# REFERENCE NEUTRON SPECTRA IRRADIATION FACILITIES

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**Abstract.** *The reference neutron spectra irradiation facility represents useful experimental tools for reference measurements, measurement unit preservation, and international intercomparisons. Such experimental facilities have been developed also in the frame of R&D programs of the Institute for Nuclear Research. These are the thermal flux cavity, the ΣΣ reference spectrum system and the TRIGA-ACPR central dry channel. The last one, even if it is not recognized as reference spectrum, it may be used for some experiments, the neutron spectrum being reproducible and having a well characterized neutron field. The paper presents considerations about the reference neutron spectra, a constructive and functional description of the irradiation facilities, and computation and measurement results. At this moment formalities are being made in order to recognize the thermal flux cavity as national standard of the thermal neutron flux density unit.*

**Keywords:** irradiation facility, neutron spectrum, thermal neutron flux

## 1. Introduction

The nuclear energy development required the knowledge about the neutron characteristics of nuclear reactors, both for control and safety purposes, and also for calibrating the apparatus working in neutron fields. Different facilities producing reproducible neutron fields, with different characteristics, have been developed for neutron measurement standardization. The neutron metrology cannot be contrived without standards preserving the neutron flux density unit. This amount shall be consistent with the internationally recognized reference systems.

Different existing experimental facilities that generate neutron fields with different spectral characteristics are reported in the literature. AIEA recommends a set of reference neutron spectra, published in the IRDF 2002[i] library.

The neutron metrology is a R&D activity to create the methodology, infrastructure and legal framework for neutron flux density and derived measures measurements. Standard neutron sources and facilities generating standard neutron fields based on nuclear reactors or accelerators were created. The scope is to cover the energies and intensity ranges useful for calibration and the metrological testing of apparatus working in neutron fields, to improve the measurements precision refining the experimental and computational methods, to preserve the measurement units and to allow it's transmittal to other standards.

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At the TRIGA research reactor from the Institute for Nuclear Research from Pitesti, in the R&D programs framework, two reference neutron spectra irradiation facilities have been developed:

- The thermal neutron reference spectrum
- The ΣΣ-ICN intermediate energy reference neutron spectrum

These irradiation facilities valorize the TRIGA-SSR graphite thermal column neutrons. The TRIGA Reactor thermal column is a rectangular graphite block (1716x1144x710 mm) formed by 98 rectangular graphite cells (12 rows x 8 bricks) in Aluminium cladding placed in the reactor pool, on the North side of the steady state core. The graphite bricks (with adequate positioning end gap) are positioned on a support grid fixed on the bottom of the reactor pool.

A flux distribution flattening lens aimed to improve the axial flux density distribution is placed between the TRIGA-SSR core and the thermal column. The flattening lens active part is the variable thickness water layout created between the core and the graphite irradiation device placed on the TRIGA-SSR core North wall, by introducing a variable thickness graphite plate, aluminium covered.

Similar facilities have been operated at the VVR-S reactor thermal column at NIPN Bucharest. The thermal flux cavity was recognized as secondary standard and as Romanian national standard. Now the VVR-S reactor is shuttled down and will be decommissioned. The ΣΣ system compounds and parts of measurement systems have been transferred to the TRIGA Reactor and used for the above mentioned facilities development.

The TRIGA-ACPR reactor is a pulsed reactor with a compact core having a large central dry irradiation channel. The reactor, dedicated mainly for work in pulse mode, may be used in steady-state mode up to power levels of hundred kW, limited by the natural convection heat removal capacity. No core arrangement modifications are produced during the time, as consequence the neutron spectrum from the central channel due not affected. It is a “hard” spectrum, having a significantly fast neutron compound. Based on a measurement and computational program, it can state that the location of radiations are well characterized and can be used for reference measurements.

## 2. The thermal flux cavity

### 2.1. Functional and constructive description

The thermal flux cavity was accomplished by replacing 36 graphite cells from the central area of the thermal column with a big graphite block having a 50 cm diameter central dry cavity. The graphite block is covered with aluminium and extended with a large, dry tube for access and instrumentation purposes.

