INR TRIGA RESEARCH REACTORS: A NEUTRON SOURCE FOR RADIOISOTOPES AND MATERIALS INVESTIGATION

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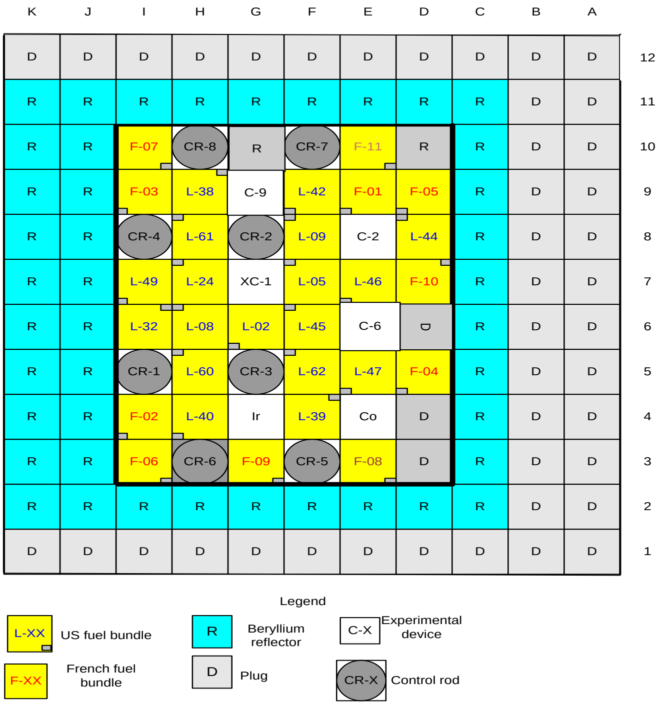
1. INTRODUCTION

At the Institute for Nuclear Research (INR) there are two high intensity neutron sources. These sources are in fact the two nuclear TRIGA reactors: 14 MW TRIGA research reactor and TRIGA Annular Core Pulsed Reactor (ACPR). Both reactors are open pool type.

1.1. TRIGA 14 MW research reactor

The TRIGA reactor steady state core, Figure 1, operated by the INR in Pitesti, Romania, has a rectangular shape which holds the fuel bundles. Each fuel bundle is composed of 25 nuclear fuel rods containing LEU and the fuel bundle has a 89 mm^2 cross section. The reactor core is surrounded with 20 beryllium reflectors with a 33 mm central hole and 24 without a hole. Beryllium reflector square cross-section is identical to the fuel bundle [1].

The TRIGA steady state reactor is provided with several high level thermal neutron flux in-core irradiation channels. Other out-of-core irradiation channels are located in the vertical holes in the beryllium reflector blocks. The 14 MW TRIGA core is a relatively short core (57.5 cm). Along the horizontal direction the thermal neutron flux is well reflected by the beryllium blocks. In the axial direction leakage is important, so that the axial distribution is similar to the cosine shape of many other reactors, with some non-uniformities, such as an asymmetrical maximum, a peculiar ratio of the maximum to the mean value of thermal neutrons (APF) and a peculiar ratio of thermal to fast neutrons. The presence of a relatively large number (8) of efficient control rods, partially inserted in the core for controlling reactor power, may disturb the axial flux distribution and the neutron flux value over the entire core. The thermal neutron flux axial distribution in the central channel, labeled XC-1, measured with a mobile Co self-powered neutron detector is shown in Figure 2. During this distribution measurement the reactor was operated at a power level of 12 MW. The ratio of maximum-to-mean value of thermal neutron flux in XC-1 core channel is 1.29 [2].



K	J	I	H	G	F	E	D	C	B	A	
D	D	D	D	D	D	D	D	D	D	D	12
R	R	R	R	R	R	R	R	R	D	D	11
R	R	F-07	CR-8	R	CR-7	F-11	R	R	D	D	10
R	R	F-03	L-38	C-9	L-42	F-01	F-05	R	D	D	9
R	R	CR-4	L-61	CR-2	L-09	C-2	L-44	R	D	D	8
R	R	L-49	L-24	XC-1	L-05	L-46	F-10	R	D	D	7
R	R	L-32	L-08	L-02	L-45	C-6	D	R	D	D	6
R	R	CR-1	L-60	CR-3	L-62	L-47	F-04	R	D	D	5
R	R	F-02	L-40	Ir	L-39	Co	D	R	D	D	4
R	R	F-06	CR-6	F-09	CR-5	F-08	D	R	D	D	3
R	R	R	R	R	R	R	R	R	D	D	2
D	D	D	D	D	D	D	D	D	D	D	1

Legend

L-XX	US fuel bundle	R	Beryllium reflector	C-X	Experimental device
F-XX	French fuel bundle	D	Plug	CR-X	Control rod

Fig. 1. Layout of TRIGA 14MW reactor core.

