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The applications of research reactors

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FOREWORD

The purpose of this publication is to present descriptions of all of the current uses of research reactors. The necessary criteria to enable an application to be performed are outlined for each application. In many cases, the minimum requirements as well as the desirable requirements are given.

This publication will be of particular benefit to those seeking to increase the utilization of their facilities and to those thinking of installing a new research reactor or modifying an existing facility. The order in which the applications are presented progresses from those that are possible on any reactor, such as training, to those that require higher power and more specialized reactors with expensive experimental facilities, such as neutron capture therapy.

In addition, a simplified research reactor capability matrix is developed and presented in Appendix I, which at a glance enables the determination of the applications that may be appropriate for a particular power level reactor.

The IAEA officer responsible for this publication was B. Dodd of the Division of Physical and Chemical Sciences.

CONTENTS

1. RESEARCH REACTOR CAPABILITIES AND USES

Owners and operators of many research reactors are finding that their facilities are not being utilized as fully as they might wish. Perhaps the original mission of the reactor has been accomplished or a particular analysis is now performed better in other ways. In addition, the fact that a research reactor exists and is available does not guarantee that users will come seeking to take advantage of the facility. Therefore, many research reactor owners and operators recognize that there is a need to develop a strategic plan for long term sustainability, including the ‘marketing’ of their facilities. An important first element in writing a strategic plan is to evaluate the current and potential capabilities of the reactor.

The purpose of this document is to assist in such an evaluation by providing some factual and advisory information with respect to all of the current applications of research reactors. By reference to this text, each facility owner and operator will be able to assess whether or not a new application is feasible with the reactor, and what will be required to develop capability in that application.

Applications fall into four broad categories: human resource development, irradiations, extracted beam work and testing.

(1) The *human resource* category includes public information, training and education and can be accomplished by any reactor.
(2) *Irradiation applications* involves inserting material into the reactor to induce radioactivity for analytical purposes, to produce radioisotopes or to induce radiation damage effects. Almost all reactors can be utilized for some irradiation applications, but as the reactor flux gets higher the range of potential uses gets larger.
(3) *Beam work* usually includes using neutron beams outside of the reactor for a variety of analytical purposes. Because of the magnitude of the fluxes needed at some distance from the core, most beam work can only be performed by the intermediate and higher powered research reactors.
(4) *Testing* nuclear fuel and experiments in loops running through the reactor core is highly specialized, and usually only performed by national laboratory level facilities.

The presentation of the uses of research reactors in this document follows the progression outlined above. For each application the specific requirements are generally discussed under the headings: flux/power level, reactor facilities, external equipment, personnel and funding. However, there is some flexibility in these topics as appropriate for each application.

For the purposes of this document, unless specifically referenced in the text, low power research reactors should be regarded as those less than 250 kW and high power research reactors are those above 2 MW. Naturally, intermediate power reactors are in between.

2. EDUCATION AND TRAINING

Every research reactor facility is capable of being used for education and training purposes. When reviewing the potential uses of existing reactors, then this application should not be dismissed lightly as being a trivial or unworthy mission. Conversely, it should be thoroughly explored and utilized to the benefit of the facility. As discussed in this section, educating a knowledgeable public usually means less opposition and more support. Similarly, educating and training the scientific community is the equivalent of planting the seeds for future customers and users.

This section begins by discussing the lower level of education and training, and moves up to full university courses in nuclear engineering and power reactor operator training.

2.1. Public tours and visits

Encouraging and assuring the successful implementation of educational tours for the public, pre-college science students, community college students, teachers and other interested groups has great potential for building quality usage of a reactor facility. When interested facility staff successfully implement presentations, experiments and practical activities for such visitors, the short term advantage can be an interest developed by one or more students in doing science fair or similar projects. In the longer term, the number of college students majoring in nuclear science and technology can be increased. In the even longer term, education and research usage of a reactor facility can be synergistically increased as others note that the facility is active and being utilized.

Tours and visits may involve time commitments from a few minutes for one staff member to most of a day for several staff members. Such activities can involve a simple facility walk through for a few visiting non-technical students to a full day visit by a high school honours physics class. During such a visit, lectures could be presented on reactor capabilities and usage, a reactor start-up could be demonstrated and experiments could be performed, followed by one or more detailed tours. These experiments could include a rabbit system irradiation of a pure single element nuclide (e.g., aluminium) for half-life measurement as well as irradiation of a volunteer hair sample for identification of trace elements. Other activities may involve a dress out in anti-contamination clothing with training usage of survey meters to measure radiation dose rates associated with low activity radioactive materials such as thorium bearing lantern mantels, uranium bearing dishes (e.g., Fiestaware), or radium bearing watch and clock dials. Handling of simulated radioactive material also works well. Fluorescent materials such as motor oil or powdered laundry detergent can be used since they fluoresce under an ultraviolet light. Students undertake careful handling of such material in transfers and packing and then utilize an ultraviolet light to see how successful they were. They can then clean the area using standard decontamination techniques and evaluate the degree of success using another check with the ultraviolet light.

Some of the keys to successful reactor facility usage in this area are:

(1) Know the group well enough to make presentations at the proper level.
(2) Answer questions directly and provide ample time for questions, answers and further interaction.
(3) Do not speak down to the group.
(4) Provide a mix of lecture and practical/experimental activities to maintain student attention.
(5) Provide sufficient experimental equipment to avoid students waiting to be involved.
(6) Provide written material, samples, and brochures for students to take with them.

2.1.1. Flux/power level required

For this category of education and training usage, any power level is sufficient. Even critical facilities can be successful in this area of utilization even though they might not be able to reap the full benefits of growing a research program. Regardless of power level, visiting groups of pre-college and non-technical university classes can undertake visits to learn about the reactor, its uses and capabilities and perform practical activities and experiments to gain understanding of nuclear science and technology. The research reactor staff can assist this through:

(1) Lectures describing the reactor and its capabilities and usage, making liberal use of any available models of fuel assemblies, the reactor facility, and power reactors.
(2) Demonstrations and practical exercises in the use of survey meters, self-reading pocket dosimeters, and anti-contamination clothing.
(3) Providing a detailed walk through tour of the facility emphasizing physical components and systems reviewed or referenced in the lecture. One demonstration available at some facilities is the emergency evacuation alarm, which can provide the basis for explaining emergency response for research and power reactors.
(4) Allowing the students to observe a reactor start-up and approach to full power.
(5) Performing an inverse square law measurement using a low-level radioactive source and simple detector. Performing a shielding experiment.
(6) Conducting a half-life measurement using a radioisotope made in the reactor.
(7) Showing the students how to prepare a sample for irradiation and have them prepare one or more samples for irradiation. One or more standards can also be prepared.
(8) Irradiating a hair sample and showing the students how to identify and even quantify elemental concentrations. As time and the number of students permit, count and analyze the samples (and standards) to obtain some normally identifiable elements such as Na, Cl, Mn, Al, V, and Mg.
(9) Involving the students in other activities such as may be available at the facility.

2.1.2. Reactor facilities required

The only requirement to be able to perform meaningful practical activities in this category is to have a reactor. Any power level is acceptable. The power level is only restrictive in terms of the complexity of the practical activities that will normally occur at the reactor facility. Even when maintenance or other activities make the reactor unavailable, tours and visits such as those described here should still be possible but without the portions dependent upon irradiating a sample.

2.1.3. Experimental equipment required

The experimental equipment required to begin utilization in this area should already exist. However, one of the key considerations for successful group visits should be assuring active involvement of the visiting group in all or most of the activities. Therefore, when larger groups are involved, additional sets of experimental equipment should be available to facilitate subdividing into smaller groups. Groups containing 3 or 4 students are ideal. These activities can still be undertaken without subdivision but in this case it will be difficult to maintain student interest. For analysis of an activated sample, one germanium detector and computer based multi-channel analyser should be sufficient for an analysis demonstration. However, if two or more computer analysers and screens can be used, student’s interest is more likely to be maintained.

2.1.4. Personnel requirements

A tour or visit of this type requires a reactor operations person with the skills to perform the lectures and demonstrations. However, for groups of more than 5–6, additional personnel will be necessary to assure the success of the practical hands-on activities. The size of the laboratory and the quantity of experimental equipment will determine the group size but it is recommended that a group of more than 30 members be encouraged to come in two groups of 15 to assure active participation in the lectures and demonstrations.

2.1.5. Funding

Existing equipment and materials should allow a facility to get started in these activities. Funding for additional equipment should not be needed for the contamination control exercise described above except for the ultraviolet light (~$100). Additional staff time may be needed especially if visitors prefer to come after normal working hours. In addition, funding for extra sets of already existing equipment such Geiger-Müller (GM) detector systems, and self-reading pocket dosimeters, may be needed. However, none of this equipment is too expensive.

2.1.6. Public relations and staff co-operation

Public relations and staff co-operation are very important for reactor utilization in this area. Every effort must be made to provide interesting and informative lectures making use of demonstrations, pictures, models and hands-on activities. Individuals presenting such material and overseeing such activities must be enthusiastic. Successful first interactions/visits will assure return visits and word of mouth advertising to colleagues. The facility itself should also send out periodic notices of the availability of the reactor for visits by college, community college, high school and other groups to build up a regular clientele of satisfied customers who will themselves do more advertising. Finally co-operation will be needed by facility personnel to accommodate the occasional interest in a group visit outside of normal working hours. Staff personnel must also show a collegial attitude during all visits and most importantly, they must be respectful and encouraging toward all visitors. The reactor manager should encourage this attitude.

2.2. Teaching physical and biological science students

Those research reactor facilities that are associated with educational institutions will have a natural audience for this application. However, even if physical and biological science classes are being taught near the reactor, there is still a need to approach the teachers and recruit these classes to use the facility. Non-university research reactors should not be discouraged from this application, since there will often be one or more educational institutions within a few hours reach of the reactor facility.

Students in scientific disciplines such as chemistry, physics, geology and biology can often be attracted to more sophisticated utilization of a research reactor when their initial contact is used to reveal the utilization opportunities available. In this instance, students are educated in the use of the reactor for application in several disciplines. For example, geologists may be interested in using instrumental neutron activation analysis (INAA) to determine rare earth element content in sedimentary rocks while a biologist might be interested in quantifying the trace mercury content in catfish. Because of the broad range of applications, the initial lecture and facility tour to familiarise students and visiting faculty with its capabilities must be presented by a knowledgeable individual dedicated to communicating and demonstrating the possibilities. These students and faculty may then be encouraged to seek more sophisticated usage of the reactor such as for a course level project or perhaps eventually for a funded research project.

2.2.1. Flux level required

A minimum flux of 1×10^{10} n cm^{-2} s^{-1} is probably necessary to demonstrate the possibilities in trace element analysis. Simple materials such as pure aluminium, elemental iodine, pure $CaCO_3$ or other material may be irradiated and the resultant radioactive half-life measured on an available counting system such as a GM counter, gas flow proportional counter, NaI or Ge detector system. Such an introductory experiment is most appropriate following a lecture and tour of the facility. The tour should emphasize the capabilities and possible usage especially as related to the discipline involved. Frequently, prior to arrival, someone in the discipline (perhaps the class instructor or the students themselves) should be consulted to determine the type of application that would be of interest. This allows the reactor representative to relate to a potential use.

At this initial session, a simple application should be demonstrated. One of the most successful is to explain the presence of trace elements in hair and to then obtain a hair sample (perhaps two) one of which is cleaned with alcohol and the other not. The resultant spectrum obtained on a Ge detector following sample irradiation is used to demonstrate the capabilities of INAA to identify and quantify trace elements in the hair sample. The presenter must explain this forensic application and extend the discussion to further possibilities in trace element analysis in other areas.

After the initial demonstration, specific discipline usage of the reactor will vary depending upon the course. A course of special interest is radiochemistry, which can utilize the reactor for a series of experiments including half-life measurements, trace element analysis using INAA, measurements of variation of detector efficiency with source location and inverse square law measurements, as well as other experiments. Courses such as geology, anthropology, biology would usually be interested in the trace element analysis technique while neutron and gamma irradiation effects on materials as well as neutron transmission will be of interest to materials science, physics and biological science courses. In the latter, effects of irradiation on biological material could include the effects of dose rate and integrated dose. A minimum flux of 10^{11} n cm^{-2} s^{-1} will allow the performance of these experiments. However, they will become more realistic and effective with flux levels at or above 5×10^{11} n cm^{-2} s^{-1} where significant trace element analysis projects can be performed.

A student designed semester project is an important area of utilization. These projects can make excellent use of reactor facilities by employing techniques previously learned in the courses. Courses such as radiochemistry and radiation biology can make special use of such facilities for semester projects. Some examples are dose rate characterization of experiment facilities, trace element analysis of water filters, and detection of osmotic water movement through concrete (requires a collimated beam). All these experiments can be accomplished with a flux of 1–5×10^{11} n cm^{-2} s^{-1} or higher and represent excellent breeding grounds for producing students with interest in performing research using a reactor.

2.2.2. Reactor facilities required

The only requirement to be able to perform experiments involving activation and simple radiochemistry is an irradiation system (e.g., a rabbit system) to facilitate sample irradiation.

2.2.3. Experimental equipment, personnel and funding required

The experimental equipment needed would normally be available around a reactor facility. As more advanced experiments are performed, the equipment required may become more complex. However, it should be possible to obtain the equipment from existing research or service applications. There is usually no need to acquire new equipment for educational purposes.

There are no additional operating personnel requirements since an existing staff member can perform the work.

Since all educational involvement will use the existing reactor and experimental instrumentation and equipment, the only additional funding needs would be for staff overtime commitments and supplies (e.g., for rabbit capsules).

2.2.4. Customer relations

Educational users (e.g., a university class with a directing faculty member) should receive encouragement and dedicated assistance and supervision of the reactor usage for their class visits. It is essential that their first experience be successful to encourage continued and expanded educational usage by this faculty member and science, engineering and other faculty colleagues who learn of this successful usage by word of mouth.

Another important aspect in encouraging reactor usage is to survey the needs of faculty in science, engineering and other departments at the reactor's own educational institution and, where applicable, at other educational institutions. Capable, upper level, reactor facility personnel should perform such surveys periodically and then volunteer to provide instructional input and laboratory experiences for interested faculty. One especially promising promotional technique is to provide seminars reviewing the reactor facility, its capabilities and in many cases usage as well as its availability for use for a series of experimental activities in a variety of disciplines. This lecture type promotion can produce extensive increases in research reactor utilization.

2.3. Teaching radiation protection and radiological engineering students

Only those research reactor facilities that have nearby educational institutions teaching these topics can really avail themselves of this opportunity. So this application is a lot more limited.

Education and training in radiation protection and radiological engineering for students and technologists is an activity that can be undertaken by reactor facilities at all power levels. However, the exercises can be more complex at facilities where significantly activated materials are produced and significant potential radioactive effluents are possible. This material can be taught as individual stand-alone classes or used for training in an independent laboratory course where the trainees receive practical experience in applying the principles of radiation protection. These activities should be able to be accomplished with existing reactor facility radiation protection equipment and in many cases can even be the actual activities required to be performed for license requirements.

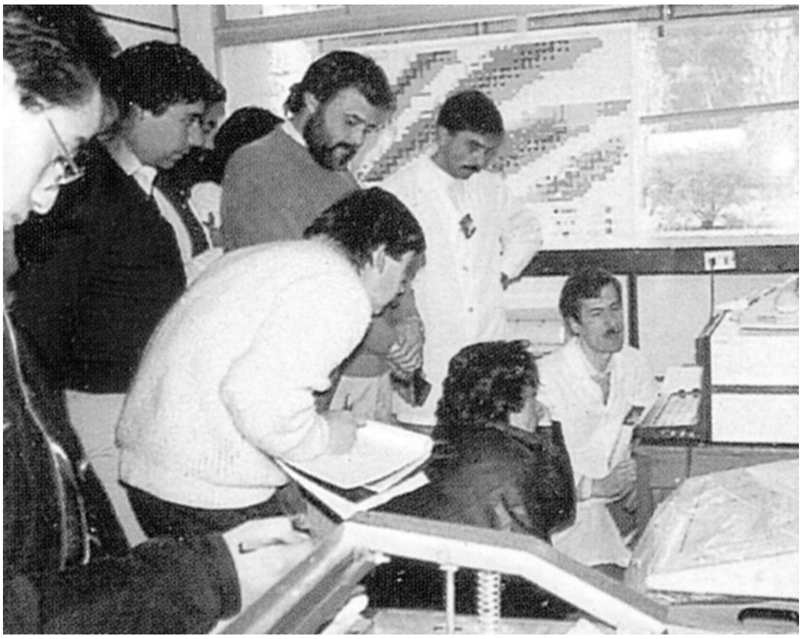


FIG. 1. Students in a laboratory class.

2.3.1. Flux/fluence required

Sufficient fluence must be available to activate samples to produce detectable activities. Very low power research reactors can often provide this fluence. The following set of experiments would be typical where the training activities for students and technicians would be conducted via a series of lectures, demonstrations and associated practical activities and experiments.

2.3.2. Typical laboratory experiments

(1) Reactor pre-operational and operational surveys can be performed including collecting and analysing air, water and swipe (smear) samples. The experiments can include the use of counting equipment such as gas flow proportional counting systems, NaI and Ge or detector systems to identify radioisotopes. If no real activity or contamination exists, the decay products of radon will show up in high volume air samples.

(2) The use of anti-contamination clothing can be demonstrated based on the discussion presented earlier.

(3) Gamma and neutron radiation surveys utilizing different kinds of survey meters can be used to demonstrate instrument characteristics and sensitivity as reactor power level is varied, beam ports are opened and closed and the shield is modified. The sensitivity of these instruments can be demonstrated using gamma ray sources with various energies. Proper posting of areas should be emphasized to demonstrate proper radiological controls.

