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TECHNOLOGY AND USE OF LOW POWER RESEARCH REACTORS

REPORT OF A CONSULTANTS MEETING
ON THE TECHNOLOGY AND USE OF LOW POWER RESEARCH REACTORS
ORGANIZED BY THE
INTERNATIONAL ATOMIC ENERGY AGENCY
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FOREWORD

The research reactor is a versatile tool, useful in a large number of scientific disciplines and technologies. Research reactors have played a significant role in the development of the scientific and technical infrastructure of developed and developing countries and can assume an important role in the training of manpower tuned to the requirements for the introduction of nuclear power in a country.

Several developing countries with emerging programmes in nuclear science and technology are considering purchasing a multipurpose research reactor. A reactor in the 1-2 megawatt range is an expensive undertaking and can cost a minimum of $8-12 million. A low power research reactor, power level up to 100kW, may adequately serve the needs of many centres developing a nuclear science and technology programme. The small research reactor has cost advantages, both capital and operating, and can still play a significant role in a research and training centre.

In order to assist these countries considering the acquisition of a research reactor, the Agency convened a Consultants' Meeting to develop information on the technology, operating cost and utilization of low power research reactors. The meeting entitled "Technology and Use of Low Power Research Reactors" was held in Beijing, People's Republic of China, during 30 April to 3 May 1985.

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SUMMARY OF DISCUSSIONS

The IAEA Nuclear Research Reactor Data Base (RRDB) includes information on over 300 operating research reactors ranging in power from zero to 250 MW thermal. Approximately half of these reactors (152) are classified in the zero to 100 kW range. Of the 152 reactors, 129 (85%) are classified as less than 100 kW with 59 (46%) being of "zero" power. The distribution of these reactors is as follows:

100 kW	11-99 kW	1-10 kW	< 1kW
23	16	32	81

This group includes the following major types of reactors:

Argonaut
SUR
AGN 201/211
Slowpoke
TRIGA
Homogeneous (Liquid)
Homogeneous (Solid)
Critical Assemblies

The participants in the meeting (see Appendix B) came from seven institutes representing the following types of research reactors:

Argonaut	30 kW
TRIGA	18 kW
SUR	Zero Power
Slowpoke	20 kW
Miniature Neutron Source Reactor	27 kW
Training Reactor	10-100 kW
Training Reactor	100 kW

The participants were selected to represent different types of reactors, power levels, application environments, i.e. hospitals, universities, national research centres and nuclear power training centres, and well developed utilization programmes. A summary of the discussions follows.

I. REACTOR UTILIZATION (EXCEPT FOR MEDICAL USES AND TRAINING)

A. *Features of Small Reactors That Facilitate Utilization*

Compared to higher power (viz. > 1 megawatt), high neutron flux research reactors, units having power levels below 100 kW and neutron fluxes at 10^{12} n/cm^2/s or below, offer a number of distinct advantages to a variety of users and for these reasons would be generally described as 'user friendly'. Among these reasons are: typical irradiated samples are not highly radioactive so that fewer handling restrictions are required, nor is the administrative screening of samples submitted for irradiation or inspection of their packaging urgently required. The actual insertion of samples for irradiation in a position in the reactor can either be done by reactor staff or even by the experimenters themselves.

There can be greater 'permissiveness' in the variety of sample type and containment: simple, inexpensive, plastic irradiation capsules can be used and re-used many times without risk of radioactivity build-up, embrittlement or risk of failure; organic matter can be safely irradiated as can liquids, even highly volatile, combustible or explosive organic or petroleum liquids, wet tissues, excreta from humans or animals (without the need for drying or tedious sample preparation).

Another feature that can often be an advantage when the material to be inserted in a small reactor is not limited in quantity or is not very uniform in composition because of its inherent characteristic, is that a much larger quantity can be placed in the reactor without fear that there will be an excessive quantity of radioactivity induced. Generally, this will be the case when fluxes of the order of 10^{11} n/cm^2/s and irradiation times of less than one hour are involved.

The only disadvantages of small reactors are an inability to produce high specific activity radioisotopes, such as are available commercially, and a somewhat decreased sensitivity for the neutron activation determination of certain elements. The latter disadvantage can be partially overcome by using short-lived nuclides instead. On balance, most agree that the advantages of operating the safer, lower power reactors and the very much lower costs and staffing requirements more than outweigh these disadvantages.

B. Breakdown of Typical Small Reactor Uses

Uses may be broadly sub-divided as follows (these are not listed in any particular order with respect to their relative degree of utilization):

a. Radioisotope production, especially short-lived radionuclides such as Mn-56, Na-24, K-42, Br-82, In-116m or I-128, nuclides not generally available for international supply but of considerable use in demonstration, study of their characteristics, and application in teaching and research is also important. The use of short-lived nuclides is particularly suited to teaching because of their inherent safety when a local reactor is available. The preparation of radioisotope calibration sources for a variety of applications in radiation analysis, instrumentation development and calibration, is also possible and very useful.

b. Studies of reactor characteristics: e.g. reactor neutron spectra; mixed n and gamma radiation in in-reactor sites; nuclear reactor kinetics/dynamics; responses of a variety of nuclear detectors and dosimeters to neutrons, gammas, charged particles; instrumentation research and development.

c. Uses of extracted neutrons: (i) neutron dosimetry studies; (ii) neutron beams: diffraction, scattering and particularly neutron radiography for non-destructive testing for light element constituents; (iii) fast neutron converters: allow studies, e.g. of fast neutron effects on tissues.

d. Thermal, epithermal and fast neutron activation analysis: technique can be optimized to measure a wide variety of the chemical elements at low concentration in a wide range of matrix types. Small reactors equipped with a set of optional attachments and dedicated radiation analysis instruments, on-site, including rapid transfer pneumatic sample lines, automated irradiation controllers, cyclic irradiation systems and computerized radiation analyzers, can constitute a very comprehensive instrumental trace analysis facility.

A survey of the world's small nuclear reactors would probably show that instrumental neutron activation analysis (INAA) constitutes a major fraction of all the uses of reactor neutrons. At one of the more heavily-utilized small reactor facilities, the University of Toronto SLOWPOKE reactor, an average of about 15,000 samples are irradiated per year, more than 95% are for INAA and among these uses about 200,000 - 250,000 elemental analyses are accomplished. Since the operating cost is about $90,000 per year, the facility thus provides reliable, rapid trace analysis at a cost of a few cents each.

C. Examples of Typical Small Reactor Use

Among the examples of these types of uses are:

- studies of neutron transport in media of interest in nuclear reactor design: light and heavy water, graphite
- neutron energy mesurements both with Cd-covered Au and In foils and with 'time of flight' chopper methods
- determination of reactor parameters using pulsed neutron sources
- neutron spectrum determination also by the multiple foil activation method
- determination of the void fraction in two-phase liquid systems
- use of neutron beams for non-destructive testing, e.g. of different shielding materials, of reactor fuel elements, of PuBe neutron source capsules, of explosive caps for use in deployment of spacecraft. Neutron radiography especially of enriched reactor fuel elements are better using epithermal neutrons with greater penetration ability; also the ability to distinguish between U-235 and U-238
- development of two-dimensional tomography by computer analysis of several neutron radiograph images at different angles
- neutron and gamma mixed field dosimetry using a combination of 6LiF and CaF2 TLD dosimeters
- INAA for up to 35 trace constituents of environmental samples such as air filters, soils, sediments, not only for toxic heavy metals but also for a range of elements such as Al, Sb, As, Br, Ca, Cl, Cr, Co, Cu, I, Fe, La plus several other REEs, Mg, Mn, Hg, K, Sc, Na, Ti, Th, U, V and Zn

- INAA as a standard reference method for the establishment and calibration of standard samples for trace analysis: rocks, soils, sediments, coals, fly ash, biological materials, hair, etc.
- INAA of a variety of geological materials including those of interest in resource development, metals extraction, and fossil fuel sources
- INAA of key trace elements in biological materials of biomedical importance, including human scalp hair which has proven useful in public and occupational health surveys of exposed population groups
- INAA applications in scientific crime investigation including gun-shot residues, toxicological examinations, etc.
- INAA applications in archeometry for provenance studies of hand-crafted relics, examination of ancient processes of metal working, and studies of early geographical transfers of developing technology.

II. REACTOR UTILIZATION IN MEDICINE AND BIOLOGY

The major application of a low power nuclear reactor in medicine and biology is in the area of neutron activation analysis, whether it be for total elemental composition of trace elements, speciation of trace metals or the determination of trace molecular concentrations in biological matrices. Another important application is the production of radioactive tracers in the elemental, ionic or molecular form which can be employed for determining pathways in biological systems.

The radiation flux associated with a low power reactor can be employed as a source for the determination of radiolytic effects on biomolecular molecules. The fact that the reactor has a lower radiation flux is also important in reducing damage to biologically important compounds in lengthy neutron irradiations.

Various types of specialty experiments employing radioactivity produced in the reactor can be utilized to determine physico-chemical effects within a biological system: for example, determination of mechanistic details of the Auger effect producing radiotoxicity in biological systems.

Unlike higher powered nuclear reactors, low power reactors cannot be employed for the routine production of radionuclides important in radiopharmacy.

III. REACTOR UTILIZATION IN UNIVERSITIES

Many universities own, for teaching and research purposes, nuclear reactors. Of these, there is a range of all types of research reactors from several megawatts to zero power reactors of fractions of a watt. The original cost of the reactor is so important that early considerations of their use must be considered. The type of use in research and teaching determines the optimal type of reactor. Thus the question for each university planning to purchase a reactor is:

What type of reactor is required?

To answer this, one must know how a reactor can be utilized and what aspects and capabilities of the reactor can support particular research projects.

Universities carry on teaching and research. In both areas, one can use nuclear reactors with results. In fields of learning, a nuclear reactor lends to a programme for engineers and physicists which puts the experience of nuclear engineering students into the foreground. Also, service arrangements for other natural sciences such as Medicine, Chemistry, Biology etc. are possible. Along this line could be a specific training programme for reactor operators. In the field of research, one should be aware that in the core areas of nuclear engineering like neutron physics, thermohydraulics etc. (those using nuclear reactors), research is conducted primarily in big research centres with large personnel and large financial support. This still leaves a large area of research for the universities; these not only serve the development of scientists, but also present an important service suitable to other fields of the university and even institutions outside the university.

A. Teaching

At universities with a strong history in nuclear engineering, a reactor can be used to supplement courses with exercises.

These courses are:

1. Radiation measurements
2. Isotope production, use and research
3. Reactor theory
4. Reactor dynamics

Some aspects of topics such as reactor design, reactor thermohydraulics, safety theory do not require a use of the reactor.

Radiation Measurement courses may cover:

Atom model, radioactive isotope, γ, α, β, n radiation, interaction between radiation and matter, radiation detection and dosimetry, standard measurements like activity, lifetime, energy, dose, etc. and statistical computation.

Application of the Reactor:

Source for thermal and fast neutrons; production of weak and short lived isotopes for measuring purposes; shielding experiments in experimental channels of thermal column; Measurement of the radiation field in the vicinity of the reactor.

Reactor Requirements:

Neutron flux: min. 5×10^6 n/cm^2/s
Experimental channels and thermal column.

The application and use of radioactive isotopes in science and technology are dealt with in Radioisotope Technique Courses. This includes production and measurements of radioactive isotopes, their application as tracer, and radiographical measuring techniques of material properties, basics of radiography as well as activation analysis.

Application of the Reactor:

Radioactive tracer production.
Radiation source to demonstrate radiography as well as activation analysis.

Reactor Requirements:

Neutron flux: min. 5 x 10^6 n/cm^2/s; for radiography: min. 1 x10.
Experimental channels.

The following are handled in Reactor Theory Courses: Interaction of neutrons with matter, neutron fields, criticality calculations by use of Diffusion and Transport calculations, homogeneous and heterogeneous reactor calculations and Perturbation theory.

Reactor Application:

Demonstration experiments of the energy distribution of neutrons with crystallspectrometer and time-of-flight-analysis with a chopper or pulsed reactor.

Measuring cross-sections using similar procedures. Determination of neutron flux with activation foils in multiplying and/or absorbing media. Measurements of: Diffusion length, Albedo and Fermi-age.

Reactor requirements:

Neutron flux: min. 5 x 10^6 n/cm^2/s
Experimental channel through to mid-core, thermal column with water or graphite.

Covered in Reactor Dynamics Courses are the time-behaviour of reactor power stations. This includes: the kinetics of zero-power reactors, the reactivity effects of temperature, burnup, breeding, poisoning as well as the computer simulation of power stations and their control.

Application of the reactor:

Critical experiments with loading of reactor.
Measurements of reactivity under the procedures of: Rossi, Feynman, rod drop, source jerk, pulsed neutron source etc. Measurements of reactor parameters by analysis of pulse distribution and neutron noise. Measurement of transfer functions with reactivity oscillator. Control experiments with different control modes and devices.

Reactor requirements:

Neutron flux: min. 5 x 10^6 n/cm^2/s
Access to fuel for loading and reloading.
Experimental channels for insertion of neutron detectors, sealed neutron tubes of neutron generators, and additional control rods

B. Research

Research in the area of reactor construction, reactor thermohydraulic and reactor safety with use of high flux reactor is only possible in the big research centres, but not possible in universities. However, there are still three areas with growing significance for research. These areas are:

Activation analysis
Nondestructive testing by neutrons
Production of short-lived radioisotopes

Practically all fields of natural science and technology, especially with medicine, biology, chemistry, geology and metallurgy, can be served by these procedures.

Activation Analysis

This is a very efficient detection and measuring procedure for very small quantities of a sample. Its application ascends quickly. Samples are investigated by irradiating for short periods in a reactor - minutes or seconds - and then measured. In this way, some of the material is transformed into radioactive isotopes. The samples are investigated, after removed from the reactor, with regards to radiation energy, intensity and, in certain circumstances, also decay constants. Out of these results, a computerized analyzing system can determine the composition of the sample.

Reactor requirements:
Neutron flux: 1×10^{11} n/cm^2/s

Measuring devices:
High quality pulse height analyzer with semiconductor detectors and computer with specific software. Sample preparation and transport system.

Nondestructive Testing by Neutrons

This novel diagnostic technique is used to improve on the knowledge of materials structures and of defects in materials. The neutron radiography is a modern investigation procedure resembling x-ray analysis but with neutrons instead. With it, for example, material damages in light materials such as aluminum can be shown. The "picture" is registered on an x-ray film, in which the film is activated by photons produced in a conversion foil via neutron interaction.

This application is also applicable to computer tomography with neutron beams to obtain information about spatial location from two dimensional projection. This technique is under development and seems to be a good application of research reactors.

Reactor requirements:
Neutron flux 5×10^{11} n/cm^2/s
Channel and collimator systems

Production of Radioactive Isotopes

Radioisotopes are a powerful tool in research. Research reactors can produce isotopes with short half lives, of less than a few days, which is too short to be obtained commercially. They are used for tracer research at universities and hospital laboratories.

C. Remarks to the Types of Reactors for Universities

A number of different research reactors are offered in different countries. If the reactors are traded or moved to other countries, they must be adapted to the new regulations in areas of radiation protection, instrumentation, construction materials, etc.

Research reactors traded or sold to foreign countries may thus need to be modified. Specific needs via modifications of the reactor in upgrading for teaching and research at universities should therefore be formally stated. They must be evaluated for their placement, number of experimental channels, accessory instrumentation adaptability, as well as addition of control devices. Also, one with a thermal column can be an important experimental device.

If the reactor is to be used for the training of nuclear engineering students, then the students should be able to operate the reactor individually, getting the feel for the specific reactor time behaviour.

The reactor must be inherently safe, by having a large negative temperature coefficient, a small excess reactivity, and a safe shutdown system in case of excessive power. The question concerning the power rating can be addressed: for training only a few watts; for research in the given application listed above, a power rating between 5 kW to 30 kW.

It must always be kept in mind that the cost for personnel, insurance and especially for fuel and waste disposal, goes up with the power of the reactor.

IV. REACTOR UTILIZATION FOR TRAINING

A. Introduction

Training is one of the important uses of low power reactors.

Generally speaking, a reactor is not chosen (power, type of design, fuel ...) for a single application (physics, radioisotope production, training ...) but it appears that practically all the low power reactors in operation throughout the world are used at least partially and at least during one period of their life, for training purposes.

This interest in training activities concerns both countries with an important national nuclear programme and those who are just beginning their national programme.

Several types of training are also available, depending on the trainees (students, physicists, operating personnel ...) the degree of abstraction sought after (theory and practice), the length of the training courses (from a few days to several months), and of course the characteristics and potential of the reactors (power, installation, safety regulations, accessibility ...).

B. Desirable Features of Reactors for Training Purposes

The following are the desirable features for nuclear reactors for training purposes:

High degree of safety: safety is, of course, an overriding requirement in training devices, especially in nuclear reactors.

Ease of operation: training reactors should be designed so that a minimum number of restrictions are imposed on the students and instructors (for example, the control console can be operated safely by inexperienced students after a short instruction time).

Ease of maintenance: equipment should be arranged to provide easy access for maintenance, and components should be selected for life and minimum maintenance.

Ease of experiments for students and instructor: for training reactors, ease of a wide variety of training and research experiments for students is highly desirable.

C. Training Programmes

It is difficult to give an outline of the training programmes run on low power nuclear reactors without taking into account the trainees involved (students, physicists, operating personnel ...) or mentioning the possibilities and limitations offered by each type of reactor (power, accessibility, flexibility ...).

In order to make the presentation not too complicated, the following classification may be proposed.

Training students and physicists

Low Power Reactor (< 1 MW). This type of reactor (< 1 MW) enables training to be given on:

- nuclear radiation measurement and application (activity, dose, half-life, energy, reaction with materials, activation analysis and statistics ...);
- reactor theory, neutron transport (by using, for example, spectrometer, neutron chopper, foil activation dosimeters ...);
- reactor kinetics, reactor dynamics (by experiment, detector pulses ...);
- plant operation and control (by using an associated computer to simulate the reactor operation and control).

Besides the above exercises, other types of exercises are possible. The following are particularly worth mentioning:

- criticality and power increase of the reactor
- relative and absolute flux measurements
- reactivity measurements
- control rod calibration
- temperature coefficient measurement
- poisoning effect measurement
- spectrum measurement
- void coefficient determination
- radiation protection and shield measurement
- neutron radiography
- analysis by activation
- radioisotope determination

Training operating personnel

Generally speaking, the emphasis is placed on all the procedures and operations involved in reactor operation and safety, in particular:

- fuel loading and unloading
- approach to criticality
- effects of prompt and delayed neutrons
- poisoning effects (Xenon, Samarium)
- temperature effects
- reactivity effects
- load variations
- instrumentation and calibration
- flux and power measurements
- reactor kinetics and dynamics
- radiation protection
- radiochemistry

Training for research: related applications

Low power reactors can also be used for a whole series of related applications, involving the field of basic or applied research.

The following are particularly worth mentioning:

- archeometry
- biological applications
- chemical applications
- earth sciences
- environmental sciences
- medical applications
- metallurgy
- industrial applications

D. Other Training Equipment Associated with Nuclear Reactors

Among the numerous other equipment associated with nuclear reactors for training purposes, the following are worth mentioning.

Simulators

The use of reactor simulators is becoming more and more generalized. This equipment is flexible, adaptable, simple to implement, of relatively low cost, providing training means which are greatly appreciated in the nuclear power field (for training both nuclear engineering students and power plant personnel). There is a large amount of literature in this field dealing with the different types of simulators and their main assignments (basic principle simulators, full scope representation, accident, function simulators...).

Computer assisted teaching

This is a more autonomous formula generally used to keep up a certain level of knowledge and for individual refresher course purposes. Its usefulness is directly related to the importance of the data base which is built in.

V. REACTOR AS A NEUTRON SOURCE FOR RADIOGRAPHY

Any nuclear reactor equipped with beam tubes and capable of operating at a power greater than 1 kW may be useful for neutron radiography. But naturally, the higher the power - the greater the source flux - the more convenient the methods and the better the radiographs.

A high quality radiograph is known to be composed of some 10^9 quanta or registrations per square centrimetre on average. On the other hand, as few as 10^4 quanta or registrations per square centimetre are sufficient to produce a recognizable image of a wide variety of everyday objects. Thus, if we have an image recorder with a thermal neutron registration efficiency of 10%, the system must be arranged so that between 10^5 and 10^{10} n/cm^{-2} are incident on the image plane in a reasonable time.

The neutron beam is directed onto the sample by simply allowing it to pass through a specially constructed opening in the reactor shielding, the collimator. Collimators are characterized by their L/D ratio, where L is the source-to-detector distance and D is the width of the source aperture (the opening at the source end of the collimator). The larger the L/D ratio, the greater will be the potential geometric resolution of the system: the images of thick objects will be sharper for improved collimation. On the other hand, improved collimation decreases the available neutron intensity.

A high quality radiograph for a thick (> 10 cm) object needs a high L/D ratio (> 200), which can be realized only at a reactor in the MW range. Lower quality or radiographs of thin objects can easily be obtained at small reactors.

Epithermal energy neutrons have been used to obtain improved neutron penetration of materials that have high attenuation for thermal neutrons. The most widely used application involves neutron inspection of enriched reactor fuel. The increased penetration over thermal neutrons, often a factor of about 40, provides images showing internal fuel details such as cannot be revealed by thermal neutrons because of their higher attenuation. Similar penetration advantages can be demonstrated in other materials such as those containing hydrogen. An advantage of resonance neutrons for radiograph is the significant increase in detectability for a given material.

Significant energy tailoring neutron beams for radiography is restricted to reactors in the MW range. Epithermal neutron radiography (Cd filtered beam), however, can be available in the kW range with an irradiation time of a few hours. In all of the cases, the main advantages of a small reactor are the low radiation levels, flexibility, and much lower cost. Testing highly irradiated materials (fuel), however, may cause problems in a university environment.

VI. SOME REMARKS ON THE SAFETY OF LOW POWER RESEARCH REACTORS

Besides being versatile and of a wide scope of application, many low power research reactors have unique user-friendly safety features. For the reactors discussed in this meeting, most of them have a large negative temperature coefficient of reactivity (10-4 Δ k/k/^{o}C) and void coefficient due either to the under moderation of the core or in some cases, (e.g. TRIGA) to the increase of neutron temperature by the crystalline effect of the moderator used (ZrH). This negative temperature coefficient is effective in limiting the power excursion during a sudden insertion of reactivity. For TRIGA reactors, since this coefficient is prompt due to the intimate mixing of the fuel and moderator, a large insertion of reactivity can pulse the power of the reactor to a very high value while the self limiting property of the prompt negative temperature coefficient quickly brings down the power surge so that the temperature rise of fuel is limited to a safe level. While for other reactors of water moderation, (e.g. Slowpoke, MNSR), the temperature coefficient is mainly due to the moderator heating up and is not as prompt. A sudden reactivity insertion will lead to an instant power surge and the temperature of the fuel will rise. With good thermal conductivity between the fuel and the cladding, heat will quickly be transferred to the cooling water raising the temperature of water and the moderator negative temperature coefficient will come into play and decrease the excess reactivity. The reactor power will settle down to a level determined by the initial reactivity and the negative temperature coefficient together with the coolant flow rate. As a result the power surge will be quenched which in turn will limit the rise of the fuel temperature.

Secondly, being of low power, built-in reactivity can be kept quite low, mostly for compensation of temperature rise, Xe poisoning and sample loading with a small investment for fuel burn-up. In many low power research reactors, this low excess reactivity coupled with a large negative temperature coefficient of reactivity and limited coolant flow rate, limits power level and fuel temperature to safe values for power transients which may happen. This self-limiting and self-regulating behaviour of reactor power make such reactors inherently safe. These inherent safety features are valuable for safe operation of low power research reactors (cf. papers in this meeting).

Notwithstanding these inherent safety features, one cannot really design and construct a completely foolproof reactor without taking due account of foreseeable human and equipment failures. It is generally agreed for nuclear safety that reactors should follow the defense in depth approach to guard against inadvertant release of fission products from the fuel to the environment and to personnel. Thus, as a first level of defense, one must pay attention to careful design, construction, operation and maintenance so that malfunctions which could lead to accidents will be unlikely. For this purpose one must use established and conservative engineering practices and with adequate margins of safety in design, high quality construction and manufacturing, excellence in operation, use of tested components and materials, etc. As a second level of defense, one must have means to protect against possible human or equipment failures. For example, in case of jamming of the shutdown rod(s), it should still be possible to shut down the reactor safely by other means. Usually one requires that in case of failure of one safety-related component or system, the safety function is not impaired (single failure criterion), either by redundancy and/or by built-in inherent safety feature. For a low power research reactor, a serious accident might cause some damage to reactor fuel with some release of fission products, for example, through blockage of fuel cooling channel by a loosened part in the reactor core. To avoid such accidents, the best policy is to take preventive safety measures especially in quality assurance of important equipment during maintenance and routine surveillance, qualification and adequate training of operators, and detailed analysis of abnormal event and taking due corrective measures.

Taking into account the knowledge and experiences gained in safety and with adequate regulatory measures, we believe that safety of low power research reactors can be ensured and incidents or accidents should be rare and could be harnessed in an acceptably harmless way, even if not completely eliminated.

CONCLUSIONS

Advantages of LPR's:

Low capital cost. The exact cost information for these reactors is not available since most of them have been installed for a number of years. Best estimates for the less than 30 kW reactors range from about US$ 400,000 for the simplest reactor to about 1 to 1.5 million US dollars. This compares to a price of about 5 million US dollars for a reactor of several hundred kilowatts power. The lower end of the price range depends on the amount of local design and construction performed. The available option, i.e. experimental facilities, instrumentation, etc., could significantly influence the cost.

Low operating cost. The operating cost of the reactors represented are in the range of US$ 100,000 per year and less. However, because of differences in economic conditions, it may be more reasonable to express this in terms of personnel requirements. This usually includes, as a minimum, one operator, one supervisor (part-time), and repair, maintenance and radiological protection services, from the overhead of the institute in which the reactor is located. The experience of the participants has been that these reactors are very reliable and relatively free of problems. The failure rate of reactor components is typically less than one per year. Annual cost for consumible supplies is estimated at $10-15,000.

Low burnup. Because of the low operating power, the fuel burnup is extremely small and most reactors in this class have "lifetime" cores. In the Slowpoke- and MNSR-type reactors, reactivity adjustments are made by adjustment of the beryllium shims. The low burnup and limited radioisotope production capability result in minimal radwaste problems.

Simple to operate. This class of reactor of simple design is easy to operate and requires little operator training. The two 100 kW reactors, designed for operator training, are more complex and require correspondingly more detailed training.

Safe. These reactors are relatively safer to operate than the larger reactors. The smaller reactors ($P < 27$ kW) are power limited due to the negative temperature coefficient. All are able to withstand a loss of coolant accident. Occupational radiation doses are also lower. As with all reactors, however, any fuel manipulations must be carefully supervised.

Less restrictive containment and siting requirements. Because of the low fission product inventory, safety in reactivity transients and in loss of coolant accidents, the siting and containment requirements for this class of reactors is much less restrictive. Most of the reactor facilities discussed at the meeting were housed in normal buildings (with controlled access) and in populated areas. However, the matter of siting and containment must be left to the national authorities where the reactors will be located.

Versatility. These reactors are very well suited for training activities because of the flexibility of scheduling use. The freedom to startup, shutdown or change operating power is usually not found in larger reactors. These .reactors are also excellent tools for neutron activation analysis, as evidenced by the papers appended to this report. These reactors have also been active in the development of nuclear detection instrumentation.

Disadvantages of LPR's:

Lower sensitivity for NAA. Naturally, because of the lower available flux, the sensitivity for NAA is less. However, this lower sensitivity also can result in less interference from ions that are not activated to as great an extent.

Limited radioisotope production. Production of radioisotopes is limited to those with short half-lives, for use in calibration, teaching or research.

Limited use of neutron beams. Performance of neutron diffraction and scattering experiments is limited. This is also true for fast neutron studies.

Limited access to the core. In some of these reactors, the core is not normally accessible. While this adds a measure of safety, this inhibits some experiments in reactor physics.

Licensibility. The simple instrumentation and control system for some LPR's may present a problem of licensing in some countries. This may be the case for the Slowpoke and MNSR where there is a single control rod thereby violating safety criteria in some countries.

PAPERS PRESENTED AT THE MEETING

THE ZERO POWER REACTOR SUR AND ITS APPLICATION

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Abstract

This low-power reactor, rated nominally at 100 milliwatts, has a cylindrical core of 26 cm in diameter and 24 cm high consisting of U_3O_8 powder in a polyethylene matrix. The fuel is 20 percent enriched and the critical mass about 700 g. The excess reactivity is about 3 mk. The reactivity is controlled by two cadmium sheets in addition to a back-up system that drops the inner reflector. The reactor has no active cooling system. Personnel costs include a supervisor and an operator. The reactor is used for training in Reactor Theory (including use of a neutron chopper), reactor kinetics, nuclear technology, reactor operations and for doctoral thesis research.

I. Summary

In the field of reactor development it is evident that the employed physicist or engineer need not have any extensive special knowledge of nuclear technology to work with success. The most emphasis is placed on training in the respective discipline, e.g. physics, electrical engineering, heat and fluid dynamics, mechanical engineering. But, in addition, knowledge of basic principles of nuclear theory and technology is advantageous for mutual understanding and for teamwork between the expert groups. Particularly in this sector of science, it is necessary to communiate the most important features with the help of well prepared reactor training courses.

The alternatives - power research reactor or zero power reactor or subcritical assembly are often discussed.

Research reactors are recommended for long living well organized programs are staffed with operators and are operated twenty four hours day by day at full power. A subcritical assembly is a facility for the investigation of definite problems dealing with neutron physics and core technology. In both cases power research reactor and subcritical assembly we have to recognize the possibility of dangerous excursions so that the training of students is often restricted to a state of observers during reactor operation.

The Technical University of Berlin possesses a SUR low power reactor since 23 years. In spite of the very low power of 0.1 watt it is a very important device in the training program for students of nuclear engineering.

Compared with other reactor types and subcritical assemblies one can point out:

- The absolute safety against any kind of power excursions
- negligible radiation and no problems with waste
- low operating costs.

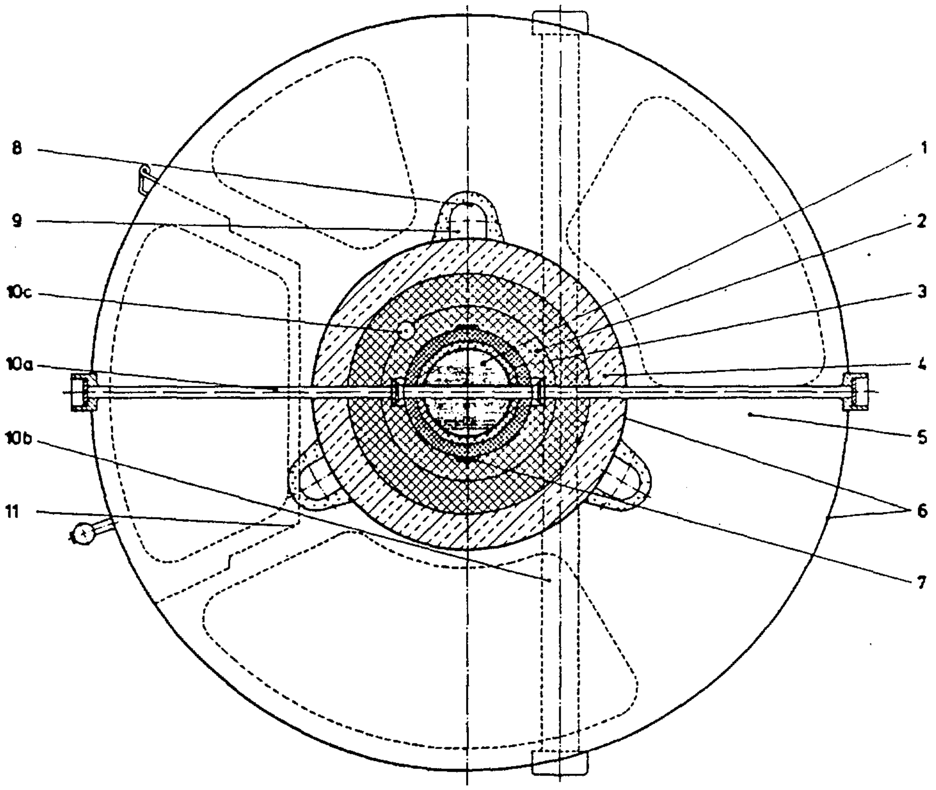
The reactor SUR provides the students with a good feeling for the special behaviour of nuclear reactors. They are allowed to operate the reactor without any restriction after a short instruction time.

A brief description of our training program is given in this paper.

II. Description of the Reactor

The main parts are (Fig. 1):

- Core	with fuel and moderator
- reflector	
- shielding	γ and neutron
- controldivices	control rods separation of core halves
- instrumentation	nuclear and safety
- experimental devices	horizontal and vertical channels thermal column



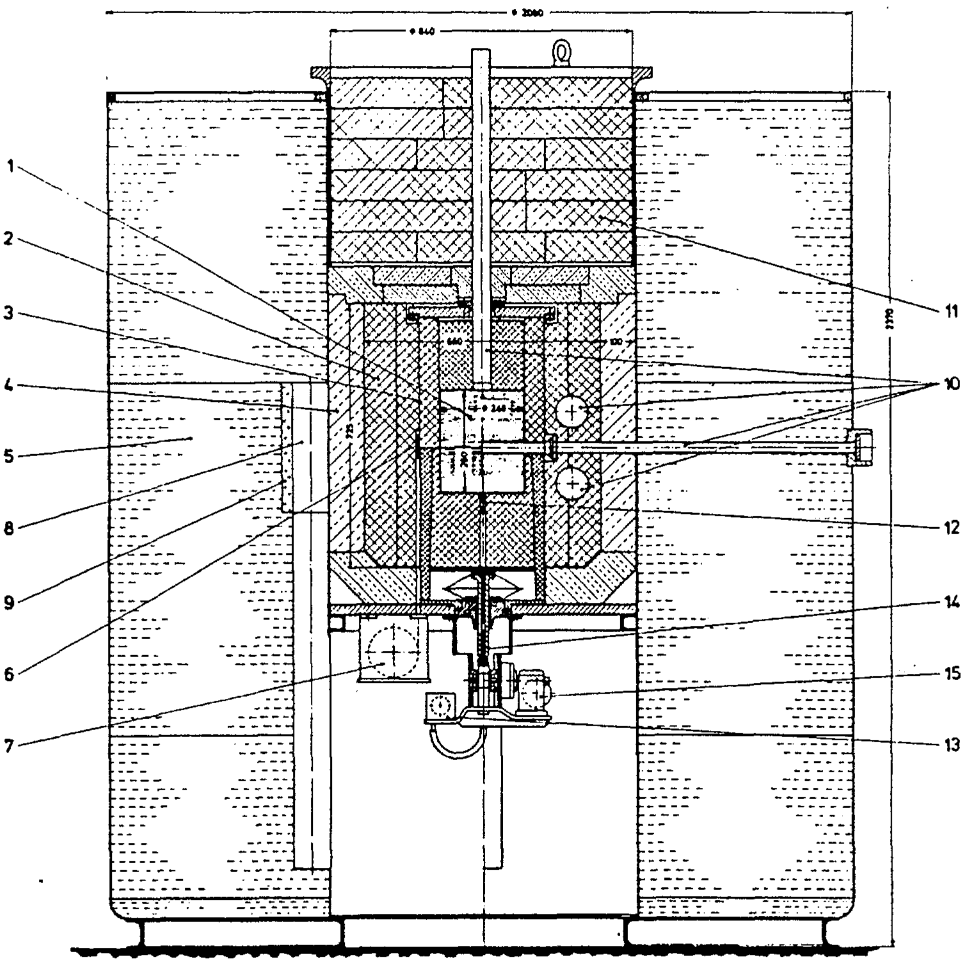
1	Core	8	Neutron Detector	
2	Reflector (Graphite)	9	Reflector of Neutron Detector	
3	Inner Reactor Vessel	10a	Central Horizontal	Experimental Channel
4	Lead Shielding	b	Lateral Horizontal	
5	Water Shielding	c	Lateral Vertical	
6	Outer Reactor Vessel	11	Reactor Door	
7	Control Plate			

Fig. 1a: Reactor SUR

The reactor itself consists of a vessel - 2,5 m diameter and 3 m high - and a separated control desk.

Core

Its cylindrical shape has a height of approximately 26 cm and a diameter of 24 cm built up with a number of disks of indivitual height.



1 Core
2 Reflector (Graphite)
3 Inner Reactor Vessel
4 Lead Shielding
5 Water Shielding
6 Control Plate
7 Drive for Control Plate
8 Neutron Detector
9 Reflector of Neutron Detector
10 Experimentation Channel
11 Thermal Column
12 Neutron Source
13 Drive for Neutron Source
14 Hoist for Reactor Core Half
15 Motor for Hoist

Fig. 1b: Reactor SUR

The core consists of a highly compressed mixture of U_3O_8 and polyethylene powder. The fuel is enriched up to 20 % with the fissile isotope 235 U. Polyethylene has a high hydrogen content and acts as moderator and its large thermal expansion coefficient provides an exceptional inherent safety. The critical quantity is about 700 g 235 U and the excess reactivity is usually about 0,3 % or about 0,5 $ and is determinated by critical experiment.

The lower half of core can be moved about 5 cm down such that the criticality is decreased about 5 % or 8 $ to an absolute safe shut down state.

Reflector

The reflector surrounds the core in a 20 cm thick layer and consists of highly purified graphite. There are an inner and an outer reflector. Between both an aluminium tank is provided which acts as a barrier for gaseous fission products.

Shielding

The shielding consists of a 10 cm wall of lead. About 95 % of all γ-quants leaving the reflector from fission products and other neutron reactions are here absorbed. But the lead is no absorber for neutrons and therefore the ring shaped room between the inner and outer reactor vessel is filled with boric acid saturated water. This solution acts as a moderator for fast neutrons and as a absorber for thermal neutrons.

If necessary the room under the core can be filled up with some layers of borated polyethylene disks to prevent neutron radiation into the ground of the reactor. The thermal column is covered with a 2,5 cm thick layer of borated polyethylene. Fig. 2 shows the radiation fields around the reactor.

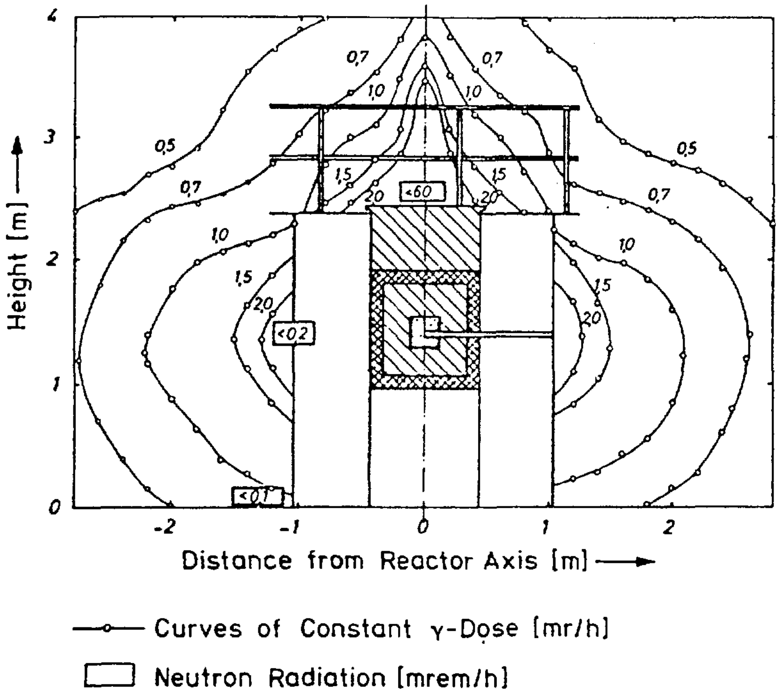


Fig. 2: Radiation Field of SUR, Power 0,1 W

Controldevices

The two control plates are located outside of the core in the reflector and both are capable to shut down the reactor in any case. They consist of Cadmium sheet as neutron absorbers, are moved by a motor with gears and, if scrammed, the plates are quickly driven by springforce to the position nearest the core (Fig. 3).

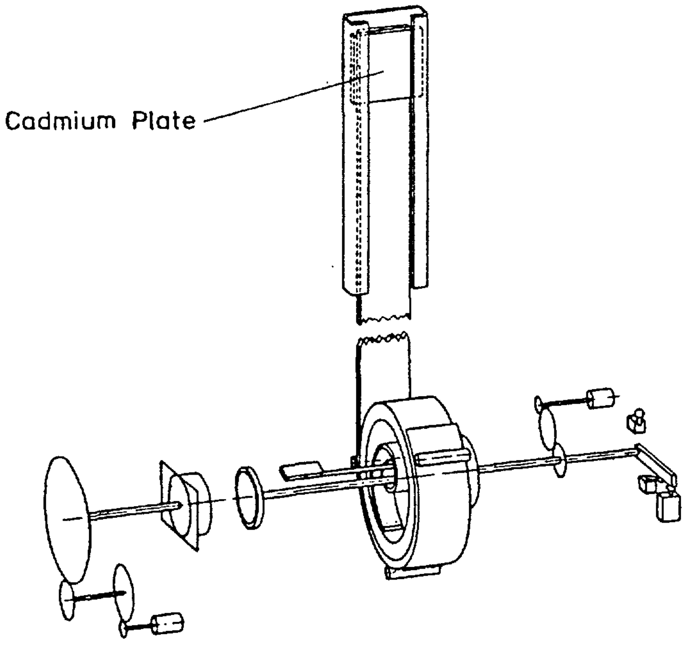


Fig. 3: Control Rod Drive

The second fully independent safety system is the movable lower core half plus lower inner reflector part. The core hoist consists of geared rack and ponion drive with electromagnetic coupling. In case of shut down the core half drops in less than one second down with an effective reactivity value of about - 8 $ (Fig. 4).

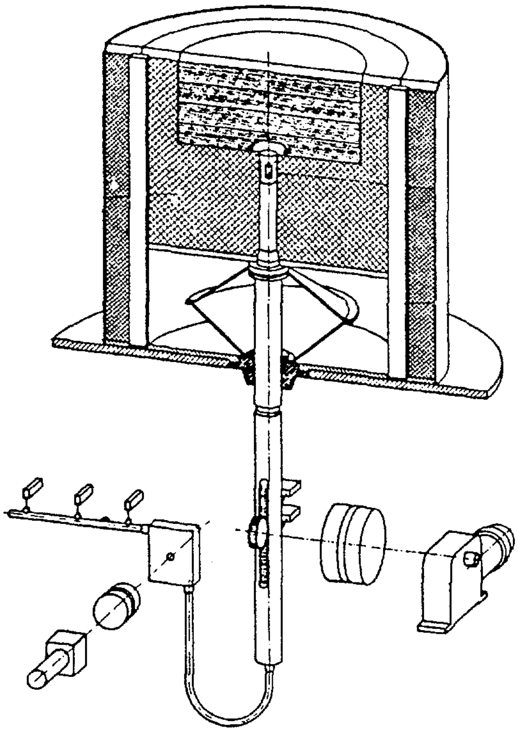


Fig. 4. Core Hoist and Neutron Source Drive

Instrumentation

The nuclear instrumentation is used to display to monitor and to registrate the operating status of the reactor. The power level depends of neutron flux so that the neutron flux is monitored for control reasons. Under start conditions the power is logged by pulse-channels with BF_3 counters. If the power is increased, the DC channels are activated. Here two compensated BF_3 ionisation chambers are in use, one for a logarithmic and the other for a linear channel.