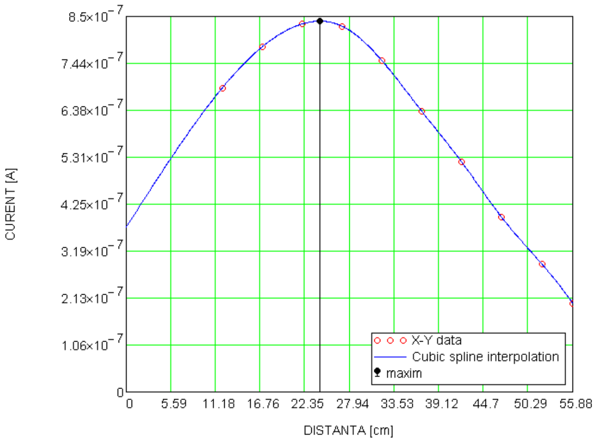


Fig. 2. Thermal neutron flux axial distribution in XC-1 channel.

The thermal neutron flux spectrum in the XC-1 core channel was determined using the selected multi-foil activation technique. The flux density per unit lethargy spectrum output of the SAND2 code for 621 energy groups in the XC-1 water filled irradiation channel is shown in Figure 3.

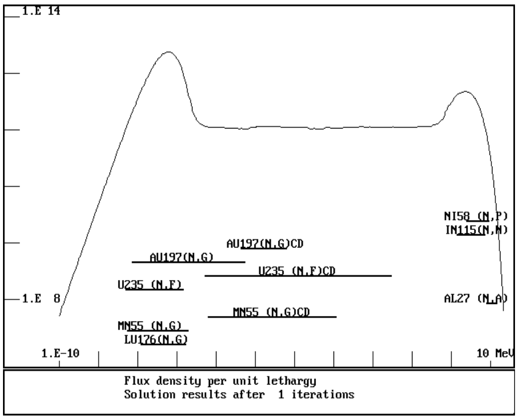


Fig. 3. Flux density per unit lethargy in XC-1 channel water filled.

The maximum value of the thermal neutron flux having energy lower than the Cd cut-off energy (E_{Cd}=0.55eV) at 14 MW of reactor power is: $\Phi_{Scd} = 2.46\times10^{14}\,cm^{-2}s^{-1}$. The integrated neutron flux (0<E>18MeV) is: $\Phi = 3.86\times10^{14}\,cm^{-2}s^{-1}$. The cadmium ratio, R_{Cd}, and respectively, the thermal-to-epithermal neutron flux ratio, f, are: $R_{Cd} = 3.02$, f = 31

1.2. The TRIGA ACP reactor

The secondary high intensity neutron source at INR Pitesti, is the TRIGA Annular Core Pulse Reactor (ACPR), Figure 4.

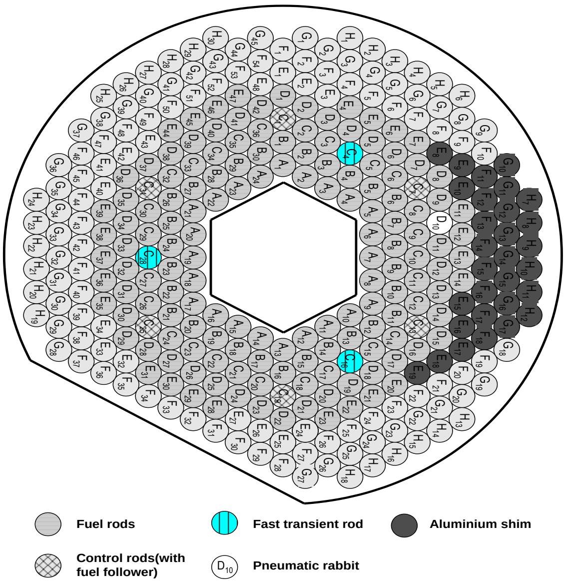


Fig. 4. Layout of TRIGA ACPR core.

