NAA as an analytical method must point out that the principal detection methodology on which NAA is based is gamma ray spectroscopy. Gamma ray spectroscopy is also used to study the fate of administered radio-tracers in both animate and inanimate materials. Combining NAA with radio-tracer assay using gamma ray spectroscopy thus extends nuclear methods into areas that cannot be studied directly by other analytical means.

Applications and Research Productivity of NAA

In support of a broad range of research projects, many neutron activation analyses are performed in the United States (estimated at ≥100,000 per year). The number is growing as appreciation of the technique grows. A significant portion of these analyses (≥60,000 per year) is performed at university research reactors.

Most analyses use neutrons in the lower energy range (E_n<1 keV); for special applications, neutrons with energies up to about 1 MeV and beyond can be used. These thermal neutron energy ranges are accessible with many present-day URRs.

The analyses are generally of three types. First a substantial number are associated with research on natural materials where the nature of the problem requires the analysis of many samples. Examples of this type are the analysis of aerosols to study the transport of material in the atmosphere and the origin of pollutants, the analysis of artifacts in archeological studies, and the analysis of biological materials. Second and at the other extreme are analyses of a much smaller number of samples in connection with specific physical, chemical, and biological experiments. In this type of work, the procedures can be tailored to take advantage of the ultimate sensitivity of NAA. The third is research on NAA itself, establishing the conditions for improving the accuracy, reproducibility, and sensitivity, and extension to new elements in the periodic table. Research of this type requires many analyses.

Of the 36 university research reactor facilities, almost all do some neutron activation work. The load ranges from fewer than 100 samples to more than 10,000 per year. Thirteen URRs analyze more than 1,000 samples per year; most of them are in the 1 Mw or larger power range. Not all reactors in this power range are particularly active in NAA programs; emphasis depends largely on the research activities and interests of the faculty and staff.

Examples of Scientific Discoveries Using NAA

During the last 10-15 years, NAA has made possible many significant scientific discoveries. Of great general interest is the evidence for a catastrophic impact on the earth some 65 million years ago by an extraterrestrial body, an impact that may have eliminated many (if not most) species of living organisms (Alvarez, 1987). There is some evidence that such catastrophies, having been initiated by collisions with large extraterrestrial bodies or by unusually large volcanic eruptions or both, have occurred many times, possibly periodically, with important consequences for the evolution of life on earth. This fascinating discovery was made at a university research reactor. It probably could not have been made without NAA.

Another significant contribution of NAA is the fingerprinting of aerosols: establishing a pattern of minor element content characteristic of a given source of a pollutant. In this way, the aerosols from power plant emissions (as in the Midwest) can be distinguished from those from smelter operations, local airborne particulates, or marine evaporates. The contributions to a collected sample from each source are calculated from the relative abundance of the particular minor elements as determined by NAA. Not only can the sources of pollution be identified, but information about the diffusion and transport of materials in the atmosphere can be obtained.

URRs have been at the forefront in the analyses of lunar samples and studies of meteorites. Thus, NAA is providing important clues about the origin of the solar system. Listed in Table 2-1 are additional scientific uses of neutron activation analysis at university research reactors (Harling, Clark, and von der Hardt, 1984).

The Role of NAA in Education

The role of NAA in university education merits comment. The theory and techniques of NAA are relatively easy to impart to students at an early stage of their scientific education as well as to students in a variety of disciplines. At the same time, the results of NAA can be directed at many contemporary research problems. Thus, students using NAA become involved in research more quickly than students in areas of research requiring more sophisticated experimental techniques.

Conclusions for Neutron Activation Analysis

Neutron activation analysis is one of the most valuable research activities at URR centers. It is a basic and widely used technique that makes possible the economic accumulation of the very large amounts of data needed for significant analytical work in environmental sciences, medicine, nutrition, geology, and other fields. It has been essential in many important scientific advances of the last 10-15 years. It is one of the most important methods for trace element analysis, and in some cases the only practical method available.

Table 2-1. Selected Contributions from Neutron Activation Analysis at University Research Reactors

Field	Example
Geology	Iridium evidence for catastrophic impacts on the earth
	Analysis of geological samples in ore and petroleum exploration
	Discovery of anomalies in rare earth concentrations in lunar samples
	Establishment of meteorite influx onto the earth and moon
	Use of trace elements in volcanic ash and lava to study sources of volcanic activity
	Rare earth and other trace elements in deep sea cores as indicators of ocean floor spreading
Environmental Studies	Analysis of atmospheric dust to identify sources and study transport of pollution
	Halogen analyses as monitors of PCBs and other dangerous chemicals in the environment
	Analyses for mercury and other toxic heavy elements in food and the environment
	Elemental analyses to study impact of ocean drilling on aquatic life
Archeology	Tracing the sources of metals, obsidians, and sea shells in prehistoric and early historic civilizations

Table 2-1. Selected Contributions of Neutron Activation Analysis at University Research Reactors (Continued)

Field	Example
Archeology	Use of trace element analyses to help in the reconstruction of ancient art objects
	Authentication of art work
Forensic Studies	Detection of poisoning by toxic elements such as arsenic
	Identification of gunshot residues
	Characterization of materials such as bullet lead
	Determination of common origin of objects such as hair, fabric, etc.
Medicine/Nutrition	Studies of the role of selenium in the human diet and in cancer risk assessment
	Studies of copper metabolism
	Variations in trace element concentrations in organs as a function of diet and age

NEUTRON SCATTERING RESEARCH AT UNIVERSITY RESEARCH REACTORS

Description

The use of low energy neutron beams from research reactors to study the physical properties of materials has been a primary area of research with reactors since their early development. Indeed, some of the earliest work on this research technique was published be E. Fermi and L. Marshall in 1947; others quickly followed with significant accomplishments (Zinn, 1947; Shull et al., 1948).

This research activity was generated by the availability of neutron fluxes many orders of magnitude larger than those available from any pre-reactor neutron sources. Directed neutron beams of controlled quality became available from research reactors, beams of immense usefulness in studying a variety of solid-state and condensed matter materials.

One of the first characteristics to note about the interaction of neutrons with matter is that the uncharged neutron does not encounter electrostatic forces upon collision with matter. Therefore, the principal interaction between the neutron and the material depends upon the nuclear forces exerted between the nuclei of the material and the incoming neutron. These collision processes are somewhat analogous to those between hard spheres, but these processes are modified by a second phenomenon, the wave nature of the neutron. Diffraction effects can occur, modifying the angular distribution of scattered neutrons, for example.

A measure of the wave-like nature of thermal neutrons, the so-called de Broglie wavelength, is of the order of 0.1-0.2 nm. The wavelength, therefore, is comparable to the interatomic distances in crystals; this fact is the basis for neutron probing of the structure of matter. Because of this, intense thermal neutron beams from nuclear reactors may be diffracted by crystals in a manner similar to that of x-rays or electrons. The scattering mechanisms that make interference and diffraction effects possible are quite different for the three radiations. X-ray scattering results from the electromagnetic interaction between photons and atomic electrons. Electron scattering is due to the electrostatic interaction between the electron and the atom. For slow neutrons, the principal scattering mechanism is due to strong nuclear forces as modified by wavelike effects. An important additional scattering mechanism that is unique to the neutron involves the internal magnetic structure of the neutron. This magnetic structure allows the neutron to probe both the magnetic structure of the material via an electromagnetic interaction and its physical structure through nuclear scattering.

Applications of Neutron Scattering

These unique features of neutron interaction with matter can be exploited by studying the scattering and diffraction of directed neutron beams and the associated energy and momentum changes in the beam. A wealth of information on the atomic crystalline configuration and the electronic and thermal excitations existing in materials can thus be gained. This flourishing science has extensive applications in condensed matter physics, chemistry, biology, materials science, and polymer science. Figure 2-4 is a diagram of neutron scattering features, wherein the neutrons from the reactor interact with the material being tested and a position sensitive detector monitors the resultant scattered neutron beam. Data obtained in this fashion are analyzed by electronic circuits and computers to determine the physical structure and other related properties of the material.

The applications of neutron scattering research and the important features of this technique on the national level are discussed in three reports (National Academy of Sciences, 1977; U.S. Department of Energy, 1980; National Research Council, 1984). The study panels preparing these reports looked into the adequacy of the facilities and their support levels in relation to other disciplines. All the panels noted the scale of worldwide activity in the neutron scattering field and compared foreign and U.S. efforts. URR contributions and research programs were somewhat overshadowed by the larger higher power national laboratory reactor facilities.

Need for Adequate Neutron Flux

It is important to recognize that neutron scattering research at URRs is limited to the few reactors with high neutron flux density. Though initial explorations in the field were accomplished with reactors producing a flux of about 10^{12} neutrons/cm^2-sec, solving current state-of-the-art problems requires fluxes at least an order of magnitude larger. Experimental scattering involves neutron beam collimation, monochromatization, sample scattering, and possibly energy analysis, all in successive steps, with consequent intensity loss at each step. This requirement for high intensity generally implies an operating power level of 2 Mw or more for the reactor source. As shown in Table 1-1, only a few meet this requirement: the University of Missouri at Columbia, Massachusetts Institute of Technology, Rhode Island Nuclear Science Center, University of Michigan, and Georgia Institute of Technology; most neutron scattering research is concentrated at the first three.

Availability of Spectrometers

The five highest power URRs now have 19 neutron spectrometer units distributed as follows: The University of Missouri at Columbia, 9; Massachusetts Institute of Technology, 5; Rhode Island Nuclear Science Center, 2; University of Michigan, 1;[1] and Georgia Institute of Technology, 2. The spectrometer population at the five U.S. national

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[1]The University of Michigan spectrometer is reportedly inactive.

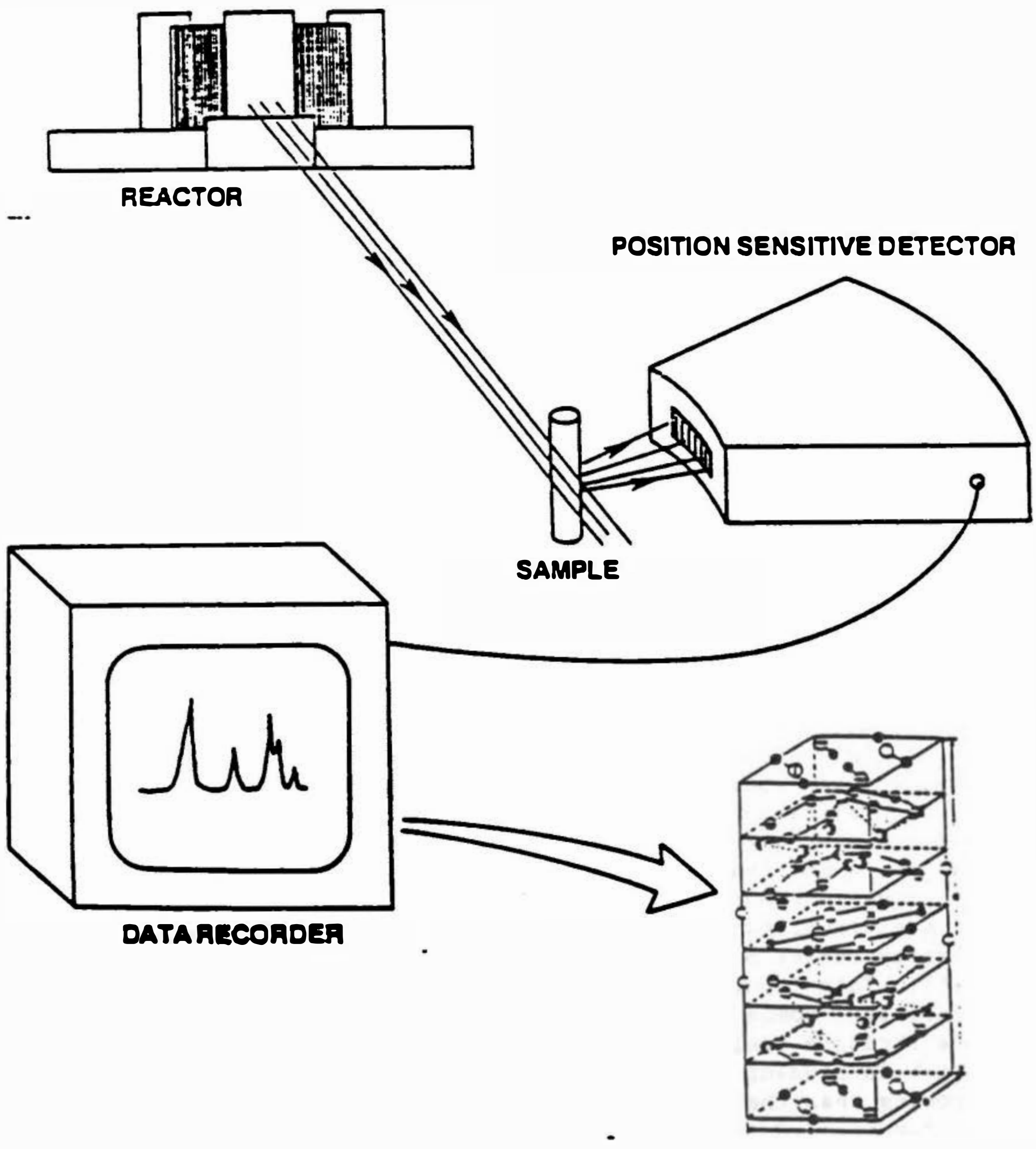

Figure 2-4. Neutron Scattering.

laboratory sites total 45: Brookhaven, 12; Oak Ridge, 10; Argonne, 9 (including accelerator-based facilities); Los Alamos, 6; and the National Bureau of Standards, 9. The worldwide count as of 1984 was about 170 spectrometer units; the number has probably risen to 270-300.

There is, of course, a wide range of sophistication in these units because they were all custom-built according to their intended use. In addition, the cost of a state-of-the-art neutron spectrometer for analyzing the scattered beam is $0.5-1 M, including computers, magnets, cryostats, and other appendage facilities. It must be noted that the U.S. university family of spectrometer units (with the exception of several of the Missouri spectrometers) may be considered below standard, with consequent limitations on research.

Applications and Research Productivity of Neutron Scattering

Research applications are diverse, ranging over condensed matter physics, chemistry, biology, polymer science, materials science, and neutron physics. As discussed above, neutron scattering is unique but complementary to x-ray and electron scattering. Illustrative of its uniqueness are its sensitivity to hydrogen atoms present in biological materials, its response to dynamic processes occurring naturally in condensed matter, and its portrayal of atomic level magnetization phenomena in matter. The reports noted earlier on neutron scattering discuss the research in detail. Table 2-2 lists areas where neutron scattering analysis has been applied. Wide applications have attracted the attention of scientists in many disciplines.

One can assess neutron scattering by considering the user population and publication productivity. For this purpose, a user of a neutron facility is defined as a scientist who participates directly in at least one neutron scattering experiment during a given year. A National Research Council report (1984) suggests a worldwide total of users approaching about 2,000; 510 are active U.S. participants affiliated with national laboratories, industrial centers, and universities.

As of 1983, research publications totaled almost 1,000 per year worldwide, with about 250 originating in the United States each year. The U.S. publication rate is probably larger owing to new and expanded facilities at the Argonne, Oak Ridge, and Los Alamos National Laboratories and the National Bureau of Standards and also to a growing focus on user-oriented facilities.

An additional measure of activity in neutron scattering at the five university research reactors is the annual publication rate; it was 51 in 1985. This figure represents about 20 percent of total U.S. productivity, commendable in view of the limited facilities and neutron source strength available at university centers. There is also strength in student participation in university research, but concern is growing that the number of students may not be able to meet future needs for trained professionals. This aspect is discussed in Chapter 4.

The use of national laboratory spectrometer facilities by outside users is encouraged at all national laboratories, and many local user

TABLE 2-2. Selected Applications of Neutron Scattering

Atomic crystallography
Magnetic systems
Phase transitions
Order-disorder
Exotic materials
Dimensionality
Crystal dynamics
Defect systems
Surfaces and overlayers
Liquids, glasses, and amorphous materials
Quantum fluids
Hydrides and hydrogen-bonded compounds
Ionic conductors
Ceramics
Superconductivity
Charge density structures
Molecular, vibrational, magnetic, and very low energy
Spectrometer
Macromolecular and protein structure and crystallography
Neutron optics and physics
Neutron interferometry
Quantum physics
Internal stress and texture
Polymer conformation

groups evaluate research priorities and encourage the interests of the total research community. The participation of university scientists in this use of national laboratory facilities either with or without collaborative effort of the local staff is significant, and university scientists form the dominant group in the user population today.

Without question, much of the neutron scattering research productivity arises from scientists using national laboratory facilities. On the other hand, the contributions of a small group of scientists (fewer than 50) using university research reactors cannot be ignored. Table 2-3 lists salient contributions derived from research at university reactor centers.

Examples of Scientific Discoveries Using Neutron Scattering

Discussion of all the URR facility contributions is not feasible, but a few highlights are in order. Research has continued over the years on the fundamental diffraction process occurring with radiation (x-rays, electrons, or neutrons) passing through materials. An important result is the realization that a crystal could split radiation into phase coherent, spatially separated beams that can then be recombined to show phase interference. Such interferometer systems, long used in optics, was first demonstrated with x-rays in 1972 and shortly afterward with neutrons. This pioneering work was done with university radiation sources. Programs in this field have evolved at the University of Missouri and Massachusetts Institute of Technology where many innovative and important contributions have been made both in interferometer technology and in obtaining physical information.

New forms of interferometers have been conceived and tested. Because they are exceedingly sensitive to extraneous environmental temperature and vibrational effects, the operating parameters of the equipment have been thoroughly characterized. Interferometers have been used in studies of neutron interaction with material, atoms, and fields in studies of quantum physics. An important example is an experiment that resulted in quantifying the interaction of neutrons with the gravitational field of the earth. Elevating one of the two beams in a neutron interferometer by about a half millimeter changes the relative phase of the two waves by 180°, which is easily measurable as an intensity effect. Another example is enhanced response to applied forces of neutrons diffracting in a crystal. In one experiment, the neutrons exhibited an effective mass 200,000 times smaller than the normal mass of the neutron. Moreover, they existed in both negative and positive mass states, suggesting that when such neutrons are subjected to the gravitational field, they would be attracted or repelled separately.

Unique Features of Neutron Scattering at University Research Reactors

Experimental programs at university research reactors are frequently more extended and time-consuming than they are at national laboratories

Table 2-3. Selected Contributions from Neutron Scattering at University Research Reactors

Polarized neutron beam technology: This technique is widely used in characterizing the magnetic structure of materials.

Mapping of internal magnetization: Magnetization within a material is found to arise not only from electrons within an atom but also from those migrating in intervening space between atoms.

Nuclear polarization scattering: Atomic nuclei become aligned when subjected to high magnetic fields (of either external or internal origin) and low temperatures, drastically changing their neutron scattering properties.

Mosaic and high reflectivity monochromators: All scattering spectrometers use monochromators to select purified neutron radiation their efficiency can be improved significantly by processing so as to modify their mosaic and angular reflection structure.

Aligned paramagnetic and diamagnetic scattering: This technique is used to explore perturbations of the electron magnetization with applied magnetic field.

Neutron spin-orbit scattering: Neutrons moving through the intense electrical structure of atoms are found to exhibit a novel interaction beyond the usual nuclear and magnetic forms.

Instant photography of neutron beams: Suitable absorbing screens coupled with normal instant photography techniques can produce fast imaging of neutron beams and patterns.

Pendellosung fringe measurement: Neutrons diffracting in perfect crystals exhibit an internal interference action that can be exploited to determine diffraction parameters with precision.

Precision determination of neutron scattering amplitudes: Use of Pendellosung interference and neutron interferometer systems has led to the establishment of new standard scattering amplitudes of high precision.

Electric neutrality and electric dipole moment of neutrons: Significant contributions to the continuing studies of these fundamental parameters have been made.

Drift velocity of diffracting neutrons: Diffracting neutrons travel through a crystal with a reduced speed that, in limiting cases, can become arbitrarily small, suggesting the use of crystals as a potential storage medium.

Table 2-3. Selected Contributions from Neutron Scattering at University Research Reactors (Continued)

Refractive index bending: Studies of neutron bending and focusing by media and fields are unique to neutron spectrometers.

Neutron interferometry development: Conception and testing of new types of neutron interferometers are carried out to determine the criteria for successful use.

Gravitational interaction of neutrons: The gravitational potential of neutrons has been examined through sensitive phase shift measurements using interferometers.

2-Pi-Inversion of neutron wave function: This technique allowed the first direct observation of a tenet of quantum mechanics using a neutron interferometer--sign reversal upon full rotation.

Neutron wave packets: Assessment of the spatial extent of the neutron wave function.

Complex scattering amplitudes: Accurate determination of out-of-phase component of neutron scattering amplitude has been made.

Fizeau moving lattice, coriolis effects: Media in motion produce modifications in neutron scattering.

Schrodinger wave equation and function variants: Possible modifications in the basic propagation description of neutron particles (waves) are sought.

Effective mass of neutrons in crystals: Dramatic changes from the normal response of neutrons to applied forces were demonstrated.

Magnetic neutrality of neutrons: An upper limit to the possible difference in dipole magnetic strength was established.

Spin density magnetization in chromium: A helical magnetization distribution among magnetic chromium atoms was established.

Charge density wave structures: The electric polarity of atoms can have cyclic variations in a crystal.

Lithium low temperature structure: A new model of stacking faults in the martensitic transition was generated from neutron studies.

Small angle scattering using double crystal techniques: Ultra-small angle scattering becomes analyzable with this technique.

Table 2-3. Selected Contributions from Neutron Scattering at University Research Reactors (Continued)

Small angle scattering with polarized neutrons: Important characteristics of magnetic fields are provided.

Hard magnet characterization: Complete crystallographic and magnetic structure characterization of the new magnetic material $Nd_2Fe_{14}B$ and related compounds was carried out.

Stress and texture profiling in materials: The easy penetration of neutrons into engineering materials supplies important characterization information.

Single crystal neutron filter development: Such filters permit purification of thermal neutron beams that simplifies the design of neutron spectrometers.

Search for novel neutron interactions: New types of interactions between neutrons and nuclei, electrons, and fields have been explored.

Neutron focusing by magnetic gradients in crystals: Anomalously large focusing effects were demonstrated by combining normal refractive index action with dynamical diffraction effects in crystals.

Position sensitive detector development: Significant contributions to the design and operation of such devices that greatly enhance data collection were made.

Neutron spin--Pendellosung resonance: Combining Larmor spin rotation with Pendellosung action in a crystal under resonance conditions can enhance sensitivity in establishing new types of spin-orbit interactions.

for several reasons. First, the available neutron source strength is smaller, so data collection takes longer (a spectrometer may be occupied for 6-8 months to establish some subtle effect). Second, student training and education are not always time-efficient. Third, other academic responsibilities draw faculty from research. And fourth, problems sometimes take a lot of time. Even with today's automation, staff dedication is required. A corollary of these features of university spectrometer operation and the small ratio of staff to instruments at university reactors is the low publication rate for URR research.

The more research-oriented programs at university reactors as compared to national laboratories, require staff and users who can spend the time necessary to develop new techniques and instruments and carry out long-term experiments. This point is reflected in many of the topics shown in Table 2-3. It is more apparent in Western Europe. Many innovative and advanced scattering instruments and components in use at the multinational Institut Laue-Langevin research reactor in France (see Chapter 5) were first developed at the smaller Munich and Julich reactors. Further, development continues on magnetic neutron scattering methods at the smaller Delft, Braunschweig, Berlin, and Munich research reactors.

In the United States, too, work initiated at the smaller URR facilities has resulted in development of new techniques at the national laboratories. For example, the University of Missouri at Columbia laboratory first developed scattering instruments using linear position detectors. There, both the small angle neutron scattering instrument (which uses 43 twenty-four-inch long detectors forming a two-dimensional array) and the powder diffractometer that uses three position-sensitive detectors have been successful. This technique has been copied in Japan, Canada, and elsewhere. The position-sensitive detector instrument, rather than conforming to a fixed diffractometer circle, corrects for all parallax errors computationally. It has increased data acquisition rates by a factor of 50 and has improved resolution. Similar technology is now in use for powder diffraction at the Rhode Island research reactor and the McMaster University reactor in Canada and for single crystal diffraction in the flat cone geometry at the National Bureau of Standards research reactor.

Powder diffraction spectrometry is widely used, broadening use of the smaller low power research reactors. The Missouri diffractometer has become a significant national resource, collecting approximately 500 spectra per year for use in studies of magnetism, zeolite structure, superconductivity, and materials science, and other areas. An example is shown in Figure 2-5, which gives the observed and calculated powder diffraction patterns for a sample of $Nd_2Fe_{14}B$, an important new magnetic material. In this manner, neutron powder diffraction data were used to establish the atomic structure also shown in the figure.