(4) Calibration checks can be performed on air particulate detectors, stack radiation monitor detectors, area radiation monitors and reactor coolant radiation monitors using standard source(s). The sources can also be used to confirm inverse square law calculated predictions.

(5) Scenario development and emergency evacuation drill simulation with response and evaluation of student teams. This is an excellent experimental activity to teach students to perform as an effective response team.

(6) Radioactive sample monitoring and characterization can be performed with the development of documentation so that the sample can enter a transportation cycle.

(7) Air samples can be collected and analysed to characterize activity (e.g., ^{41}Ar or other gaseous radionuclides) in gaseous effluent and evaluation of actual levels with respect to allowable levels. The students can then develop resultant restrictions on hours of reactor operation or allowable power levels.

(8) Radiation source leak checks can be performed including the reactor neutron source and sealed gamma sources.

(9) Activation can be performed of materials containing a single element (e.g., Al, I, Ca) or multiple elements (e.g., AgI) to allow measurement of individual half-life. In the case of the multiple element sample, the analysis can demonstrate how first one and then the other decaying radioisotope dominates the half-life.

(10) Gamma spectrometry on irradiated samples can be performed to demonstrate the process for identification of radioisotopes using the photopeaks in the spectrum. The discussion should include the applications of this technique to identify radioisotopes in various types of samples (e.g., atmospheric, geological, forensic.)

(11) Shielding effectiveness experiments can be undertaken where a beam port or other radiation source is accessed and shielding is placed to reduce the radiation field to meet the required radiation dose rates. This experiment works best if several types of portable reactor shielding materials are available. As part of this experiment, students may learn to develop a radiation work permit for use in a radiation or a contaminated area.

(12) A frisker type hand held radiation meter may be used to survey low levels of contamination and may be used to demonstrate the use of a portal monitor. If a whole body counter is available, student monitoring can be a useful experiment. It can be performed with and without radioactive materials concealed in or on clothing (e.g., lantern mantels, or other available unlicensed materials.) The same can be performed with hand held survey meters, perhaps allowing one group to hide sources and another group to find them.

2.3.3. Reactor facilities required

The only requirement for the performance of meaningful practical activities in this area is a research reactor of any power level. At higher power level reactors, more complex experiments are possible.

2.3.4. Experimental equipment, personnel and funding required

The training activities discussed earlier will use readily available radiation protection materials and supplies since the training is based on normally performed radiation protection activities modified for training and education purposes. Extra quantities of materials such as anti-contamination clothing may be needed to allow for a larger number of participants.

If the program expands to a large number of students, additional survey instruments and other equipment may be necessary.

Additional personnel are not generally needed. However, if large numbers of students are involved, assisting personnel will be required to provide personalised training.

Minimal additional funding is needed above normal operation budget. However, funding for additional reactor operating hours and assisting personnel for large groups of students may be necessary especially if training takes place outside of normal working hours. The only extra equipment is the ultraviolet light for the contamination detection and control simulation experiment which would cost about $100.

2.3.5. Public relations and communication

Facility availability for radiation protection training and education should be communicated to industrial organizations and academic and research institutions that may require personnel trained in radiation protection. Such training may also be offered to students in related academic disciplines such as environmental science and chemistry. Training of high school science teachers should be a priority.

2.4. Nuclear engineering students

Only those research reactor facilities that have nearby educational institutions teaching nuclear engineering can really avail themselves of this opportunity. So this application is quite limited.

Four types of experimental reactor usage for nuclear engineering education are possible. The first type is reactor physics experiments to measure reactor static and kinetic parameters, including experimental facility characteristics. The second type is reactor utilization for experiments such as neutron activation analysis, and extracted neutron experiments. Finally, the third and fourth type involves operator training for nuclear engineering students and future research and power reactor operators to give them experience in operations involving reactivity changes and effects and temperature changes and how theory and practice are related. The experiments are often divided into two groups: below the point of adding heat and above the point of adding heat. The level of theoretical explanation for nuclear engineering students should be at a higher level than that for operator trainees.

2.4.1. Typical experiments

The next four sections describe some of the experiments that are possible.

2.4.1.1. Reactor physics experiments

(1) Measurement of flux spectrum/flux variations (such as beam ports and thermal columns).
(2) Measurement of reactor kinetics parameters (β/l).
(3) Sub-critical multiplication/shutdown margin measurements with approach to critical.
(4) Control rod/control blade calibration using the in-hour equation.
(5) Excess reactivity and shutdown margin measurements.
(6) Measurement of reactor period with correlation to one and six delayed neutron groups.
(7) Measurement of temperature coefficient and heat up rate.
(8) Calorimetric heat balance and nuclear instrument calibration.
(9) Absorber reactivity worth measurements.
(10) Measurement of hot channel factors (as allowed by facility design and operational limits and conditions) and effects of control rod positions on nuclear instrument indications.
(11) Power decay and delayed neutron group measurements.

2.4.1.2. Utilization experiments

These applications would be demonstrated only when the experimental facilities already exist. They would not normally be developed specifically for educational purposes.

(1) Trace element analysis.
(2) Neutron radiography.

(3) Neutron transmission experiments using beam ports.
(4) Neutron scattering experiments using beam ports.
(5) Fermi chopper thermal neutron time-of-flight experiments using a thermal column.

2.4.1.3. Reactor operations experiments below the point of adding heat.

These experiments are similar to the reactor physics experiments discussed earlier. However, the emphasis is now on operations and reactor control and instrumentation systems and understanding basic physics measurements. The objective is to provide the student with operations experience similar to that of a reactor operator.

(1) Pulling of control elements to demonstrate subcritical multiplication.
(2) Neutron source effects with sub-critical multiplication.
(3) Start up to critical with source followed by source removal effects.
(4) Approach-to-critical; inverse multiplication experiment.
(5) Measurement of stable reactor period and criticality demonstration.
(6) Control rod calibration measurements using in-hour equation
(7) Low power measurements with observation of delayed neutron effects.
(8) Manual versus automatic control and speed of response.
(9) Temperature and void coefficient measurement.
(10) Effect of control rod positions on nuclear instrument readings.

2.4.1.4. Reactor operations experiments above the point of adding heat

These experiments are similar to the reactor physics experiments discussed in Section 2.4.1. However, the emphasis is now on operations and reactor control and instrumentation systems and understanding basic physics measurements. The objective is to provide the student with operations experience similar to that of a reactor operator.

(1) Pulling of control elements to demonstrate subcritical multiplication.
(2) Approach to critical experiment.
(3) Control rod worth measurements by rod pull or rod drop methods.
(4) Measurement of temperature coefficient and heat up rate.
(5) Automatic control and speed of response with observation of delayed neutron effects.
(6) Calorimetric heat balance and nuclear instrument calibration.
(7) Effect of control rod positions on nuclear instrument readings.
(8) Measurement of hot channel factors (as allowed by facility design and operating limits and conditions).
(9) Controlled cool down transient (cold slug) demonstration.
(10) Shutdown with immediate restart (hot restart operations).

2.4.2. Reactor facilities required

These experiments are possible on reactors of any power level with the required experimental facilities. However, they are most easily performed on a low power training reactor.

2.4.3. Experiment equipment required

Neutron flux and neutron spectrum measurements require an assortment of neutron activation foils and threshold detectors (e.g., Au, In, Cd, A1) as well as counting facilities such as gas flow proportional counters, NaI or HPGe detectors to any level of sophistication desired.

An approach-to-critical experiment may require one or more neutron detection systems using BF_3, ^{10}B, or fission chambers, along with amplifiers and readout devices. All other experiments will normally utilize existing equipment.

2.4.4. Personnel requirements

All experiments require a reactor operator. Some reactor physics experiments (e.g., a critical experiment) will require measurements and data collection in addition to that provided by the existing reactor instrumentation. In this case, a staff member is required to set up and operate the equipment. The reactor operator or another individual must be capable of assuring understanding of the experiment and its results for the students involved.

Utilization experiments require an individual actually working in the area of the experiment. This individual should provide an introduction to the experiment and should oversee and direct the student work.

Some operations experiments may be conducted with only a highly skilled reactor operator. Other experiments (e.g., an approach to critical) will require several other professional individuals.

2.4.5. Funding

Additional funding is usually not required for utilization and operations experiments.

Reactor physics experiments that require instrumentation not available in the reactor instrumentation will need some funding for this instrumentation. The cost will depend on level of sophistication desired in the experiment and may vary from US $5000 to US $40 000.

Flux and flux distribution measurements may make use of existing counting systems. However, several thousand dollars may be required for the required activation foils and wires if not already available.

2.5. Nuclear power plant operator training

For a research reactor to practically perform this type of training, there must be a nuclear power reactor within a reasonable distance of the research reactor. However, it could be quite a bit further away than the educational institutions discussed in the earlier sections. Many nuclear power reactor facilities will be willing to send some of their reactor operator trainees for a residential course away from their power plant.

It should be recognized that training of operators for nuclear power plants using research reactors has become less frequent in many countries as plant specific, power plant simulators have become more prevalent. Nevertheless, this activity continues at some locations in industrialized countries and has the potential for considerable utilization in developing countries. This training usually consists of a set of experiments intended to provide hands-on experience in manipulation of reactor controls and designed to provide experience with and understanding of the principles of sub-critical multiplication through full power operation.

2.5.1. Flux/power level required

Low power level reactors may be utilized to perform the experiments presented in Section 2.4.1.3. Higher power level reactors may be utilized to perform the experiments presented in Section 2.4.1.4.

2.5.2. Other considerations

Almost all the other considerations are the same as those for teaching nuclear engineering students discussed earlier.

2.5.3. Opportunities

Every opportunity should be taken to communicate internationally that a particular facility is available for operator training. This is especially important in developing countries where power reactors are anticipated being built since it takes some time to build up the personnel resources and infrastructure knowledgeable in the nuclear field.

3. NEUTRON ACTIVATION ANALYSIS

Neutron activation analysis (NAA) is a qualitative and quantitative analytical technique for the determination of trace elements in a variety of complex sample matrices. It can be performed in a variety of ways depending on the element and its levels to be measured, as well as on the nature and the extent of interference from other elements present in the sample.

Next to education and training, NAA is the most simple and widely used application of research reactors. Almost any reactor of a few tens of kilowatts and above is capable of irradiating samples for some sort of NAA. In addition, many of the uses of trace element identification can be directly linked to potential economic benefits. Therefore, NAA should be looked at as a key component of most research reactor strategic plans.

The NAA technique can be broadly classified into two categories based on whether chemical separations are employed in the analytical procedure. Under favourable conditions, the experimental parameters such as irradiation, decay and counting times can be optimized so that the elements of interest can be determined without the need of physical destruction of the sample by chemical treatments. This process is called non-destructive NAA. However, it is more commonly referred to as instrumental NAA (INAA) and is the most widely used form of NAA.

The INAA technique generally involves a neutron irradiation followed by a decay period of several minutes to many days. In some cases, cyclic INAA (CINAA) is employed whereby a sample is irradiated for a short time, quickly transferred to a detector and counted for a short time. This process of irradiation–transfer–counting is repeated for an optimum number of cycles. The INAA technique uses reactor neutrons that are a combination of thermal and epithermal neutrons. When mostly epithermal neutrons are used for irradiations, the technique is called epithermal INAA (EINAA).

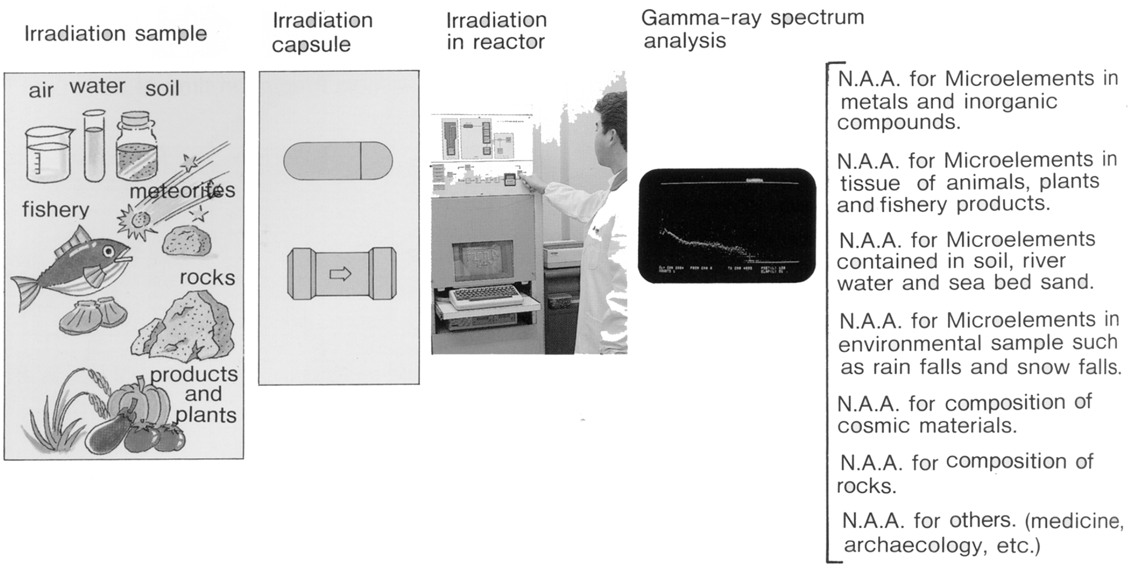


FIG. 2. Overview of neutron activation analysis.

It is possible that interference from the other elements present in the sample is so severe that the element of interest cannot be reliably determined by INAA. Furthermore, if the concentration of the element of interest is lower than the detection limit, non-destructive INAA cannot be used. Under such circumstances, chemical separations are often employed in conjunction with NAA. This process is referred to as destructive NAA. This type of NAA can be further classified into two categories. If the irradiation is followed by a chemical separation then the technique is called radiochemical NAA (RNAA). If the element is chemically separated prior to irradiation; the technique can be further sub-classified into pre-concentration NAA (PNAA) and derivative NAA (DNAA). In DNAA, the element of interest is either replaced or complexed with another element that can be determined by NAA with better sensitivity. All other pre-irradiation chemical separations are included in PNAA.

INAA can be classified into six categories depending on the half-life of the nuclide produced. These are:

(1) Very short lived nuclides (half-life <500 ms),
(2) Short lived nuclides (500 ms–100 s),
(3) Short to medium lived nuclides (100 s–10 min),
(4) Medium lived nuclides (10 min–15 h),
(5) Long lived nuclides (15 h–365 d),
(6) Very long lived nuclides (1–5 years).

The requirements for the detection and measurement of each type of nuclide are presented below.

3.1. Flux/fluence required

Although a minimum neutron flux of 10^{10} n cm^{-2} s^{-1} can be used for the determination of some elements in some matrices, a neutron flux of greater than 5×10^{11} n cm^{-2} s^{-1} is desirable for the measurement of most elements. The typical neutron flux in low power level reactors varies from 2.5 to 10 × 10^{11} n cm^{-2} s^{-1}, while the flux range is between 0.1–10 × 10^{13} n cm^{-2} s^{-1} for medium-to-high power reactors. Very short lived, short and medium lived nuclides can be easily assayed using low flux. However, many of the long lived and very long lived nuclides require either a medium to high neutron flux level or a long irradiation time at low flux to attain comparable saturation activities.

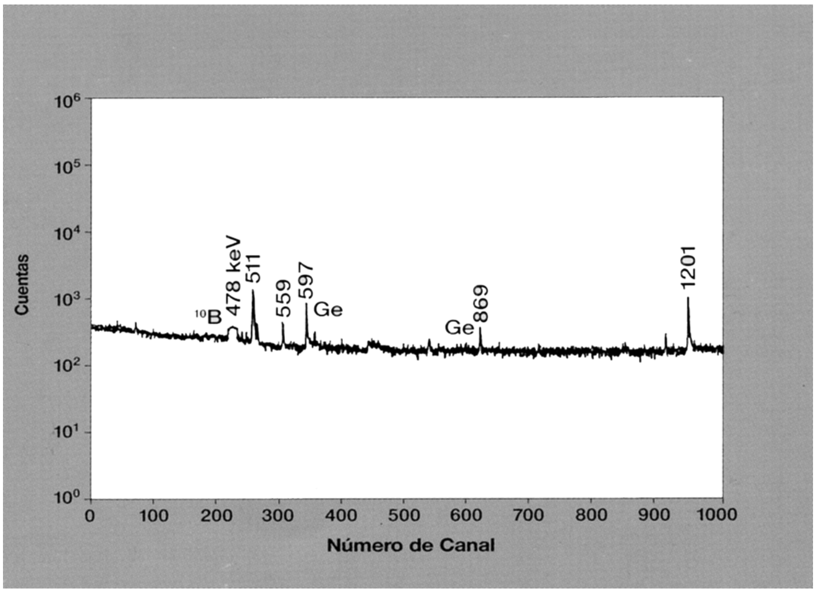


FIG. 3. A simple gamma-ray spectrum.

3.2. Reactor facilities required

3.2.1. Neutron energy spectrum

The thermal neutron cross-section for most elements is much larger than the epithermal and fast neutron cross-section. This makes NAA possible even though most reactors have a higher flux of fast neutrons compared to thermal neutrons. In most reactors, the thermal flux has been optimized in irradiation positions designated for NAA. Most of the high power and some of the low to medium power level reactors have an epithermal flux greater than 10^{10} n cm^{-2} s^{-1}. This can be advantageously employed in epithermal NAA (ENAA) for minimizing interferences from certain elements (e.g., Na, Cl, Mn, V) that have high thermal neutron cross-sections. In many research reactors, the fast neutron flux may also be used for NAA.