This research reactor is of a peculiar concept, and it is designed to be operated mainly in pulsed mode for a maximum power of 20 000 MW and a full width at half maximum of approximately 3.4 ms. The TRIGA ACPR may be also operated at steady state for a maximum power level of 500 kW. The core of this reactor is not surrounded with reflector blocks. Instead of this, all fuel rods are provided with top and bottom end graphite reflectors. The pulsed core is provided with two dry irradiation channels: the central tube, 304 mm diameter and 228 mm height, and the pneumatic rabbit located in the D10 channel of the core. The central tube is designed for large experiments, but it may be also used for NAA purposes.

The thermal neutron flux distribution in the ACPR dry central tube measured with a copper wire for stationary mode operation at P=100 kW is shown in Figure 5.

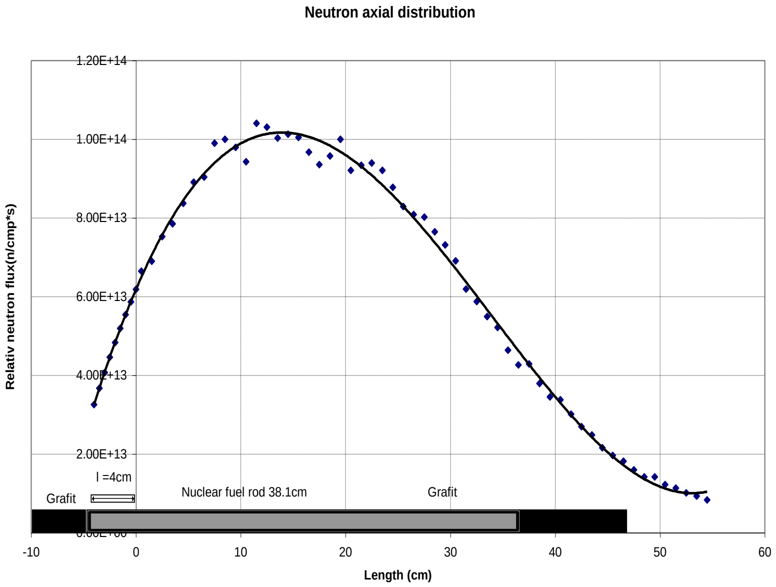


Fig. 5. Thermal neutron axial distribution in the ACPR central tube.

The ratio of maximum-to-mean value of thermal neutron flux in the above mentioned channel is 1.22. For the same mode of reactor operation, the thermal neutron flux in the central dry irradiation channel is:

$$\Phi_{Scd} = 5.03\times10^{12}\ \text{cm}^{-2}\text{s}^{-1}.$$

Fast neutron flux (E>0.1MeV) and f factor are:

$$\Phi_f = 4.7\times10^{12}\,\text{cm}^{-2}\text{s}^{-1};\ f = 4.67.$$

Thermal neutron flux in the pneumatic rabbit from dry channel D10 at P=100 kW in stationary mode and f factor are:

$$\Phi_{Scd} = 4.68\times10^{12}\,\text{cm}^{-2}\text{s}^{-1};\ f= 12.$$

This reactor is provided with two dry horizontal beam tubes, one of them being radial and other tangential, having an inner diameter of 280 mm and a total length of 5 m.

2. NEUTRON ACTIVATION ANALYSIS TECHNIQUES

The INR Pitesti TRIGA research reactors are used as neutron sources for several experimental nuclear techniques. One of these techniques is neutron activation analysis (NAA).

2.1. In core irradiation devices for NAA

The SSR Reactor is provided with two pneumatic rabbits. These devices are not permanently installed. Due to the large flexibility of the core and according to specific investigations requirements, the pneumatic rabbit may be installed in appropriately selected vertical channels in the reflector or core.

For the beryllium channels, a pneumatic rabbit with cartridge dimensions of 12x30 mm is available. This pneumatic rabbit is manually operated. Another irradiation device, also of pneumatic rabbit type, is provided with an underwater storage rack having a capacity of 12 cartridges. It has an automatic timing control.