Fig. 5 shows the scheme of the instrumentation. In addition to the flux the reactor period is determinmated from the logarithmic neutron flux. The period is a direct measure for the change of neutron flux per time interval.

γ-channels take care of measurement and monitoring the γ-dose rate in the direct vicinity of the reactor and the control desk near the place of the operator.

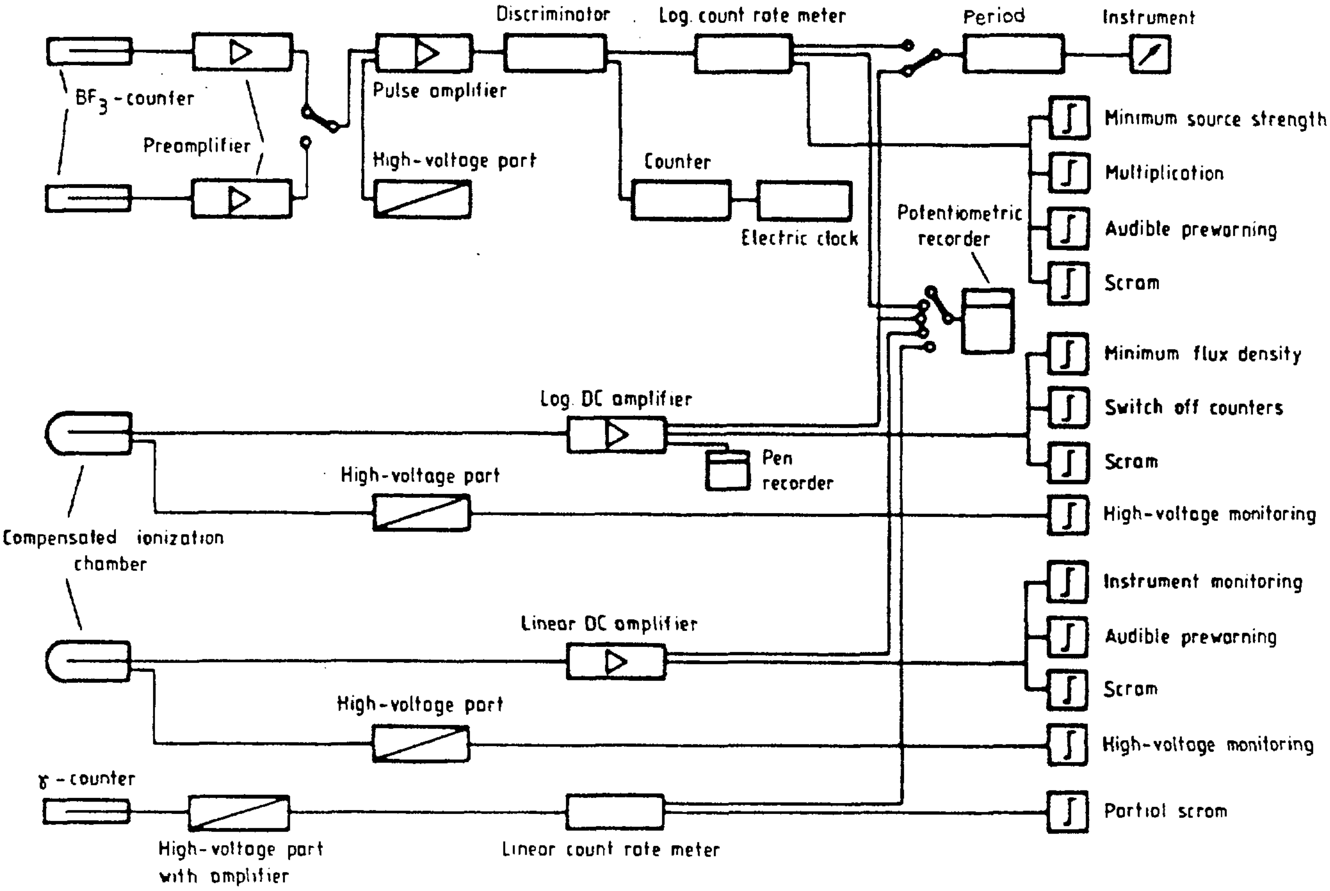


Fig. 5: Nuclear Instrumentation

Before starting of the reactor all instrumental functions are checked as well as the recommended status of the reactor. An electronic interlocking system connected with the neutron and radiation channels allows starting and operating the reactor only in the permissible manner (Fig. 6).

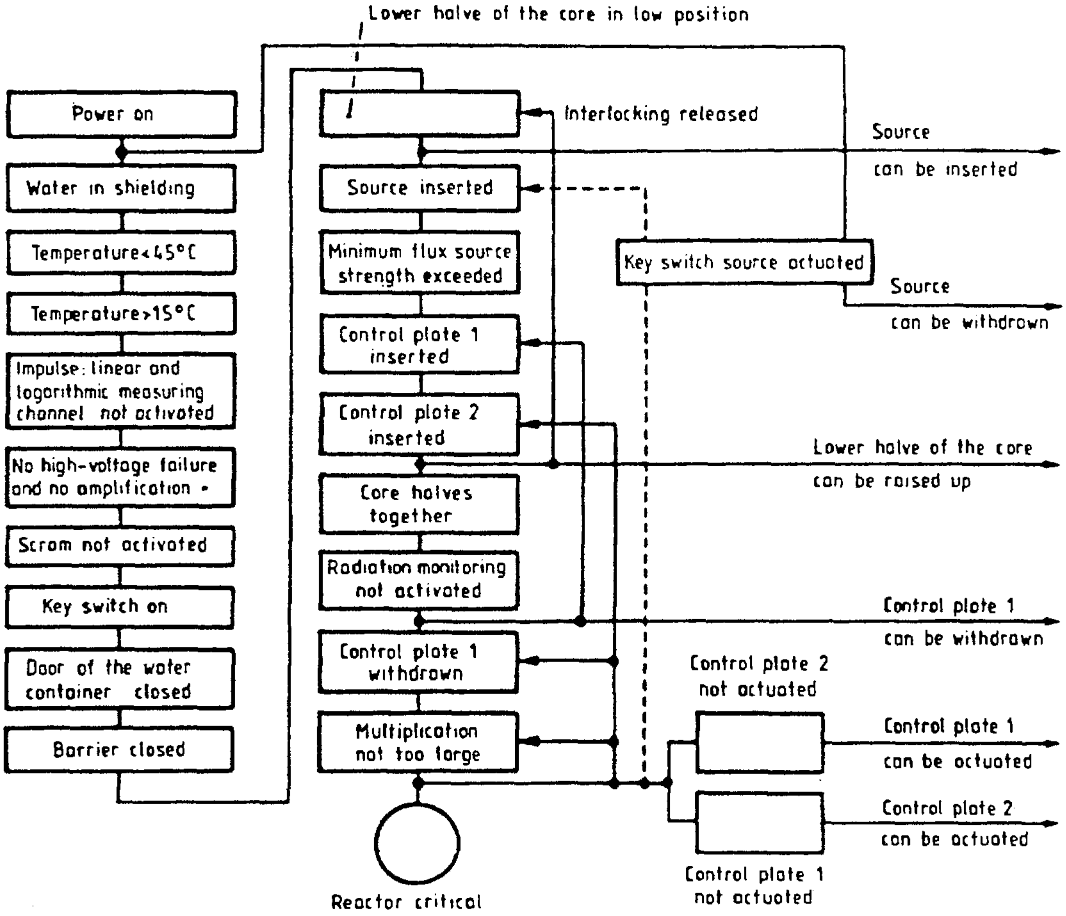


Fig. 6: Interlocking System

Any disturbance of reactor instrumentation - e.g. fail of instrumentation, too large neutron flux, too low or too high core temperature, too low liquid level in shielding, will cause a shut down. Operating errors like wrong measure range or a start up without neutron source and similar mistake are followed by a shut down.

Experimentation Facilities

The reactor has three horizontal experimentation channels. One of them is going through the center of the core and has a diameter of 2.5 cm. The other two are going through the reflector. They have larger diameters of 5 and 10 cm and are capable to contain ionisation chambers or the tube of a neutron generator.

From the two vertical channels one goes through the thermal column to the surface of the core. The other vertical channels are going through the reflector and can be used for a third control rod, if automatic reactor control is prefered. If not used, all channels are closed with fillers of graphite lead or polypropylene.

The thermal column is another experimentation facility designed to study neutron transport phenomenes.

It consists of an aluminium container - height 55 cm, diameter 85 cm - normally filled with graphite, which can be easiliy replaced by other moderators like water or organic liquids.

III. Operating Costs

The reactor can be installed in normal laboratories without special conditions caused by radiation, air or water contamination or handling of waste.

A place of six to ten meters is sufficient for training of students. Only the weight of 15 tons is to be taken into consideration. The personal costs include the expenditure for the persons responsible for the reactor, generally a physicist or engineer with university degree and one assistant as a reactor operator. There are no fuel costs for refilling. The power consumption is about three kW.

The costs for insurance in West Germany are about $ 7.000,-- per year. Other costs arise from experimentation equipment used for student training. One can start without special devices using only the normal electronic equipment, but it is possible to construct and build special devices like:

Control rods and controllers, pile oscillators, neutron spectrometer, neutron chopper and others.

IV. Application of the Reactor

The reactor is used for student training in an engineering department and belongs to the Institute fo Nuclear Engineering.

The training courses are a part of the lessons given in the institute which are:

Nuclear Radiation, Measurement and Application
Reactor Theory - Neutron Transport
Reactor Kinetic and Dynamic
Plant Operation and Control.

A reactor course with the same name belongs to each of these lessons.

Nuclear Radiation Measurement and Application

In this course for beginners the student learns the use of instruments to measure the properties of radiation like: activity, dose, half life time, energy, reaction with matters, activation analysis and statistics; furthermore, production and handling of open and sealed radioactive probes. The reactor is used for production of radioactive isotopes from

Ag, Br, Co, Dy, Eu, In, Mn, Rh, V, ...

in quantities and specific activities sufficient for measurement training.

In the case of activation analysis a secure domonstration of small quantities of Al, Cl, Cu, J, K, Mg, Na, ... is possible. In the center of the core is a neutron flux density of

$$6 \cdot 10^6 \text{ n cm}^{-2} \text{ s}^{-1}.$$

Under this condition longer living isotopes e.g.
Au → $T_h = 2{,}7$ d have a specific activity of 0,42 μC g^{-1} after a radiation time of one hour.

Short living isotopes with high activation cross sections like Indium builds up the higher specific activity of 53 μC g^{-1}. But in this case the half life time is shorter than one hour. So we have in both cases no trouble with waste and contamination. One day later we have always "clear conditions" in our laboratories.

Reactor Theory - Neutron Transport

The first group of experiment treats neutron energy measurement and neutron reactions with matter.

It starts with the simple measurement of neutron energy using energy dependent activation foils. In spite of the very rough energy distribution this is an effective experiment, because a good comparation with neutron theory is possible.

The next step is the use of a crystal spectrometer. The scattered neutrons are registrated with an analyser system. The angle depending count rate shows the energy distribution of neutrons. In case that the neutron beam extracted from the reactor is filtered by thin film-like foils it is possible to measure the cross section of foil matter.

The best results of energy mesurement are obtained by using a neutron chopper in a "time of flight" experiment. In spite of the very short flight way - less than two meters - the results for thermal and intermediate neutrons are comparable with the results from multigroup diffusion calculation and from simple transport theory. The determination of cross section, especially for 1/v absorbers showed satisfying results. The second group of experiments considers the neutron transport in non-multiplying and in multiplying materials.

The diffusion behaviour of neutrons in the thermal column is inquired by cadmium covered and uncovered Au-foils. The results are three-dimensional fields of thermal and intermediate neutrons fluxes in the graphite column. These can be compared to results of diffusion theory.

The distribution of neutrons in the core is also determinated by foil activation. The first step is the activation of covered and uncovered foils along the core axis. The relative neutron distribution is the result. Later on in a second step a foil is activated in the center of core. The absolute activity is determinated by coincidence technics. The absolute neutron flux distribution can be calculated with the result of this measurement and the power of the reactor is known. The result is comparable to a two-group computation for cylindrical core geometry.

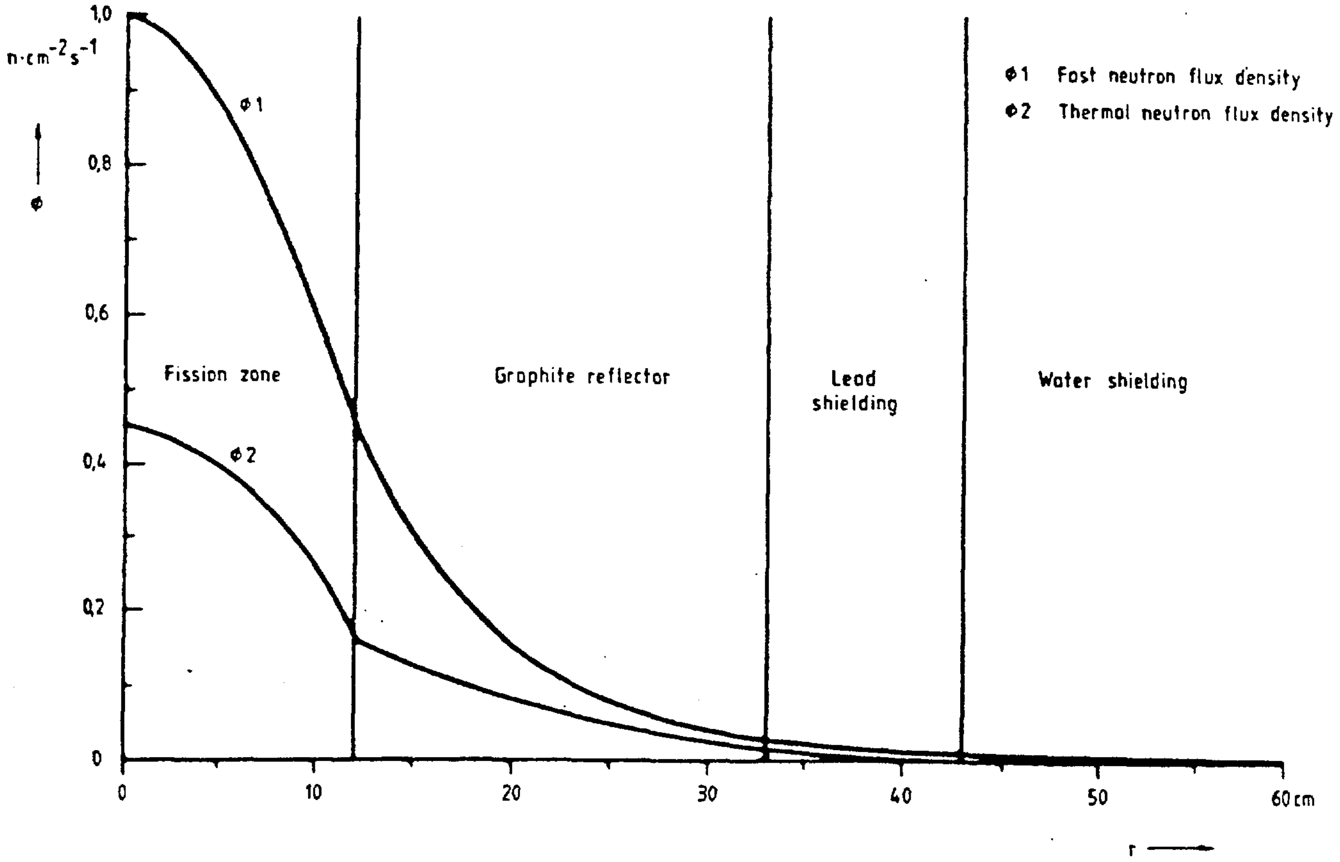


Fig. 7: Relative Neutron Flux Distribution

Reactorkinetic - Reactordynamic

The first group includes all the main experiments dealing with time behaviour of the neutron population in undercritical and critical status. The neutron chains in the undercritical state are observed by

Rossi α-experiment
Feinman α-experiment
distribution of detector pulses
variance to mean and so on.

Similar results are obtained using a pulsed neutron source. In the critical state of the reactor the determination of reactivity is possible by Rod Drop and Source Yerk experiments. A number of experiments are established to measure the overall time behaviour of the reactor. The reactivity is modulated by use of a pile oscillator over a range of frequencies.

The transfer function in magnitude and phase is the result and shows the lifetime of neutrons and the influence of delayed groups. The analysis of neutron noise is a more sophisticated experiment using time series or correlation analysis to compute the power spectral density.

Plant Operation and Control

The simulation of the reactor with analog computer is the preparation of the control experiments. The influence of different controller parameters setting up to instability of the simulated reactors are observed and discussed.

Next steps are done on the reactor. A control circuit with a separate control rod in a vertical experimental channel is established.

Here we substitute the controller by analog computer. Later on we use an industrial controller. The application of a modern digital computer follows. It can be programmed to control the reactor in many kinds of modern control theory and acts also as data monitor of reactor and so on.

Besides the courses the reactor is often used for doctor thesis works. Many works are done with neutron noise and reactor control. Here the main advantage of the reactor is the missing cooling. The neutron population is only influenced by statistic of fission and follows the theory of reactor kinetic.

V. Reactor Data

Power	100 mW
Maximal thermal neutron flux (Fig. 7)	$6 \cdot 10^{6}\ N \cdot cm^{-2} \cdot s^{-1}$
Life time of neutrons	$4 \cdot 10^{-5}\ s$
Max. radiation on wall of outer reactor vessel	$< 2{,}5\ mrem\ h^{-1}$
Neutron dosis on thermal column underside	$10\ r\ h^{-1}$
γ-dosis on thermal column underside	$100\ r\ h^{-1}$
burn up of uranium in one year full power	$30\ \mu g\ \ 235\ U\ \ Y^{-1}$
reactivity control rod	∿ 0,6 $
reactivity core halves separation	> 7 $
temperature coefficient	$- 0{,}034\ \%\ grd^{-1}$

Remarks

The reactor can be used without any change at higher power levels up to ten watt, if the shielding is reinforced by a wall of concrete blocks around the reactor vessel.

APPLICATIONS OF A LOW POWER NUCLEAR REACTOR

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Abstract

The Omaha Nebraska Veterans Administration Medical Center (OVAMC) TRIGA reactor is a research reactor designed and fabricated by General Atomic. The reactor first achieved criticality on June 30, 1959. It is a below grade, open-tank-type, light water moderated, cooled, and shielded reactor that currently is authorized to operate in the steady-state mode at thermal power levels up to 18KW with an excess reactivity limitation of 0.79% Delta K/K.

REACTOR CORE

The reactor core consists of a relatively compact array of standard aluminum clad TRIGA fuel elements, graphite dummy elements, three boron carbide control rods, control rod guides, an americium beryllium neutron startup source, and irradiation facilities (Fig. 1). The fuel elements are spaced so that about 33% of the core volume is occupied by water, yielding a fuel-to-water ratio resulting in a critical mass near the minimum value for 20% enriched uranium fuel. The elements are held in concentric rings by an upper and a lower grid plate. The reactor currently requires 56 fuel elements to achieve criticality and to provide the authorized excess of reactivity (0.79% Delta K/K) necessary to meet operating requirements. The balance of the 85 fuel element positions are occupied by experimental facilities or graphite-reflector elements. The latter are elements in which the U-ZrH_x fuel is replaced by graphite.

The reactor core geometry of the Omaha VAMC reactor is similar to that of most of the 58 TRIGA reactors in operation throughout the world, 27 of which are in the United States. However, the cladding for the OVAMC reactor fuel is

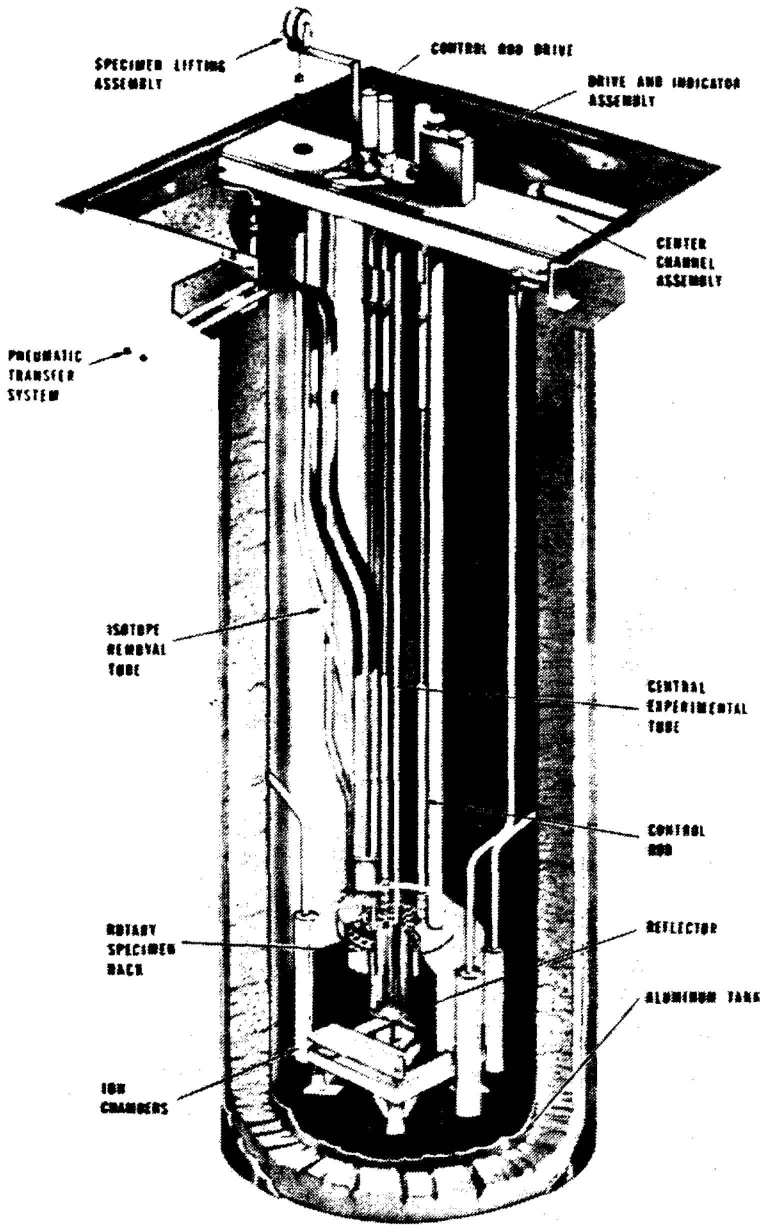


Fig. 1. Elevation view of TRIGA Mark 1 Reactor

aluminum, which was used only in the first few TRIGA reactors. The instruments and control are similar to those on other research reactors licensed by the U.S. Nuclear Regulatory Commission. The core is surrounded by a cylindrical graphite reflector that is completely encased in a welded aluminum container. Flooding of the reflector container because of a leak would decrease reactivity.

FUEL ELEMENTS

The active part of each aluminum clad TRIGA cylindrical fuel element (Fig. 2) is approximately 3.6 cm in diameter by 0.36 m long and is a solid homogenous

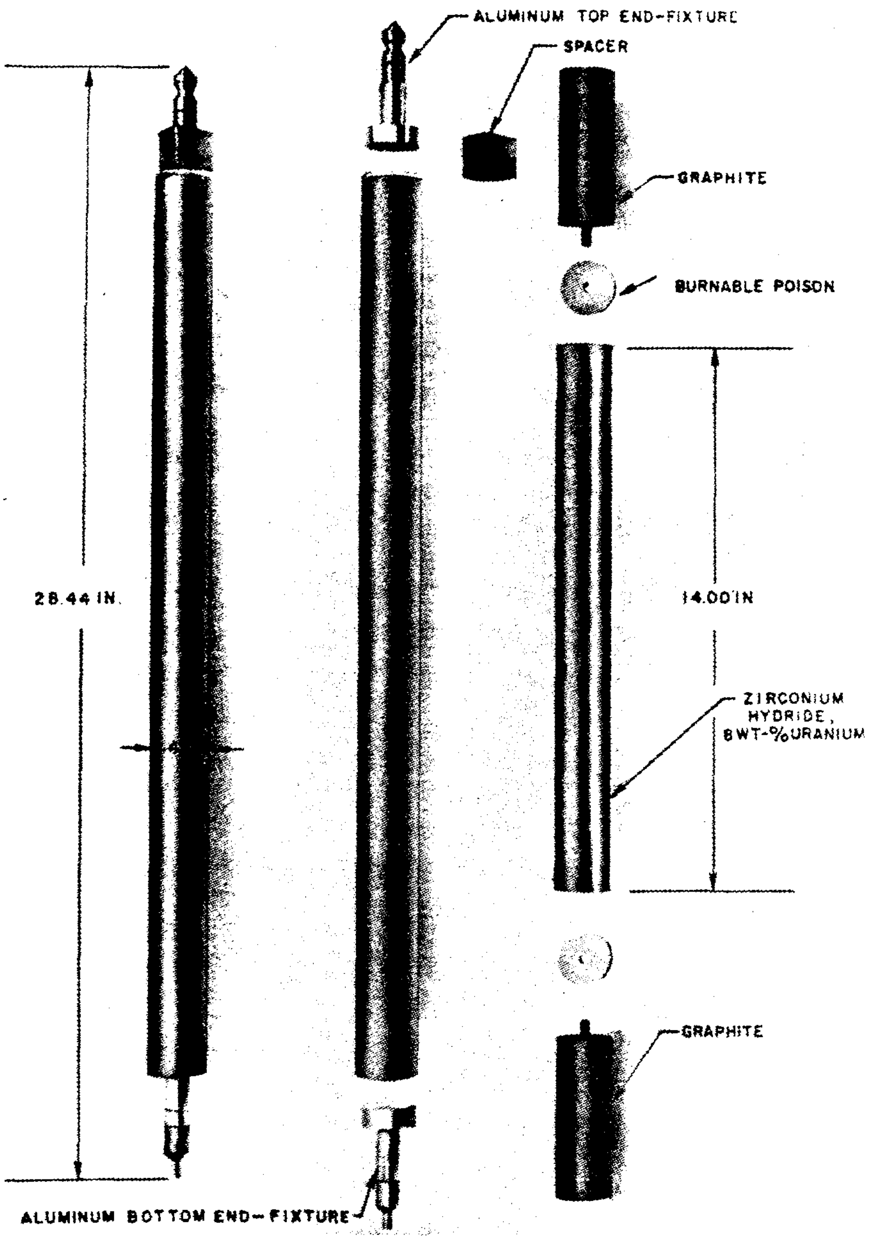


Fig. 2. TRIGA fuel-element assembly

mixture of a $U-ZrH_x$ alloy containing 8 weight-percent uranium enriched to less than 20% in ^{235}U. The hydrogen-to-zirconium ratio is approximately 1.0. A thin aluminum wafer at each end of the active fuel contains samarium oxide as a burnable poison. Each element is jacketed with a 0.076-cm-thick aluminum can. Ten-cm sections of graphite are inserted in the can above and below the fuel to serve as top and bottom neutron reflectors for the core. Aluminum end fixtures are attached to both ends of the can. The overall length of each element is approximately 0.72m. Visual examination of fuel elements on a quarterly basis has shown no indication of any deterioration or swelling. The alternative stainless-steel cladded element which is the current standard is identical to the aluminum clad element with the exception that the hydrogen-to-zirconium is approximately 1.65 to 1.7 and the active part of the fuel element is 0.38 m long. The burnable poison is aluminum-samarium and the cladding is 0.05-cm-thick stainless steel.

CONTROL RODS

The power levels in the reactor are regulated by three boron-carbide control rods. The control rods operate in perforated aluminum guide tubes. The guide tubes are attached to the bottom grid plate, and the upper grid plate provides lateral support. Each control rod has an extension tube that connects to a drive mechanism through an armature and electromagnet system (Fig. 3). One control rod, designated as the safety rod, is completely withdrawn during

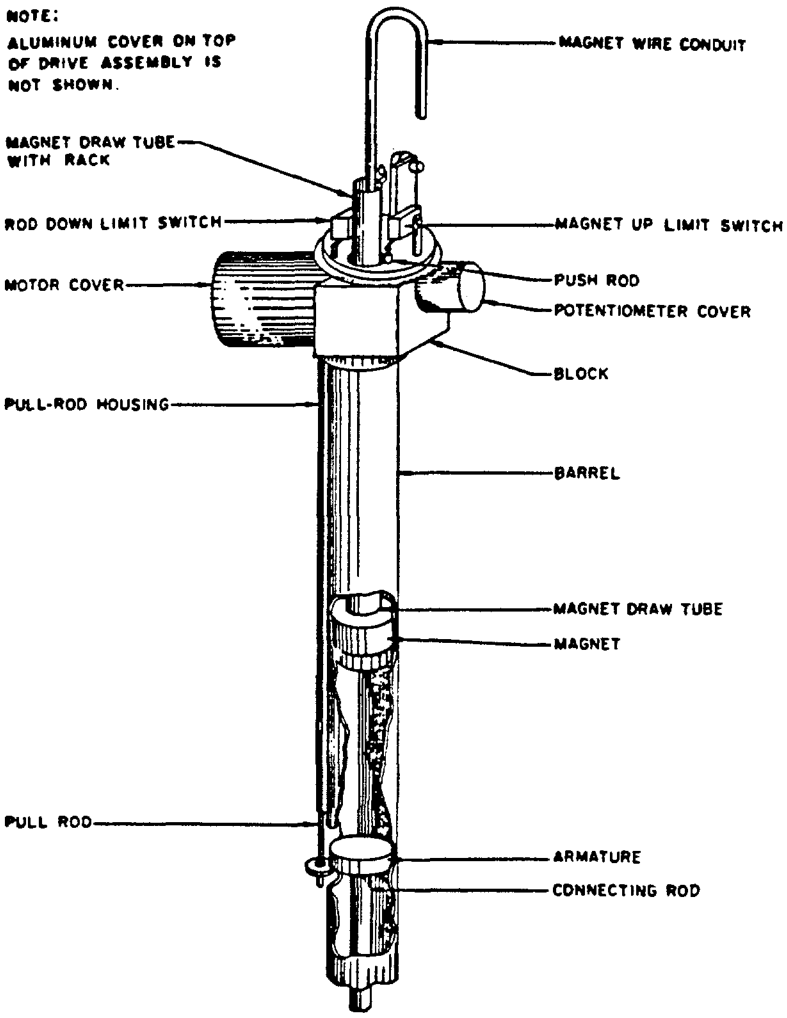


Fig. 3. Control-rod drive mechanism

operation and is worth approximately 1.5% Delta K/K. The other two control rods are worth approximately 1.5% Delta K/K and 0.36% Delta K/K respectively.

REACTOR TANK

The reactor is near the bottom of a below-grade cylindrical pit (Fig. 1) located in the basement of the 12-story OVAMC hospital building. The pit contains a 2.1 m-inside diameter steel tank with a 0.64 cm-thick wall. The tank rests on a 0.28 m-thick concrete slab. A 0.25 m-thick poured concrete wall surrounds the outside of the tank. The concrete slab and wall provide a protective barrier between the tank and the surrounding soil. The inside of the tank is covered on the sides by a layer of pneumatically applied mortar approximately 5 cm thick and the bottom by a layer of poured concrete approximately 10 cm thick. The entire inner surface is coated with two applications of waterproof epoxy resin coating. Visual observation of the tank with binoculars shows no evidence of deterioration of the tank during the past 26 years. The reactor tank contains approximately 15,140 liters of deionized water with a normal shielding depth of 4.9 m above the top grid plate. The natural thermal convection of this water adequately dispenses the heat generated in the core by the normal operation of the reactor. The pool water is pumped at 38 l/min through a 60,000 BTU/hr chiller unit that ultimately disposes of the heat to the atmosphere outside of the Medical Center building. If the external cooling system fails with the reactor operating at 18 KW the rate of rise of the temperature of the water in the reactor tank will be less than 1°C per hour.

REACTOR COOLING SYSTEM

Cooling water flows from the reactor tank to a water monitor chamber where temperature, conductivity, and gamma radioactivity are measured. The circulating pump takes water from the monitor and discharges it through a refrigerated heat exchanger, a 10 micron filter, a 85 liter mixed bed deionizer, a flow meter and back into the reactor tank (Fig. 4). The cooling water loop takes suction from the reactor pool at a point about 1 m below the pool surface. Thus a piping rupture could draw the pool down only 1 m and would still leave the reactor core adequately shielded.

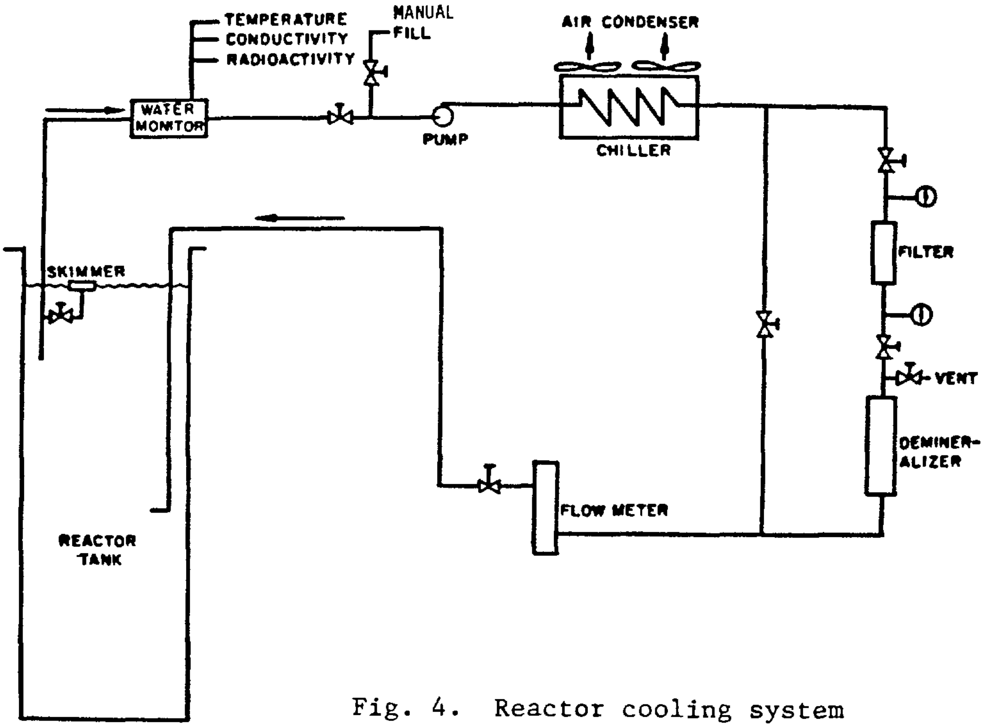


Fig. 4. Reactor cooling system

REACTOR INSTRUMENTATION

The operation of the reactor core is monitored by four separate detector channels. A fission chamber, two boron-lined compensated ion chambers, and a boron-lined uncompensated ion chamber constitute the reactor core monitoring system. These detectors monitor the neutron-flux density of the core and provide trip signals to the safety circuits.

DYNAMIC DESIGN

The safe operation of a TRIGA reactor during normal operations is accomplished by the control rods and is monitored accurately by the core power-level detectors. A backup safety feature is the reactor core's inherent large, prompt, negative temperature coefficient of reactivity resulting from an intrinsic molecular characteristic of the U-ZrH_x alloy at elevated temperatures. Because of the large, prompt, negative temperature coefficient, step insertion of excess reactivity resulting in an increasing fuel temperature will be compensated for by the fuel mixture rapidly and automatically. This will terminate the resulting excursion without any dependence on 1) the electronic or mechanical reactor safety systems or 2) the actions of the reactor operator. Because of the large, prompt, negative temperature coefficient of reactivity, changes of reactivity resulting in a change in fuel temperature during steady-state operation also will be rapidly compensated for by this special fuel mixture, thus limiting the reactor-steady power level. Similarly, this inherent characteristic of the U-ZrH_x fuel has been the basis for designing TRIGA reactors with a pulsing capability.

EXPERIMENTAL FACILITIES

a) Pool Irradiations

The open pool of the reactor permits bulk irradiations in the water outside the cylindrical graphite reflector.

b) Pneumatic Transfer System

A 3.18 cm outside diameter pneumatic transfer tube is provided for the rapid transport of samples to and from the reactor core. The sample holders can be inserted or removed while the reactor is in operation through a constant exhaust system powered by a vacuum cleaner motor. The exhaust is vented through a filter to the exhaust duct. The pneumatic system has automatic timing controls and is used for short irradiations.

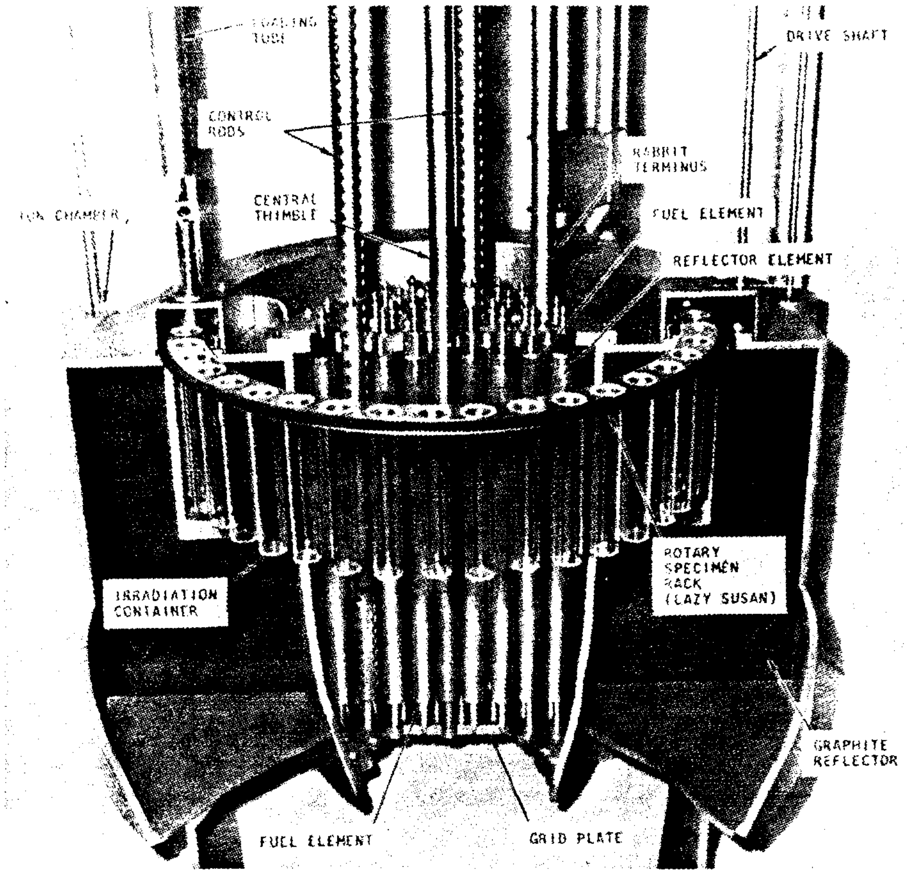


Fig. 5. TRIGA Mark I Core Configuration

c) Rotary Specimen Rack (Fig. 5)

The rotary specimen rack consists of an aluminum ring (located at the level of the top grid plate) that can be rotated around the core. Forty evenly spaced aluminum cups are hung from the ring and serve as irradiation specimen holders. The ring can be rotated manually from the top of the reactor pool so that anyone of these cups can be aligned with the single isotope-removal tube that runs up to the top of the reactor. An indexing and keying device is provided to ensure positive positioning of the cups. The rotary specimen rack is enclosed completely in a welded aluminum container which is designed to be watertight. Flooding this container will decrease the reactivity of the reactor. In order to maintain a constant neutron flux for all samples during a long irradiation, a motorized drive continuously rotates the specimen rack.

d) Central Thimble

A central thimble is provided to permit irradiations in the region of maximum neutron flux. It consists of a vertical 3.4 cm inside diameter aluminum tube leading from the top of the reactor pool through the center of the reactor core and terminating below the bottom of the core. The bottom of the tube is capped, but holes drilled in the wall of the tube directly above the upper grid plate ensure that the portion within the fueled region will be filled with water during reactor operation. Removing the shield water from the portion of the central thimble above the upper grid plate using air pressure provides a highly collimated beam of neutron and gamma radiation. The neutron flux of the various irradiation facilities is shown in Table I.

Table I. Facility neutron flux

OMAHA V.A. MEDICAL CENTER REACTOR FACILITY

REACTOR: 18KW TRIGA MARK I

1. NEUTRON FLUX AT 17 KW OPERATION
   - A. ROTARY SPECIMEN RACK
     - (1) THERMAL: 1.15×10^{11} n/cm^2-sec.
     - (2) 2.9mev: 3.37×10^{9} n/cm^2-sec.
     - (3) 6.3mev: 3.72×10^{8} n/cm^2-sec.
     - (4) 8.7mev: 6.87×10^{6} n/cm^2-sec.
   - B. PNEUMATIC TRANSFER TUBE: 3.17×10^{11} n/cm^2- sec
   - C. CENTRAL THIMBLE: 7.89×10^{11} n/cm^2-sec.

COST

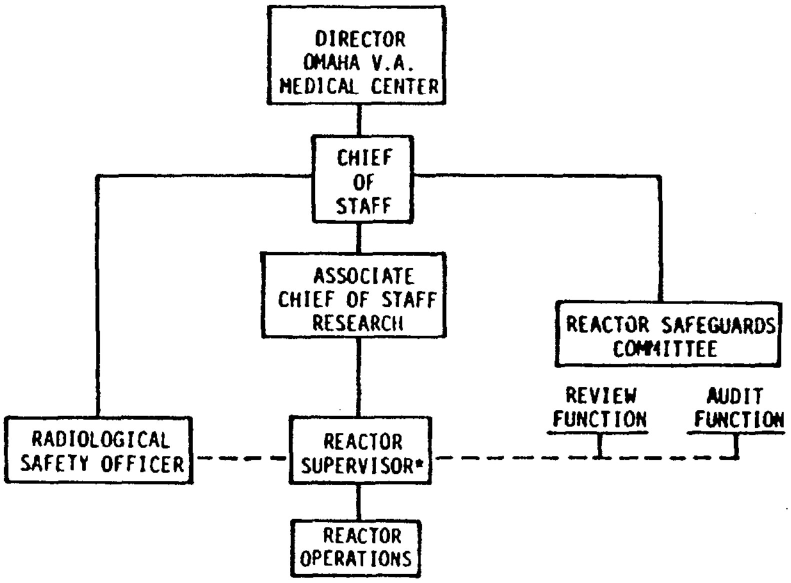
The cost of the complete reactor facility installed in the basement of the 12 story Veterans Administration Hospital on June 30, 1959, was $167,000. Based on current costs a similar 250kW reactor today would cost $3,000,000. to $3,500,000. Currently, our yearly operating costs are $84,000. per year which include the salaries of a Reactor Supervisor/Principal Scientist, a Consulting Professor/Principal Investigator, and a Chemist/Reactor Operator. The facility has been very reliable requiring less than $250. per year in replacement parts such as vacuum tubes, and other electronic and mechanical components. Maintenance is done by the VA Research Service Electronics Unit.

FUEL UTILIZATION

An important advantage of a low power research reactor is the small amount of ^{235}U burnt up. Since start up on June 30, 1959, the facility has been operated for 343 Megawatts and the total ^{235}U burn up is 16.21 g ^{235}U. The current enrichment is 19.66% and the average yearly burn up of ^{235}U is 0.66 g. The original inventory of ^{235}U was 2033.21 g with an enrichment of 19.8%.

STAFFING AND ORGANIZATION

The responsibility for safe operation of the reactor facility is vested within the chain of command shown in Fig. 6. The Reactor Supervisor is delegated responsibility for overall facility operation. The Reactor Supervisor and one Reactor Operator are the only paid full time staff of the Reactor Facility. The audit function is carried out on a volunteer basis by representatives of the local Power Reactor.