3.2.2. Flux homogeneity, stability, and reproducibility

It is extremely important to map the neutron flux in all irradiation sites in terms of homogeneity, stability, and reproducibility. Flux monitors in each irradiated sample, or group of samples, are usually used to obtain reliable quantitative results.

For INAA, it is desirable that the neutron flux be as stable as possible during the irradiation of the sample and standard and be reproducible from one run to the other. For studying short lived nuclides by CINAA, it is essential that the flux be both highly stable and reproducible. In these cases, flux monitoring is normally possible.

3.2.3. Sample transfer system

Irradiations for conventional INAA, PNAA, and RNAA are usually performed using a pneumatic sample transfer system (rabbit system) normally available in the reactor. In some cases, a hydraulic system is employed. For ENAA, samples can be irradiated in specially built pneumatic sites fitted with thermal neutron shields (e.g., Cd, B, Gd). The samples may also be wrapped in one of these shields and placed in a conventional rabbit system.

A sample recycling pneumatic rabbit system must be made available for CINAA. It is essential that the recycling system be installed as close as possible to the reactor so that the sample transfer time is minimal. Consideration must be given to the type and level of radiation in the surrounding areas so that the gamma ray spectrum of a sample is not influenced by the background radiation.

The sizes of the vials that can be used for INAA depend on the sizes of the rabbits. The rabbit size is dependent on the installed rabbit system. Large sample irradiations are usually done outside the immediate vicinity of the reactor core, and their sizes will vary depending on the reactor type.

3.3. Space requirements

Space appropriate for the samples being analyzed is required for sample preparation (e.g., drying, weighing, encapsulation). For all samples, contamination must be avoided. In some cases a clean room may be necessary. In other cases, a special fume hood may be appropriate.

A counting room for detector systems and a room for the storage of irradiated samples are also required. The size of the rooms will depend on the extent of activities.

3.4. Experimental equipment required

3.4.1. Counting equipment

At least one gamma ray spectrometry system is needed for doing INAA. This system will consist of a semiconductor detector, either pure Ge or lithium drifted Ge (GeLi), connected to a multi-channel analyser (MCA). Personal computers with a MCA card are often used. Such a system may cost US $20 000–30 000 depending on peripherals and the quality of the detector. For INAA, a detector with high resolution (<1.8 keV), high efficiency (>35%), and a high Peak-to-Compton ratio (>60:1) is desirable. This may increase the cost. The detector should be shielded by Pb with Cu and Cd linings to absorb X and γ rays. The cost of a commercial shield can be as high as US $10 000.

The detection limits can be further improved by lowering the background activity using a Compton suppression spectrometer (CSS). A fairly simple CSS would consist of a high resolution Ge detector surrounded by a Na guard detector and an array of electronic modules. The peak-to-Compton ratio can be improved to 550 to 650. The cost of a CSS can vary between US $75 000–100 000.

A survey meter is needed for the counting and the radioactive sample storage rooms. Personnel monitoring is needed for each of the experimenters.

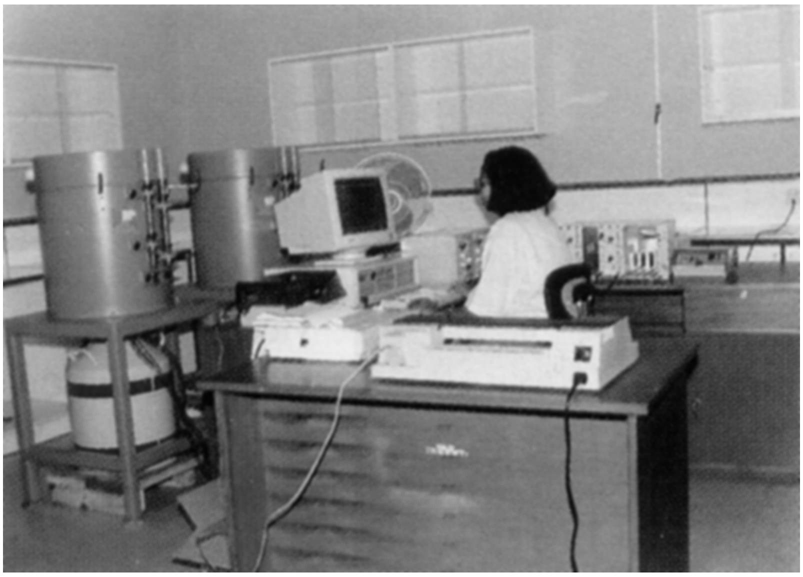


FIG. 4. Gamma spectrometer counting laboratory.

3.4.2. Sample loader and sample changer

If a large number of samples are analyzed for medium lived, long lived and very long lived radionuclides, a sample changer can be used to increase the efficiency of operation. A changer can also be used to provide a better counting geometry. Many facilities have designed and constructed their own sample changers for modest cost. The cost for a commercial sample changer to be used with a conventional gamma ray spectrometer can be US $10 000 or more. A sample changer for use with a CSS is not presently commercially available.

3.5. Personnel requirements

At least one person is necessary to lead the facility effort in INAA. This is often a member of the operating staff who combines this function with the operational duties. The number of persons required would depend on the amount of work that has to be done. In some reactor facilities, students and experimenters are trained to irradiate and count their own samples while the reactor is in operation. For at least one low power level reactor type, it is sometimes possible for one person to operate the reactor as well as to analyse the samples.

It is relatively easy for reactor facilities to insert, irradiate and remove NAA samples from the reactor for experimenters to then count and analyse themselves. However, there is a much larger number of users who do not have the background and training to perform NAA, nor have any desire to learn, but who nevertheless would like to make use of the technique. To this end, a research reactor facility may well gain a significant number of additional users if it provides a complete NAA service involving sample preparation, irradiation, counting, and data reduction with just the analytical results returning to the customer. Clearly such an effort will require at least one or two additional staff depending on the total sample throughput.

4. RADIOISOTOPE PRODUCTION

Genuine production of significant quantities of isotopes for commercial utilization typically requires a higher reactor power and a major investment in hot cell equipment for processing. Prospective isotope producers are advised to analyse international market prices, assess the market situation in their region and contact potential users to assess the potential customer base before making this a major part of their strategic plan for the facility.

However, many research reactor facilities are capable of irradiating materials to produce certain isotopes in small quantities for research applications. In this way, they can supply the needs of their more local users, perhaps at a university.

References to additional information on isotope production are listed in the Bibliography.

FIG. 5. Typical forms of isotopic radioactive sources.

4.1. General

Some isotope production is possible in a low (<10^{13} n cm^{-2} s^{-1}) flux reactor. However, more is possible in an intermediate (10^{13}–10^{14} n cm^{-2} s^{-1}) or high (>10^{14} n cm^{-2} s^{-1}) flux reactor. It should be recognized that in order to be able to realistically produce radioisotopes, the operating cycle of the reactor for all but short lived isotopes needs to be as long as possible.

Flux traps are useful for reactors of all power levels and a variety of irradiation facilities is desirable (e.g., pneumatic transfer, hydraulic transfer, irradiating baskets in core, or in beam tubes). Similarly, capabilities for thermal interactions and fast neutron irradiations should be available.

A gamma spectroscopy system is needed for quality assurance purposes to provide reliable measurements of radioactivity levels and purity. Indeed a complete quality assurance (QA) program must be in place for any commercial work in this field.

The reactor facility should develop encapsulation techniques for the range of fluxes, fluences and irradiation environments available there. After irradiation, a shielded device, often in a fume hood, must be available for opening irradiation capsules safely.

There are some significant issues relating to safety analysis, and licensing that must be addressed prior to radioisotope production. It should be determined that possible abnormal occurrences during the production process are within the bounds of the reactor design basis and the operational limits and conditions. In addition, the use of radioisotopes requires licensing by a competent authority. For first time users, the operating organization should be willing to assist the user in the licensing process. Special requirements are necessary for the use of medical isotopes on humans and animals, and this may require special considerations during the production process.

4.2. Low flux reactor ($<10^{13}$ n cm^{-2} s^{-1})

4.2.1. Potential isotopes and fluence required

In a low flux reactor the fluence available is also often low because the reactor is only operated for one shift. In addition, one shift operation dictates the production of short half-life radioisotopes if the saturation activity is desired. For these reactors isotopes are usually produced on request from local users.

Among the possible isotopes that low flux reactors might be able to produce are: ^{24}Na, ^{32}P, ^{38}Cl, ^{56}Mn, ^{41}Ar, ^{64}Cu, and ^{198}Au.

4.2.2. Experimental equipment, personnel and funding requirements

There are few equipment requirements beyond those normally located at a research reactor facility and those mentioned earlier in the introduction of this section.

The first time production of a new radioisotope at a facility would typically require the attention of a professional radio-chemist to establish the procedure; however, future production should be possible using a technician.

Minimal funding is required beyond that required to implement the earlier suggestions. Annual funding requirements are small enough to be assumed in the regular operating budget.

4.3. Medium flux reactor (10^{13}–10^{14} n cm^{-2} s^{-1})

4.3.1. Potential isotopes and fluence required

A reactor with this flux may operate for one or two shifts, or for a longer cycle. One and two shift operations should be capable of extending their operating hours, when required, for the production of a particular marketable isotope.

In addition to the isotopes suggested in Section 4.2, it should be possible to produce ^{90}Y, ^{99}Mo, ^{125}I, ^{131}I, and ^{133}Xe.

4.3.2. Experimental equipment, personnel and funding requirements

There are few equipment requirements beyond those normally located at a research reactor facility. Additional equipment may include special encapsulation materials (e.g., quartz) and portable shielding (e.g., lead pigs).

Additional technician level personnel may be required beyond those for a low power reactor if the production rate is too high for one individual to handle.

Funds may be required beyond those for the low flux case for encapsulating materials such as quartz and portable shielding.

4.4. High flux reactor (>10^{14} n cm^{-2} s^{-1})

4.4.1. Potential isotopes and fluence required

A high flux reactor usually operates continuously (e.g., 100 hours) to meet the requirements of its experimental users and radioisotope production fits easily into this schedule.

In addition to the isotopes suggested in Sections 4.2 and 4.3, it should be possible to produce ^{14}C, ^{35}S, ^{51}Cr, ^{60}Co, ^{89}Sr, ^{153}Sm, ^{169}Yb, ^{170}Tm and ^{192}Ir.

4.4.2. Experimental equipment, personnel and funding requirements

Full scale isotope production will require considerable equipment beyond that already discussed. Because of the high level of radioactivity of some possible isotopes, remote loading and unloading equipment may be necessary, including a hot cell.

Depending on the radioisotope production workload, a full time radio-chemist and additional technicians may be required.

While some start up costs may be absorbed by the operating organization, cost recovery for production and distribution should be the goal.

5. GEOCHRONOLOGY

Use of research reactors for geochronology is a more specialized application. Reasonable power levels are required and the user base is a relatively small group of geologists. In addition, there is a tendency towards loyalty to the reactor facilities that they are currently using due to the lengthy individual facility calibrations needed.

5.1. Argon geochronology

Argon geochronology is a dating method whereby the age of small (mg) quantities of minerals can be determined by methods based on the radioactive decay of natural potassium. Radiogenic ^{40}Ar is generated in the sample as a result of ^{40}K decay. Therefore, determination of the amount of ^{40}Ar present as well as the original quantity of potassium will enable the age of a sample to be determined. The amount of potassium is determined by putting the sample in a reactor and using the ^{39}K (n,p) ^{39}Ar neutron interaction. Using automated gas extraction-mass spectrometry systems, the ratio of ^{40}Ar/^{39}Ar is measured in the material after irradiation. Samples as young as 2000 years and as old as the earth itself (about 4.6 billion years) can be dated, depending on the nature of the sample.

Because of its specialized nature, and the expense of the equipment involved, there are only about six laboratories world wide performing this type of work. Therefore, in most cases, the reactor facility will only be performing the irradiations and the samples will be sent off-site for analysis.

5.1.1. Flux/fluence requirements

The ^{39}K (n,p) ^{39}Ar reaction has a threshold of about 1.2 MeV and most of the interactions are from neutrons in the 1.2 to 7 MeV range. Therefore, fast neutrons are required for this methodology.

All of the argon isotopes from 36 to 40 are usually measured. Since each isotope has more than one source, efforts are made to reduce contributions from interfering reactions to negligible levels. In particular, there is an interference reaction (^{40}K (n,p) ^{40}Ar) which is driven entirely by thermal neutrons. This can be corrected by a factor that is constant with age. For rocks about 5 000 000 years or older, it is very small. Therefore, the inaccuracy of not applying the correction is not a significant factor. For younger and younger rocks, not applying the correction can add significant (50% or more) uncertainty to the age.

There are two ways to correct for this uncertainty:

(1) Measure the correction with each sample position in each irradiation (which can be cumbersome); or

(2) Reduce the thermal neutrons by shielding with Cd.

The latter method is preferred and reduces the correction to the point where it can be made precisely even with rocks only a few thousand years old. For older rocks the Cd shielding is not necessary but, if Cd is used, it does not interfere with the process. For young rocks, the use of Cd is very important.

Since it is best to keep the ^{40}Ar/^{39}Ar ratio in the range of 1:1 to 1:100, young rocks will need a much smaller neutron fluence than older rocks. The requirement can range from a fast neutron fluence of about 2×10^{15} n/cm^2 for young rocks up to 10^{18} n/cm^2 for very old rocks. Typically, this means from 30 minutes to 300 hours in a 1 MW reactor.

5.1.2. Reactor facilities required

Clearly, the flux must be high enough so that long irradiation times are not required. Typically this means a power level about 1 MW for young rocks, with 10 MW being needed for the very old rocks. In addition, the fast neutron flux has to be reasonably flat over the entire sample. Reproducibility of the fluence is of high importance for these determinations. This means that the sample must be able to be placed in exactly the same position in the core every time.

Samples for these irradiations are typically individually wrapped in foil and stacked on top of one another inside quartz vials, which are heat sealed. Flux monitors are placed at intervals in each stack. Several vials are often irradiated together. The length of the vials is usually a function of the flux variation in the irradiation position. The stack will be limited so that the flux variation over the length will not be more than a few percent. Clearly, the flatter the axial flux in the irradiation position, the more samples can be irradiated at one time.

An irradiation position of 2 or 3 cm in diameter and 15 to 20 cm long is sufficient. Usually this will be an in-core irradiation position.

An important aspect of argon irradiations is that the temperature of the sample should not exceed 200°C. Otherwise the argon diffuses out of the mineral matrix and errors are introduced into the dating analysis.

5.1.3. Experimental equipment, personnel and funding required

Since the samples are almost always analysed off-site by the experimenter, no experimental equipment is required.

Additional reactor staff is not needed. However, since irradiated samples are shipped off site, often internationally, expertise in radioactive material shipments is required. A customer with the required laboratory equipment (mass spectrometers) to perform Ar/Ar analysis is necessary.

The initial investment for a facility to perform dating irradiations involves the in-core irradiation facilities. Most reactors already have such irradiation positions. For the analysis of older rocks, a Cd lined facility is not required. For the analysis of young rocks, it is essential. If such a facility is not available, it could be installed for a few thousand dollars or less. The only recurring expense is for irradiation capsules and shipping materials.

5.2. Fission track geochronology

Fission track geochronology is a method for dating minerals containing uranium, particularly apatites and zircon. Apatite is a calcium phosphate that is common in granites and metamorphic rocks. Zircon is a zirconium silicate that is also common in similar rocks. The sample age is determined by counting fission tracks in the material from spontaneous fission of ^{238}U. These tracks are a function of the U content and the age since “closure” when the fission track clock started. A research reactor is then used to irradiate the samples and induce fission in the ^{235}U present in the sample. By comparison of the before and after track count, the U content in the sample is determined.

Since tracks are annealed at temperatures above about 120^{o}C for apatites and 200 to 300^{o}C for zircons, the method is also useful for the determination of the thermal history of a sample.

Because of the specialized nature of the analysis, most reactor facilities will only be performing the irradiations and the samples will be sent off-site for analysis.

5.2.1. Flux/fluence required

In addition to the uranium, all samples will contain low concentrations of thorium. Both the thorium and ^{238}U will fission when irradiated with fast neutrons. Therefore, it is important that the samples are irradiated with well thermalized neutrons. This allows for the assumption that all of the fission events produced during irradiation are from the fission of ^{235}U.

It is important that the flux is stable during the irradiation.

Total fluence requirements are determined by the U concentration present in the mineral to be examined. Apatites typically have concentrations from 5 to 100 ppm, requiring a thermal neutron fluence of about 10^{16} n cm^{-2}. Zircons, with 50 to 500 ppm, require around 2 to 4 × 10^{15} n cm^{-2}. As a practical example, this translates to about 30 hours in the thermal column of a 1 MW reactor. However, the irradiations do not have to be continuous.

5.2.2. Reactor facilities required

Highly thermalized neutrons are required such as those produced in a thermal column. For irradiation, mineral grains are mounted, polished and etched, then sandwiched between thin mica detectors. All new fission events within 10 μm of the mineral surface are recorded in the overlying mica (provided the fragments are directed outward). Glass monitors are also packaged with the layers to measure the flux gradient. This results in a typical package about 5 to 10 cm long and 2 cm diameter encapsulated in a polyethylene tube. The thermal column must accommodate one or more of such packages.

A mounting device is required for ease of handling the radioactive samples at a distance, as well as reproducibly placing the samples in the thermal column.

5.2.3. Experimental equipment, personnel and funding required

Except for the sample handling and mounting device, no experimental equipment is required since the samples are usually prepared and analysed off-site by the experimenter.