URR-initiated technology has led to widespread use of polarized neutron beams in studies of electron spin configurations in magnetic atomic structures. University reactor groups can be credited with introducing high efficiency polarizing crystals, radiofrequency

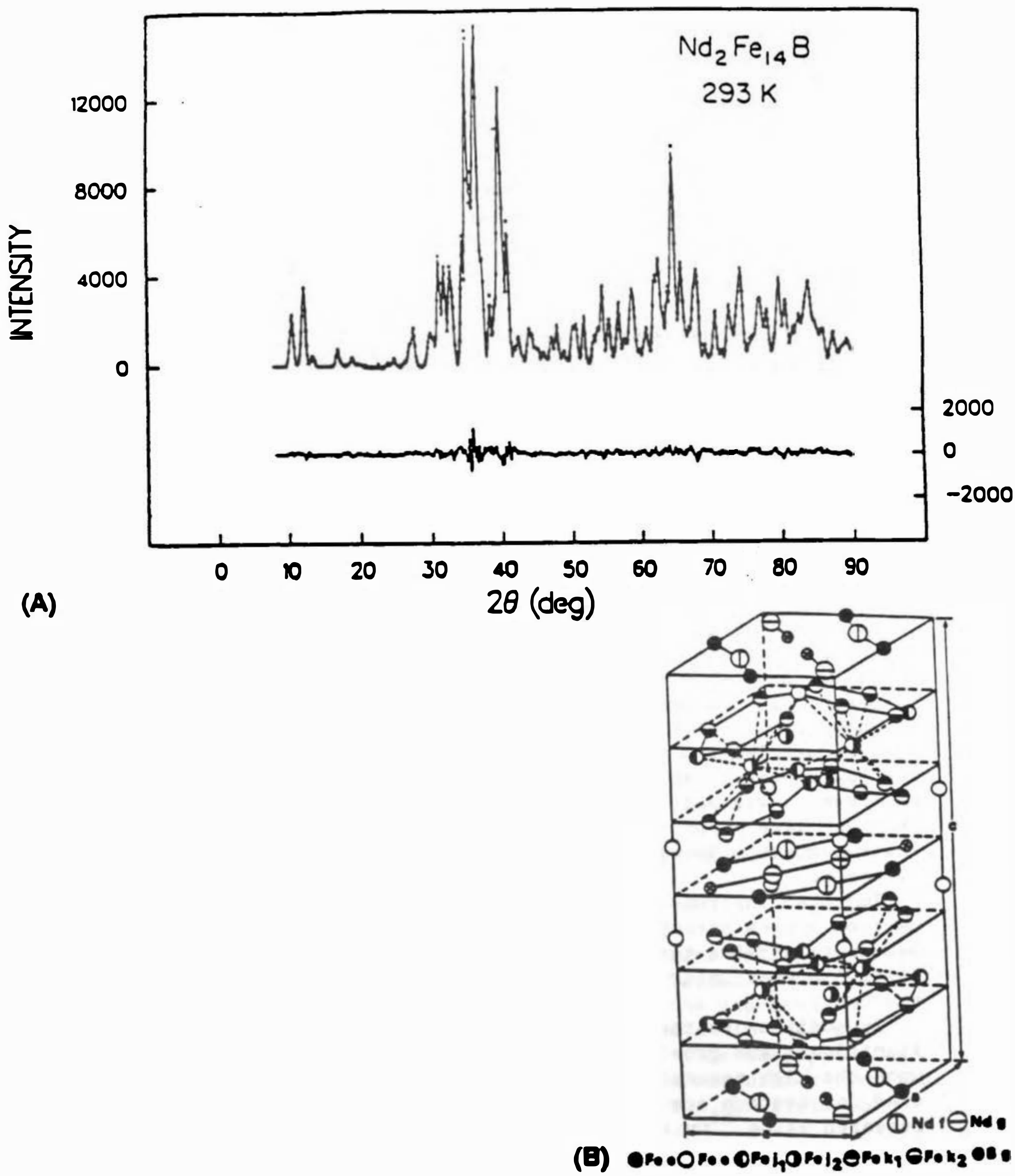

FIGURE 2-5. Neutron Powder Diffraction Data for $N_2Fe_{14}B$ and Its Atomic Structure Obtained from the Diffraction Data.
SOURCE: University of Missouri (Columbia) Research Reactor.

excitation of neutron spin flipping, polarization analysis after scattering, recognition of competing forms of interaction between polarized neutrons and polarized atoms and nuclei, and polarized neutron techniques applied to small angle scattering studies. Regarding the last topic, the Rhode Island researchers are pursuing important studies of ferro-fluids. Other URR contributions include the use of cryogenically cooled single crystal filters to purify thermal neutron beams and the use of double crystal small angle scattering. It is clear that the URR facilities serve as centers of innovation in developing methods and techniques in the field of neutron scattering.

Concern for U.S. Lag in Neutron Scattering

Overall, the United States has fallen behind Western Europe in developing advanced neutron scattering instruments and components. As discussed further in Chapter 5, many advanced instrument techniques originated in Western Europe at URRs. The cold neutron source, for example, provides a much enhanced flux of very low energy neutrons. This technique was developed in England 25 years ago and is now available at nearly 20 large and small reactor centers in Europe. In contrast, the first effective cold neutron source was installed in a U.S. research reactor only in 1982, and the second is now being installed.

Other examples of foreign leadership in instrumentation development include small angle scattering instrumentation, neutron guide techniques, hot source facilities, focusing monochromators, position-sensitive detectors, fabrication techniques of effective beryllium crystal monochromators, backscattering spectrometers, and spin-echo spectrometers. These developments become part of the technology base of a high-technology economy, and ultimately relate to U.S. industrial productivity. Many of these developments originated at smaller research reactors associated with universities where the environment was suited to creative development. Some of these are not yet used here. For the United States to catch up on neutron scattering instrumentation development, the creative input from the URR community is needed.

Improved instrumentation can sometimes overcome limitations in neutron source strength. For example, use of position-sensitive detectors permits the accumulation of scattering data at a high rate. Using improved instruments also contributes to the use of lower power sources.

In addition to the widespread activities in neutron scattering, significant and growing applications in condensed matter science depend upon the high neutron fluxes available at some of the same facilities used for neutron scattering. These areas include slow positron beam research using ^{64}Cu ($T_{1/2}$ = 12 hr), now carried out only at Brookhaven, gamma ray diffraction and Compton scattering using short-lived radioactive sources, and applications of Mossbauer effects using short-lived intense sources. These techniques are largely exploratory, although gamma ray diffraction and Compton scattering are routinely used at several Western European laboratories. Consequently, most of the work in these areas is being done at university research reactors. It is difficult to predict whether these techniques will flourish, but without participation of the university research community, it is unlikely that their viability as important tools and methods will be proved.

Though restricted to only a few of the larger university research reactors, neutron scattering research has been and continues to be significant in developments in physics, chemistry, biology, polymeric science, and materials science. These activities complement those pursued at the larger national laboratories. University-based investigations are frequently more fundamental and innovative because of the wide range of interests among scientists in an academic environment. Most of the work in these areas is being done at university research reactors. It is difficult to predict whether these techniques will flourish, but without participation of the university research community, it is unlikely that their viability as important tools and methods will be proved.

Conclusions for Neutron Scattering

Neutron scattering is a basic research tool in solid-state physics, condensed matter studies, chemistry, and biology. Research work also depends upon the availability of state-of-the-art neutron spectrometer units. In general, the number and quality of spectrometers at U.S. university reactor facilities are not adequate for world class research on a parity with Europe and Japan.

While most university research reactors have too low a neutron flux for full scale neutron scattering investigations, they have played an important role in preparation of experiments for high flux reactors, and in the design of instruments. In addition, powder diffraction spectrometry has broadened the applicability of low-power reactors for investigations in areas such as magnetism, super-conductivity and zeolite structure.

NEUTRON RADIOGRAPHY AT UNIVERSITY RESEARCH REACTORS

Description

The selective transmission and absorption of neutrons passing through material and structures have led to wide use and varied applications of neutron radiography. This technique complements the standard techniques of x-ray and gamma ray radiography, and it is used when contrast and penetration viewing can be improved. The absorption or transmission of neutrons passing through materials can differ from that of x-rays and gamma rays, and this factor delineates the fields of application.

A prime example of these differences arises for metallic structure systems containing hydrogenic liquids. X-rays and gamma rays are nearly oblivious to the presence of hydrogen atoms; for neutrons, the presence of hydrogen atoms frequently dominates the absorption compared to that of the surrounding metallic components.

In its simplest form, static neutron radiography involves the production of an image of film exposed to secondary radiation (electrons, gamma rays, photons, or charged fragments) from a neutron absorbing screen. More sophisticated versions make use of a television screen, permitting observation of dynamic features in real-time radiography.

Neutron radiographic installations generally make use of large area neutron beams, and the neutron intensity is usually of secondary importance. Consequently, university research reactors with power as low as 100 kW can be effective neutron sources. This feature has been attractive to university centers, and active research programs are being carried out at 10 university reactors. Other facilities plan to develop facilities for radiographic studies.

Geometrical collimation and selective filtering of the neutron source beam are important features in determining the quality of the resultant images. Much effort to improve the sensitivity and resolution features in these systems has been made in recent years, with university facilities doing most of the work. High quality real-time systems, which are expensive (about $0.25 M), are available at five university centers: the University of Virginia, University of Michigan, Pennsylvania State University, University of Missouri at Columbia and Oregon State University.

Several URR features make them particularly useful in this field. Their flexibility in changing shielding configurations and in filtering the neutron spectrum can be exploited to improve radiographic images. For TRIGA reactors, the ability to pulse the reactor momentarily to high power enhances the real time aspects of the radiographic image.

Applications and Research Productivity of Neutron Radiography

The scale of activity in neutron radiography is indicated by two international conferences, one in San Diego in 1981[1] with 130 technical presentations and the second in Paris in 1986[2] with 100 presentations. Session topics at the Paris conference included reactor facilities, non-reactor sources, industrial applications, corrosion inspection, neutron tomography, and dimensional measurements. The papers given represent activities at 17 U.S. organizations, including the University of Virginia, University of Michigan, Cornell University, Pennsylvania State University, and Georgia Institute of Technology.

The field has grown to the stage at which reactors of modest power are specially designed for neutron radiography, and a number of reactors in the United States (three) and elsewhere are commercial. Non-reactor sources of neutron radiation, such as accelerator sources or radioactive sources of ^{252}Cf, are also exploited. It is clear that radiography research is an important activity at URRs. Table 2-4 lists the areas in which neutron radiographic techniquss have been applied.

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[1] First World Conference on Neutron Radiography.
[2] Second World Conference on Neutron Radiography.

Table 2-4. Selected Applications of Neutron Radiography and Associated Techniques

Composite metal assemblies	Water flow through porous media
Bone tissue	Examination of historic paintings
Lubricant and fuel distribution	Corrosion of hidden surfaces and in engine joints
Botanical growth in soils	Combustion processes
Explosives components and burning	Spring and hydraulic dampers
Gasket and rubber diaphragm	Plastic injection molding conformation processes
Insulation integrity	Tritium, noble gasses in metals
Two-phase flow of fluids	Aircraft components
Plastic and ceramic assemblies	Boron in shielding materials
Biomechanical connectors	Archeological artifacts
Forensics	Biological species
Geological specimens	Satellite heat pumps
Aerosol filtration	Adhesion studies
Nuclear fuel and control assemblies	

An example of the usefulness of neutron radiography is given in Figure 2-6, which shows the flow of automatic transmission fluid in an operating front wheel drive transmission of an automobile. As in the figure, fluid flow in a particular lubrication channel was inadequate; a design modification improved the lubrication flow. Similar radiographs have been obtained to monitor the fluid fuel profile in the fuel injector for a gas turbine engine. The photographs were obtained in the real-time neutron radiographic facility at the University of Michigan; they clearly illustrate the selective sensitivity of neutrons to hydrogenous fluids. X-ray and gamma ray radiography would have been useless in these cases.

Neutron radiography has also been used to examine botanical material. Figure 2-7 shows a real-time neutron radiograph of an iris taken at the University of Virginia. (The radiograph also shows a beetle inside the flower.) Other university developments in this field are listed in Table 2-5.

An extension of two-dimensional imaging radiography is neutron tomography. In this technique, a three-dimensional view of a structure is obtained by reconstruction from multiple exposures taken at different viewing angles. Additionally, systems have been developed that use spatially distributed neutron activation over the specimen in order to obtain time-dependent autoradiographic images. Even the rudiments of possible holographic examination have been explored; here the phase coherence features of neutrons are exploited for three-dimensional viewing. Recent advances in neutron resonance radiography, in which selective neutron absorption at localized neutron energies is exploited, have been significant. These new and emerging techniques were highlighted at a 1987 summer conference held at Los Alamos National Laboratory.

Concern for Under-Utilization

Neutron radiography is under-used. Basic neutron radiography is a mature technology, but the laboratory facilities and instrumentation are lacking. Moreover, no major facilities are available at the national laboratories.

In the university environment, with the URR available, there is opportunity for cross coupling between the neutron radiography researchers and mechanical engineering, biology, petroleum engineering, and other disciplines, and additional multi-disciplinary research can be performed. Valuable relationships have been formed between universities and several industries, and they can be expanded. Such collaboration can accelerate the development of innovative production methods.

Conclusions for Neutron Radiography

While not developed to its full potential, the availability of neutron radiography at URRs has led to many important and useful applications. Widespread uses have developed, and new applications can be developed readily. URRs have played a direct and vital role in developing both the methods and the techniques.

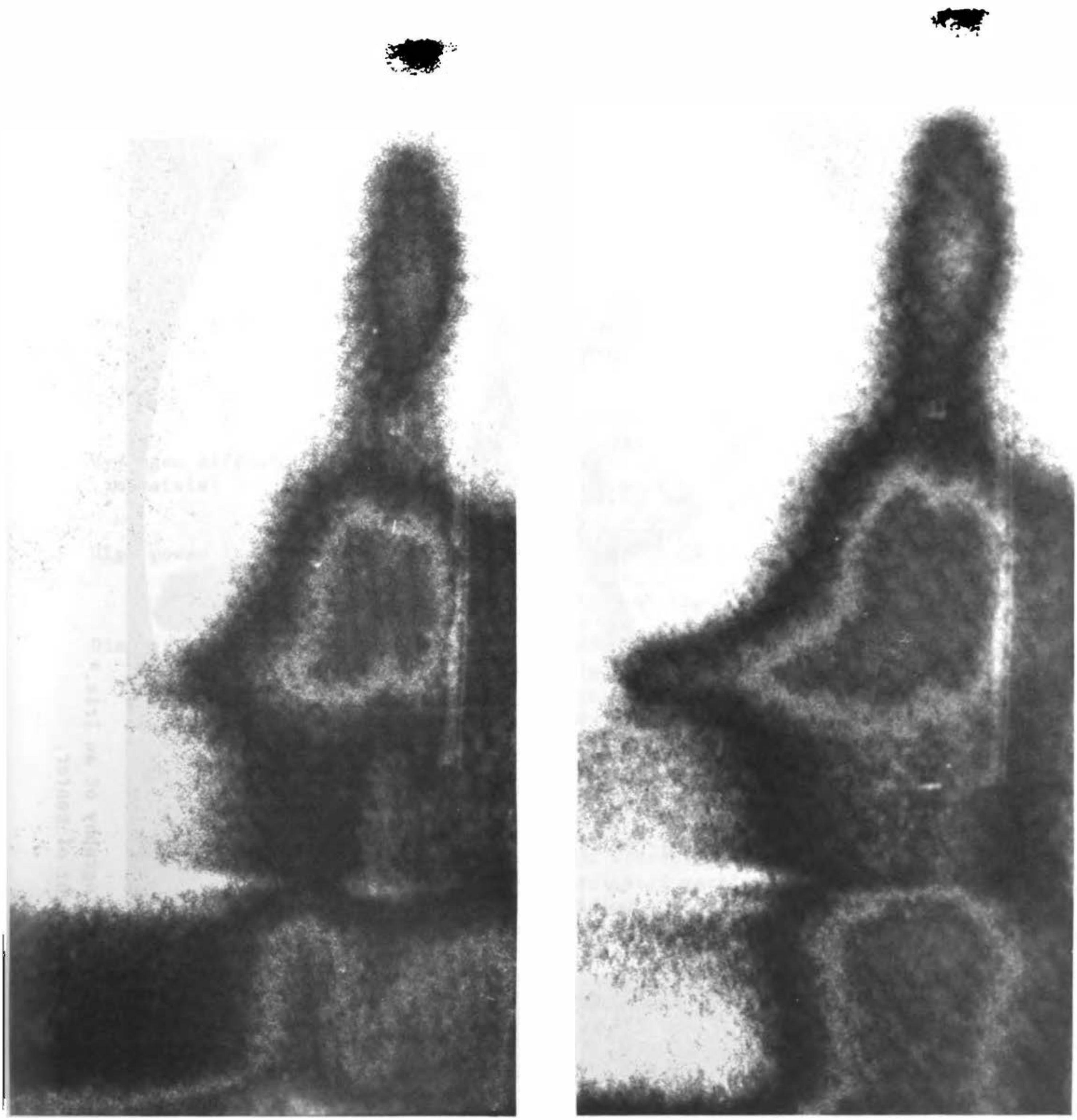

FIGURE 2-6. Real Time Neutron Radiographs of Automatic Transmission Fluid Flow in an Operating Wheel Drive Automobile.*

***The left photo shows hindred flow in a lubrication channel; the right photo shows correction after design modification.**

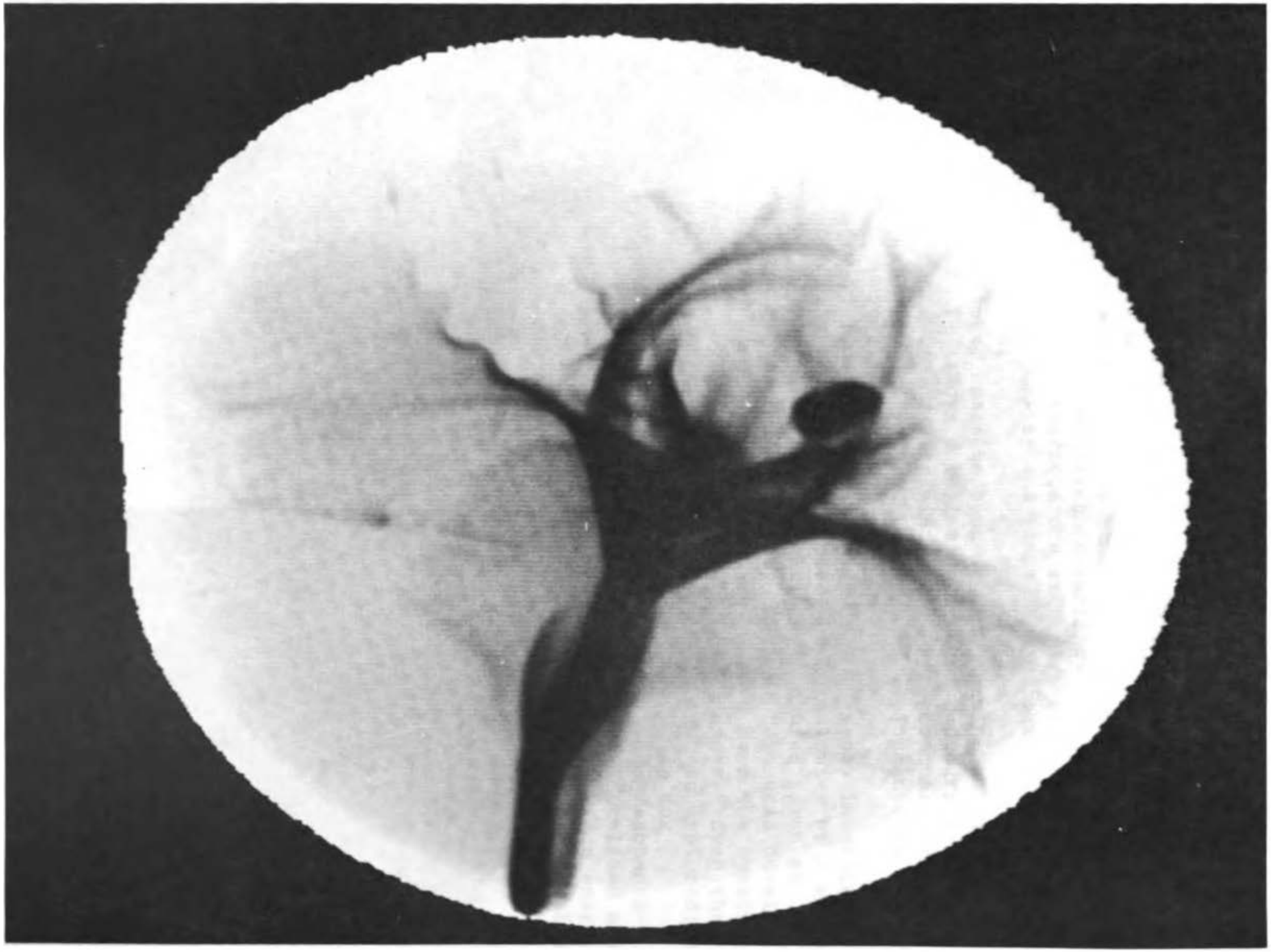

FIGURE 2-7. Real Time Radiography of an Iris.*
***NOTE: The beetle just right of center.**

Table 2-5. Selected Contributions from Neutron Radiography at University Research Reactors Centers

Real-time imaging:	Monitoring of lubrication and fuel burning patterns in automobile engines.
High-speed radiography (10,000 frames per second)	Imaging very rapid processes such as burning powder in a projectile.
Neutron tomography	Neutron tomographic reconstruction techniques have been demonstrated for inspection of reactor fuel bundles.
Analytic techniques	Application of Fourier transforms and the modulation transfer-function for evaluating the effect of controllable variables on the image forming capability of neutron radiography.
Hydrogen diffusion processes in metals:	The diffusion rate of hydrogen and its concentration in many metals have been studied.
High power laser mirrors	Evaluating coolant flow and corrosion within narrow cooling passages contained in high power laser mirrors.
Dimensional measurement	The accuracy of the technique in performing dimensional measurements, particularly with cylindrical objects, has been tested and evaluated. In its simplest form, static neutron radiography involves the production of an image on film exposed to secondary radiation (electrons, gamma rays, photons, or charged fragments) from a neutron absorbing screen. More sophisticated versions make use of a television screen, permitting observation of dynamic features in real-time radiography. Figure 2-8 is a diagram of neutron radiography.

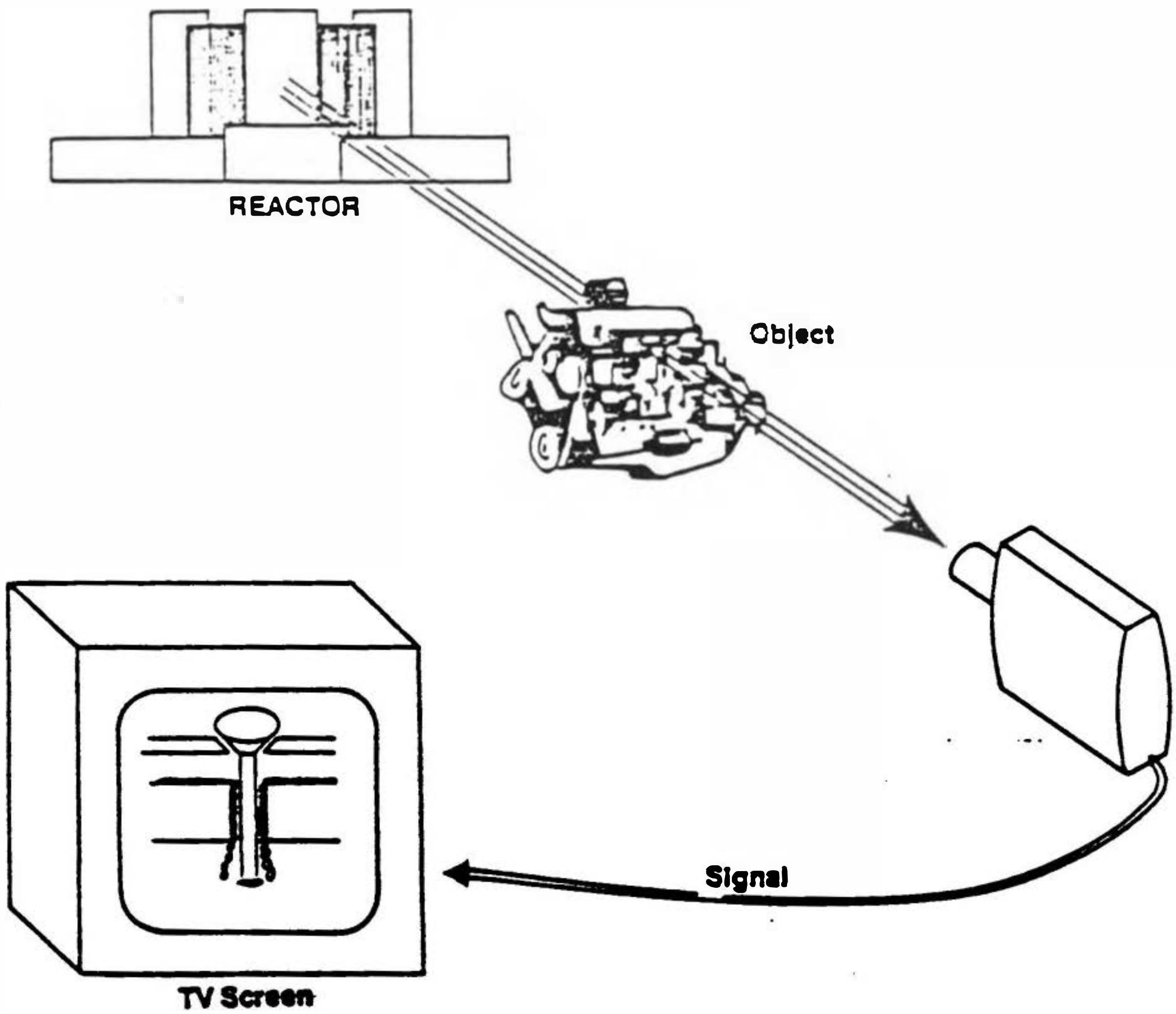

Figure 2-8. Neutron Radiography.