*Responsible for Facility Operation

Fig. 6. Facility Organization

UTILIZATION OF THE FACILITY

I. Training of Power Reactor Operators

Although most of the candidates for the course had either received previous training in the Westinghouse Reactor Operator Training Program, had operated nuclear submarine reactors or had previously operated power reactors, they were not offered the opportunity to perform the extensive manipulation of a reactor that a small research facility will allow.

In designing the course it was decided that for 100% participation in each experiment by the trainees, they would be divided into two groups of not more than five each. Each group was allotted four hours per experiment and while one group was performing an experiment the other group was in a class room with an instructor writing up and critiquing the previous lab and preparing for the next experiment. It was also decided that for maximum effectiveness, students would be allowed to write up each experiment during the discussion period.

Table II, shows the schedule for a 10 day course given for Omaha Public Power Company Fort Calhoun Station Operators. A course was also held for Nebraska Public Power District Cooper Nuclear Station Operators.

Prior to the training period on the reactor, each group had an on-site 12 week Nuclear Fundamentals Course conducted by the University of Nebraska. Thus it was not necessary to start with basic fundamentals.

Table II. Power Reactor Operator Training Course

Class Schedule

Day	Experiment	Group A	Groups B
1	Instrumentation Familiarization and Calibration - Exp. #2	AM Experiment PM Discussion	Discussion Experiment
2	Unloading Fuel Exp. #1 Fuel Loading Exp. #3	AM Experiment PM Discussion	Discussion Experiment
3	Unloading Fuel Exp. #1 Fuel Loading Exp. #3	AM Discussion PM Experiment	Experiment Discussion
4	Reactor Shutdown and Reactivity Measurements, Exp. #4	AM Experiment PM Discussion	Discussion Experiment
5	Approach to Critical with Control Rod & Normal Startup and Shut Down Exp. #5	AM Experiment PM Discussion	Discussion Experiment
6	Power Level Control and Rod Manipulation Exp. # 6	AM Experiment PM Discussion	Discussion Experiment
7	Delayed Neutron and Compensation in CIC - Exp. #7	AM Experiment PM Discussion	Discussion Experiment
8	Rod Calibration Exp. #8	AM Experiment PM Discussion	Discussion Experiment
9	Internal Reactivity Changes Exp. #9	AM Experiment PM Discussion	Discussion Experiment
10	Gamma Effects and Programmed Power Changes Exp. #10	AM Experiment PM Discussion	Discussion Experiment

Some of the highlights of the individual experiments are as follows:

Instrumentation Familiarization and Calibration: Includes source-detector geometry effects demonstrated by placing the Fission Counter in a fixed position and varying the location of the neutron source.

Unloading Fuel: Fuel from the reactor is completely removed from the core and stored in racks around the walls of the reactor tank. This experiment demonstrates fuel handling procedures, including fuel inventory, and radiation safety and monitoring procedures.

Fuel Loading: Includes the planning and execution of a fuel loading plan for safe approach to critical and demonstrates 1/M techniques and the importance of source-detector geometry. During the approach to critical experiment the student is instructed to observe the reactor kinetic behavior during subcritical operation and to note how this behavior changes as criticality is approached.

Reactivity Measurement and Shutdown Margin: Demonstrates the rod-drop, prompt jump, and positive period method of measuring reactivity and provides a measurement of shutdown margin for the reactor.

Approach to Critical with Control Rod: Uses the 1/M technique for approach to criticality using a control rod and again demonstrates reactor kinetics.

Delayed Neutron Effect: The effect of delayed neutrons for both positive and negative reactivity insertions are studied.

Compensation Effects on Compensated Ion Chambers: The response of compensated ion chambers during startup and shutdown are shown for over-compensation and under-compensation of the instruments.

Internal Reactivity Changes: The instructor simulates Xenon buildup on a condensed time basis by inserting the regulating rod causing a decrease in power. It is then the responsibility of the trainee to hold the power level constant to ± 1%.

Gamma Effects: The effects of high gamma fluxes on the reactor instrumentation is investigated.

Programmed Power Changes: This experiment combines the knowledge and experience gained in earlier experiments. The trainee is given a prescribed set of reactivity changes from which he predicts the reactor response. The student then carries out the prescribed reactivity program and compares the actual results with those predicted.

After presenting the course to 40 trainees it was found that without exception the students were able to understand better the operation of a reactor and had the opportunity to obtain answers to many questions that they had not been able to have answered during their prior experience with reactors. This was primarily due to the fact that by utilizing a small research reactor they had more opportunity to manipulate the controls of the reactor and to observe the reactor kinetics. The students were asked to bring the recorder chart made during each of their laboratory periods to the discussion period, and a very popular part of the course was the discussion that arose from examining these charts. Many times the critique of the charts led to further investigation of reactor kinetics during the next laboratory period. After the initial training period was completed, there were unexplored possibilities for using the research reactor as a refresher course for operators prior to relicensing.

II. Biomedical Research

The Omaha Veterans Administration Medical Center (OVAMC) Nuclear Reactor is utilized in four broad categories: 1) As a VA common resource; 2) for development of procedures for determination of trace element and trace molecule concentration in biologic systems; 3) to assess isomeric transition as a biologic tool; and 4) for a fundamental research program. Each of these categories will be explained in detail.

A. Utilization of the Nuclear Reactor as a V.A. Common Resource

The major purpose of the nuclear reactor laboratory in this category is to serve as a common resource for the VA Medical Center investigators in Omaha and throughout the country. Specifically, it can be contacted as to whether trace element or trace molecular analyses related to specific medical problems can be accomplished. If there is no literature or VA Medical Center Reactor Laboratory procedure available, the feasibility of developing a unique procedure will be explored with the investigator. If there is an alternative procedure such as atomic absorption spectrometry or mass spectrometry that can be used elsewhere to assay the samples this information can be related to the investigator.

Neutron activation analysis (NAA) has been shown (1) to be one of the most sensitive tools for determining trace amounts of radioactivatable elements in biological samples. By irradiating a sample of tissue or body fluid with reactor neutrons, concentrations of the order of parts per billion for over 45 elements can be determined. However, in the past, the availability of a nuclear reactor for activating samples was limited. Because most of the reactors that would be available are large megawatt facilities and have a high operating cost, the analyses for a large number of biological samples has been expensive and, consequently, not very cost effective. Of the 41 biological applications papers presented at the 6th International "Modern Trends in Activation Analysis Conference" held in Toronto, Canada, in June, 1981, only eight papers were presented by investigators from the United States and they utilized only five separate reactors. The operating budgets of four of the five reactors were over $120,000. per year (2) with only the Omaha VA Medical Center reactor having an operating budget of $73,000. being less. Of the 35 U.S. Research Reactor Facilities capable of performing neutron activation analyses on biological samples, only seven reported an operating budget of less than $90,000. per year (2).

Any analytical technique contributes to medical research only if it can provide information to solve a specific medical problem. Quite often activation analysis techniques are developed with no specific application in mind at available facilities instead of answering specific medical questions. The Omaha VA Medical Center reactor resource is unique in that it has: 1) a low operating budget allowing samples to be irradiated on a cost-effective basis, and 2) a research team, which includes radiochemists from the University of Nebraska at Lincoln, biochemists, physicists, and medical investigators from Omaha Medical Schools and outstate VA investigators. Consequently, techniques have been developed and applied to solve specific medical problems. The Omaha VA Medical Center has the only nuclear reactor laboratory located within a hospital facility in the world. Having this resource adjacent to the medical research wing further adds to the usefulness of the facility. Its record as a common resource and its publishing record of the past 13 years demonstrates this fact.

B. Development of Procedures for Determination of Trace Elements and Trace Molecule Concentration in Biological Systems.

1) Elemental Analyses

In general the most widely used NAA approach for trace element determinations, involving biological samples, as seen in the literature has been by instrumental neutron activation analysis. However, due to the abundance of the interferring ions sodium and chlorine in biological samples, we sometimes find it necessary to use pre-or post-irradiation chemistry to separate out these ions. Table III shows the methods that have been developed in our laboratory. Precise techniques for each element can be found in the <u>Analytical Chemistry</u> papers listed in the bibliography.

Table III. Neutron Activation Analysis Methods

ELEMENTAL NEUTRON ACTIVATION PROCEDURES

ELEMENT	METHOD	BRIEF PROCEDURE	ANALYZED PHASE
COPPER (3)	SOLV. EXT.	DITHIZONE 'd' IN CCl_4	ORGANIC AS Cu 'd''
ZINC (3)	SOLV. EXT.	AQUEOUS LAYER OF ABOVE ADDED TO SODIUM THIOSULFATE AND 'd' IN CCl_4	ORGANIC AS Zn 'd''
MANGANESE (3)	SOLV. EXT.	AQUEOUS LAYER OF ABOVE ADDED TO SODIUM DIETHYLDITHIOCARBAMATE AND $CHCl_3$	ORGANIC AS Mn-DIETHYLDITHIOCARBAMATE
MAGNESIUM (3)	SOLV. EXT.	AQUEOUS LAYER OF ABOVE ADDED TO N-BUTYLAMINE AND TTA IN $CHCl_3$	ORGANIC AS Mg-TTA
CADMIUM (4)	SOLV. EXT.	'd' IN BENZENE, SODIUM POTASSIUM TARTRATE AND NaOH, ORGANIC PHASE WASHED WITH NaOH, AND H_2O DISSOCIATED WITH HCl, ACID PHASE PUT INTO ADDITIONAL SEPARATION FUNNEL WITH 'd' AND CCl_4	ACID LAYER
SELENIUM (5)	N.D.	DIALYZE AND LYOPHILIZE LIQUID SAMPLES. LYOPHILIZE SOLID SAMPLES	LYOPHLIZED SAMPLE
IODINE (6)	SOLV. EXT.	HNO_3-H_2O_2 OXIDATION WITH CCl_4 EXTRACTION	ORGANIC
ALUMINUM (7)	CATION EXCH.	AG50WX8 CATION EXCHANGE RESIN. ELUTION WITH 1M HNO_3	RESIN
VANADIUM (8)	CATION EXCH.	AG50WX8 CATION EXCHANGE RESIN. ELUTION WITH H_2NO_3 AND NH_4OH	ELUENT

d = DITHIZONE
d' = DITHIZONATE
SOLV. EXT. = SOLVENT EXTRACTION
TTA = THENOYLTRIFLUOROACETONE
EXCH. = EXCHANGE
N.D. = NON DESTRUCTIVE

2) Molecular Neutron Activation Analysis (MONAA)

Because of the complexity of living organisms and the paucity of analytical techniques, it has been difficult up to now to determine the molecular nature of trace elements in biological matrices. However, with the increasing emphasis for information on the molecular nature of the trace elements in biological systems and recent improvements in separation and detection methods such as gas chromatography (GC) and high performance liquid chromatography (LC), it is now possible to devise approaches in chemical neutron activation analysis for trace molecule determinations. One of the most powerful new techniques is liquid chromatography. However, it suffers in that the most sensitive LC detectors currently available are only 1/1000 as sensitive as GC electron capture detectors. Because of the trace amounts of molecules in biological samples it is necessary to devise unique methods of combining chromatography and neutron activation analysis in order to assay samples in the parts per billion range.

By combining neutron activation detection with gel filtration and high-performance liquid chromatography (LC) our laboratory has developed a method for detecting and quantitating the iodoamino acids MIT and DIT and the thyroid hormones T_2, T_3, and T_4 in urine (9). Although the procedure developed is not as simple as radioimmuno assay (RIA) it allows the simultaneous detection of trace quantities of thyroid derivatives and offers an alternate technique for assigning thyroid hormone assay values for various biological systems. Except for the reported values for thyroid derivatives in serum, there is a paucity of data for urine values. It is interesting to note

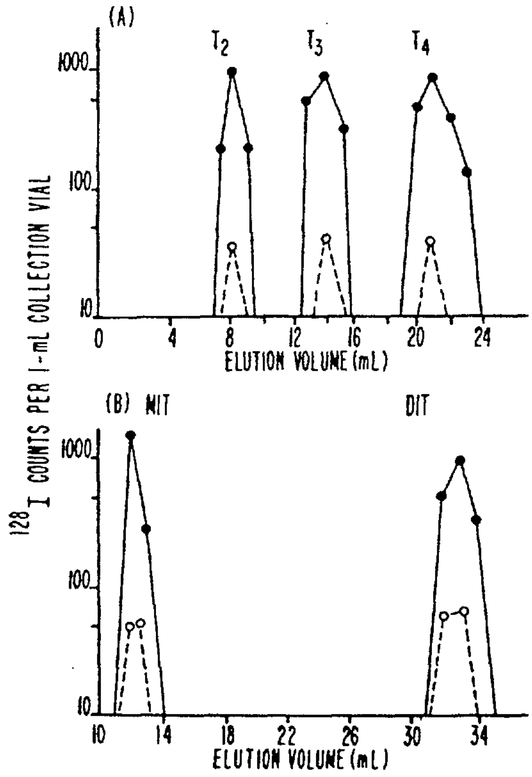


Fig. 7. Chromatograms of human urine (---) and human urine spiked with 1 ppm iodoamino acids and hormonal iodine (——), employing neutron activation detection of ^{128}I after a gel-filtration step through a Bio-Gel P-2 resin. The HPLC mobile phase is (A) water/methanol (40/60 (v/v)) + propionic acid (0.25%) and (B) water/methanol (85/15, (v/v)) + propionic acid (0.25%).

that because of the number of compounds present in urine, it is not possible to distinguish trace quantities of the thyroid derivatives by conventional techniques such as LC-UV (254 nm) detection. Fig. 7 shows chromatograms of the final separation.

The next procedure developed was for the determination of chlorinated pesticides in urine (10). While the tri-chloro bis (p-chlorophenyl) ethane family of compounds (DDT) has been banned from use in many countries, it is still widely used in some countries, and thus its use can constitute a serious problem for the global population. The urinary excretion of DDA, a metabolite of DDT, can be used as an indicator of exposure to DDT. The most widely used technique, especially by the U.S. Environmental Protection Agency laboratories, is GC separation employing an electron capture detector.

Unlike previous procedures, where chemical disintegration is employed prior to GC separation our molecular neutron activation analysis procedure involves physical separation of DDA from other compounds by liquid chromatographic (LC) separation with subsequent neutron activation of the collected eluent producing ^{38}Cl. Radioassay of the contents of the irradiated vials then yields quantitative results. Chromatograms of the procedure are shown in Fig. 8.

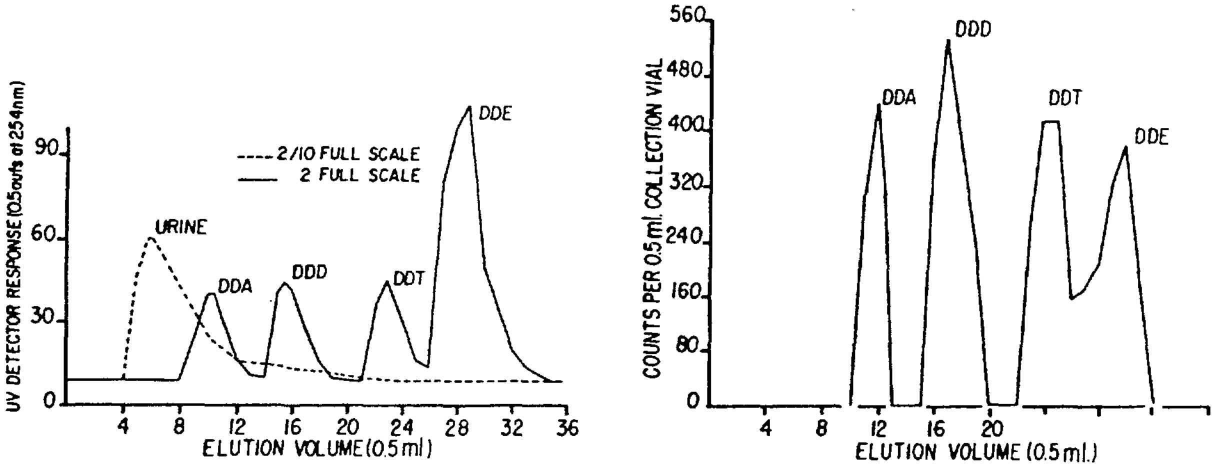


Fig. 8. Chromatograms of human urine (---) and human urine spiked with 1.0 ppm of the chlorinated compounds (—) after a solvent extraction step (on the left), employing a neutron activation detection of ^{38}Cl after a solvent extraction step (on the right).

Our most recent effort has been the development of a method for the determination of trimethylselenonium ion (TMSe) in urine by anion exchange - cation exchange chromatography, selectively capturing the TMSe on the cation exchange resin (11). The TMSe fraction is irradiated with neutrons and radioassayed for ^{77M}Se activity. TMSe is an important urinary metabolite at doses of selenite insufficient to trigger the respiratory excretion of demethylselenide (DMSe). The procedure is very effective in isolating the TMSe from selenocysteine and selenomethionine as can be seen in Fig. 9. The inorganic selenium, not shown in the figure was also shown to be eluted in the first 5 mililiters. The lower limit of detection of this method at the current neutron flux of 3.7 x 10" n/cm^2-sec is 10 ppb TMSe.

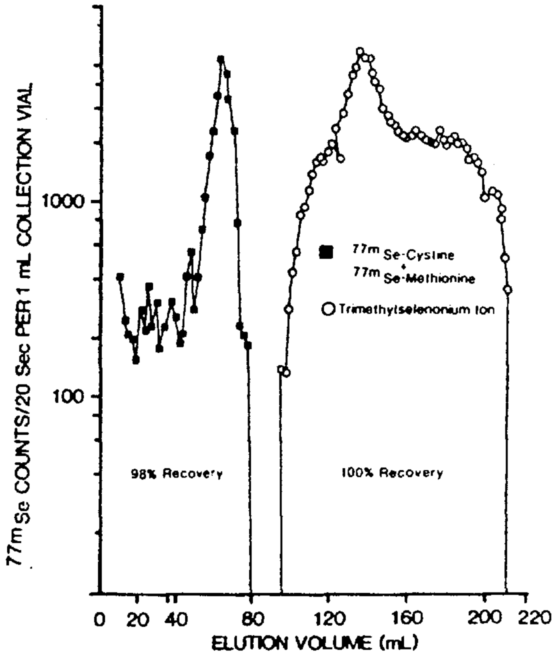


Fig. 9. Chromatogram of human urine spiked with selenium compounds employing neutron activation detection of ^{77m}Se after an elution with 0.5 M $LiNO_3$ solution through the tandem ion exchange chromatography columns.

C. The Assessment of Isomeric Transition as a Biologic Tool.

As a result of nuclear reaction, a nuclide may be left in a high energy level (metastable nuclear state). The lifetime of the metastable state is usually on the order of 10^{-17} to 10^{-12} second. However, a nucleus can exist in a metastable state for a length of time long enough to be measured. A number of isomers which have a comparatively long half-life have been found in the last decades for example, Co-60m (10.7 min.), Br-80m (4.4h), Br-82m (6.2m) and I-130m (9.2 min.).

De-excitation of a nucleus from its metastable state to the ground state (isomeric transition) results in internal conversion or release of energy in the form of gamma-ray emission. During the internal conversion process extra-nuclear or orbital electrons may acquire enough energy to be released from the atom. The ejected electron is called an "Auger electron". Since the discovery of the isomers ^{82m}Br with a half life of 6.2 minutes and ^{130m}I with a half life of 8.9 minutes it is possible to study the consequences of the Auger effect in simple chemical systems, aqueous solutions of biomolecules and in biological systems. The biological consequences of the Auger effect are well documented (12,13,14,15). There are drastic chemical and biochemical consequences associated with the Auger effect which result in double strand breakage of the DNA molecule. Up to the present time the mechanisms leading to the biological damage especially by Auger isotopes such as ^{125}I is not well understood. The question is how applicable is the Auger effect Coulombic explosion model to condensed phase biological systems? That is, what is the relative importance of charge neutralization, ionization and/or excitation by direct interaction with Auger electrons? This laboratory has been involved for the past 20 years in the study of isomeric transition reactions of ^{82m}Br and ^{130m}I in organic and biological systems. In order to realize the potential of isomeric transition as a diagnostic or therapeutic tool it is important to develop a long range program evaluating the physical and chemical consequences of the effect in simple systems and extrapolate these results to more complex biological systems. Already we have determined the kinetic energy spectrums of bromine ions and iodine ions involving simple organic molecules in the gas phase by virtue of isomeric transition Coulombic explosion for ^{82m}Br (16) and ^{130m}I (17). The number of fundamental studies we have reported is too numerous to indicate here. One of the important experiments we have already completed involves the applicability of the Auger effect Coulombic explosion model to condensed phase systems (18). We have found that the Auger effect Coulomb explosion model has applicability to simple organic molecules such as methyl bromide dissolved in water. It is important to realize that whether it is for diagnostic or therapeutic purposes radioiodine labeled derivatives have the same chemical properties as the non-radioactive pharmaceutical. On the other hand, iodine-130m-an isomer of iodine -can undergo high energy chemical reactions in a "test tube" releasing tremendous amounts of localized radiation by virtue of the Auger process. This amplification effect has been reported in the recent literature, especially involving X-ray resonance absorption of zinc in biological systems. We are mainly interested in studying iodine reactions activated by isomeric transitions in thyroid-related derivatives in an aqueous medium, observing reaction selectivity not found in the usual radio-iodine labeled reactions and in applying our results as a tool for molecular biologists (thyroid chemical applications as a diagnostic or therapeutic tool).

Radionuclides which decay with emission of Auger electrons produce more localized radiation damage than radionuclides which are pure beta emitters, and much research has been done recently concerning the particular toxicity of the Auger effect. For example, it has been found that the toxicity of I-125 which decays 100% by electron capture is about 5-10 times greater than tritium (H-3), a pure beta emitter, when incorporated into DNA and thyroid gland. So far, experiments on toxicity of the Auger effect only emphasize empirical observations. Perhaps one of the difficulties in determining the reaction mechanisms involved is the change in nature of the incorporated radioisotope after decay. For example, the incorporated I-125 decays to Xe-125 which is a stable isotope. Therefore it will be difficult to analyze the products formed as a result of the Auger effect caused by the decay of I-125. However, if one can incorporate an isomer of a radioisotope into a molecule, the daughter of the radioactive isomer can be easily detected since the daughter is also a radioactive atom.

By incorporating I-130m produced by radioactive neutron capture into a biomolecule, e.g., MIT or DIT, one could detect the products formed as a result of the Auger effect caused by the isomeric transition of I-130m → I-130. Analysis of the product distribution will allow one to obtain some insight into the reaction mechanisms involved. Another advantage of using I-130m is that experiments can be conducted in the absence of interfering radiolytic effects due to the gamma-radiation in the reactor. The low-neutron flux of a low power reactor has proved to be ideal for this work.

A better understanding of the reaction mechanisms will allow us to obtain a more realistic evaluation regarding the question of health physics and the potential of applying isomeric transition to biological experimentation and medicine. Since there are a large number of radioactive elements which are important in biology and which may decay by isomeric transition, e.g., Co-54m (IT) → Co-54 and Zn-69m (IT) → Zn-69, the study of isomeric transition of I-130m → I-130 may serve as a model for future studies of the isomeric transition of these atoms in other biomolecules.

D. Fundamental Research Program - Under the Direction of Professor E.P. Rack, University of Nebraska-Lincoln, Nebraska and Reactor Consultant.

Hot atom, high energy or "hot" chemistry, is an important tool for basic research in areas important to energy, environment and medical technology. "Hot" chemistry is a probe, an interactive science which embraces many fields; from hot atom reactions in simple hydrocarbon systems to theoretical development of high energy particle reactions. Utilizing reactive species possessing non-Boltzmann energy distributions, high energy chemists have discovered and characterized new reaction channels in organic and inorganic systems; contributed to the theories of energetics, dynamics and systematics; developed new techniques of chemical detection and analysis; and aided biological and medical sciences.

High energy distributions of atoms and/or ions can be produced via two classes of activation: chemical accelerators and bulb techniques. Each type of experiment produces reactions that can contribute to the characterization of high energy species. Each experimental class relates properties unique to its technique.

Chemical accelerators impart kinetic energy to atoms, ions or molecules by use of electromagnetic, pressure differential or ultrasonic gradients. The particles are accelerated in a straight line (linear or tangential, hence the name "beam" experiment) with a resultant kinetic energy distribution of narrow bandwidth (generally a Boltzmann distribution centered about the terminal accelerator energy). The atomic-, ionic- or molecular-beam is produced in a near vacuum and permits the examination of atom-molecule and/or ion-molecule single collision reactions. The data obtained reveal information on intrinsic properties of reactions; e.g. reactive cross sections as functions of scattering angle and energy. However, chemical accelerators are limited in their abilities to measure endoergic reactions, to have energy resolution and product identification simultaneously, to orient molecules (dynamics), and to study the effect of environment (even 1 torr pressure) and multiple collisions on reactivity.

Bulb techniques are multi-collisionally oriented. The kinetic energy imparted to atoms or ions are the result of nuclear recoil or photochemical recoil activation. While photochemical and some nuclear activation modes produce atoms, ions or radicals within narrow kinetic energy limits, the multi-collisional nature of the technique results in collisional "cooling" of the "hot" entities, producing a broad spectrum of kinetic energies.

Extrinsic properties are readily measured (the hot species or medium taken in bulk) and intrinsic properties are inferred. New reaction channels (both exo-and endoergic) have been observed and characterized. Although molecules cannot be oriented, the ease of product indentification (including diastereomers and enantiomers) permits study of reaction dynamics. The effect of the molecular environment on the reaction systems from low pressure gas to solid state glasses and crystals is easily studied in bulb experiments. These studies can significantly contribute to a better understanding of the photocatalytic cage effects or de-excitation processes, an area that may be important in photochemical energy conversion processes.

In our research work employing the bulb technique, we are interested in the area of monovalent high-energy physical-organic chemistry, concentrating on heavy halogens activated by radiative neutron capture.

E. Problems and Limitations Related to Low Power

The only limitation of having a low power reactor is the lack of sensitivity in neutron activation analysis. In many cases, however, this is balanced by being able to analyze the short half-life isotopes of the element since the interferring ions are not activated to as great an extent thereby keeping the dead time of the radiation detection system in a working range.

In summary, we feel that the advantages of a low power research reactor such as low fuel burn up, low security requirements, low operating budget, and the necessity for less radiation safety requirements due to the lower neutron flux far outweigh the advantages of operating a higher power facility for training and NAA of biological specimens.

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SLOWPOKE-2: LABORATORY REACTOR FOR NEUTRON IRRADIATION

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Abstract

The Slowpoke is a small pool-type nuclear reactor designed for use in universities, hospitals and research centers. The reactor has a low critical mass of less than 1kg of HEU fuel. The AECL has recently developed LEU replacement fuel for these reactors. The reactor is controlled by a single Cd control rod which could cause licensing problems in some countries. Maximum excess reactivity is limited to 3.5mk. In regular use, 10,000 to 20,000 capsules can be irradiated per year yielding 250-350,000 data points in derived results. With an annual operating budget of US$80,000, the estimated cost per result obtained is in the order of US$0.20 - $0.40, which is much lower than most instrumental trace analysis methods. Examples of recent uses include archeometry, biological sciences, chemistry, earth sciences, environmental science, medicine, metallurgy, and industrial uses. The greatest number of irradiations are performed at 2kW. Forth nine percent or irradiations are for less than 1 minute and 44 percent for 1-10 minutes. The reactor has experienced less than one system malfunction per 3 reactor years.

SUMMARY

SLOWPOKE is a novel new type of 5 to 50 kW hybrid pool reactor developed by AECL, Canada and intended for use in universities, hospitals or research institutes. The reactor is compact, reliable, 'user-friendly' and inherently safe to operate and to use over long periods of time as a source of neutrons at fluxes up to or slightly over 10^{12} $cm^{-2} \cdot s^{-1}$. Its design entails a number of features: low critical mass of fuel, high flux-to-power ratio, provision for passive reactivity adjustment for 10-15 operating years, inherent safety through highly negative moderation temperature and void coefficients, absence of conventional automatic 'scram' devices, or need for an attending reactor operator.

The SLOWPOKE design involves a segregation of a volume of water (∿ 1.5 m^3) surrounding the reactor core from the reactor pool itself by having the reactor assembly enclosed in a reactor vessel which is installed in a cylindrical pool of 7-8 metres depth (27 m^3 volume). This arrangement not only limits the circulation of any radionuclides arising from the reactor assembly to a dedicated purification system, but it also restricts and delays heat transport for the reactor core to the surroundings, particularly in the event of any reactor power surge. Principal reactor control over the short-term (daily) basis is by a cadmium adjuster rod and over the longer-term (1-15 years) by adjustments to the core reflector. Stand by shut-down capability using Cd capsules installed manually, is provided also.

Typically a SLOWPOKE-2 is operated for 1500-2500 $h \cdot a^{-1}$ for a total 'nvt' of approximately 2 x 10^{18} per year whereas a useful reactor core lieftime is estimated to be 3 to 3.5 x 10^{19} nvt before replacement. In regular use as a neutron source, about 10,000 to 20,000 capsules containing a wide variety of materials to be neutron-activated can be irradiated per year, yielding as many as 250-350,000 individual data points in derived results. Considering that typical annual reactor operating costs range from \$(U.S.) 60-80,000, the estimated unit cost per irradiation, or per result obtained through access to SLOWPOKE, is of the order of \$(U.S.) 0.20-0.40 which is much lower than most instrumental trace analysis methods.

The operating experience gained by the combined total of 60 SLOWPOKE reactor operating years has proved the reactor to be well-designed, reliable (less than one system malfunction per 3 reactor years), and safe for use in institutions which are situated in heavy-populated urban areas.

1. Introduction

A considerable number of research reactors (about 300) have been installed in both governmental and private institutions mostly during the past three decades. While a fraction of these were dedicated to reactor physics, neutron and radiation physics and materials research, other reactors were operated primarily as a local source of neutrons for (i) radioisotope production and (ii) neutron activation of selected target materials.

Most pool-type research reactors which were designed to operate at power levels of 100 kW or greater have utilized specialized enriched U cores, duplicated safety shut-down and control systems and reactor buildings with restricted exhaust ventilation. These features and the attendant requirement for a sufficient number of licensed operators and radiological safety technologists have usually entailed a reactor capital cost for installation of $(U.S.) 5-10 million and annual operating and maintenance costs of about $(U.S.) 1 to 1.5 million. Because of these costs many research centres, universities or hospitals both in developed and developing countries have considered that the installation and operation of a dedicated nuclear reactor plus associated nuclear instrumentation was too expensive to be justified in terms of the limited extent of nuclear physics, reactor physics, neutron or radiation research that could be performed. It has been for such reasons of cost and staffing requirements, among other reasons it seems, that a substantial fraction of the world's research reactors installed by the 1950's and early 1960's have been closed down.

On the other hand there is much useful pure and applied research possible when sources of neutrons with fluxes greater than 10^{10} are available, and the number and variety of such neutron uses continue to expand, many of which are, potentially of importance to developing countries. Examples of some of these beneficial and unique applications of neutrons that have been made in Canada are cited below in this report. It seems therefore that there is a need to find lower cost and safer sources of neutrons to permit such research and the associated applications to be developed. The development of alternate, low power, simple and safe nuclear reactors can meet such needs. This report describes one such reactor, SLOWPOKE-2, which has the advantages of low costs, safety, compactness and suitability for installation in a regular laboratory building without special containment or ventilation.

Up to the present date, a total of 11 SLOWPOKE reactor installations have been undertaken: the prototype SLOWPOKE, 7 SLOWPOKE-2 units in universities and research laboratories, 2 in foreign countries: Jamaica and West Germany - the latter which has not been completed for reasons for licensing. Among these reactor units extending back to start-up in 1970, there has now been accumulated a total of about 60-65 reactor operating years' experience on which to base assessments of reactor reliability and safety as well as estimates of capital and operating costs.

2. SLOWPOKE Reactor Specifications

SLOWPOKE-2 is a small pool type nuclear reactor using fully enriched uranium fuel, water moderator and beryllium reflector. Operation is at a thermal flux of

$$0.5 \times 10^{11} - 1 \times 10^{12} \text{ n}\cdot\text{cm}^{-2} \text{ s}^{-1}$$

It is designed for use in universities, hospitals and research centres for activation analysis and isotope production. Access to the neutron flux is by "rabbit" irradiation tubes.

The reactor is housed in a closed container suspended in a water pool. This restricts access to the core and provides for limited and controlled release of fission products.

A negative temperature coefficient and low excess reactivity make the reactor inherently safe. Conventional electro-mechanical safety devices are unnecessary and a full-time operator is not required.

A SLOWPOKE-2 installation comprises five major components, each with a distinct fuction. These are the reactor, the pool, the control console and the irradiation and service systems.

2.1 Reactor

The reactor (figures 1, 2, and 3) consists of the core, beryllium reflectors, control rod and drive, neutron detector, thermocouple, five

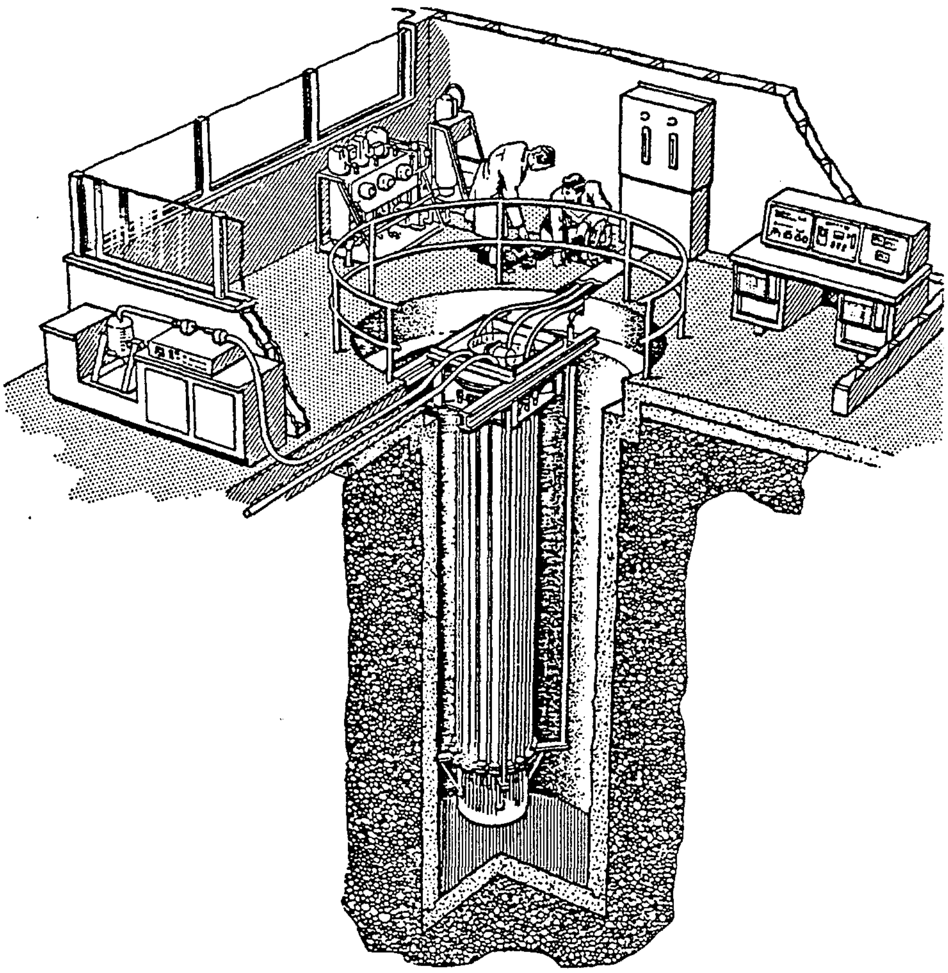
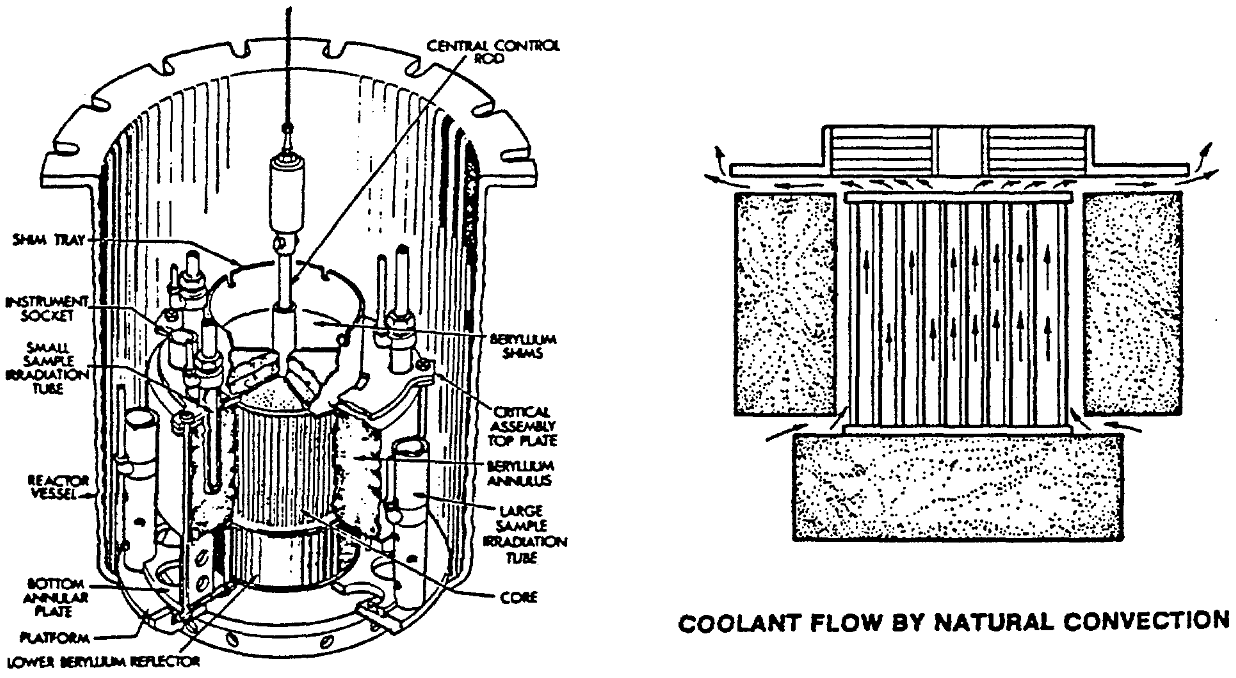


Figure 1. A SLOWPOKE Installation



COOLANT FLOW BY NATURAL CONVECTION

Figure 2. Critical Assembly & Reactor Container

small (inner) irradiation tubes, five large (outer) irradiation tubes and the reactor container.

Figure 2 is a cut-away view of the critical assembly, mounted in the reactor container lower section.

The core comprises the fuel cage and fuel elements. The cage is a spool-shaped assembly of aluminum alloy with space for up to 342 fuel elements. The control rod moves within its central spindle. The fuel elements are ^{235}U enriched uranium-aluminum alloy, extrusion clad with aluminum.

The core sits within the annular beryllium reflector, resting on the lower beryllium reflector. The lower reflector and beryllium annulus are spaced to form the lower orifice, which controls water flow through the core. The critical assembly top plate and annulus are spaced to form the upper orifice. The shim tray holds the upper reflector which consists of semi-circular beryllium shims. Shims are added approximately once per year to compensate for fuel burn-up and poisoning.

The reactor is cooled by natural convection (figure 2). Water enters the core through the lower orifice, rises through the fuel elements, and leaves the core via the upper orifice. It then sinks within the reactor container, transferring heat through the container wall to the pool water.

The control rod is a cadmium tube encased in aluminum. It moves in the centre of the fuel cage, guided by a tube in the shim tray. The control rod is suspended by cable from a single turn drum, mounted on the reactor top plate (figure 3). The drum is driven by a bidirectional AC synchronous motor. Control rod travel is normally limited by electrical microswitches in the drive mechanism, but if these should fail mechanical stops on the drum will limit travel. The rod position potentiometer is incorporated in the drive assembly.

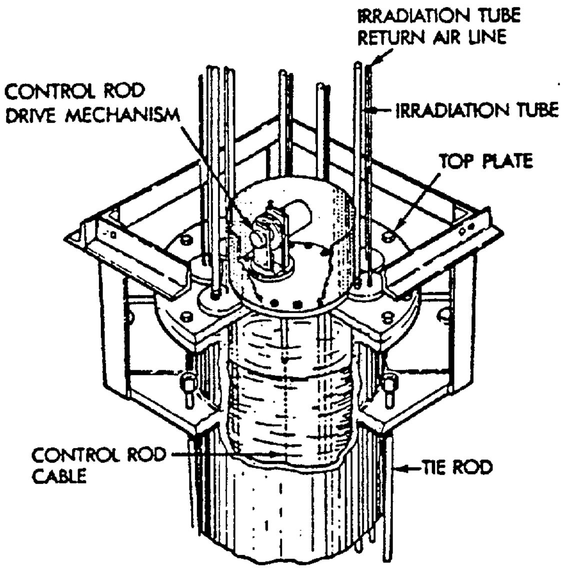


Figure 3. Reactor Control Mechanism and Mounting Assembly

There are ten irradiation sites. Five inner irradiation tubes are installed in equispaced holes within the beryllium annulus and five outer irradiation tubes are installed outside the beryllium annulus.

Reactor instrumentation comprises one thermocouple, located in the upper orifice and one flux detector, located in a hole in the beryllium annulus.

The reactor container provides support, location and containment for all reactor components. It is suspended from two steel "I" beams placed across the pool. The container is built in two parts. The lower part contains the critical assembly. It can be separated under water from the tubular section, thus enabling either the core or the entire critical assembly to be manipulated while completely under water.

2.2 Control Console

The control console contains the reactor control system, the radiation monitoring system readouts and a service panel monitoring the auxiliary systems.

The control system causes the control rod to move in response either to a changing flux detector signal (automatic control) or to a manual command (manual control).

Flux monitoring is by a self-powered cadmium neutron flux detector located in a vertical hole in the beryllium annulus.

In the event of a failure of the electrical power line all systems will cease to operate, except temperature recording and radiation monitoring which switch automatically to an auxiliary power system. Auxiliary power is derived from lead acid batteries. During normal operating the batteries are continuously charged. Battery voltage is indicated by a meter on the service panel (figure 4). The auxiliary power ON light on the service panel is illuminated during operation of the auxiliary system. The operator is informed of a temporary line failure that occurred during his absence by the MEMORY light.

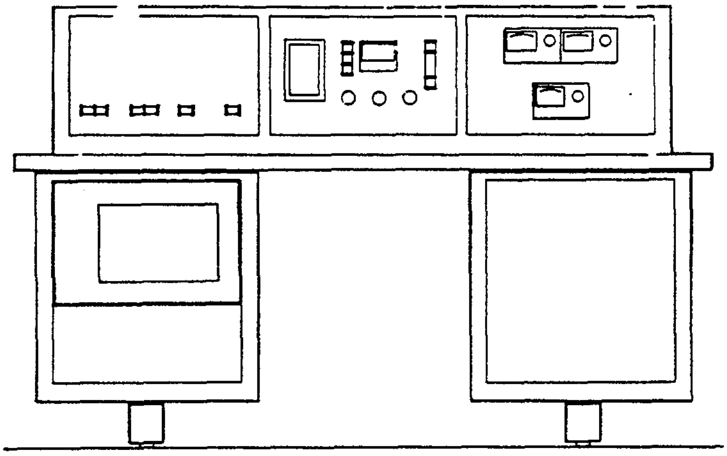


Figure 4. Control Console

2.3 Service Systems

These systems are for water purification and level monitoring, cooling and gas purging.