Additional reactor staff is not needed. However, since irradiated samples are shipped off site, often internationally, expertise in radioactive material shipments is needed. A customer with the required laboratory equipment and expertise is necessary.

Reactors either have a thermal column or they do not. It is highly unlikely that a facility will install a thermal column for this application alone and therefore the cost of doing so is not relevant. Hence, only minimal funds are necessary for construction of a sample mounting and handling device.

6. TRANSMUTATION EFFECTS

This category of applications includes all those uses where the neutrons and/or gamma radiations are used to cause a change in the material properties. Because transmutation effects usually require significant fluences to induce the effect within a reasonable time period, then intermediate and higher powered reactors are needed. Additionally, to produce sufficient quantities of product to make it worthwhile, fairly large, uniform flux irradiation positions are often required.

6.1. Silicon transmutation doping

Neutron transmutation doping (NTD) of silicon is the process of irradiating ingots of high purity silicon with thermal neutrons to convert some of the silicon to phosphorus through an (n,γ) reaction. The advantage of this doping technique over the non-nuclear techniques is that it is possible to produce better uniformity of the doping material because of the penetrability of neutrons in the silicon.

NTD has some attractiveness to reactors because it is a potential income generator. The demand for doped silicon is about 100 tons per year and a large facility can produce 20–30 tons per year. At the time of writing (early 2000), it appears that the production is greater than the demand. However, old reactors will probably produce less and less per year, but this is offset by the fact that several newly constructed and designed reactors have dedicated production facilities built into them.

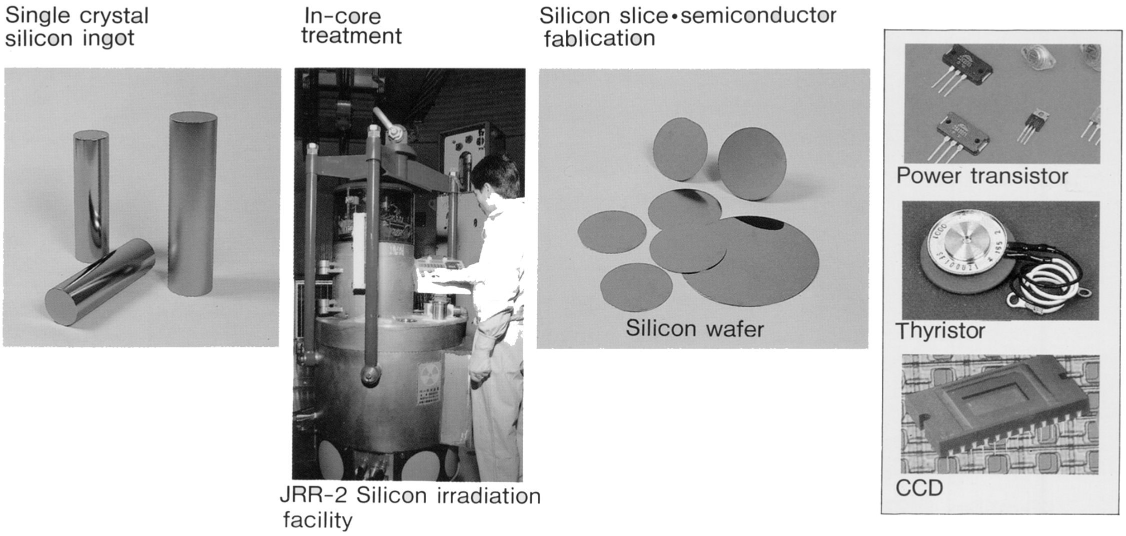


FIG. 6. Outline of neutron transmutation doping of silicon.

A facility wanting to break into this market needs to be able to produce the NTD silicon either with greater uniformity, in larger ingots or much cheaper. To this end, a research reactor should start with small quantity production using a simple irradiating rig and should not expand without a reasonable expectation of demand from the industry, because of the current market glut.

Many of the characteristics of a facility that make it useful for NTD (good flux and fluence homogeneity) also make it an attractive tool for other purposes (e.g., INAA).

6.1.1. Flux/fluence required

A low power reactor (e.g., 250 kW) with a neutron flux of 2×10^{12} n cm^{-2} s^{-1} can be used to produce useful quantities of doped silicon. However, for the production of commercial quantities of doped silicon, the flux should be greater than 10^{13} n cm^{-2} s^{-1} but not more than about 2×10^{14} n cm^{-2} s^{-1}. This lower neutron flux limit comes about because of the desire to achieve an economic payoff. The upper neutron flux limit comes about for several reasons such as keeping the irradiation time greater than just a few minutes and because the highest resistivity silicon demanded is about 1000 ohm cm.

6.1.2. Constraints on flux

The irradiating neutron flux must be highly thermalized and the in-homogeneity of the flux should be less than 5% along the radial and longitudinal axis of the silicon ingot. Along the radial axis, the required homogeneity is easily accomplished by rotating the ingot. Longitudinal homogeneity is accomplished using shaped shielding or lateral motion, continuously or step wise as discussed later. Heat removal from the sample may be required, especially for high flux irradiations.

6.1.3. Personnel requirements

For the commercial production of doped silicon, one engineer (preferably electronic) and one technician are required. The ingots will normally be inserted and removed from the irradiation facility by the operating staff.

6.1.4. Irradiation facility

The typical form of a silicon ingot is a cylinder with a diameter of 5–15 cm and a height up to 70 cm. The trend is to longer and larger diameter ingots. The irradiations may take place in a beam tube or other horizontal facility. Alternately, a vertical facility may be used.

Although the flux in a horizontal beam port is usually not very thermal, it may still be used for an ingot irradiation. To achieve radial homogeneity in the doping, the ingot can be rotated. To achieve longitudinal homogeneity, shaped neutron shielding may be used along the long axis. Alternately, it may be possible to turn the ingot end for end half way through the irradiation.

To achieve homogeneity in a vertical irradiation facility, the ingot can be rotated and moved up and down.

The surface contamination of the ingot after irradiation must be minimal.

6.1.5. Experimental equipment and funding required

In addition to the irradiation facility, special handling tools, a storage place for decay, and a decontamination facility will be required. An important aspect of the complete system is the flux monitoring equipment since this often dictates the quality of the product.

The funds required will depend on the local capability to fabricate equipment and the equipment already available (e.g., self powered neutron detectors, micro-ammeters, activation foils, and a computer). If this equipment is already available, it should be possible to construct an in-core facility locally for under US $5000.

6.2. Materials irradiation

While it may take a significant neutron flux to be useful for most materials irradiations, almost any reactor can use its fuel while shutdown for gamma irradiations.

6.2.1. Neutron irradiations

Fast and thermal neutron irradiations are sometimes performed to determine the effects of irradiation on materials. Examples of materials testing include the following:

(1) Metals (e.g., power reactor pressure vessel steel) to determine the service lifetime because of property changes (embrittlement, stress corrosion, ageing);
(2) Electronic components;
(3) High temperature reactor materials (e.g., SiC, graphite);
(4) Materials for use with a spallation neutron source (e.g., window material);
(5) Fusion reactor materials (e.g., blanket testing, first wall materials, plasma facing materials, windows for microwave heating systems, breeder blanket materials).

6.2.1.1. Flux/fluence required

The thermal neutron flux required to perform these irradiations in a reasonable time period should be greater than 10^{13} n cm^{-2} s^{-1}. In addition, the fast neutron flux needs to be greater than 5×10^{13} n cm^{-2} s^{-1}.

The fluence required for observable effects ranges from 10^{17}–10^{21} n cm^{-2}. The lower limit is typically required for some electronic components and organic materials (e.g., rubber gaskets) while the upper limit is required for metals.

6.2.1.2. Other requirements

The requirements for reactor facilities, experimental equipment, personnel and funding are similar to the requirements for fuel material testing discussed later.

6.2.2. Gamma irradiations

6.2.2.1. Reactor facilities required

With low investment a gamma irradiation facility can be easily developed at a research reactor for such purposes as irradiating plants and seeds. If fuel assemblies are utilized, the dose rate achievable is dependent on reactor power and cooling time. Fuel element storage racks can be used to hold the assemblies during the gamma irradiation, and very little extra is needed with respect to facilities, equipment, personnel and funding.

Dose rates will vary from 2 Gy h^{-1} for fuel elements from a low power reactor up to about 200 kGy h^{-1} for fuel elements from a high power reactor with fluxes beyond 10^{14} n cm^{-2} s^{-1}.

Operation of such facilities is very easy, even with the reactor shutdown and members of the operating staff can usually perform such gamma ray irradiations.

6.2.2.2. Experimental equipment required

The required additional experimental equipment includes:

(1) Gamma dose rate and total dose monitoring equipment;
(2) Special conditioning equipment for items to be irradiated and tested;
(3) Handling equipment.

6.3. Weapons hardness testing

This application of research reactors is included in the document for completeness and historical reasons. It is not expected that many research reactors today will have radiation damage resistance, or hardness, testing as part of their strategic utilization plan.

During the cold war period, it was especially important to understand how various materials, especially electronic components withstood very high pulses of neutron and gamma radiations. To this end some pulsing reactors were especially built with large cavities for insertion of materials and components.

For obvious reasons, these facilities were government owned. However, other reactors were contracted to perform materials tests on various components and dosimeters.

6.4. Gemstone coloration

Gemstones may be irradiated with neutrons to improve their properties (e.g., change to a more desirable colour) in order to increase their demand and monetary value. The most common neutron irradiation being performed at research reactors is for topaz. Therefore, the following information is pertinent to topaz irradiation.

Like NTD of silicon, there is potential for the generation of significant income through gemstone irradiations. However, there are also some difficulties associated with it that those wanting to become involved should be aware. For both NTD and gemstone applications there is an understandable reluctance amongst those performing the irradiations to disclose the specific details about the process.

The world of gemstones and the world of reactor management, operation and utilization are culturally very different. The market for the stones is whimsical and difficult to assess. It is dependent on the size and the colour of stones currently in vogue. This often makes the behaviour of the gem trader also appear to be whimsical. In addition, the operating schedule for the research reactor and the time required for the irradiation and processing of stones is often incompatible with the needs of the trader.

Because of the decay times needed, the trader's investment risk in the virgin material is a long time compared to the gem trade's cultural time frame. The reactor facility has an investment risk in the irradiation devices and the development of the measuring equipment. The facility is also dependent on the delivery of good quality virgin material so that it is not left with a large quantity of material that is useless because of long lived activation products.

Nevertheless, several research reactors worldwide are irradiating topaz commercially and performing research on irradiation of gemstones, but only three facilities have applied for the license required in the USA.

6.4.1. Flux/fluence required

The colour in topaz is induced by the interaction of fast neutrons. If thermal neutrons are allowed to irradiate the topaz, then significant undesirable radioactivity will be induced in the gemstone.

The required fluence is dependent on the specific batch of topaz stones and the depth of the desired blue coloration. The fast neutron fluence is typically of the order of 10^{17}–10^{18} n cm^{-2}. For a 2 MW research reactor, about 50 to 100 hours of irradiation is required to achieve this fluence.

6.4.2. Reactor facilities required

The stones are batch irradiated in containers. At one facility a batch consists of about 2 kg of stones. Since only fast neutron irradiations are desired, the containers or the irradiation facility are often covered with Cd or boron. Because the temperature during irradiation must be controlled, some method of cooling the stones is necessary.

If the temperature of the gemstones approaches 300°C the damage to the topaz will anneal and de-coloration will occur. In addition, if the temperature is too high the stones will be prone to flaking during post-irradiation handling. A typical temperature during irradiation should be between 100 and 150°C. At one facility, the conditions of irradiation and the characteristics of the topaz batch produced a heat load of about 0.5 W g^{-1} of topaz. Therefore, the batch of stones must be cooled during irradiation but if this is done by water, undesirable re-thermalization of the neutrons takes place.

An irradiation container and facility is required. The container or the facility into which it is placed might be cadmium covered in which cooling is provided by a small amount of water. Ideally, it might consist of a boron shielded container or facility in which the stones are cooled by the flow of nitrogen gas. This latter device is expensive to operate.

The irradiation could take place in an aluminium tube placed in a grid position and fixed at the upper reactor bridge structure. It could also take place in a beam tube.

6.4.3. Other facilities required

After irradiation, a storage facility must be available for the stones until their radioactivity has decayed below the release limit. The storage time period is strongly dependent on the characteristics of the stones. At one facility, it was possible to release 70% of the stones after 2 months. After 8 months, 80% of the stones were released.

Because of market forces, it is desirable to release the stones as soon as possible. This requires frequent determination of the radioactivity of the stones and predictions of release date.

At one facility, an automatic handling and activity measuring robot has been used to perform the periodic measurements of the stones.

In some countries, the radioactivity limits for releasing the stones have become nuclide specific. This will require the use of a multi-channel analyser as well as a system for determining the beta emissions from the stones.

6.4.4. Personnel requirements

Topaz irradiation is a time consuming process with much manpower involvement. The initial preparations will require the services of a radio-chemist and an individual trained in heat transfer calculations and techniques. Even when automated equipment is used for the post irradiation analysis, several technicians will be required for the work.

6.4.5. Funding

The cost of an automated system with commercial viability is high. Cost recovery over some time from the customer may be possible.

A facility manager desiring to enter this field should start with small quantity production using a simple irradiating rig and existing counting systems in order to become familiar with the techniques. Expansion should not take place without a commitment from a customer.

6.5. Actinide transmutation

For many years it has been recognized that it is theoretically possible to transmute some of the long lived actinides in spent nuclear fuel into shorter lived products, thereby reducing the potential waste disposal hazard. To this end some actinide ‘burners’ have been designed but none have yet been built for this specific purpose. It is possible that some reactors may be utilized for test irradiations of fuel plates or elements.

7. NEUTRON RADIOGRAPHY

7.1. Static radiography

Static neutron radiography produces an image on film that has been exposed to the secondary radiation produced when neutrons from the reactor penetrate the specimen and interact with a neutron absorbing screen.

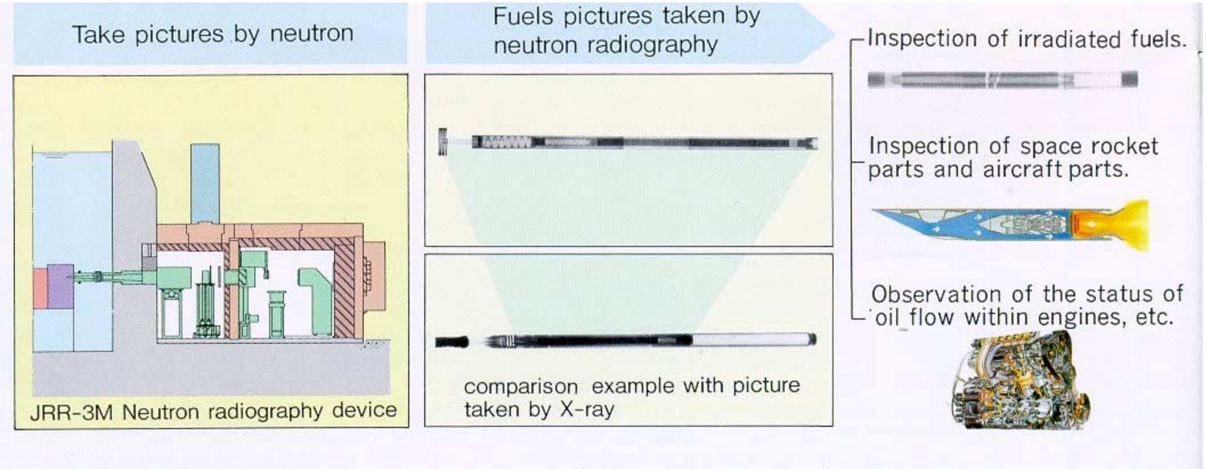


FIG. 7. Outline of neutron radiography process.

7.1.1. Flux/fluence required

Low power level research reactors with a beam port are well suited for static neutron radiography. The thermal neutron beam intensity at the specimen position should be greater than 10^5 n cm^{-2} s^{-1} in order to avoid unacceptably long exposure times. The thermal fluence is dependent on the nature of the specimen.

7.1.2. Reactor facilities required

Fast neutrons cause a loss of contrast in the film image due to specimen and shielding scattering. The use of a radial beam port requires filters and a collimator to produce a highly thermalized beam. Therefore, the use of a tangential beam port is preferable. At some reactors, the radiography facility neutrons are provided by a cold neutron source.

Obtaining an appropriate length to diameter ratio (L/D) for the set-up may require extension of the beam tube. It should be noted that the space requirement for the external portion of the set-up (specimen, converter, film station, shielding) is significant.

7.1.3. Other equipment required

A facility for processing film is required in addition to the requirements stated above.

7.1.4. Personnel requirements

The design, fabrication and installation of the facility will require a professional nuclear engineer working with appropriate workshop mechanics and technicians. A procedure must be developed by a professional staff member for each type of radiograph performed. After the procedure is tested, a technician should be capable of performing the work. For the greatest utilization of this neutron radiography process, it is recommended that the operating organization provide a complete service.