The TRIGA ACPR research reactor is provided with a pneumatic rabbit. The dimensions of the cartridge used in this pneumatic rabbit are: $\Phi=14$ and $h=190$ mm. The pneumatic rabbit may be operated manually or automatically timed. The pneumatic rabbit for the ACPR reactor is permanently installed in the D10 channel.

2.2. Available gamma spectrometers and software analysis package

In the lab three high-resolution gamma ray spectrometers are available. All gamma ray detectors are HPGe type having a relative efficiency of ~20%. Two of the spectrometry chains are provided with an AQUSPEC multi-channel analyzer and GENIE2000 software analysis package. Also, in the NAA lab, the K_0-IAEA V1.01 software analysis package is available. Gamma ray measurements are performed inside a low background shielding with an adjustable source-detector distance. Detector efficiency calibration is performed by standard sources (50-1410 KeV) from the Laboratory for Measurement of Ionizing Radiation (LMRI) in France, AMERSHAM plc in the UK and the Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN –HH) of Romania.

2.3. NAA method

The analysis methods most frequently used in labs, whose results are not affected by significant errors, are the relative methods. Generally, the standards cannot cover completely the distribution range of the chemical elements found in the analyzed samples.

For use at the stationary TRIGA reactor, the zirconium bi-isotopic foil standardization method for multi-elemental concentration measurement has been developed in our lab. Zirconium has two natural isotopes, ^{94}Zr and ^{96}Zr. The method is based on the two specific neutron capture reaction of zirconium: $^{94}Zr(n,\gamma)^{95}Zr$ and $^{96}Zr(n,\gamma)^{97}Nb$. These reactions allow us to calculate the thermal-to-epithermal neutron flux ratio, and also the elemental concentration in the analyzed samples. Now in our lab, k_0 standardization is used for NAA purposes. Usually, for NAA purposes beryllium reflector channels are used, but also in-core irradiation channels can be used for above mentioned purposes. The neutron flux parameters in the K-11 beryllium channel are summarized in Table 1.

TABLE 1. NEUTRON SPECTRUM PARAMETERS OF THE K-11 IRRADIATION CHANNEL

Parameters	Mean	±	SD (k=2)
α	0.0116	±	0.0020
R_{Cd}	3.75	±	0.94
f	48.63	±	1.82
Φ_{th}	8.34×10^{12}	±	1.67×10^{11}

During the years 2005 to 2009, the NAA lab at INR has participated in an international inter-comparison task at the European level. The reference and measured values of elemental concentration in standard stainless steel samples denominated as ECRM 379-1 measured in the NAA INR lab are presented in Table 2 [3].

TABLE 2. CERTIFIED AND EXPERIMENTAL ELEMENTAL CONCENTRATION IN ECRM 379-1

		Reference values		**Measured average values**		
No.	Element	Concentration (%)	Stdev (k=3)	Concentration (%)	Stdev (k=1)	Diff (%)
1	Mn	1.84	0.17	1.83	0.25	0.53
2	Ni	30.83	0.06	30.23	1.20	1.95
3	Cu	0.983	0.08	0.95	0.08	3.81
4	Cr	26.77	0.04	26.71	0.16	0.22
5	W	0.01	0.0001	0.0104	3.8E-04	-4.2
6	Mo	3.29	0.11	3.33	0.15	-1.07
7	Fe	35.7	0.04	35.97	1.30	-0.77
8	Co	0.0384	0.001	0.038	0.002	2.21
9	As	0.0028	0.0001	0.0029	1.75-04	-1.79
10	Sb	5.70E-04	0.0001	5.60E-04	3.40E-05	1.75
11	V	0.066	0.002	0.064	3.84E-03	3.03

2.4. Prompt gamma neutron activation analysis

At INR Pitesti, a prompt gamma ray NAA (PGNAA) has been designed, manufactured and put into operation. It is linked to the horizontal radial beam tube of the TRIGA pulsed reactor. For PGNAA purposes, the pulsed reactor is operated in steady state mode. A schematic layout of this facility is shown in Figure 5 [4].