The pool water and reactor water are maintained at specified purity levels by separate water treatment plants. Separate plants are used to ensure that there is no mixing of pool and reactor water.

The reactor water plant contains a mixed bed deionizer. This bed is replaced when depleted. Reactor water level is maintained by manually adding deionized water through the purification plant.

Both treatment plants incorporate flow and conductivity meter.

The pool is cooled by city water flowing through a simple panel heat exchanger. This water is discharged to the site drain. At no time does it come into contact with either the reactor or pool water. Water flow is controlled by a manual valve and flow meter. A light on the service panel is illuminated when cooling is on.

There is a very slow build up of hydrogen in the reactor container head space from radiolytic decomposition. This is purged once per week by blowing air through the head space. The purge air is taken from the building supply, filtered and then passed through a timing valve and flow meter into the reactor. It exhausts through a filter to atmosphere.

2.4 Irradiation Systems

SLOWPOKE-2 will accept ten irradiation systems, each comprising an irradiation tube (the part within the reactor container) and capsule transfer system.

The five inner irradiation tubes and the five outer irradiation tubes are included in the basic reactor package.

Three cadmium capsules are provided with the reactor to act as auxiliary reactor shut-down devices. If the reactor is installed with less than three small (inner) capsule transfer systems, simple closed loops are connected to the irradiation tubes.

2.5 Reactor Core Details

Thermal power at 1×10^{12} $n \cdot cm^{-2}$ s^{-1} - 20 kW

Fuel element positions - 342

Core dimensions diameter - 22 cm (8.66 in)

height - 22.6 cm (8.91 in)

volume - 8580 cm^3 (0.30 ft^3)

Water volume in core - 6940 cm^3 (0.245 ft^3)

Steady state temperatures	Water temperature rise through core (°C)	Mean core water temperature above pool temp. (°C)
1.0×10^{11} n·cm^{-2} s^{-1}	4	3
2.5×10^{11} n·cm^{-2} s^{-1}	7	6
5.0×10^{11} n·cm^{-2} s^{-1}	12	10
1.0×10^{12} n·cm^{-2} s^{-1}	19	17

Critical mass of ^{235}U - 828-898 g

Fuel life - 3.2×10^{19} nvt (10 yrs at 1×10^{11} n·cm^{-2} s^{-1})

Fuel elements, number - 300-325

Reflectors (beryllium)

Annulus internal diameter - 22.10 cm (8.70 in)

outside diameter - 42.47 cm (16.72 in)

height - 22.75 cm (8.96 in)

Bottom plate - thickness - 10.16 cm (4 in)

diameter - 32.23 cm (12.69 in)

Top shims - diameter - 24.31 cm (9.50 in)

thickness (each) - 1.27, 0.64, 0.32, 0.16 cm (0.5, 0.25, 0.125, 0.062 in)

maximum total thickness - 10.16 cm (4 in)

Reactor Container

Diameter - outside - 0.610 m (24 in)

Length - overall - 5.270 m (17.29 ft)

lower section - 0.829 m (2.72 ft)

Length - upper section - 4.445 m (14.58 ft)

Wall thickness - 0.953 cm (0.375 in)

Flanges - ends - 0.762 m (30 in) diameter

support - 0.806 m (31.75 in) square

Material - 5052 aluminum

Water - level - As pool water

volume - 1.38 m^3 (49 ft^3)

conductivity < 1 μmho/cm

2.6 Pool

Inside diameter - 2.5 m (8.2 ft)

Depth below grade - 6.10 m (20 ft)

Depth of water above core - 4.42 m (14.5 ft)

Depth of water surface below floor - 0.9 m (3 ft)

Water

volume - 27 m^3 (950 ft^3)

conductivity - < 10 μmho/cm

2.7 Control Console

Control System

Control rod (cadmium) diameter - 0.40 cm (0.16 in)

Control rod (cadmium) length - 25.4 cm (10 in)

Control rod travel - 20.3 cm (8 in)

Control rod speed (60 Hz line power) - 1.06 cm/s (0.42 in/s)

Control rod time for full travel (60 Hz line power) - 19 s

Neutron flux detector type - Self powered cadmium detector

Neutron flux - operating range - 0.5×10^{11} - 1×10^{12} $n \cdot cm^{-2}\ s^{-1}$

Neutron flux - meter range - 0 - 1.5×10^{12} $n \cdot cm^{-2}\ s^{-1}$

recorder range 0 - 1.5×10^{11}, 3.75×10^{11}, 7.5×10^{11}
and 1.5×10^{12} $n \cdot cm^{-2}\ s^{-1}$

Temperature recorder range - 0 - 150°C

Thermocouple type - Iron-Constantan (ISA type J)

Recorder chart speeds - neutron flux - 2.54 cm/min (1 in/min) and
2.54 cm/h (1 in/h)

temperature - 2.54 cm/h (1 in/h)

Radiation Monitors

Number - 3

Reactor room - low level alarm - dependent on installation

high level alarm - dependent on installation

Reactor deionizer - indicating only

Type (typical) - Victoreen Model 855 Series G-M gamma monitoring systems

display - single logarithmic scale

range - 0.01 mR/h - 1 R/h

energy dependence - ± 15% from 0.1 to 2.5 MeV

directional dependence - < 30%

accuracy - better than 20%

Auxiliary Power Systems

Output - 115 Vac, 18 Vdc

Running time - 24 h

Maximum charging current - 5 A

Batteries - type - lead acid automotive

capacity - one - 12 V, 90 Ah

two - 6 V, 90 Ah

2.8 Service Systems

Water Purification and Level Control

	Reactor Container	Pool
Deionizer		
Conductivity meter range	0.05-3 μmho/cm	0-300 μmho/cm
Flow rate	7.5 L/m (2 USGPM)	19.1 L/m (5 USGPM)
Working pressure	3.5 kg/cm^2 (100 psig)	3.5 kg/cm^2 (100 psig)
Water level		
deviation warnings	± 5 cm (2 in)	± 5 cm (2 in)

Cooling System

Cooling water flow rate - 22 L/m (6 USGPM)

Cooling water temprature rise at 2.5 x 10^{11} $n \cdot cm^{-2}$ s^{-1} - 3°C

Pool water temperature at 2.5 x 10^{11} $n \cdot cm^{-2}$ s^{-1}, with cooling water flow of 6 USGPM at 15°C inlet temperature - 24°C

Gas Purge System

Flow rate - 11 L/s (24 SCFM)

Purge time - 1 min

2.9 Irradiation Systems

Large (Outer): Small (Inner) site thermal neutron flux ratio (typical) - 0.5

Small (Inner) System

Capsule type - polyethylene vial

diameter - 1.58 cm (0.625 in)

length - 5.4 cm (2.125 in)

volume - 7 cc (0.43 in^3)

Total daily operation - 9 x 10^{15} nvt

e.g. - 24 hr at 1.0 x 10^{11} $n \cdot cm^{-2}$ s^{-1}

or - 10 hr at 2.5 x 10^{11} $n \cdot cm^{-2}$ s^{-1}

or - 5 hr at 5.0 x 10^{11} $n \cdot cm^{-2}$ s^{-1}

or - 2.5 hr at 1.0 x 10^{12} $n \cdot cm^{-2}$ s^{-1}

Flux uniformity (typical) - vertical - ± 2.6%

horizontal - ± 1%

Large (Outer) System

Capsule Type - polyethylene vial

Diameter - 2.9 cm (1.125 in)

Length - 5.4 cm (2.125 in)

Volume - 27 cc (1.65 in^3)

Total daily operation (Typical) - 5.2×10^{15} nvt

e.g. - 24 hr at 0.5×10^{11} $n \cdot cm^{-2}\ s^{-1}$

or - 10 hr at 1.2×10^{11} $n \cdot cm^{-2}\ s^{-1}$

or - 5 hr at 2.5×10^{11} $n \cdot cm^{-2}\ s^{-1}$

or - 2.5 hr at 5×10^{11} $n \cdot cm^{-2}\ s^{-1}$

Flux uniformity (Typical) - vertical - ± 0.7%

horizontal - ± 6%

Irradiation Controller

Time range - standard - 0.1 - 999.9 min

optional - 0.1 - 999.9 h

2.10 Operating Balance Conditions

(1) Cooling system maintains daily start-up temperature at 20°C.

(2) 9×10^{15} nvt/day operation.

(3) Maximum excess reactivity in clean cold system (i.e., immediately following reactivity adjustment by shim ing) is + 2.9 to 3.4 mk. A nominal value of 3 mK is used in the following table.

Neutron flux ($n \cdot cm^{-2}\ s^{-1}$)	1.0×10^{11}	2.5×10^{11}	5×10^{11}	1.0×10^{12}
Temperature and xenon load at daily shutdown (mk)	0.8	0.9	1.3	2.0
	0.8	0.9	1.3	2.0
^{235}U burn up and ^{149}Sm poisoning (mk)	0.8	0.8	0.8	0.8
Maximum capsule load (mk)[a]	2.2	2.1	1.7	1.0
Minimum capcule load (mk)[b]	1.4	1.3	0.9	0.2

(a) At daily shut-down following compensation for ^{235}U burn up and ^{149}Sm poisoning by beryllium shim addition.

(b) At daily shut-down immediately prior to beryllium shim addition.

Long Term Changes

Reactivity Loss Due to
^{235}U Burn-up and ^{149}Sm Poisoning

1.0×10^{19} nvt	Years at $10^{11}\ n\cdot cm^{-2}\ s^{-1}$ Continuous	^{235}U Burn-up (mk)	^{149}Sm (mk)	Reactivity Loss (mk) Cumulative Total
0.16	0.5	0.2	0.7	0.9
0.315	1.0	0.4	1.4	1.8
0.63	2.0	0.8	2.5	3.3
1.26	4.0	1.5	4.1	5.6
1.89	6.0	2.3	5.1	7.4
2.52	8.0	3.0	5.8	8.8
3.15	10.0	3.8	6.2	10.0

Reactivity Control

Control rod - regulation - 3.0 mk

shut-down - 2.1 mk

Total worth - 5.1 mk

Control rod - speed - 1.06 cm/s (0.42 in)

Control rod - rate (average) - 0.21 mk/s

Cd capsule in inner radiation sites

dropped into empty site = -1.8 mk/capsule

dropped on top of sample capsule in site - -1.3 mk/capsule

Core emperature coefficient at 25°C = -0.07 mk/°C

2.11 Building Services

Electrical, 3 circuits, each - 115 Vac, 60 Hz, 15 A

Note: Equipment can be matched to other voltages and 50 Hz.

Water - 23 L/m (6 USGPM) city water outlet. For effective pool cooling, temperature must not exceed 15°C.

Drain - Aid resistant drain to sewer.

Compressed Air - Minimum pressure 5.6 kg/cm^2 (80 lb/in^2) at 2830 L/m (100 SCFM). Requirement in intermittent. Maximum is 710 L (25 SCF) in any 1 minute period. Typical continuous average is 142 L/m (5 SCFM).

Vent - Pipe to outside of building above roof level. Maximum back pressure at 2830 L/m (100 SCFM) to be 0.07 kg/cm^2 (1 lb/in^2).

3. Reactor Operation and Performance

The first 8 SLOWPOKE-2 reactors (and the original prototype) were fuelled with highly enriched uranium in the form of 28% alloy with Al, clad in Al. Although small reactor cores in light water are prone to more neutron loss by absorption and leakage, the use of beryllium neutron reflector in SLOWPOKE results in a requirement of approximately 800-900 g U-235 for criticality, which is not much larger than the theoretical minimum and, compared to some other reactor designs, this small critical mass results in saving of initial fuel costs and replacement costs. Newer SLOWPOKE-2 reactors use a re-designed fuel core with less than 20% U-235 enrichment which is in the category exempt from requirements for international inventory inspection.

Further, the small fuel core (approximately 25 cm x 22 cm diameter) and the relatively thick Be reflector (20 cm) produce a relatively high useful neutron flux for applications of 10^{12} cm^{-2} s^{-1} in the irradiation sites in the reflector even at the low thermal power of 20 kW. (Fuel and moderator temperature elevations are modest at 20 kW, and although this is currently the licensed power maximum, it has been demonstrated that operation at 50-60 kW is feasible, with or without enhanced coolant flow - providing fluxes of 3 x 10^{12}.) This high flux-to-power ratio results in low uranium consumption and fission product production for a given time-integrated flux, leading to a useful fuel core lifetime (approximately 10-15 years with extensive reactor operation of 2500-3000

$h \cdot y^{-1}$) which is considerably extended relative to most reactors with larger cores. This infrequent fuel core replacement, together with the small critical mass of uranium makes the fuelling cost of SLOWPOKE-2 quite low (see section below on costs). Although the small volume limits the access to high flux regions for neutron uses, the available 10 irradiation sites each capable of loading with 2 capsules, have proved more than adequate.

SLOWPOKE-2 is characterized by a negative temperature coefficient of reactivity and negative void coefficient. Although the reactivity change due to a rise in reflector temperature is positive, the large reactivity change cause by a rise in core temperature is much larger and produces a net negative reactivity change. This produces an inherent safety feature, a self-regulation of excess reactivity when combined with design-limited restriction of coolant flow to the core by size of coolant inlet orifices and limits power levels and fuel temperature to safe values during any power transients no matter how they are caused. Due to this self-limiting mode of reactor-behaviour, and in view of licensing restrictions of maximum excess reactivity, the usual automatic safety (shut-down) systems are not needed, and it has been judged by Canadian licensing authorities that SLOWPOKE can be left to operate unattended.

The two excess reactivity-consuming factors are (i) increase in moderator temperature with time of operation and (ii) buildup of Xe-135 poison. On a daily basis, the control rod having a reactivity worth of about 3 mk is withdrawn to compensate for poison and temperature effects. Long term reactivity adjustment is accomplished by adding a Be shim plate to the top reflector occasionally (approximately each 12 months of operation).

Automatic limitation of reactor power excursions occurs even if there is a loss of regulation such as, for example, the control rod cannot be re-inserted into the reactor core after start up for mechanical reasons or loss of drive action (in an electrical failure mode). In such an event, the reactor power increases above the normal maximum operating power of 20 kW.

Although the core continues to be cooled by the normal ('un-pumped') convective flow of water upwards through the core, the temperature of the water in the core eventually becomes elevated to the point (approximately 40-50°C increase) when the corresponding reactivity loss cancels the effect of the withdrawn Cd control rod. Thus, the reactor power is limited by intrinsic reactor behaviour independent of operator intervention or external control mechanism such as a duplicated 'scram' system.

Within these design limitations, SLOWPOKE-2 reactors operate indefinitely at 5 kW, greater than 10 h at 10 kW and up to 1.5 h at 20 kW before temperature increases in the moderator begin to limit continued operation. Because experience has shown that the earlier designs and licenced reactivity limits were quite conservative, some research has been done on the safety implications of (i) permitting greater excess reactivity during fuelling and 'shimming' and (ii) deployment of chilled water injectors adjacent to the core coolant flow orifices. A 15 kW chiller unit has been installed at the Toronto SLOWPOKE and it has been demonstrated that much extended 20 kW operation or operation at power levels (and fluxes) greater than 20 kW can readily be achieved with acceptable reduction in inherent reactor safety and no physical alternations in reactor or fuel design. That is, such a unit retro-fitted to an existing SLOWPOKE-2 reactor can offer these extensions in operational modes, viz. to higher fluxes for longer periods.

Current SLOWPOKE reactors operate with remarkable reliability for up to 2000 h per year at power levels ranging from 5 to 20 kW. Reactor start-up is automatic, is accomplished with 100-200 seconds after certain routine system checks, and subsequent operation for up to 72 hours do not require direct operator supervision (however, licensing requires a minimum of remote surveillance of power level from time to time). Failure to operate owing to electronic or mechanical faults of reactor components have been encountered quite infrequently, typically once per 3 reactor operating years.

4. SLOWPOKE Utilization

Examples of some recent (1983-85) SLOWPOKE uses in a variety of disciplines are: archeometry - provenance studies of ceramic fragments from Iran, Yemeni, Yugoslavia, Greece, China, NWT, Egypt; biological sciences - ion transport across cell walls, composition of bird (eagle) feathers, fish subjected to acidic precipitation, Mn in fish eggs, Al uptake by plants, effects of heavy metal deposition from acid rain on vegetation; chemistry (pure and applied) - composition of coordination compounds, trace copper instrumental analysis, composition analysis of LaNi hydrogen-storage alloys, heavy metal ion absorption on synthetic and natural absorbers, Ba and K content of video-display glasses, new zeolite and rhodium catalysts, standard reference method for As in biological materials; earth sciences - platinum metals in Cu-rich ores, and in G and H chromate seams, rare earths in Felsic Volcanics, in Jimberlana Intrusion (Australia), Bushveld Complex (So, Africa), in Archaen Volcanic Rocks (E. Canada), development of chemical separations for Re-Os, Lu/Hf ratios in zircons, nuclear-track age determination; environmental sciences - trace impurities in 3 Chinese environmental reference standards, in Chinese and Canadian coals and their combustion products, analysis of uranium tailings, comparison of sediments from Yangtze and Don Rivers (China and Canada), airborne particulate matter, mobile street dusts, toxicity of industrial fly-ash; medicine - tissue Se in infants and children, bone fluoride determination in rats and in clinical research, effects of proctasyclin on blood flow, measurement of body water compartments, trace elements in cystic fibrosis patients, in welding workers, steel plant workers, rare-earth workers; metallurgy - segregation of impurities in continuously-cast steel billets, recovery of U and Th from Cl and sulphate leach liquors, milling of Al dross, Cu in hydrometallurgy, effect of Mn on Si control in blast furnaces; industrial uses - trace elements in fossil fuels, in plastics and polymers, in phosphate furnace deposits and slags, in analytical standards.

Many (∿ 90%) of the above uses involve neutron activation of selected samples followed by instrumental gamma spectrometry involving (typically) 20-40 radionuclides of short (0.8 s to 25 min half-lives) and intermediate (38 min to 30 day half-lives) and required mostly 1 to 2 minute irradiation times. A smaller fraction required 16-18 hour irradiation periods and were measured up to 2 weeks later for longer-lived nuclides.

Other applications made use of radioisotope tracers of half-lives too short to be prepared at commercial reactors, but sufficiently long to permit their safe utilization in tracer research in a variety of university and hospital laboratories, e.g., Ba-139 (85 min), Mn-56 (2.6 h), Na-24 (15 h), K-42 (13 h), As-76 (27 h) and Hg-197 (65 h).

These uses involved about 70 professors and their research associates and fellows (64), post graduate students (61), undergraduate research students (44), and more than 300 other students performing assigned laboratory procedures utilizing SLOWPOKE. It can be estimated that the 15,135 sample irradiations performed during 2636 operating hours (1983-84) produced an estimated 200,000 individual measurements, many of which could not be performed otherwise. On the basis of SLOWPOKE annual costs (see below) it can be estimated that the unit costs for irradiations is $4-6 per capsule irradiation or $0.20-0.50 per individual measured result. These are costs substantially lower than most instrumental trace analysis methods and the multielement analytical results obtained are often superior in accuracy and concentration sensitivity.

SLOWPOKE Cost Estimates

The costs of installing, operating and maintaining a SLOWPOKE-2 reactor facility (in 1985 dollars) are given by category as follows:

SLOWPOKE Installation: (Capital)

Reactor + operating and safety systems: $800,000

Optional systems: $75,000
(additional sample lines, cyclic system, core chiller)

Nuclear Instrumentation (for users): $100,000

Enclosure (reactor pool, room, associates labs): $500,000 (new building)
75,000 (install in existing laboratory)

<u>SLOWPOKE Operating</u>: (annual)

Part-time operator: $25,000

Supplies & services: $10,000

Fuel costs (est.): $50,000 (depending on source of fuel)

<u>SLOWPOKE Maintenance</u>:

Reactor adjustments: $2,500

Instrumentation maintenance: $10,000

Utilization and Maintenance Detail

Further details of the operating experience, reactor performance and program of utilization of the 8 currently operating SLOWPOKE-2 reactors can be obtained by consulting the annual SLOWPOKE reports, contacting the reactor supervisor, or referring to published papers from: AECL Radiochem. Co., Ottawa; University of Alberta, Edmonton; Dalhousie University, Halifax; L'Ecole Polytechnique, Montreal; Royal Military College (and Queen's University), Kingston; Saskatchewan Research Council, Saskatoon; University of Toronto; University of the West Indies (Jamaica).

Table 1

1983-84 SLOWPOKE Operating Statistics

Month	Oper. Days	Oper. Hours	Hours/ Day	No. of Irrads.	Irrads./ Day	Research Irrads.	Student Irrads.	Total Irrad. Hours	Primary Irrad. Hours	Primary Irrads./ Day	Primary Use %	Energy (kWh)
July	20	225	11.3	1352	68	1352	-	658	175	8.7	77	1291
Aug.	23	226	9.8	1491	65	1486	5	578	176	7.6	78	1460
Sept.	22	246	11.2	1313	60	1232	81	1076	198	9.0	81	1263
Oct.	22	230	10.5	1526	69	1396	130	1069	205	9.3	89	1187
Nov.	22	241	10.9	1467	67	1195	272	906	189	8.6	78	1264
Dec.	17	134	7.9	848	50	814	34	393	115	6.8	86	917
Jan.	22	213	9.7	826	38	651	175	1068	184	8.4	87	1250
Feb.	21	213	10.1	1248	59	849	399	1049	178	8.5	84	1339
March	22	243	11.0	1771	81	1078	693	1342	209	9.5	86	1556
April	20	222	11.1	1236	62	1116	120	859	182	9.1	82	1278
May	22	208	9.4	890	40	859	31	706	172	7.8	83	1117
June	21	235	11.2	1167	56	1167	-	994	176	8.4	75	1323
Total	254	2636		15135		13195	1940	10698	2159			15245
Av./ Month	21	220	10.4	1261	60	1100		892	180	8.5	82	1270

Table 2

Distribution of Irradiations by Power

	Power (kW)					
Month	< 0.2	1	2	5	10	20
July	-	-	704	89	150	409
August	-	-	632	145	283	431
September	-	-	696	239	63	315
October	4	-	776	222	304	220
November	-	188	784	143	36	316
December	-	-	188	260	129	271
January	-	-	216	183	118	309
February	-	-	384	286	157	421
March	-	150	412	333	365	511
April	-	372	181	205	183	295
May	-	234	247	130	67	212
June	-	-	502	140	237	288
Total	4	944	5722	2375	2092	3998
%	-	6	38	16	14	26

Table 3

Distribution of Irradiations by Time

Month	Time				
	< 1 m	1-10 m	10-60 m	1-8 h	> 8 h
July	771	527	9	-	39
August	751	680	29	-	31
September	666	548	33	4	62
October	785	629	39	13	60
November	760	602	55	-	50
December	193	606	28	1	20
January	378	353	32	-	63
February	489	679	15	3	62
March	842	777	73	-	79
April	766	404	14	-	52
May	557	263	29	-	41
June	521	556	32	-	58
Total	7485	6624	388	21	617
%	49	44	3	-	4

Table 4

Utilization Distribution History

	July 1983-June 1984		July 1982-June 1983		July 1981-June 1982	
	Irrads.	Hours Used*	Irrads.	Hours Used*	Irrads.	Hours Used*
Undergraduate	1940	1801 (17%)	1799	1564 (19%)	1854	1501 (12%)
Graduate	4157	2422 (23%)	3435	2083 (25%)	6514	6317 (52%)
Faculty	5870	4974 (46%)	5303	3129 (38%)	5648	3680 (30%)
Non U. of T.	3168	1500 (14%)	2450	1469 (18%)	2796	664 (6%)
	15135	10697	12987	8245	16812	12162

* Irradiation hours.

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THE MNSR REACTOR

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Abstract

This tank-in-pool reactor is based on the same design concept as the Canadian Slowpoke. The core is a right circular cylinder, 24 cm diameter by 25 cm long, containing 411 fuel pin positions. The pins are HEU-Aluminum alloy, 0.5 cm in diameter. Critical mass is about 900 g. The reactor has a single cadmium control rod. The back-up shutdown system is the insertion of a cadmium capsule in a core position. Excess reactivity is limited to 3.5mk. In both the MNSR and Slowpoke, the insertion of the maximum excess reactivity results in a power transcient limited by the coolant/moderator temperature to safe values, independent of any operator action. This reactor is used primarily in training and neutron activation analysis. Up to 64 elements have been analyzed in a great variety of different disciplines.

Summary

In utilizing the existing larger and medium research reactors, in order to match to the reqirement of economic development in districts or department, the Miniature Neutron Source Reactor (MNSR) has been designed and developed completely in 1984. The reactor is equipped with ten irradiation facilities for elements quantitative analysis of products and materials. The reactor particularly suites for multielement trace analysis of organisms body fluid and environmental samples. The thermal neutron flux in irradiation sites is 1 x 10^{12}n/cm^2.s. Amount of samples analized is up to tens per day. The volume of the reactor core is 11 litre. Loading of highly enriched U-235 is less than 1 kg. The core lifetime is about ten years, so frequent refuelling may be avoided. The reactor possesses inherent safety, without danger of runaway, and nuclear contamination would not be bring about. In operating, the radiation dose rate of working area is more lower than the level permited. Outside reactor building, the radiation level is low as natural, so the reactor can be installed in city without misgiving. Fission heat is removed from core by natural convention. The reactor is simple in structure, convenient for operating. Analysts would be concurrently operator, and in establishment of staff personnel, the special operators would not be necessary. Moreover consumption of U-235 is only several mg per day, the operation expenses of the reactor is the lowest in the practical research reactors, and the construction cost is about three or four times less than ordinary Triga type reactor, or about ten times less than medium swimming-pool reactor.

During a year, the reactor has been started up for 238 times, total evergy generated has estimated about 6550kw-hr. The reactor has exhibited excellent performance and operation stability. 1397 different samples have been analyzed. 64 kinds of stable elements have been detected quantitatively, including F, which half-life is 11.03 second; and Co, which half-life is 5.26 years.

We have carried out an unattended operating system for overnight irradiation, and have realized to control the reactor by a computer.

At present, we are developing commercial reactor with more excellent performance.

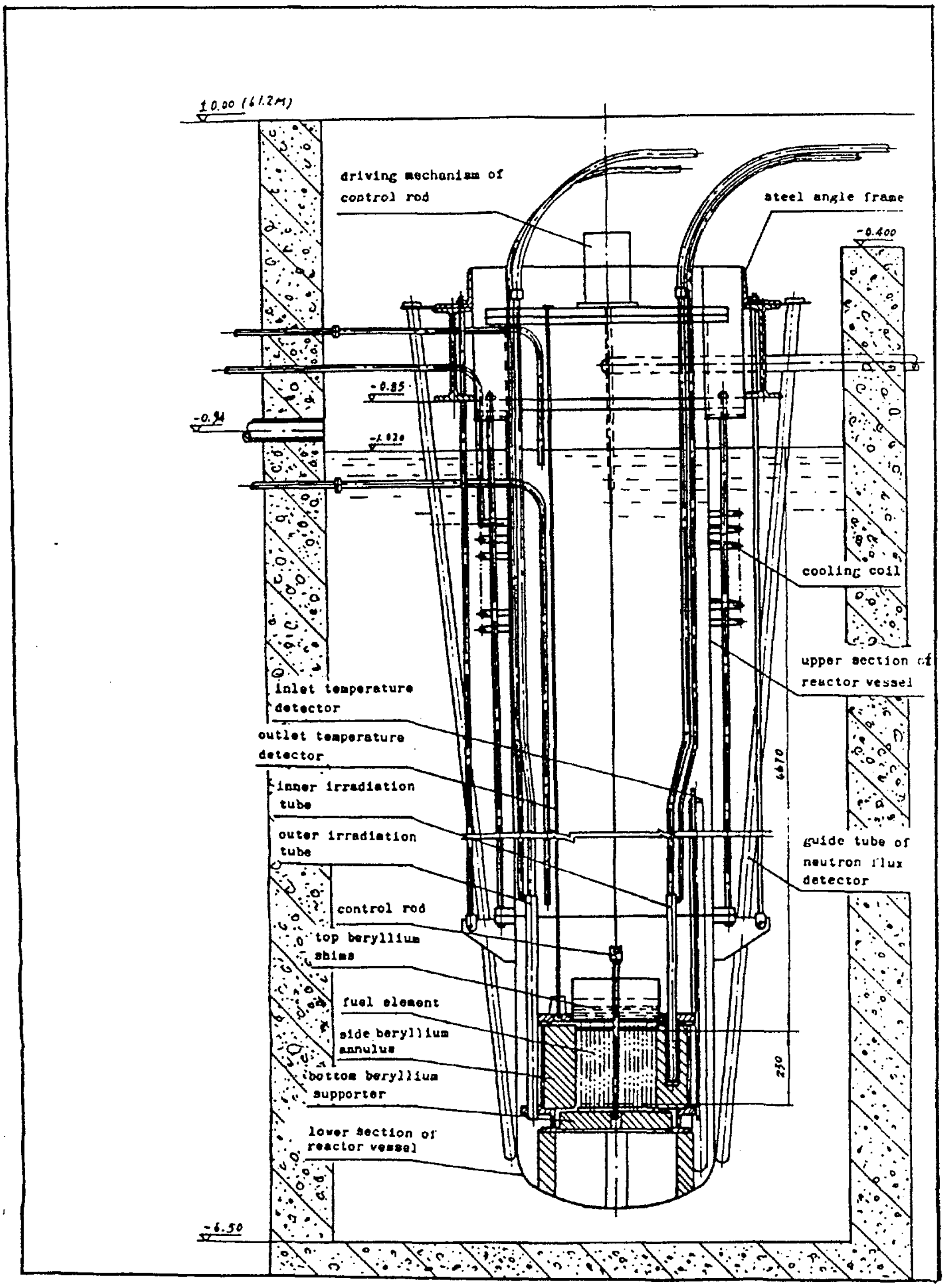
THE MNSR REACTOR

By 1984 there have been several medium and larger research reactors in China, including heavy water reactor, swimming-pool reactor, and tank type High Flux Engineering Test Reactor (HFETR). Their power is from 2000kW up to 125MW. The industry and technique developed and accumulated in these reactors have played an important role in developing the subsequent research reactors in our country.

With respect to neutron activation analysis these reactors are expensive in operation costs, lower operating availability, and its location far from economical developed districts, so many users hope that they would rather have own minature nuclear facilities than send the samples to existing reactor.

For these reasons since 1980 the Miniature Neutron Source reactor (MNSR) has been developed. The prototype reactor is located in Institute of Atomic Energy in Beijing. It is designed for neutron activation analysis, short-lived isotope production and as a teaching and training facility.

The practice of HFETR showed that the high-enriched uranium and light water core surrounded by sufficiently thick metallic beryllium reflectors exhibited a low critical mass. applied this experience, the MNSR uses 90% concentration uranium aluminum



THE MNSR REACTOR

ally as fuel, well operated in HFETR, light water as moderator and coolant, and beryllium as reflectors. The right cylinder core with 11 litre of volume is surrounded by 100mm thick beryllium annulus and 50mm thick bottom beryllium plate. In the case of existing 10 irradiation tybes and some detectors in the reactor total mass of U-235 is less than 1 kg.

The fuel element are extruded U-Al alloy meat of 26.18 wt%U, extrusion clad with o.5mm thickness of Al cladding, the meat is 4mm diameter and 250mm long. Al end caps were welded at each end of the cladding to ensure its hermetization. The electron beam welding technique with small current is successfully adopted. This technique not only gave a reliable sealing of fuel elements, but also yielded a surprisingly low overall surface contamination level of less 2 x 10^{-9} g U-235/cm^2 of fuel cladding. This greatly decreases the radioactive species escaped by recoil from the fuel cladding to the coolant, and then greatly lowers the radiation level of the reactor water.

One of the essential intention of design is to assure safety of reactor in operation, so the core is undermoderated. The ratio of hydrogen to U-235 by atom is about 240. Through the thermo-hydraulic experiments, the coolant flow area of core at inlet and outlet were regulated, and then the resonable temperature difference between inlet and outlet of core was set. These resulted in a considerable negative temperature coefficient of the reactor. On the other hand, 3.5 mk of maximum excess reactivity was established during construction of the reactor. The two factors make the reactor ingerently safe.

The core assembly consists of 376 fuel elements, one central control rod guide and two grid plates, being connected by 5 Al tie rods. The fuel elements are arranged in a multi-concentric array. Each fuel element is secured to the bottom grid plate by slight conic self-locking fitting, but is free to expand upwards through the hole in the top plate. The real core assembly has experienced 10,200 cycles duplicated earthquake tests with different amplitude and frequency by vibro-bench, and long time corrosion test in water under same conditions of temperature and purity. The results of tests demonstrate that the conic self-locking fitting device possesses durability of resistance to seism and corrosion, and is easily fabricated.

Fission heat is removed from core by natural convection. The reactor configuration enables to have good heat transfer through the core.

Because the reactor is designed to have self-limiting power excursion characteristics, There is only one control rod in the centre of the reactor core, and the on-off type scheme is available in design of the reactor cotrol system. The cadmium control rod is used to start-up and shutdown the reactor, automatically regulate the power level, as well as compensate reactivity. In long term operation , reactivity for fuel burn-up and samarium poising is balanced by means of adding the top Be shim plate at yearly intervals.

There are two control modes for the reactor. One is the operator's control, and the other is computer control. In operator control, the reactor is permitted to operate by licensed operator, who performs the operational procedures and surveys the parameters on the control console located in the reactor room working area. The BF_3 ion chambers are located in the pool adjacent to the reactor vessel, and are connected in the system to measure neutron flux and to transmit the flux signal to amplifier to control the reactor. But during overnight irradiation the reactor is allowed to operate unattended for lower power, then the operating parameters are recorded and alarmed by the computer. In the computer control made, instead of using the ion chambers, a small neutron fission type chamber located in an outer irradiation site is connected into the computer. All of the control procedures including setting the power level, start-up and shutdown of the reactor, and auto-regulating the neutron flux level would be performed according to control code by the computer. The operating parameters are displayed on the video keyboard in the computer room. As soon as the any excursion parameter exceeds the presetting limit, the sonic alarm works at once. After shutdown of reactor, the printer would provide the daily operating data sheet on time.

The reactor consists of the core, beryllium reflectors, a control rod and drive mechanism, water temperature and neutron detectors, ten irradiation tubes and the reactor vessel. The reactor vessel with 0.6 m dia. and 5.7 m overall length, and 10mm wall thickness, is made of Al alloy. There is about 120 litre of head space in the reactor vessel, where the hydrogen from radiolytic decomposition of water is slowly built up. This is pumped every week's interval at ahutdown of reactor by start-up the airpump for less than 1 minute. The pumped gas is exhausted through a filter to atomsphere, and at the same time the flesh air from building is entered through a filter into the reactor.

The reactor vessel is suspended from two flanged beams placed across the pool. The pool is designed in accordance with civilian building standards. Its inside dia. is about 2.7m, and depth below grade is about 6.5m.

The pool base is a 400 mm. thick annulus of reinforced concrete, the white glazed ceramic liner tiles are used as the interior finish of the pool. All the concrete gaps at joint between the adjacent ceramic liner tiles were filled with water proofing and anti-radiation resin coating. Compared with the metallic liner technique of Al alloy, the ceramic liner tiles technique greatly shortened construction time and decreased inner liner cost by 9/10. The depth of water above core is about 4.67 m. Since low radiation level of reactor water and sufficient protection depth of water, the top shielding cover of the pool is not necessary.

It results in easy handling of the experiments and measurements, as well as directly viewing the Cerenkov radiation with eyes in teaching applications of nuclear energy.

The reactor has equipped with service systems and high sensitivity Gamma-spectrometer. The service systems include reactor water purification, pool water exchange and cooling, reactor gas pumping and 10 of pneumatic transfer. There are four pneumatic transfer systems connected to the irradiation tubes. For neutron activation analysis a Ge(Li) detector with lead shielding, a multi-channel analyzer and a PDP-11/34 computer with self established analysis code named SPAN are used.

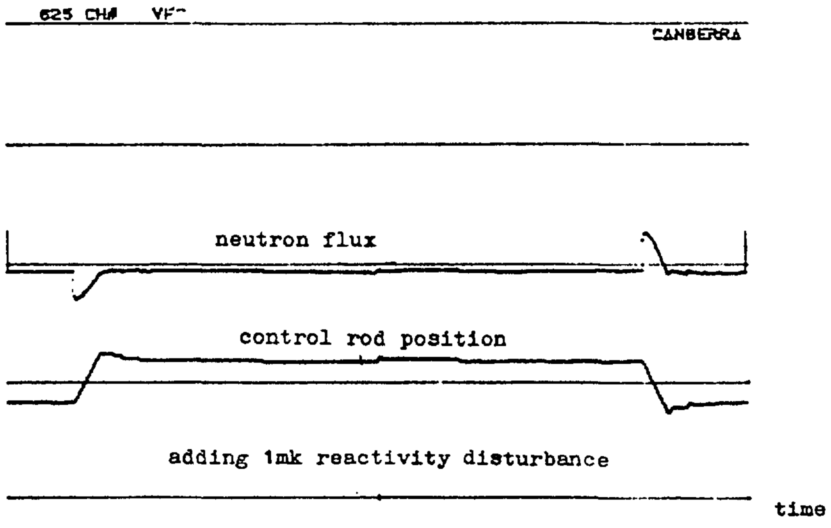
To detect the reactor characteristics and to test the instrumentations, The BF_3 ion chambers, small fission type neutron chamber and Gamma-chamber, self-powered cobalt detector, water temperature detectors of thermocouple type for inlet, outlet, and difference, and radiation detectors, are located in irradiation sites near the core, or outside the reactor vessel.

The reactor began on construction in December 1981, and reached the nominal power on 31 March last year. During the first year's operation period, some researches such as reactor operating characteristics, neutron flux and temperature in irradiation sites, radionuclide activity in the pumped gas stream and in the sampling of reactor water, radiation fields inside and outside the reactor building, and a series of reactivity transient tests have performed.

Operational performance is summarized in table and some of them is illustrated in figures.

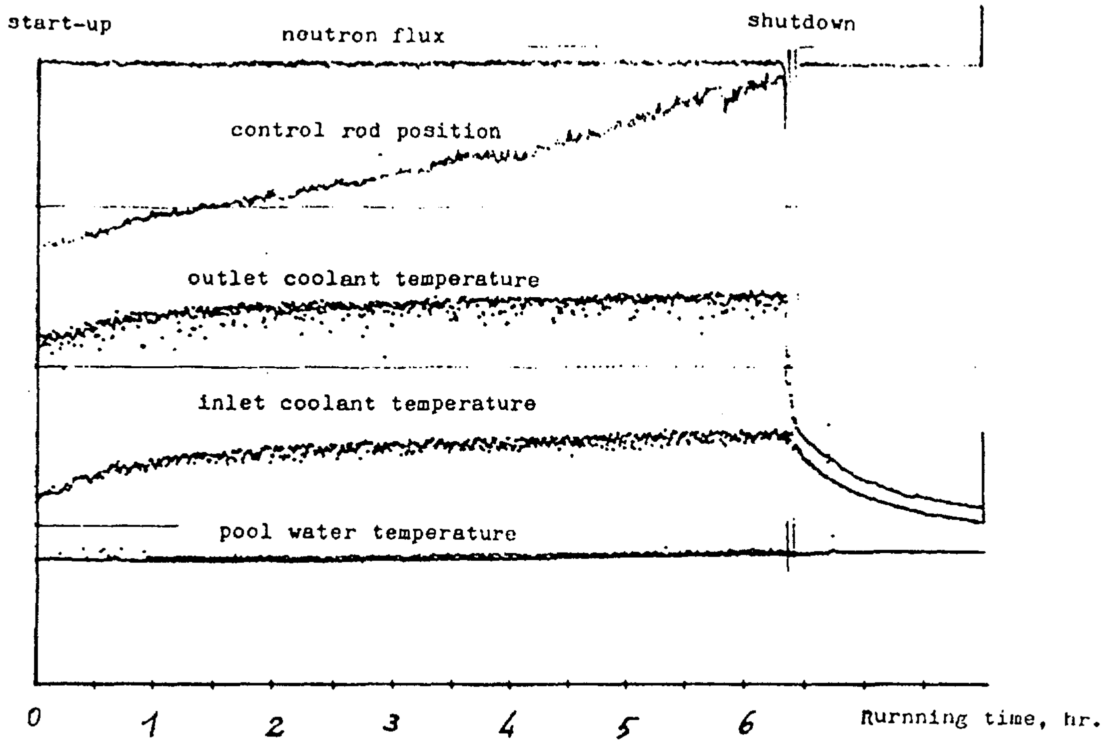
The main is listed as follows:

- Neutron flux in the inner irradiation sites is 1 x $10^{12} n/cm^2.s$ at 27 KW thermal power in core. The daily operation time is up to 2.5 hr. The ratio of neutron flux in inner site to the outer site is about 0.5. The fluctuation band of neutron flux in longer continuously operation is less than 2% of the setting value.
  - The uniformity of flux level between 5 inner sites is about 1% of nominal value.
  - The uniformity of flux distribution in capsule in inner sites, alone vertical and peripheral, is less 3%.
  - The Cd ratio of Au in inner site is about 3.
  - The ratio of reactivity invested in temperature and Xenon load at daily shutdown to the excess reactivity in clean and cold reactor is about 70% under nominal power. When 6550 kw·hr of energy was generated, reactivity loss due to burnup and samarium poison is estamited about 0.4 mk.
  - When insertion or withdrawal of 1 mk Cd abosober to or from the inner site, the max. amplitude of oscillation is about 10% of the setting value, time damped to equilibrium is less 1o sec.



RUNNING STABILITY IN NOMINAL POWER

  - In reactivity trainsient tests, 1.0, 1.5, 2.0, 2.4, 3.0, up to 3.6 mk gradually increasing amounts of reactivity were inserted either by step or linear into the reactor. For example, with a steped reactivity insertion of 3.6 mk, the trainsient is automatically limited to safe levels by the

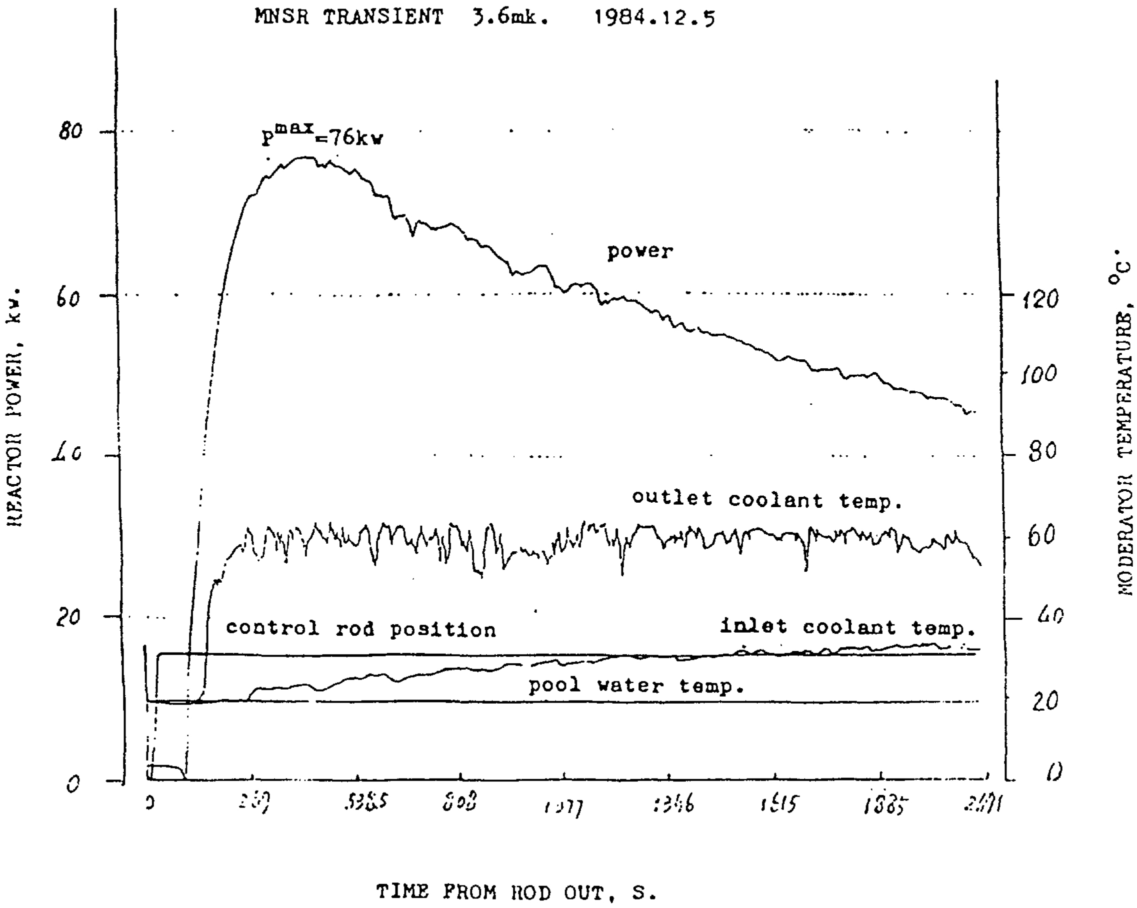


OPERATIONAL CHARACTERISTICS OF MNSR IN NOMINAL POWER

inherent negative moderator temperature coefficient. The value of peak power is about 76 kw, and time to peak is about 6 min. During the trainsient, the maximum wall temperature of fuel elements is lower about 20°C than the water saturation temperature at the same position level. Performed these tests, the inherent safety characteristics of MNSR were demonstrated.