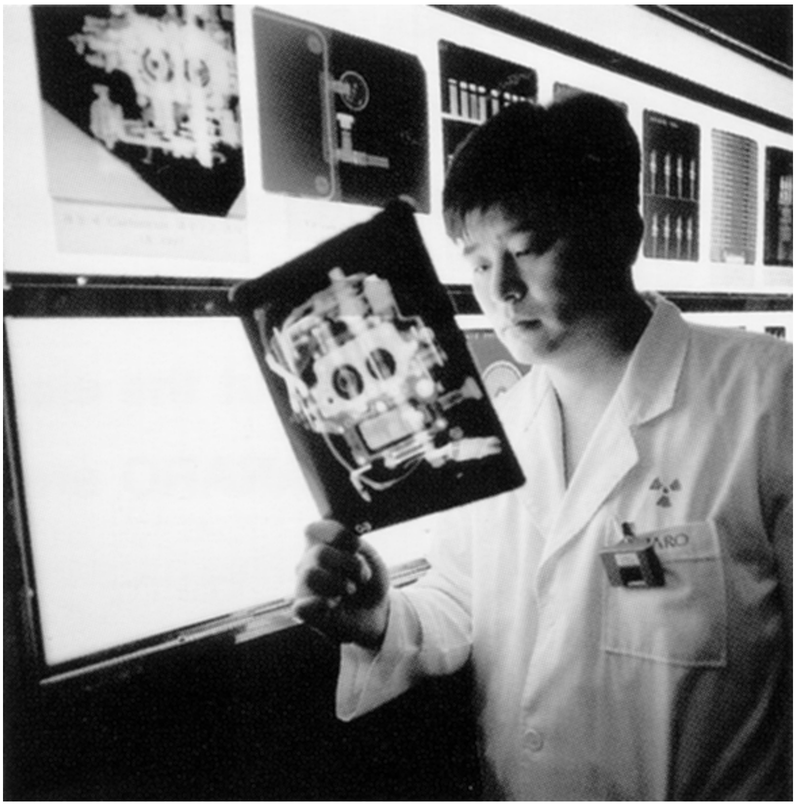


FIG. 8. Reviewing radiography pictures.

7.1.5. Funding

The design, construction and installation of a static facility at an existing beam port can usually be performed within the existing operating organization. The equipment required for radiography based on film images is inexpensive. The annual operating costs are minimal.

7.2. Motion radiography

Motion (often called real time or dynamic) radiography uses geometric collimators, neutron energy filters, shutters and a television system and is capable of producing high resolution images in real time.

7.2.1. Flux/fluence required

Real time neutron radiography does not have the ability to integrate the neutron exposure for the long periods of time necessary to obtain a statistically meaningful image in a low intensity beam. This leads to the requirement of higher flux level than is required for static neutron radiography. Real time radiography is difficult in beams with neutron intensities less than 10^6 n cm^{-2} s^{-1}.

7.2.2. Reactor facilities required

The reactor facilities required are similar to those discussed in for static radiography.

7.2.3. Personnel requirements

For a research reactor to acquire a capability in real time radiography, the full time attention of one engineer in the operating organization will be required. On-site shop mechanics may be used to fabricate and install filters and collimators under the supervision of operations personnel. A technician will be required. The image processors and host computer will need to be purchased from vendors.

7.2.4. Funding

The components in the beam are susceptible to design and fabrication at the facility. The image processor and the host computer are not. The costs of the image processor and host computer have been dropping, but still remain about $100 000–$250 000.

The annual cost of operation should be minimal and recoverable to justify the installation of a new facility.

7.2.5. Other issues

Many neutron radiography facilities are under-utilized. Therefore, prior to installing a new facility, it is recommended that a reactor planning the installation be assured of a significant local market that cannot get its needs met elsewhere. Alternatively, the design and installation of a real time radiography facility could be based on new and previously untried applications that cannot be performed at existing under-utilized facilities.

7.3. Tomography

Neutron tomography is essentially real time radiography with additional computer analysis of the images that enables three dimensional information to be garnered. Hence the requirements are very similar to those given above.

8. MATERIAL STRUCTURE STUDIES

Material structure studies have been performed using research reactors in the low, intermediate and high power level range. While it is still possible to perform some studies using low power level reactors, the use of intermediate and high power level reactors are the most efficient reactors for this application. Many high power level research reactors have been constructed primarily for this application.

Material structure studies are performed using reactor produced neutrons that are extracted from the reactor through beam ports. The energy of these emerging neutrons covers a range from below thermal to several MeV. Using various techniques, neutrons within a small energy band are selected for use in experiments.

These neutrons are allowed to interact with samples using a wide variety of instruments. The instruments are referred to as "spectrometers" and the experiments as "neutron scattering experiments".

A wide range of experiments from fundamental physics to biological science is now performed using many kinds of neutron spectrometers.

While some information on neutron scattering at high power level reactors is presented, this section concentrates on the use of low and intermediate power level reactor neutrons as probes of materials, stressing the experiments that are possible and the spectrometers that could be used.

8.1. Properties of neutrons as probes

The following properties of neutrons make them useful in neutron scattering experiments:

(1) High penetration of matter due to the lack of an electrical charge.
(2) Scattering by nuclear interactions in a sample is dependent only on elements in the sample.
(3) Special sensitivity to hydrogen and hydrogenous substances with large difference in scattering by hydrogen and deuterium.
(4) Scattering is by magnetic interactions with the unpaired electrons in magnetic atoms.
(5) The de Broglie wavelength of thermal neutrons is of the same order as inter-atomic distances.
(6) The energy of thermal neutrons is of the same order as that of many excitations in condensed matter.

8.2. Neutron sources

Since Chadwick first produced free neutrons in 1932, neutrons have been used in investigations in physics, chemistry, material science, and biology.

While the key parameter for most of these applications is the flux at the sample location in the beam, one can give a broad assessment of a reactor's potential for materials studies by discussing the flux in the core. Thermal neutron core fluxes exceeding 10^{15} n cm^{-2} s^{-1} are currently available at several high power level research reactors which accept experiments from scientists worldwide. However, in most research reactors currently operated, the thermal neutron core flux is less than 10^{14} n cm^{-2} s^{-1}. While some neutron scattering experiments are possible in these reactors, a co-operative relationship is strongly recommended between the low and medium flux reactor and the high power reactor. In this way, the intermediate power level reactors can develop new techniques (e.g., better targets, counters, experiments) which can then be taken to the high power research reactors for data collection. In addition, the low and intermediate power level reactors train scientists for future employment at the high power level reactors. The lower power reactors are typically much more easily accessible to students than high power reactor reactors, where commercial applications must be emphasized and operating costs per hour are much higher.

It should be noted that pulsed spallation neutron sources using proton accelerators are used to produce pulsed thermal neutron fluxes with the same usefulness and intensity as research reactors.

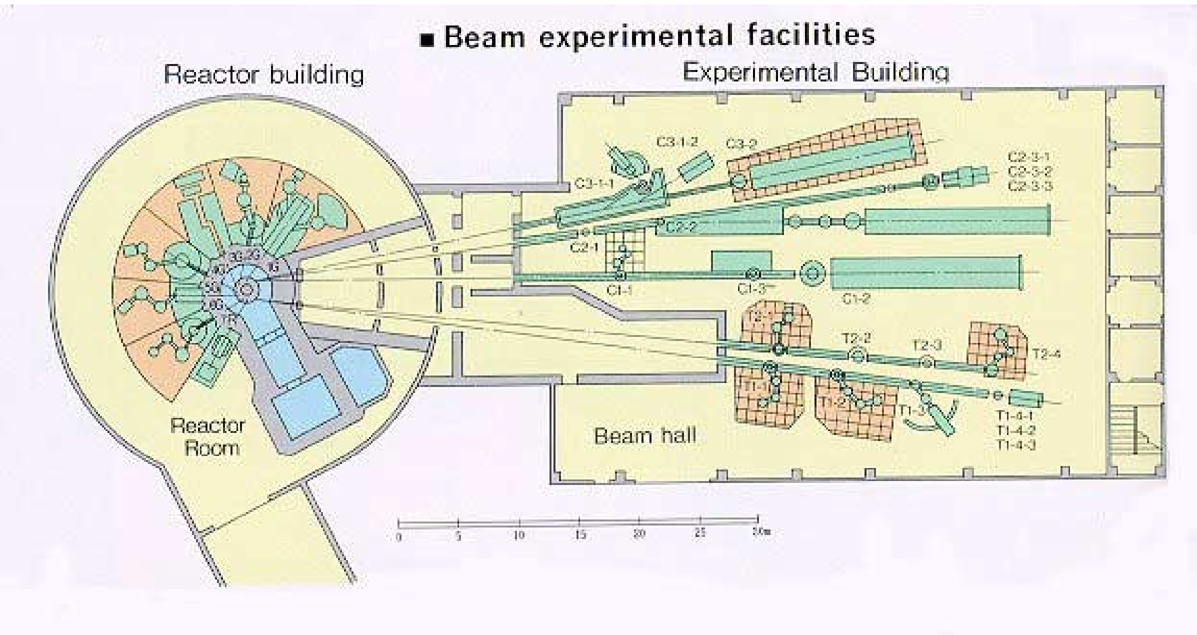


FIG. 9. A typical neutron scattering beam hall layout.

8.3. Differences between a pulsed source and a reactor from the view point of beam port experiments

The energy of the neutrons from a spallation source is selected using time of flight techniques, while a chopper or a crystal monochromator is used to select the neutron energy for neutrons from a reactor. For a reactor, the double chopper inelastic spectrometer is used while for the pulsed spallation source, one chopper is used for matching the neutron pulse duration to that from the moderator.

The reactor based diffractometer uses an incident neutron of single wavelength and measures the variable scattering angle using a single detector or a position sensitive detector. The accelerator based diffractometer uses a time of flight technique to give a continuous scattered wavelength scan at one scattering angle.

8.4. Neutron scattering applied to material science

Neutron scattering instruments may be divided into two types. The first type measures an angular dependent differential cross-section integrated over energies. The second type measures the energy and angular dependent double differential cross-section. In the first type, elastic scattering of the neutrons occurs while inelastic scattering takes place in the second.

A neutron reflectometer utilizes the “optical” phenomenon that neutrons incident on the material surface undergo refraction and reflection if the refractive indices on each side of the surface interface are different. A neutron interferometer using a perfect silicon crystal is analogous to the Mach-Zender interferometer of classical optics. The neutron wave amplitude coherently split by the Bragg reflection is superposed again at the second beam splitter and results in interference effects. Both the reflectometer and the interferometer are included in the elastic scattering instrument category for simplicity.

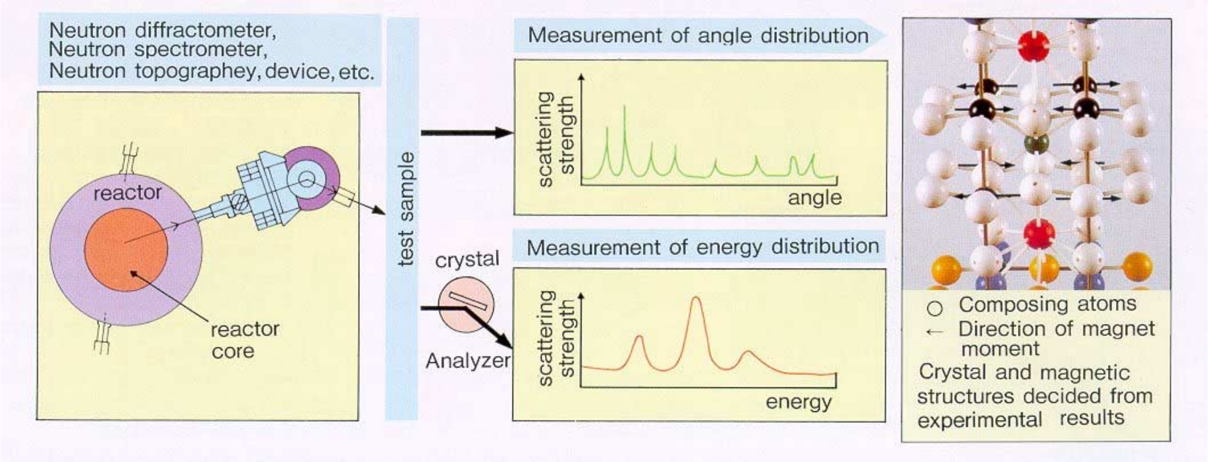


FIG. 10. The neutron scattering methodology.

A spin echo instrument measures the incoming and outgoing velocity of a neutron by making use of the Larmor precession of the neutron spin. A small energy transfer by the sample can be measured from the change of the neutron velocity. This concept is very different from usual inelastic scattering instruments. The spin echo instrument is included in the category of inelastic scattering instruments.

8.5. Role of neutron scattering instruments

In practice, several kinds of instruments are used for investigating material properties and dynamic phenomena occurring in materials. Neutron instruments not only play a complementary role with each other and but also with other instruments using X rays and light.

8.6. Use of a neutron guide

Thermal neutron guides, including super mirror guides, can be used to conduct the neutrons from the beam port to a region away from the background neutrons near the reactor. In many cases, the neutrons are conducted through a guide into a separate building adjacent to the reactor building. This process provides a major improvement in the signal to noise ratio (neutron signal to neutron background ratio). While guides are routinely utilized at high power level research reactors, they are especially useful for an intermediate power level reactor.

Cold neutrons of wavelengths longer than 4 ångströms can be extracted and a reflectometer installed for investigating layered structures of polymers. A spin interferometer with multi-layer spin splitters can also be installed for investigating spin interference phenomena. Studies of this phenomenon are good subjects for students and young scientists to work on in order to understand the concepts of quantum mechanics (e.g., what the superposed state is).

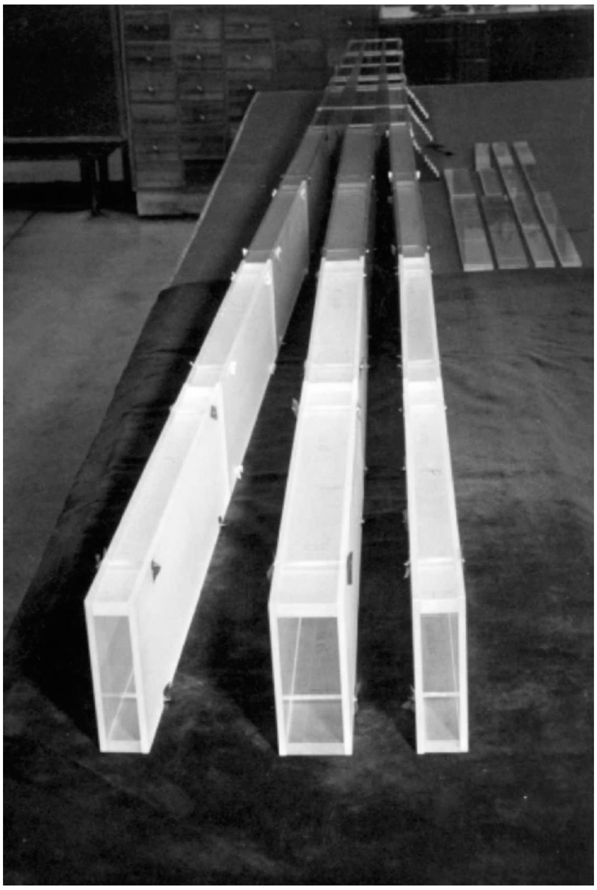


FIG. 11. Neutron beam guide tubes.

8.7. Cold neutron source

Cold neutrons are commonly defined as those having wavelengths longer than 4 ångströms, corresponding to the Bragg cut-off in beryllium. The intensity of cold neutrons is only about 1 to 2% of the total neutron flux in the thermal distribution for the normally extracted neutron beam of a research reactor. A device for increasing the cold neutron flux about 20 to 40 times the normal value at 5 ångströms using a low temperature moderator is called a cold neutron source (CNS).

In general, only elastic scattering instruments using crystals are useful in reactors with a thermal power level around 2 MW. When a CNS is installed with cold neutron guide tubes in a 2 MW reactor, potential utilization is enhanced to the point that some quasi-elastic or inelastic scattering instruments can be installed and utilized effectively. However, the cost for construction of a CNS is very large, often more than US $5 000 000. Maintenance and operating costs are also high. In addition, if good data are to be obtained, expensive, sophisticated instruments similar to those in high power reactors must be installed. These costs and the potential number of users must be considered when a CNS installation is planned for an intermediate power level reactor. (At the time of writing a newly developed cold neutron source was installed in a 1 MW reactor for about US $200 000.)

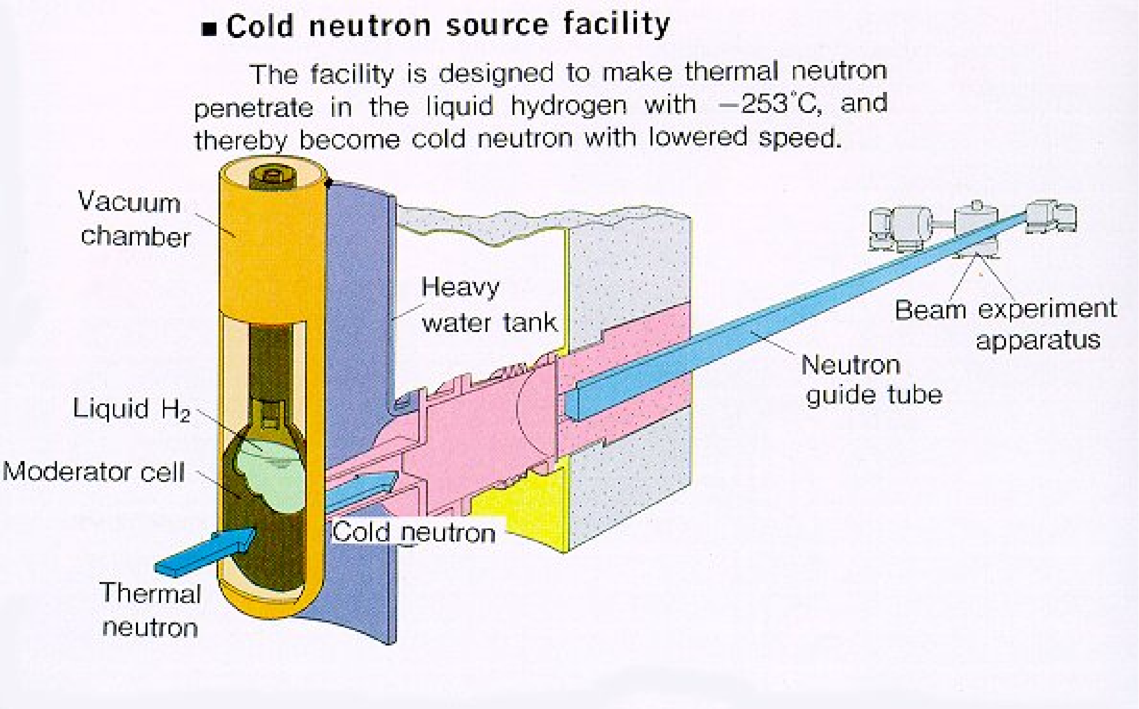


FIG. 12. A typical cold neutron source arrangement.