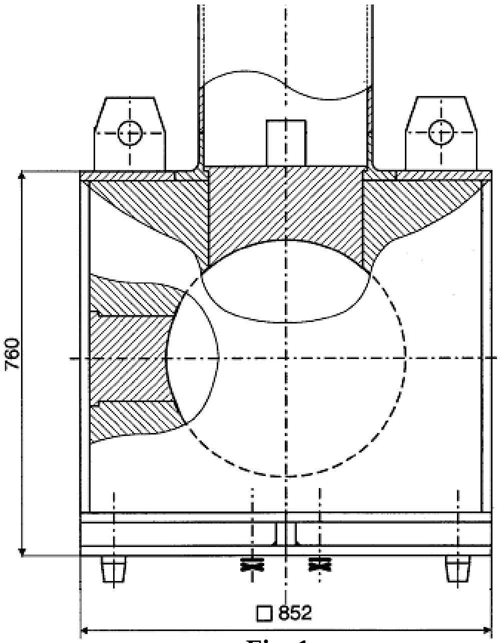


**Fig. 1.**

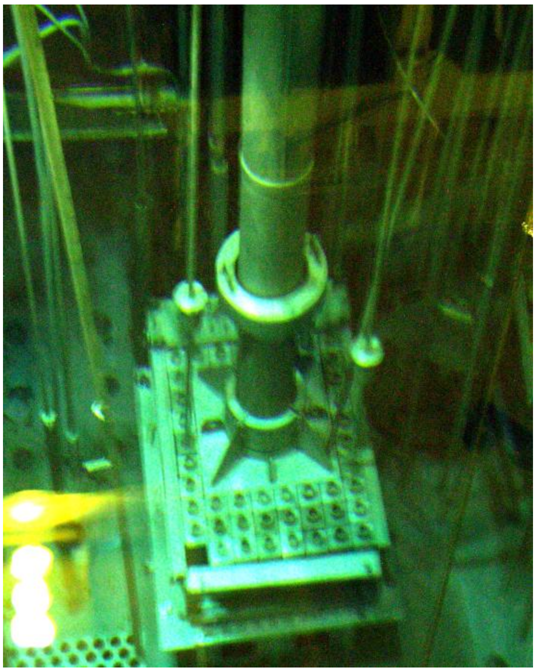

**Fig. 1.**

Figure 1 presents a section through the graphite block and figure 2 presents the image of the thermal column with the new device placed in the central area.

The dry channel allows the 30 cm diameter cavity plug insertion and removal. For instrumentation purposes the large objects can be attached to the plug. For small samples and detectors exposure (e.g. activation foil detectors) the plug penetration can be used. The dry channel supports also the biological shielding. The main shielding is placed in the tube, near to the cavity, and the supplementary shielding covers the end cap of the tube. The shielding is built from borate polyethylene and lead, aiming to absorb the neutrons emerging from the cavity.

There was created a kit of instrumental devices penetrating the cavity plug, that contain: pneumatic systems for foil detectors or small samples exposure, devices for miniature fission chambers exposure and a dry channel for sample exposure up to 3 cm diameter. The plug removal is necessary only in the case of large objects irradiation.

The thermal maxwellian neutron spectrum is produced by the fast neutrons from the TRIGA core slowing-down in graphite block.

## 2.2. The thermal flux cavity neutron field characteristics

The thermal flux cavity neutron field was characterized by computation and measurements in order to determine the neutron flux density and spatial distribution. The absolute measured values of the cavity neutron flux density are reported to the local monitoring system indications. The local monitoring system is formed by two fission chambers placed in the thermal column, near to the cavity. They cover the range of the reactor power, starting with a few kilowatts up to the nominal power of 14 $MW_{th}$.

The MCNP Monte Carlo radiation transport code has been used for computation. The code allows close modeling of three dimensional geometries. The optimal position of the cavity in the thermal column has been established using MCNP computation. The cavity, initially placed in the central position of the thermal column, has been shifted one row more to the end of the column to obtain the optimal compromise between the three criteria: the neutron flux density, the weight of the thermal neutrons, and the flux density spatial distribution.