- Low radiation field is detected in operation of reactor. The radiation dose rate in the reactor room working area is less $0.05\frac{mRem}{hr}$, in rooms about reactor room is about $0.01\ \frac{mReM}{hr}$, outside the reactor building is same as the natural background, even in the 3.6 mk of reactivity trainsient, the max. radiation dose rate is about $0.2\ \frac{mRem}{hr}$ at reactor room work area.

During the first year of operation, the reactor has been started up for 238 times, 107 times of them was operated with power. Total energy generated has estimated about 6550 kw-hr. Various the detectors, the instruments and the equipments are operated normally. Testing the reactor behaviour, 1397 different samples have been analyzed. These samples used for calibrating various standard specimens from the country and abroad; for



analyzing composition of ore, meteoric stone, marine deposit and industrial products; for detecting poisonous elements in fruit and plant, and for analyzing trace element in the atmospheric dust and the samples of living organisms include hair. To date, 64 kinds of stable elements have been detected quantitatively, including F, which half-life is 11.03 second, Co, which half-life is 5.26 years. The quantitative order of detectable element is from ppm to ppb.Moreover, some of short lived radioisotopes have been produced for tracer investigation and for the emitter of neutron source induced by radiation. The results from performed study and from analysis in application exhibite that, design of reactor and auxiliary systems is feasible, operation is facile, safe, reliable. The capacity of analizing samples is up to tens per day. Sensitivity and degree of accuracy in analysis are high. However, in performance or in application, the MNSR has rather potentialities.

Today, we are developing advanced design, it aims at increasing suitably excess reactivity and decreasing ratio of temperature and xenon effect at daily shut-down in operating balance of reactivity, so that times of both adding top beryllium shim plates and reloading the core of the reactor would be decreased, operation duration and lifetime of the reactor would be prolonged. We shall provide market commercial reactor with more superior performance.

PERFORMANCE OF MNSR

Date of information 1985

Feature	Detail Specification (in 27kw, routine oper. $20^{\circ}C$ start-up temp.)
Availability for Use	5 inner sites in Be annulus, 7c.c capsule vol. 5 outer sites adjacent to outside of annulus, 25c.c capsule vol. Neutron flux ($n/cm^2.s$), daily operation time (hr), flux fluctuation in operation: in inner sites: 1×10^{12}, 2.5. 5×10^{11}, 5-6. $< 2\%$ of the setting value in outer sites: 5×10^{11}, 2.5. 2.5×10^{11}, 5-6. Irradiation temperature ($^{\circ}C$), with irradiating flux ($n/cm^2.s$) in inner sites: <45 (1×10^{12}), <40 (5×10^{11}) in outer sites: <36 (5×10^{11}), <32 (2.5×10^{11})
Inherent Safety	Total excess reactivity: 3.5 mk in cold clean system Core temperature coefficient: -0.1 mk/$^{\circ}C$ ($15-40^{\circ}C$) Results of 3.6 mk reactivity transient: peak power: 76kw time to peak: 360s. outlet cool. temp.: $62^{\circ}C$ max. wall temp. of fuel element: $92^{\circ}C$
Low Radiation Level	Overall surface contamination level of fuel elwment: $< 2 \times 10^{-9}$ g U-235/cm^2 Depth of water above core top: 4.67 m. Radiation dose rate (mRem/hr): in reactor room working area: <0.05. ≤ 0.2 at max. power of 3.6mk transient in area adjacent to reactor room: 0.01 in enviroment outside reactor building: natural background
Economical Operation Costs	Estimated as less 1/10 of SPR's annual operation expense per year including the depreciation of fuel, Be, and the permanent equipments and the consumption of water and power.

CONTROL SYSTEM FOR THE MNSR

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Abstract

The MNSR has two modes of control: manual and automatic. The automatic system is based on the computer, PDP-11/34. Because the control system for the MNSR consists of only one control rod, the system for its control is correspondingly simple. Neutron flux levels can be adjusted between 1.0×10^8 to 1.2×10^{12} n/s cm^2. A data logging and annunciation capability is also available.

Two types of control systems have been developed for the miniature neutron source reactor. The first is an operator's control system, the neutron flux level can be kept in a given band. Recently, the computer closed-loop control system has been developed and has more advantages. I want to deal mainly with the computer closed-loop control system.

It is very safe, which is one of the intrinsic attributes of the MNSR, and the latest computers are very reliable so it is possible to perform the control of the MNSR with a single computer. In our reactor a PDP-11/34 computer has been used, it's operating system is RSX11M time share system. The control of the MNSR is simple; it only has a control rod, so the control of the reactor only shares a little time of the computer, the main time of the computer is shared by the activation analysis and other works.

The control system includes the computer, the operating data acquisition system and the executive body, as shown in Fig. 1. Since March 1985, the computer control system has been operating and works well. The computer closed-loop control system has the following characteristics:

A. The neutron flux is very stable.

The measured fluctuation of the neutron flux level (averaged in 5 s.) is less than 0.8% within 24 hours, as shown in Fig. 2.

B. The neutron flux level is continuously adjustable from 1.0E+8 to 1.2E+12n/s.cm.cm.

C. A small fission ionization chamber is used for the measurement of neutron flux. It is sensitive with the thermal neutrons so that the thermal neutron flux level can be kept constant and the correct results of activation analysis can be easily obtained.

D. Display.

The operating data of the reactor are shown on a CRT terminal clearly, as shown in Fig. 3.

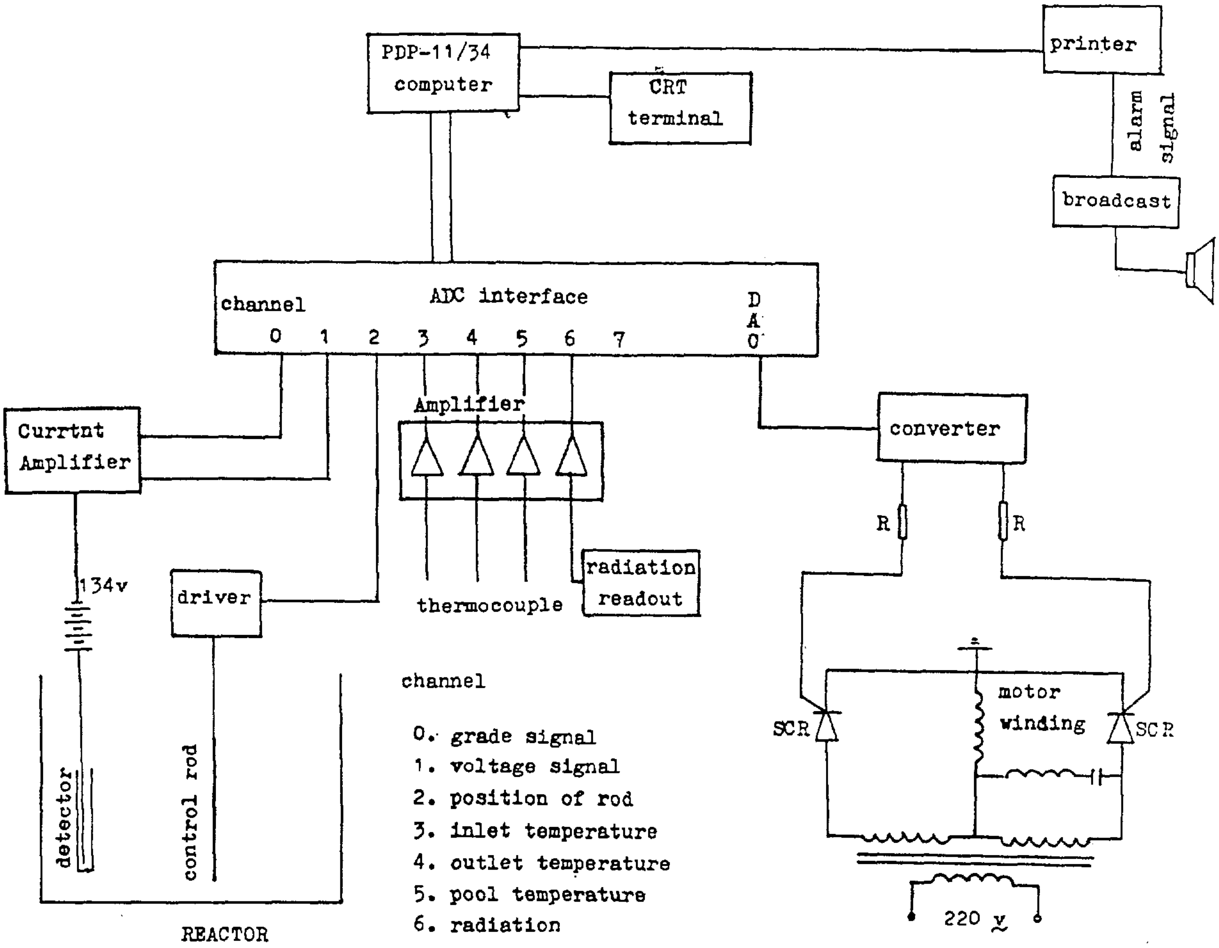

FIG.1 The block diagram of control system

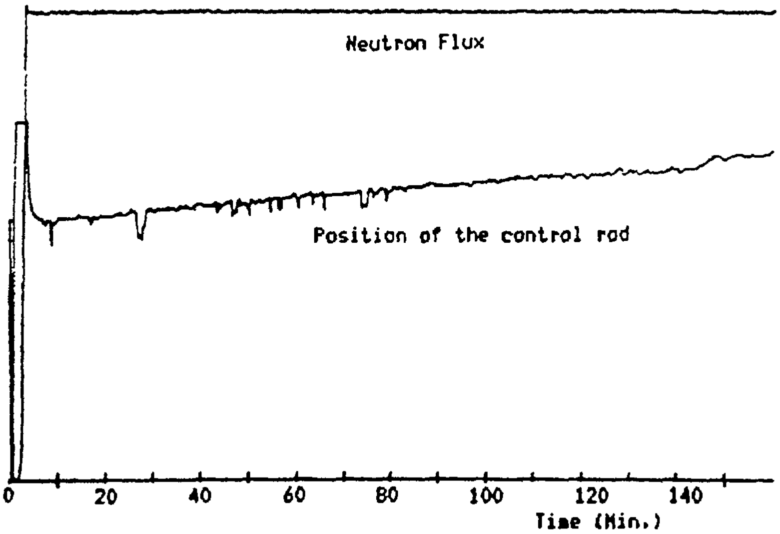

Fig. 2 The operating recording of the MNSR

```
10:23:14 9.968E+11 1.0E+12n/s/cm.cm 182.37mm T=21.74 42.19 15.24  1.17ur/s 2246.1mv
10:23:15 9.968E+11 1.0E+12n/s/cm.cm 182.37mm T=21.85 41.87 15.24  1.20ur/s 2243.7mv
10:23:16 9.968E+11 1.0E+12n/s/cm.cm 182.37mm T=21.96 41.37 15.20  1.15ur/s 2243.7mv
10:23:17 9.968E+11 1.0E+12n/s/cm.cm 182.37mm T=22.00 40.90 15.20  1.16ur/s 2246.1mv
10:23:18 9.968E+11 1.0E+12n/s/cm.cm 182.37mm T=22.00 40.94 15.24  1.23ur/s 2246.1mv
10:23:19 9.968E+11 1.0E+12n/s/cm.cm 182.37mm T=21.93 41.15 15.24  1.23ur/s 2246.1mv
10:23:20 9.968E+11 1.0E+12n/s/cm.cm 182.37mm T=21.89 40.86 15.24  1.25ur/s 2248.5mv
10:23:21 9.990E+11 1.0E+12n/s/cm.cm 182.37mm T=21.78 40.65 15.24  1.26ur/s 2248.5mv
10:23:22 9.990E+11 1.0E+12n/s/cm.cm 182.37mm T=21.70 40.33 15.24  1.22ur/s 2251.0mv
10:23:23 9.990E+11 1.0E+12n/s/cm.cm 182.37mm T=21.66 40.15 15.28  1.25ur/s 2253.4mv
10:23:24 9.990E+11 1.0E+12n/s/cm.cm 182.37mm T=21.70 40.65 15.24  1.27ur/s 2253.4mv
10:23:25 1.001E+12 1.0E+12n/s/cm.cm 182.37mm T=21.78 41.22 15.24  1.29ur/s 2253.4mv
10:23:26 1.001E+12 1.0E+12n/s/cm.cm 182.37mm T=21.85 41.44 15.24  1.28ur/s 2253.4mv
10:23:27 1.001E+12 1.0E+12n/s/cm.cm 182.37mm T=21.93 41.80 15.24  1.27ur/s 2255.9mv
10:23:28 1.004E+12 1.0E+12n/s/cm.cm 182.37mm T=22.04 42.01 15.24  1.26ur/s 2258.3mv
10:23:29 1.004E+12 1.0E+12n/s/cm.cm 182.37mm T=22.08 42.19 15.24  1.29ur/s 2258.3mv
```

Fig. 3 The operating data shown on a CRT terminal

E. Audible alarm can be broadcasted:

   a. if any operating data go beyond the limit,
   b. if the executive body is out of order.

F. Convenient for activation analysis.

The control and the neutron activation analysis share the same computer, but they do not interfere with each other. And the control system can give neutron flux value for neutron activation analysis directly.

G. The operating journal can be obtained after the reactor shut-down, and accumulation of the burn-up and the operating time can be performed, as shown in Fig. 4.

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                          REACTOR OPERATING JOURNAL
                                  16-APR-85

      Time           Neutron-Flux      R.H.   Temperature     R.     Ref.  Int.flux
             (s)     n/s/cm.cm          mm    in.  out. pool ur/s     mv    n/cm.cm
  09:20:46    51   2.276E+09 0.0E-01   -0.5   15.4 16.1 16.9 0.01     7.3 0.000E-01
  09:23:12   197   1.001E+12 1.0E+12  217.8   15.5 17.1 16.9 1.05 2258.3 2.983E+13
  10:00:00  2405   9.990E+11 1.0E+12  187.7   23.0 40.6 16.8 1.21 2270.5 2.235E+15
  11:00:00  6005   9.945E+11 1.0E+12  206.1   28.9 42.2 16.8 1.33 2294.9 5.830E+15
  11:30:45  7849   9.968E+11 1.0E+12  215.6   27.8 47.7 17.0 1.36 2307.1 7.672E+15
  11:31:22  7886   1.980E+11 2.0E+11   -0.5   29.7 42.9 17.0 0.52  466.3 7.687E+15

   Warning:         0                 Hardware Error:   0
   Operating time:  2.1764hours       Sum Total:        41.2372hours
   Burn-up:     7.687E+15n/cm.cm      5.440E+01kw.h
   Sum Total:  8.511E+16n/cm.cm       6.023E+02kw.h  from 21-MAR-85 to 16-APR-85
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Fig. 4 The operating journal of the MNSR

H. Reasonable.

Ony a few components are needed for an existing computer.

The computer closed-loop control system is satisfactory. This work is not only useful for the MNSR, but also for other reactors. There are the common characteristics of reactors in the MNSR, and there is not any danger in the MNSR to test the software and hardware, so that we can use it as a tool to develop more complex computer control systems for other reactors.

APPLICATION OF THE MINIATURE NEUTRON SOURCE REACTOR

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Abstract

The Miniature Neutron Source Reactor, built by the Institute of Atomic Energy, operates at a maximum power of 27 kW and a maximum available flux of 1×10^{12} n/cm^{2}s^{-1}. It is used primarily for activation analysis in a large number of fields – medicine, foods, geology, environment, industry, etc. Over 1500 different samples have been analysed. The majority of samples are irradiated between 1 and 10 minutes in a flux of 4×10^{11} n/cm^{2}s^{-1}. The gamma spectra are analysed using a locally developed software package called the SPAN on a PDP-11/34 computer.

The Miniature Neutron Source Reactor (MNSR) has been built up in March 1984 in Beijing. The kind of reactor is very good for neutron activation analysis. Since then abount 1500 different samples have been analyzed with the MNSR, these samples include:

Food
Traditional Chinese medicine
Greens
Serum
Hair
Resin
Atmospheric dust
Meteoric stone
Ore (gold ore, iron ore and others)
Water
Stained glass
Alloy
Soil
others.

Accoudings to the irradiation time we classify the samples into four groups, they are shown in Table 1, and the most samples lie in the range of 1-10 minutes.

Table 1. The classification of samples on irradiation time

Time	1m	1-10m	10-60m	60m
Number	240	867	36	208
	17.8%	64.2%	2.7%	15.3%

(from 84.4 through 85.3)

We also classify the samples on neutro flux as shown in Table 2. The most samples are irradiated at the level 1.0 to 4.0 x 10^{11}n/s.cm^2, so the radioactivities of these sample are high enough to measure. Especially for the short live nuclide the neutron flux level must be much lower, if not, the instrument will not be able to measure the samples becouse the radiactivaties are too intensive.

Table 2. The classification of samples on neutron flux level

Neutron flux	4.0 x 10^{11}	6.0 x 10^{11}	8.0 x 10^{11}	1.0 x 10^{12}
Number	713	144	39	455
	52.8%	10.7%	2.9%	33.7%

The results of activation analysis are satisfied as shown in Table 3, and we also are pleased with our facility, it includes the MNSR, the capsule transfer system and the gamma ray spectrum data acquisition and processing system.

First I want to describe why the MNSR is very good for neutron activation analysis, in summary the MNSR has following advantages.

A. The neutron flux level is very stable. Now a computer closed-loop control system has been developed for the MNSR. The neutron flux level can be kept constant with the control system, and the fluctuation is less than 1% within 24 hours. The measured value of the variation of neutron flux level (averaged in 5 s.) is 0.8%. The operating recording is shown in Fig. 1.

Table 3. The analysed results of the Mn standard samples

No	Measured Value (ppm)	Mean Value	Standard Deviation
1	29.42	30.00	0.68
2	29.15		(2.3%)
3	29.24		
4	30.72		
5	29.99		
6	29.68		
7	30.08		
8	30.92		
9	30.40		
10	28.87		
11	30.24		
12	29.53		
13	30.73		
14	31.06		
15	29.99		

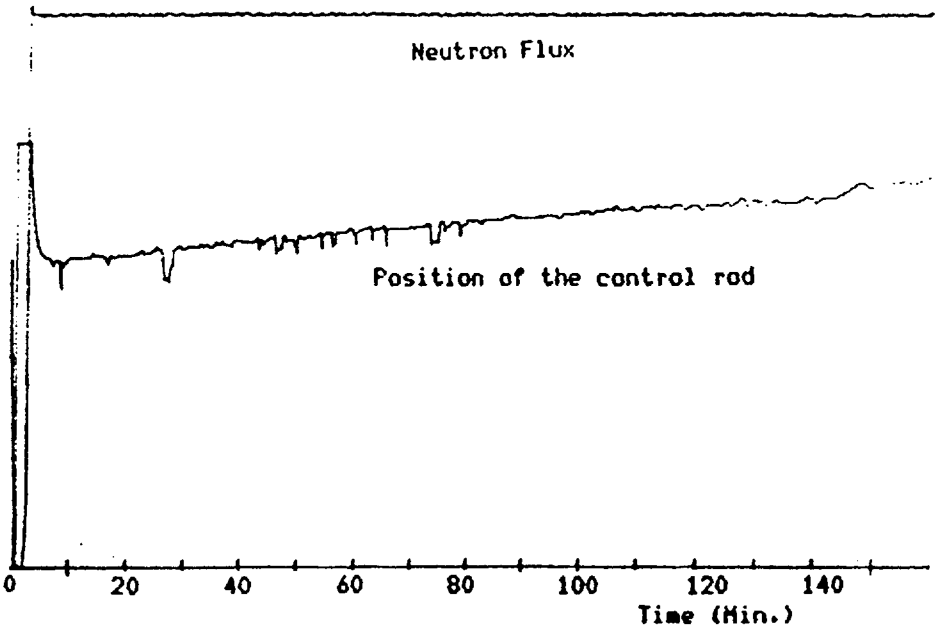


Fig. 1 The Operating Recording of the MNSR

B. The neutron flux level is continuously adjustable from 1.0×10^8 to 1.2×10^{12}n/s.cm^2 as per need of activation analysis, and to change the neutron flux level is very easy.

C. The temperature is less than 45°C in the irradiation tubes of the MNSR. So that the biological sample and the liquid sample can be transferred into the MNSR for irradiating directly.

D. When the reactor is running the temperature will be stable gradually as shown in Fig.2, and the neutron spectrum will be stable gradually too. Because the change of the temperature is not large too. So that the satisfactory results could be obtained.

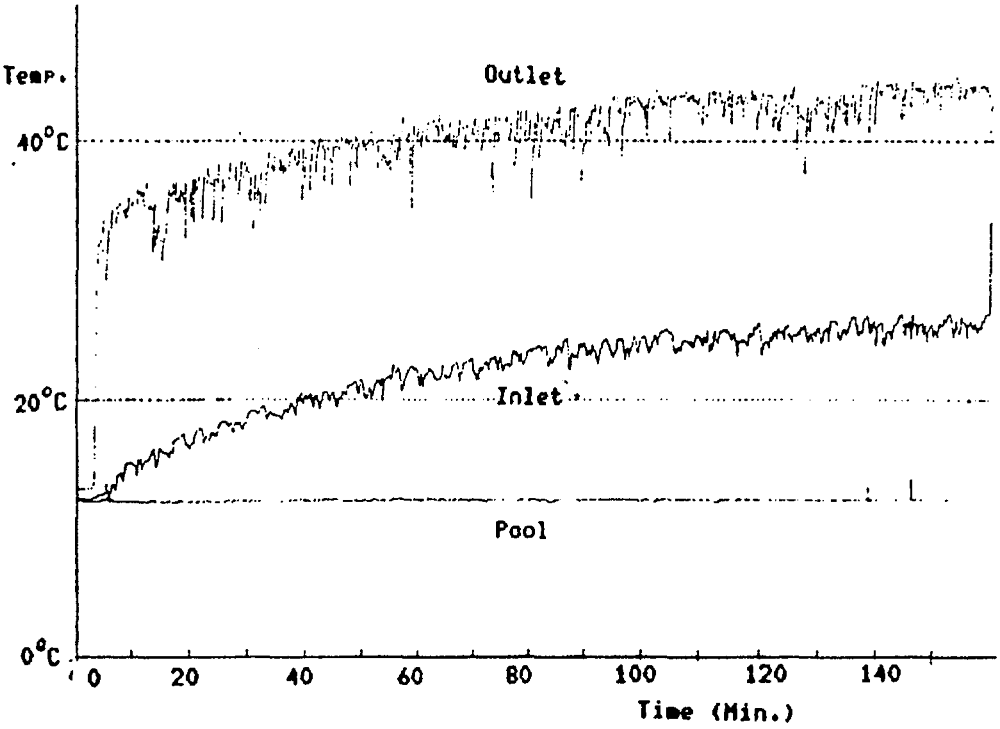
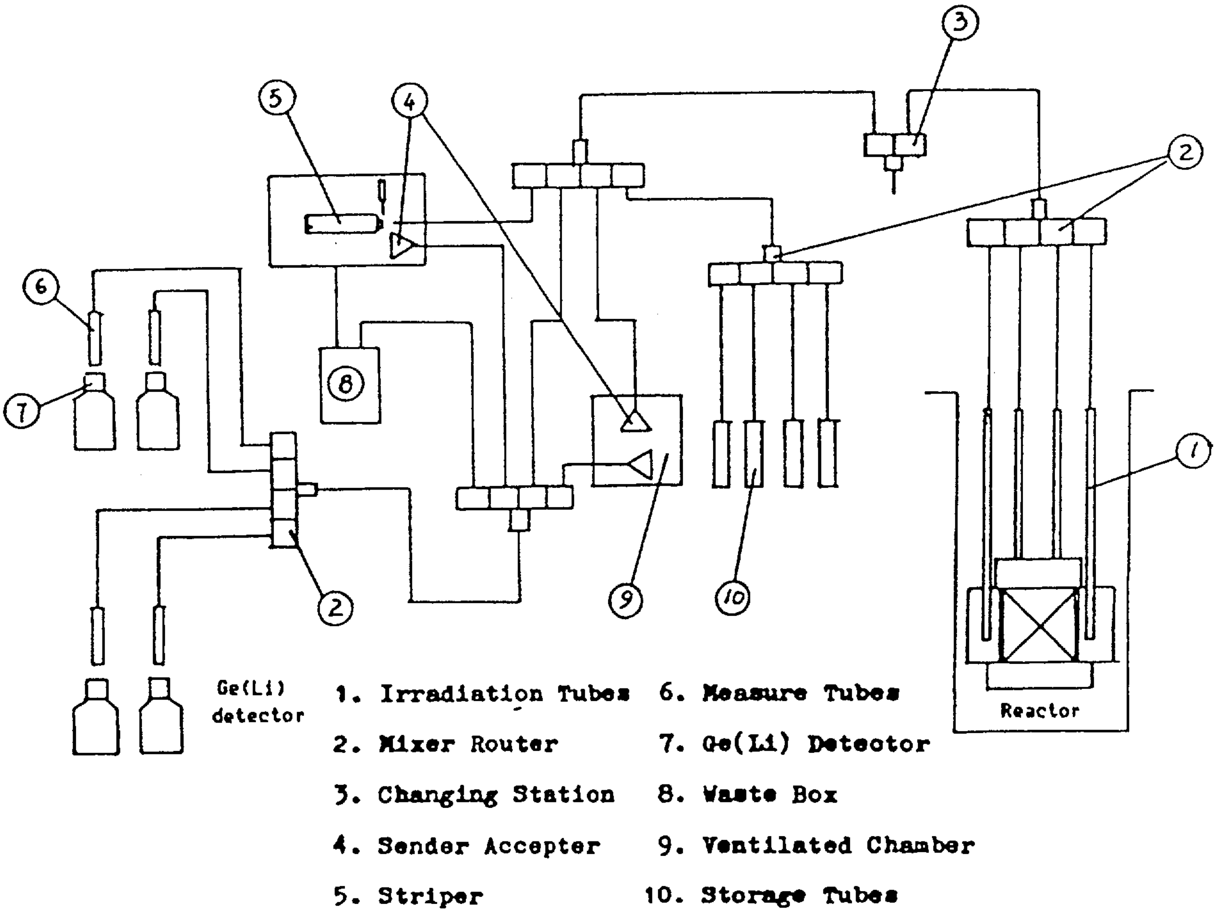


Fig. 2 The Temperature Recording of the MNSR
(Neutron flux level=1.0×10^{12}n/s.cm^2)

E. A small fission ionization chamber is used for measurement of neutron flux. It is sensitive with the thermal neutrons. so that the thermal neutron flux level can be kept constant. The majiority of neutron activation analysis use thermal neutrons, so that the correct results could be easily obtained. Table 3 shows the analysed results of 15 standard samples irradiated at diffirent neutron flux levels.

F. The destribution of neutron flux is same in diffirent irradiation tubes and in every space of a tube, its deviation is less than 3%.

Of couse the MNSR has some other advantages, for example, plenty of irradiation tubes, safe in operation etc. Take it all the MNSR is a very good facility for neutron activation analysis.



1. **Irradiation Tubes**
2. **Mixer Router**
3. **Changing Station**
4. **Sender Accepter**
5. **Striper**
6. **Measure Tubes**
7. **Ge(Li) Detector**
8. **Waste Box**
9. **Ventilated Chamber**
10. **Storage Tubes**

Fig. 3 The Capsule Transfer System

A powerful capsule transfer system has been built in our laboratory, the system is shown in Fig.3. The capsule can be transferred into reactor to irradiate with the system, the irradiating time can be controled with a timer. After irradiation the capsule could be transferred to detector to measure gamma ray directly, or to the gloves box and to uncover the capsule with a striper, or to the ventilated chamber for chemical processing, or to the store tube for cooling, A capsule can be transferred from one space to any others, all the operations can be done on a control board.

A matter of especial importance is the application of a change station. it connects across the two loops of the capsule tranfer system, it can prevent the active air from escaping into laboratory. The capsule transfer sustem is very safe.

An automatical capsule tranfer system controlled by a computer is under development. In the future the capsule transfer system would be more advance and powerful.

The gamma ray spectrum data acquisition and processing system, it includes a Ge(Li) detector, a Series-80 multichannel analyer and a PDP-11/34 computer. The resolution of the detector is 2.0 kev, and the efficiency of it is 25%. But the application software is developed by us, it called SPAN (Neutron Activation Analysis Package). The SPAN has following characteristics.

A. Full Functions
  a. The peak analysis.
    - To search peaks automatically.
    - To fit background line.
    - To resolve multiplets.
    - To calculate the central channel, energy, net area, error, and FWHM of each peak.
    - To do geometry corrections.
    - To identify nuclide.
    - To calculate the radioactivity of the nuclide.
    - To print the peak analysis report as Table 4 and Table 5.
  b. The activation analysis calculation.
    - To correct the irradiation time and decay time.
    - To calculate the concentration or detection limit of each element.
    - To print the activation analysis report as Table 7.
  c. Remote control of the MCA.
  d. Many auxiliary functions:
    - To list analysis reports as Table 8.
    - To modify the analysis reports.
    - To transfer spectrum data.
    - To calibrate the instruments.
    - To do automatic recalibration of energies.
    - To edit the nuclear data library.
    - To edit the elements of interest.

Table 4. A peak analysis report of the SPAN

```
                              ****************************************
                              *  SPAN SOFTWARE PEAK ANALYSIS REPORT  *
                              *           10:06:53  16-APR-85        *
                              ****************************************

   Spectrum number: 2635      Geometry number: 2      Group number: 3      Active Time:  600.0s      True Time:  609.0s

                                         From   40 Channel to 4000 Channel
----------------------------------------------------------------------------------------------------------------------------
No  Centr.Ch.  Ray-Energy   Peak-Area    Error  GFD  FWHM     Nuclide Half-Life    Energy    Intensity Most-Intense Radioactivity
----------------------------------------------------------------------------------------------------------------------------

 1P    93.34    73.284Kev     131.3c   43.51%  0.00 1.09Kev
 2C   210.50   165.120Kev     212.4c   19.22%  1.35 0.93Kev  Hg197m 2.400E+01H   165.000Kev 0.32000   133.945Kev  5.496E+01dps
 3C   215.60   169.118Kev     122.2c   32.11%  1.35 0.93Kev
 4    278.31   218.264Kev     203.8c   31.91%  0.00 2.80Kev
 5C   495.07   388.146Kev     299.2c   11.57%  1.37 1.71Kev  Sr87m  2.810E+00H   388.400Kev 0.82500   388.400Kev  5.391E+01dps

 6C   499.53   391.639Kev      84.9c   35.92%  1.37 1.71Kev  Sn113  1.152E+02D   391.400Kev 1.00000   391.400Kev  1.271E+01dps
 7    564.24   442.351Kev    4740.0c    1.69%  0.00 1.37Kev  I128   2.499E+01M   442.917Kev 0.20500   442.917Kev  3.793E+03dps
 8P   590.85   463.199Kev      65.1c   48.06%  0.00 1.39Kev
 9C   651.53   510.755Kev    2700.9c    2.39%  1.38 2.79Kev  Tl208  3.100E+00M   510.808Kev 0.23000  2614.600Kev  2.149E+03dps
                                                             Annih. 0.000E-01S   511.000Kev 1.00000   511.000Kev  4.942E+02dps
10    671.14   526.119Kev     356.9c   10.79%  0.00 1.25Kev  I135   6.700E+00H   526.500Kev 0.11300  1260.500Kev  5.910E+02dps

11C   786.84   616.777Kev     202.8c   15.71%  1.69 2.47Kev  Br80   1.760E+01M   616.200Kev 0.07000   616.200Kev  6.119E+02dps
12C   791.50   620.428Kev     110.0c   27.54%  1.69 2.47Kev  Cl38  1642.420kevDE
13    930.00   728.943Kev      56.8c   48.31%  0.00 1.47Kev
14    966.49  -757.533Kev     111.2c   31.60%  0.00 2.41Kev  Al28  1778.900kevDE
15C  1076.34   843.591Kev    1640.1c    2.99%  1.72 1.57Kev  Mg27   9.450E+00M   843.800Kev 0.72000   843.800Kev  6.122E+02dps

16C  1080.17   846.590Kev    2557.8c    2.26%  1.72 1.57Kev  Mn56   2.587E+00H   846.600Kev 0.99000   846.600Kev  6.962E+02dps
17   1207.20   946.100Kev      66.8c   37.09%  0.00 1.80Kev
18   1228.38   962.688Kev      53.3c   38.00%  0.00 1.62Kev
19   1294.16  1014.217Kev     474.8c    7.94%  0.00 1.73Kev  Mg27   9.450E+00M  1014.400Kev 0.28000   843.800Kev  5.257E+02dps
                                                             K42   1524.700kevSE
20   1325.85  1039.037Kev     499.8c    7.68%  0.00 1.78Kev  Cu66   5.100E+00M  1039.000Kev 0.09000  1039.000Kev  1.754E+03dps

21C  1462.01  1145.684Kev     244.1c   12.36%  1.73 2.62Kev  Cl38  2167.550kevDE
22C  1467.58  1150.053Kev      59.6c   43.44%  1.73 2.62Kev
23   1617.59  1267.538Kev      87.6c   28.68%  0.00 2.01Kev  Al28  1778.900kevSE
24   1650.70  1293.466Kev    1197.2c    3.83%  0.00 1.99Kev  In116m 5.410E+01M  1293.430Kev 0.85000  1293.430Kev  5.279E+02dps
                                                             Ar41   1.830E+00H  1293.600Kev 0.99100  1293.600Kev  4.528E+02dps
25   1746.52  1368.503Kev    3191.6c    2.07%  0.00 2.17Kev  Na24   1.502E+01H  1368.534Kev 0.99990  1368.534Kev  1.250E+03dps

26   1796.86  1407.919Kev      59.2c   43.59%  0.00 1.97Kev  Eu152m 9.300E+00H  1408.025Kev 0.01700  1408.025Kev  1.394E+03dps
27   1830.13  1433.975Kev     198.1c   15.32%  0.00 2.05Kev  V52    3.760E+00M  1433.960Kev 1.00000  1433.960Kev  8.050E+01dps
28   1945.69  1524.463Kev      67.3c   34.93%  0.00 1.09Kev  K42    1.236E+01H  1524.700Kev 0.18000  1524.700Kev  1.595E+02dps
29   2096.48  1642.522Kev    2766.8c    2.13%  0.00 2.27Kev  Cl38   3.724E+01M  1642.420Kev 0.40000  2167.550Kev  3.128E+03dps
30C  2114.37  1656.532Kev     216.1c   12.73%  1.31 2.86Kev  Cl38  2167.550kevSE

31   2210.73  1731.969Kev     236.8c   10.67%  0.00 2.39Kev  Na24  2753.921kevDE
32   2270.61  1778.849Kev    3622.4c    1.83%  0.00 2.35Kev  Al28   2.243E+00M  1778.900Kev 1.00000  1778.900Kev  1.745E+03dps
33   2311.31  1810.711Kev     365.6c    7.97%  0.00 2.52Kev  Mn56   2.587E+00H  1811.200Kev 0.30000   846.600Kev  5.953E+02dps
34   2633.06  2062.557Kev     452.9c    6.57%  0.00 2.57Kev  Ca49  3084.410kevDE
35   2657.36  2081.576Kev     140.6c   13.07%  0.00 2.26Kev  S37   3103.330kevDE

36   2697.65  2113.114Kev     169.4c   14.00%  0.00 2.57Kev  In116m 5.410E+01M  2112.140Kev 0.15000  1293.430Kev  6.235E+02dps
                                                             Mn56   2.587E+00H  2112.600Kev 0.15000   846.600Kev  6.235E+02dps
37   2767.03  2167.410Kev    2892.1c    2.05%  0.00 2.48Kev  Cl38   3.724E+01M  2167.550Kev 0.54500  2167.550Kev  2.990E+03dps
38C  2863.17  2242.647Kev     273.9c    9.15%  1.45 2.79Kev  Na24  2753.921kevSE
39C  2867.27  2245.859Kev      45.1c   42.91%  1.45 2.79Kev
40   3285.53  2573.129Kev     569.1c    5.79%  0.00 3.92Kev  Ca49  3084.410kevSE

41   3310.16  2592.403Kev     189.1c   12.59%  0.00 3.43Kev  S37   3103.330kevSE
42   3516.60  2753.900Kev    1623.5c    2.89%  0.00 2.89Kev  Na24   1.502E+01H  2753.921Kev 0.99900  1368.534Kev  1.109E+03dps
43   3894.54  3049.518Kev      43.7c   21.15%  0.00 2.35Kev
44   3938.60  3083.981Kev    2474.5c    2.06%  0.00 3.09Kev  Ca49   8.720E+00M  3084.410Kev 0.92100  3084.410Kev  2.008E+03dps
45   3963.11  3103.146Kev     816.9c    3.60%  0.00 2.83Kev  S37    5.060E+00M  3103.330Kev 0.99700  3103.330Kev  6.155E+02dps


Gamma spectrum analysis finished, has  45 peaks. 18:39:00  16-APR-85
--------------------------------------------------------------------------
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Table 5. The peak analysis report of the spectrum of ^{152}Eu and ^{154}Eu

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                 SPAN SOFTWARE PEAK ANALYSIS REPORT

   Spectrum number :2003                   11:46:59  16-JAN-85
   Active Time : 4000.0s                   True Time : 4384.0s
   Geometry number: 2                      Group number: 2

                 From   40 Channel to 4000 Channel

-----------------------------------------------------------------------
No   Central   Ray-     Net-Peak  Error    GFD  FWHM   Nuclide   Radio-
     Channel   Energy    -Area                                   activity
                Kev        c        %           Kev                dps
-----------------------------------------------------------------------
 1     56.14    45.314    1541.4   27.74   0.00 1.231  Eu152    3.527E+04
 2c   107.01    85.099    6549.0    3.35  30.24 7.104
 3    132.46   104.999    2510.3   18.43   0.00 1.565
 4C   153.91   121.779 1004118.6    0.11   2.28 0.975  Yb177    4.872E+05
                                                       Eu152    5.046E+04
                                                       Co57     1.658E+04
 5C   155.42   122.958  214764.9    0.31   2.28 0.975  Eu154    7.681E+03
 :
 :
41    609.42   478.026     593.0   40.50   0.00 1.659
42c   623.15   488.758    8353.4    2.35   2.57 1.434  Eu152    5.529E+04
43c   629.03   493.362     659.2   25.90   2.57 1.434  Eu152    4.518E+04
44    641.83   503.375    2826.8    9.39   0.00 1.294  Eu152    5.115E+04
45    650.89   510.456    1011.2   27.86   0.00 3.019  Tl208    1.206E+02
                                                       Annih.   2.774E+01
                                                       Eu152    7.300E+04

46    663.33   520.186    1069.6   22.91   0.00 1.481  Eu152    5.616E+04
47    681.12   534.097    1072.2   27.80   0.00 2.101  Eu152    7.180E+04
48    710.55   557.114     767.4   31.99   0.00 1.966
49c   719.34   563.990    9918.6    2.13   2.99 1.564  Sb122    4.659E+02
50c   722.22   566.239    2857.8    6.60   2.99 1.564  Eu152    6.680E+04

51C   742.33   581.968    1421.5   12.19   0.80 1.342
52C   747.79   586.241    7866.6    2.44   0.80 1.342  Eu152    5.305E+04
                                                       Eu152 1608.355kevDE
53C   754.87   591.779    8619.7    2.19   0.80 1.342  Eu154    5.293E+03
54    797.54   625.150     687.6   32.95   0.00 1.952  Eu152 1647.310kevDE
55    837.52   656.414    2461.2   10.11   0.00 1.823  Eu152    5.760E+04

56C   860.90   674.702    2878.9    6.06   1.21 1.618  Eu152    5.340E+04
57C   865.85   678.569    7909.9    2.39   1.21 1.618  Eu152    5.940E+04
58C   878.70   688.619   14444.7    1.43   2.01 1.553  Eu152    6.074E+04
59C   883.49   692.367    2925.2    6.03   2.01 1.553  Eu154    5.754E+03
60c   909.39   712.623    1855.5    9.13   6.64 1.542  Eu152    6.943E+04

61c   917.88   719.263    5424.1    3.30   6.64 1.542  Eu152    6.024E+04
62c   922.97   723.245   31689.6    0.79   6.64 1.542  Eu154    5.617E+03
63C   965.69   756.657    7895.4    2.56   1.70 1.798  Zr95     5.360E+02
                                                       Eu154    6.806E+03
64C   969.46   759.606     574.7   29.87   1.70 1.798
65C   976.09   764.789    3076.8    5.53   1.52 1.524  Eu152    6.647E+04

66C   981.31   768.868    1526.6   10.57   1.52 1.524  Eu152    6.510E+04
67    993.88   778.698  195377.7    0.29   0.00 1.690  Eu152    5.830E+04
68C  1014.33   794.695     702.2   23.34   1.10 1.782  Eu152    1.112E+05
69C  1019.39   798.656     440.5   36.13   1.10 1.782
70C  1034.31   810.320    5008.4    3.50   1.85 1.696  Eu152    6.273E+04
                                                       Co58     1.977E+02

71C  1040.30   815.003     760.6   20.86   1.85 1.696  La140    1.309E+02
72C  1074.03   841.382    2110.3    7.62   1.45 1.609  Eu152    5.306E+04
73C  1079.44   845.618     949.4   16.49   1.45 1.609
74c  1107.04   867.204   58623.1    0.52   0.00 1.735  Eu152    5.903E+04
                                                       La140    4.389E+04
75c  1114.47   873.009   18596.3    1.10   0.00 1.735  Eu154    6.579E+03

76c  1119.01   876.561    1803.8    8.23   0.00 1.735
77c  1122.50   879.294    1743.0    8.45   0.00 1.735  Tb160    2.418E+02
78c  1126.50   982.422    1220.6   11.81   0.00 1.735
79c  1130.71   885.709    1171.9   12.52   0.00 1.735
80c  1138.96   892.164    1749.3    8.16   0.00 1.735
 :
 :
131C 2196.23  1719.019     132.7   10.54   2.22 2.248
132C 2253.87  1764.098      46.2   20.95   2.46 2.407
133C 2259.85  1768.775      79.0   14.08   2.46 2.407  Eu152    6.609E+04
134  3219.34  2519.138       9.4   39.90   0.00 2.609
135C 3340.81  2614.134     105.4   10.82   0.36 2.845  Tl208    1.034E+01

Gamma spectrum analysis finished, has 135 peaks. 09:08:52  14-APR-85
***********************************************************************
```