8.8. Recommendations for scientists utilizing an intermediate power level research reactor

While the staff at a low or intermediate power level research reactor should always consider improving or upgrading the reactor and experimental equipment for increasing the intensity of neutrons available at the sample, the role of these reactors in material structure studies should not be underestimated.

The main impediment to successful material structure experiments at a low or intermediate power level research reactor is the amount of time necessary to collect data. However, one important role of these research reactors is as a feeder for supplying new concepts that have been tested at the reactor for implementation and data collection at a high flux reactor. In fact, many of the ideas and concepts for new research or improving instruments installed at a high flux reactor were born in small research reactors.

In addition, graduate training in neutron scattering can be more easily performed in the environment of the low and intermediate power level research reactor. The trained scientists are then a valuable source of personnel at the high power reactors.

8.9. Elastic scattering

Table 1, Appendix II, presents a list of the elastic scattering instruments in use for materials studies. The table includes the neutron flux, spectrum and beam size and the space required for the instrument.

Table 2, Appendix II, for the same instruments, provides a list of the additional equipment required to operate the spectrometer and the construction, operation and maintenance costs.

Table 3, Appendix II, for the same instruments, provides a list of the personnel requirements, research fields, industrial applications, use in education and training and use by guest scientists.

8.10. Inelastic scattering

Table 4, Appendix II, presents a list of the inelastic scattering instruments in use for materials studies. The table includes the neutron flux, spectrum and beam size and the space required for the instrument.

Table 5, Appendix II, for the same instruments, provides a list of the additional equipment required to operate the spectrometer and the construction, operation and maintenance costs.

Table 6, Appendix II, for the same instruments, provides a list of the personnel requirements, research fields, industrial applications, use in education and training and use by guest scientists.

Comments on all Tables are presented following Table 6.

8.11. Flow chart

Figure 1, Appendix II, presents a flow chart based on reactor power level for the use of these instruments with and without a CNS.

9. PROMPT GAMMA NEUTRON ACTIVATION ANALYSIS

Prompt gamma neutron activation analysis is a process similar to INAA that was discussed in Section 3. While INAA uses the radioactivity emitted by the activation products for analysis, PGNAA uses the prompt gamma rays emitted during the neutron capture.

PGNAA enjoys limited use because of the scarcity of suitable neutron beams. Typical applications are analysis of samples in geological and atmospheric sciences. The technique is useful for analysing for the following elements: H, B, C, N, P, S, Cd, Pb, Sm, and Gd.

9.1. Flux/fluence required

PGNAA requires a neutron beam with a well collimated flux greater than 10^8 n cm^{-2} s^{-1} which illuminates a representative part of the sample (about 2 cm in diameter).

9.2. Reactor facilities required

A beam tube is needed to perform PGNAA. (A tangential beam tube is preferred over a radial beam tube).

9.3. Desirable reactor facility options

Although it is not necessary, the most effective PGNAA systems are operated with neutrons provided by a cold neutron source.

9.4. Experimental equipment required

A high resolution and high throughput gamma ray spectrometer with a Ge detector is required. A computer based multi-channel analyzer (MCA) with software to control data acquisition and to analyze spectra is also required. The detector assembly must be well shielded to minimize neutron activation of the detector itself and to reduce the background components.

9.4.1. Desirable experimental equipment options

A guided beam of cold neutrons will provide the highest intensity neutron beam with the lowest background at the sample position. Therefore, the use of a neutron guide is desirable. In addition, a pair spectrometer or a Compton suppression system is a desirable option, although this need is decreasing due to better detectors, MCAs and analysis software.

9.5. Personnel requirements

The establishment and operation of a PGNAA facility will require a research physicist in charge. A well trained technician can be utilized for routine operation. A nuclear chemist is beneficial, but the experimenter utilizing the facility can often provide this expertise.

Co-operation with other analytical groups such as those using INAA and X ray fluorescence will enhance the operation and utilization of the PGNAA facility.

Mechanical engineers are necessary for the design of filters, collimators, the sample position and the shielded detector assembly.

If a cold source is used, a person experienced in the design, installation, and operation of a cold source will be required.

9.6. Funding

The costs for establishing a PGNAA facility are high. Some typical costs in the USA and Europe are given for various aspects:

(1) The installation of a thermal facility at an existing radial or tangential beam tube costs about US $150 000.
(2) Thermal beam filters and collimators, about US $20 000–50 000.
(3) Advanced computer gamma analysis software, US $3000–5000.
(4) The sample and detector station, about US $10 000.
(5) A PC based simple multi channel analyzer, about US $40 000.
(6) A pair spectrometer or Compton suppression system, about US $150 000.
(7) A single beam port cold neutron source in a low or medium powered reactor, about US $200 000.
(8) Neutron guides made from borated glass and Ni mirrors, about US $1000 per meter.

These costs could be somewhat lower in countries where skilled scientists, engineers, and technicians are available at a low cost.

10. POSITRON SOURCE

Positrons can be used as particle probes, suitable to detect low concentrations of defects in materials. Positron physicists generally are in need of intense positron beams for applying positron annihilation techniques such as two dimensional (2D) Angular Correlation of Annihilation Radiation (ACAR) for investigating surfaces and interfaces of materials. The 2D-ACAR technique allows high resolution measurements of the electron momentum distribution for depth, localized defects, thin layer systems, and interfaces. In addition, a sub-micrometer size positron beam can be created for defect depth profiling on a lateral scale smaller than a micrometer. Vacancy type defects can be mapped in a three dimensional fashion.

In the past, scientists were restricted to investigating bulk samples with lower intensity beams. The creation of intense positron beams ($>10^8$ e^+ s^{-1}) is feasible at research reactors under certain conditions. The main design problems are in coping with the hostile environment that hinders the sustainment of high quality vacuum and electrical fields in a position located close to the reactor core.

The three methods for establishing a positron source at a research reactor are as follows:

(1) Activation method — a target is placed at or near the reactor core, or the activated source is moved in and out of the reactor. Positrons can be created by activation of a source material (e.g., copper) by thermal neutrons. The positrons can then be extracted after their emission or by moving the source material out of the activation zone to the experimental set up (as a solid source type or loop type).

(2) Capture gamma rays converter method — thermal neutrons are captured in cadmium and the cadmium gamma rays then create positrons in platinum or tungsten. Positrons can also be created by hard gamma radiation that arises either from neutron-gamma capture or directly from fission and fission products. For neutron-gamma ray capture, cadmium is a suitable material since the gamma rays are sufficiently energetic for creating positron-electron pairs in materials such as platinum and tungsten.

(3) Hard gamma ray direct converter method — hard fission gamma rays create positrons in tungsten. In a direct conversion type system, electron-positron pairs are created directly in the tungsten target material by the fission gamma rays emitted from the reactor core. Extraction of the positron beam is a delicate matter. Electrostatic fields are used for extraction of the tungsten surface emitted slow positrons. (The positron diffusion length may be about 50 nm. This means that nearly all positrons slowed down in a border zone of 50 nm at the surface, have a high probability of being surface emitted). The extracted positrons are further transported through a magnetic beam guide, where the positrons have helical trajectories.

10.1. Flux/power required

To generate a 10^7 positrons per second, the minimum reactor power level is 100 kW with an available thermal neutron flux of 10^{12} n cm^{-2} s^{-1} and a gamma dose rate of 0.1 MGy h^{-1}.

To generate 10^8 positrons per second, the reactor power level needs to be greater than 1 MW with an available thermal neutron flux greater than 10^{13} n cm^{-2} s^{-1}, a gamma dose rate greater than 1 MGy h^{-1}.

10.2. Reactor facilities required

A beam port with at least 25 m^2 of experiment floor space at the beam port is required. However, a beam port with about 200 m^2 of experiment floor space at the beam port and equipment space with a minimum length of 30 m is much more desirable.

The target will normally occupy a position at or near the reactor core with the positron beam emanating from a beam tube. Ideally, the installation will be retractable when not in use so as to minimize target costs and interference with other reactor experiments. Shielding should be designed to be flexible and movable.

10.3. Other requirements

The minimum additional equipment requirements are:

(1) Positron beam extraction (electric and magnetic field equipment, high voltage, high vacuum equipment.
(2) Positron detectors.
(3) Sample and target handling equipment.
(4) Inter-disciplinary measurement facilities.
(5) Radiation detection and shielding equipment.

The desirable additional equipment is:

(1) Beam extraction and re-moderation equipment.
(2) Position sensitive gamma cameras for 2D angular correlation of annihilation radiation measurements.
(3) A scanning electron microscope.
(4) Advanced data collection and handling equipment.
(5) General laboratory facilities.
(6) A clean room.

Facilities will be required for irradiated target disposal, and it is also desirable that facilities be available for target production.

An understanding of vacuum technology is essential to the fabrication and operation of the positron facility.

10.4. Personnel requirements

Scientists from a user's group and engineers from the operations group will be required for a feasibility study and the design, safety review and installation of the loop.

In addition to the personnel normally required to operate the reactor, a scientist will be required to serve as the positron facility supervisor. At least one experimenter and several technicians will be required to utilize the facility.

A facility of this type would normally be utilized by a large group of knowledgeable resident professional scientists and guest experimenters conducting research in several areas.

Utilization of the positron facility will be greatly enhanced if the operating organization (host group) provides expertise support to potential and actual experimenters.

10.5. Funding

The annual budget to operate a reactor based positron source is US $300 000 to US $500 000 for personnel costs, target handling and replacement and research. The larger budget not only will allow more research but also more elaborate research.

Contract research agreements would normally be a component of the utilization of a positron facility.

11. NEUTRON CAPTURE THERAPY

When ^{10}B absorbs a neutron it emits an alpha particle that is highly ionizing and has a range in tissue about equal to the diameter of a cell. Therefore, the methodology in boron neutron capture therapy (BNCT) is to load a tumour with a borated compound and irradiate with neutrons. If the conditions are right, then the tumour dose is much higher than that to the rest of the surrounding tissue, resulting in subsequent preferential killing of tumour cells.

Thermal neutrons are desired at the tumour location because the ^{10}B interaction probability is much higher with slower neutrons. Therefore, surface or shallow tumours can be irradiated with thermal neutrons, while those at a depth of a few centimetres can be irradiated with epithermal neutrons which then become thermalized by the overlying tissue. Thermal neutrons are also useful for research involving cell cultures or small animal irradiations.

As currently practiced, most neutron capture therapy makes use of boron compounds; however, other compounds (e.g., gadolinium compounds) can also be used.

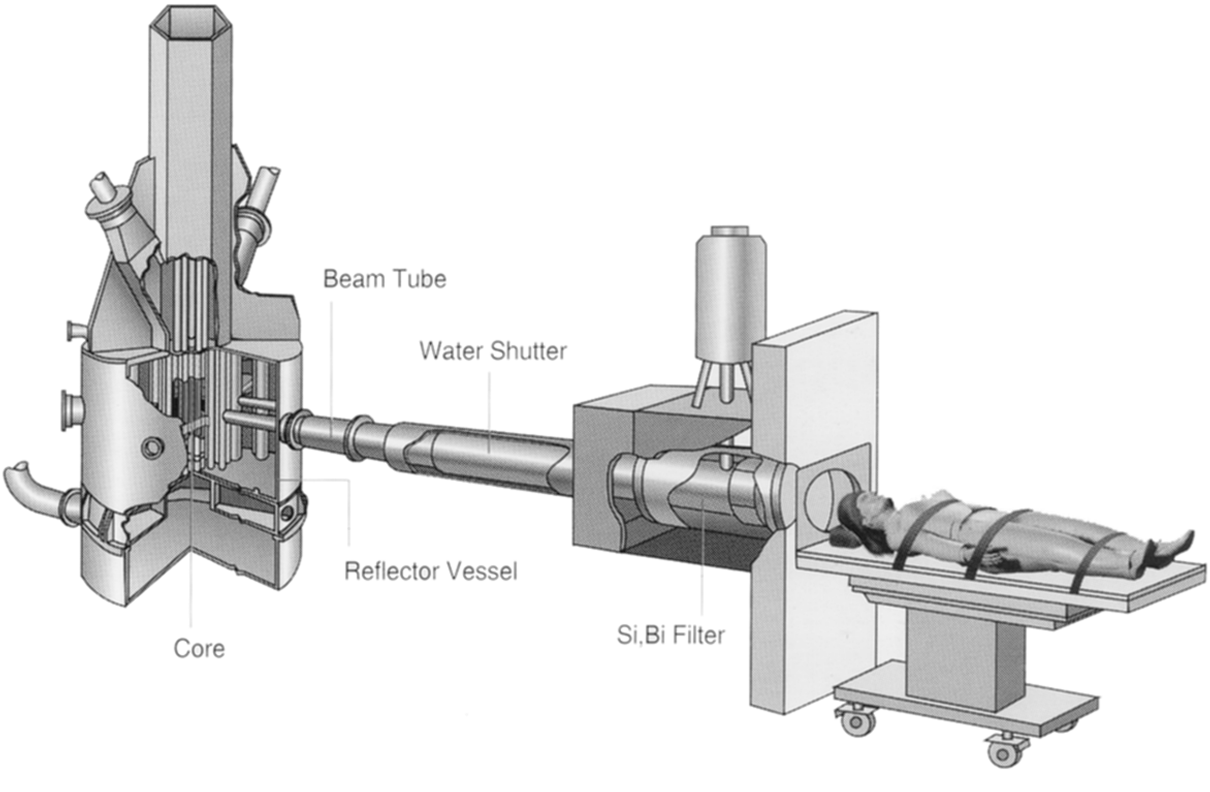


FIG. 13. An arrangement for neutron capture therapy.

Most neutron capture therapy research has focused on malignant melanomas and brain tumours, particularly glioblastoma multiforme (GBM). While the incidence of GBM is quite low (about 20 per million population per year), its median survival is only about 8.6 months.

It should be emphasized that NCT is still in the research phase with no Phase III clinical trials having yet been performed. In addition, it has been concluded that the results of 320 patients treated in BNCT studies have not demonstrated any significant benefit for these patients.

Current research efforts are directed toward providing the dose to the tumour in a short time period (minutes instead of hours) and reducing the dose to normal tissue through higher flux, better neutron energy selectors, shielding and collimation and better drugs.

BNCT research varies in several aspects from one treatment centre to another as follows:

(1) In Japan, thermal neutron beams have typically been used with surgery.
(2) In Europe and the USA, epithermal beams are more commonly used.
(3) In the USA, the dose is usually administered all at once.
(4) In Europe, the fractionated dose technique is being studied.

The reactor facility, while obviously important, is only one part of a very large infrastructure which is necessary for the performance of neutron based therapy, as discussed later.

11.1. Flux/fluence required

The current discussion will focus on epithermal beams, since that is where the research appears to be leading. The commonly accepted definition of epithermal neutrons as being those between 0.5 eV and 10 keV is used. Current experience shows that a desirable minimum beam intensity would be 10^9 epithermal neutrons cm^{-2} s^{-1}. Beams of about half this are useable, but result in rather long irradiation times.

Tumour boron concentration will affect the requirements of beam intensity. If the concentration can be raised from the current values, the beam intensity requirement (or treatment time) will be reduced proportionately.

It should be recognized that the quality of the beam is often more important than the intensity. Beam quality is determined by four parameters under free beam conditions. These are listed below in order of importance.

(1) The fast neutron component needs to be reduced as much as possible while keeping the dose from epithermal neutrons as high as possible ($>= 2 \times 10^{-13}$ Gy cm^2 per epithermal neutron).
(2) The gamma ray component needs to be as low as possible to reduce unnecessary dose to normal tissue (again, a target value of $>= 2 \times 10^{-13}$ Gy cm^2 per epithermal neutron is desired).
(3) The ratio of thermal flux to epithermal flux should be minimized to reduce damage to the scalp. A target value for the ratio is 0.05.
(4) The ratio between the total neutron current and the total neutron flux provides a measure of the fraction of neutrons that are moving in the forward direction. A high value (>0.7) is desired.

In addition, reasonable sized apertures of 12 cm to 15 cm are desirable.

Table I presents information for eight facilities either planning to use, or already performing BNCT.

Table I. A comparison of BNCT facilities

FACILITY	TREATMENT TIME[(1)] min.	FLUX AVAILABLE $n\ cm^{-2}\ sec^{-1}$	METHOD	REACTOR POWER LEVEL
NEW MITR[(2)]	0.33	5×10^{10}	Fission converter	5 MW (150 kW)[(7)]
MUSASHI STUDY[(3)]	4.9	3.4×10^{9}	Fission converter	100 kW
NEW BROOKHAVEN	6.2	2.7×10^{9}	Fission converter	3 MW
U OF C, DAVIS[(4)]	8.3	2×10^{9}	Direct	1 MW
BROOKHAVEN	9	1.8×10^{9}	Direct	3 MW
FINLAND[(5)]	17	1.8×10^{9}	Direct	250 kW
PETTEN[(6)]	50	3.3×10^{8}	Direct	45 MW
MITR	83	2×10^{8}	Direct	5 MW

[(1)] For a fluence of 10^{12} $n\ cm^{-2}$.