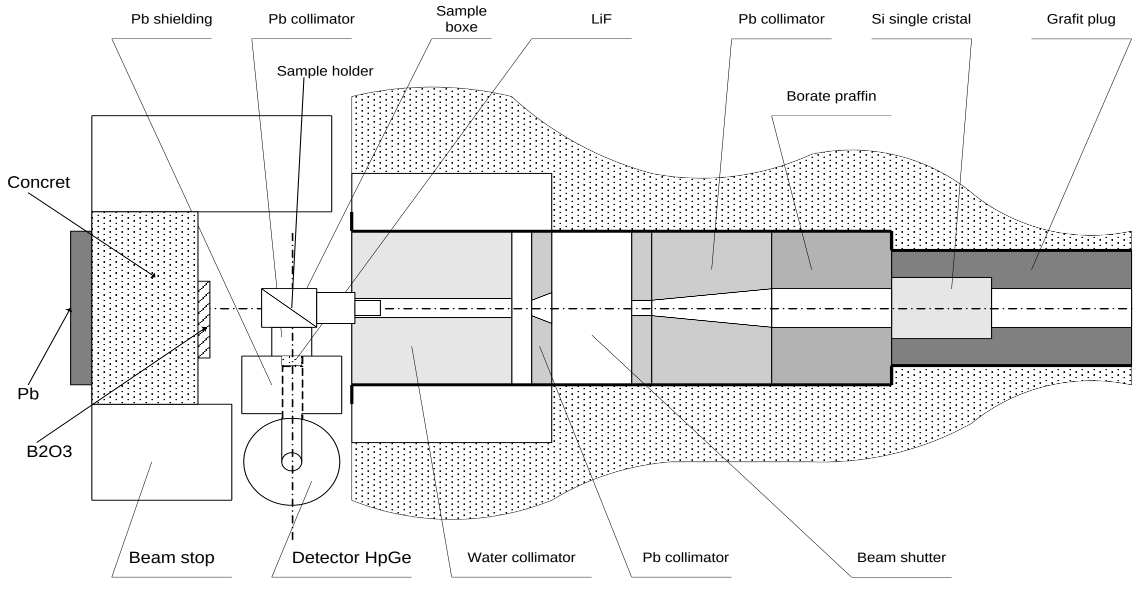


Fig. 5. PGNAA schematic layout.

2.4.1. Characteristics of the neutron beam

The thermal neutron flux ($E<E_{Cd}$) measured by gold foil activation method and the cadmium ratio are:

$$\Phi_{scd} = 10^6 \text{ n/cm}^2\text{s};\ R_{Cd} > 40.$$

The beam shape at the sample holder obtained by radiographic method is shown in Figure 6. In the radiographic film a circular spot was observed, 50mm in diameter, having a good contrast and slightly diffuse edge and being very homogenous.

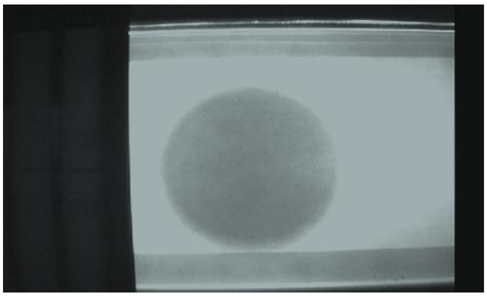


Fig. 6. Neutron beam radiographic image.

The analysis of this image shows a good collimation of the thermal neutron beam in a circular beam with a 50 mm diameter even up to 300 mm distance from the collimator exit. No other impression besides the central spot was observed.

3. NEUTRON SCATTERING

3.1. Neutron diffraction

A focusing high-resolution neutron crystal diffractometer has been put in operation at the INR Pitesti. This experimental facility is presented in detail in [5].

A new concept of high resolution neutron diffractometer has been developed in INR Pitesti. This kind of configuration allows high resolution performances to be achieved, comparable with the best existing conventional diffractometers, even for medium flux neutron sources (10^{13}–10^{14} $cm^{-2}s^{-1}$) and therefore gives special opportunities for most of the existing research where medium flux neutron sources are available. For high flux neutron sources ($>10^{15}$ $cm^{-2}s^{-1}$), an optimization of the experimental setting can be realized, giving a better luminosity and consequently shorter times to raise diffraction patterns.