BIOMEDICAL USES OF RESEARCH REACTORS[3]

The use of neutron producing fission reactors, university research reactors in particular, for biomedical research and practice continues to be uniquely important. Radionuclides generated in these reactors and subsequently labeled compounds are used extensively in research as well as in many diagnostic and therapeutic procedures. Because a list of references on this important research topic would be voluminous, only a few survey references and some specific research efforts are cited (Harrison and Swindell, 1981; Rao, Chandra, and Graham, 1983; Sorenson and Phelps, 1986; Maruyama, Beach, and Feola, 1985); International Atomic Energy Agency, 1981; Wagner, 1968; Harling, Clark, and von der Hardt, 1984); ed. or author, 1986; Freeman, 1984, 1986; Jones and Smith, 1986; Ketring, 1987; ed. or auth., 1983).

The distinction between research and service aspects for biomedical activities at URRs is not always clear. Service is detailed in Chapter 5. This section discusses biomedical research, with some unavoidable overlap into the service category.

Biomedical applications of nuclides and labeled compounds can be summarized as being either metabolically located in the body or mechanically located in or near the body. In this context, metabolic is used loosely to include biological location and/or manipulation of radionuclides in vivo in non-encapsulated form.

Monitoring Biomedical Processes

Living organisms depend for survival on a complex interplay of physical and biochemical processes in order to fulfill essential physiological functions such as nutrition, excretion, respiration, etc. Following an element or compound along its metabolic pathway is important in studying life processes, and radionuclides are essential to these studies. Radioactive elements or compounds labeled with a radionuclide can be introduced into the system; their route can then be followed by many techniques developed for quantitative imaging and analysis coupled with techniques for identifying the metabolized compounds. Figure 2-9 is a diagram of radioactive isotope monitoring of the body's biomedical processes.

URRs have been instrumental in supplying physiological short-lived isotopes such as ^{24}Na and ^{42}K to researchers for in vitro study of essential hypertension, cystic fibrosis, cancers, and other diseases. Because of their moderately short half-lives of approximately 15 hours and 12 1/2 hours, respectively, obtaining these radionuclides from commercial sources is generally not economic or convenient. One URR has supplied several thousand shipments of ^{24}Na and ^{42}K in the last 10 years to a university researcher (Ketring, 1987).

[3]For additional views on medical applications, see Brill (1987).

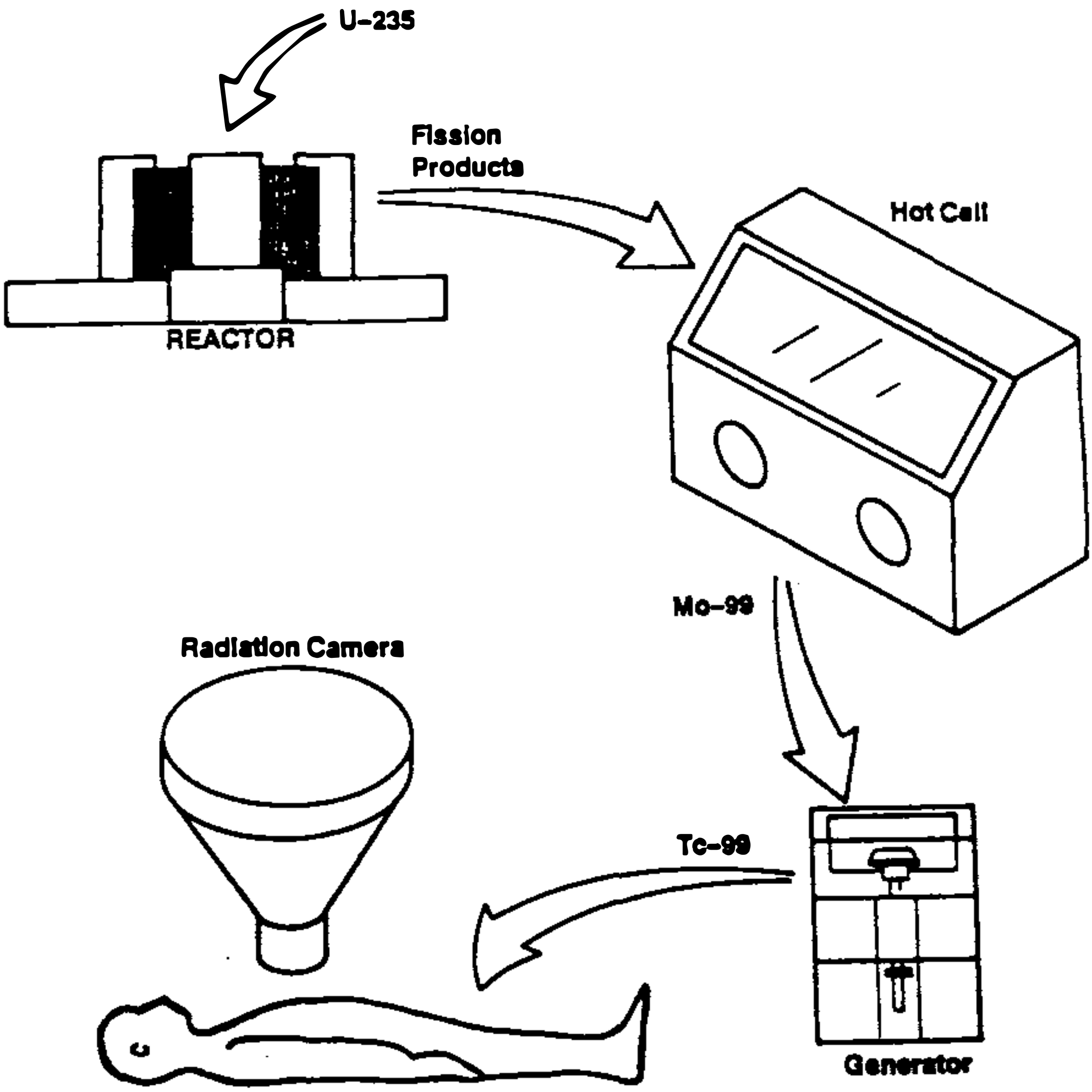

Figure 2-9. Medical Application of Radioisotope Production.

The use of radionuclides as tracers has contributed a great deal to understanding physiological functions. With tracers it is possible to establish limits of normal function on which to base diagnostic tests in clinical medicine. For example, the normal and pathological behavior of iodine in the body has been studied in detail, enabling its role in human physiology to be quantified.

Nuclear Medicine Therapy

When radioactive isotopes are used for diagnostic tests, the radiation doses delivered to any part of the body are insufficient to modify cellular function. In radiation therapy, on the other hand, with a sufficiently large amount of a radionuclide, the radiation dose can be sufficient to cause deliberate modification of the cellular function. For example, ^{131}I is used for treatment of thyroid gland disorders and metastatic thyroid cancer. There is considerable ongoing research on using monoclonal antibodies labeled with suitable radionuclides for therapeutic purposes.

Numerous new and exciting radionuclide procedures have been developed at URRs, or at facilities using isotopes produced at URRs, over the past several years as nuclear therapy research grows. For example, cancer metastases to bone are especially common from such primary cancer sites as the prostate and the breast. Because these cancers are often disseminated throughout the body, they can be treated only by a systemic therapy such as chemotherapy. In this connection, two new radioactive compounds have been developed, Samarium-153 EDTMP and Rhenium-186 HEDP. These two phosphonate complexes are taken up selectively on exposed bone mineral surfaces and are effective in irradiating metastatic deposits within the bone from tumors of other origins. For spontaneous bone tumors in dogs, ^{153}Sm therapy has been beneficial. This development was possible only through the close cooperation of a veterinary school near a URR. The ^{186}Re radionuclide has been supplied to a university medical facility by another university with a URR. The flexibility and informal, creative atmosphere of a research reactor facility in a university setting have been prime factors in these developments.

Some of these techniques are being used in clinical trials on human patients. Figure 2-10 shows nuclear scans of two patients: the one on the left with no cancer and the one on the right with prostate cancer that has spread to several locations in the skeleton. They are the darker spots in the figure. For the left scan, ^{99}Tc-MDP was used for diagnosis. For the right scan, ^{153}Sm-EDTMP was used to carry a strong beta emitter to the cancerous locations and thus deliver a large local radiation dose to the tumors.

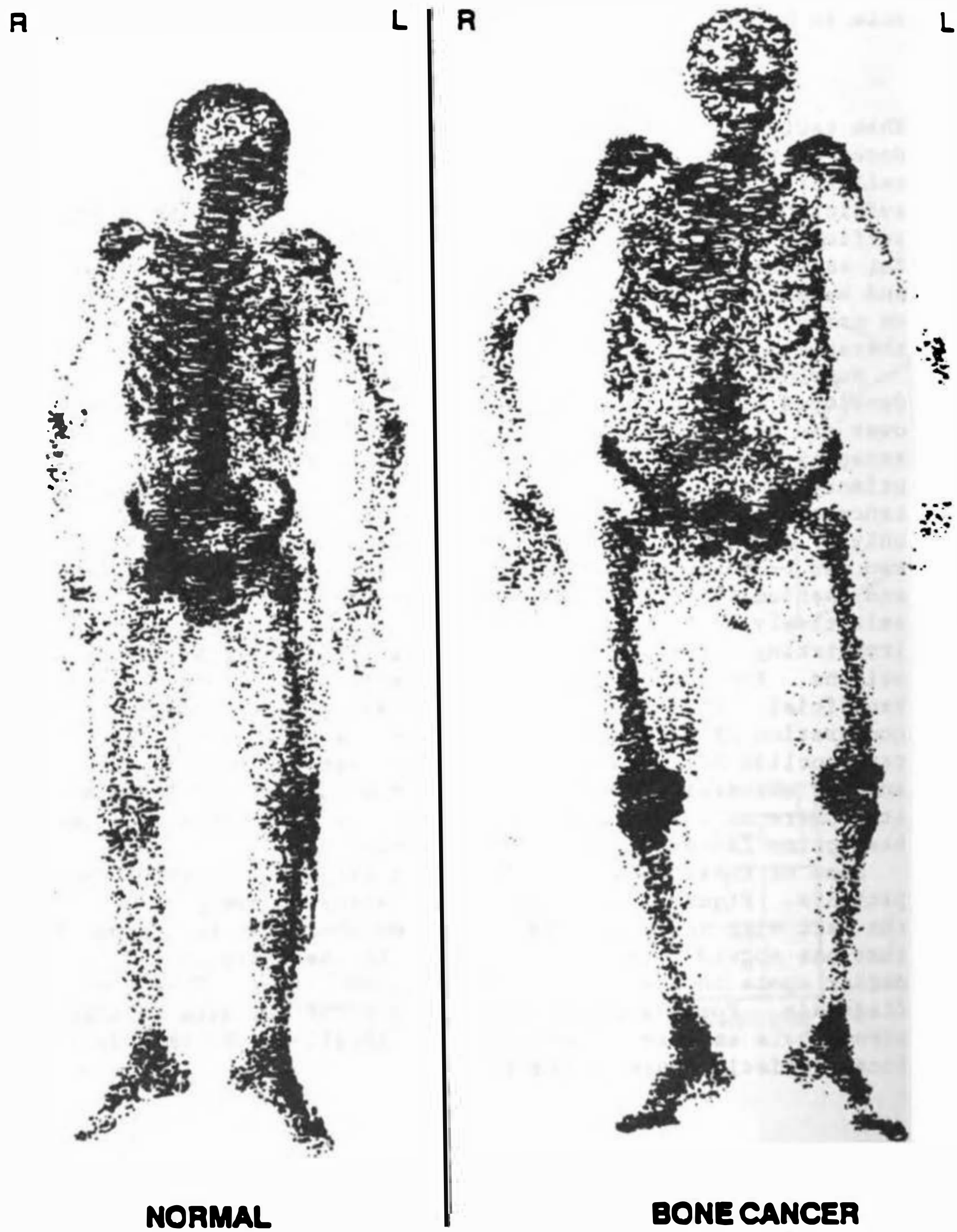

FIGURE 2-10. Nuclear Medicine Scans of a Patient with no Cancer and a Patient Whose Prostate Cancer has Metastasised.

Collaboration between two URRs and a private company has produced a new treatment for liver cancer using intra-arterial injection into the body of activated yttrium-doped glass microspheres of high chemical durability. This treatment was used in 32 liver cancer patients in Canada in the last year; it is apparently successful in stopping tumor growth, with dramatic improvements in symptoms and general condition of most patients. The product, Y-90 TheraSphere, which is awaiting Food and Drug Administration approval for trials, originated at MIT and the University of Missouri respectively, whose staffs were willing to tackle this kind of innovative research.

Researchers at another URR have developed the therapeutic technetium generator in the form of a Tungsten-188/Rhenium-188 radionuclide generator. It is the first of its kind to be practical for producing large multi-curie quantities of 16.98-hour half-life ^{188}Re from 69.4-day half-life ^{188}W. ^{188}Re, a chemical analogue of ^{99m}Tc, can label antibody fragments with diamide dimercaptide in yields and purity virtually identical to those labeled with ^{99m}Tc. Such labeled antibodies offer a hope for abating small cancer metastases because of their high selectivity and effectiveness anywhere in the body. The development of radiolabeled antibodies that destroy the metastases of common cancers as effectively as radioiodine therapy affects well-differentiated thyroid metastases would be a major breakthrough in the treatment of cancers.

^{188}Re could be available on demand at a hospital in the form of a sterile saline no-carrier-added solution obtained from a therapeutic technetium generator; it would last two months or more. ^{188}Re from such a generator may also be useful in treating metastatic cancers in the bone and as a sulfide colloid for the study of intra-articular radiation treatment of rheumatoid arthritis. Similarly, ^{165}Dy in the form of macro-aggregates is used to treat arthritic knee joints. Beta-emitting radionuclides offer a simple, less expensive, and less traumatic approach than surgery. The renaissance of the highly promising technique of radiation synovectomy is almost completely due to the efforts of one researcher working with URR faculty and staff. This procedure could provide a simple cost-effective treatment for millions of rheumatoid arthritis sufferers. Researchers at another URR are investigating alternative isotopes and particulate forms for radiation synovectomy of small joints, again using small university research grants. The use of radiation for treating nonmalignant diseases is prescribed with caution. URR and medical researchers are collaborating on development of these procedures.

As mentioned above, radionuclides can be localized in the body because of the metabolic properties of the element they represent or those of the compound with which they are labeled. A major example results from the fact that most metabolic processes use carbon and hydrogen atoms for synthesizing or modifying organic compounds. The beta emitting isotopes of carbon and hydrogen, ^{14}C and ^{3}H, are used extensively in biochemical research because they are easily incorporated into biologically significant compounds. Tritium, ^{3}H, has a half-life of 12.33 years and a maximum beta energy of 18 keV, and ^{14}C has a half-life of 5,730 years and a maximum beta energy of 156 keV. Both isotopes are produced by neutron capture reactions with high specific activity. Though their primary use has been in in vitro research on compound metabolism, some in vivo studies have been performed.

Most radionuclides are used in vivo. For diagnosis and research, particular radionuclides with the associated gamma rays are used for imaging in situ and for quantification. Therapy, on the other hand, generally employs radionuclides that are strong beta emitters. Table 2-6 lists many of the metabolically localized radionuclides and their primary biomedical application.

Another technique using enriched stable nuclides followed by neutron activation analysis is a powerful method for non-invasive study of human metabolism of some nutritionally important elements. There is no exposure to radiation, and it requires only ingestion under dietary protocol. Subsequent neutron activation of samples containing the ingested stable tracers permits precise quantification of these elements using NAA. Table 2-7 lists selected stable nuclides and their biomedical applications.

In therapeutic procedures, most radionuclides are encapsulated and are mechanically, rather than metabolically, located in or near the body. These radionuclides are administered by insertion in natural body openings, by interstitial implantation, and by external irradiation, as a gamma ray beam. The principal therapeutic radionuclides are listed in Table 2-8. It should be noted that all these radionuclides are produced in reactors, and most of them were conceived or developed at a university.

Another example of a developing nuclear medicine technique, and a new approach to tumor therapy, is boron neutron cancer therapy, which was unsuccessfully tried in the 1960s but is beginning to show some promise. It also exemplifies the value of close and collaborative relationships between URR and medical researchers. This approach to tumor therapy rests on the properties of the neutron capture reaction in boron, $^{10}B\ (n, ^{4}He)\ ^{7}Li$, in which the alpha particles are emitted with a mean energy of 1.48 MeV and the recoil lithium ions have a mean energy of 0.58 MeV. The ranges of these particles at their respective energies are several micrometers, which corresponds to cellular dimensions. Neutron irradiation of boron in a tumor produces ionizing radiation, with therapeutic results. Necessarily, a high concentration of boron in the tumor is required along with the element's known temporal variation.

Promising results have recently been obtained by a URR research team in Japan using boron therapy to treat difficult brain tumors. In the United States, research on the synthesis of boron rich compounds, the temporal behavior of ^{10}B concentrations, macro- and micro-dosimetry, and reactor neutron beam design to obtain improved epithermal neutron beam parameters is under way at several research reactors. A major new initiative including clinical trials has begun at the Massachusetts Institute of Technology and at the New England Medical Center; other therapy facilities are being designed for the Georgia Institute of Technology and the University of Missouri at Columbia (MURR).

Table 2-6. Selected Reactor Produced Radionuclides Used Biomedically (Metabolically Localized In-Vivo or In-Vitro)

Radionuclide [a]	Compound or Agent	Application
^{3}H	Compounds of biological interest	Studies of metabolism
^{10}B	Boron containing complexes	Boron neutron capture therapy
^{14}C	Body compounds of biological interest	Studies of metabolism
^{18}F	Flurodeoxyglucose	Studies of glucose utilization
^{24}Na	Chlorides	Studies of hypertension Studies of sodium balance Studies of cystic fibrosis
^{32}P	Na_3PO_4	Treatment of polycythaemia vera
^{38}Cl	Chlorides	Monitoring Cl concentration in CSF Measurements of extracellular fluid space
^{40}K	Naturally present	Monitoring of lean body mass during cancer chemotherapy
^{42}K	Chlorides	Studies of hyptertension
^{51}Cr	Red cells Human serum albumin Chromates	Spleen imaging Gastrointestinal protein loss Red cell survival and volume
^{59}Fe	Citrates Chlorides	Studies of iron kinetics
^{64}Cu	Chlorides	Studies of Wilson's disease Studies of copper metabolism and kinetics
^{82}Br	Bromides	Postoperative measurement of extra-cellular fluid
^{75}Se	Methionine	Studies of protein metabolism

Table 2-6. Selected Reactor Produced Radionuclides Used Biomedically (Metabolically Localized In-Vivo or In-Vitro) (Continued)

Radionuclide [a]	Compound or Agent	Application
^{90}Y [d]	"Theraspheres"	Treatment of intra-arterial live tumors
	Citrate colloid	Studies of arthritis treatment
^{99m}Tc [e]	Antimony trisulfide colloid	Imaging of lymph nodes
	DPTA	Imaging of the brain and renal organs
	Glucoheptonate	Imaging of renal organs and the brain
	HIDA	Imaging and functional studies of the liver and bile duct
	Human serum albumin	Imaging and functional studies of the cardiovascular system
	Iron complexes	Imaging of the renal organs
	Macro-aggreates, microspheres	Imaging of the lungs
	Pertechnetate	Imaging of the brain and the thyroid
	Polyphosphate, pyrophosphate, diphosphate, methylene diphosphate	Imaging of bones
	Red blood cells	Imaging and functional studies of the cardiovascular system
	Sulfur colloids	Imaging of the liver and spleen
^{109}Pd	Hematoporphyrin	Lymphatic ablation
	Monoclonal Antibodies (MoAb)	Treatment of selected tumors tumors
^{113m}In [f]	Colloids	Imaging of the liver and bone marrow
	Monoclonal antibodies	Imaging of particular tumors
		Detection of clots
^{125}I	Iodides	Labeling for radio-immuno-assays
^{131}I	Iodides	Imaging and therapy of the thyroid gland
(fission product)	Iodohippurate	Imaging of the renal organs
	Macro-aggregates	Imaging of the lungs
	Monoclonal antibodies	Imaging of selected tumors

Table 2-6. Selected Reactor Produced Radionuclides Used Biomedically (Metabolically Localized In-Vivo or In-Vitro) (Continued)

Radionuclide [a]	Compound or Agent	Application
^{133}Xe	Gas	Studies of lung perfusion and ventilation Studies of blood flow (brain tissue following injection)
^{153}Sm	Monoclonal antibodies EDTMP	Treatment of tumors Treatment of metastases in bones
^{165}Dy	Macro-aggregates of ferric hydroxide	Treatment of arthritis
^{169}Yb	DTPA	Imaging of cerebrospinal fluid
^{186}Re	HEDP	Treatment of metastases in bones
^{188}Re [b]	Alternative label to ^{99m}Tc	Antibody therapy Treatment of metastases in bones Treatment of arthritis
^{191}Ir [c]	Chlorides	Used in first-pass angio-cardiography
^{195}Pt	Cisplatin label	Treatment of cancers

[a] Unless otherwise noted, the radionuclides listed are produced by neutron capture reactions in nuclear reactors.
[b] Product of ^{188}W generator produced by neutron capture.
[c] Product of ^{191}Os generator produced by neutron capture.
[d] Daughter of ^{90}Sr generator produced by neutron capture.
[e] Eluted from ^{90}Mo generator produced as a fission product or by neutron capture.
[f] Eluted from ^{113}Sn generator.

Table 2-7. Selected Stable Nuclides Irradiated by Neutrons for Biomedical Use

Stable Nuclide	Application
Calcium	Determination of whole body calcium by in vivo neutron irradiation to produce ^{49}Ca (8.2 min) is available for patient examination, for example, using ^{252}Cf neutrons in a whole body counter to study calcium levels as a function of age, diet, drugs, and osteoporosis.
Aluminum	Preliminary studies have been undertaken to determine aluminum concentrations in brain tissues of rats fed different diets.
Copper	A method for the study of the metabolism of both stable isotopes of copper (^{63}Cu, ^{65}Cu) in trace amounts in the human diet has been developed. A precise dietary protocol permits quantitative use of radiochemical neutron activation analysis (RNAA) of samples (feces, plasma, red cells, urine, etc.) for a non-invasive determination of human metabolism of copper.
Zinc	A comprehensive method has been developed to study the metabolism of different stable isotopes of zinc by RNAA of samples (feces, urine, blood). The fate of intrinsic zinc (e.g., incorporated in chickens from their feed) can be distinguished from an extrinsic tag (a single stable zinc isotope added to the diet). Results indicate that though the extrinsic tag could provide an estimate of zinc metabolism, the inorganic supplement does not completely exchange with the zinc intrinsically incorporated in the diet.
Selenium	A comprehensive method using RNAA and any or all the stable isotopes of selenium has been successfully applied to studies of human gastrointestinal absorption using a dietary protocol. A possible correlation was found between serum levels of selenium and cancers.
Essential and non-essential trace elements in renal disease	RNAAs were made of the levels of essential trace elements (Co, Cr, Cu, Fe, Se, Mn, Zn) and non-essential elements (Br, Cs, Rb) in serum, in packed cells, and in dialysate of patients in end-stage renal failure on dialysis.