[(2)] Under construction; licensing complete, start up testing in early 2000.

[(3)] Design study of an epithermal neutron beam for BNCT at the Musashi reactor, Journal of Nuclear Science and Technology, Vol. 32, No.2, pp. 87–94, Feb., 1995.

[(4)] Formerly McClellen Air Force Base reactor.

[(5)] Exclusive use of reactor.

[(6)] Using fractionated dose technique.

[(7)] Power level in converter.

11.2. Reactor facilities required

A filtered, collimated neutron beam with the characteristics discussed above is required to perform BNCT. There are several ways to obtain such a beam. A popular method moderates the fast neutrons leaking from the core down to the appropriate energy. This works well in facilities that have a large thermal column that can be unstacked and replaced with appropriate moderators and filters. The addition of a fission converter consisting of a row of fuel elements can significantly increase the epithermal neutron fluence rate at a distance from the core. If the facility does not incorporate a thermal cavity or other large void space near the core, shield removal is an alternative to provide direct access to the core or for the installation of a converter.

In a reactor that only has rather narrow and long beam tubes available, then the pure filtering method must be used. Filtering transmits neutrons of the desired energy while blocking those of other energies. Generally, filtering is more wasteful of neutrons so that a much higher original source flux (and therefore reactor power) is needed.

In addition, it has been demonstrated that even a quite low power (5 kW) fast reactor can produce epithermal neutrons at the desired intensity levels.

At a multi-purpose reactor, shutters will also be required in order to stop the beam without shutting down the reactor.

The beam must emerge into a well shielded treatment room that allows for observation of the patient during treatment and the reactor control and safety system must be expanded to include an interlocked system for the BNCT facility.

New reactors frequently incorporate facilities to enable BNCT capability in their design. However, most existing reactors generally have not done so. The ease at which an existing reactor can be modified will be very dependent on the facility design.

11.3. Other facilities required

11.3.1. At the reactor

It will be necessary to create medical facilities (e.g., patient preparation and holding area, blood laboratory) at the reactor. These facilities should provide a hospital atmosphere for the comfort of the patients.

Many facilities use a prompt gamma neutron activation analysis (PGNAA) system to measure boron in blood samples although there are other methods.

11.3.2. At a nearby hospital

BNCT is a medical procedure that is administered under the supervision of a physician and a medical staff associated with a nearby hospital. Often, the hospital is a teaching hospital associated with a medical school.

The hospital staff will provide the diagnostic equipment and services (e.g., magnetic resonance imaging [MRI]), CAT scan, computer modelling, patient selection) and all other medical services (e.g., patient transportation).

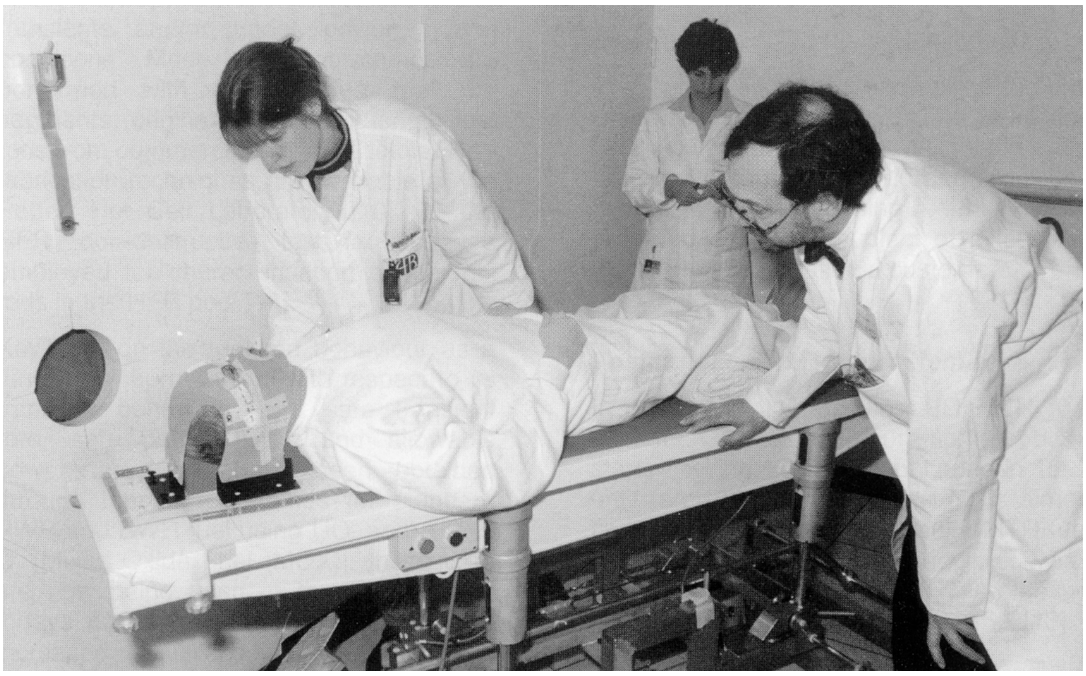


FIG. 14. A patient being carefully aligned and made comfortable.

11.4. Other requirements

BNCT requires the development of medical treatment protocols based on mathematical modelling of the tumour. These protocols sometimes require the approval of a governmental health agency in addition to a nuclear regulatory body.

Medical liability insurance may be a requirement for the research reactor facility.

11.5. Personnel requirements

A large infrastructure with experts in many areas will be required for the development and operation of the facility and for the medical treatments. Co-operation and interaction is required between these experts during the design, installation and operation of the BNCT facility.

11.5.1. Reactor operating organization

The reactor operating organization will usually need to provide the personnel for a feasibility study, the development of specifications, design, installation, testing and operation of the facility at the reactor. Contractors to the operating organization may also perform these tasks.

The operating organization normally provides a senior staff member who is well acquainted with the facility, as well as most aspects of the treatment process, to serve as a joint Chief for Treatment along with a physician.

11.5.2. Medical organization

The medical organization will provide the personnel for all the medical aspects of the design, testing and treatment protocols, and treatment. In addition to the personnel needed to provide the normal hospital functions (e.g., CAT scans), the medical organization will provide personnel such as physicians in several specialities (e.g., neuro-oncology, radiation oncology, nuclear medicine, radiology), a research nurse, medical physicist for dosimetry, technicians and a technician for computer modelling. A protocol must be created for the selection of patients who will respond best to the treatment.

The medical organization normally provides a senior physician well acquainted with the BNCT facility to serve as joint Chief for Treatment along with the senior staff member from the operating organization.

11.6. Funding

The cost for the installation of a BNCT facility at an existing reactor will depend heavily on the modifications necessary at the reactor to install the facility as discussed earlier. Based on actual reactor modification costs at several research reactors, the following estimates are presented:

(1) To install a fission converter facility using reactor fuel into an existing space, US $2 500 000;
(2) To create a large cavity in the reactor shield, US $800 000;
(3) To design and fabricate shielding, filters, collimators and shutters, US $500 000;
(4) To install the shielding, filters, collimators and shutters, US $500 000;
(5) To install a facility in an existing thermal column, US $600 000.

11.7. Time requirements

Based on worldwide experience, the time necessary for development of a BNCT facility, even before any patient treatment can begin, is about five years.

11.8. Need and market analysis

Before any facility considers becoming involved with neutron capture therapy there are several factors that should be evaluated. First, since BNCT is still in the research phase, and since the efficacy of the treatment is still unproven, many people believe that there are enough facilities currently available for the necessary studies and that additional facilities are not needed at this point. Second, even if BNCT eventually becomes a viable treatment option, a market analysis should be performed to determine the number of potential candidates that would be available for treatment. An example of a simplified approach to the study follows.

The central brain tumour registry of the United States estimates, that 2.6 of 100 000 people develop glioblastoma multiforme in the United States each year. The largest single age group diagnosed with this cancer is age 65 to 74, followed by age 75 and up. Approximately 2/3 of the diagnosed patients are over age 65. If the incidence rate were assumed to be the same as in the USA (2.6 out of 100 000), there would be about 780 cases per year in a country that has a population of 30 000 000. Because the expected lifetime in some countries is lower than in the USA, the incident rate should be lower. In addition, for a country with a widely dispersed rural population, some diagnoses will be missed. Based on this, the number of patients in such a country could be well below the 780 calculated.

12. TESTING

12.1. Instrument testing and calibration

Almost any type and size of reactor can do some instrument testing and calibrations, even if it is just for low level radiation protection instruments. Typically the work involves neutron and/or gamma ray detection instruments that need to be tested to ensure that they have the appropriate characteristics and need to be calibrated to ensure accurate readings.

12.1.1. Flux/fluence required

The minimum requirements for this type of work will depend on the type of testing and calibration being performed. However, because much of it relates to radiation protection instruments the actual neutron flux and gamma radiation level requirements are quite low. Dose rate levels from a few micro-Sv h^{-1} to a few milli-Sv h^{-1} are often all that is necessary.

12.1.2. Reactor facilities required

The only requirement is access to a very well characterized field of neutron or gamma radiation. Such a facility must make it easy to move the instruments in and out of the radiation field and to adjust them as necessary. This facility will normally be external to the reactor shielding. A radiation field monitor is necessary to indicate the actual dose received.

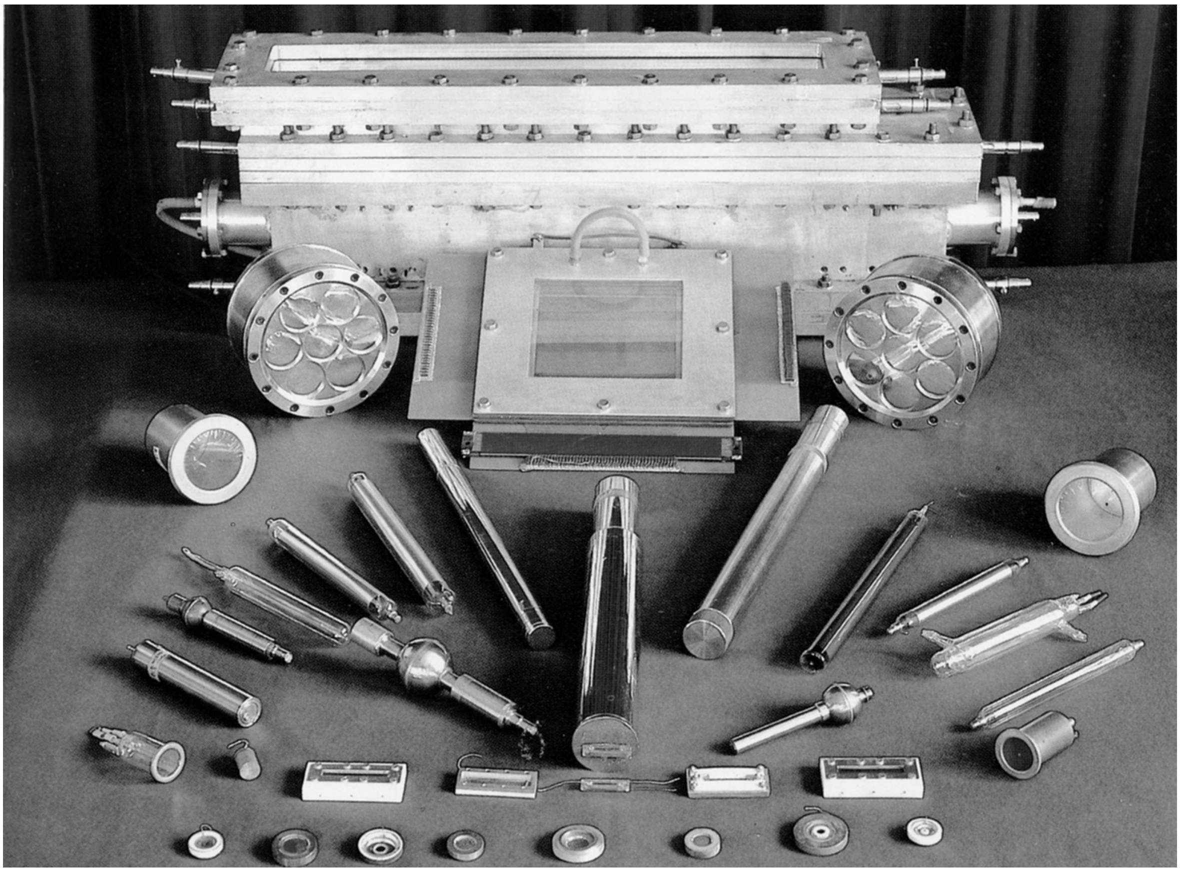


FIG. 15. *An array of typical detectors than need testing and calibration.*

12.1.3. *Other considerations*

If calibrations are being performed, then there will usually be a need to have the facility certified or accredited by an appropriate national or international organization. This certification entails a large amount of additional effort for quality assurance, record keeping and similar requirements.

12.1.4. *Personnel requirements*

A health physicist is needed to set up, analyse and calibrate the radiation field. Once this is done, then it needs to be re-calibrated at routine intervals. Routine work of positioning and adjusting the instruments can be performed by a reactor staff technician. However, if there is a significant amount of such work then an additional staff member may be required.

12.1.5. *Funding*

Good radiation monitors cost about $1000–2000, and the rest of the facility can be constructed by reactor staff without much additional funding. If the facility is to be accredited, then this may cost $10 000–20 000 for the initial effort and $5000 every few years thereafter for re-accreditation.

12.2. Loops for testing nuclear fuels

Many medium and high power research reactors operate closed loops for testing prototype fuel elements for high power research reactors and power reactors. These loops are designed to isolate the test specimen from the reactor and to provide a controlled environment for the specimen. Typically, this application is quite specialized and is usually performed at government owned reactors at sites that are part of national laboratory facilities.

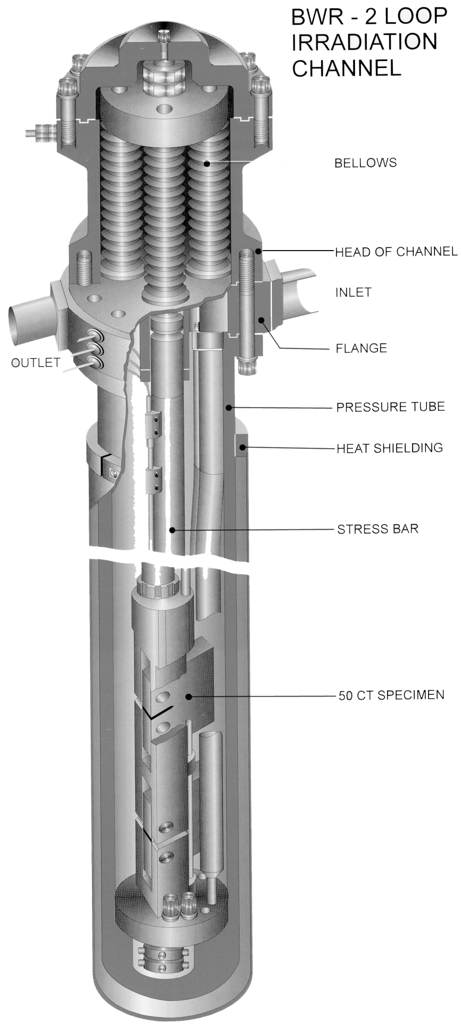


FIG. 16. A power reactor irradiation loop.

12.2.1. Flux/fluence required (typical)

The minimum thermal and fast neutron flux required at the location of the specimen are 10^{14} n cm^{-2} s^{-1} and 5×10^{14} n cm^{-2} s^{-1} respectively. However, the desirable thermal and fast neutron flux required at the location of the specimen are greater than 5×10^{14} n cm^{-2} s^{-1} and greater than 5×10^{15} n cm^{-2} s^{-1} respectively. In these fluxes, fuel burnup in the specimen approaching 100% has often been achieved.

Filters have been employed in test loops to create a neutron spectrum similar to that which the fuel will experience in its reactor.

12.2.2. Reactor facilities required

An in-core loop will occupy space in the reflector region close to the core. The minimum reactor facility requirements are a loop with:

(1) Temperature control and monitoring.
(2) Fission product monitoring for the test loop coolant.

(3) Fluence monitoring for the specimen.
(4) Cooling facilities.
(5) Fuel performance monitoring.

In addition to these minimum requirements, desirable options include:

(1) Spectrum trimming capability (e.g., using a fission converter).
(2) Overpower, transient, power ramping and cycling capabilities.
(3) In-loop, loss of coolant accident testing.

12.2.3. Additional equipment required

A hot cell is necessary for post irradiation handling of the specimen. The testing equipment usually employed includes:

(1) Non-destructive test facilities (e.g., dimensional measuring equipment).
(2) Destructive testing equipment.

In addition, data processing, storage and retrieval hardware and software are required to establish a database.

12.2.4. Space requirements

The portions of the loop external to the reactor shield will occupy about 5–25 m^2 of floor space.

12.2.5. Personnel requirements

Engineers will be required for the design, safety review and installation of the loop. In addition to the personnel normally required to operate the reactor, a loop facility supervisor and technicians will be required to operate the loop.

Personnel from nuclear fuel companies, fuel laboratories and materials research institutions will usually be available during design and operation of the loop.

12.2.6. Funding

An initial investment of US $100 000–500 000 is typically required. In addition, there will be recurring expenses for personnel, experiment design and installation and support facilities (e.g., water, electricity, radioactive waste treatment and disposal).