Figure 3 shows the cavity and monitors positions in the thermal column.

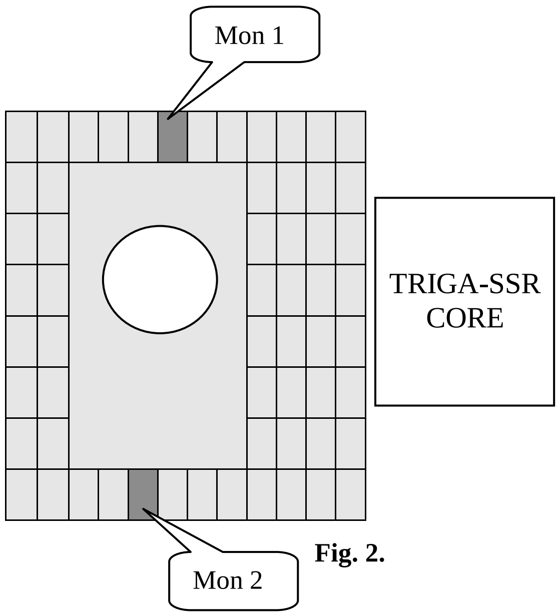


**Fig. 2.**

The neutron spectrum shape and the flux density's spatial distributions have been obtained through computation. In completion, the measurements of absolute reaction rates allowed the spectral shape adjustment, using unfolding procedures. The absolute values have been reported to the monitoring system records. The flux density spatial distributions have been also measured using activation wires[ii].

The main characteristics of the neutron field inside the thermal flux cavity are:

- Neutron temperature (37 ± 4) $^{o}C$
- Cadmium ratio for $^{197}Au(n,\gamma)$ reaction 52.1 ± 3%
- Neutron flux densities reported to the local monitoring system records ($S_U$ count rate):

    - $\Phi/MON_1$ $(6.48\pm0.32)\times10^8$ neutrons/$m^2\cdot s\cdot$cps
    - $\Phi/MON_2$ $(9.14\pm0.46)\times10^{10}$ neutrons/$m^2\cdot s\cdot$cps
- Thermal neutrons weight (E<0.135 eV) = (95.2±1)%
- The measured gamma dose rate reported to the monitor 2 SU count rate is 0.27 Gy/h/cps.

The global flux density range covered by the monitoring system is

$$2\cdot10^{10} - 5\cdot10^{14} \text{ neutrons/m}^2\cdot\text{s}.$$

At the low limit establishment a count rate of 30 cps has been imposed in order to obtain acceptable statistic. In the same time, the reactor operation at power levels bellows 100 W in stable conditions is delicate.

The neutron flux density and the neutron spectrum in the thermal flux cavity have been obtained by using the unfolding techniques. The SAND II[iii] unfolding code coupled with the IRDF-90[iv] dosimetry file were used. As guess spectrum (first iteration) we have used the MCNP[v] computation results, as well a spectrum generated by using measured integral data (cadmium ratio for gold reaction). The final results due not differ significantly. Figure 4 shows the solution spectrum obtained by the measured unfolding reaction rates. The activation rates have been measured using activation foils, while the fission rates have been measured by using absolute calibrated fission chambers.