Using the general principles given above, the focusing high resolution crystal diffractometer DIR1 was constructed (Figure 7.). The main characteristics of this instrument are: a monochromatic beam take-off angle of 83°, a wavelength of 1.3855 Å, a silicon perfect crystal monochromator of 200 mm diameter and 3 mm thickness cut upon the (100) plane, a reflection plane (511), and a cutting angle of $\chi_m=-15.8^{\circ}$. The distances of source-monochromator, monochromator-sample and sample-detector are 5200, 2800 and 1200 mm, respectively. The sample-detector distance can be modified in the range of 1200-3000 mm and the detector window width can be chosen in the range 0-10 mm. The sample positioning can be done by using a step-by-step motor.

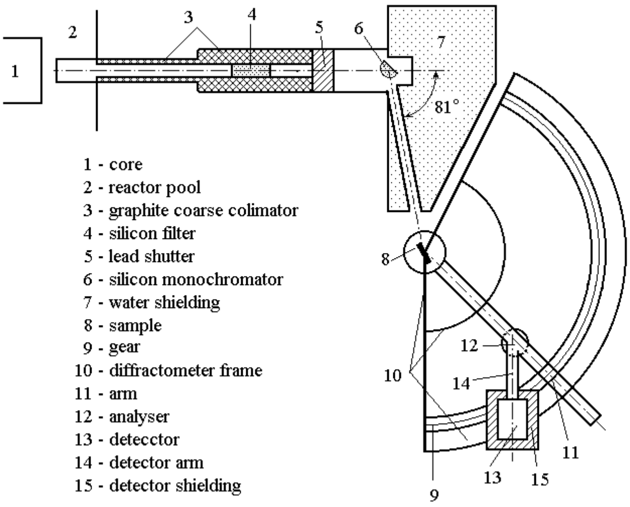


Fig. 7. Layout of neutron diffractometer DIR1.

The high resolution neutron diffractometer is used for structural examinations of polycrystalline samples (including superconductors), stress determinations or hydrogen concentration evaluations by measuring diffraction line integral intensity.

3.2. Small angle neutron scattering (SANS)

At INR Pitesti the performance of the SANS facility is under characterization. The application of SANS at lower power reactors and in developing countries nevertheless is possible in well selected topics where only a restricted Q range is required, that is, when scattering power is expected to be sufficiently high or when the sample size can be increased at the expense of resolution. Examples of this type of applications are: 1) Phase separation and precipitates in material science, 2) Ultra fine grained materials such as nanocrystals and ceramics, 3) Porous materials such as concretes and filter materials, 4) Conformation and entanglements of polymer chains, 5) Aggregates of micelles in micro emulsions, gells and colloids, 6) Radiation damage in steels and alloys. Taking into account that the TRIGA reactor existing at INR Pitesti is a medium flux reactor and that the available dimension for the SANS facility is severely limited by the dimensions of the room where the facility has to be installed, this experimental configuration has been chosen as the most suited for the situation existing in our institute. In Figure 8 the schematic layout of the INR Pitesti SANS facility is presented.

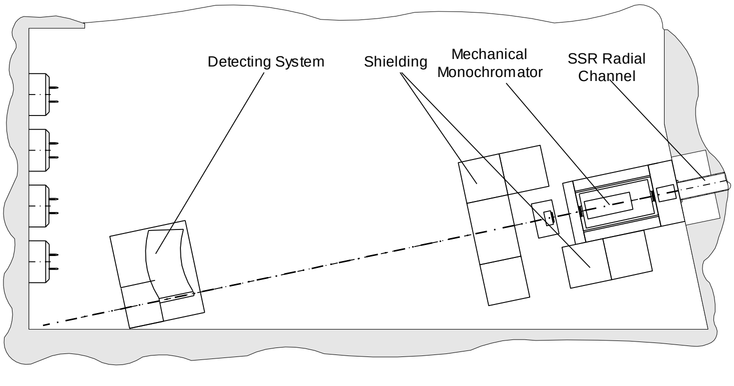


Fig. 8. Layout of SANS facility at TRIGA 14 MW.

