1. INTRODUCTION

The TRIGA Mark II Reactor in Ljubljana began its operation on May 31, 1966. The power of the reactor is 250 KW. TRIGA utilizes solid fuel elements with 20% and 70% enriched uranium. The reactor has the following experimental and irradiation facilities: 2 radial beam ports, 2 tangential beam ports, 2 thermal columns, 40 position rotary specimen rack, pneumatic transfer tube, central thimble and extra irradiation position in F ring.

Until 1980 the reactor operated about 2700 hours per year. Since then the reactor is in operation about 4200 hours per year (Fig. 1) because of the great demand for radioactive isotopes for medicine. Usually it is in operation three or four times per week overnight. The staff consists of seven operators and reactor manager. Operational costs are about $200,000 per year, in which the cost of the fuel is not included.

Until now, no major problem in the operation of the reactor has occurred. During the last twenty years of its operation we have found some new solutions which have greatly improved operation and utilisation of the reactor. In the next few chapters there is a list of the most important improvements and a short description of the basic and applied research.

2. IMPROVED PERFORMANCE OF THE REACTOR

2.1. DRY CENTRAL THIMBLE. In order to facilitate the irradiation of the samples in the central thimble the water was removed. The samples can be inserted or removed in non-water tight irradiation containers and sent directly to the hot cell. At the bottom of the new pipe in the centre of the core, a graphite cylinder is inserted which extends 3 cm below the vertical middle point of the core. There is almost no difference in neutron flux in the central thimble because of this modification. The new pipe is bent at the top of the reactor tank.
2.2. NEW PNEUMATIC SAMPLE LIFTING DEVICE. Due to the large demand for irradiation (each year there are about 2000 samples irradiated) a new pneumatic facility for loading and unloading of samples in the rotary specimen rack, central thimble and F ring has been constructed and installed. The sample is loaded or unloaded with the help of differences in the air pressure. The sample can be sent by this facility directly to the hot cell. Operators are not exposed to the radiation when lifting the irradiated samples, because of the remote control mechanism.

2.3. NEW ROTARY SPECIMEN RACK, The original rotary specimen rack (Lazy Susan) became defective very soon after the reactor was critical. The failure of the Lazy Susan has been noticed at almost all TRIGA Reactors. Therefore we redesigned the original Lazy Susan so that the loading and unloading of the samples is performed by a pneumatic system which is described in the chapter 2.2. Also the bearing was replaced by stainless steel and graphite balls which are not affected by high irradiation. This system has been in operation for 10 years and we are not having any problems with it.

2.4. MODERNISATION OF INSTRUMENTATION. Since 1972 we have gradually substituted some of the original instrumentation of the reactor because of its ageing. In 1982 the instrumentation for the power control system and the safety channel was replaced with the modern Hartmann-Braun instrumentation. Apart from this, the following new instruments are already in operation:
- 3 fuel temperature meters coupled to the instrumented fuel elements consist of an additional safety channel;
- water level indicator;
- mechanical rod position indicators were replaced by the three digit display fed by the signal from the shaft encoder;
- new conductivity meter for water quality measurements;
- integrator for measurement of the reactor power (digital display);
- system for data logging of reactor parameters based on two microcomputers.

2.5. PROBLEMS WITH THE REACTOR. The main operational problems we had up to now were the following:
- excessive elongations (up to 36.8 mm) of some Al-clad fuel elements;
- 3 dummy elements in F ring were stuck in the upper grid plate because the Al-cladding was badly damaged;
- 2 leaking fuel elements (in 1983 and 1985). Inspection has shown that the damage of the fuel elements was caused by improper cladding material.
- difficulties with the rotary specimen device and the recorder (common to almost all TRIGA Reactors).

4. BASIC RESEARCH

The TRIGA Mark II reactor is the main research facility in the Reactor Physics Division and in the Nuclear Chemistry division of the "Jožef Stefan" Institute. Basic research in these divisions is being conducted in the following main fields: solid state physics, neutron dosimetry, neutron radiography and autoradiography, reactor physics, examination of nuclear fuel using gamma scanning, irradiation of semiconducting materials and neutron activation analysis.