Table 6. The peak analysis report of SPECTRAN-F for the above spectrum

```
*************************************************************************
*                                                                       *
*                    G A M M A   S P E C T R U M   A N A L Y S I S      *
*                                                                       *
*************************************************************************

CANBERRA SPECTRAN-F V2.01  SOFTWARE

13-APR-8517:04:47

             A N A L Y S I S   P A R A M E T E R S
                                                              MULTIPLET ANALYSIS PERFORMED

MCA UNIT NUMBER:   1 / DETECTOR NUMBER:   1 / GEOMETRY NUMBER:   1
ADC UNIT NUMBER: 1.0
SPECTRUM SIZE:  4096 CHANNELS                                 SPECTRAL DATA READ DIRECTLY FROM MULTICHANNEL ANALYZER AND:
ORDER OF SMOOTHING FUNCTION:      0                           SAMPLE DESCRIPTION: EU152
NUMBER OF BACKGROUND CHANNELS:  4 ON EACH SIDE OF PEAK        ANALYZED BY:        WANG
PEAK CONFIDENCE FACTOR: 75.0%                                 COLLECT STARTED ON 16-JAN-85 AT 11:47:00
IDENTIFICATION ENERGY WINDOW: +- 1.00 KEV
ERROR QUOTATION: 1.00 SIGMA UNCERTAINTY                       COLLECT LIVE TIME:     4000. SECONDS


                                      13-APR-8517:04:47

                                   P E A K   A N A L Y S I S

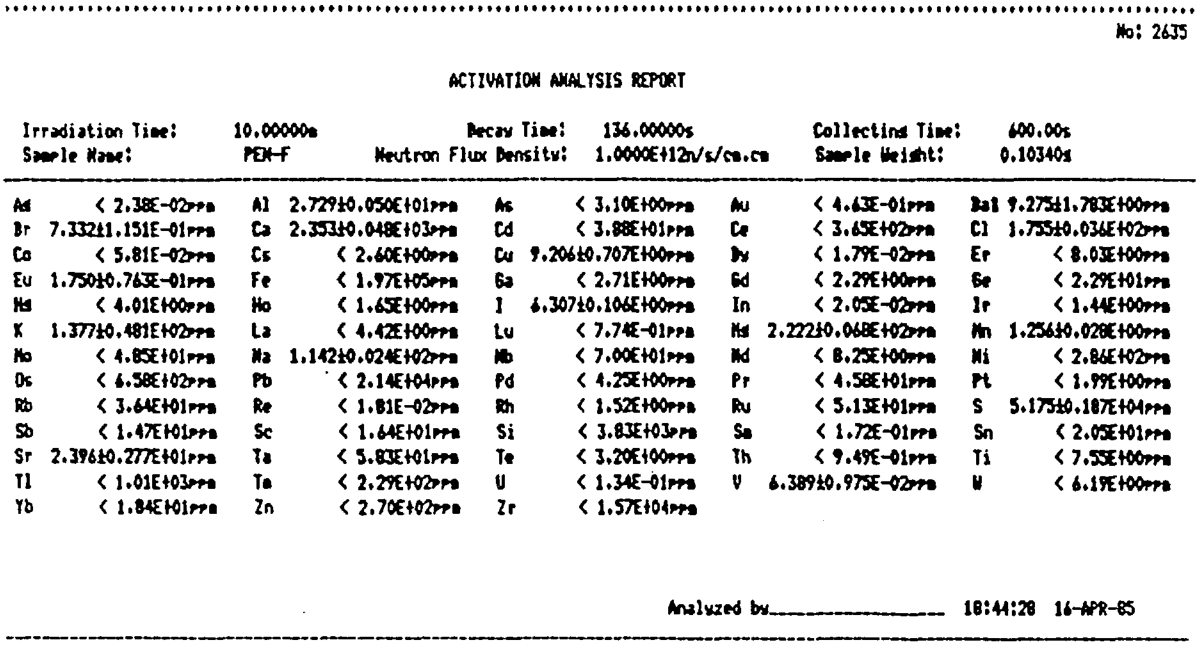
PK  START - STOP  CENTROID  ENERGY  FWHM    GROSS    BACKGND   NET AREA  ERROR    GFIT      NUCLIDES
      CHANNEL     CHANNEL    KEV    KEV     COUNTS   COUNTS    COUNTS     %

PEAK AT CHANNEL     59.6 DROPPED FROM MULTIPLET ANALYSIS
 1?    23 -   62    31.31    25.69   2.0   104039.   18256.     85783.    3.2 6.96E+02
 2?    23 -   62    35.01    28.59   2.0    92175.   31660.     60516.    4.1 6.96E+02
 3?    23 -   62    38.80    31.55   2.0    95202.   45367.     49835.    4.8 6.96E+02
 4?    23 -   62    42.54    34.48   2.0   104106.   58902.     45204.    5.4 6.96E+02
 5?    23 -   62    46.17    37.32   2.0   105764.   72043.     33721.    7.2 6.96E+02
 6?    23 -   62    49.77    40.14   2.0   108567.   85049.     23518.   10.3 6.96E+02
 7?    23 -   62    54.47    43.82   2.0   113097.  102084.     11013.   22.1 6.96E+02
 8C   126 -  160   153.80   121.57   1.4  1864407.  540081.   1324326.    0.1 ******** SE-75,CO-57
 9E   176 -  197   187.32   147.81   4.3   225889.  220052.      5837.   13.4 ******** PU-241
10?   305 -  322   311.03   244.64   1.3   329710.   53872.    275838.    0.6 5.17E+01
 :
 :
 :
22N   608 -  636   622.99   488.79   1.5    35765.   28160.      7606.    7.6 1.75E+00
23N   608 -  636   628.85   493.37   1.5    28654.   28069.       585.   22.0 1.75E+00
24.   635 -  659   641.85   503.55   1.5    32247.   29173.      3074.   12.6 1.01E+00
25.   635 -  659   650.14   510.04   1.5    30028.   29312.       716.   21.5 1.01E+00 TL-208,NA-22,ANN-RD
26.   635 -  659   652.47   511.86   1.5    30009.   29351.       658.   23.2 1.01E+00 NA-22,ANN-RD
27    674 -  688   681.47   534.55   1.9    35151.   34455.       696.   36.7 ********
28C   703 -  729   710.48   557.25   1.6    33253.   32493.       760.   15.3 6.82E-01
29C   703 -  729   719.21   564.08   1.6    42700.   32482.     10218.    4.4 6.82E-01 CS-134,SB-122
30C   703 -  729   722.20   566.42   1.6    35379.   32478.      2901.    5.8 6.82E-01
31.   735 -  762   742.22   582.09   1.5    31025.   29227.      1798.    9.8 1.66E+00
32.   735 -  762   747.66   586.34   1.5    36716.   28312.      8404.    3.8 1.66E+00
33.   735 -  762   754.72   591.87   1.5    36143.   27124.      9019.    3.8 1.66E+00 MO-101
34    830 -  844   837.45   656.60   1.8    32180.   29726.      2455.    9.8 ********
35C   853 -  873   840.74   674.82   1.6    29883.   27000.      2882.    5.6 1.16E+00
36C   853 -  873   845.68   678.68   1.6    34282.   26542.      7740.    4.0 1.16E+00
37    871 -  886   878.54   688.75   1.8    47482.   34768.     12714.    2.3 ********
38C   902 -  930   909.26   712.79   1.6    28834.   26995.      1839.   10.6 2.30E+00 SB-124
39C   902 -  930   917.74   719.42   1.6    32842.   27299.      5562.    4.0 2.30E+00
40C   902 -  930   922.82   723.40   1.6    59425.   27482.     31943.    1.7 2.30E+00 SB-124,I-131,ZR-95
41    958 -  973   965.56   756.83   1.9    41188.   33095.      8093.    3.4 ******** ZR-95
42?   984 - 1001   993.88   778.99   1.7   224443.   30899.    193544.    0.3 2.44E+01
43   1027 - 1041  1034.22   810.55   1.7    29043.   24673.      4370.    5.1 ******** I-132,CO-58
44   1066 - 1081  1073.96   841.64   1.6    29787.   28300.      1487.   16.2 ********
45?  1099 - 1122  1106.93   867.44   1.7    82419.   25184.     57235.    1.0 6.34E+00
46?  1099 - 1122  1114.38   873.26   1.7    41958.   25069.     16889.    2.5 6.34E+00
 :
 :
 :
84C  2028 - 2074  2038.86  1596.27   2.2     1931.     103.      1828.    3.3 1.71E+00 LA-140
85C  2028 - 2074  2051.35  1606.03   2.2      180.      90.        90.   17.0 1.71E+00
86C  2088 - 2113  2098.85  1643.17   2.3      414.      81.       334.    8.5 2.40E+00 CL-38
87C  2088 - 2113  2104.69  1647.73   2.3      199.      75.       124.   16.3 2.40E+00
88   2185 - 2204  2196.12  1719.22   2.4      186.      47.       140.   11.5 ********
89C  2242 - 2268  2253.71  1764.24   2.3       90.      41.        50.   22.1 1.28E+00 BI-214
90C  2242 - 2268  2259.79  1768.99   2.3      116.      35.        81.   17.6 1.28E+00 XE-138
91C  3327 - 3350  3341.12  2614.02   3.2      106.       6.       100.   10.9 8.44E-01 TL-208

ERROR QUOTATION AT 1.00 SIGMA
PEAK CONFIDENCE LEVEL AT 75.0%

C - MULTIPLET ANALYSIS CONVERGED NORMALLY
N - MULTIPLET ANALYSIS DID NOT CONVERGE
F - MULTIPLET ANALYSIS ERROR
. - MULTIPLET ANALYSIS CONVERGED DUE TO LACK OF CHI-SQ IMPROVEMENT
  - MULTIPLET ANALYSIS CONVERGED BUT GFIT > 4
```

Table 7 The activation analysis report of the SPAN



No: 2635

ACTIVATION ANALYSIS REPORT

Irradiation Time:	10.00000m	Decay Time:	136.00000s	Collecting Time:	600.00s
Sample Name:	PEN-F	Neutron Flux Density:	1.0000E+12n/s/cm.cm	Sample Weight:	0.10340g

Ag	< 2.38E-02ppm	Al	2.729±0.050E+01ppm	As	< 3.10E+00ppm	Au	< 4.63E-01ppm	Ba1	9.275±1.783E+00ppm
Br	7.332±1.151E-01ppm	Ca	2.353±0.048E+03ppm	Cd	< 3.88E+01ppm	Ce	< 3.65E+02ppm	Cl	1.755±0.036E+02ppm
Co	< 5.81E-02ppm	Cs	< 2.60E+00ppm	Cu	9.206±0.707E+00ppm	Dy	< 1.79E-02ppm	Er	< 8.03E+00ppm
Eu	1.750±0.763E-01ppm	Fe	< 1.97E+05ppm	Ga	< 2.71E+00ppm	Gd	< 2.29E+00ppm	Ge	< 2.29E+01ppm
Hf	< 4.01E+00ppm	Ho	< 1.65E+00ppm	I	6.307±0.106E+00ppm	In	< 2.05E-02ppm	Ir	< 1.44E+00ppm
K	1.377±0.481E+02ppm	La	< 4.42E+00ppm	Lu	< 7.74E-01ppm	Mg	2.222±0.068E+02ppm	Mn	1.256±0.028E+00ppm
Mo	< 4.85E+01ppm	Na	1.142±0.024E+02ppm	Nb	< 7.00E+01ppm	Nd	< 8.25E+00ppm	Ni	< 2.86E+02ppm
Os	< 6.58E+02ppm	Pb	< 2.14E+04ppm	Pd	< 4.25E+00ppm	Pr	< 4.58E+01ppm	Pt	< 1.99E+00ppm
Rb	< 3.64E+01ppm	Re	< 1.81E-02ppm	Rh	< 1.52E+00ppm	Ru	< 5.13E+01ppm	S	5.175±0.187E+04ppm
Sb	< 1.47E+01ppm	Sc	< 1.64E+01ppm	Si	< 3.83E+03ppm	Sm	< 1.72E-01ppm	Sn	< 2.05E+01ppm
Sr	2.396±0.277E+01ppm	Ta	< 5.83E+01ppm	Te	< 3.20E+00ppm	Th	< 9.49E-01ppm	Ti	< 7.55E+00ppm
Tl	< 1.01E+03ppm	Tm	< 2.29E+02ppm	U	< 1.34E-01ppm	V	6.389±0.975E-02ppm	W	< 6.19E+00ppm
Yb	< 1.84E+01ppm	Zn	< 2.70E+02ppm	Zr	< 1.57E+04ppm				

Analyzed by__________________ 18:44:28 16-APR-85

B. The analysis results are accurate.

a. No peak is lost.

We have used the SPAN and the SPECTRAN-F (CANBERRA's software) to analyse the same spectrum, the part of the results is shown in Table 5 and 6, the results were carefully checked and compared, as shown in Fig.5, we can find all the peaks, that can be found by the man's eyes, have been found by the SPAN, but some peaks are lost by the SPECTRAN-F, these peaks include some intensive ones.

b. The integral peak technique has been used.

This technique can produce a step background line, it can finely describe the background under peaks and can directly subtract the background from a spectra. So the accurate value of net peak area can be obtained.

c. The SPAN is powerful in resolving multiplits.

The least squares fitting (LSF) method and the Experimental Peak Shape Function have been used for peak analysis. They are capable of resolving the multiplets, as shown in Fig. 4. The limit of identification for closed doublet of equal intensities is about half of the FWHM.