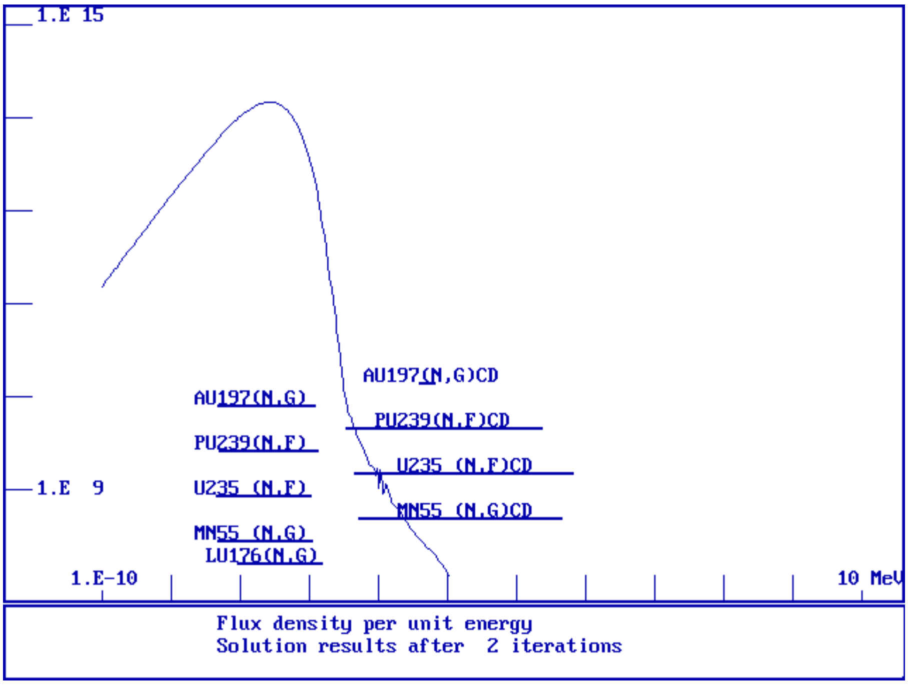


**Fig. 3.**

The thermal flux density distribution was obtained by computation as well by measurement using Mn activation wire. The comparison of the computed and measured distributions shows a very high fitness.

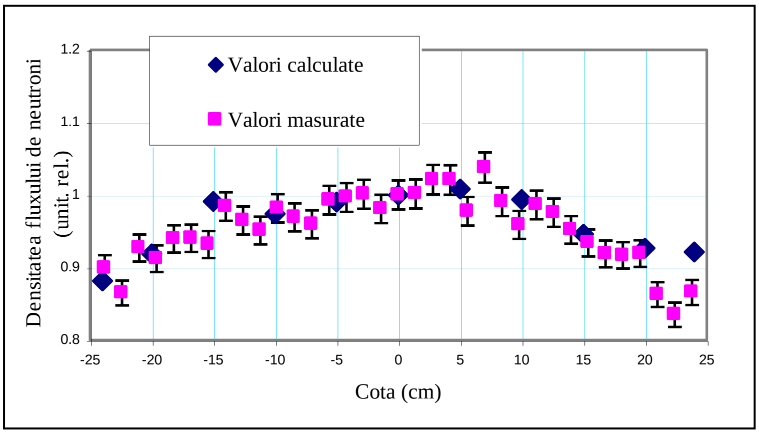


**Fig. 5.**

Figure 5 prove this fitness for the vertical axis (*Oz*). Discrepancies may be observed only at the top end, due to the presence of the plug penetration (not considered for the computational model).

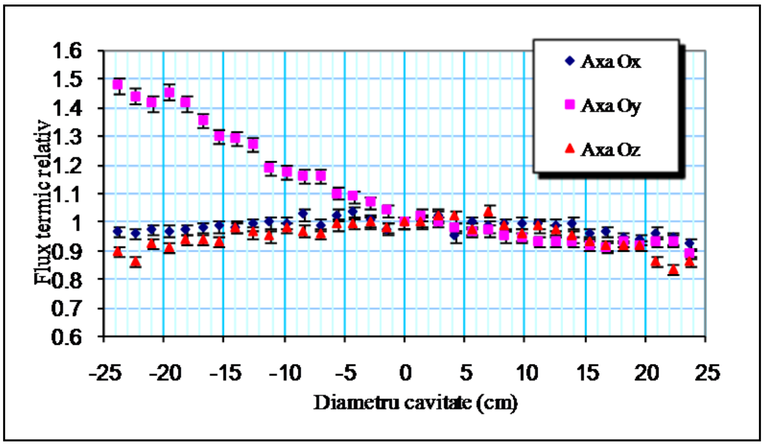


**Fig. 6.**

Figure 6 shows the measured distributions on the three axes (vertical, horizontal and transversal). It can be noticed that the longitudinal distribution (*Oy* axis) follows the thermal column gradient, with the observation that while on the first half diameter the flux density decreases with 32%, on the second half the flux gradient is reduced to 10%. The flux density distribution due not show an exponential form, seeming to be closer to a polynomial form. The transverse flux distribution (*Ox* axis) shows a good uniformity. The vertical distribution presents the same tendencies as the *Ox* axis, with the observation that an important decrease of the flux density is observed on the upper end, on the last