4.1. RESEARCH IN SOLID STATE PHYSICS BY NEUTRON SCATTERING

Through neutron inelastic scattering experiments detailed information can be gained on phonon spectra and dispersion curves, phonon lifetimes, thermal diffusion of atoms, the time dependence of the spin correlation in magnetic substances, etc., especially in the case when a sample contains atoms with a high incoherent or coherent cross section for neutrons. For instance, neutron scattering by hydrogenous substances is almost entirely incoherent due to the large incoherent cross section of the proton. Therefore, when hydrogen atoms are present in the molecule, neutrons are scattered mainly by these atoms, providing relatively easy interpretation.

Incoherent inelastic neutron scattering spectra can be measured by cold neutrons (energy gain method) with a neutron energy lower than 5 meV (a wavelength is 4 Å). The spectra of scattered neutrons are very often measured by a time-of-flight method. A pulsed beam of almost monoenergetic neutrons produced by a rotating single crystals of lead or copper is scattered by a sample into a bank of neutron detectors arranged at different scattering angles to the incident beam direction at a distance 2-3 m from the sample. The energy spectrum of the scattered neutrons is analysed by measuring the scattered neutrons time-of-flight from the velocity selector to the neutron detector by means of a multichannel analyser.

Such a spectrometer was built at our reactor. Because we are faced with the problem that the flux of neutrons in the low energy tail of the thermal spectrum is low, a cold neutron source using solid methane as a moderator was placed in the tangential beam hole.
The cold neutron flux was increased by a factor of 8.2 compared with a graphite scatterer of the same dimensions as the methane source. With this cold neutron facility it is possible to perform experiments which otherwise could not easily be carried out with a low flux reactor (1-3).

The rotating crystal time-of-flight spectrometer together with the cold neutron source and the neutron diffractometer represent very valuable experimental tools for research in the field of solid state physics by neutron inelastic and elastic scattering. At our reactor the system is used for the study of optical and acoustic lattice vibrations, phase transitions, and diffusive motions in (4-13):
- ferroelectrics and antiferroelectrics: \( \text{KH}_2\text{PO}_4, \text{CO}_2\text{Sr(CH}_3\text{-COO)}_6, \text{PbCa}_2(\text{CH}_3\text{-COO)}_6, \text{NH}_4\text{H}_2\text{PO}_4 \)
- liquid crystals: MBBA, PAA, Na-palmitate, Na-stearate, anisalazine, etc.
- biological samples: LiDNA, NaDNA
- polyethyland oxide solutions
- hydratization of cement

4.2. NEUTRON RADIOGRAPHY AND AUTORADIOGRAPHY

Neutron radiography and autoradiography are nondestructive techniques of inspection which provide additional or complementary information to that given by the usual gamma or X-ray radiography.

At the reactor in Ljubljana development of neutron radiography began in 1969. Since then, research in the fields of thermal neutron radiography and its applications stimulated the development of related fields like microneutronography, neutron induced autoradiography, autoradiography and radiography with back-diffused electrons. At present two permanent neutron radiographic facilities are in operation. The thermal column facility is used for inspection of large objects while the vertical beam tube from the core of the reactor is intended primarily for examinations of small samples. In the thermal column the graphite scattering plug was replaced by a 2 m long Cd lined conical collimator. The vertical beam tube was designed primarily for high resolution microneutronographic examinations of thin metallurgical or geological samples, where the discernment of structural details of microscopic size is required. For irradiations in the vertical beam tube, a special vacuum cassette, suitable for accommodating samples up to several mm thick and up to 30 mm wide was constructed.