Table 2-8. Principal Reactor Produced Radionuclides Used in Encapsulated Form for Therapeutic Applications

Radionuclide	Application
^{60}Co	As used in teletherapy units, a large cobalt source (>10,000 curies) is employed about 1 meter from the patient and is collimated to produce a well-defined gamma ray beam.
^{125}I	Iodine-125 in encapsulated form in small seeds was introduced as a substitute for radon-222 and gold-198 sources for interstitial implantation. The soft x-rays from ^{125}I are so readily absorbed that the distribution of dose is determined primarily by absorption processes rather than by geometrical divergence (inverse square law decreases); this facilitates concentration of the dose in the lesion. The rapid decrease of the dose with distance further protects the rest of the patient and reduces staff exposure. ^{125}I is frequently used in non-resectable lung lesions and prostate irradiation. Clinical observation is that its use has a higher therapeutic ratio than that achieved with other implanted x-ray sources. This result may be associated with its low overall dose rate, sustained continuous irradiation, and a somewhat higher relative biological effectiveness. ^{125}I implants are ordinarily permanent.
^{137}Cs	Cesium-137 is used in some shorter range teletherapy units designed for head and neck irradiations. ^{137}Cs is also used in cervical applicators as a replacement for radium.
^{145}Sm	Implanted as encapsulated seeds in a tumor in combination with the administration of ^{127}IudR, the ^{145}Sm low energy radiations excite the emission of low energy electrons and x-rays from the iodine that, in turn, is incorporated into the DNA. Research is in the animal stage.
^{153}Gd	Gadolinium-153 as a source of gamma rays ($\simeq$100 keV) together with Europium K-shell x-rays is used in dual energy bone scanning systems for osteoporosis studies.

Table 2-8. Principal Reactor Produced Radionuclides Used in Encapsulated Form for Therapeutic Applications (Continued)

Radionuclide	Application
^{192}Ir	Iridium-192 is used in the form of small wires, approximately 3 mm long, encapsulated in stainless steel tubes with an overall diameter of 0.5 mm. These seeds are inserted in nylon ribbons and are implanted in tumors to produce a specified distribution of dose. The ribbons are removed when the total prescribed dose is achieved.
^{198}Au	Gold-198, with a half-life of 2.7 days and an effective photon energy of 0.42 MeV, has been used in seed form for implantation as a substitute for radon seeds. Its energy is more convenient than that of radon, but its half-life is also somewhat short for therapeutic application.
^{252}Cf	Californium-252 is a product of fusion reactors that decays by alpha particle emission, with a half-life of 2.7 years, and by spontaneous fission, with a half-life of 85.5 years. The radiobiological rationale for its use is due to reduced oxygen enhancement ratio for neutron irradiation of biological systems. As an encapsulated source, it has been used in several radiation centers with favorable clinical results, primarily in intra-cavitary applications. Because of the increased shielding and handling problems, ^{252}Cf is used in only a few centers. ^{252}Cf sources are also used for whole-body irradiation to activate such radionuclides as ^{49}Ca for in vivo studies of calcium levels in patients.

Origin of Biomedical Contributions

Many biomedical contributions have come from the university campus, including medical schools, affiliated hospitals, and veterinary schools. Contributions to radiation treatment have been and are being made by university researchers working at university and government research reactors. It is noteworthy that in the publications from the university reactor group at MURR, biomedical projects constituted one quarter of all publications between 1980 and 1986. Similarly, of the 1,031 publications based on MIT reactor research for 1958-1985, 161 were biomedical. Several other URR groups are also quite active in biomedical projects.

Again, the value of nuclear medicine to education in a multidisciplinary university deserves special emphasis. URR and medical facilities provide the training ground for students, thus contributing to the supply of trained researchers and practitioners in nuclear medicine research.

There is an intimate collaborative relationship between reactor researchers and medical researchers in the university/hospital environment. If there were no URRs, standard radionuclides could be obtained in other ways. However, URRs are a vital source of advanced labeled compounds, nonstandard radionuclides, and moderately short-lived materials. Important also is the knowledgable URR staff.

Conclusions for Medical Diagnostics and Therapy

Reactor-produced radionuclides and subsequently labeled compounds are vital in biomedical diagnosis, treatment, and research. Some are important for patients because of their metabolic localization and others in encapsulated form because of their mechanical localization.

Nearly all biomedical radionuclides and labeled compounds originated with university faculty collaborating with university research reactor or with government reactor faculty and staff or with government reactor laboratory staff. Use of URRs is a most convenient and synergistic arrangement when medical research faculty are on the same campus.

The flexible, informal, and creative atmosphere of research reactor facilities together with medical schools and teaching hospitals in the university environment have contributed to development of new and innovative procedures in nuclear medicine. The synergism between the URR centers and the teaching hospitals and medical schools and the wide variety of skills available at these facilities are effective in training students and researchers.

MATERIALS RESEARCH USING NEUTRON IRRADIATION

Description of the Method

For many years, the changes in the physical properties of materials brought on by radiation (electromagnetic, electron, ion, x-ray, neutron) have interested scientists challenged to understand fundamental processes involved and technologists challenged either to exploit or counteract these changes. The complex effects of the many types of irradiation on materials have been outlined (American Physical Society, 1975; U.S. Department of Energy, 1981).

Irradiation effects are particularly important in nuclear reactor systems, either fission or fusion, because of the high neutron radiation fluxes present. In some cases, irradiation effects limit the design or operational scale of reactors. It is not suggested that all irradiation effects are deleterious, as conveyed by the commonly used term radiation damage; many useful changes in materials can be produced, for example, by ion injection or transmutation doping.

When a material is subjected to neutron irradiation, three reactions occur: transmutation, fission, and atom displacement. Within nuclear reactors, the dominant irradiation effects are caused by high energy neutron collisions with lattice atoms within the material, wherein large cascades of displaced atoms are produced. Such displaced atoms or defects are mobile, interacting with each other, impurity atoms, and grain boundaries, and the complex defect structure that is formed can significantly alter the physical and mechanical properties of the material.

Need for a Low Temperature Irradiation Facility

For study of the fundamental defect process in materials, a low temperature irradiation facility is usually required, along with a reactor providing a relatively high neutron flux density so that a stabilized defect structure may be obtained in a reasonable time. Neutron irradiation of the material samples at low temperatures in the 4-5 K range reduces the mobility of the defects and thus allows a quantitative and unambiguous study of the fundamental material properties. Though the available neutron flux at the larger URRs is adequate, no low temperature irradiation facilities are currently operated at universities though several have been proposed and one is planned at the University of Missouri. As a consequence, programs of studies of the fundamental processes resulting from high energy neutron interaction with materials are limited. In contrast, a productive low temperature irradiation program has been supported at several Western European reactors for more than 20 years.

University versus National Laboratory Reactors

University faculty in the United States collaborate with staff at Oak Ridge and until recently at the Argonne pulsed neutron source, where liquid helium temperature irradiation facilities are available. This use of remote facilities by faculty does not support the educational mission or fully involve students and other faculty in university based research.

Nevertheless, significant materials research and testing have been carried out at some large URRs, including MIT, the State University of New York at Buffalo, University of Missouri at Columbia, University of Michigan, University of Virginia, and Pennsylvania State University, where the neutron flux is sufficiently high to result in reasonable periods of irradiation. This work embraces a wide range of technical areas, from irradiation effects in electronic systems and components, to superconductivity, to irradiation effects on structural alloys used in power reactors. Some of the work is primarily service irradiations; some is an integral part of university research activities.

Several of the higher flux URRs, especially those at universities with strong materials science and engineering departments, have been used as nuclear radiation sources in major research efforts in nuclear materials. In some cases, university expertise and facilities for characterizing irradiated material and handling radioactive material have enabled university groups to study radiation effects of materials irradiated elsewhere, for example, at the high flux national laboratory neutron centers.

It is noted that Oak Ridge National Laboratory recently constructed its Low Temperature Neutron Irradiation Facility (LINIF) at its Bulk Shielding Reactor, and that this facility is open to academic users.

Applications of Neutron Irradiation in Materials Science

Embrittlement of reactor pressure vessels have been studied at several URRs. This research, not requiring a high neutron flux, can be carried out effectively in reactors with power levels as low as about 1 Mw. In fact, the smaller reactors usually have easier access for large sample containers and are often better suited for this type of work than the larger national laboratory class of test reactors. Much of the information available on pressure vessel embrittlement phenomena was obtained from URR irradiation tests.

Irradiation tests to establish the influence of surface damage on the bulk mechanical properties of structural alloys that are to be subjected to a fusion reactor environment began at a URR. These sophisticated experiments involving end-of-life testing would have been difficult to perform at the high flux national laboratory facilities where innovative but time-consuming experiments compete with the standard very long term irradiations that can be carried out only at these high flux reactors. In addition, maintaining schedules is under less pressure at URRs than at national laboratory facilities. In one university program, the reactor had the necessary capabilities for major fusion reactor alloy development. This research enabled the university group to focus its advanced powder metallurgy and rapid solidification processing on the critical problems of first wall structural alloys for use in future fusion power reactors. Because of the nuclear materials testing and handling capabilities available at the URR, a wide range of structural alloys designed and produced at the university was tested for irradiation performance. Further, as part of this research effort, new and innovative approaches to miniaturized mechanical property testing of radioactive alloys were developed.

URR students receive unique experience and training in developing and testing materials. Other URR research is listed in Table 2-9.

Neutron irradiation may also be used to introduce impurity centers into materials in a controlled way by neutron transmutation doping. Controlled introduction of impurity atoms into materials such as silicon is a major effort in the semiconductor processing industry. In the neutron transmutation doping process, an isotope of the material

Table 2-9. Neutron Irradiation Research Reactors at University Research Reactors with Application to Materials

Type of Research	Application
The effects of neutrons and gamma rays on fusion reactor magnet insulators	Magnets to produce fusion plasma confinement and control are an essential component of magnetically confined fusion reactors.
Irradiation assisted stress corrosion cracking	The service life of critical in-core components of light water reactors is affected by neutron irradiation.
Irradiation enhanced corrosion	Such corrosion can decrease power reactor plant life and also decrease reactor safety margins.
Reduction of soft errors in semiconductor memory chips	Soft errors limit the maximum practical size and the reliability of high capacity memory chips.
Crack growth rate under irradiation	Crack tip chemistry, microchemical and microstructural changes induced by irradiation affect crack growth rate in reactor bulk structural materials.
Mili-pore filters by fission track etch techniques	Superior micro-filter performance is achieved by this method of production.
Radioactive daughter recoil yields	Radioactive recoils in the primary coolant systems of reactors critically impact the ease and cost of reactor maintenance.

Table 2-9. Neutron Irradiation Research Reactors at University Research Reactors with Application to Materials (continued)

Type of Research	Application
Neutron sputtering studies	Neutron sputtering rates affect both plasma impurity generation in fusion power reactors and radiation exposure levels in all types of neutron producing reactors.
Irradiation effects on electronic components and systems	Studies to produce radiation resistant electronic components, particularly semicondutor components, have used university facilities.
Radiation degradation of organic reactor coolants	Organic coolants offer some potential advantages over water and gas for power reactors.
Defect cluster evolution	These clusters affect radiation hardening and embrittlement, a crucial effect with respect to reactor pressure vessel embrittlement.
Void nucleation and growth	Swelling of materials under neutron irradiation is of great importance for fast breeder reactors and future fusion power reactors.
Helium bubble behavior	Helium effects represent a major issue in fusion power reactor first-wall structural materials.
Basic studies of irradiation induced defect generation and evolution	This effect is critical to the prediction of semiconductor performance and the design of devices.

Table 2-9. Neutron Irradiation Research Reactors at University Research Reactors with Application to Materials (Continued)

Type of Research	Application
Transmutation doping of semiconductors	Improved doping quality is achieved by neutron transmutation doping techniques applied to semiconductor processing.
Radiation hardness testing	Device and system performance must be understood and optimized to assure adequate performance of critical defense and space systems.
Irradiation effects on food	Large economic savings are potentially available through the reduction of waste from spoilage when particular foods are subjected to irradiations.

captures a thermal neutron and then decays to a new desired element. This process is diagramed in Figure 2-11. Neutron irradiation yields impurity centers uniformly distributed over the entire volume of the material, in some cases, a great advantage over chemical insertion or ion implantation in the near surface region of the material. Using this technique, MURR routinely prepares special high power silicon controlled rectifiers for the electric power industry.

Closely allied with neutron radiation effects are those produced by gamma ray radiation fields. Many university reactors produce radioactive sources. The primary interaction of gamma rays with materials is through the atomic electrons. Though this interaction does not result in a local disruption of the lattice, as for neutrons, electrical transport and other physical properties may be modified. Biological and botanical processes are also sensitive to such radiation effects. The use of gamma ray facilities is widespread, and URRs are important in irradiation testing.

Conclusions for Materials Research

Materials research is a major area of high-technology with important implications for science, industry, and the future health of the U.S. economy. Research techniques using neutron irradiation have made many important contributions. In particular, university research reactors have contributed to applications involving corrosion, semi-conductors, embrittlement, and resistance to radiation.

U.S. reactor research in the material sciences is not on a level with work done in Europe. In particular, there is a need for low temperature irradiation facilities at university reactors, if the community is to participate more fully in world class materials research.

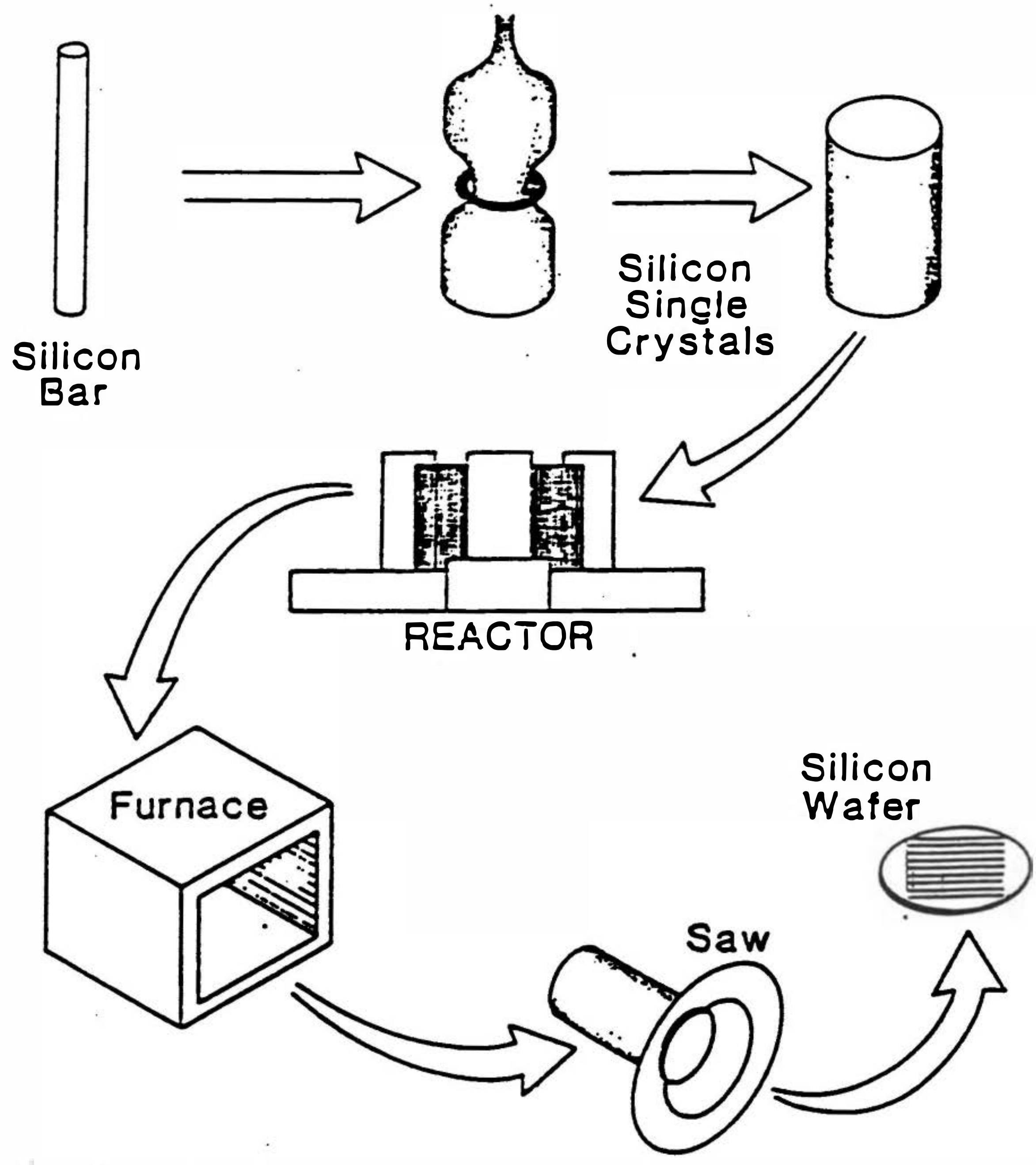

Figure 2-11. Doping Using Reactor Produced Neutron.

NUCLEAR REACTOR ENGINEERING AND REACTOR PHYSICS

Introduction

Since the 1950s, when the first university research reactors went into operation, URRs have served as tools of the engineers and scientists and have played important roles in the development and proof-testing of the basic theory and design of nuclear reactors. Early research studies, concerned chiefly with learning URR parameters, were parochial and thus were not considered as journal material. However, the interpretation of these experiments stimulated a number of basic theoretical papers, examples of which are shown on Table 2-10. In that era, the major Atomic Energy Commission (AEC) laboratories were the principal reactor research facilities, and the universities had to compete in the research market by finding specialties that had not been well-explored or were not being pursued vigorously at the laboratories. Two such specialties were neutron activation analysis and neutron radiography. In addition, the AEC encouraged on-campus service in isotope use.

Another popular area is reactor dynamic studies using reactor power fluctuations (neutron noise). This field became a focus of university activity following publication of Albrecht's work in 1962. Neutron noise received a large fraction of National Science Foundation support for nuclear engineering (annual expenditures for the field were not large) for about 20 years, and only recently was support discontinued. As a result of the collective effort, mostly at universities, neutron noise is a standard reactor diagnostic technique at nuclear test reactors and power plants.

There are presently about 110 operating nuclear power plants generating electricity in the United States. Good engineering practice dictates that research should be directed toward making them more efficient while operating safely. The currently operating URRs are typically enriched uranum fueled, hydrogen (water) moderated, fission reactors that require the use of engineering design and analysis techniques analogous to those applied to the large, electric power producing reactors. Thus, URRs are excellent test beds for selected new analytical techniques and computer codes to improve the quality and efficiency of reactor analysis. The core symmetry and piping system simplicity make most URRs geometrically easy to model, while comparison to actual performance provides real tests for the analysis methodology.

Areas of Research

Reactor Lattice Experiments

Standard techniques of experimental investigation on subcritical reactor assemblies--essentially, reactor samples--can be used to support reactor design at any installation that has a strong neutron source. The Massachusetts Institute of Technology has had two reactor

Table 2-10. Early (1956-1964) Reactor Engineering and Physics Citations Stimulated by URR Experiments

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Verification of Reactor Theory with Experiments

- Reactor lattice design (Honeck and Kaplan, 1960); Clark and deSobrino, 1961)
- Asymptotic reactor theory (Zweifel, 1961)
- Theory of the slab geometry (Mingle, 1961)
- Cadmium covered foil analysis (Powell et al., 1964)

Improvement of Reactor Reliability, Performance, and Enhancement of Safety

- Measurement of voids (Perkins et al., 1961)
- Energy release from decay fission products (Perkins and King, 1958)
- Axial heat conduction in fuel plates (Fagan and Mingle, 1964)

Development of Reactor Transfer Function Theory and Applications of Noise Analysis Techniques

- Theory and experiment on random fluctuations in the period of neutron multiplication as reactors go critical (Grim, Barrow, and Simon, 1956)
- Verification of theory and techniques using the MIT research reactor (Gyftopoulos and Smets, 1959)
- Noise analysis to measure critical reactor parameters (Albrecht, 1962; Uhrig and Boynton. 1964)

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design research projects the reactor heavy water lattice project and the fast reactor blanket project; (Harling and Clark, 1983). Both projects were centered on the large graphite-lined hohlraum that provides a large area/volume, highly thermalized neutron source. The reactor drove a D_2O moderated low enrichment uranium subcritical lattice facility and also a thermal-to-fast neutron converter irradiating mock-up of fast reactor blankets. In addition to logging a substantial inventory of benchmark data, these projects contributed in an important way to experimental and analytical methods development. For example, in the D_2O lattice work, it was shown that the measurements on a single fuel pin could provide results allowing inference of the neutronic properties of an entire lattice of fuel elements.

Even a small URR, 1 kW or more in power, provides such a source more efficiently than artificial sources. However, sponsoring agencies tend to believe that current reactor theory and existing benchmark experimental results provide an adequate basis for reactor design. This situation has made it difficult to obtain funding. Nevertheless, limited university research in this field has been supported from time to time.

Two examples from the MIT reactor experience can be cited. Both made extensive use of a hohlraum bathed in thermal neutrons. MIT installed the hohlraum as a standard experimental facility. The hohlraum concept was original research. In the late 1960s, neutrons from this hohlraum were used to drive a D_2O moderated low-enrichment uranium subcritical facility. A considerable amount of benchmark data was produced, and single-cell measurement to permit inference of complete lattice properties was checked (Driscoll et al., 1967).

More recently, methods were developed and applied to optimize the material composition for economic performance of fast reactor blankets (Driscoll, 1983). These studies were among the first to illustrate the advantages of axial internal blankets. To date, the projects have generated 38 Ph.D. theses, 62 M.S. and other theses, and 117 technical reports and journal publications. Such measurements of moderator and blanket assemblies continue at several URRs.

A related project under way at Purdue is another fast reactor blanket facility (Ott, 1987). Work to date has uncovered discrepancies between the calculated behavior of neutrons and their behavior in a real system. Calculated-to-experimental ratios of neutron absorption in sample materials deviate from unity with a systematic trend as one goes farther into the blanket.

Fission Product Decay Power

During the 1970s, under joint sponsorship of the Nuclear Regulatory Commission, the Department of Energy, and the Electric Power Research Institute, a coordinated effort was conducted to specify the decay power from fission products as a function of reactor shutdown time. This power is the principal source of the energy that must be removed by an emergency core cooling system after a reactor accident or incident. The team included researchers from universities, private laboratories, and national laboratories. The universities involved were California at Berkeley and Oregon State.

The Berkeley work consisted of an integral measurement of decay power in a sample, by calorimetric methods, after it had been irradiated in a high flux reactor for an appreciable time. The sample was transferred to the shielded calorimeter by a pneumatic "rabbit" so that measurement could begin soon after irradiation. The final experiment was conducted at the General Electric test reactor, but all the set-up work was done at Berkeley. The data (Schrock et al., 1978) were an important input to the American Nuclear Society (ANS) standard that was developed as a result of the coordinated program (1978).

The Oregon State work was analytical. It drew on the body of measurements that had been made on decay characteristics and yields of fission products to estimate decay power as the sum of the powers from these individual decays. Many research reactor centers around the world contributed to this work. Data from a number of URR facilities working on nuclear measurements were a significant contribution. Oregon State (Spinrad et al., 1977) also made an important contribution to the ANS standard.

Reactor Control Studies

URRs are contributing significantly to nuclear engineering in developing and testing advanced instrumentation and control techniques. This work explores automation as a way to ensure safety of the systems against human errors.

Automation research has led to licensing the MIT reactor to operate under closed-loop digital computer control (Harling and Clark, 1983). Important contributions from this research include:

- Development of a general method for digital, non-linear, closed-loop control of reactor power and other essential parameters, such as temperature during both steady state and transient operation
- Demonstration of the parity space approach for both signal validation and instrument fault detection
- Development of the reactivity constraint approach, a method to determine whether a change should now be made in the control signal in order to avoid a future power overshoot. Permitting a non-linear system such as a reactor to be operated on closed-loop control without challenging the safety system
- Demonstration of techniques for the on-line reconfiguration of both hardware and control algorithms
- Development and testing of specific control algorithms under a variety of operating conditions.

Loop Tests

In the past 10 years, not only several URRs but many research and test reactors at national laboratories and virtually all the reactors built by industry for reactor development have closed. The remaining URRs are now the principal national resource for progressive improvement to existing nuclear power plants. They are also vital tools for developing new and improved react rs.

Neutronics work toward these goals can be carried out in all but the very small URRs. Reactors of even 1 kW thermal power are adequate neutron sources for most lattice studies. However, many of the most pressing problems are concerned with the technology of fuels and materials exposed to high neutron fluences. For example, the highest flux test reactor in the world--the 250 Mw advanced test reactor in Idaho--is fully committed to experiments that support the Navy's reactor program. The higher power URRs are the only reactors available to the power reactor community for doing similar research.