4. NEUTRON RADIOGRAPHY

A neutron imaging facility is currently being developed at the INR TRIGA reactor at Pitesti, Romania. Neutron radiography tests performed through the transfer method involving indium and dysprosium foils and radiographic films, as well as thermal neutron flux determinations by neutron activation analysis of indium and gold foils established that an advanced neutron radiography facility would provide numerous new opportunities.

The collimation of the neutrons on the tangential beam port of the ACPR reactor is done, in fact, with a pin hole collimator with an aperture of 45 mm placed at the distance of 125–152.5 cm from the surface of the illuminator, which has a thickness of 7 cm and a diameter of 18 cm. The estimated beam intensity for thermal neutrons with a bismuth filter is 3.96×10^5–$4.65\text{x}10^5\,\text{cm}^{-2}$ and 4.85×10^5–$5.70\times10^5\,\text{cm}^{-2}$ without a Bi filter. The estimated values for gamma debit doses (for the 152.5 cm distance) are: 17.5 mSv/h without and 2.13 mSv/h with a bismuth filter. The estimated n-gamma ratio is $1.03\times10^8\,\text{cm}^{-2}\text{mSv}^{-1}$ and $8.44\times10^8\,\text{cm}^{-2}\text{mSv}^{-1}$, respectively. The divergent angle of the collimator is $3\text{-}3.3^{\circ}$ and the collimation ratio 100-92.8 for the domain of distances 125-152.5 cm between the illuminator and main aperture.

The facility can be used for investigations that involve direct (this can be done also by a sweeping method) and indirect methods in the first stage. After the construction of the detector based on a CCD camera, the facility will be used for dynamic investigations and tomographic reconstructions.

5. RADIOISOTOPE PRODUCTION

The TRIGA 14 MW reactor has been designed also for radioisotope production for medical and industrial use. The design of the reactor core allows simultaneous use of different irradiation channels for isotope production. For short half life radioisotope production the Beryllium reflector vertical irradiation channels are used, for which load and unload operations can be done during normal reactor operation.

For in-core isotope irradiation an aluminum special device was designed and manufactured in INR, as is presented in Figure 9.

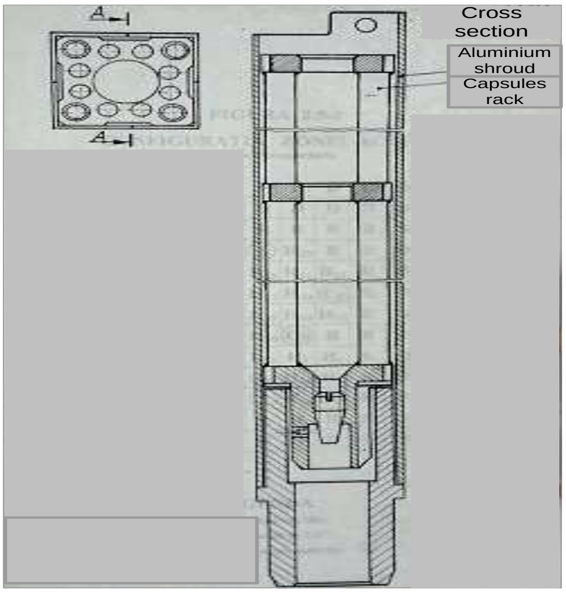


Fig. 9. Radioisotopes irradiation device.

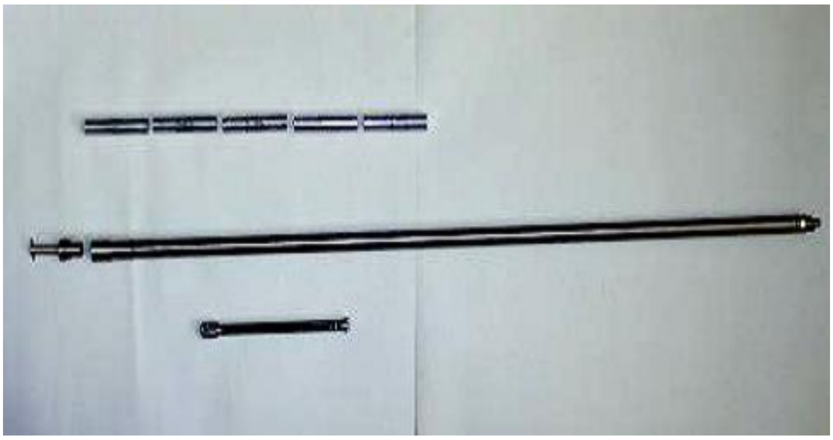


Fig. 10. Pin holder loaded with capsule.