A survey of past and current research activities is summarised in Table 1. Listed are fields of research and applications and the main problems studied.
4.3. NEUTRON DOSIMETRY AND RADIATION DAMAGE

Although reactors have a fixed geometry, the neutron flux density throughout the reactor core and reflector will vary with time due to control rod movement, fuel burn-up and other changes in the core. However, for studying radiation damage effects in various materials, as well as for nuclear fuel burn-up calculations and neutron dosimetry, the reactor neutron energy spectrum should be known in order to determine the neutron dose or burn-up. The practice has been to calculate theoretically a relative neutron spectrum and then to normalize this spectrum to the experimental response of some activation detectors at known neutron energy response. Detectors are available that are sensitive to neutrons in different energy ranges. Foils of gold, indium, chromium, iron, manganese, copper, cobalt, dysprosium and uranium 235 are examples of detectors used for thermal and intermediate neutron flux measurements. Threshold detectors such as nickel, titanium, copper, iron, sulphur, phosphorus and uranium 238 foils are examples of detectors used for fast-neutron measurements.

Accurate knowledge of integral cross sections for neutron induced threshold reactions is very important as they are used as activation detectors in neutron spectrometry as well as for assessment of radiation damage. The present goal for the accuracy of these measurements is under 2-3% level.

Since 1970 the fast neutron spectrometry group at the TRIGA Mark II reactor in Ljubljana has devoted continuous effort to improving the accuracy of integral cross-sections for a set of selected threshold reactions, measured in a pure U-235 fission spectrum (26-28). The present measurements have been made with an accuracy of 2-5%. Both measured and evaluated values match quite well for almost all reactions.

Measurements of the effects of fast neutron irradiation on the mechanical properties of reactor structural materials are also in progress because an accurate knowledge of the transmutation product effect due to the elastic collisions of fast neutrons with atoms in the metals could prolong the lifetime of a nuclear power plant.

4.4. REACTOR PHYSICS

Activities in reactor physics should be established around a reactor in order to have a group of research workers with a broad knowledge in power reactor design, maintenance, reactor technology and safety. Thus staff at the research reactor who are occupied with reactor physics research could be of great help in planning and running of future nuclear power stations.
The efforts of such a group should be aimed towards optimum exploitation of nuclear power plants by developing good calculation methods which play a major role in reactor start-up, testing, maintenance, safety and good utilization of reactor fuel. With this in mind, a group was established at our reactor centre in order to develop modern computer programmes for burn-up calculation and safety assessment. The results have been tested partially on TRIGA fuel elements with a well-known burn-up history (29).

Another possibility is reactor noise measurement where a good knowledge of the physical background on reactor operation can be gained (30). At the same time, this technique could be employed to predict failures of particular parts of a power reactor.

Some shielding measurements and calculations using fast neutrons were also performed at our reactor.

4.5. ASSESSMENT OF NUCLEAR FUEL BURN-UP

The burn-up of nuclear fuel can be determined by the measurement of the amount of an appropriate fission product, or from the ratio of masses of two isotopes. But neglecting the local variation of the linear attenuation coefficient for gamma rays is the main factor affecting the accuracy of gamma spectrometric estimation of fuel burn-up. However, up to now, this effect has not been considered. Recently, we have started a study of how to take these effects into account. It has been decided to combine the gamma ray scanning technique with a transmission experiment. In the future we intend to develop the method in such a manner that an additional source of gamma rays will be not necessary.

First of all, the method was elaborated from the mathematical standpoint. We developed a computer programme which calculates the local dependency of the attenuation coefficient for gamma rays and the isotopic distribution. For measurement of gamma ray spectra, a high resolution Ge (Li) detector was used. It views two shielded fuel elements already used in the TRIGA reactor. One of them serves as an additional gamma ray source. For the computation of the specific activity of an observed photopeak, a special programme has been developed (31). With this new method using gamma spectrometric examination for burn-up measurements more precise data could be obtained.
4.6. NEUTRON ACTIVATION ANALYSIS

Neutron activation analysis taking place represents one of the major usages of our TRIGA Mark II reactor (approximately 800 samples and 4000 elemental determinations per week). Among developments in nuclear analytical methods, destructive and non-destructive methods of activation analysis for determination of Ag, As, Au, Co, Cr, Cu, Hg, I, Mn, Mo, Pd, S, Sb, Se, Sn, U, V, Th and Zn at nanogram and microgram levels, and their application to studies of environmental and biological samples raw materials and geological samples were emphasized. The methods developed were checked by the analysis of different standards reference materials, the characterization of which is also studied.