In anticipation of this need, MIT recently installed test loops in its reactor (Harling, Bernard, and Driscoll, in press). These are tubes in which fuel and materials samples of appreciable size can be exposed to the high research reactor flux. The loops are separately cooled, and the loop coolant circuit is isolated from the main reactor coolant circuit. Consequently, the effects of burnup and high fluence in a reactor that is different from the URR can be studied. The MIT program is in fact expected to be one that emphasizes radiation effects on both solid reactor materials and reactor coolant chemistry.

Given support, the other high flux URRs could install similar facilities. The existence of about 90 Gwe nuclear power industry, representing more than 15 percent of U.S. electric generating capacity and still growing, justifies their use.

Future URR Research Opportunities

Table 2-11 lists additional research topics relating to nuclear engineering and reactor physics, to which URRs can make fruitful contributions provided that dedicated research teams are maintained, existing reactors upgraded, and necessary instrumentation and other equipment are purchased.

Contributions to Reactor Design Codes and Capability

The reflected, heavily loaded, compact cores of several URRs result in significant neutron spectrum changes in very short distances. This provides a necessity for determining neutron cross-sections for reactor materials and performing neutronics analysis with considerable energy spectral detail. From experience gained in the use of reactor physics and thermal hydraulic analysis codes with the URRs, the typical nuclear engineering student is well-prepared to undertake these types of design problems that are encountered in the commercial nuclear power industry.

Efficient Use of Fuel

One major challenge in today's commercial nuclear reactor industry is to design and operate the fuel elements so as to have as large a fraction of the fuel as possible producing their maximum permissible power. In this manner, the fuel elements are operated within the required safety margin for departure from nucleate boiling conditions but at as high an average power as possible. This can be accomplished by flattening the neutron flux and power profiles. The goals of this research are to devise means of accomplishing this power flattening

Table 2-11. Topics of Future Nuclear Engineering and Reactor Physics Research

Irradiation effects in LWR materials
Irradiation enhanced stress corrosion cracking
Pressure vessel steel embrittlement and annealing, also similar effects in shielding materials
Irradiation effects in electronic materials and systems
Basic studies
Radiation hardness testing
Irradiation effects in fusion reactor materials
Insulators
Breeding materials
Superconducting magnet materials
Irradiation effects in space reactor materials
Thermionic diode insulators
Thermionic converters
Development of advanced instrumentation and control techniques
Effects of ion implantation, stress and temperature cycling on the mechanical performance of fusion reactor first wall alloys
In-pile coolant loop research
LWR corrosion and dose reduction project
Research on nuclear pumped laser states
Development of improved neutron cancer therapy beams

with a mixture of new and partially used elements and to extend the use of each element to its maximum allowable (and tested) fuel burn-up condition.

These conditions of extended fuel life are similar to the operational goals of several URRs and are aided by the use of improved codes. Over the last 20 years, the sophistication of computer analysis codes and techniques has grown substantially. These tools have progressed from the simple few-group, one-dimensional diffusion codes of the 1960s to the two-dimensional, multi-group with burn-up diffusion codes and the two-dimensional transport codes of the 1980s. New and more sophisticated codes are being developed and tested on URRs for use on the next generation of reactors.

Neutron Spectra and Inherent Safety Analysis

Both in the present commercial nuclear power industry and in what appears to be the new generation of nuclear power plants, the improvements needed in the design and analysis techniques center around two principal aspects: more detailed neutron spectra and techniques to evaluate the degree of inherent safety of a particular reactor design under loss of flow and/or loss of coolant conditions. The spectral detail issue, particularly involving neutron transport rather than diffusion theory, becomes paramount when the liquid metal breeder reactor is considered. The need for improved spectral detail and transport theory is critical to the work with URRs to develop specifically tailored neutron spectrum beams for a particular application. The inherent safety analysis work involves the use of complex and sophisticated thermal hydraulic analysis codes such as the RELAP code (Wang, Kunz, and McKibben, 1987). This code was first applied to the safety studies for several URRs work involving Ph.D. dissertations and is now being applied to safety analyses in its newest and most sophisticated version.

Conclusions for Nuclear Engineering and Reactor Physics

The number, size, and activity of nuclear engineering research groups have been decreasing (see Table 1-4). Their hallmark facilities, research reactors, are fewer, and regulations covering operation of the remaining reactors are growing severe (see Chapter 6). The remaining URRs are becoming increasingly important tools for this research as comparable industrial and national laboratory reactors have been phased out.

The capability for meaningful research in nuclear engineering nevertheless remains impressive, as indicated by the examples presented in this section. The Committee is concerned that the capability to carry out this kind of research is declining at universities. The future of technologies such as nuclear power, space power, and other direct application of reactor technology will depend upon an adequate level of diversified research at a variety of reactor centers and facilities. The Committee is concerned that further decline in the capabilities of university based reactors to participate in this research will reduce diversity of effort and result in a reduction of innovation in these importance fields.

3

RESEARCH REACTORS IN EDUCATION AND TRAINING

INTRODUCTION[1]

University research reactors (URRs) are important to education and training in the nuclear sciences and related disciplines.[2] URRs range from low power reactors acquired primarily as tools for laboratory instruction of nuclear scientists and engineers to high power world class research reactors (see Table 1-1). Their uses are as varied as the interests of students and faculty in physics, chemistry, biology, health sciences, materials science, and other disciplines. Because research and education are clearly integrated at a university, the development of students' skills in research activities is basic to their education. Educational uses of reactors include:

- A demonstration or laboratory tool to teach reactor and nuclear science properties
- A source of neutrons and other radiations to demonstrate nuclear techniques
- An instrument to practice reactor operating skills
- A tool for the performance of student and faculty research (see Chapter 2).

This chapter discusses the range of educational practices for URRs with virtually zero power through 20 Mw. It also discusses problems associated with URRs:

- Constraints on reactor use
- The need for nuclear engineers
- Distinction between education and training
- Appropriate reactor use.

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[1]For historical and other background, see Spinrad (1987).
[2]For a description of the needs of nuclear energy engineering departments, see Nuclear Engineering Department Heads Organization (1985).

EDUCATIONAL USES OF URRs

Reactor and Nuclear Science Laboratories

Most laboratory experiments on reactor properties are performed within structured nuclear engineering courses. Over the years, the experiments have changed little. Tables 3-1 and 3-2, adapted from two of the earliest textbooks on reactor experiments, list uses of reactors in nuclear engineering experiments. Most of these experiments are intended to show properties rather than uses of reactors. Modern courses--at least, in undergraduate laboratories--use some of these experiments. For example, Table 3-3 lists undergraduate course experiments at Iowa State University (ISU), whose nuclear engineering department offers somewhat more than average reactor laboratory exposure to its undergraduates. Nine of the 11 experiments are run to demonstrate reactor properties. The ISU reactor--an Argonaut-- is run for up to 200 hours per academic year in reactor laboratory courses. In comparison, Oregon State University uses a TRIGA reactor approximately 110 hours per year for undergraduate nuclear engineering coursework alone; it is also used for coursework in other departments (Schmidt, 1987). Nuclear engineering departments at other universities use a reactor 100-200 hours per academic year for undergraduate nuclear engineering coursework, about 3-6 hours per week. Such a low service rate is not unusual for course use of sophisticated experimental equipment, but economics dictates that the reactor must be inexpensive to operate or it is used for other purposes as well.

Small swimming pool reactors, low power Argonauts and AGNs are common for teaching reactor properties and behavior. Rensselaer Polytechnic Institute uses a critical or zero power facility in which reactor core components can be reconfigured to illustrate various properties (Harris, 1987).

Most nuclear engineering departments are more oriented to graduate programs than traditional engineering departments are. This orientation is dua to the relative newness of the discipline and to its syncretic nature. A significant fraction of M.S. candidates in nuclear engineering received their bachelor's degrees in non-nuclear disciplines. Therefore, they first need to learn the basic properties and principles of a reactor. Instruction at this level often involves student research. Thus graduate reactor laboratories often provide student practice with experimental facilities that were set up for research programs. For this reason, graduate level reactor laboratory courses can use research grade reactors more profitably than undergraduate courses do. Though time of reactor use in graduate courses tends to be less than half that in undergraduate courses, this use is a vital part of the graduate nuclear engineering curriculum.

Table 3-1. Student Experiments Using Reactors

A High Flux Research Reactor (CP-5)

Irradiation of antimony (source preparation)
Absolute flux measurement using calibrated foils
Subcritical multiplication vs. control rod withdrawal
Cross section measurement in beams
 Annular counter for scattering
 Transmission with crystal spectrometer
 Transmission with slow chopper
Measurement of flux in a simulated fuel assembly
Attenuation of gammas and neutrons in shields
Reactor power measurement using
 foils
 Process instruments
Reactor start-up and shut-down
Reactivity and period measurement: control and calibration
Temperature coefficient of reactivity
Decay power
Gamma radiation from spent fuel

A Low Power Training Reactor (Argonaut)

Neutron temperature measurement
Isotope production
Global flux distribution in the reactor
Internal exponential experiments
Control rod worth
Control rod flux perturbation
Approach to criticality
Reactor cross section by danger coefficient and by oscillation
Cell flux distribution
Fuel sample comparisons
Shielding experiments
Power measurement
Temperature coefficient of reactivity
Importance mapping

SOURCE: Hoag, 1958.

Table 3-2. Additional Student Experiments Using Reactors

Determination of reactivity and lifetime
Control rod calibration
Measurement of gamma rays and neutron heating during operation
Irradiations for solid state damage experiments
Periods and the in hour equation
Flux mapping
Power calibration
Gamma decay heat
Temperature coefficient of reactivity
Void coefficient of reactivity
Spatial statistical weight
Danger coefficient and effective absorption cross section
Reactor neutron temperature
Reactor neutron spectrum
Properties of neutron noise
Auto- and cross-correlation of reactor signals

SOURCE: Glover, 1965.

Table 3-3. Experiments Using the Argonaut at Iowa State University

Reactor start-up
Precritical checks
Reactivity and multiplication
Approach to criticality
Rod worth calibration
Use of reactor instrumentation for determining area background
Power decay after scram
Reactivity coefficients--temperature and void
Cross section measurements by beam transmission
Reactor neutron spectrum
Diffusion length in graphite
Safety system performance

SOURCE: Hendrickson, 1987.

Laboratories on Nuclear Experimental Techniques

Graduate and Undergraduate Levels

It is in research reactor laboratories that students in fields such as physics, chemistry, biology, medicine, and material sciences, learn how to measure properties of matter and materials. Reactor use for learning experimental techniques was originally thought of as a service for other departments, but it is now usually considered part of the nuclear engineering program. At many universities, the disciplinary definition of nuclear engineering now includes aspects of medium energy physics, such as measurement of neutron cross-sections; radiochemistry applications, such as the properties of fission products and the study of the fission process; and the study of new nuclear techniques, such as neutron activation analysis and neutron radiography. In Table 3-4, some adjunct reactor uses for instructional purposes are listed; a major use is connected with graduate nuclear engineering study. Table 3-5 lists some graduate level experiments performed at North Carolina State University. In graduate education, emphasis is on using the reactor and its radiations in general scientific work rather than on demonstrating how the reactor works.

Table 3-6 lists experiments performed in undergraduate physics courses at the Massachusetts Institute of Technology. These experiments are also done for guest classes from nearby universities. Similar experiments are offered at Oregon State University. Courses given by departments other than nuclear engineering actually use more reactor time than nuclear engineering courses do (see Table 3-7). There is always some ambiguity about the best place in the curriculum for courses in activation analysis and radiation health.

The education of specialists in many practical and research areas can benefit considerably from student time at a reactor. Neutron activation analysts, materials scientists interested in neutron diffraction, clinical practitioners in radiation medicine and biomedical researchers, nuclear physicists, radiochemists, and non-destructive examination specialists require an understanding of the techniques that are available by their working at a reactor. For example, health physics and medical school students, exposed only to isotope or accelerator radiations, are not prepared to deal with the variety of radiation sources around a reactor or with the exposures arising from them.

Laboratories for General Science Education

In addition to the education of specialists, university reactors can also contribute to general education in science. In an era that has been dubbed the atomic age, even high school students need some exposure to nuclear science at a basic level, including laboratory experience.

Table 3-4. Educational Uses of a Reactor as Neutron and Irradiation Sources

Preparation of sources for
- Radiation detection laboratories
- Subcritical assemblies, standard piles, and nonmultiplying migration length experiments
- Shielding experiments

Provision of irradiated samples for
- Measuring optical and electrical radiation effects on solids
- Annealing experiments
- Engineering (creep and hardness) effects of irradiation
- Biological effects of irradiation
- Neutron activation analysis

Provision for neutron beams for
- Neutron cross section measurement
- Neutron radiography experiments

Table 3-5. Graduate Level of Experiments Using the North Carolina State University Reactor

Fission
- Kinetic energy of fragments
- Performance of surface barrier detectors
- Kinetic energy vs. fragment mass

Thermal neutronic reactor measurements
- Neutron spectrum with a crystal spectrometer
- Cross section measurement by oscillation
- Neutron temperature from foil activations

Kilovolt neutron energy measurements
- Response of a He-3 detector
- Cross section measurement vs. neutron energy
- Microdosimetry

Fast neutron spectrum measurement
- Prompt gammas from fission
- Neutron depth profiling
- Neutron radiography

SOURCE: Wehring, 1987.

Table 3-6. Third Year Physics Experiments Using the Massachusetts Institute of Technology Reactor

Reactor thermal neutron spectrum
Operation of a neutron chopper
Use of a boron trifluoride proportional counter
Bragg diffraction of neutrons
Transmission cross sections for slow neutrons
Bragg diffraction from alternate crystal planes

SOURCE: Miller, 1987.

Table 3-7. Teaching Uses of the TRIGA Reactor Oregon State University

Department	Course Title	Departmental Use (hr/yr)
Nuclear Engineering	Nuclear Engineering Orientation Nuclear Radiation Detection and Measurement Radiation Protection Engineering	109
Chemistry	General Chemistry Laboratory Radioactive Tracer Methods Activation Analysis	81
General Science (Radiation Health)	Field Practice in Radiation Protection	372

SOURCE: Schmitt, 1987.

Several university reactors are used as host laboratories for other educational institutions. The Texas A&M University reactor serves nine other universities and colleges. The Ohio State University reactor serves 4 universities directly plus 12 colleges and universities through a nuclear science education program. In addition, it has a special program with two high schools. Most experiments in these reactor sharing programs are geared to the basics of radiation science or reactors. Table 3-8, a list of the experiments performed at Ohio State University through its high school program, shows that even at this level a broad program is possible.

Training for Nuclear Operational Skills

Training on Reactors

University reactors are often used for training in commercial reactor operations. Though education illustrates principles and promotes a deeper understanding of science and engineering, training prepares students to respond to specific circumstances. Training may be a minor component of university courses, but it is the major purpose of certain vocational curricula. Training is also a major function of specialized industries, such as the nuclear power industry; it operates extensive operator training programs both in-house and at URRs.

At universities, student and faculty operators must complete regular training programs and be licensed according to Nuclear Regulatory Commission regulations. Students compete for the the privilege of being operators, considering it a valuable enrichment of their curriculum.

Operators of commercial power reactors are required to perform several reactor start-ups to qualify for their licenses. Several university reactors have served as host sites for their start-ups; operating utilities often prefer that practice operations not be done on the power plant itself.

Training on Computer Simulators of Reactors

It is sometimes proposed that a reactor simulator of the type used for training at nuclear power plants might be preferable to a university reactor laboratory. A simulator can model a range of real nuclear power plant behavior that has no counterpart in a university reactor, for example, effects of electrical power system loads, failure of components, and dynamics of the cooling system. Such simulators can cost as much as a small reactor, and its features can be made to correspond quite closely to a particular commercial power reactor.

But a reactor simulator is not a source of neutrons. It cannot provide the experimental and research experience for the multi-disciplinary reactor uses described herein. Moreover, it is a single purpose tool useful for training in the operation of a specific power plant.

Table 3-8. Experiments in the Westerville High School Using the Ohio State University Reactor

Class demonstrations	
	Reactor programs
	Half-life Measurement
	Neutron activation analysis
Laboratory group investigations	
	Approach to criticality
	Control rod calibration
	Scram responses
	Neutron activation analysis
Individual projects	
	Neutron activation analysis
	Neutron radiation dosimetry
	Materials irradiations

SOURCE: Miller, 1987.

Student Research Using Reactors

URRs have been used extensively by students over the past 30 years in research activities ranging from nuclear science, engineering, and medicine to fundamental solid state physics, metallurgy, geology, oceanography, forensics, and analysis of fine art. Education through participation in URR research enables graduates to enhance their chosen careers with expertise in the nuclear sciences.

The overriding issue involving all this research, irrespective of the level--undergraduate, master's, etc.--is use of the research reactor itself. Without real experience, students see reactors and radiation primarily through theories and models. The opportunity to work with a reactor is often cited by students as both a high point in their learning experience and a point of departure for study and research of other nuclear devices, techniques, and applications. In other words, the URR provides a focus for their study of nuclear sciences, as an interdisciplinary pursuit as well as a foundation for careers in nuclear engineering.

Though nuclear engineering research can be done without an on-campus reactor, the Committee believes that an on-campus URR enhances interest and is more efficient. Alternatively, students would be required to arrange some type of reactor laboratory experience at a national or other off-campus facility. This situation would diminish the experience because of the time lags and because of limited hands-on time. Moreover, the national laboratories are not set up to provide student level hands-on experience.

CONSTRAINTS ON EDUCATIONAL REACTOR USE

Public Perceptions

The once highly favorable public attitude toward university reactors has given way to various feelings, including, in the extreme, hostility. This change has placed some universities in an awkward position relative to their communities, and it is an important factor when university administrators consider whether and at what level the reactor is to be supported.

Safeguards and Regulations

As discussed in Chapter 6, safeguard and security measures required at research reactors add to operating costs and decrease their use as demonstration facilities for education of the general public.

Correspondingly, the tightening of regulations concerning radiation exposure has led to occasional extreme situations affecting nuclear science education. University authorities may be reluctant to permit display of natural uranium in exhibits or to approve certain experiments that involve brief exposure to mildly irradiated fuel well below established public exposure limits. Overly restrictive regulations often impose conditions that add to the costs and complexity of experiments.

Costs and Budgets

Educational use of reactors is being questioned by institutions called upon to provide funding. The operation of a reactor cannot command budget support without thorough justification when even library and computer center budgets are being reduced. There is a need to communicate the academic values of URRs to university administrations, who are ultimately responsible for budget priorities. Federal support is also needed. Costs are discussed further in Chapter 7.

University-Industry Differences

The assumption is often made that engineering education is a type of training. This perspective is common in both industrial and regulatory circles, and it requires further discussion. Particularly at state universities, which turn out the largest number of nuclear engineers, there is an understandable sensitivity to the needs of the industry that will employ the engineering graduate. Many such universities pride themselves on the practical nature of their undergraduate engineering programs. Yet, in the university/industry relationship, a major function of the university is to anticipate industrial needs and applications, which may not be understood or favored at any given time within industry.

Industrial concerns in other fields include electrical engineering departments going into solid state electronics and computer applications and metallurgical engineers specializing in microscopic properties of materials. In nuclear engineering, little support is given to applications of computers for nuclear system control, robots for radioactive maintenance, or new technological discoveries for intrinsic redesign of reactor systems. Though there have been recent signs of interest in nuclear engineering, the nuclear industry continues to give universities a low priority. Moreover, the industrial view of engineering education has often been geared to the engineer as an employee who is assigned tasks rather than to the engineer as an industrial innovator. Universities use various mechanisms to counteract this influence, most notably by insisting on the design role of the engineer. Yet, many firms assign engineers to work that is within the competence of engineering technologists, and it is quite common for the job title "Engineer" to be little related to an individual's level or field of study.

These different perspectives of the function of engineers continue to be a source of tension between educators and industry. At best, this tension can be, and is, constructive in stimulating both parties to reevaluate their practices.

The Loss of Reactor Programs

That a reactor laboratory provides a unifying theme in nuclear engineering education is a view widely held by nuclear engineering faculties. Without a laboratory, students study reactors primarily through models. But models lack only a sense of reality: physical responses are inexorable, real instruments are faulty, controls need adjustments, and so on. Several universities with no reactors arrange for students to get reactor experience off campus through a reactor sharing program.

Not all nuclear engineering faculties believe that a reactor is essential to its educational mission. The University of California at Berkeley recently announced that it is abandoning its reactor but is continuing its nuclear engineering program (Walsh, 1987). It is one of several reactor terminations in the last several years which have included the University of California at Los Angeles, Stanford, Northwestern, and the Virginia Polytechnical Institute. No other reactors are near Berkeley, so reactor sharing is not a convenient alternative. Instead, other neutron source equipment will be procured. The University of Washington is reportedly considering a similar step at its Seattle campus. This situation would be less drastic for student experience because the university has continued access to research reactors at Hanford.

The recent closure of reactors at Berkeley and other schools seems to be motivated by the desire to perform advanced research in other areas now associated with nuclear engineering. More research papers can be generated from experiments with accelerators--which both institutions are considering procuring-- than from reactor experiments, particularly when the reactor is considered obsolete or otherwise not world class. The impact on their nuclear education programs is unclear.

WORKFORCE FOR THE NUCLEAR PROCESSIONS

The Nature of the Workforce Need

Individuals trained in nuclear science and technology are needed to provide the following services:

- Design and operate nuclear power plants
- Design and operate nuclear material manufacturing facilities
- Design and operate nuclear reactors in the civilian and military sectors
- Design and manage the disposal of spent fuels and radioactive wastes
- Monitor radiation and manage health physics programs
- Manage safeguard programs for nuclear materials in the power and weapons sectors
- Provide federal and state government nuclear-related regulatory services
- Provide technical expertise for U.S. and international programs involving nuclear materials, non-proliferation, safety, and energy development
- Carry out programs of research and development using nuclear reactors
- Provide environmental analytic services in air and water quality using nuclear science methods

- Educate university students and train reactor operators
- Oversee the safe handling of nuclear and irradiated materials as applied to chemistry, biology, medicine, physics, and other fields.

The university environment is the principal and almost exclusive place in the United States for educating and certifying persons as competent to provide the above services. In addition, because of the extensive use of a wide variety of irradiated materials, radioisotopes, and high energy beams for science research in the areas of medicine, biology, physics, and other fields, on-campus nuclear science education reaches out to most other science and engineering departments.

Many jobs in the nuclear industry can be performed by personnel trained for specific tasks at an industrial or military service site. However, the competent management of such personnel and their work as well as the performance of design, development, and other integrative jobs in the industry require the deeper, broader based knowledge that characterizes the educated, as against the trained, person. Such people come from university programs.

Nuclear Engineers

A major part of educational reactor use is to produce nuclear engineering professionals. A Workshop run by Oak Ridge Associate Universities (ORAU) in October 1986 brought together a representative group of educators and employers to exchange views on future nuclear employment (Johnson and Blair, 1987). Presentation of statistical information from a Department of Energy sponsored survey of personnel needs and supply (1985) provided a background for discussion. The nuclear personnel problem was included in an earlier symposium on trends and needs for the entire energy sector in May 1986, also arranged by ORAU (Blair and Smalley, 1986).

Table 3-9 shows the number of B.S., M.S., and Ph.D. degrees earned by nuclear engineers from 1972 to 1985 and the number of Ph.D. degrees earned by U.S. citizens. These latter data are important because a large fraction of the foreign nationals who receive doctorates in engineering return home, and a major employment sector for nuclear engineers at the doctoral level is in government owned laboratories that perform security sensitive work.

The declining enrollments and degrees earned since 1977 are reflected in other indicators. For example, in 1984, B.S. nuclear engineers received higher entry level salaries than most other engineers (Johnson and Blair, 1987, pp. 54-56); nuclear engineers as a whole had a low under-utilization rate--that is the fraction who do not have jobs in their specialities and are actively seeking them (pp. 61-62); and in 1985, they were listed as being in short supply by recruiters (pp. 67-68).

Table 3-9. Number of Degrees Earned by Nuclear Engineers at U.S. Universities, 1972-1985

Year	B.S.	M.S.	Ph.D.	Ph.D's Awarded to U.S. Citizens
1972	561	436	151	112
1973	701	453	128	100
1974	661	465	128	100
1975	599	468	103	72
1976	734	468	146	100
1977	820	555	126	88
1978	878	487	112	71
1979	828	463	117	82
1980	732	366	116	67
1981	692	315	132	69
1982	681	342	127	71
1983	674	324	124	60
1984	728	316	132	73
1985	660	306	113	48

SOURCE: U.S. Department of Energy, 1985
Nuclear Engineering Degrees

Nevertheless, employment projections in 1984 and again in 1986 were for low hiring rates by the nuclear utility industry, suppliers, and engineering firms. Between 1986 and 1991, the total number of jobs in nuclear engineering was expected to decline, with hiring limited primarily to replacement for natural attrition[3]. There are other considerations, however. Industry employment projects are generally conservative, and employment projections at defense-related laboratories (which hire mostly at the M.S. and Ph.D. levels) have also tended to be lower than what was previously needed. Further, academe as an employer is having difficulty recruiting nuclear engineers at the Ph.D. level who are U.S. citizens or at least permanent residents.