A versatile irradiation system uses the standard TRIGA fuel shroud with grids, which can accommodate up to nine thin-walled reusable Zircaloy irradiation pins (Fig 10). Each pin can receive up to 40 iridium disks in reusable capsules, or various other capsules. Iridium targets are obtained in INR's laboratories.

INR has licenses for ^{192}Ir, ^{60}Co bulk or sealed sources, ^{131}I and ^{125}I production. Now INR is involved in the implementation of CINTECHEM technology for ^{99}Mo-^{99m}Tc radioisotope production by irradiating nickel-coated LEU targets. A new irradiation device has been designed, manufactured and tested. For ^{99}Mo production the high neutron flux XC-1 irradiation channel will be used. Isotope production is accelerated by quick access to the neighbouring hot cells.

6. MATERIAL INVESTIGATION

For nuclear fuel behavior under special irradiation conditions, several irradiation devices are available (capsule, loop etc).

The loop A irradiation device is designed for testing of CANDU nuclear fuel under simulated pressure and temperature conditions. Unlike the CANDU reactor, the cooling agent used in this loop is light water.

TABLE 3. MAIN CHARACTERISTICS OF LOOP A

No.	Main parameters	CANDU channel	Loop A
1	Cooling water	D_2O	H_20
2	Water chemistry (pH)	10.2–10.8	10.2–10.8
3	Temperature:		
	—Input in channel	266°C	<297°C
	—Output from channel	312°C	310°C
4	Pressure:		
	—Input in channel	111 bars	<120 bars
	—Output from channel	102 bars	114 bars
5	Water flow rate	10.4–26.7 kg/s	1.5 kg/s
6	Specific power/fuel pin	450 W/cm	550 W/cm max.

The tests developed in LOOP 'A' are:

- Over power test;
- Power ramp test;
- Power ramp multiple test;
- High burn-up power ramp multiple test.

The Loop ‘A’ device is also used for special nuclear material testing under fast and thermal neutron flux. This device was used for Cernavoda NPP Zr-2.5% Nb pressure tube sample irradiation.

The irradiation devices Capsule C1 and C2 are used for:

- Characterization of fission gases pressure and composition in CANDU nuclear fuel;
- CANDU nuclear fuel fission gases pressure and composition analyzing;
- Dimensional measurements;
- Power ramp;
- Residual cladding deformation determination;
- Central temperature measurement in experimental CANDU fuel rods.

For CANDU nuclear fuel behavior during power cycling, a special irradiation device designed in INR is available. This device allows irradiating the experimental nuclear fuel rod in a power cycle regime by moving the device under flux at constant reactor power.

7. POST IRRADIATION EXAMINATION

A hot cell for post irradiation investigation for microscopy, composition, impurities, mechanical properties, etc., is available.

The Post Irradiation Examination Laboratory (PIEL) is built aside the TRIGA reactor and is connected via an underwater transfer channel with a reactor pool, allowing the transfer of irradiation devices (lower part tubes) conducting experiments in hot cells without casks and without disturbing irradiated materials. This facility allows intermediate and interim examination of samples and the continuation of irradiation of samples, or to perform relocation of samples or. The data obtained from post-irradiation examinations are used on one hand to confirm the integrity, safety and performance of the irradiated fuel and on the other hand for further progress in CANDU fuel development.

The examination cell has seven working stations and allows visual inspection, mechanized measurement, gamma scanning or activity measurement of samples, and also cutting and machining of samples are available in inert atmosphere (i.e. dry nitrogen).

Some new computer-assisted instruments, installed last year, and available for post irradiation examination are listed below:

- Optical Microscopy by a Leica TELATOM 4 Remote Controlled Inverted Widefield Metallographic Microscope;
- Scanning Electron Microscopy by Tescan MIRA II LMU CS High Resolution Schottky Field Emission Variable Pressure Scanning Electron Microscope;
- Testing by an INSTRON 5569 Tensile Testing Machine;
- Gamma scanning and tomography device;
- Eddy current;
- Metallography.

8. REFERENCES

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