In the framework of the environmental monitoring programme, emphasis is put on the contents and distribution of several trace elements in sediments, water and selected representatives of indicator organisms from background and contaminated terrestrial and aqueous systems (32). It was shown that in most cases organisms from different levels of the food chain can be used as bioindicators for following environmental pollution with toxic trace elements. Measurement were also made on two critical points, Idrija and the Bay of Kastela (33) characterized by high inputs of mercury. Sediments and organisms from these two areas were found generally to contain increased mercury concentrations. As well as trace elements, studies are also performed on radionuclide levels in the environment. In particular, investigations on the uptake and distribution of Ra and U in typical areas, especially with reference to the commencement of the Yugoslav nuclear power programme (Uranium mining, Nuclear power station) are made (34, 35).

Studies involving distribution of heavy metals between water and sediment, their transport and the efficiency of a sedimentation system, have been pursued using nuclear and spectrometric techniques.

In the field of the life sciences, sensitive nuclear activation techniques for selenium (36, 37), and iodine (38) and molybdenum (39) determinations were developed and applied to biological samples (human fluids and tissues), including milk. Studies of the trace element characterization of human milk were carried out on both local samples and as a reference laboratory for the analysis of "difficult" trace elements in samples collected from six countries under an IAEA/WHO co-ordinated international project (40, 41).
A study of the vanadium content of human dental enamel and its relationship to carries using a rapid NAA method (42), and work on the level of arsenic of human bones and the long term effect of burial in the soil for forensic purposes, were also included in this part of the research programme. Further studies on mushrooms have revealed silver (43) and arsenic (44) accumulating species.

The section is also continuing a programme of analysis of biological reference materials; some problems concerning the status and certification of such materials are also studied (45, 46, 47, 48).

5. APPLIED RESEARCH

5.1. PRODUCTION OF RADIOACTIVE ISOTOPES

In the reactor TRIGA due to the rather low neutron flux mainly the short lived radioactive isotopes are produced and which are used for some unique medical and industrial applications. Isotopes being produced are the following:

a) Technetium-99m. In order to utilize the reactor as much as possible and at the same time to introduce the domestic production of 99mTc, we developed the method for production of high concentration and high purity 99mTc. This isotope is today the most widely used radionuclide in diagnostic nuclear medicine. In a research reactor with a low flux it is not possible to achieve a high specific activity of 99Mo, and therefore for everyday routine production of 99mTc a solvent extraction method has been adapted. At our reactor it was proved that the minimum neutron flux necessary to produce medically suitable quantities of 99mTc by neutron activation of natural molybdenum is about 3 x 10^{12} n/cm² with irradiation times of about 150 hours. Even at this low flux it is possible to produce 50 GBq of 99mTc per week. However, routinely we produce 80 - 100 GBq by the irradiation of the sample of 85 grams of Mo for 80 hours in the central thimble. This isotope is produced five days a week for the hospitals in Ljubljana.

b) Fluorin-18. Carrier-free $^{18}$F has a half-life of 109 m. It is positron emitter and the resulting 511 keV annihilation radiation is easily detected. These physical properties and the rapid blood clearance means that the radiation dose to the patient is low. $^{18}$F is now used in medical centres in the form of simple inorganic species for bone scanning and other diagnostic work.
The $^{18}$F is produced by neutron irradiation of mixed, enriched and natural lithium carbonate and is separated by the distillation procedure with sulfuric acid. The irradiation is carried out for 5 hours in the central thimble. The yield of $^{18}$F is of about 1 GBq per day.