The Committee believes that there is a relationship between the decline in URRs available for on-campus teaching of nuclear engineering laboratory skills, and the decline in enrollments as reported above. However, the available studies and surveys do not explain all of the factors. One of the key uncertainties is the future demand for nuclear engineers, and the particular technical skills that will be needed in the nuclear engineering professions. These may include more advanced computer technology than in the past, robotics, environmental sciences and other topics once considered peripheral, but which may be vital for comprehensive engineering of the future nuclear fuel cycle. Moreover, the future demand for nuclear facilities and hence engineers, depends to a large extent on public policy decisions in the areas of energy and national defense. A study of these factors in relation to the nuclear engineering education is beyond the scope of this study. It is noted that the National Research Council has recently been asked by the Department of Energy to specifically study issues related to nuclear engineering education in the United States.

Health Physicists and Radiation Engineers

While the Committee did not study this issue in depth, a recognized shortage for health physicists and radiation protection engineers is noted. There are simply not enough graduates in these fields to satisfy the growing need in medicine and the nuclear industry. From a relatively small number of institutions comes a steady but inadequate flow of graduate who command high salaries. It is difficult to retain faculty under these circumstances, and there is a clear need for more institutions to enter the field, but the entry price, in faculty and laboratory equipment, is higher than many universities can afford.

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[3]"Data from INPO surveys indicate only 816 nuclear engineers will need to be hired by nuclear utilities over the period 1986-96 after growth, vacancies and replacement needs are considered. Estimates by [Oak Ridge Associated Universities] project a 0.4-percent annual decline of overall engineering employment in the civilian nuclear industry between 1986 and 1991" (Johnson and Blair, 1987).

DECISION FACTORS AFFECTING NUCLEAR EDUCATION PROGRAMS

Though a URR is clearly a useful teaching tool, whether it can be justified in terms of conflicting demands on university resources is questionable.

One can identify the university programs that emphasize research and service. For them, program success is measured in research results and the unique services provided to the research community, industry, and public bodies. Reactors that perform these functions are expensive to procure and operate.

Most universities try to strike a balance between scholarly activity and instruction. Though research is encouraged and rewarded, the education of undergraduates for professional careers is the primary mission. This point is particularly applicable to departments that operate low or medium power reactors closely associated with nuclear engineering programs. Low power reactors are inexpensive to operate and maintain, but they limit the range of research. Medium power reactors cost more but do permit several lines of research and can often generate service income to defray their costs. Universities with low or medium power reactors often use them for preliminary set-up activity on experiments that will be run off campus. Ideally, the research should take place within a network on the example of the European system (see Chapter 5). This model combines support for on-campus and peripheral research reactors.

For the central mission of education, university reactors are generally under-used because of inadequate funding. Faculty in nuclear engineering and other fields need an incentive to emphasize teaching nuclear science, such as chairs funded specifically for nuclear education. Twenty-five years ago, the Atomic Energy Commission funded institutes, practicums, and workshops in nuclear science. Today, however, teaching nuclear science, particularly reactor use, is lacking a significant portion of its prior support. Restoration of funding is merited.

The principal educational use of reactors remains instruction in nuclear engineering and health physics, the disciplines that are important to nuclear energy. The ultimate question is how a university decides whether to support programs in these disciplines. Most nuclear engineering programs have fewer students than other engineering disciplines. Too low an enrollment may result in program discontinuation; further, not every university needs a program in every discipline.

More reactor programs will certainly survive given increased federal support. Decisions whether to close or retain programs will no doubt be influenced by the availability of such support.

Program survival is particularly important at state-supported institutions, where student tuition is subsidized. Many students choosing nuclear careers may lose that choice if programs do not exist at their local state universities.

CONCLUSIONS

Reactors are general purpose laboratory facilities, useful in teaching nuclear science at all levels from high school through graduate school. Education in science and engineering is significantly enriched when the academic curriculum includes reactor experience. Using the reactor, students gain a much better understanding and appreciation of the physical process and underlying principles.

URRs are an integral part of the educational process in a broad multi-disciplinary sense, involving students from several academic departments. For nuclear science and engineering students to meet the needs of the next generation, they must have a firm understanding of basic physical principles. University research reactors provide this knowledge directly through laboratory courses and hands-on research experience.

University reactors are of particular value in providing a unifying theme for nuclear engineering programs, in presenting reactor behavior in a realistic way, and in being a primary research tool.

As a science teaching tool, university reactors are often under-used, perhaps because of staff costs or the perception that they are useful only in nuclear engineering education.

Larger teaching and research university reactors not only offer expanded opportunities for work in certain research areas but also permit a broad spectrum of experience in a wide variety of disciplines. But they are expensive to operate.

Smaller teaching reactors are less capable of offering research opportunities either in nuclear engineering or in other sciences. Nevertheless, they are valuable for a broad spectrum of undergraduate educational programs. They are relatively cheap to operate, but they require faculty commitment to their use in teaching.

The educational value of reactors would be enlarged by addressing a broader base of students in chemistry, physics, biology, and mechanical engineering, as well as majors in nuclear engineering.

Not all universities--or all state universities--need a nuclear reactor or a nuclear engineering department. However, if education in nuclear engineering and in the spectrum of neutron science applications is to provide an adequate grounding and motivation for students, nuclear reactor laboratory experience is essential. Those universities with on-campus reactors will be best equipped for this purpose.

The future demand for workers in the nuclear-related fields, combined with recent declines in enrollments in nuclear science and engineering, is a source of national concern. Affected areas include defense applications of nuclear engineering, the electrical power industry, and other industries.

4

RESEARCH REACTOR SERVICES FOR OTHER USERS[1]

INTRODUCTION

An essential function of university research reactor programs is outreach or extension involving the transfer of scientific and technical information to users or beneficiaries outside the university.

The form of the service depends upon the size (power) of the reactor, its principal uses, the resources and interests of the operating staff, and the university commitment to support the facility. Reactor services stimulate new investigations, drive additional research once major strides have been made in a particular area, and provide a mechanism for technology transfer. The concept of service is somewhat arbitrary, because virtually any service provided to an off-campus reactor user may be closely tied to on-campus education and research.

For the larger facilities, an important service dimension is reactor sharing, programs in which researchers and students from other institutions acquire hands-on experience.

In September 1985, the International Atomic Energy Agency sponsored a week-long seminar on applied research and service for research reactor operation held in Copenhagen, Denmark (Priest et al., 1987). It brought together research reactor managers, operators, and users to promote international exchange of ideas and information on their applied research and service activities. The consensus of the 130 delegates from 43 nations was that though service and applied research produce valuable income and justify continued support, URRs also have a direct economic and social impact on the country. The range of applications is listed in Table 4-1.

[1]Also see Alger (1987).

Table 4-1. Typical Services Provided to Off-Site Reactor Clientele

Radioisotope production and application
Neutron activation analysis
Neutron radiography
Neutron gauging
Neutron scattering
Gamma ray scattering
Standardization assays
Radiation shield testing
Personnel training
Radiation chemistry
Safety analysis

DESCRIPTION OF SERVICES

Three categories of service are recognized: general use of the reactor, research support, and technology transfer. The diversity of interests of reactor users distinguishes URRs from services provided at national laboratories.

General Services to Off-Campus Clientele

This category includes activities that simply facilitate use of the reactor by off-campus clientele (e.g., irradiation services). Often the activity is of interest only to the individual being served and not to the department that maintains the reactor.

Small Reactor Facilities (<10 Kw)

These facilities usually have a limited staff (one or two faculty members plus graduate students) and budget. The reactor is operated on an as needed basis with no set schedule. Faculty members have other responsibilities and duties, and operating the reactor for others may be viewed as a burden. All reactor activities--tours, irradiations, inspections, and even laboratory exercises--may take the responsible faculty members away from their principal duties. Nevertheless, in the URR community, most willingly accept these added responsibilities because they believe that reactors are a scarce resource to be shared, and they want the reactor to be used as fully as possible. Some small facilities continue to exist through the efforts of one or two faculty members who provide services to the outside community. In these circumstances, education and service are usually integrated.

A typical reactor facility in this class may operate approximately 100 days per academic year, for 200 to 500 operating hours. Operating time is not the only gauge of utility and value. There are tours and demonstrations, staff assistance to potential users in planning experiments, developing special techniques for particular irradiation samples or radioisotopes, and advising potential users on the application of nuclear science to their specific technical areas. Though this kind of staff support does not add reactor operation time, it enhances the role of the URR in academic life.

Medium Size Reactor Facilities (100 kw-250 kw)

By comparison, most medium size reactor facilities have a larger staff, with some assigned full-time. Because of their size, these facilities cannot be operated as informally as the smaller facilities. These reactors may operate on a reasonably fixed schedule--usually regular working hours--and scheduled services are often on a fee-paid basis. Such users need to be balanced against on-campus research and educational needs. URRs of this size are generally sufficient to support interdisciplinary research and development in radioisotope production, neutron activation analysis, neutron radiography, radiation damage testing, personnel training, and many other areas.

Reactors of this size are generally more involved with on-campus departments and nearby colleges and universities than are the small facilities. Texas A&M University, for example, reported URR involvement of an average of 40 faculty members per year from 16 academic departments within the university plus an average of about 500 faculty and students per year from 12 other colleges and universities in the area. Medium size reactors also typically host a number of tours; Texas A&M reported that about 1,400 of its students tour the facility each year, and there are approximately 5,000 additional visitors per year.

Large Reactors (1-20 Mw)

As reactor power increases, there is generally a shift toward more research and service activities and fewer educational and training activities. Sponsor-funded research and development is more important at these facilities. Reactor staff may be large owing to the need for sustained operation over long periods. In fact, the facility may be operated in essentially the same way as at national laboratories. Research not possible at smaller facilities (e.g., neutron scattering experimentation) is conducted at these large facilities.

Large URRs are also significantly involved with research agencies, other colleges and universities, federal and state agencies, and industry. These groups often make use of URRs because of their unique capabilities, the expertise of particular faculty members, and frequently, the cost effectiveness of using a university program. Table 4-2 lists the state and federal agencies receiving services from the University of Missouri research reactor at Columbia.

The number of U.S. industries involved with URR services is growing, and the list is varied (see Table 4-3). URRs clearly contribute to local economic development through service and technology transfer.

It would be useful to describe and quantify their contributions and economic impacts. To do so would require detailed case studies and analysis that are beyond the scope of this study. Examples of technology transfer are given in a later section of this chapter.

Service in Support of Research: The Case of Topaz

URR services increase the ability of researchers on and off campus to identify and solve new technical research and development problems. A significant example relates to understanding the effects of radiation on crystalline structures.

Several URRs--at the University of Missouri at Columbia, University of California at Los Angeles, University of Virginia, University of Michigan, Texas A&M University, and Massachusetts Institute of Technology-- have been irradiating topaz to produce a blue semiprecious gem stone (Priest et al., in press). This activity has stimulated efforts to understand color center production in crystals and has led to new and exciting research investigations. The existence of such a color center that absorbs light in the red (i.e., preferentially

Table 4-2. State and Federal Agencies Supported by the University of Missouri (Columbia) Reactor

Argonne National Laboratory
Columbia National Fishery Research Laboratory
Fred Hutchinson Cancer Research Center
Harry S. Truman Veterans Administration Hospital
Idaho National Engineering Laboratory
Lawrence Berkeley Laboratory
Los Alamos National Laboratory
Missouri Department of Natural Resources
National Cancer Institute
National Bureau of Standards
National Heart, Lung, and Blood Institute
National Institutes of Health
Sandia National Laboratories
U.S. Army
U.S. Department of Agriculture
U.S. Department of Commerce
U.S. Department of Energy
U.S. Department of the Interior
U.S. Environmental Protection Agency
U.S. Navy
Wright Patterson Air Force Laboratory

Table 4-3. Industries Served by University Reactors

Aircraft
Agriculture
Automobile
Chemical
Communications
Construction
Manufacturing
Medical
Mining
Oil and Gas
Semiconductor
Transportation
Utilities

absorbs light in the red end of the visible spectrum making the stone appear blue) has been known for years. But now it has been found that when this color center is produced by fast neutron radiation damage, the color center is strongly polarized, with maximum absorption along the a-axis of the crystal. Further, the color center is stable up to approximately 500°C. This thermal stability makes irradiated topaz a good candidate for a new and improved solid state laser material. Even more significant is a second defect detected by electron spin resonance. This second defect does not anneal until about 900°C, making it one of the most stable color center defects known. It appears to be the origin of a broad ultraviolet absorption band that makes a fast neutron damaged topaz a promising material for development of a high power ultraviolet solid state laser.

Another important discovery resulting from studies in topaz is the striking similarity between the observed 630 nm wavelength (red) optical absorption in topaz and the same wavelength occurring in drawn quartz fibers. Such quartz fibers are used for optical communications. Because topaz has SiO_4 structural units (as do quartz fibers), it should not be too surprising that their electronic properties are similar (though crystalline quartz does not show this same radiation damage center). What is significant is that the regularity of the topaz structure provides a much better environment for studying this defect than does the random irregular structure of an amorphous quartz fiber. Even though most current optical communication is done with near-infrared radiation, the 630 nm absorption band is broad enough to affect transmission at the longer wavelengths. Understanding this defect is important for improving transmission in optical fibers. From study of this defect in topaz, it will be possible to test models proposed for the similar defect, in quartz fibers, to learn more about the nature of the defect to suggest ways to eliminate it, and thus to develop more efficient optical communication fibers.

Additional studies of radiation damage in topaz will improve the understanding of radiation damage in silica and other materials. In particular, these studies have shown that the polarization of the red-absorbing color center is strongly dependent upon the type of radiation that creates it. Gamma radiation from Cobalt-60 produces maximum absorption along the b-axis, fast neutron irradiation produces maximum absorption along the a-axis, and high energy electron radiation produces comparable absorption along all three crystalline axes. Thus, at least two and perhaps three closely related defects must be present in topaz. Each defect interacts differently with the surrounding lattice, giving rise to variations in the electronic properties of the color center. When fully understood, this variability will give important information about the radiation damage centers in solid state materials.

In principle, research involving studies of the crystal and electronic structures of materials can be conducted at URRs of any size. But because the effect is determined by an integrated dose (i.e., flux times time), the smallest reactors may require too high an irradiation time to be practical.

Technology Transfer

Technology transfer is critical to the maintenance of any economically competitive industry, and URRs are important to nuclear-related industries for this reason. Some examples are discussed below.

Neutron Transmutation Doped Float Zone Silicon

Basic research in the late 1960s demonstrated the feasibility of doping silicon through transmuting Silicon-30 to Phosphorus-31 by neutron capture. By the mid-1970s, a few semiconductor devices had been made from neutron transmutation doped (NTD) silicon (Meese, 1979). However, the semiconductor industry did not have the expertise to develop the large scale doping process necessary to use the unique properties of NTD silicon fully.

It was at this point that the University of Missouri at Columbia and the University of Michigan became the driving force in the technology transfer, leading to rapid development of an efficient large-scale neutron transmutation doping technique. The NTD process has been so successful that NTD products dominate the float zone silicon marketplace today. Moreover, technology transfer is continuing even for the relatively mature NTD process. Missouri (Columbia) is participating in development of a viable NTD process for the new magnetic Czochralski silicon material. Success in this area will open an entirely new market for NTD silicon that could potentially dwarf the already successful NTD float zone silicon market.

The need to overcome technical difficulties is a strong incentive for research. As noted in the NTD example above, the need to obtain the optimum neutron transmutation doping material for semiconductor fabrication also required a better characterization tool for studying the complex defect interactions in neutron irradiated silicon.

Deep Level Transient Spectroscopy

At the same time the NTD process was being developed for silicon, a new technique for characterizing defects in semiconductors became available --deep level transient spectroscopy (DLTS) (Meese, Farmer, and Lamp, 1983). It was rapidly applied to the problem of optimization of NTD material. Application of DLTS, together with the more traditional analytical tools, quickly led to optimization of the annealing process that best removes neutron damage.

Even after the silicon/NTD process became routine, URR service activities continued to encourage characterization of defects in semiconductors. NTD has been applied to other semiconductors, primarily germanium and gallium-arsenide (GaAs). Early NTD work in germanium uncovered some discrepancies in the accepted values of the neutron capture cross sections. For GaAs, the defect structures are more complex than in single element semiconductors, and much more research remains to be done before the processing parameters can be optimized for this material.

The DLTS studies of defects were a great asset in the development of NTD silicon. However, one shortcoming soon became clear. DLTS gives a characteristic signature of the defects in irradiated semiconductors but does not give any direct quantitative information about the structure of those defects. Such structural information is essential in sorting out the more complex defect interactions involved in neutron irradiated semiconductors. To help overcome this deficiency, stress transient spectroscopy (STS) was developed. With this new technique, uniaxial stress is applied to the material during the standard DLTS analysis.

The stress removes the defect orientation degeneracy and provides direct information concerning the symmetry of the defect. This additional information is crucial to identification of the defect and makes it possible to understand some of the complex defect interactions that occur in neutron irradiated material. STS has already been used to identify defect symmetries in silicon and germanium, and it offers the promise of understanding some of the more complex interactions that occur in irradiated GaAs.

Reactor Sharing

Each year, the Department of Energy makes available limited funds for faculty and student travel to work at off-site reactor facilities. In fiscal year 1986, funding amounted to approximately $385,000. Faculty members at many colleges and universities take advantage of this program to expand their research capabilities and/or provide their students with an educational experience not available on campus. These federal funds provide seed money to stimulate the application of nuclear science to many research areas.

This is a modest beginning toward developing an effective U.S. research reactor network like that in Europe; it is described in Chapter 5. Expanding the service role of URRs should be part of the design of a national network.

CONCLUSIONS

University research reactors play a vital role as a service facility in the nuclear science-related disciplines. They provide service to other departments on campus, other colleges and universities, and industrial organizations. They are an important resource for industrial researchers, and in nuclear science-related technology transfer activities, URRs can help pay their way through revenues generated by these services. The DOE reactor sharing program allows students to use off-campus research reactor facilities. This program helps to develop new research and development efforts and applications for the nuclear sciences.

5

RESEARCH REACTORS IN WESTERN EUROPE

INTRODUCTION

There are approximately 300 research and test reactors in the world (International Atomic Energy Agency, 1986). Many are located at universities and research institutes, and some are at national laboratories. Approximately two thirds of them are in the United States and Western Europe, divided about equally. Because the U...ted States and Western Europe are comparable in population, scientific establishments, and economic bases to support and be served by reactors, it is instructive to examine the reactor based research in Europe and compare it with that in the United States.

A comparison is particularly pertinent to this study in view of the perception among most researchers that Western Europe occupies a position of leadership in reactor based science. This leadership is strikingly evident in condensed matter research, materials research, and other disciplines using neutron beams (National Academy of Sciences, 1984). The Western European approach to the support of reactor based research is characterized by two features that are markedly different from U.S. practice: a close and active cooperation between small university class reactors and the large international research center at Grenoble and more generous base support for operating university class reactors. In this chapter, university class reactor signifies facilities that are not URRs administratively but are comparable to URRs in power and use.

THE EUROPEAN NETWORK OF REACTOR OPERATIONS

Reactor research in Western Europe is dominated by the multinational Institut Laue-Langevin (ILL) reactor facility in Grenoble, France. It is a joint venture of the French Commissiart a l'Energie Atomique and the Centre Nationale de la Research Scientifique, the British Science and Engineering Research Council, and the West German Kernforschungzentrum Karlsruhe. Spain will soon join as a limited partner.

The ILL operates a high flux (57 Mw) research reactor with approximately 40 experimental facilities devoted to condensed matter studies, materials research, nuclear and particle physics, and biochemical and biological investigations. The ILL is the premier facility in the world for neutron beam research. The United States has no reactor strictly comparable to the ILL.

The relevance of the ILL to this study lies not only in its success as a scientific research center but also in the relationship between this large central facility and small university class reactors. This close relationship extends beyond the member countries to facilities throughout Western Europe.

The ILL operates as a user facility with strong emphasis on visiting scientists' research. This mode of operation is encouraged by reimbursement for travel expenses for member country visitors, an experiment proposal procedure that is easily accessible by outside users, and other administrative policies. The ILL has also cultivated an ethic among its own research staff in which assisting and collaborating with visitors is viewed as worthy and respectable. As a result, the ILL is the central focus for reactor based science throughout Western Europe.

Links with Small University Class Reactors

Many users come from institutions operating small university class reactors. Often they come to continue projects that require higher flux or more sophisticated instrumentation for completion.

In addition to providing a source of users for the ILL, smaller reactor facilities are also a source of new ideas and techniques that have been incorporated at the ILL. In fact, a substantial number of the novel features of the ILL developed in this way. Researchers from smaller facilities have brought time of flight spectroscopy, multi-detector arrays, and neutron interferometry to the ILL. Table 5-1 lists other techniques and instruments that were ultimately incorporated into the ILL facility.

This situation is not surprising because, as discussed in earlier chapters of this report, the environment at a university based research reactor is often more conducive to such developmental work than it is at a major user facility. At larger reactors, competition for limited beam and/or instruments time is often intense. Moreover, continual travel required for a remote development project would be inefficient for a long-term development program.

In contrast, European university faculties typically have easier and more flexible access to reactor facilities. Faculty investigators are

Table 5-1. Selected Instruments and Techniques Incorporated into the Institut Laue-Langevin from Smaller Facilities

Technique or Instrument	Facility of Origin
Neutron guides	FRM (Munich)
Cold neutron source	EL3 (Saclay)
Interferometers	Atominstitut (Vienna)
Diffractometers	Siloe (Grenoble)
Small angle scattering	FRJ2 (Julich)
Hot source	FR2 (Karlsruhe)
High resolution backscattering	FRM (Munich)
Nuclear physics methods	FRM (Munich)
Curved crystal gamma spectrometers	DR3 (Riso)
Ultra cold neutron source	FRM (Munich)

SOURCE: Glaser, 1987.

more consistently present, and a pool of available graduate students is on hand. This atmosphere is often better suited to work on the multi-year time scales required by the vagaries of new and innovative technological development.

The close linkage between university facilities and the ILL is enhanced by the organizational scheme of the ILL itself. The Scientific Council, which makes general policy decisions and acts as an advisory panel to the directors, is staffed primarily by university faculty from the member countries. The scientific subcommittees that review and pass on the numerous experimental proposals are similarly staffed. Thus, the close relationship between large and small facilities extends to administrative as well as technical and scientific cooperation.

That the same funding agencies and advisory panels are responsible for administering the large multinational facilities as well as smaller university based reactors is surely important to the vitality of neutron physics programs in Western Europe. Without such an organizational model, large scale program planning involving the integration of contributions from university departments, university reactors, and larger facilities would not be possible. The mere existence of large and small reactors does not assure such coordination. In the highly successful Western European model, cooperation is not an accident. It is the result of farsighted management.

Support for University Class Reactors

Even within such a favorable organizational framework, vitality is not assured without adequate support. In Western Europe, national funding agencies provide ongoing base support for the operation of individual programs. Support usually provides a high standard of reactor operations, that is, high operational availability with adequate staff and support for research and new equipment. For each of the two major university research reactors in West Germany, BER-II in Berlin and FRM in Munich, this base support was approximately $2.5 M in 1985 (Harling, 1985).

Federal support for operating comparable URRs in the United States is essentially limited to providing fuel for the reactors. In fiscal year 1987, support for fuel totaled $1.9 M for all URRs.

In addition to base support in Western Europe, significant resources are allocated to major upgrades and new equipment at existing facilities. The university research reactor at the Hahn-Meitner Institute in Berlin (BER-II), for example, is undergoing major renovation costing approximately $50 M (Harling, 1985). Further base support for scientific work is expected after this upgrade. The URR at the Technical University in Munich is also planning an ambitious upgrade that includes construction of an entirely new 20 Mw reactor core. This project is estimated to cost more than $100 M (Boening, 1987).

Base support for operations has important implications for the level at which scientific research can be carried out. For example, sample irradiations for activation analysis or materials studies need not be charged the full cost for reactor use (as is common in the United States). Not only does this kind of operation allow greater flexibility in reactor use, but it encourages use of the reactor by a broader community of researchers. Because a significant fraction of reactor research use is by workers in fields quite distinct from nuclear engineering, ease of access greatly enhances reactor productivity.

Outside users also benefit from the enhanced staffing levels available. This is an important point, because many potential users lack the expertise to carry out their reactor studies without help. Without available staff, many potential users would be discouraged from applying potentially powerful reactor based techniques to their research.