Table 8 The final report of activation analysis

```
                  ****************************************
                  *                                      *
                  *      ACTIVATION ANALYSIS REPORT      *
                  *    The Institute of Atomic Energy    *
                  *                                      *
                  ****************************************
                                                                   unit = ppm

              1409                2269                3409               0
            Hair-1              Hair-2              Average
------------------------------------------------------------------------------

Ag        <2.62E-02          <2.82E-02          <2.62E-02
Al   1.134±0.043E+01    1.207±0.046E+01    1.170±0.037E+01
As        <8.25E+00          <8.94E+00          <8.25E+00
Au        <1.26E+00          <1.37E+00          <1.26E+00
Br        <1.37E+00          <1.49E+00          <1.37E+00
Ca   5.291±0.378E+02    5.664±0.405E+02    5.477±0.187E+02
Cl   8.486±0.128E+02    9.105±0.138E+02    8.795±0.309E+02
Co        <1.29E-01          <1.40E-01          <1.29E-01
Cs        <6.73E+00          <7.32E+00          <6.73E+00
Cu   6.867±1.181E+00    7.451±1.263E+00    7.159±0.292E+00
Dy        <4.65E-02          <5.05E-02          <4.65E-02
Eu        <1.24E+00          <1.34E+00          <1.24E+00
Ga        <7.59E+00          <8.20E+00          <7.59E+00
Gd        <3.40E+00          <3.65E+00          <3.40E+00
Hg        <9.95E+00          <1.08E+01          <9.95E+00
Ho        <4.25E+00          <4.62E+00          <4.25E+00
I         <5.10E-01          <5.51E-01          <5.10E-01
In        <5.22E-02          <5.64E-02          <5.22E-02
Ir        <3.82E+00          <4.13E+00          <3.82E+00
K    7.848±1.434E+02    8.495±1.541E+02    8.172±0.323E+02
Lu        <2.07E+00          <2.24E+00          <2.07E+00
Mg   1.019±0.092E+02    1.097±0.099E+02    1.058±0.039E+02
Mn   5.099±0.429E-01    5.477±0.461E-01    5.288±0.189E-01
Na   5.639±0.090E+02    6.057±0.096E+02    5.848±0.209E+02
Pd        <6.79E+00          <7.34E+00          <6.79E+00
Pt        <4.99E+00          <5.40E+00          <4.99E+00
Re        <4.13E-02          <4.49E-02          <4.13E-02
Rh        <6.25E-01          <6.74E-01          <6.25E-01
S    4.448±0.248E+04    4.750±0.265E+04    4.599±0.151E+04
Sm        <4.02E-01          <4.36E-01          <4.02E-01
Te        <7.63E+00          <8.28E+00          <7.63E+00
Th        <2.28E+00          <2.47E+00          <2.28E+00
U         <3.27E-01          <3.55E-01          <3.27E-01
V    4.484±1.372E-02    4.748±1.465E-02    4.616±0.132E-02
W    3.714±0.434E+01    3.989±0.469E+01    3.851±0.138E+01

                          Analyzed by____Wang__________  08:10:22  13-FEB-85
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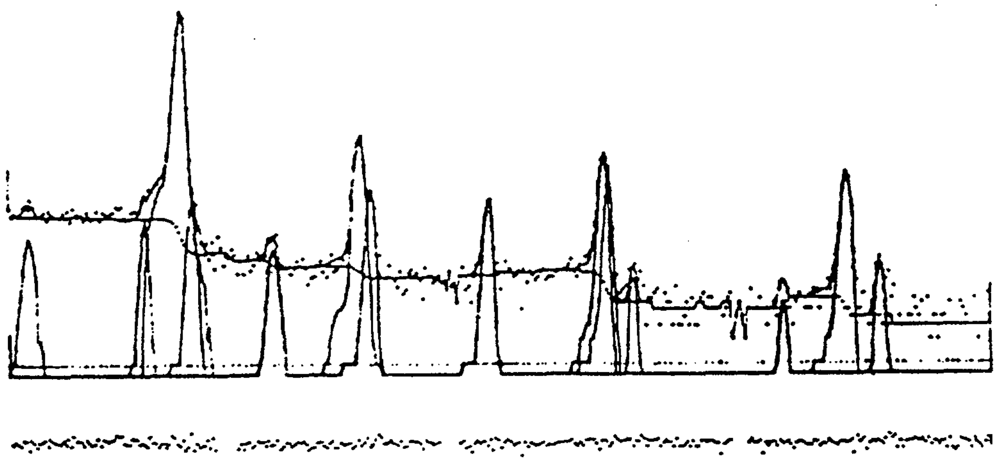
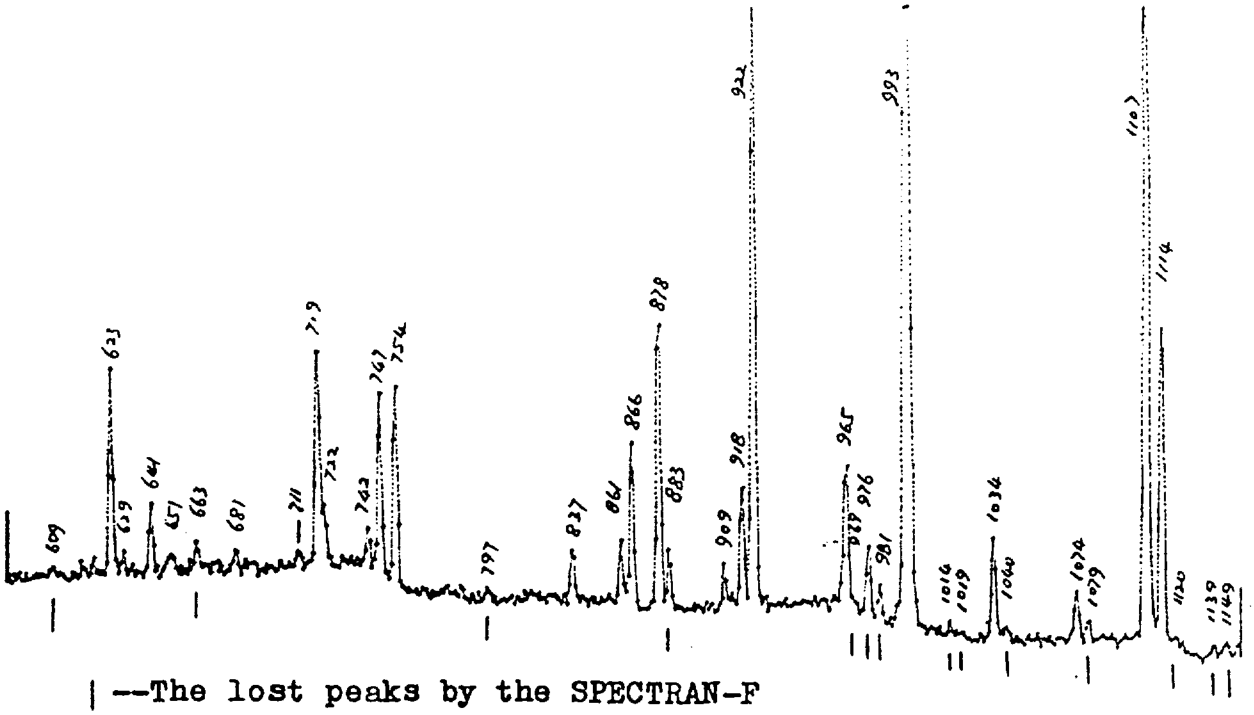


Fig.4 The step background line and the ability to resolve multplets



| —The lost peaks by the SPECTRAN-F

Fig. 5 The Comparison between the SPAN and the SPECTRAN-F

C. Very easy to use.
  a. Multiple options are supplied for user.
  b. Parameters will be memorized.
  c. A single command is enough to finish a task.
  d. Many complex commands can perform a series of tasks.
  e. 'LEARN' function is very useful for a lot of common samples.
  f. LOOP and PAUSE are available.
  g. Lowers work as capital Letters.
  h. HELP is available

As mentioned above the facility is a very good tool for neutron activation analysis, and the facility also suits for trainning of the analyst. In our laboratory the trainee can learn the technique of neutron activation analysis, which involves the knowledges of the nuclear physics, the nuclear chemistry, the automatic control and the use of the computer etc.

Of course the MNSR is a neutron source, it also can produce some radioactive isotopes, and it also can perform neutron photography and other research works. The MNSR is very useful, safe and reasonable, hopefully, the MNSR would have more and more users in the world in the near future.

MNSR–A SATISFACTORY TOOL FOR TRAINING AND TEACHING

GUO CHENGZHAN
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Beijing, China

Abstract

The MNSR is an epitome of general reactor in view of the structure and behavior, because the reactor is inherent safe, simple in structure and convenient in operation. It can not only be utilized at neutron activation analysis and produce short lived radioisotopes, but also is a satisfactory tool for training and teaching in universities and research institutes.

Since the reactor reached its rated power, many experts and students from home and abroad have visited this facility. They are all interested in its simplicity, security, reliability and practicality. In particular, its operational constraints are minimal, the reactor is simple so it is easy for a student to understand, there are no automatic trip devices to interfere with the experiments, consequently students are able to investigate the nuclear engineering characteristic of typical light water reactor in a very direct manner and understand those concepts learned in the class room easily.

Briefly the typical experiments which can be performed on this reactor are:

(1) Critcial test and rising power test.
(2) Absolute neutron flux measurements, axial and radial flux profile measurements.
(3) System cold excess reactivity measurements.
(4) Control rod worth calibration.
(5) Temperature coefficient of reactivity measurements.
(6) Observation of poisoning reactivity.
(7) Determination of absolute thermal neutron flux of reactor from xenon load.
(8) Spectrum index measurements, axial and circular related flux measurements in irradiation site.
(9) Reactor transient experiments and comparing their results with that of theoretical calculation.

(10) Studying the static and dynamic characteristics of reactor instrumentation(e.g. a high sensitivity helium detector, miniature fission ionization chamber, miniature gamma ionization chamber, titanium ionization chamber, cobalt self powered detector, platinum self powered detector).

(11) Investigation of optimum distribution of reactivity.

(12) Studing beryllium reflector influence on the reactor consisted of high enriched uranium and light water moderator.

(13) Automatically start up and unattended operations being used by computer.

(14) Miscellaneous studies.

Moreover MNSR is equiped with a PDP computer, multichannel analizer and neutron activation analysis program. Power, outlet and inlet temperature, control rod position, gamma dose, integrated flux were recorded by computer.

In the end we would like to serve for training licensed operator and activation analyst from home and abroad in short date.

OPERATION AND UTILIZATION OF THE ARGONAUT TYPE LOW FLUX REACTOR

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Abstract

The Low Flux Reactor (LFR) is in operation since 1960. Until 1983 the maximum power level has been 10 kW. In order to perform irradiations and experiments at higher neutron fluences, the power level was increased to 30 kW in 1983. In connection with the power upgrading several modifications to the reactor installation were necessary. The LFR is utilized for: (a) thermal neutron activation analysis, by means of a fast rabbit system, in combination with semi-automatic spectrometry equipment, (b) fast neutron effect studies on a.o. biological specimens; by means of a thermal-to-fast neutron converter system, (c) neutron radiography development studies by means of a neutron radiography collimator and exposure system, suited for the "direct" method (gadolinium foil), (d) training and education purposes. In view of its favourable neutron-gamma ratio future utilization of the LFR for neutron capture-gamma ray spectrometry studies is being considered.

PAST, OPERATION, MAINTENANCE AND UTILIZATION

The Low Flux Reactor, LFR, (1,2,3) is a water moderated and cooled reactor of the well known and widely used Argonaut type. The reactor is owned and operated by the Netherlands Energy Research Foundation (ECN) and is situated at Petten (North-Holland).
The reactor has been in operation since 1960 at power levels up to 10 kW. In June 1983 the maximum power level was increased to 30 kW, corresponding to a maximum thermal neutron flux density of $5{,}7 \times 10^{15}\ m^{-2}\ s^{-1}$ at the most favourable irradiation channel. A front view of the LFR is given in fig. 1, a horizontal cross section through core and irradiation positions is given in fig. 2, while a simplified LFR flow diagram is given in fig. 3.
The reactor has been operated without major problems. Major repairs and modifications implemented throughout the 10 kW period have been:
(1) replacement of the heavily corroded inner reactor tank.
(2) coating of all graphite reflector elements in order to prevent moisture pick-up, which previously had occurred and which had lead to gradual core reactivity changes.
(3) repair of the dump tank, in view of heavily corroded wall.
(4) replacement of the reactor control desk in order to improve the configuration of the instrumentation and also to provide for additional control and instrumentation for 30 kW operation.
Utilization of the reactor has initially been focussed on radiobiology, reactor physics and instrumentation testing, while after 1975 radio-analysis, neutron radiography and operator training have become the more dominant utilization areas.

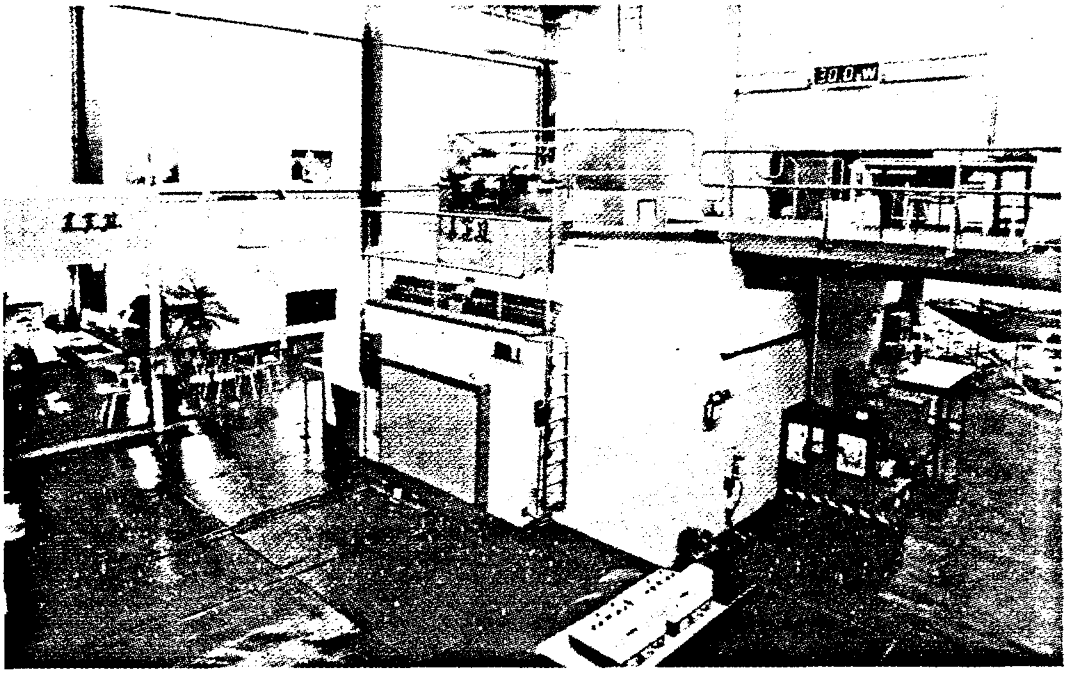


Fig. 1. The LFR with in front the irradiation trolley and on top the neutron radiography facility.

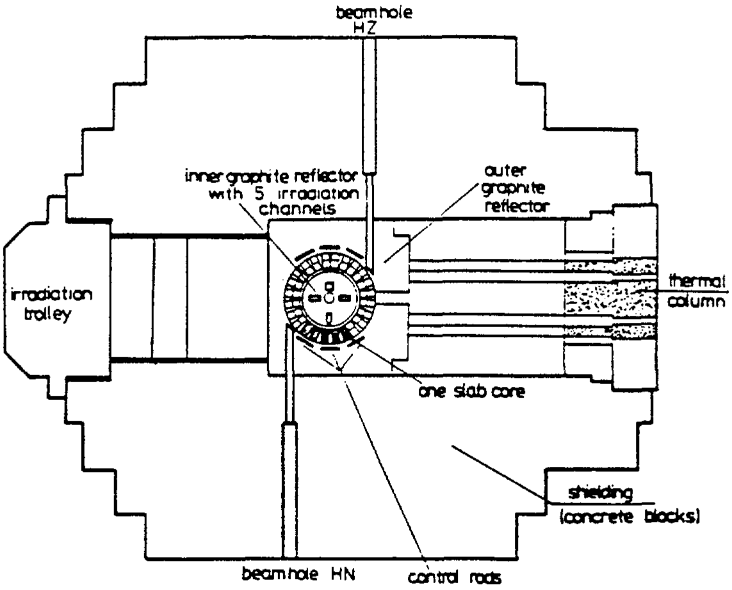


Fig. 2. Horizontal cross section.

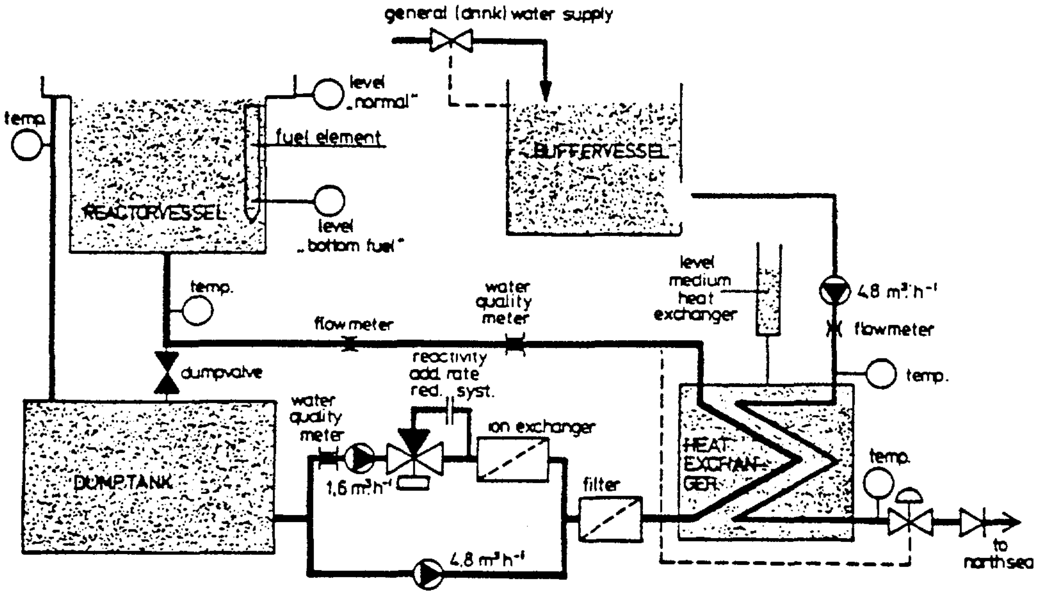


Fig. 3. Simplified LFR flow diagram.

POWER UPGRADING AND ASSOCIATED TECHNICAL MODIFICATIONS

The maximum power level has been increased from 10 kW to 30 kW in order to perform irradiations with neutron fluences up to 10^{20} within the normal 8-hour daily operating period.

Associated with the power upgrading the following technical modifications have been carried out:

(1) Increase of the cooling capacity of the primary and secundary cooling system (in order to maintain the temperature conditions of the fuel elements at "10 kW" level) by:
   - installation of an additional primary cooling pump with a three-fold capacity increase in relation to the existing pump
   - replacement of the secundary cooling pump by a larger pump (also three-fold capacity increase)
   - installation of a larger, plate-type, heat exchanger
   - adaptation of piping and lay-out to the increased flow rates.

(2) Improvement of the biological shielding around the reactor by installation of additional concrete blocks and other local provisions (a.o. around thermal column and irradiation trolley).

(3) Adaptation of the primary cooling control logic, in order to limit reactor vessel fill-up rates at $K_{eff} > 0.95$ to 20 $pcm.s^{-1}$, (as required by the Dutch Licensing Authorities).
   - a level control system which prohibits operation of the large pump between the levels "bottom fuel" and "normal" ("normal" means : reactor vessel completely filled with water).
   - a level/time relais control system which reduces the flow rate of the small pump by means of an electromagnetic valve controlled restriction in the delivery pipe of this pump at the water levels corresponding to $K_{eff} > 0.95$ and $d\rho/dt > 20$ $pcm.s^{-1}$.

(4) Installation of air-activity monitoring instrumentation at the core ventilation outlet duct in order to measure ^{41}Ar activit and thus enable verification of the ^{41}Ar release limit, as se by the Dutch Licensing Authorities.

UTILIZATION

Radio-analysis

The combination of a constant neutron flux and a high ratio of thermal to epithermal neutrons (50) offers a good opportunity for elemental analysis using instrumental thermal neutron activation. Most analyses concern minor- and trace elements in solid samples like geological materials, sediments, coal, fly-ash or fuel-oil. Environmental samples, like surface water and bone, are regularly analysed as well.
The major part of the analyses demands short turn-over times. This implies the use of short-lived radionuclides. For this purpose samples of up to 500 mg weight are irradiated for 2 or 10 minutes in a thermal neutron flux of about $3 \times 10^{15}\ m^{-2}s^{-1}$, using the fast pneumatic rabbit system. Gamma-ray spectrometry is done after decay times from 2 up to 60 minutes. The use of a small computer enables the on-line data processing of the recorded counting results to elemental concentrations. Elements like sodium, chlorine, aluminium, manganese, vanadium and titanium are determined on a routine base this way.
Another application is neutron activation of long-lived radionuclides. Up to 40 samples can be irradiated simultaneously in the VC-rotating facility during circa 6 hours. After different decay-times, gamma-ray spectrometry leads to the analysis of up to 20 elements in samples of geological origin.

Nuclear physics

A high neutron flux is not necessary for certain capture experiments (e.g. the low-energy γ-spectroscopy or (γ/γ) coincidence work) but a favourable yield to background ratio and good collimation are of great importance. These conditions are easy to obtain at the LFR. Low background and good collimation allow measurements with small samples and detectors close to the target. This results in suppression of background peaks on the low-energy γ-spectrum and in few accidental counts for the coincidence work.

Fast neutron effect studies

These studies will be performed in the Fast Neutron Irradiation Facility, FNIF, on the irradiation trolley. The horizontal cross section of the irradiation with the FNIF is shown in fig. 4. The FNIF produces a pure fast-neutron flux, $\phi_n(f)$: $2 \times 10^{12}\ m^{-2}s^{-1}$, which is uniform over a large area. The neutron spectrum has been determined by proton-recoil spectrometry and by measuring the fission rates of threshold detectors ^{232}Th, ^{237}Np and ^{238}U. The mean neutron energy is 1.04 MeV.
The facility is very capable to perform irradiations of- and experiments with voluminous objects.

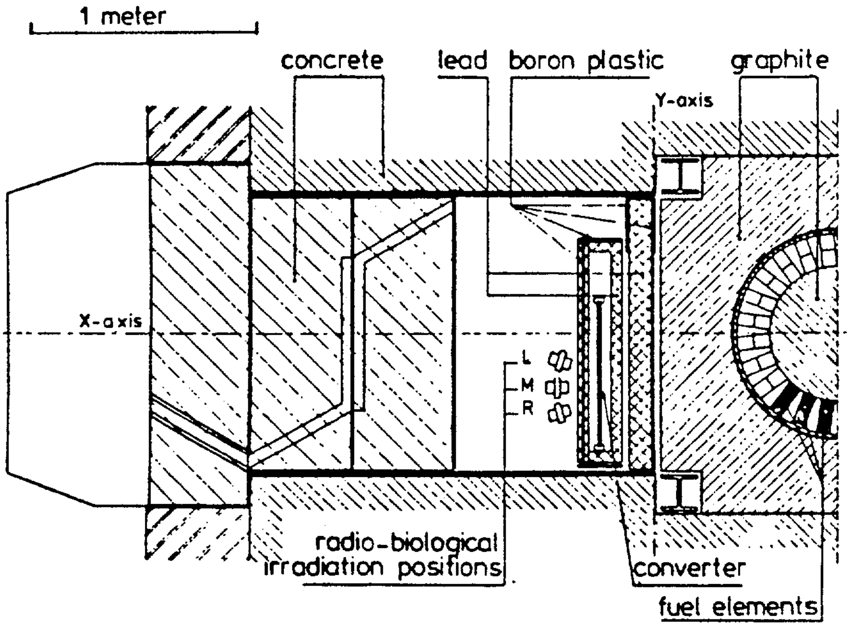
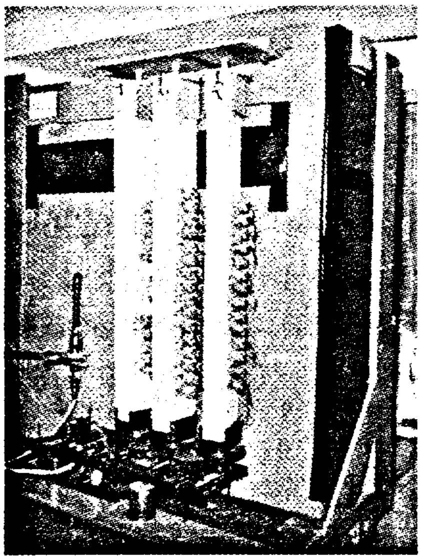


Fig. 4. Horizontal cross section of the irradiation trolley with the Fast Neutron Irradiation Facility, FNIF, and its geometry to the reactor core.



The facility is mainly used for radiobiological research on the effects of high-LET neutrons (4,5). In the facility small to medium sized animals can be exposed. Forth mice may be irradiated in the same fast-neutron centreline dose rate equal to 0.1 Gy.min^{-1} at a power level of 10 kW.
Fig. 5 shows the exposure arrangement for mice. The gamma contribution to the total centreline dose in the mice is 9%.

Fig. 5. Exposure arrangement for mice.

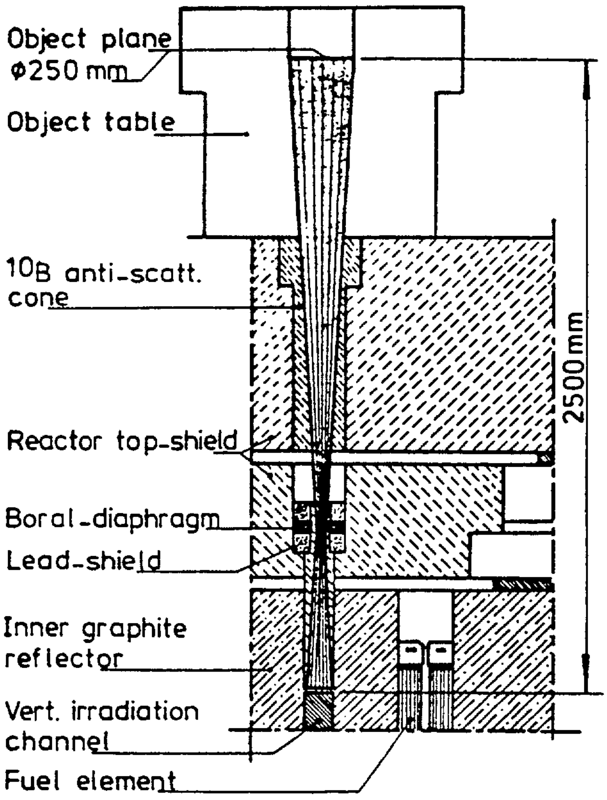


Fig. 6. Collimator system.

A neutron radiography facility can be installed at the top of the LFR. The position is just above the vertical irradiation channel of the inner graphite reflector. The accessibility for the large and heavy objects was one of the reasons to select this position. The neutron beam at the object plane (with a rather good homogeneous distribution) is obtained by a diabolo collimating system. Fig. 6 shows the position and the geometry of the collimator. The characteristics of the collimator are :

- collimator ratio: 127
- diaphragm diameter: 15 mm
- diaphragm material: lead rings with 2 x 4 mm Boral
- diameter object plane: 250 mm
- $\phi_{n(th)}$ object plane: 9.10^9 $m^{-2}s^{-1}$ (30 kW)
- Cd ratio: 40
- irradiation time: av. 10 min.

As the neutron-gamma ratio is high the system is very well suited for the direct method. Normally a gadolinium conversion screen with a thickness of 0.1 mm is used in combination with different X-ray films. The facility has been successfully in use during several years (6).

Training

For the education of university students and as a part of courses on reactor physics, reactor kinetics, radio chemistry, health physics, etc., the LFR is regularly in use to perform practical experiments.
As the reactor is very accessible, the core configuration is easy to change (even the number of fuel plates in the fuel element) and a broad scope of reactor kinetic experiments can therefore be performed.
Basic training of most of the operators of nuclear power stations of Belgium and The Netherlands is conducted at the LFR with emphasis on reactor operation (start/stop, power setting/-change/-control, etc.).

PERSPECTIVE IN FUTURE OPERATION AND USE

It is expected that the reactor will be more and more operated at the 30 kW power level. A gradual change in utilisation is expected towards radio analysis and nuclear physics. The latter implies installation and testing of new equipment and training students in the use of such equipment, partly in the context of later application in one of the HFR beamtube facilities.

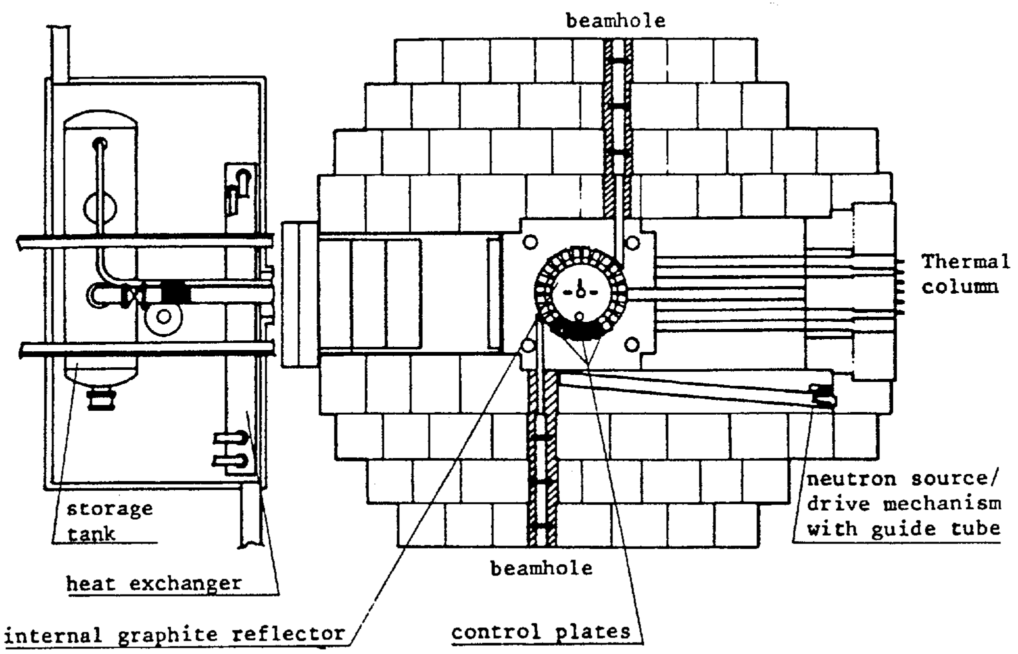


Fig. 7. Low Flux Reactor: Horizontal section. The fuel elements are arranged in single-slab core configuration; remaining space between tanks is filled with graphite.

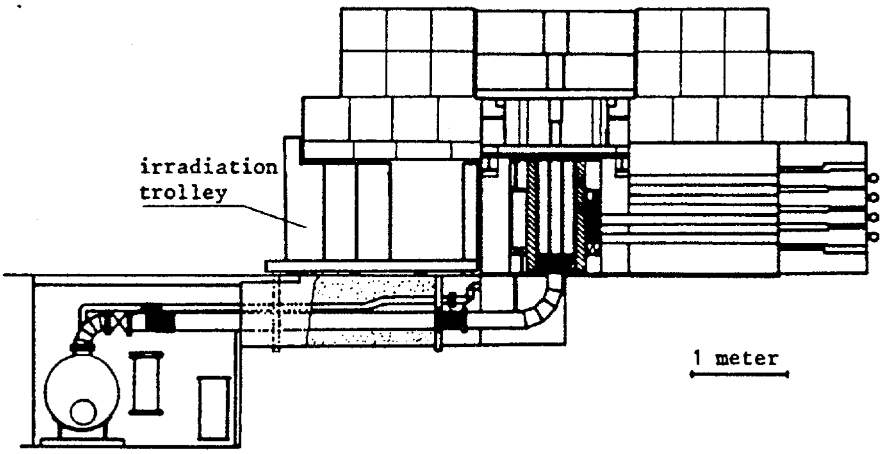


Fig. 8. Low Flux Reactor: Vertical section. In the core at left a graphite wedge, at right a fuel element in the outer annulus, a graphite filler element in the inner annulus.

BRIEF DESCRIPTION OF THE LFR
(Fig.'s 7 and 8)

Core and reflector

The reactor core is built of fuel elements placed in the annular space between two aluminium vessels; the outer vessel with a diameter of 90 cm, the inner vessel with a diameter of 60 cm.
The annulus contains 24 graphite wedges coated with epoxy resin. These wedges, centred vertically, are supported by an aluminium bottom lattice

plate and clamped to the top of the outer vessel. Between the wedges are rectangular openings, 15 x 7.5 cm, in each of which two core elements may be placed, which can be either graphite blocks or fuel elements. These elements are fixed by the lattice plate and by aluminium plates on the top of the wedges.
Each fuel element consists of a fuel box in which a maximum of nine fuel-plates can be placed. These plates are of the flat sandwich-type construction, prepared by picture frame techniques, with an active length of 600 mm. A standard fuel plate contains 21.3 gram 235U, 90% enriched. Shim plates are available which contain 10 gram 235U.
The inner reactor vessel is supported by seven structural members which are resting on the bottom plate of the outer vessel. The inner vessel, open at the top, is completely filled with graphite, thus providing a reflector and experimental region in the centre of the reactor. The outer vessel is surrounded by a graphite reflector stacked to a square block, 150 x150 cm in cross section and 120 cm high.

Typical core configurations are:
1. "Annual" core, in which the complete outer ring of core positions is filled with graphite elements and the inner one with fuel elements containing 8 or 9 fuel plates. Minimum critical mass 4363 gram 235U.
2. "One slab" core, in which there are 10 filled fuel boxes in a double row at the north side of the core annulus; the remaining space is filled with graphite. Minimum critical mass 1866 gram 235U. (This configuration is used for 30 kW operation).
3. "Two slab" core, consisting of two such double rows opposite each other. Minimum critical mass 3573 gram 235U.

Shielding

Stacked blocks of barytes concrete with a density of approximately 3.5 g/cm^3 constitute the main body of the shield. Block dimensions are 450 x 450 mm and 450 or 650 mm long. The shield thick. ness varies: at points needing a maximum attenuation, 1800 mm is provided. The 50 cm thick top shield is made of steel-shot concrete with a density of 5.2 gr/cm^3. This shield is pierced with a stepped opening to accomodate a plug which can be rotated. The insert plug, in turn, contains unloading parts which can be indexed over any fuel or experimental position in the core or inner reflector.
Additional shielding blocks are placed on the top shield when the reactor is operated above 500 W.

Water/cooling system

The annual core space in which the fuel elements are placed is filled with water during reactor operation. This primary water is pumped from a 1500 liter aluminium storage tank through a heat exchanger into the bottom of the outer reactor vessel. An overflow through a 50 mm diameter return line to the storage tank completes the cycle. The purity of the water is maintained by a by-pass through an ion exchange column and a filter.

The secondary cooling water is supplied from the general (drink) water supply.
The heat exchanger originally consisted of two separate spirally wound tubes, through one of which flows primary, through the other

secundary water. Both spiral tubes are immersed in a water-filled tank. This construction prevents leakage from the primary to the secundary side or vice versa in the event of a hole in one of the spirals. In such circumstances the level of the intermediate water will increase which is indicated by a sight tube and by a high level alarm, see figure 3.

Reactor control

The excess reactivity of the reactor, kept below 0.5% $\Delta k/k$, is controlled by the "fine", "coarse" and "safety" control plates. The arrangement of the control plates (max. 6) around the outer reactor vessel depends on the type of core configuration used.

The cadmium control plates can be raised and lowered in aluminium guides fixed to the side of the outer reactor vessel. Each Cd-plate is fixed to steel sheet wound on a drum which is coupled to an A.C. electric motor by an electro-magnetic clutch.

In the event of an emergency shut-down, the magnetic clutch is de-energized and the Cd-plate will fall under gravity assisted by the spring action of the steel sheet. An emergency shutdown action comprises also the fast draining of the water from the annulus via a 150 mm diameter dump line into the storage tank. The dump line is closed off under normal reactor operation by a butterfly valve which is held closed by a magnetic clutch. Interruption of the power supply to the clutch results in opening the valve.

Instrumentation

An interlock system ensures that reactor operations are performed correctly.

Four neutron detecting channels have been provided to follow the reactor condition from the shutdown position to full power. The channels are :

* a pulse channel with a fission counter for reactor start-up, indicating logarithmic count rate and doubling time.
* a multi-range D.C. linear power channel. Each range is provided with a low and high trip.
* a D.C. logarithmic power channel and doubling time meter.
* a shut-down channel for the initiation of high level trip only.

Two gamma health monitor channels have been installed and initiate a trip at 10 mrad/hr (adjustable). The range of the channels runs from 0.1 to 100 mrad/hr.

Temperature, level, flow and conductivity meters enable a constant check on the condition of the water systems.

Experimental facilities

The inner graphite reflector is two feet in diameter and has five removable stringers of varying dimensions. Access to the stringers is possible through ports in the top shield plug.

Against the west face of the outer reflector a graphite thermal column is built, 150 cm wide, 120 cm high and 150 cm long. This column has fifteen removable graphite stringers 100 x 100 mm, shielded by concrete plugs. To facilitate irradiations of foils and samples four stringers are equipped with holes, equally spaced over the length of the stringer.

An irradiation trolley (210 cm long, 150 cm wide and 100 cm high) is placed against the face of the reflector opposite the thermal column. The trolley is driven by an electric motor.

Two horizontal holes 100 x 100 mm, provided with removable shield plugs, penetrate the shield and the reflector at the actual lattice midplane. These beamholes are at right angles to the thermal column and the irradiation trolley and extend to the outer reactor vessel. Space and structural strength is provided for exponential experiments on top of the core region. Removal of the upper shield plug leaves a five foot square distributed neutron source which may be shaped by addition of a graphite pedestal. Performance of such experiments temporarily precludes any access to the core.

COST

The cost of the complete reactor facility installed in a semi-airtight hall of the E. Fermi Laboratory, excluding this hall and fuel, in 1960 was about $ 170.000 ($ rate April 1985). At the start of the reactor the fuel has been ordered on a renting base. Later on the fuel was purchased.

The yearly operating costs, 1985, are $ 110.000. This costs include the salary of the reactor operating staff and maintenance etc. but exclude the infrastructure- and overhead costs of the research institute.
The operating staff consists of a manager (50%), a supervisor and two operators, all fully licensed according the obligations of the national safety regulations. To operate the reactor a minimum staff of two licensed operators is required.

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SOME EXPERIENCE WITH OPERATION AND USE OF A TRAINING REACTOR

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Abstract

This reactor was originally designed for 10kW and upgraded to 100kW in 1980. It is a pool-type reactor with a primary and secondary cooling circuit utilizing EK-10 cylindrical rod fuel of UO_2 with enrichment of 20 percent. This design is similar to other reactors operating up to 2MW. The experimental facilities include five horizontal beam tubes, a large tunnel useable as a thermal column, vertical in-core and reflector irradiation positions and a pneumatic transfer system. The staff for the training center consists of about 50 people responsible for the operation, maintenance, repair and utilization of the reactor. The reactor is used primarily for training university and outside personnel but is also used for research, non-destructive testing, neutron radiography and development of nuclear radiation instrumentation. Its low neutron flux, however, does not permit neutron diffraction or scattering activities.

History

The first nuclear research reactor in Hungary went the first time critical in 1959 with an initial power of 2 MW which was later increased to 5 MW. Following this a series of zero power critical facilities have been constructed and used. Based on experience gained with these facilities a fully hungarian-made university reactor has been designed and constructed. Construction work began in 1967 and the reactor went first critical in June 1971 with a maximum power of 10 kW, which was increased in 1980 by an order of magnitude to 100 kW. The reactor is located in a University Campus.

The main objectives for establishing a Nuclear Training Center with a reactor were as follws:

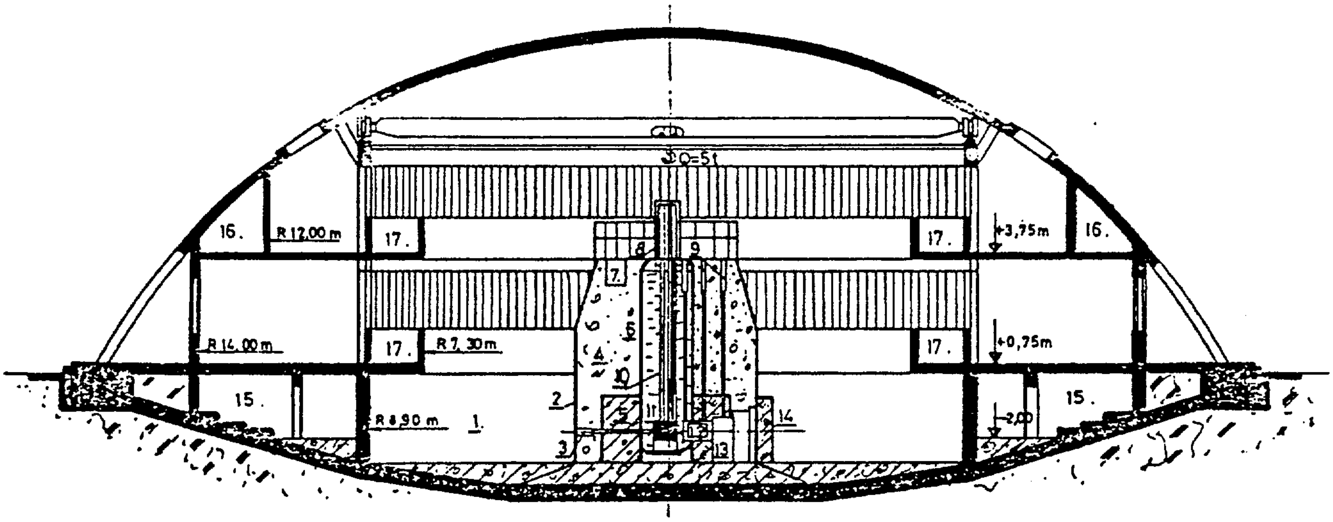
- Providing nuclear education at university level in a very broad range of nuclear sciences for all hungarian universities;

- Promotion of the formation of an overall nuclear scientific and technical infrastructure within the country in order to prepare for a nuclear power programme.

I. Description of the reactor

1. The reactor block arrangement

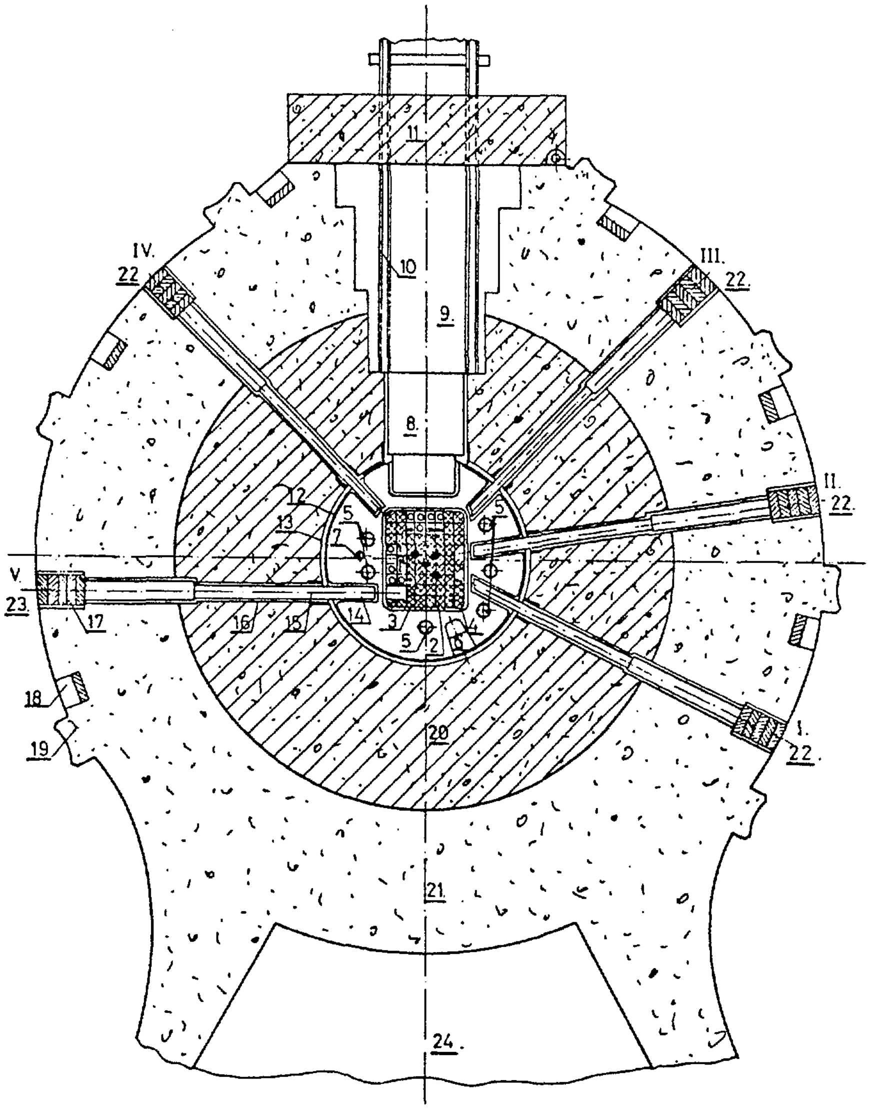
The reactor is located in a University Campus. The reactor block is in the centre of the reactor building surrounded by laboratories /fig.1/. It is a pool type above ground arrangement with desalinated water moderator and coolant /fig. 1 and 2/. This gives an easy access to and manipulations inside the core area which are important for training purposes. The shielding is made of standard and heavy concrete. The level of the beam tubes is below the ground.



1- Reactor hall; 2 - Reactor block; 3 - Horizontal channel; 4 - Ordinaryconcrete radiation shielding; 5 - Heavy-concrete radiation /biological/ shield; 6-Reactor tank; 7 - Experimental shaft; 8- Plexiglass bellcover; 9 - Vertical channels; 10 - Safety and control rods; 11 - Active zone; 12 - Water tank; 13 - Radiation tunnel. 14 - Heavy concrete shielding door; 15 - Basement; 16 - Mouting floor; 17 - Inner circular gallery.

Fig.1.

Cross section of the reactor building



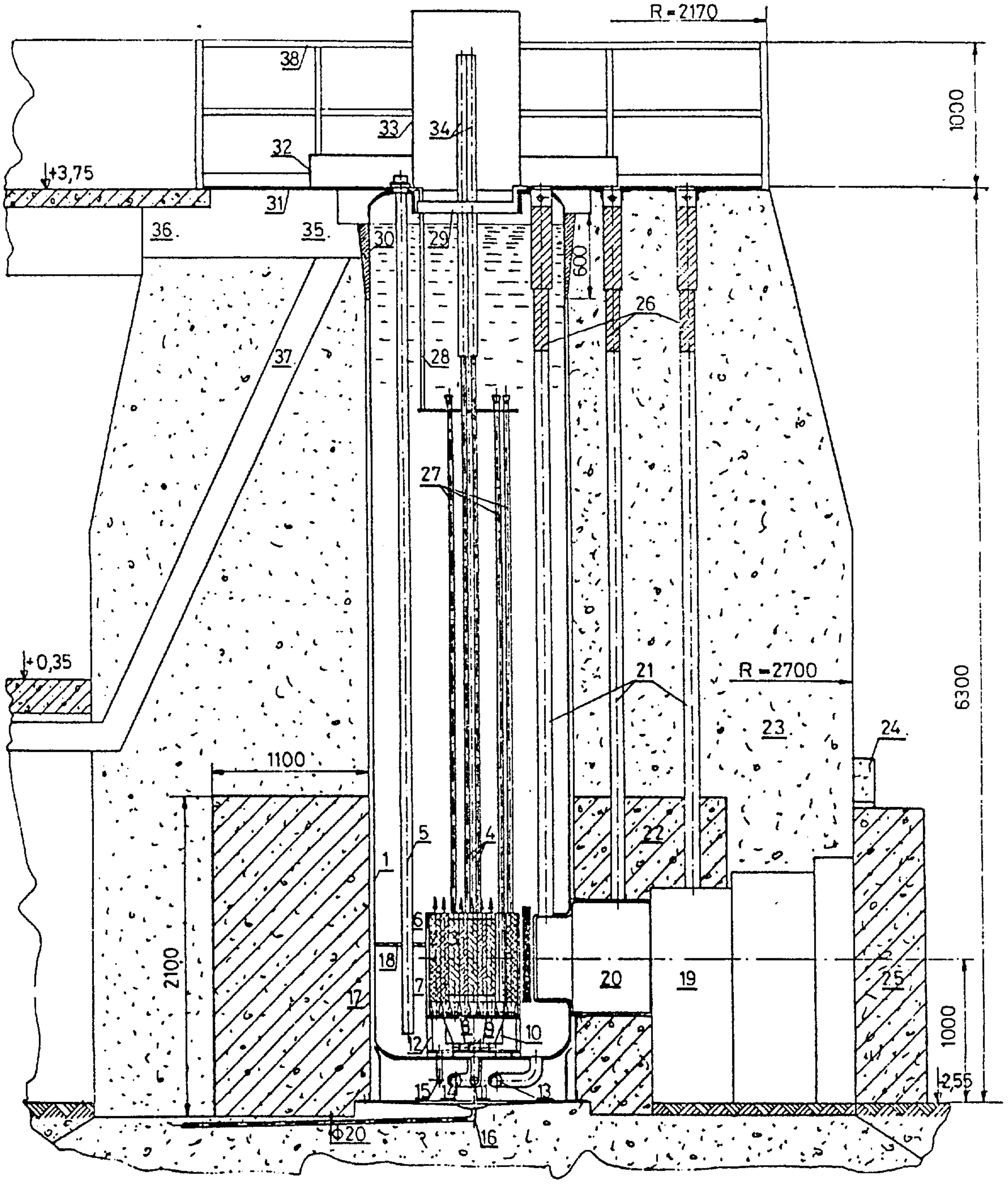
1 - Fuel assemblies; 2 - Graphite elements of reflector; 3 - Zone tank; 4 Zone supporting mantle; 5 - Detector tubes; 6 - Basket for temporary fuel strorage; 7 Cooling water outlet pipeline; 8 - Water tank for irradiation channel; 9 - Irradiation tunnel; 10 - Railway; 11 - Heavy concrete shielding door; 12 - Reactor tank; 13 - Protecting cylinder; 14 - Horizontal channel protecting tube; 15 - Water trap for horizontal channel; 16 - Protecting tube; 17 - Steel protecting disc; 18 - Valve box; 19 - Radiation shielding ribs; 20 - Heavy concrete; 21 - Normal concrete; 22 - Radial horizontal channels I. II. III. and IV.; 23 - Tangentional horizontal channel V.; 24 - Hot cell maintenance space.

Fig. 2.

CROSS-SECTION OF THE REACTOR BLOCK

2. Active core

The active core is supported by an Aluminium grid construction blocks at the side. The initial core with an excess reactivity of less than 1 $ contained 23 bundles /fig.4/ and 353 elements. Teh upgraded core with an additional bundle



1-Reactor tank, 2-Graphite reflector elements; 3-Fuel element assemblies; 4-Safety and control rods; 5-Detector tubes; 6-Zone tank; 7-Zone holder mantle; 8-Diffusor; 9-Injectors; 10-Division chamber; 11-Cooling water inlet pipeline; 12-Zone holder ribs; 13-Draining pipeline; 14-Cooling water outlet pipeline; 15-Filling pipeline for the water trap of horizontal channel; 16-Tunnel and pipeline for leakage water; 17-Protecting cylinder; 18-Perforated plate; 19-Irradiation tunnel; 20 Water tank of irradiation tunnel; 21-Vertical channels of irradiation tunnel; 22-Heavy-concrete radiation (biological) shield; 23-Normal-concrete radiation shield; 24-Radiation shielding girth and columns; 25-Heavy concrete shielding door; 26-Heavy-concrete protecting plugs; 27-Vertical irradiation channels 28-Supports of vertical irradiation channels; 29-Supporting bridge for control rods; 30 Centering and radiation shielding wedges; 31-Reactor flat top cover; 32-Reactor double cover; 33 Plexiglass bell-cover; 34-Servomechanisms of control and safety rods; 35-Cable duct; 36 Packing-gland bushings; 37-Suction air duct; 38-Reactor-top railing.

Fig.3.
LONGITUDIONAL SECTION OF THE REACTOR BLOCK

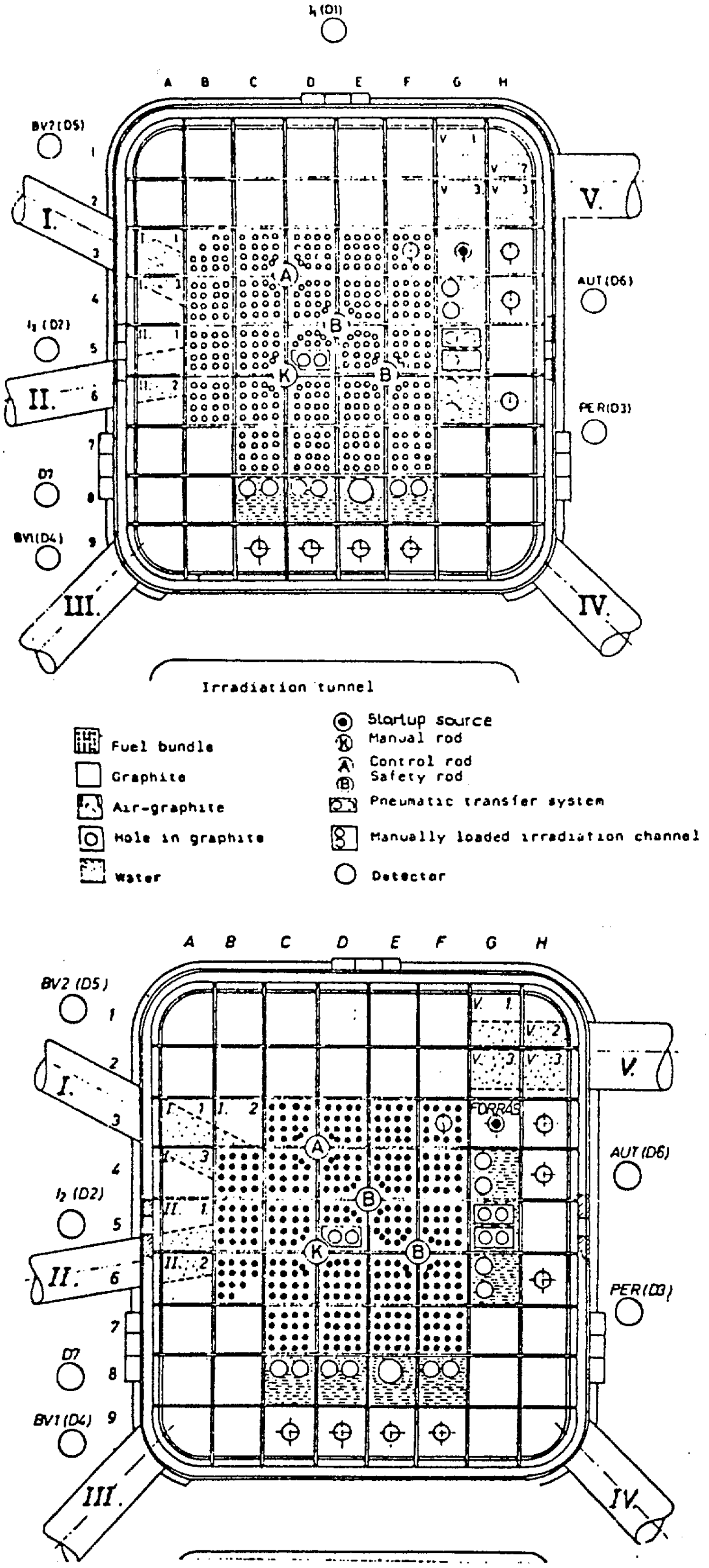


Fig. 4. Core configurations
above: excess reactivity 156 cent, power max 100 kW
below: 71 cent, max 10 kW

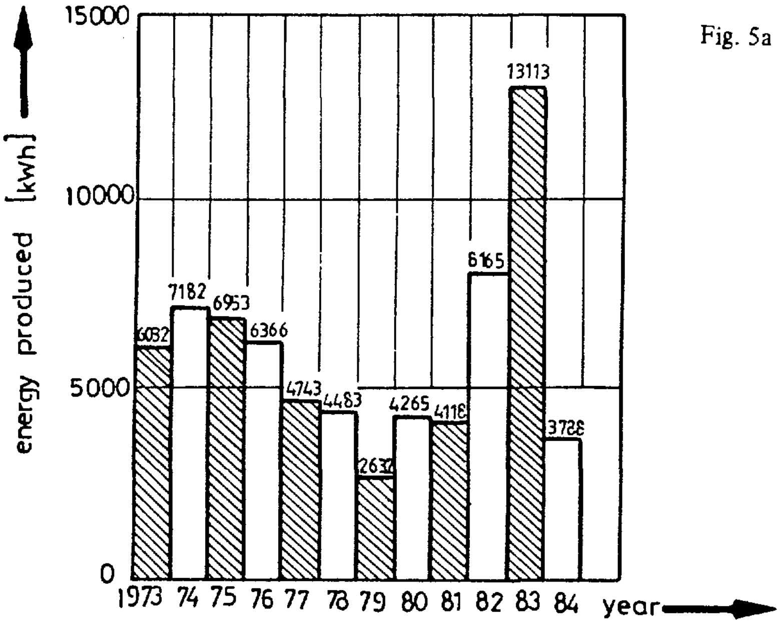

energy produced [kWh]
15000
10000
5000
0
6032
7182
6953
6366
4743
4483
2632
4265
4118
8165
13113
3728
1973
74
75
76
77
78
79
80
81
82
83
84
year

Fig. 5a

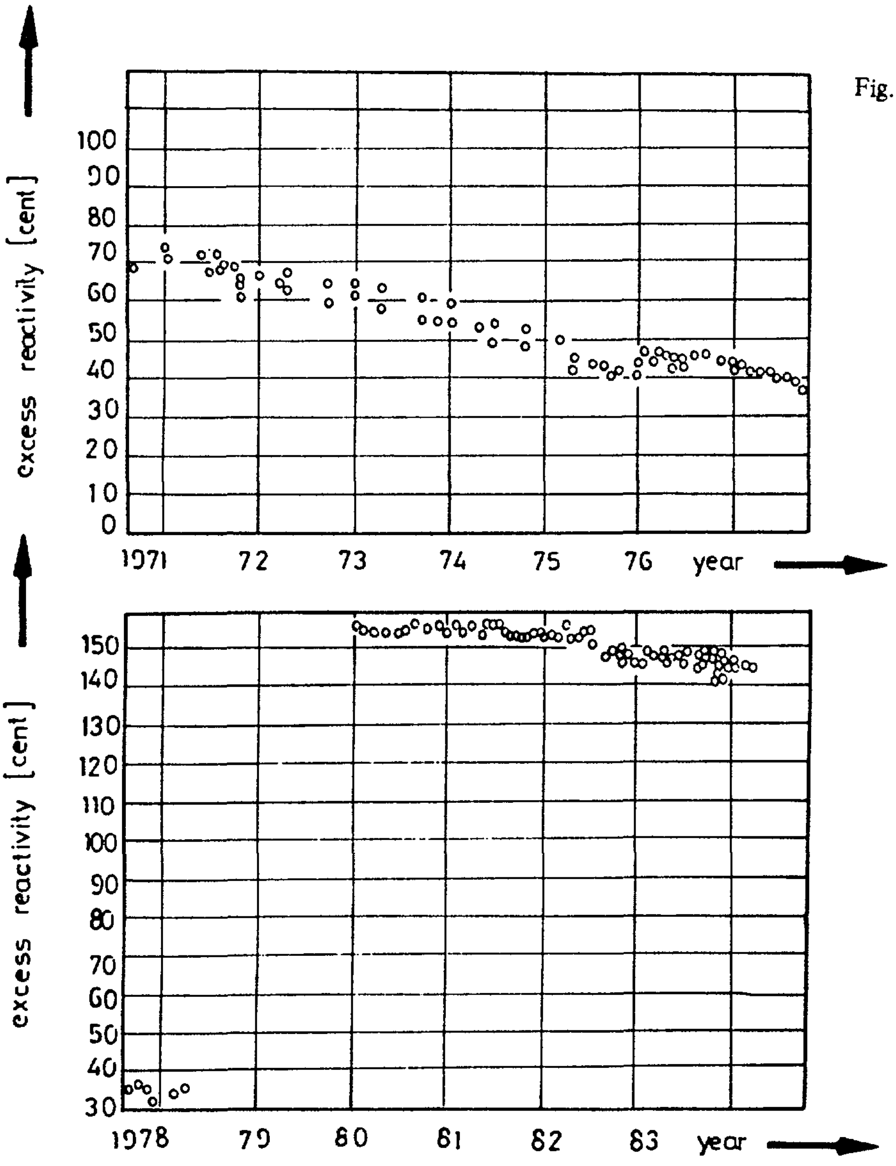

excess reactivity [cent]
100
90
80
70
60
50
40
30
20
10
0
1971
72
73
74
75
76
year
excess reactivity [cent]
150
140
130
120
110
100
90
80
70
60
50
40
30
1978
79
80
81
82
83
year

Fig. 5b

/total 369 elements/ had the reactivity balance as follows /September 1981/:

- Poisoning /due to 36 hours operation/	66 cent
- Loss due to power effect	37 cent
- for irradiation	30 cent
- for control	23,3 cent
cold clean excess reactivity	156.3 cent

The neutron flux distribution in the core is highly distorted. Neutron traps ensure peaks of neutron flux in locations of irradiation positions /fig.6/. The peak thermal flux is $2,7.10^{16}$ $m^{-2}s^{-1}$, the figure of peak flux per unit power being thus $2,7.10^{11}$ $n/m^{2}sW$ a value ranging among top figures of similar reactors.

3. Fuel

The fuel is of soviet made type EK-10 cylindrical rod shaped with an outer diameter of 10 mm and 1,5 mm thickness Aluminium cladding. The UO_2 fuel is enriched to 10 %, and is assembled in a 4 by 4 rectangular array forming a bundle. This is a standard assembly designed for VVRSZ type research reactors operating at 2 MW power level.

4. Fuel consumption

A very important advantage of a small reactor is its low fuel consumption and practically no need for refuelling. Fuel consumption depends on energy produced and causes a decrease of available excess reactivity which limits its use for a particular task and at a value it limits its operation.

The total energy produced yearly by the Training Reactor before and after the power upgrading can be seen in fig. 5/a and the resulting measured excess reactivity loss in fig.5/b. Most of the training uses need low energy operation, research and service activities need mostly higher power level.

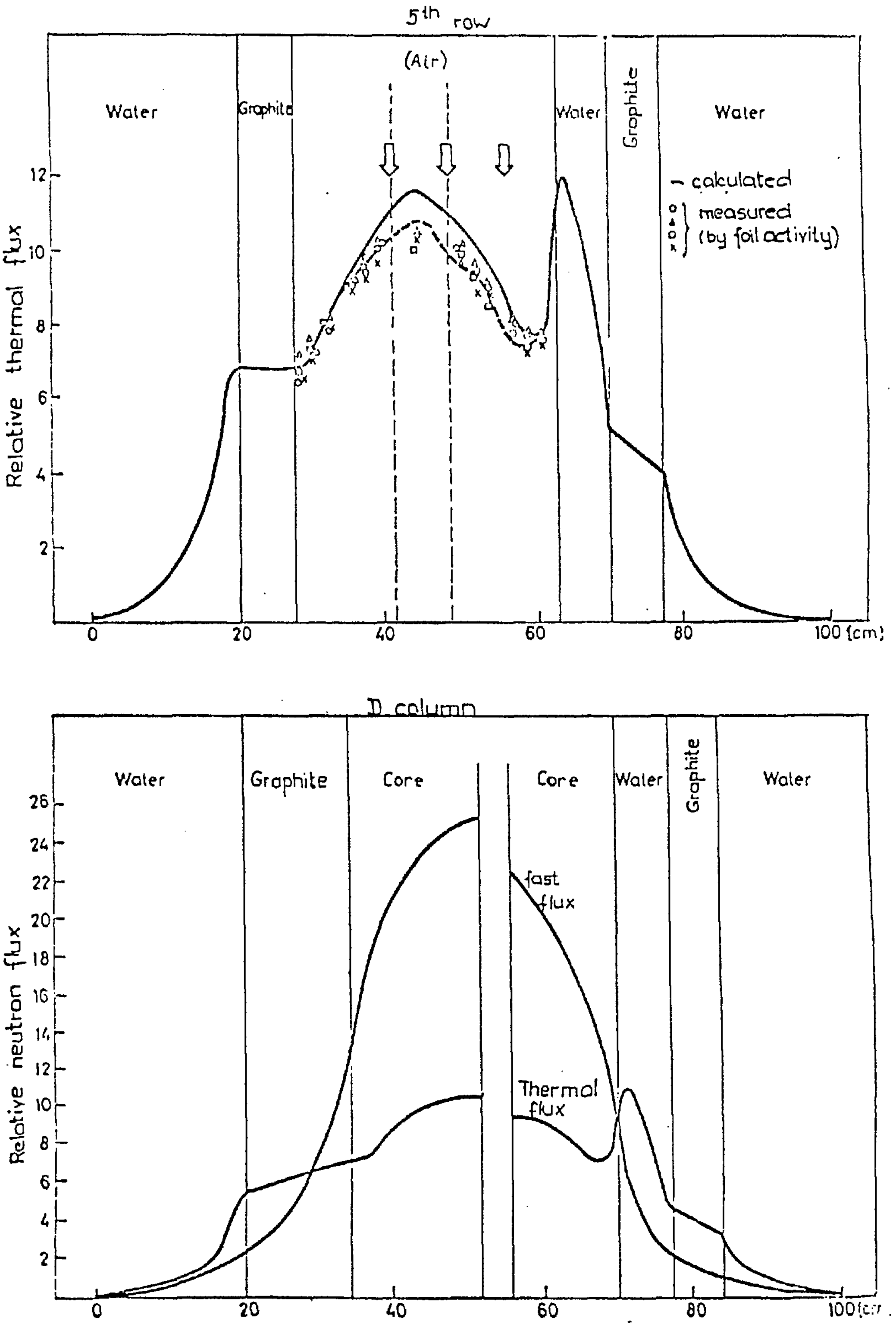


Fig. 6.
Neutron flux distributions inside the core.

The total energy produced till April 1985 is 3,23 MWdays. The arrow in Jan. 1977 indicates a results of a fuel bundle repair, where the bundle in position F3 was replaced by another one because of mechanical failure in the grid supporting structure. The figures give a rough estimate of 15-20 years life for the core assuming the same use of the reactor as has been previously, and failure free operation.

5. Reactor cooling system

The coolant circuits are composed of primary and secondary parts both with forced circulation. The desalted wated flows upwards through the core. Below 2 kW power no need for forced circulation. All the components in the system are made of Aluminium. /fig.7/

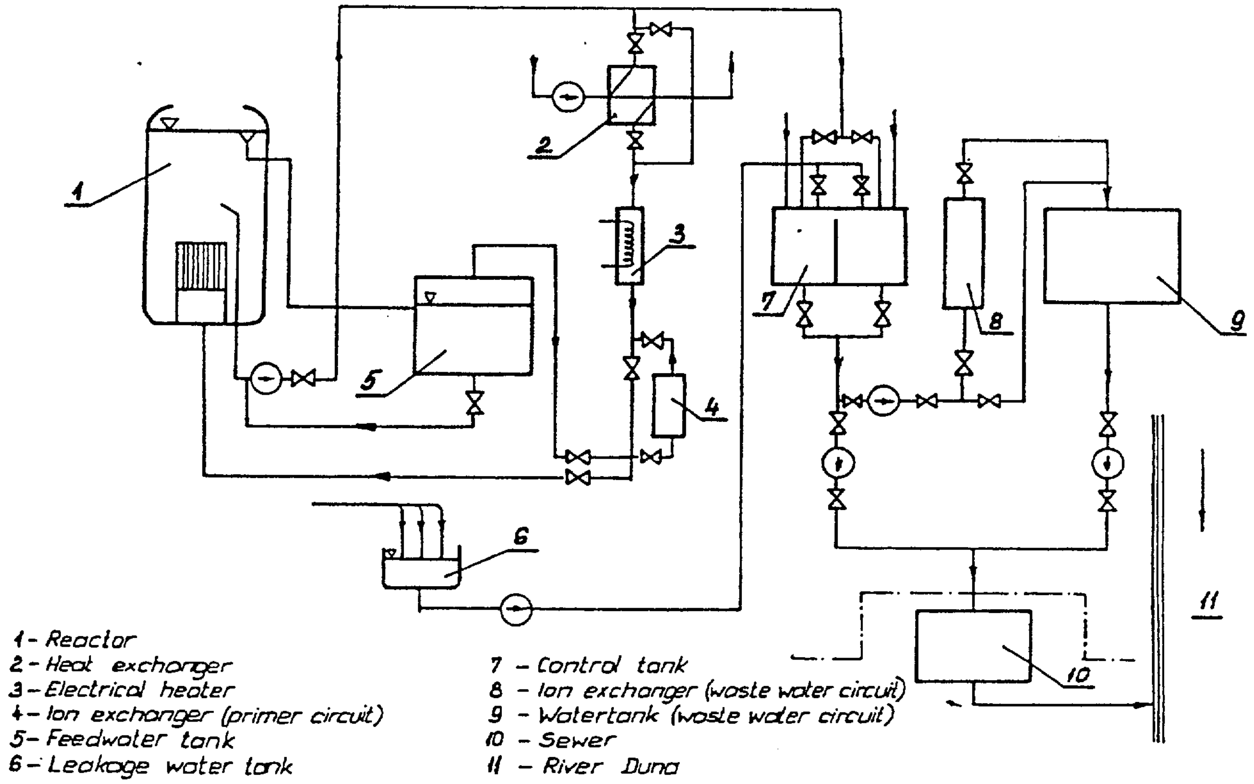


Fig. 7.

Water circuits of the reactor (Technical University, Budapest)

6. Control and protection system

The control and protection system shematic can be seen in fig. 8. 6 neutron channels 2 safety, 1 shim and 1 fine control rods are use. The present instrumentation was the prototype of the new hungarian product and has been used since 1979 giving excellent performance and reliability figures.

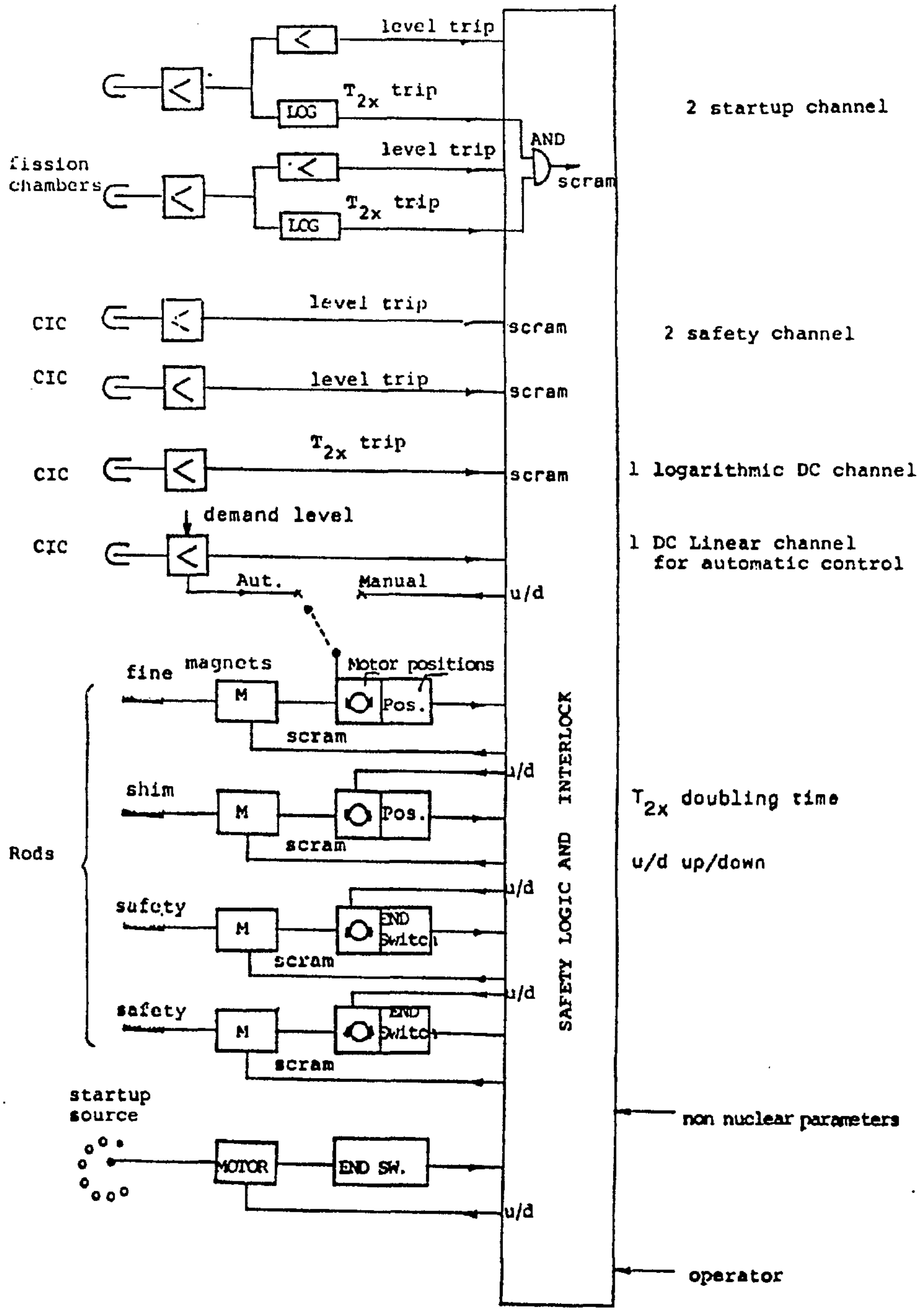


Fig. 8. Control and safety system shematic, 100 kW University Reactor

The hierarchy and sophistication of the system have been demanded by safety level necessary for a reactor in a university campus /14, 22, 23/.

7. Experimental facilities

- Beam tubes and tunnel

Five horizontal beam tubes and a large area tunnel are connected to the core. Each has different connections and different neutron spectra. The tunnel offers high flexibility in its utilisation. The distance between the inner surface ant the graphite block is only 9 cm. In this gap different couplings /air, water, metal e.t.c./ can be realized inside the vessel.
If the whole space inside the tunnel is filled with graphite block, it can be used as a thermal column.

- Manually loaded irratiation channels

In core and in-reflector positions there are a variety of locations /in water or in graphite/ for irradiation by a thermal flux value of $1 \div 2{,}6.10^{16}$ n/m^2s.

- Pneumatic transfer system

In core position /D5/ and 2 in reflector positions /G5/ there are locations for irradiation by a fast pneumatic transfer system. The layout of the transfer system as well as the interconnections between laboratories can be seen in fig.9.

- Hot cell

A cell consisting of two compartments is provided for manipulating radioactive materials. The irradiated sample from the manually loaded channels is sent through a tube in the shielding by gravity into the hot cell. The material processed can be transported to the radiochemical laboratory either by means of a pneumatic transfer system or in a shielded container placed under the cell.

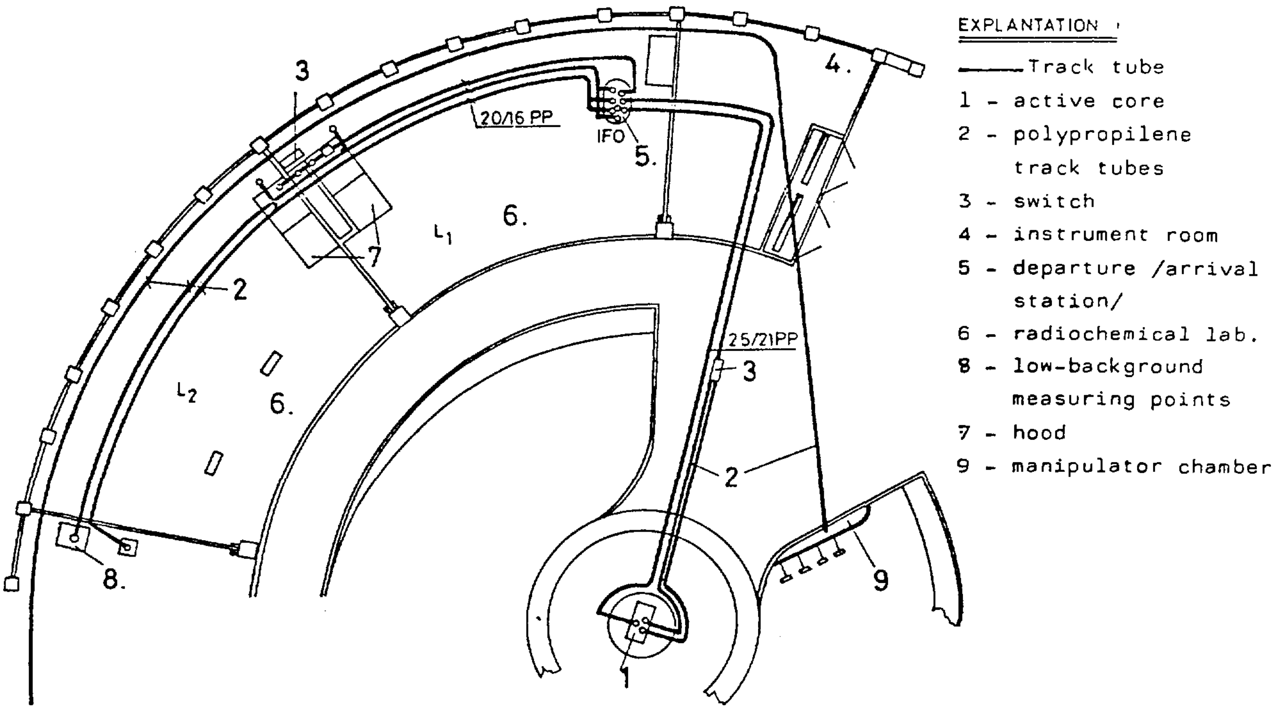


Fig. 9 .
Layout of pneumatic transfer system

8. Laboratories and staff

The reactor is a part of a Nuclear Training Center. There are laboratories for radiation protection, radiation chemistry, reactor physics, nuclear electronics and computer center. Hot cells are also provided. Two sample transfer systems ensure connection between the reactor, laboratories and hot cells.

The staff consists of some 50 persons. This includes 20 scientific research workers namely 7 electronic and electrical engineers, 6 physicists, 4 mechanical engineers, 2 chemists, 1 geologist.

II. Utilization of the reactor

Basic requirements are summarized as follows:

- a/ Nuclear power programme requirements
  The fist hungarian nuclear power station has been operating since 1982. More units are under construction.

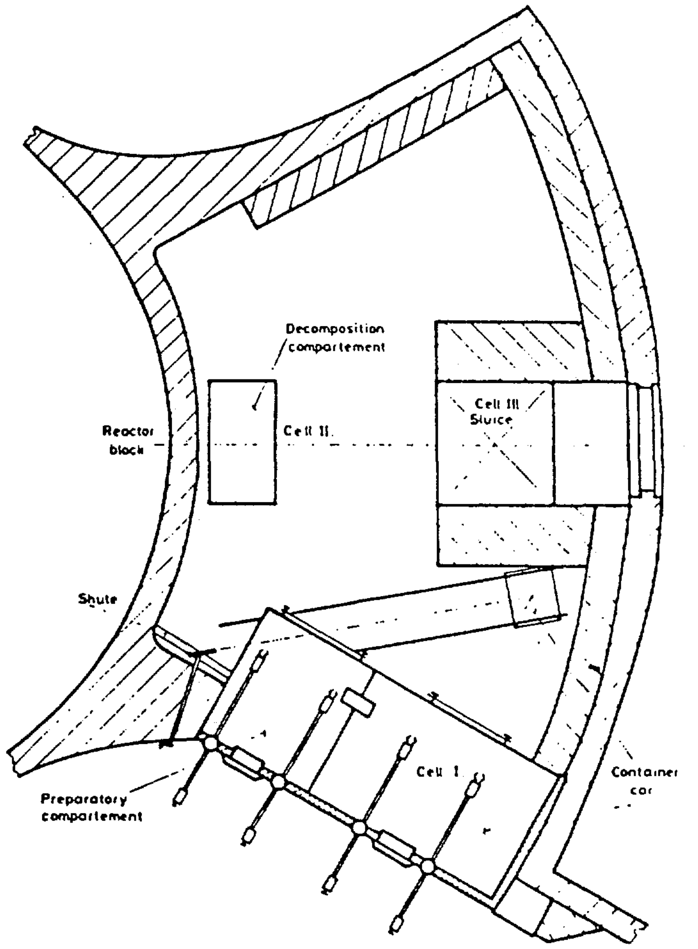


Fig. 10.

Layout of manipulator chamber /hot cell/

The requirements are summarized as follows:

- programme oriented supporting activities comparising research and development;
- participation in nuclear manpower development.

- b/ University requirements
  - providing nuclear education at university level by offering special courses, postgraduate training, degree work and special laboratory exercises for all hungarian universities and for foreign partners which are in cooperation with Hungary. This large variety of partners shows that a broad range of sciences has to be dealt with;
  - research directly sponsored by the nuclear power projects /mainly on contract base/;
  - assisting industry adopting nuclear technology

- Training exercises.

  Bread scope of research which is possible and the ability to support simultaneously many experiments from different branches of sciences and engineering are striking features of a research reactor of even moderate size. A series of experimental exercises have been developed which are instructive and pleasent for the fields of interests. They are developed in the fields of neutron physics reactor physics and many other fields.

  Sample training exercises are given in this paper. A detailed description of laboratory experiments and their required laboratories and equipments can be found in /9/ and /10/.

<u>Sample training exercises provided by the 100 kW reactor at the Technical University, Budapest</u>

1. Digital computer simulation training.
   Using a sumulator with full scale control desk provides kinetic simulations, study dynamics and feedback effects, operator training e.t.c.
2. Reactor operation training.
   Using the reactor for daily operations and for all types of manipulations.
3. Control rod calibration by doubling time method.
4. Control rod calibration by subcritical counting.
5. Determination of control rod worth by use of pulsed neutron source.
   Using a neutron burst injected into the reactor by a sealed tube neutron generator and measuring the response for determining reactivity.
6. Determination of the reactivity worth function for neutron absorbers.

   A Cd absorber is insertdd into the reactor and the resulting reactivity is measured in different positions.

7. Determination of void coefficient of reactivity.
   Reactivity effect of an air void inserted into the core is determined as a function of position.
8. Critical and subcritical experiments.
   An approach to criticality experiment and measuring excess reactivity are performed.
9. Determination of delayed neutron parameters and Uranium content.
   Uranium sample is irradiated in the core by the rabbit system and emitted neutrons are measured by a time analyser.
10. Thermal neutron flux measurement in the core with the help of an Dy wire, axial flux distribution of the core is determined.
11. Radiation protection and shielding measurements in a neutron-gamma field.
    Measuring neutron-gamma dose rates at the beam tubes and behind shielding as a function of reactor power are performed.
12. Measurements with thermoluminexcent dosimeters.
    Practicing TLD technique by dose measurements is realized.
13. Measurement of surface contamination decontamination.
    /A decontamination practice/
14. Rod-drop technique
    Large values of reactivity are measured by analysing neutron density decay after shutdown.
15. Determination of neutron dose intensity in the core of the reactor on the basis of neutron spectrum measurement.
    A practice on neutron spectrum measurement by foil activation technique.