APPENDIX I
SIMPLIFIED RESEARCH REACTOR UTILIZATION MATRIX

Power Level	Education & Training	NAA	Isotope Production	Geochronology		Transmutation Effects			Neutron Radiography (2)	Material Structure Studies (2)	PGNAA (2)	Positron Source (2)	NCT (1 or 2)	Testing	
				Ar/Ar	Fission Track (1)	Silicon Doping	Materials Irradiation	Gemstone Colouring						Instr. & Calib.	Nuclear Fuels (3)
30 kW	X	x	x											x	
250 kW	X	x	x						X				x	X	
1 MW	X	X	x	x	x	x	x	x	X	x	x	x	X	X	
2 MW	X	X	X	x	X	x	X	X	X	X	X	X	X	X	
>=10 MW	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

x Some capability
X Full capability

(1) Requires a thermal column.
(2) Requires a beam tube.
(3) Requires a loop or special irradiation facility.

APPENDIX II
NEUTRON SCATTERING INSTRUMENTS AND THEIR CHARACTERISTICS

TABLE 1. FLUX, SPECTRUM, BEAM SIZE AND SPACE REQUIREMENTS FOR EIGHT ELASTIC SCATTERING SPECTROMETERS

Instrument	Minimum flux n cm^{-2} s^{-1}	Desirable flux n cm^{-2} s^{-1}	Spectrum wavelength nm	Beam size cm × cm	Required space m × m
Diffractometer	10^6, at sample 10^3	10^7, at sample $>10^4$	0.1~0.2	2 × 3	3 × 3
Powder Diffractometer	10^6, at sample 10^3	10^7, at sample $>10^4$	0.1~0.2	2 × 3	3 × 3
Crystal SANS	10^6, at sample 10^3	10^7, at sample $>10^4$	0.1~0.2	4 × 12	>10 m in length
Polarimeter	10^6, at sample 10^3	10^7, at sample $>10^4$	0.1~1.2	4 × 4	3 × 6
TOF spectrometer	10^7, at sample $>10^3$	10^8, at sample $>10^4$	0.1~0.3	4 × 10	4 × 5
Reflectometer	10^6, at sample 10^3	10^8, at sample $>10^5$	0.1~1.2	3 × 4wide	3 × 6
Interferometer	10^6, at sample 10^3	10^8, at sample $>10^5$	0.1~2.0	4 × 6	3 × 5
SANS	10^7, at sample $>10^4$	10^8, at sample $>10^5$	0.2~1.2	4 ×12	>20 m in length

TABLE 2. ADDITIONAL EQUIPMENT AND FUNDING REQUIREMENTS FOR EIGHT ELASTIC SCATTERING SPECTROMETERS

Instrument	Equipment & Devices	Funding		
		Construction	Operation	Maintenance
Diffractometer	1) monochromator, 2) monitor, 3) Soller collimator, 4) sample table 5 detector(multi-detector, desirable) 6) ancillary(cryostat, etc.)	0.5 M$, 1 M$ (including multi-detector)	Cryostat, Magnetic & pressure cell cryogen	Ancillary equipment Computer system
Powder diffractometer	1) monochromator, 2) monitor, 3) Soller collimator, 4) sample table 5) detector(multi-detector, desirable) 6) ancillary(cryostat, etc.)	0.5 M$, 1 M$ (including multi-detector)	Cryostat, Magnetic & pressure cell cryogen	Ancillary equipment Computer system
Crystal SANS	1) monochromator, 2) monitor, 3) Soller collimator, 4) sample table 5) position sensitive detector 7) ancillary(cryostat, etc.) 8) polarizer, analyzer 9) pi-flipper	3 M$ (including PSD)	Cryostat Magnetic & pressure cell Cryogen	Computer system
Polarimeter	1) Monochromator 2) Polarizer, analyzer 3) 3-D polarization rotator 4) sample table 5) detector 6) ancillary(cryostat, etc.)	$200,000 in case of multidetector, much more	Ancillary equipment	Computer system
TOF spectrometer	1) chopper 2) TOF system 3) gonio-meter 4) ancillary(cryostat etc.)	$200,000	Ancillary equipment	Computer system
Reflectometer	1) monochromator 2) sample table 3) 2-D detector 4) vibration-isolation system 5) polarizer 6) analyzer 7) pi-flipper	$500,000	Ancillary equipment	Computer system

Instrument	Equipment & Devices	Funding		
		Construction	Operation	Maintenance
Interferometer	1)monochromater 2)Si-crystal 3)phase-shifter 4) detector 5) ancillary equipment or	$300,000	Ancillary equipment	Computer system
	1) monochromator 2) polarizer 3) pi/2-flipper 4) multi-layer spin splitter 5) pi-flipper 6) analyzer 7) detector 8) ancillary equipment	$200,000		
SANS	1) monochrometer 2) sample table 3) position sensitive detector 4) polarizing monochromator 5) pi-flipper 6) analyzer 7) ancillary (cryostat, etc.)	1 M$	Ancillary equipment	Computer system

TABLE 3. PERSONNEL REQUIREMENTS, RESEARCH POSSIBILITIES, INDUSTRIAL APPLICATIONS AND EDUCATIONAL AND TRAINING OPPORTUNITIES FOR EIGHT ELASTIC SCATTERING SPECTROMETERS

Instrument	Staff	Users	Feasible research fields	Industrial applications	Education & training	Co-operation
Diffractometer	2 scientists + 2 technicians	5–10	1) crystallography 2) 10^{-11}–10^{-9} m size atomic structure in crystal, metal alloy amorphous solids, super ionic conductor	1) super ionic conductor 2) composite materials	Students & young scientists	Exchange scientists in national regional & inter-national community
Powder diffractometer	2 scientists + 2 technicians	10	1) crystallography 2) magnetic materials 3) high temp. super conductor 4) texture in alloys 5) order-disorder phase transition	1) composite materials 2) catalytic agent 3) residual stress, creep, fatigue	Students & young scientists	Exchange scientists in national regional & inter-national community
Crystal SANS	1 scientist + 1 technician	10	1) 1–100 nm size microstructure and inhomogeneities 2) porous materials (cement pastes, plasma-sprayed ceramics, glasses) 3) large precipitates in metals 4) magnetic domains 5) phase transition	1) residual stress in material 2) composite 3) ceramics 4) sintered materials 5) austenite-ferrite phase transition	Postdoctoral scientists	Exchange scientists in national regional & inter-national community
Polarimeter	1 scientist + 1 technician	5–10	1) 0.1–1 µm magnetic structure 2) magnetic dispersion ferro fluids 3) domain structures 4) magnetic super conductor	1) recording tapes 2) magnetic super conductor	PhD course & young scientists	Exchange scientists in national regional & inter-national community
TOF spectrometer	1 scientist + 1 technician	5	1) crystallography 2) 10^{-11}–10^{-9} m size atomic structure in crystal, metal alloy amorphous solids, 3) magnetic structures	1) composite materials 2) magnetic structures	Students & young scientists	Exchange scientists in national regional community

Instrument	Staff	Users	Feasible research fields	Industrial applications	Education & training	Co-operation
Reflectometer	1 scientist + 1 technician	5	1) layered structures, surface structures 2) depth profiling 3) density profiles 4) polymer, magnetic structures at interfaces	1) magnetic recording tapes 2) polymer 3) catalytic agent	Students & young scientists	Exchange scientists in national regional & international community
Interferometer	1 scientist + 1 technician	5	1) interference of neutron wave 2) interference of spin components of neutron 3) fundamental physics		Students & young scientists	Exchange scientists in national regional & international community
SANS	2 scientists + 2 technicians	5–10	1) morphology of materials 2) 1–500 nm structure 3) microstructure of proteins 4) micelles 5) polymers 6) biological polymers	1) porous media 2) ceramics 3) polymers 4) magnetic structure	Students & young scientists	Exchange scientists in national regional & international community

TABLE 4. FLUX, SPECTRUM, BEAM SIZE AND SPACE REQUIREMENTS FOR THREE INELASTIC SCATTERING INSTRUMENTS

Instrument	Minimum flux n cm^{-2} s^{-1}	Desirable flux n cm^{-2} s^{-1}	Spectrum wavelength nm	Beam size cm × cm	Required space m × m
TOF spectrometer	10^7, at sample 10^4	10^8, at sample 10^5	0.1–0.6	4 × 8	3 × 6
Triple-axis diffractometer	10^7, at sample 10^4	10^8, at sample 10^5	0.1–0.2	4 × 8	3 × 5
Spin-echo	10^7, at sample 10^4	10^8, at sample 10^5	0.4–1.2	4 × 8	3 × 10

TABLE 5. ADDITIONAL EQUIPMENT AND FUNDING REQUIREMENTS FOR THREE INELASTIC SCATTERING INSTRUMENTS

Instrument	Equipment & Devices	Funding		
		Construction	Operation	Maintenance
TOF spectrometer	1) double-chopper or chopper + mono-chromator 2) gonio-meter 3) multi-detector 4) TOF system 5) ancillary (cryostat etc)	$300,000 in case of multidetector, much more	Ancillary equipment	Computer system
Triple-axis diffractometer	1) monochromator 2) sample table 3) analyzer crystal 4) Soller slits 5) detector 6) gonio controller 7) air-cushion table: desirable 8) multi detector	1 M$	Ancillary equipment	Computer system
Spin-echo	1) polarizing monochromator 2) pi/2 flippers 3) pi-flipper 4) precession coils 5) analyzer 6) detector	1 M$	1) cooling system 2) magnetic coil system 3) ancillary equipment	1) magnetic coil system 2) computer system

TABLE 6. PERSONNEL REQUIREMENTS, RESEARCH POSSIBILITIES, INDUSTRIAL APPLICATIONS AND EDUCATIONAL AND TRAINING OPPORTUNITIES FOR THREE INELASTIC SCATTERING INSTRUMENTS

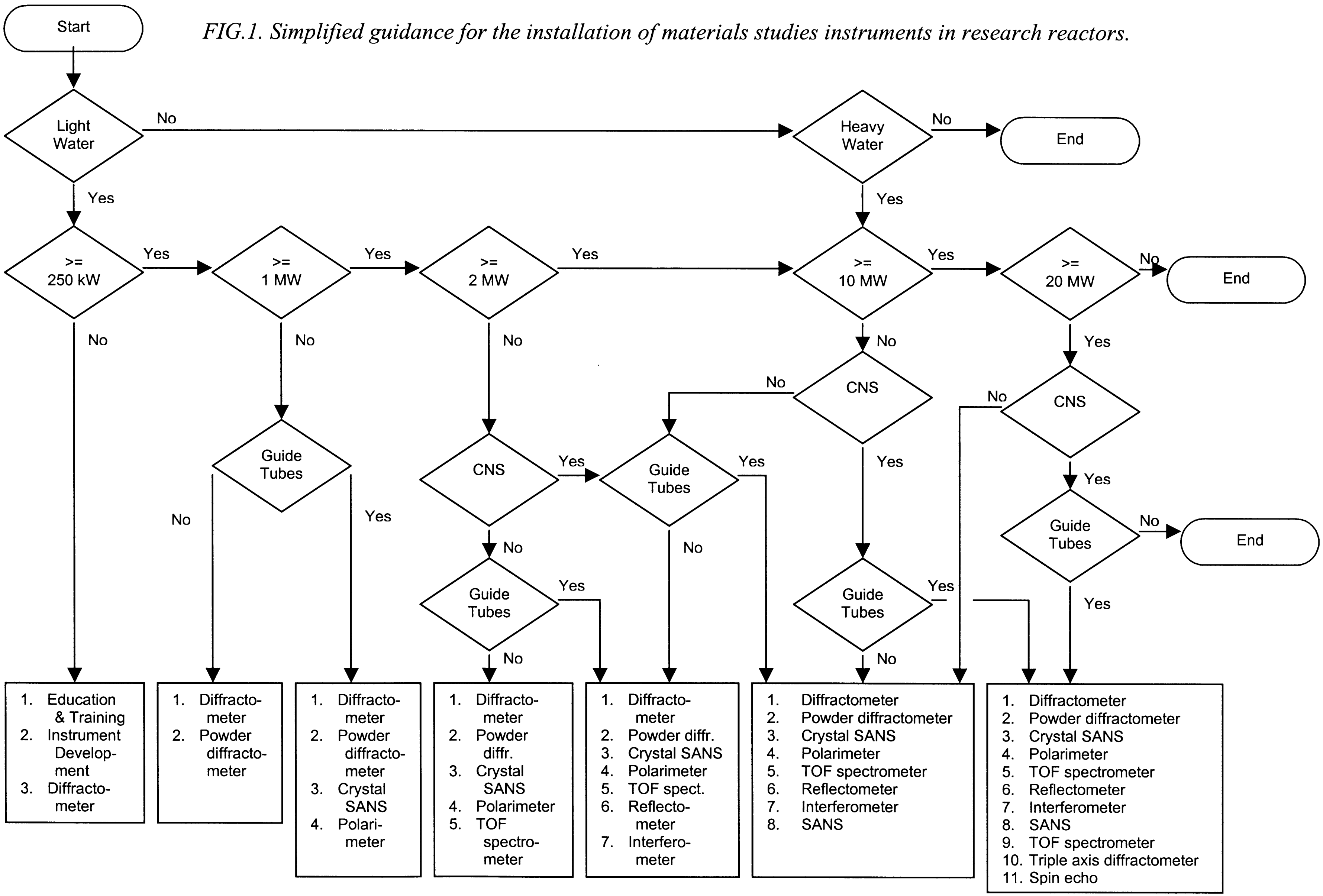
Instrument	Staff	Users	Feasible research fields	Industrial applications	Education & training	Co-operation
TOF Spectrometer	1 scientists + 1 technician	5	1) translational diffusion 2) collective excitation in liquids, liquid metals, molecular crystals 3) rotational motions in molecular crystals 4) hydrogen diffusion 5) electrolytes 6) vibrational energy levels in liquid metals 7) surface excitations of adsorbent	1) hydrogen diffusion in metals 2) catalyst 3) high-temp. superconductor 4) hydrogeneous materials	PhD course & young scientists	Exchange scientists in national regional & international community
Triple-axis diffractometer	2 scientists + 2 technicians	5–10	1) translational diffusion 2) collective excitation in liquid metals, 3) rotational motions in molecular crystals 4) hydrogen diffusion 5) electrolytes 6) vibrational energy levels in liquid metals 7) surface excitations of adsorbent	1) hydrogen diffusion in metals 2) catalyst 3) high-temp. superconductor	PhD course & young scientists	Exchange scientists in national regional & international community
Spin echo	1 scientists + 2 technicians	5	1) diffusional and rotational motions in solids, liquids, molecular crystals, which requires high energy resolution (qu1 micro eV) 2) fundamental physics	1) diffusional motions 2) polymer solutions	Students & young scientists	Exchange scientists in national regional & international community

Comments on TABLES 3–6

(1) The TOF method is applied to elastic and inelastic scattering instruments. In both cases, neutron choppers are used to produce pulsed beams for time of flight experiments. TOF instruments use time of flight to give a continuous wavelength scan at one or many fixed angles.

(2) Now spin echo methods are used for a small angle neutron scattering instrument and a triple axis spectrometer to increase the momentum- and energy transfer sensitivities. However, these instruments are not typical because they require novel techniques.

FIG.1. Simplified guidance for the installation of materials studies instruments in research reactors.



Comments on Fig. 1:

(1) Average flux assumed versus thermal power of reactor:

250 kW	1 MW	2 MW	10 MW	20 MW
1×10^{13}	2×10^{13}	3×10^{13}	1×10^{14}	2×10^{14}

(2) A research reactor of thermal power larger than 20 MW is always considered as having a cold neutron source (CNS) and neutron guide tubes.
(3) End means that this case is not considered here.

BIBLIOGRAPHY

IAEA-TECDOCs that are relevant to applications of research reactors are listed below:

IAEA-TECDOC-204	Neutron Scattering in Applied Research	1978
IAEA-TECDOC-257	Research and Teaching Nuclear Sciences at Universities in Developing Countries	1981
IAEA-TECDOC-351	Research Reactors and Alternative Devices for Research	1985
IAEA-TECDOC-384	Technology and Use of Low Power Research Reactors	1986
IAEA-TECDOC-409	Research Reactor Activities in Support of National Nuclear Programmes	1987
IAEA-TECDOC-435	Comparison of Nuclear Analytical Methods with Competitive Methods	1987
IAEA-TECDOC-456	Silicon Transmutation Doping Techniques and Practices	1988
IAEA-TECDOC-459	Nuclear Analytical Techniques for On-Line Elemental Analysis in Industry	1988
IAEA-TECDOC-515	Fission Molybdenum for Medical Use	1989
IAEA-TECDOC-564	Practical Aspects of Operating a Neutron Activation Analysis Laboratory	1990
IAEA-TECDOC-836	Use of Neutron Beams for Low and Medium Flux Research Reactors: R&D Programmes in Materials Science	1995
IAEA-TECDOC-837	Use of Neutron Beams for Low & Medium Flux Research Reactors: Radiography and Materials Characterization	1995
IAEA-TECDOC-974	Trends and Techniques in Neutron Beam Research for Medium and Low Flux Research Reactors	1997
IAEA-TECDOC-1065	Production Techniques for Molybdenum-99 and Technetium-99m	1999
IAEA-TECDOC-1212	Strategic Planning for Research Reactors	2001
IAEA-TECDOC-1218	Quality Aspects of Research Reactor Operations for Instrumental Neutron Activation Analysis	2001
IAEA-TECDOC-1223	Current Status of Neutron Capture Therapy	2001

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