Measures of Effectiveness

A comprehensive analysis of utilization effectiveness is beyond the scope of this report. One reasonable measure relates to the number of full-time-equivalent (FTE) reactor users per year. At three Western European research reactors (Berlin, Munich, and Vienna), FTE users per reactor averaged more than twice the number at the seven highest power U.S. university research reactors (the University of Missouri at Columbia, Georgia Institute of Technology, Massachusetts Institute of Technology, University of Michigan, Rhode Island Nuclear Science Center, University of Virginia, and State University at Buffalo). It is evident that U.S. URRs can be used profitably for additional research operations.

Success of the Western European research endeavor is possible because of several favorable factors. Perhaps foremost is a rational community-wide management that encourages efforts at reactors of all sizes and also encourages close cooperation among them. This successful experience is especially relevant to the national neutron physics projects planned in the United States. These projects include the cold neutron facility at the National Bureau of Standards and the advanced neutron source at Oak Ridge National Laboratory.

Whether URRs as a national resource are adequately employed is germane to the planning for the estimated $400 M advanced neutron source. Also germane is whether there will be an adequate community of younger scientists and engineers to operate and use this and other national facilities.

CONCLUSIONS

A successful model for operation and integration of large and small research reactor facilities is in operation in Western Europe. This model is characterized by close and integrated planning for university class reactors and the large central user facility at Grenoble. The Western European model should be considered for incorporation into the overall U.S. research reactor program. The Western European program is adequately supported by the various national governments.

The role of U.S. university research reactors relative to the large national facilities should be reviewed. This analysis is particularly relevant to the proposed advanced neutron source that is currently in the planning stage for Oak Ridge National Laboratory and the cold neutron source to be installed at the National Bureau of Standards reactor in Gaithersburg, Maryland.

6

SAFETY AND SAFEGUARDS OF UNIVERSITY RESEARCH REACTORS

INTRODUCTION

"Safety" of URR operation deals with the identification and control of physical hazards inherent to any reactor operation. "Safeguards" on the other hand deals with the identification and control of hazards posed by the intervention of persons who would steal nuclear materials, or seek to damage the reactor. To a small degree, research reactors share some of the hazards of nuclear reactors in general. Because such hazards exist, the university research reactors (URRs) are subject to regulation, supervision, and public control. The principal hazards of URR facilities are listed in Table 6-1. These hazards deserve serious and impartial evaluation.

In today's world, policy makers are now concerned with explosion risk associated with acts of terrorism as well as coventional accidents. The Committee cannot comment on the probability of terrorists seeking to cause an explosion at a URR core. In fact, biological, chemical, and other university laboratories may be at higher risk from terrorist sabotage when relative vulnerability is considered. It can be said, however, that an act of sabotage that actually destroys the core and containment and releases radioactive meterials would require both a large quantity of explosives and expertise in placing the explosive.

However remote the possibility, however small the risk, however limited the consequences, public policy requires that prudent measures be taken to protect against explosion and other conceivable hazards, from whatever course.

This chapter first discusses some issues related to the size difference between URRs and power reactors that apply to both safety and safeguard considerations. This is followed by a discussion of the issues associated with risk of theft or diversion of nuclear materials. Finally, a discussion is provided of the risks of damage to the reactor fuel resulting from conventional accident or from sabatoge.

Table 6-1. Principal Potential Hazards at a University Research Reactor Facility

Safety Hazards

Damage to the fuel or core and consequent spread of radioactivity in or beyond the reactor containment building

Spread of small amounts of radioactivity or medical isotopes from experimental programs

Spread of radioactive coolant in the event of leakage

Injury to personnel from weapons, fire, and explosive devices

Safeguard Hazards

Theft and diversion of nuclear material

Intrusion and theft of materials or equipment other than nuclear materials

Intrusion, sabatoge, and vandalism

DISTINGUISHING URRs FROM POWER REACTORS

A basic premise of risk management is that control and protection efforts should be in close proportion to the risks involved. Excess resource allocation to one risk results in inadequate attention to other risks when resources are limited, thereby increasing total societal risk. Excess allocation to risk management in general reduces the productivity and benefits of a reactor.

Certain URR features result in hazards qualitatively different from those of power reactors. In addition, to those bearing on reactor power, stored energy, and mass, some URRs use fuel that is much more highly enriched than power reactor fuel, but their fuel inventory is much lower. URRs are maneuvered--brought up and down in power--far more often, and a varied clientele ranging from on-going researchers to occasional users need access to URRs. Questions of fuel diversion and sabotage are raised for these reasons.

The most important point is that the radioactive inventory of any URR (up to 10^5 curies) is three orders of magnitude smaller than that of a typical power reactor[1].

Correspondingly, the fuel mass and stored energy within a URR are also comparatively small. This statement does not mean that chemical explosions at URRs releasing radioactive materials to the environment are impossible in an absolute sense. It does mean that the risk (owing to lower available energy) is much lower, and the consequences (owing to smaller amounts of radioactive mass) are also much lower. From a practical point of view, nuclear engineers do not consider the risk of a chemically induced explosion resulting from a low probability loss-of-coolant event at a URR to be significant. This risk is largely managed by design limits, controls, and interlocks.

URRs are civilian facilities licensed and regulated by the Nuclear Regulatory Commission (NRC) (Spinrad and Zebroski, 1987). NRC sets standards for and reviews design and construction of the reactors. Most research reactors operating today were designed by national laboratory or major industrial company staff. The reactors are tested extensively by the supplier, with NRC oversight. In addition, more than 200 research reactors have been built outside the United States to similar or identical design specifications.

[1]The equivalent thermal power rating ranges up to 10Mw for the large URRs and up to 2 Mw for the small and medium size reactors. A typical modern power reactor has a 3,000 Mw thermal power rating.

URRs follow the same licensing procedures as large commercial power reactors, despite the vast differences in the reactors, their operations, and the risks. The URR community often feels that the regulations are inappropriately applied to its facilities (Greene, 1987).

Any significant change in the use or design features of a URR generally requires a license amendment. This is a formal procedure in which all questions of the reactor design and operation are subject to renewed scrutiny and analysis. Concerns or allegations over safety and safeguards can be used to initiate litigation or hearings before a quasi-judicial body, the Atomic Safety and Licensing Board.

For commercial power reactors, the opportunity for making allegations and initiating hearings is the principal means for intervenor groups to delay a project. Sometimes, the costs of defending a project, paying legal fees, and maintaining staff over an indefinite interim results in a project's cancellation. The outcome may be entirely independent of the merit of the allegations.

It is widely believed in the URR community that this tactic was used successfully in at least one case, a 100 kW Argonaut at the University of California at Los Angeles (UCLA). What originally seemed to be a routine relicensing hearing dragged out over two years until the university decided that the reactor was simply not worth the expense and trouble of the hearing. UCLA closed the reactor in 1985. There is no legal or statutory protection against this tactic.

This case illustrates the need to define the risks associated with URRs as distinct from large power reactors and to provide more precise regulations.

THE RISK OF FISSILE MATERIAL DIVERSION

Preventing Theft of Nuclear Materials

The presence of highly enriched (~90 percent) U-235 brings with it the possibility of theft for the purpose of making a nuclear explosive device. "The amount of inventory at a typical university research reactor facility is less than 5kg, and for some reactors less than 2kg. A would-be diverter would have to remove and recover material from at least three reactors in order to have a chance of producing a 'high-technology' device, and from at least half a dozen research reactors in order to have a chance at producing a 'low-technology' device" (Zebroski, 1984). Subsequent to this statement, NRC rules required that URRs further reduce fissile inventories by converting to low enriched fuel (20 percent U-235). Full enforcement of this rule would effectively eliminate the already low attractiveness of small fissile quantities at URRs to would-be weapon fabricators.

As a safeguard against possible fuel diversion, access to URR fuel, particularly unirradiated or lightly irradiated fuel, is physically controlled. Further, the amount of excess fuel stored on site is limited. To minimize potential problems caused by the need for maneuvering the reactor power, controls and interlocks to prevent excess reactivity are in place. To avert sabotage, the principle control is a combination of security devices preventing unauthorized intrusion, direct observation (escorted entry for visitors), and personnel clearances. Historically, these measures have been wholly successful in that no diversion of fuel or special nuclear material has occurred; nor has sabotage occurred at URRs.

The most probable constraint to continued operation of URRs on campus is apparent or alleged deficiencies in security, control of personnel, and access. There is tension between the needs of flexibility and access for research, teaching, and service and the needs for control of material, access, and discipline in operation and maintenance. Careful management of these often conflicting needs is probably the key to continued daily operation of URRs.

HEU to LEU Conversion

The conversion of research reactors from high enrichment fuel to low enrichment uranium fuel (HEU to LEU conversion) is intended to reduce the attractiveness of core materials to potential for theft with the intent of weapons production. This change does not require an NRC license amendment provided that only simple substitution of U-238 fuel is involved. Though the cost of providing the LEU fuel is to be borne by the Department of Energy (at a rate budgeted by Congress), there is no assurance that such a conversion will not provoke litigation and hearings. Because university budgets for such litigation are extremely limited, the mere filing of such actions, entirely independent of their merit, can stop a URR's operation. The NRC has ordered the fuel change in such a way that, according to its legal staff, NRC itself would bear the burden of defense if conversion to LEU is challenged. Nevertheless, in the event of litigation, university personnel necessarily will be heavily involved, and the university may have to bear undue costs beyond the legal fees.

Even though the HEU/LEU conversion ruling is generally viewed as a fait accompli, URR operators feel that the decision was not a good one. They are concerned about the failure to recognize the significant differences in the nature and magnitude of safety and security problems between URRs and power reactors. They also feel that NRC rules continue to view URRs as analogous to power reactors.

The University of Missouri at Columbia and Massachusetts Institute of Technology are currently requesting exemption from the conversion from HEU to LEU. The plantiffs argue that conversion would substantially degrade reactor performance. They maintain that existing physical security and limitations on materials inventory are adequate protection against theft.

Estimating the Risk of Diversion[2]

The nuclear materials diversion potential has received much attention that is not commensurate with risk estimates even without the HEU to LEU conversion (see Table 6-2). As a result, funds that could support research and education are diverted for security.

[2]See Leventhal and Alexander (1987, Chs. 1 and 3).

Table 6-2. Risk Analysis - Diversion of Fissile Materials

Category	Index of Risk[a]	Risk[b] Normalized to University Research Reactors
Weapons materials and facilities	.05	1,000
Large test reactors using high enriched uranium (abroad)		
Unirradiated fuel materials	.005	100
Irradiated fuel	.005	100
Large test reactors (domestic)	.0005	10
University research reactors	.00005	1

SOURCE: Zebroski, 1984.

[a]The risk index measures expected diversion loss per year in kilograms, and is the product of

- o Probability of gaining access to the material
- o Probability of non-detection and non-recovery of stolen material
- o Probability of successful weapon assembly
- o Quantity of fissile material at risk
- o Coefficient reflecting assessment of skill level, financial resources, specialized equipment, data, facilities and materials, and time to design, process, test, and assemble a weapon (the lower this level, the more fissile material is needed and the higher its quality for weapon assembly).

[b]This risk index is only a guide to planning and making comparisons. It does not actually state the probability of weapons assembly. To do so would require weighing in the probability that an attempt will occur. Moreover, in the absence of a data base, the risk index is useful only as a tool for discussion. Given the relative low attractiveness of URR fuel, weighing in the probability of attempt would produce an even larger relative risk difference.

In the table, the risk index is an approximate measure of the likelihood of successful theft of sufficient material to make a workable nuclear explosive device. On a normalized basis, the relative risk associated with URR fuels is three orders of magnitude less than the risk associated with weapons facilities. If the probability of an attempted threat were weighed into this index, the risk discrepancies would be even greater, given the relatively low attractiveness of URR fuels. This analysis does not argue against safeguards for URRs. It emphasizes the point that regulations and costs of safeguards should be based on relative risk.

THE RISK OF DAMAGE TO REACTOR FUEL

Conventional Safety Hazard

Reactor fuel can sustain damage when there is a large mismatch between the rate at which heat is produced and the rate at which cooling is provided. Such a mismatch can occur in only two ways. The first is inadvertent operation at a much higher power level than the designed level of cooling. The second is the prolonged loss of coolant from a major rupture or leakage of the reactor vessel or associated piping below the level of the reactor core.

The operation of URRs at substantially more than designed power levels is precluded by inherent design limitations, controls and interlocks, and other licensing requirements. The latter includes limitations on the amount of excess reactivity available and inherent negative temperature coefficients of the fuel and moderator. For water-cooled or pool reactors, a series of tests with successively larger and more rapid insertions of excess reactivity (above prompt critical) were conducted in the 1950s by the Argonne National Laboratory. These tests provide a firm basis for design and licensing limitations that preclude seriously damaging over-power reactor conditions.

Conceivably, fuel may also be damaged by prolonged loss of cooling. A reactor cannot continue to produce fission heat after loss of water (which is both moderator and coolant); however, some decay heat from residual radioactivity continues to be produced even after shutdown. This decay heat is too small to produce damage to fuel for reactors with a nominal power rating up to 100-250 kW. Research reactors with a power rating above 500-1,000 kW may begin to experience decay heat damage to the fuel in the event of loss of coolant. The process of overheating and damage to fuel is not instantaneous and would take many hours, possibly up to several days. Even if normal and back-up cooling systems were damaged or rendered inoperable, auxiliary emergency cooling such as from a garden hose or a fire engine pumper, is adequate to prevent the spread of radioactivity from continued overheating of the fuel. Calculation and planning of such contingencies are a significant part of the reactor licensing requirement.

Hazard of Sabotage

A further consideration is possible sabotage of a URR: causing fuel damage either by over-power operation, causing loss of coolant, or by use of explosives. Given the relatively low inventory of radioactivity in small research reactors and the requirement for thick biological shielding, the radiological consequences of sabotage would most likely be confined to the building. It is always possible to postulate indefinitely large escalations of such situations so that measurable radioactivity appears in the environs. Even in this worst case scenario, the radioactive inventory at a URR is typically 10^4 - 10^5 times smaller than that at large power reactors such as Three Mile Island or Chernobyl. The biological effects of such radiation levels from URRs would be insignificant. However, these radiation effects would be readily measurable, and the need to plan for such a possibility and communicate with the general public is evident.

The principal weapon against ignorance and panic is education of the general public, opinion leaders, and public officials. A low profile with respect to community relations is not necessarily beneficial. Publications, reactor and laboratory visits, and the active involvement of local public and environmental officials can reduce vulnerability to unfounded allegations relating to the risk and consequences of sabotage.

Though the university reactor community has no difficulty with current security requirements, it is concerned that the regulatory processes will continue to promulgate additional requirements that go beyond the attendant risks. This Committee believes that present security measures are satisfactory and that more stringent NRC requirements or interpretations can inappropriately add to the costs of operation without significant benefits. Of greater concern than costs which result in tangible upgrades in safety and security are those costs associated with hearing and litigation procedures in response to advocates whose agendas is broadly anti-nuclear, rather than objective concerns for safety and safeguards.

CONCLUSIONS

The safety record of university research reactors is excellent and well served by existing rules and practices. The three principle hazards to be avoided are: accidental damage to the reactor involving the escape of radioactive material, theft of fissile material, and sabotage of the facility. These hazards are small relative to the hazards of large commercial power reactors. Nevertheless, control of these hazards is essential for safe and secure operations of URRs.

The effective functioning and continued operation of the present family of URRs in the United States are more affected by disproportionate public and institutional perceptions of risk than by actual physical or nuclear hazards.

In the past, some regulations have imposed costly requirements and restrictions on the use and usefulness of reactors without significant benefits to safety. At present the NRC often uses risk analysis and cost-safety-benefit analysis to help insure that regulations have significant safety benefits in meeting or exceeding defined safety goals. The Committee advocates the use of these techniques specifically for research reactors, taking account of the low specific power and small inventory of radioactive elements. (Radioactive inventory is typically less than one thousandth of the inventory in a commercial power reactor). In most cases, this should preclude the application of regulations designed for power reactors to research reactors. The NRC should also seek to continue to reduce and minimize the exposure of small university reactors to hearing and litigation procedures which can result in unmanageable costs while contributing little or nothing to safety or safeguards, but which can damage or destroy the scientific productivity of the facility.

7

INSTITUTIONAL AND FEDERAL SUPPORT OF UNIVERSITY RESEARCH REACTORS

INTRODUCTION

Based on its deliberations as described in the preceding chapters, the Committee believes that a national program of support for university research reactors (URRs) is justified by their education, research, and service values to the nation. The mission of URRs cannot be fully or economically met by the national laboratory reactors or the few privately owned reactors. For now and into the foreseeable future, URRs are needed on campus for a variety of scientific fields. Therefore, besides solid endorsement from federal agencies and educational institutions, the URRs need a firm base of funding so that they can deliver neutrons and radioactive isotopes to researchers and students.

There is no such consistent, dependable pattern of support for URRs at either the local or national level. Instead, the mechanisms for funding these facilities are diverse. Some lead a hand-to-mouth existence; others, by virtue of a strong fee-based service component, fare better. The financially successful facilities generally have a mix of local institutional (i.e., university) support supplemented by a significant research and service component. Faculty and staff of many of the remaining URRs are to be complimented on their ingenuity in adverse financial circumstances. Unlike other national facilities and other federally funded university facilities, such as accelerators and materials research laboratories, URRs receive no federal funds consistently. The only direct government support is for fuel assistance through forgiveness of any uranium consumption costs, fabrication of new fuel, and faculty travel for use of off-campus reactors under the reactor sharing program. To the extent that researchers in various fields who use a research reactor are otherwise federally funded, URRs may indirectly benefit through user fees, or through internal transfer of university funds in recognition of their role in such research.

Management of the facilities is equally diverse: some are run by a nuclear engineering program and others by a more broadly based university-wide entity. Either way, the operation is a function of the local institutional structure. There are growing pressures upon universities to place priorities on their programs in terms of funding, to direct funds to programs in high current demand, and to qualify for federal grants, Therefore, URR facilities are increasingly constrained financially.

ELEMENTS OF SUPPORT

The Role of University Administrations

The Problem of Perception

Many university administrations perceive URRs as serving the narrow interests of a specific industry rather than as an academic asset with an interdisciplinary service base, on campus as well as off campus.

In the longer term, survival of the URRs will depend on how university administrations perceive their value to the education, research, and service missions of the university--in competition with other programs that also require special facilities. Criteria for administrators should include recognition of research productivity, contributions of educated nuclear personnel, and the opportunity to contribute to meeting national needs in the nuclear related industry and service functions.

The Committee does not assert that all URRs, or any particular URR, merits the support of their institutions. Each university administration has its own academic priorities, budgetary constraints, and long term developmental objectives. The decision to support an existing reactor, invest in a new one, or close a facility is necessarily a local one. Over the last several years, URR programs have been terminated for a number of reasons:

- Inadequate external financial support
- Low utilization by faculty
- Increased operating costs imposed by evolving safety and security requirements
- The cost of defending against legal actions by anti-nuclear advocacy groups
- A climate of controversy highlighted by on-campus advocates
- Competition for scarce space with new facilities deemed to have a higher priority.

The Committee does not challenge any particular URR closure; it is concerned that further attrition is harmful to the national interests.

Though some closure decisions may be consistent with a university's long term science and engineering program goals, the Committee believes that some administrations do not fully perceive the research and educational opportunities of URRs--as potential benefits to the university and to the nation.

Recognition of Value and Opportunity

Many universities remain fully committed to URR programs, and several are implementing plans involving upgrades and expansion. The University of Rhode Island, whose reactor is supported by the state, plans to upgrade its power from 2 Mw to 3 Mw because it is converting from high enrichment uranium (HEU) to low enrichment uranium (LEU) fuel. In the process, the core was redesigned to a more efficient 5 element configuration compared with 30 elements. The available funds for the conversion allowed Argonne National Laboratory to design and run computations on the new configuration. This example of URR national laboratory collaboration should be institutionalized so that it is not simply a benefit of another program. The Rhode Island facility is also purchasing new spectrometers and hiring researchers. The new core configuration is a considerable enhancement for neutron scattering research.

Ohio State University is also upgrading its 10 kW reactor, partly supported by LEU conversion funds. The new configuration will be 500 kW, with capabilities for both neutron scattering and prompt gamma research. A new biomedical research program is emphasizing boron neutron capture therapy.

The University of Texas is building a new reactor center to house a 1 Mw TRIGA reactor to replace a 250 kW reactor installed in 1963. New capabilities include horizontal beam ports for neutron radiography, enhanced neutron activation analysis, and research isotope production. The new instrumentation panel will be fully digitized and the reactor computer controlled.

The University of Missouri is planning to upgrade its 10 Mw reactor to 30 Mw. A new building will provide a neutron guide hall and a cold neutron source. It will be the only URR in the United States with a cold neutron capability. The university is also investing in new instruments and is constructing an isotope research laboratory.

These developments demonstrate the fact that URR programs continue to be regarded as vital components of university science and technology programs, meriting investment in expectation of research productivity.

Forms of Support

University administrations must ascertain as objectively as possible the value of URR programs on campus. Assuming a positive view, an administration's role is to provide vigorous institutional support, including:

- A core operating budget
- Overhead support and service
- Leadership in attracting external funding

- Advocacy of the role of the URR to the campus as well as to off-campus constituencies
- Recruitment of highly qualified research and teaching faculty to whom the URR will be a vital resource
- Encouraging interdepartmental and interdisciplinary links that will enhance the contribution of the URR, the departments, and the disciplines.

The first threshold for the URR is the university administration. Its backing is prerequisite to obtaining the external support described below.

The Role of the Federal Government

A federal charter for URRs with a specific entity/agency identified as the manager should be established. Its charter should include criteria for allocating available funds. Most likely, fewer URRs than presently exist will ultimately remain. Those that do will be enhanced by federal support.

Strong federal support of URR operations and upgrades is justified by the benefits to the nation indicated in this report. Without such support, program obsolescence will be exacerbated, and additional reactor operations will be lost, with ultimate adverse effects on the nation's ability to carry on reactor-related research, and to provide needed personnel educated in reactor principles and operations.

Federal support is needed for the following:

- Base reactor operations, including safety and safeguards provisions
- Upgrades and new equipment purchases, including safety and safeguards equipment
- Continuation of the free nuclear fuel support program
- Continuation and enlargement of the reactor sharing program
- Grants to support research using reactors in several fields of science and technology.

In order to make a recommendation on the level of federal support which is appropriate for the above purposes the Committee attempted to obtain information about reactor program expenditures in the United States. In 1983 the American Nuclear Society published an authoritative survey of research reactor installations in the United States, with an updated version scheduled for issue in 1988. Table 7-1 provides a summary of the 1983 cost data available at this time. The data base is incomplete, particularly at the lower level. Moreover, the operating budgets are not necessarily reported on a consistent basis because of: (1) differing allowances as to what constitutes overhead expenses; (2) differing ways of reporting research budgets; and (3) different ways of allocating the cost of faculty who may actually devote a considerable time to reactor management, but whose costs are allocated to other budgets, particularly at the smaller reactors where in some instances there is no budget per se identified for the reactor.

Table 7.1. Annual University Research Reactor Operating/Capital Costs

Owner	Annual Operating Budget	Reactor Facility Capital Costs	Site (Mw)
Missouri, University of (Columbia)	$3,000,000	$3,500,000	10
Georgia Institute of Technology Research Reactor	350,000	4,500,000	5
Massachusetts Institute of Technology	650,000	3,000,000 +3,000,000[a]	4.9
Michigan, University of (Ford Nuclear Reactor)	500,000	3,700,000	2.0
Rhode Island Nuclear Science Center[b]	360,000	1,100,000	2.0
New York, State University of (Buffalo Materials Research Reactor)	NA	2,000,000	2.0
Virginia, University of	154,000	1,000,000	2.0
Illinois, University of	80,000	800,000	1.5
California, University of (Berkeley)	125,000	NA	1.0
Lowell, University of	NA	NA	1.0
North Carolina State University	NA	NA	1.0
Oregon State University	200,000	830,000	1.0
Penn State TRIGA Reactor (Pennsylvania Science Center Reactor)	250,000	2,300,000	1.0
Texas A&M University (Nuclear Science Center Reactor)	527,000	1,500,000	1.0
Texas, University of (Austin)	NA	NA	1.0
Washington State University	NA	100,000	1.0
Wisconsin, University of	120,000	750,000	1.0
California, University of (Irvine)	40,000	320,000	0.25
Columbia University[c]	25,000	1,000,000	0.25

NOTES

(1) Annual budgets may reflect different assumptions about the allocation of faculty time and overhead associated with the reactors. These budgets are in 1983 dollars.

(2) Capital costs are not on a consistent basis because most of the facilities were purchased or constructed in various years from the mid 1950s to the late 1960s.

(3) Table includes data from reactors closed-See Table 1-4.