16. Thermal neutron spectrum measurement at the beam tube.
    /Chopper type time of flight technique/.
17. Measurement of the thermal neutron flux by thermoluminescent detectors.
    /Flux measurement at a beam tube by TLD/

18. Measurement of thermal neutron diffusion length in grafite. Neutron flux distribution is determined by foil activation in the thermal column.

19. Laboratory practice on neutron radiography. Nonradioactive and irradiated objects are radiographed using different techniques at beam tubes.

20. Rapid determination of Vanadium and Manganese content in steel by activation analysis. Irradiation is in the core by the rabbit system, for evaluation a GeLi detector with a multichannel analyser and reference sample are used.

21. Multielement analysis of biological materials. A practice on thermal and epithermal neutron activation and on comparator technique.

22. Determination of some gamma-emitting radioactive isotopes enriched in the water circuits of nuclear power stations by means of gamma spectrometry. /A model experiment/.

Selected research topics

1. Neutron spectroscopy

Numerous tasks in the research program of the Institute necessiated the knowledge of the neutron field in the core and at beam tubes. As in case of nuclear reactors one meets the problem of mixed /neutron and gamma/ fields the activation neutron spectrometry can advantageously be used. The activation detectors are insensitive to gamma radiation, as a result of discrimination between the two kinds of radiation /neutrons and gammas/ can easily be solved by this method. Furthermore, due to the small size of these detectors the perturbation effects in the neutron field can be decreased negligible small. For this reason activation neutron spectrometry - in special cases combined with other methods - is preferably used in our Institute for neutron field studies. The neutron flux density in the core /and e.g. in the irradiation tunnel of the reactor/ at 100 kW reactor power is high enough to get a measurable response of these detectors.

Neutron spectrum determination by multiple foil activation method

A series of activation detectors /in form of thin foils or wires/ is irradiatied in the neutron field to be studied and their activity is measured. Special "unfolding computer codes" are then used to elaborate the neutron flux density spectrum from these data. In practice the number of energy groups spreads from 50 to 640, and the number of detectors from 10 to 30 so the freedom of the system is rather high, the solution is not unique and the neutron flux density spectrum cannot be derived from these data without a priory assumption of the initial neutron spectrum based on all physical informations available in the given case.

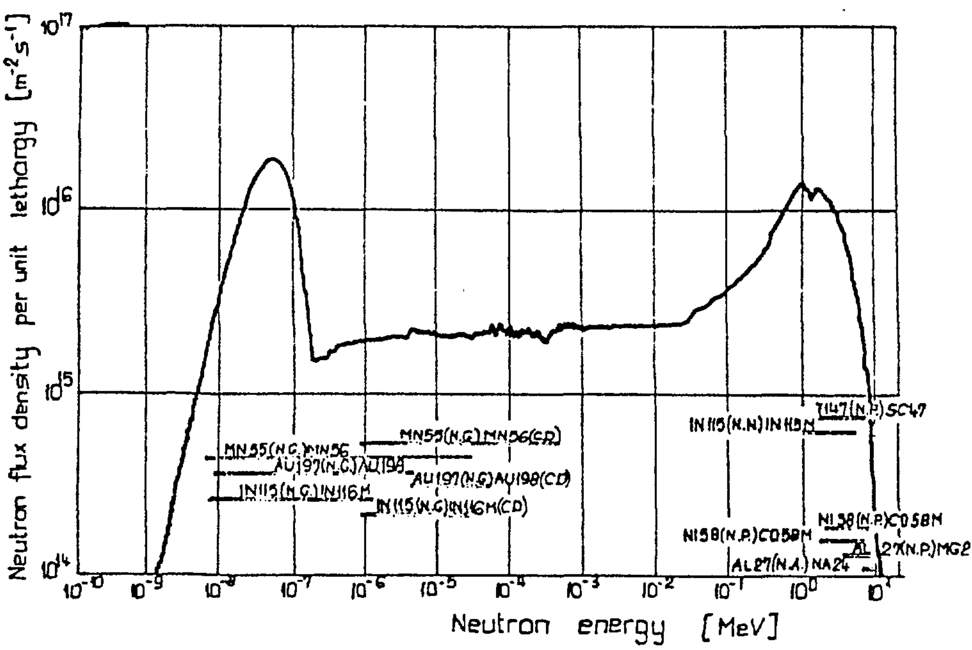


Fig. 11.

Neutron spectrum in the core position D5 of BTU's nuclear reactor at 100kW power.

Lots of neutron spectrum unfolding codes based on different phylosophies have been used so far in the literature for solution of this problem. At our institute the unfolding codes SAND II, FRSP and SANDBP /12/ have been used.

Instrumentation

For determining the activity of the detectors instruments generally used in gamma spectrometry /eg. also for activation analysis/ are applied: Ge or Ge/Li/ semiconductor detector + multichannel pulse height analyser.
For unfolding the neutron spectrum a computer with a core size of minimum 256 Kbytes /preferably 512 Kbytes/ is needed.

Other methods used for neutron spectrum determination

As the neutron flux density at the horisontal beam tubes is about 5 orders of magnitude lower than that one in the core, only a limited number of activation detectors can give a measurable response in this neutron field. In radiation shielding experiments-carried out in the irradiation tunnel of the reactor - behind thick shielding walls one meets the same problem.

Then the activation detectors are combined with BF_3 or ^3He detectors, furthermore, neutron spectrometry using proton recoil detectors and Si/Li/ semiconductor detectors /13/ are applied.

Application of the results

The results of neutron spectrometry have been widely used in the Institute's research program joining the national and international /IAEA and COMECON/ nuclear program:

- Radiation shielding experiments - results used at the first Hungarian nuclear power plant.

- Development of new neutron spectrum unfolding methods, investigations in different neutron fields - results used in the national /and COMECON/ surveillance program for nuclear power plant's preassure vessel.
- International activity: REAL-80 interlaboratory exercise organized by IAEA for international intercomparison of neutron spectrum unfolding codes and spectrum /12/ charactersitic integral parameters for radiation damage investigations; results used in the national and international surveillance program of reactor preasure vessels.
- Results of neutron spectrometry are also used in the field of health physics studies.

2. Use of the neutron beam tubes for nondestructive testing

Knowledge of the structure of a material is necessary to determine its behavior under different excitations. Neutron beam provide a probe that may be used to study of materials.

First a distinction is made between microscopic and macroscopic diagnostic techniques. Under microscopic diagnostic are classified those techniques where monoenergetic neutrons are used and provide information on the atomic scale. For macroscopic diagnostic a broad spectrum of radiation is used which enter the material to be studied and the emerging radiation scattered or uncollided are analysed thus giving information on the bulk or gross material feature under both static and dynamic conditions.

All the research work which need monochomator for selecting nearly a monoenergetic neutron flux are beyond the capability of such a small reactor, therefore only macroscopic diagnostic techniques are studied. The following specific areas will be mentioned:

- neutron radiography
- tomography.

Neutron radiographic inspection of irradiated materials

After materials have been irradiated, the difficulties involved in precision measurement by "normal" methods are much increased and alternative methods, such as measuring from a neutron - radiograph image, become attractive. This is especially so when the object is undergoing a lengthy irradiation, and periodic dimensional checks are required in course of the experiment. The rapid advance of neutron radiography in the field of monitoring radioactive materials is due one hand to the fact that heavy materials are relatively transparent to neutrons, and on the other, to the intensitivity of detectors to the gamma background noise emitted by the objects under examination.

The unique feature of neutron radiography for testing irradiated fuel: the ability to both penetrate uranium and to distinguish between the isotopes ^{235}U and ^{238}U.

Uses of fuel radiographs are nemerous but they can be summarized as checks for correct assembly /pre-irradiation/ and for changes and damage /post-irradiation/. Almost all fuel applications to date have been qualitative.

The radioactive nature of irradiated fuel elements and their high absorption for thermal neutrons has led naturally to the use of indirect and track etch neutron radiography, and using epithermal /Cd filtered/ beam with In detector.

Neutron beam tubes used for neutron radiography

	L /D	thermal neutron flux n/m^2s at the object /100 kW/	exposure method	typical exposure time
Beam No 5	25	3.10^{11}	Dy, In	
Beam No 3	40	$1,45.10^{11}$	Dy, In	
Beam No 3 with Bi filter	40	$4,8.10^{10}$	Dy	40 min /at 10 kW/
			Gd	10 min /at 10 kW/
			In	1 hr /at 100 kW/
Beam No 2	40	thermal $3,34.10^{15}$ fast $1,5.10^{15}$	In /Cd filtered/	1 hr /at 100 kW/

Tomography

A radiograph is a two dimentional projection of a three dimensional object. To obtain information about the spatial locations of different structures within the object a number of radiographs can be taken from different angles. Modern structures are, however, becoming more and more complex and the evaluation of a three dimensional object by a two dimensional shadow image is nearly impossible. This difficulty has been solved by a technique called "Computed Tomography". A tomogram is a picture of a slice. The image is reconstructed as if it had been possible to cut and view the object over a plane. A full, three dimensional picture can be obtained by stacking a sequence of such layers. For the reconstruction a series of radiographs are taken at different angles and a section image is calculated. The more the angles, the more exact the reconstruction is /6,7/. The present work aimed at taking neuutron radiographs with Cd filterdd beam using In detector at several angles of a fuel bundle and reconstructing the interior structure for nondestructive testing and safequard.

3. Neutron dosimetry research with TLD

Neutron dose rate in and around a small reactor can be conveniently measured by a specially developed technique. In this method ^{6}LiF and CaF_2 TL detectors are used together. ^{6}LiF responses to both neutrons and gammas, while CaF_2 responses to only gammas, and the difference gives neutron dose within a few percent accuracy.

This method can be used for in core measurements up to about 1 kW power, and dose rates at the beam tubes can be determined in the whole power range of the reactor. /18/

4. Instrumentation development

Reactor beams and low level flux areas are very convenient for feasibility and life testing of nuclear radiation instrumentation. New concepts for high radiation level instruments, serviceability, operational problems can be tested near the core areas. In cooperation with other hungarian institutes and factories an intensive continuous nuclear instrumentation development program is being carried out. Some of the moduls of a new reactor instrumentation system are developed by the Technical University, and the whole system is tested and calibrated at the small reactor.

- Research reactor instrumentation

A demand made by a renewal and upgrading program initiated development in reactor instrumentation /22, 23/. Some of the moduls of the new reactor instrumentation are developed by the staff and the whole system is tested and calibrated at the small reactor.

- Educational nuclear instrumentation

Some special instruments have been developed for reactor laboratory exercises and training purposes like a small computer based research reactor training simulator, which is suitable for operational training, kinetic, temperature feedback and poisoning studies with arbitrary time scaling. /9/ Automatic measurement of activity distribution along the length of a Dysposium wire irradiated in the core is another example /9/.

- Nuclear power instrumentation

Skills and experience gained with reactor instrumentation activity have resulted in development of some special instrumentation for power reactor like: continuous measurement of innert gas in effluents, boron content in primary circuit by neutron transmission. Personal and area radiation monitoring instrumentation are other areas of development work in cooperation with other institutes /3/.

- Industrial isotope technique

Several instruments have been developed using nuclear technique for industrial application, among these are: measuring ash content and humidity in coal, density of concrete /3/ e.t.c.

5. Neutron activation analysis

The considerable advances made in the last decade in gamma ray spectrometry equipment have accelerated the development of reactor neutron activation analysis techniques and applications in many fields. Increased attention is being devoted to the use of purely instrumental neutron activation analysis techniques, using Ge/Li/ gamma ray spectrometry.

In this respect the reactor may be regarded as an instrument that enables the chemist to expose samples to a desired neutron flux for a desired length of time /usually anywhere from seconds to hours/, and it is preffered that the samples not be exposed to appreciable temperatures, gamma ray dose during activations.

Samples to be irradiated are sent to the in core or in reflector areas either by the pneumtic transfer system or by a manually operated loading system /into vertical irradiation channels/.

After irradiation samples are sent to the radiochemical laboratories either directly by the pneumatic transfer system, or through the hot cell by another transport system.

Simultaneous irradiation of the samples and a standard of known mass will give the mass of the target isotope from the ratio of activaties, provided the effective flux is the same in both cases. In accurate comparisons this equality of fluxus raises the problem of perturbation of the flux by the samples; materials with high thermal neutron cross sections or strong resonancies require considerable care from this point of view. The production of the active isotope by fast neutron bombardment of different elements in the sample may also lead to the need for correction or for separate measurement of their contribution by irradiation with the sample shielded from thermal neutrons by cadmium.

For large series of measurement acceptable accuracy can be obtained by using comparator technique, where only one element /comparator/ is used for calculating concentrations. For some cases activation by epithermal neutrons ensures the requested selectivity. For unknown samples usually three irradiation are taken /15 min, 1 hs, 12 hrs/ and measurements are made after allowing different delay times.
As a service activity the following types of samples and elements are analysed successfully by using the reactor.

- Environmental pollution studies /5/
  Elements measured are: Na, Mg, Al, Cl, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Zn, Ag, Se, Bi, Rb, Sb, Cs, Ba, La, Ce, Sm, Eu, Tb, Lu, Hf,Ta, Au, Th
- Geological samples /20 /
  Elements measured are: Sc, Fe, Co, La, Ce, Nd, Sm, Cu, Tb, Tm, Yb, Lu, Hf, Ta, Th

- Archeological /ceramic/ samples /21/
  Elements measured are: Sc, Cr, Fe, Co, Rb, Cs, La, Ce, Eu, Yb, Ln, Hf, U.

Problems and limitations of activation analysis related to university reactor

The main limitations in activation analysis at a small university reactor are imposed by

- Training program requirement.

Activation analysis needs the reactor running at its maximum power level for the whole irradiation time which is a conflicting requirement with many of the training exercises demanding low power level.

- Flux level

The only limitation of a low power level is the lack of sensitivity.

- Economical problems

In many cases it is much more economical and practical to irradiate samples for a few hours at another 5 MW reactor, than using small reactors for a whole day irradiation.

6. Nuclear Fuel cycle study

Theoretical analysis of the nuclear fuel cycle is justified by long term energy policy /3/.

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TRAINING ON SILOETTE REACTOR AND ASSOCIATED SIMULATORS AT THE GRENOBLE NUCLEAR RESEARCH CENTRE

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Abstract

The Siloette is a plate-type pool reactor designed to train engineers and technicians for positions in the nuclear power programme. The reactor also serves as a mock-up for experiments to be conducted in the larger Siloe (35MW) and Melusine (8MW) reactors. Its beam tubes are also useful for applications in neutron radiography. The number of trainees attending courses at this reactor has increased from 165 in 1975 to 650 (expected) in 1985. Most courses last from one to three weeks. Training on the Siloette reactor is augmented by a number of nuclear power plant simulators. Compact simulators for both PWR's and GCR's are installed.

1. INTRODUCTION

Thanks to its three reactors : SILOE (35 MW), MELUSINE (8 MW), and SILOETTE (100 KW), the Reactors Department of the Grenoble Nuclear Research Centre has gained considerable experience in operation and use of research and materials testing reactors.

With its large personnel and technical resources, it is involved in the following wide-ranging fields of activity, at both national and international levels : irradiation for study and qualification of materials and fuels from the different types of nuclear power stations, basic research using neutron beams, safety studies and tests, test reactor engineering, production of radioisotopes and of neutron doped silicon, non-destructive neutron radiography tests,... and training of power station operating personnel.

It is within this general framework that the Grenoble Reactors Department has created a reactor physics training activity, based on Siloette, which has been running continuously since 1975 to cope with the increasing demand resulting from the development of nuclear power stations.

Its essential aim is initiation in the basic physical phenomena which determine reactor operation.

For this purpose, a fairly comprehensive program of practical work on reactor (SILOETTE) and nuclear power station simulators (P.W.R., G.C.R.) is proposed in addition to the lectures and conferences (general and specialized teaching on the reactor operating principle, kinetics, dynamics and thermics).

This activity is carried out in close collaboration with Electricité de France, as part of an overall training policy.

This training is mainly intended for engineers and technicians appointed to responsible positions in power plant operation :

- Engineers, technicians, supervisors and foremen from Electricité de France,

- Nuclear power industry engineers (Framatome, A.C.B., Creusot-Loire, Merlin Gerin,...),

- Nuclear Engineering students from Grenoble National Polytechnical Institute and from the University.

. Substantial efforts are also made to set up similar training courses for the benefit of engineers, technicians and students from foreign countries.

Its equipment and the qualification of its personnel also make Siloette the setting for numerous activities related to training, simulation, and reactor safety and operation problems, such as :

- computer assisted teaching
- educational research
- study of the human factors in nuclear power plant operation
- study of the reactor control panel protection systems
- development of simulation software adapted to specific problems (incidents, accidents ...)
- development of simulation in the "non-nuclear" field.

2. THE SILOETTE REACTOR

2.1. Main characteristics and uses

a) General presentation

Siloette is a pool type reactor with a power of 100 kW. The fuel used is enriched uranium in the form of aluminium clad U-Al plates. The proportion of uranium in the U-Al amalgam varies from 22 to 26 % depending on the plates. Control is by means of four Ag-In-Cd fork type rods.

b) Use

Designed as a nuclear model for the research reactors SILOE and MELUSINE, installed on the same site, SILOETTE has been used since the outset for studies and measurements on reactor cores (measuring reactivity, fluxes and spectra, rod calibration, etc...) or on associated irradiation devices (reactivity effects, flux depression, screening, etc...). Series of tests on mockups are carried out on request at SILOETTE, in conjunction with the research teams working at SILOE and MELUSINE.

The fact that SILOETTE is equipped with neutron beam tubes enables other applications that do not require large amounts of flux, such as neutron radiography inspections or certain studies connected with safety, to be carried out.

Experiments in the reactor core itself can be carried out under almost ideal conditions : little background noise, no disturbance due to the environment, unlike what can occur in an experimental reactor fitted with a large number of devices, very accurate operating periods, with very quick power rise and fall.

Among the numerous studies related to use of the SILOETTE reactor, the following are worth mentioning :

- study of a nuclear reactor protection system, for which prototype qualification was carried out on the Siloette reactor. This involves a multiprocessor unit with distributed redundancy. The tests carried out at SILOETTE have enabled progress to be made in defining architectures (redundancy, task decentralization and hierarchization) as well as in testing and auto-testing means (intrinsic safety, single failure criterion).

- void fraction measurements. This involves void fraction measurement qualification by the neutron diffusion method. It is essential that such measurements be determined to obtain good knowledge of the void fractions in two-phase flows, in steady or transient conditions (transient in pressurizing phase) which are characteristic, for example, of the PWR circuits (primary or S.G.).

2.2. Siloette, training reactor

The Siloette pool reactor is particularly suitable for training. This application has, in fact, now become its main activity. The fissile core remains visible during operation, and handling operations are very simple and can be directly observed by the trainees. The control panel is located inside the reactor confinement containing the pool, which enables all the operations being carried out on the reactor and the effects of the operating parameters on the neutron monitoring channels to be observed.

Each practical work session is arranged for a team of five or six trainees (limit purposely set for reasons of teaching efficiency and safety conditions inside the reactor).

Several practical work courses are proposed :

- approach to criticality :
  - . seeking the critical mass by loading fuel elements,
  - . seeking the critical position of the control rods ;

- flux and power measurements :
  - . vertical flux distribution with or without disturbances (display on a multichannel recorder),
  - . transverse distribution in the mid-height plane in various media (fuel, water, aluminium...) ;

- reactivity measurements :
  - . control rod calibration by different methods (period or reactivity meter),
  - . fuel element worth measurements,
  - . reactivity balances.

3. ASSOCIATED POWER PLANT SIMULATORS

3.1. Principle

Resulting from internal study needs, simulation was then used for training students from the University as a complement to the training which had already been given for very many years using the Siloette reactor. This complementarity very soon attracted E.D.F.'s attention for training their own operators. Indeed, the practical work possibilities of the SILOETTE reactor-compact simulators association offers a great deal of educational advantages to provide comprehensive basic training to all those who need to understand the physical phenomena governing reactor operation.

The Grenoble Reactors Department designed and used a first mini-simulator which has now been placed at the disposal of the University, and then designed and built two compact PWR simulators and a GCR operation simulator. These training simulators are different from both the EDF integral representation simulators and the accident sequence study and analysis simulators.

3.2. PWR PLANT SIMULATORS

a) Principle

These are nuclear power station simulators whose purpose is to initiate the trainee in understanding the main physical functions that determine the behaviour of a nuclear boiler. Thus, only the main control instruments of the simulated power plant necessary for comprehension appear on the control desk.

From this viewpoint, the objective aimed for is different from but complementary to that of a full scope simulator (like those of Bugey - EDF), the purpose of which is to acquire reflexes for reactor operation.

b) General presentation

b1] The general architecture is built around three elements enabling work to be carried out while sitting or standing.
In the upper part of these three elements, all the usual display units are to be found : recorders, galvanometers, bar graphs, signalling lamps, alarms, as well as two consoles (alphanumeric and graphic) for displaying diagrams, curves, bar graphs, etc...

The lower part is made up of two panels :
- one horizontal enabling documents to be consulted and computer peripherals such as keyboards, joysticks and plates to be used ;
- the other inclined providing the connection between the horizontal panel and the upper part on which all the actuators such as potentiometers, push-buttons, thumbwheels, etc... are located.

b2] The left-hand element performs the function of recording the data on paper. For this purpose, the following are available :
- 2 three-channel recorders
- 1 x.y plotting table
- 1 small display screen.

b3] The central element enables the power plant to be controlled by means of a moving mimic diagram and actuators. The following functions are clearly presented on it :
- a simplified chemical and volume control circuit which ensures :
    - monitoring of the volume of water in the primary circuit
    - the variation in boron content during dilution, boration and makeup

- the primary circuit represented by a loop composed of :
    - the reactor
    - the pressurizer
    - a steam generator
    - a primary pump

- the secondary circuit represented by :
    - the turbo-generator set
    - the by-pass
    - a turbine-driven pump feeding the steam generator.

b4] The right-hand element enables all the parameters which appear in the mimic diagram to be presented in a more flexible way by means of two consoles :
- one, alphanumeric, which uses menus to launch the simulator from standard power plant statuses (cold stand-by, hot stand-by, full power, etc...)
- the other, graphic, enables several graphic pages to be displayed containing all the data from the central element in more detail.

c) Support computer

This is a GOULD SEL 32.87 type computer with a 32-bit memory of 2 million bytes. It solves the various equations involved in power plant simulation permanently in real time (and if necessary in accelerated time) using programs written in FORTRAN.

The important developments in the simulation field have resulted in a second GOULD SEL 32.67 type computer being added to the first one. A connection between the two computers enables them to back one another up if the need arises.

d) PWR simulation programs

The overall computer system architecture is defined by a central monitor type core supervising three independent systems in real time :

- management of the industrial I/O
- management of the graphic features
- the model.

This monitor executes overall system management on orders and directives from the operator, via a set of dialogue menus accessible on the monitor console. The overlapping architecture of the menus and possible actions can be modified off-line by a specific editor.
The type of menus proposed with their associated sub-layers are :

- management of the simulation model core initialization points,
- management of the real time and of the intertask synchronizations (acceleration, slow-down, freeze, stop, reset, etc...),
- management of the sampling periods connected with the industrial I/O (frequencies, recorder running control by acceleration factor, etc...).

The simulation program enables the operation of a PWR power plant to be studied, in real time or in accelerated time. The model used describes the essential parts of the power plant which are necessary to calculate the main physical parameters :

1 - Core : one-point model (neutronics and thermics) with a multi-area one axial dimension version, enabling control rod movements, Xenon poisoning and flux and temperature distributions, to be simulated.

2 - Primary circuit piping : 2 loops one of which is real.

3 - Pressurizer (two non-equilibrium phase model)

4 - Chemical and Volume Control Circuit (simplified model)

5 - Residual Heat Removal System

6 - Safety Injection System (high and medium pressure)

7 - Steam generator : one axial dimension model representing the different areas (feedwater supply chamber, down channel, riser, separator and dome)

8 - Normal and emergency steam generator feedwater supply

9 - Plane array model of the secondary circuit comprising the steam header, atmospheric steam dump, turbine-driven feedwater pump supplies, generator by-pass and supply.

10 - Turbo-generator

11 - Control channels :

- primary mean temperature regulation by control rods
- primary pressure regulation with heaters and spraying
- pressurizer level regulation
- Chemical and Volume Control System tank level regulation
- Residual Heat Removal System discharge temperature regulation
- steam generator level regulation
- turbine steam by-pass regulation

e) Typical exercises

Several sessions of practical work or exercises on the study of reactor operation can be carried out using the PWR simulation program :

- Cold reactor kinetics
  Approach to criticality with search for the critical boron content.

- Control rod and boron calibration.

Determination of the integral and differential worth of the clusters and the differential worth of the boron by applying test procedures applied to power plant hot tests.

- . Temperature effects :

  - showing up the Doppler and moderator effects by power variation ;

  - influence of the value of the moderator temperature coefficient on the behaviour of the reactor ;

  - showing up the autostability of the reactor ;

- . Contractual load variations - house load operation

  - load variations with and without automatic control by means of the control rods ;

  - steam by-pass circuit studies for important load variations up to house load operation.

3.3. The GCR power plant control simulator

a) Principle

At EDF's request, development of a GCR-line simulator was undertaken in 1982. This is a teaching aid intended for general training and refresher courses for operating personnel from these plants. Thus simulation enables :

- the essential elements of the power plant and their interactions to be represented,
- the installation to be operated in real time (the phenomena take place at the same speed as in operation), very rapid transients to be observed at slow-motion speed, and slowly developing sequences to be accelerated,

- a wide range of normal or incidental situations to be studied,
- the basic physical quantities to be permanently displayed,
- the variations of all the important parameters to be studied at the end of the exercise (deferred output),
- operator actions to be taken into account,
- a series of faults or malfunctions to be introduced in the course of simulation.

b) Design

The simulation system comprises :

b1) the SEL 32.87 presented above,
b2) the control desk.

The whole control desk ensures simulation management, display of the physical quantities of the power plant and operator intervention on the simulated process. It comprises three units :

- the control and monitoring block, a diagrammatic representation of a GCR-type power plant desk enables the functions selected for simulation to be carried out,

- a display unit, essentially comprising a graphic terminal, for representation of internal variables or any other edited variables, selected by the operator (Doppler effect, Xenon effect...),

- the instructor's desk used for control of the simulation and introduction of the faults and incidents studied.

Four versions of this desk exist representing the four types of GCR reactor in operation at the present time :
- Saint Laurent des Eaux
- Chinon 2
- Chinon 3
- Bugey 1

b3) simulation programs.

A list of the main models used to simulate a GCR power plant is given below :

- neutronics : two kinetics models are used to process power generation by the reactor :
  . one-point kinetics
  . space kinetics in 2D geometry (R,) and (R,z) according to a lay-out ensuring a satisfactory representation of the power space variation phenomena.

- core thermohydraulics : this model describes the heat transfer in the fuel cartridges (uranium, cladding) and the cooling fluid.

- exchanger thermohydraulics : this model processes the heat transfer from the CO_2 to the secondary fluid for the production of steam.

The combination of these different models enables the main operation sequences of the power plant to be dealt with :

* normal operation :

- start-up from a reference state of the reactor :
  - . cold state : the reactor has been shut down for more than 24 hrs, decay or absence of xenon ;
  - . hot state : xenon poisoning is taking place in the reactor due to a rod drop.

- load reduction for shut-down of the groups
- power variation in normal operation

* incidents :

- fan failure
- feed pump failure
- tripping of one or two groups
- thermocouple failure (control variable)
- pressure sensor failure.

* accidents :

- clad burst
- CO_2 leak - depressurization
- high relative humidity
- uncontrolled control rod movements
- loss of blowing capacity.

4. OTHER TRAINING MEANS

Besides the Siloette reactor and the simulators, the Training Centre has additional training means (practical and theoretical) available to provide a backup to the training given.

4.1. Specialized courses and lectures

The scientific and technical potential of the Grenoble Nuclear Research Centre and of the University of Grenoble means that a great number of lecturers are available on as widely varied topics as :

- controlled fusion,
- cell biology and influence of radiation,
- structural materials - damages
- radiation protection,
- safety (control, regulations),
- characteristics of the different reactor types,
- fuel cycle.

4.2. Video films

The use of video films and video recorders has become commonplace to illustrate certain aspects of training at Siloette. A fairly large video film library has been built up, covering both general topics ("everyman's guide to nuclear power") and particular aspects (safeguard system or RCV Chemical and Volume Control System of the 900 MWe PWR) or dealing with the representation of plant operation accidents (T.M.I. type).

4.3. Computer assisted training

Through the EDF, Siloette is equipped with C.A.T. consoles enabling the trainees to study or revise, either on their own or with the assistance of the monitor, any parts of the courses or practical work.

Very elaborate programs relating to the PWR are available, corresponding to several hundred teaching hours.

Programs of the same kind are at present being developed for the GCR line, albeit on a smaller scale.

5. APPRAISAL OF THE TRAINING

5.1. Importance of the courses

The ever-increasing number of trainees attending the courses since 1975 reveals the impact this training has had :

Year	Number of trainees
1975	160
1976	210
1977	270
1978	350
1979	375
1980	400
1981	425
1982	450
1983	575
1984	600
1985	650

The training courses are organized according to the profile of the trainees and last from one to several weeks.
A large number of courses have already been organized for foreign trainees (Belgians, Spaniards, Algerians, Englishmen, Pakistanis,...).
The experience acquired and the excellent results obtained leave the door wide open to important further developments in the future.

5.2. Personnel assigned to training

The smooth running of this Training Centre depends among other factors on the versatility of the Siloette staff (reactor operators, physicists, instructors).

These are the people who are directly in charge of running the Centre. Their tasks include setting up the courses and drawing up the practical work schedules, teaching and supervising the different sessions, and all the administrative work involved.

The operation proper of the reactors and simulators is looked after directly by the staff, assisted by teams of specialists from SILOE and MELUSINE (control-monitoring, electrical, electronic and computer systems maintenance).

Finally, this team is completed by a secretariat in charge of reception, the smooth administrative and logistic running of the Department, and providing written documents on the subjects covered during the training courses.

Depending on the course programs, lecturers are occasionally called on from outside (from the University, the C.E.A., E.D.F., ministries concerned...).

5.3. Suitability of the training

The main conclusion that can be drawn from the experience acquired in this field is that comprehensive training of reactor operating personnel cannot leave any stage out : first of all basic theoretical training, then understanding of the main physical phenomena involved in the operation of a nuclear boiler, with application to the assigned reactor (900 MWe, 1300 MWe, GCR), and lastly retaining the knowledge acquired and keeping up the practical know-how.

The complementary nature of the means used (training reactor, multi-function simulator : comprehension, acquisition of reflexes, specific circuit, theory, diagnosis assistance,...) and the systematic repetition of the lessons seem to be the most suitable methods.

The harmony which exists between the training cycles organized by EDF and the training given at Siloette is proof of the suitability of the methods used and a guarantee of the quality and effectiveness of the training.

6. OTHER SIMULATION APPLICATIONS AND DEVELOPMENTS

6.1. In the nuclear field

The Grenoble Reactors Department is at present working to design and bring out :

a) another compact PWR simulator taking the latest developments in software and display techniques into account,

b) a 1300 MWe PWR micro-simulator

c) a simulation project with EDF and IPSN to study human factors (operator behaviour).

The simulators used in France provide a complete or partial representation of the power plant. They have been designed for training purposes and therefore cannot be used as an ergonomic image development aid.

Specific studies (on particular circuits, such as the RCV) have been carried out to test the images immediately in order to check :

- the operators grasp of the phenomena occurring in incidental situations ;
- the speed and accuracy of diagnosis ;
- the speed of the operator's interventions ;
- the speed with which control techniques are acquired.

These studies come under the overall framework of future power plant control room design.

6.2. In the non-nuclear field

The experience acquired in the field of nuclear power plant simulation has led us to widen our scope to include the related field of simulation of classic power units, electrical distribution networks, and seawater desalination plants. Especially where EDF are concerned, there is a great demand in the field of fossil fuel power plant simulators (in France and abroad).

7. CONCLUSION

The originality and effectiveness of the Grenoble Reactors Department training activities is based on the equipment used (reactor and simulators).

7.1. Reactor

Over the years, the value of a SILOETTE type reactor is increasingly appreciated. It is a powerful tool for demystifying the nuclear field, has low running costs, is flexible to use (not subject to any of the disturbances brought about by the multiplication of irradiation experiments, as is the case in a test reactor), and enables all kinds of useful activities to be developed.

The possibility of combining training activities smoothly with research, as well as physical studies based both on calculation and measurement, is also a valuable asset.

7.2. Simulator

The result of several years experience in training in close collaboration with E.D.F., the simulators have become irreplaceable training instruments in the field of nuclear power.

They are nowadays low-cost training means, which are easy to reproduce and flexible and relatively simple to use.

This experience can now be put to use profitably in the non-nuclear field where the range of possible applications remains very wide indeed.

The roles of reactor operators, physicists and instructors performed by the Siloette staff constitute a very large and varied capital of know-how and experience enabling the training given to have both the theoretical and practical dimensions which all the trainees are looking for and appreciate.

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