c) Krypton-85m. The method was developed for production of Kr$_{85m}$ by irradiating krypton absorbed in the clathrate, which can absorb krypton in a very large quantities. There is about 20 times more krypton absorbed in the clathrate than in a gas bottle under the 4 atmosphere of Kr of the same volume. Kr$_{85m}$ can be used for check-up of lungs and of blood circulation system.

d) Sodium, Bromine, Zinc. For different non-medical applications the routine production of Na$_{24}$, Br$_{82}$ and Zn$_{64}$ is carried out. Sodium and bromine are used for a leak detection in pipes situated underground and in thick walls. Because of high energy, gamma rays are emitted from irradiated Na$_{24}$, it is quite easy to detect with a scintillation detector a leak in a pipe filled with the water where Na$_{24}$ is dissolved. Br$_{82}$ is used in a solid or gas form.

Zn$_{64}$ with a half time of 247 days is as a ZnO added to a cement during a large scale production of concrete in order to test the performance of the mixing device. All our large concrete production facilities are checked regularly by this method.

e) Cobalt. Radioactive Co$_{60}$ is widely used in level measuring devices where low activity Co$_{60}$ is needed. Regularly production of Co$_{60}$ in our reactor is used for new measuring devices and for replacement of Co$_{60}$ with too low activity.

5.2. NEUTRON TRANSMUTATION DOPING OF SILICON

The TRIGA Mark II reactor is used also for irradiation of semi-conducting material (silicon) with fast neutrons in order to improve electrical properties of this material. The irradiation facility was placed in the radial channel of the reactor. Phosphorus doping of silicon with the aid of thermal neutron irradiation was developed very recently. It has been proved that even with a small research reactor phosphorus doping can be performed. The transmutation doping process involves irradiation of an undoped semi-conductor with a thermal neutron flux. The major advantage of the neutron transmutation doping (NTD) of silicon is the homogeneity which is
a result of a homogeniuous distribution of silicon isotopes in the target material and the long range of thermal neutrons in silicon. Research reactor facilities provide the best source of thermal neutrons for this purpose.

The irradiation positions used for this work are arranged in a circle at a radius of 50 cm from the core centre lines. They are situated on the annulus of graphite (reflector) and on the rotary specimen rack, where the axial and radial neutron flux gradients are small. At these positions the ratio of thermal to fast neutrons is in excess of 1000:1 because in the upper parts of the fuel elements the graphite pieces are placed, which minimises the damage which has to be removed by annealing. From this point of view the TRIGA core has a big advantage to other types of reactors. Irradiation time of the ingots is 270 hours.

An additional irradiation position used for NTD is the radial beamport where a thermal neutron flux of \(4 \times 10^{12} \text{n/cm}^2\) is available at the irradiation position where the Cd ratio is 3. The special facility was constructed and installed in the beam port which is shielded with water. The capsule with the silicon crystal is conveyed up to the irradiation position by a long rod, driven by the operator. During this procedure the water is displaced to the special water reservoir outside the beam port. The capsules are introduced to the irradiation position and extracted manually during the reactor operation. The irradiation volume has been limited to 20 cm length by 8 cm diameter.

6. NUCLEAR TRAINING CENTRE

At the Institute's Reactor Centre the Ljubljana Nuclear Training Centre (LNTC) was established where the reactor TRIGA is the main teaching equipment. This training centre can fulfill the training requirements of the first Yugoslav nuclear power plant in Krško and the requirements of the whole Yugoslav nuclear programme where this will be needed. A modular approach in defining the course contents has been adapted. As such it makes it possible or facilitates the composition of other courses to fulfill occasional needs and thus the organization of special courses with teachers hired also from abroad.

Until now about 250 students have participated at different courses organised by LNTC.
<table>
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<th>Problem studied</th>
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7. CONCLUSION

Concerning the TRIGA Mark II reactor we can conclude that it is very good experimental installation because the experimental and irradiation facilities are extensive and versatile, physical access and observation of the core are possible at all times. In addition, a low operational cost makes it suitable for use even in small and developing countries for training, research and applications.
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