Table 7.1 Annual University Research Reactors Operating/Capital Costs (Continued)

Owner	Annual Operating Budget	Reactor Facility Capital Costs	Size (Kw)
Kansas State University	NA	780,000	250
Maryland, University of	NA	750,000	250
Michigan State University	NA	NA	250
Reed College	20,000	300,000	250
Missouri, University of (Rolla)	18,000	492,000	200
Arizona, University of	90,000	500,000	100
Cornell University	NA	NA	100
Florida, University of	75,000	95,000	100
Utah, University of	5,000	200,000	100
Washington, University of	NA	1,000,000	100
Worcester Polytechnical Institute	41,000	150,000	10
Ohio State University	90,000	NA	10
Iowa State University	30,000	200,000	1
Purdue University	NA	NA	0.10
Cornell University	NA	NA	0.10
Virginia, University of	NA	NA	0.05
Brigham Young University	NA	36,000	0.10
Oklahoma, University of	NA	100,000	0.05
Idaho State University	45,000	1,200,000	0.05
New Mexico, University of	NA	NA	0.05
Texas A&M University	NA	NA	0.05
Utah, University of	NA	NA	0.05
Illinois, University of	NA	NA	0.01
Catholic University of America	6,100	95,000	0.001
Manhattan College	NA	150,000	0.001
Rensselaer Polytechnic Institute	NA	NA	-----

SOURCE: Burn, 1983.
NA = Not available.
[a]Upgrade.
[b]State operated.
[c]In standby.

To have arrived at a rigorous basis for determining the budget needs of research reactors as a whole, one would need the following for each facility:

- Operating needs including personnel, utilities, other overhead, services and materials;
- Capital needs for upgrades and new equipment;
- Statement of projected program activities to be supported by the budget in terms of research, education and service; and,
- Statement of non-federal sources of support.

In effect, federal support should be determined on a case by case basis in which the proposed research reactor budget can be assessed against the quality and value of the program. A fair assessment would require a peer review procedure.

The Committee nevertheless feels an obligation to at least provide an estimate, in a preliminary way, of an appropriate budget for a federal program to support continued operation of qualifying university reactors, and to support upgrades and new equipment purchases. Lacking a current reactor by reactor data basis, this estimate is necessarily judgemental. However, the process of soliciting grant proposals from universities with reactor programs, will subsequently provide the data. Since actual expenditure decisions will result from peer review on a case-by-case basis, the overall budgetary estimate can be approximate for the initial year, and then be adjusted in subsequent years in response to actual program experience.

In assessing support needs, the Committee segmented the URRs as shown on Figure 7.1 into size categories that generally serve distinct functions:

- 10 Mw and above--major national reactor research centers providing national and international leadership in research and service.
- 2-5 Mw--essentially research and development facilities that provide neutron beams, experimental research, and activation analysis. These reactors operate as a service to researchers on and off campus, and they cover a wide spectrum of investigations, including medical and biological applications.
- 250 Kw-1.5 Mw--facilities used primarily for education and service. The proportion of research work decreases with size. Much of the service is irradiating materials for use primarily by researchers in biology, medicine, and chemistry.
- 10-200 Kw--primarily educational and training tools with some research use at the upper end of the range.
- <10 Kw--primarily teaching tools for demonstrating basic physical phenomena.

With these observations, the Committee considers that there is a need for up to $20 million dollars annually to assist with upgrades and new equipment purchases, and the costs of operating reactors, particularly those costs associated with servicing the needs of interdisciplinary research within the university. The overriding objective of the support should be to promote the creation of modern state-of-the-art university research reactor programs at all size levels.

To provide a perspective on this figure, the Committee considers that about $60 million dollars is needed over the next three years to modernize the facilities, replace obsolete equipment, and to bring them into full compliance with Nuclear Regulatory Commission requirements on safeguards. If half of the recommended annual federal support ($10 million) is for equipment upgrades, then the federal share over the next three years would be about $30 million or 50 percent.

With respect to operational costs, the Committee estimates a need for about $35 million dollars annually. (This is based on assumed unit operating costs for a healthy program with high reactor utilization as follows: 10 Mw plus. . . $5.0 million; 2.0-5.0 Mw. . .$2.5 million; 0.25-1.5 Mw. . .$1.0 million; 10-200 Kw. . .$0.1 million, 10 Kw minus. . . $0.04 million; and, the following number of reactors in each class respectively: 1,6,14,9,10). If half of the recommended federal support ($10 million) is for operations, then the federal share in this category is less than 30 percent. Again, it is stressed that this basis for estimating is highly judgemental, and will need to be refined by an actual needs assessment at each facility, to be provided as part of the process of submitting proposals for federal support under the program.

The Committee does not have a preference about the home agency for the federal support program. Nor does the Committee prescribe criteria for allocating and awarding these funds. However, it is strongly urged that the government use peer review as an input to assure the scientific integrity of proposed URR programs.

The Role of Other Supporting Elements

As discussed above, support begins with the home university. It should include administrative and promotional assistance as well as a base funding commitment at least to the extent of overhead costs. The federal government, as the traditional supporter of research and development programs in the national interest, has a clear and specific role. Other supporting elements, which may vary among universities, continue to be essential. They include:

- State government
- Local and county/municipal governments
- Industry
- Medical institutions.

Continuation of support can be expected to the extent that these entities perceive benefits for themselves. Motivation to support URRs can include:

- Direct service benefits such as operator training, irradiations, and research services
- Services to students from other colleges and high schools

- Support of state and local government efforts to attract target industries to the area
- Enhanced prestige to public and private organizations that are associated with the reactor in some way
- Supply of graduates and faculty experts to state and local government and to industry in support of nuclear related activities.

Clearly, no single source of funds, government included, will solve the financial problems of URR operations. The reactors that survive and flourish will benefit from strong university leadership coupled with an aggressive outreach program.

CONCLUSIONS

URRs merit a base of institutional and financial support in view of their many benefits to the university community and the nation as a whole from research, education, and service in several scientific and engineering fields requiring the use of a reactor. Support begins at home with the university administrations. They need to understand the current and potential role of URRs in academic life. Decisions to support or relinquish a URR program should be made objectively, based upon a full appreciation of the benefits and costs.

URRs merit a base of federal support because of national benefits that accrue from a healthy URR program:

- The contribution to research and development in many areas of science and technology
- A supply of educated workers for a variety of vital national functions, including defense, the power industry, and environmental services
- Parity with Europe and Japan in research production in the nuclear sciences relative to technology transfer from the reactor laboratory to the commercial sector and for national defense applications.

URRs merit support from state and local governments and from industry because of:

- Their use to train workers in regulatory and commercial programs
- Their direct benefits from many services provided by URRs
- The promotional role of URR services in local economic and industrial development.

If URRs are to play a vital role in research and in the education of scientists and engineers, they need immediate funds to:

- Bring current operations up to a level adequate to maintain vital programs
- Purchase instrumentation and other equipment needed to modernize reactor operations, research, and teaching programs.

The federal government should consider committing up to approximately $20 million per annum to assist in funding URR operations and upgrades. Support should be based upon peer review of proposals. Such federal support should include the introduction of a national reactor network in which activities at major federal reactors are explicitly linked to research work at the nation's university research reactors.

Assistance is needed to upgrade URR facilities in order to replace outmoded instruments and control systems, to increase power and neutron flux, and to provide cold sources to reach new experimental regions.

URR management should vigorously pursue non-federal support sources by articulating the benefits to state, local, and industrial constituencies and by providing services on a fee basis when that is possible.

APPENDIX A

COMMITTEE ON UNIVERSITY RESEARCH REACTORS
WORKSHOP ON UNIVERSITY RESEARCH REACTORS
LAWRENCE BERKELEY LABORATORY
BUILDING 50-AUDITORIUM

AGENDA

MONDAY, FEBRUARY 2, 1987

8:00-8:30	REGISTRATION/COFFEE
8:30-8:45	WELCOME ADDRESS Dr. David A. Shirley Director, Lawrence Berkeley Laboratory
8:45-9:15	RESEARCH REACTORS IN EUROPE Dr. W. Glaser Director, Institut Laue-Langevin Grenoble, France
9:15-10:00	NEUTRON ACTIVATION ANALYSIS Mr. A.F. DiMeglio Director, Rhode Island Nuclear Science Center
	COFFEE BREAK
10:15-11:00	MEDICAL DIAGNOSTICS AND THERAPY Dr. A. Bertrand Brill Brookhaven National Laboratory
11:00-11:45	REACTORS IN EDUCATION Dr. Bernard I. Spinrad Chairman, Department of Nuclear Engineering, Iowa State University
11:45-12:30	REACTOR SERVICES AND OPERATION Dr. Donald M. Alger Associate Director Research Reactor Facility University of Missouri
12:30-1:15	LUNCHEON - LAWRENCE BERKELEY LABORATORY

1:15-3:00	PANEL ON CONTROLS, SAFEGUARDS, AND REGULATIONS Chairman: Dr. Edwin L. Zebroski Chief Nuclear Scientist, Electric Power and Research Institute Keynote: Mr. Robert F. Burnett Nuclear Regulatory Commission
3:00-3:15	COFFEE BREAK
3:15-5:00	PANEL ON REACTOR SUPPORT AND SURVIVAL Chairman: Dr. Mihran J. Ohanian, Associate Dean of Research, University of Florida
6:30-7:30	COCKTAILS AND DINNER LBL FACULTY CLUB
7:30-9:00	DINNER GUEST SPEAKER: Dr. Luis W. Alvarez Lawrence Berkeley Laboratory

TUESDAY FEBRUARY 3, 1987

WORKSHOP SESSIONS

9:00 a.m. - 5:00 p.m.

WORKSHOP ON RESEARCH

Chairman: Dr. Clifford G. Shull
Department of Physics
Massachusetts Institute of Technology

Rapporteur: Dr. Anthony L. Turkevich
University of Chicago
Enrico Fermi Institute

OBJECTIVES

1. Inform the Committee on research activities at university centers in general areas of:
   - o Neutron beam research
   - o Neutron activation analysis
   - o Irradiated materials research
   - o Medical diagnostics and therapy
   - o Reactor engineering--physics studies
   - o Neutron radiography.

2. Present and assess statistical data:
   - o Available facilities and instrumentation
   - o Faculty population and report publications productivity.

3. Discuss needs and problems for more effective use:
   - o Instrumentation
   - o Research program support
   - o Student support
   - o DOE base support for facility
   - o National laboratory/university center relationship.

4. Discuss effect of low-enrichment-uranium (LEU) conversion on research programs.

5. Discuss how to quantify the value of university reactor research.

WORKSHOP ON EDUCATION

Chairman: Dr. Bernard I. Spinrad
Chairman, Department of Nuclear Engineering
Iowa State University

Rapporteur: Dr. Mihran J. Ohanian
Associate Dean of Research
University of Florida

OBJECTIVES:

1. Assess the next generation of nuclear development and education needs:
   - o Nuclear power
   - o Space applications
   - o Irradiation applications
     - medical
     - biological

- environmental
- material sciences
- chemical analysis

- o Health physics
- o Reactor operations
- o Radio chemistry
- o Defense applications

2. Assess: are we educating well enough for these needs?

3. Discuss the role of the reactor as a teaching tool. How essentialis it in the education process?

4. Assess on-site vs. remote reactor usage for education.

5. Discuss how to quantify the value of education using research reactors.

6. Assess the supply/demand situation in nuclear related field for the long term.

WORKSHOP ON SERVICE

Chairman: Dr. John Poston
Department of Nuclear Engineering
Texas A&M University

Rapporteur: Dr. John S. Laughlin
Department of Medical Physics
Memorial Sloan-Kettering
Cancer Center

OBJECTIVES

1. Define the user community.

2. Assess the importance of reactor availability to the university research and outside user community.

3. Assess local on-site reactor vs. remote reactor.

4. Discuss how to quantify the value of reactor services.

WEDNESDAY FEBRUARY 4, 1987

8:00-10:00	PRESENTATION OF WORKSHOP REPORTS
10:00-5:00	EXECUTIVE SESSION: COMMITTEE MEETING

APPENDIX B

PANELISTS IN THE WORKSHOP ON UNIVERSITY RESEARCH REACTORS
LAWRENCE BERKELEY LABORATORY
FEBRUARY 2-4, 1987

WORKSHOP ON EDUCATION

Dr. Bernard I. Spinrad, Chairman
Dr. Mihran J. Ohanian, Rapporteur
Dr. Bernard Wehring, North Carolina State University
Dr. Don W. Miller, Ohio State University
Dr. Lee Peddicord, Texas A&M University
Dr. Donald Harris, Rensselaer Polytechnic Institute
Dr. William Kerr, University of Michigan
Dr. Roman Schmitt, Oregon State University

WORKSHOP ON RESEARCH

Dr. Clifford G. Shull, Chairman
Dr. Anthony L. Turkevich, Rapporteur
Dr. Robert M. Brugger, University of Missouri
Dr. Geoffrey Greene, National Bureau of Standards
Mr. A. F. DiMeglio, Rhode Island Nuclear Science Center
Dr. Tom Williamson, University of Virginia
Dr. Roger Pynn, Los Alamos National Laboratory
Dr. Bertrand Brill, Brookhaven National Laboratory
Dr. Steven Spooner, Oak Ridge National Laboratory
Dr. Ratib A. Karam, Georgia Institute of Technology
Dr. Frank Asaro, University of California, Berkeley
Dr. Roman Schmitt, Oregon State University
Dr. Samuel A. Werner, University of Missouri
Dr. Otto K. Harling, Massachusetts Institute of Technology

WORKSHOP ON SERVICE

Dr. John Poston, Chairman
Dr. John S. Laughlin, Rapporteur
Dr. Edwin L. Zebroski, Electric Power Research Institute
Dr. Ronald Knaus, Louisiana State University
Dr. Donald Feltz, Texas A&M University
Dr. George Nelson, University of Arizona
Dr. Gary Sandquist, University of Utah
Dr. Donald M. Alger, University of Missouri
Dr. George Miller, University of California
Dr. George Chabot, University of Lowell

PANEL ON CONTROLS, SAFEGUARDS, AND REGULATIONS

Dr. Edwin L. Zebroski, Chairman
Dr. Geoffrey Greene, Rapporteur
Dr. Bernard Wehring, North Carolina State University
Dr. Robert F. Burnett, Nuclear Regulatory Commission
Mr. A. F. DiMeglio, Rhode Island Nuclear Science Center
Dr. Herbert J.C. Kouts, Brookhaven National Laboratory

PANEL ON REACTOR SUPPORT AND SURVIVAL

Dr. Mihran J. Ohanian, Chairman
Dr. William Kerr, University of Michigan
Dr. Tom Williamson, University of Virginia
Dr. Don W. Miller, Ohio State University
Dr. Otto K. Harling, Massachusetts Institute of Technology
Dr. George Nelson, University of Arizona
Dr. Ratib A. Karam, Georgia Institute of Technology
Dr. Arthur Johnson, Oregon State University
Dr. Herbert J.C. Kouts, Brookhaven National Laboratory

Additional Participants in the Workshop on Research Reactors
Lawrence Berkeley Laboratory, February 2-4, 1987

Dr. Luis Alvarez
Lawrence Berkeley Laboratory

Mr. Ken Bogacik
Babcock & Wilcox

Dr. William R. Boyle
Oak Ridge Associated Universities

Dr. Gilbert Brown
University of Lowell

Mr. Keith Brown
U.S. Department of Energy

Dr. Merle E. Bunker
Los Alamos National Laboratory

Dr. Robert E. Carter
U.S. Nuclear Regulatory Commission

Dr. David Clark
Cornell University

Dr. Franklin Clikeman
Purdue University

Dr. Michael M. Denton
University of California, Berkeley

Dr. Gary Erhardt
University of Missouri

Dr. W. Glaser
Institut Laue-Langevin, Grenoble

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GLOSSARY OF TECHNICAL TERMS

Accelerator. A machine designed to accelerate charged particles to energy levels suitable for bombarding a target and studying the resulting nuclear reactions. Among the types of accelerators are Van de Graff electrostatic accelerators, linear accelerators, cyclotrons, and synchrotrons.

Alpha particle. A positively charged particle consisting of two protons and two neutrons, identical with the nucleus of the helium atom, emitted by several radioactive substances.

Atom. The smallest unit of a chemical element, consisting of a central nucleus surrounded by orbital electrons. The atom is held together by the electromagnetic force.

Atomic number, Z. The number of protons in an atomic nucleus.

Atomic spectrum. The spectrum of radiations owing to transitions between energy levels in an atom, either absorption or emission.

Beta decay. Radioactive transformation of a nuclide in which the atomic number increases or decreases by unity with no change in the mass number; the nucleus emits a beta particle during beta decay.

Beta particle. A synonym for an electron or a positron when it is emitted in the process of beta decay.

Binding energy. A measure of the strength with which a given physical system is bound; it is the amount of energy needed to break the bond in question and separate the particles.

Chain reaction. A self-sustaining series of nuclear reactions in which the products of the reaction contribute directly to the propagation of the process.

Charged particle. A particle whose net charge is not zero; protons and electrons are examples of charged particles; neutrons, by contrast, are uncharged.

Cold neutron. A very low energy neutron, typically $E_n << 10$ eV.

Condensed matter physics. The physics of the solid and liquid states.

Crystallography. The branch of science that deals with the geometric description of crystals and their internal arrangement.

Curie. A unit of measurement describing the radioactive disintegration rate of a substance; 1 curie = 3.700×10^{10} disintegrations/second.

de Broglie wavelength. A measure of the wavelike nature of moving matter; the wavelength is determined by h/mv where h is Planck's constant and m and v are the rest mass and the velocity, respectively, of the moving particle.

Defect (or lattice defect). Any departure from crystal symmetry caused by disorder, impurities, vacancies and interstitials, dislocations, and other imperfections.

Detector. Any device that can detect the presence of a particle or nuclear fragment produced in a nuclear reaction and measure one or more of its physical properties.

Deuterium. A naturally occurring isotope of hydrogen. A deuteron, the nucleus of the deuterium atom, consists of one proton and one neutron; hence, it is approximately twice as heavy as ordinary hydrogen.

Electron. An elementary particle consisting of a charge of negative electricity of about 1.60219×10^{-19} coulomb and having a rest mass of about 9.109534×10^{-28} gram (or about 1/1836 that of a proton).

Electron volt, eV. The amount of energy acquired by any particle with a unit electric charge when it is accelerated through a potential difference of 1 volt; keV = thousand electron volts; MeV = million electron volts.

Elementary particle. A particle that, as far as is known, has no internal structure and can be divided no further, thus is one of the fundamental constituents of all matter.

Epithermal neutron. A neutron with kinetic energy typically in the range 1 keV < E_n < 1 MeV.

Fast neutron. A neutron with kinetic energy typically in the range E_n > 1 MeV.

Fertile material. A nuclide which is capable of conversion to fissile material upon absorption or capture of a neutron.

Fissile material. Material that is capable of undergoing fission.

Fission. The division or splitting process, either spontaneous or induced, of a heavy atomic nucleus into parts of roughly comparable mass, accompanied by the conversion of a part of the mass into energy and the release of particles (usually neutrons); usually restricted to heavier nuclei such as isotopes of uranium, plutonium, and thorium.

Fission reactor. A device for initiating and maintaining a controlled nuclear chain reaction of fissile material for the production of neutrons, other radioactive material, or energy.

Flux. A quantity measuring the intensity of particle radiation; for neutron radiation, flux is typically measured in the number of neutrons per square centimeter per second.

Gamma ray. An extremely energetic photon emitted in many nuclear reactions and in the decay of many radioactive nuclides and unstable particles.

Half-life. The time it takes for half of all the nuclei in a radioactive sample to decay to some other material; each type of radionuclide has a characteristic half-life.

Heavy water. Water in which ordinary hydrogen is replaced by the deuterium isotope. Deuterium oxide, D_2O, is important in nuclear reactors as both a coolant and a moderator.

HEU. High enrichment uranium fuel, the amount of radioactive U-235 contained in the reactor fuel. By common usage, HEU describes reactor fuel in which the U-235 content is greater than 20 percent.

Hohlraum. A casing surrounded by a radiated source.

Isotope. Any specific nucleus of a given chemical element. Elements are defined by their individual atomic proton number; isotopes of a given atomic nucleus differ from one another in their neutron number.

Lattice. The pattern of arrangement of fuel elements within the core of a reactor.

LEU. Low enrichment uranium fuel, the amount of radioactive U-235 contained in the reactor fuel. By common usage, LEU describes reactor fuel in which the U-235 content is less than 20 percent.

LOCA. Loss of coolant accident.

Mass number, A. The number of protons plus neutrons ($A = Z + N$) in an atomic nucleus. Nuclei of different elements can have the same mass number.

Moderator. A material used in a fission reactor effectively to slow down or thermalize the (initially) fast neutrons produced in a fission reaction. Neutrons lose energy in a moderator primarily through elastic scattering. Typical moderators are water, heavy water, and carbon.

Molecule. A group of atoms held together by chemical forces; a molecule is the smallest unit of matter that can exist by itself and retain all its chemical properties.

Monochromatic beam. A neutron beam in which all the individual neutrons have the same kinetic energy or wavelength.

Neutron. An uncharged particle with mass slightly greater than that of the proton. The neutron is a strongly interacting particle and is a constituent of all atomic nuclei except hydrogen. An isolated neutron decays to a proton, an electron, and a neutrina with a lifetime of about 900 seconds.

Neutron number, N. The number of neutrons in an atomic nucleus.

Nuclear physics. The study of the characteristics, behavior, and internal structure of the atomic nucleus.

Nuclear reaction. Any change brought about in the states of one or more nuclei as a collision or spontaneous decay.

Nuclear spectroscopy. Study of the detailed structure of nuclei--their spectrum of energy levels, associated physical properties, decay modes, and other properties.

Nucleus. The small, dense positively charged core of the atom, consisting of neutrons and protons held together by strong nuclear forces.

Nuclide. An atomic nucleus characterized by the number of protons, the number of neutrons, and energy content.

Oxygen enhancement ratio (OER). A measure of the radiation dose required to produce a given biological effect as a function of the oxygenation level of cellular material. Sensitivity to irradiation generally increases as the level of oxygenation of the cell material increases.

Phase. A portion of a physical system (solid, liquid, or gas) that is homogeneous throughout, has definable boundaries, and can be separated physically from other phases; the type of state of a system, such as solid, liquid, or gas.

Phase transition. A change of a substance from one phase (e.g., solid, liquid, or gas) to another.

Phonon. A quantum of an acoustic mode of thermal vibration in a crystal lattice. The energy of a lattice vibration is quantized. A phonon, in analogy with the photon of the electromagnetic wave, is the quantum of energy of lattice or thermal vibration in crystals.

Photon. The quantum of energy associated with the electromagnetic wave; a massless particle, the quantum of the electromagnetic field, carrying energy and momentum.

Pool Reactor. A reactor design in which the fuel elements are suspended in a pool of water that serves as the reflector, moderator, and coolant.

Proton. A positively charged particle with a mass of about 1.672510×10^{-24} gram or about 1836 times greater than that of the electron; the charge on the proton is 1.60219×10^{-19} coulomb.

Quantum. The smallest possible unit of energy associated with any change in a physical system.

Radioactivity. Any of several processes in which a nuclide changes to another nuclide by the emission of one or more particles.

Radiography. The technique of generating radiographs or pictures produced on a sensitized surface or film by a form of radiation, typically x-ray radiography or neutron radiography.

Reactor blanket. A region containing fertile material surrounding the reactor core that contains fissile material.

Relative biological effectiveness (RBE). A comparative measure of the absorbed doses necessary to produce the same degree of biological response by two different types of irradiation.

Scattering. When two particles collide, they are said to scatter off each other during the collision.

Semiconductor. A solid crystalline material whose electrical conductivity is intermediate between that of a metal and that of an insulator; the electrical conductivity is usually strongly temperature dependent.

Semiconductor laser. A laser in which the source of the coherent light beam is a semiconductor material.

Solid. A substance that has a definite volume and shape and resists forces that tend to alter its volume or shape; a crystalline material, i.e., one in which the constituent atoms are arranged in a three dimensional lattice, periodic in three independent directions.

Spectroscopy. The branch of physics concerned with the production, measurement, and interpretation of the electromagnetic spectra arising from either emission or absorption of radiant energy by various substances.

Superconductivity. A property of some metals, alloys, and chemical compounds such that when they are cooled (in some cases approaching near absolute zero), their electrical resistance approaches zero.

Thermal neutron. A neutron with kinetic energy typically in the range $E_n < 1$ keV.

Transmutation. A process in which a nuclide of one chemical element is transformed into a nuclide of a different chemical element. A common transmutation process is neutron capture followed by beta decay.

Tritium. A radioactive isotope of hydrogen, ^3H or T. The nucleus of the tritium atom consists of one proton and two neutrons; hence, it is approximately three times as heavy as ordinary hydrogen.

TRIGA. A reactor design developed by GA Technologies, Inc. The design offers the ability for short pulse operation at high peak power in addition to comparatively low power, steady state operation.

X-ray. Highly penetrating radiation emanating from atomic transitions of an element; x-rays are produced, for example, by electron bombardment of a metallic target.

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