3-4 centimeters. This is produced by the presence of the cavity plug penetration. However, the vertical distribution flattening shows the efficiency of the flattening lens placed between the core and thermal column. The irradiation facility has been used for Cernavodă NPP Unit 2 special instrumentation functional testing[vi].

Actions are in progress to recognize the facility as national standard for the thermal neutron flux density measurement unit. According to the legislative framework, beside administrative and formal arrangements, it will be necessary to demonstrate the traceability to similar facilities internationally recognized.

## 3. The ΣΣ intermediate energy reference neutron spectrum system

The intermediate energy reference neutron spectrum concept, a fast thermal coupled assembly placed into a conventional thermal column, has been promoted by SCK/CEN Mol since 1967[vii]. It is a spherical natural uranium shell, with a 24.5 cm outer diameter x 5 cm thick, centered in a 50 cm diameter spherical cavity in graphite. It contains also a 1.5 cm thick Aluminium-clad spherical shell of vibrocompacted natural boron carbide, which in turn surrounds the central intermediate-energy exposure hole, that has 11 cm in diameter. The natural uranium shell acts as a thermal-fast converter; the bulk of the fission neutrons created within the first outer centimeter of this source undergoes appreciable energy degradation through scattering collisions in the system components (uranium shell and graphite). The boron carbide shell cuts off the neutron low-energy tail. The resulting neutron spectrum is similar to the fast reactors typical neutron spectra.

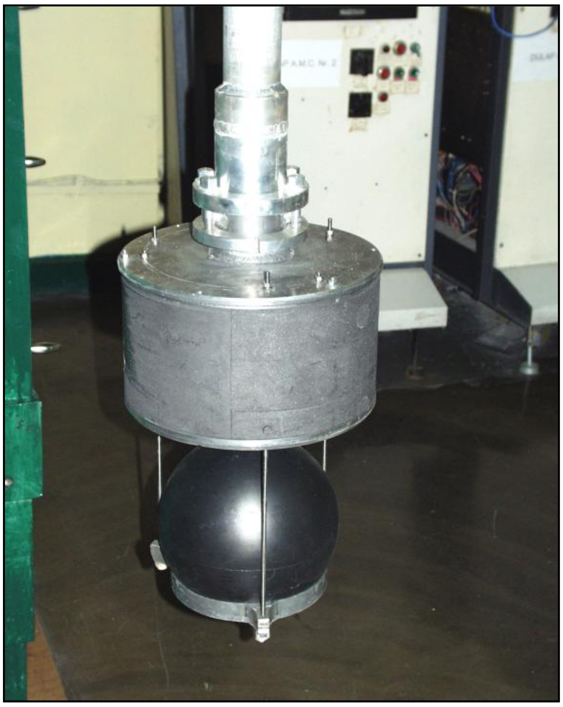

**Fig. 7.**

The ΣΣ system implementation on the TRIGA thermal column has been performed by coupling the uranium shell to the cavity graphite plug, as presented in figure 7. The assembly is introduced in the cavity through the dry channel, followed by the biological shielding. The system due not allows to be inserted with the reactor in operation.

The neutron characterization of the facility has been done in similar way to the one used in thermal flux cavity, by using computation and measurements.

Activation and fission rates absolute measurements have been performed, using foil detectors and calibrated fission chambers[viii]. For the MCNP computations the same model was used completed with the uranium shell and boron carbide shell placed in the cavity. The computed spectrum has been used as guess spectrum for the unfolding procedure. The solution spectrum, obtained by unfolding, is presented in figure 8.

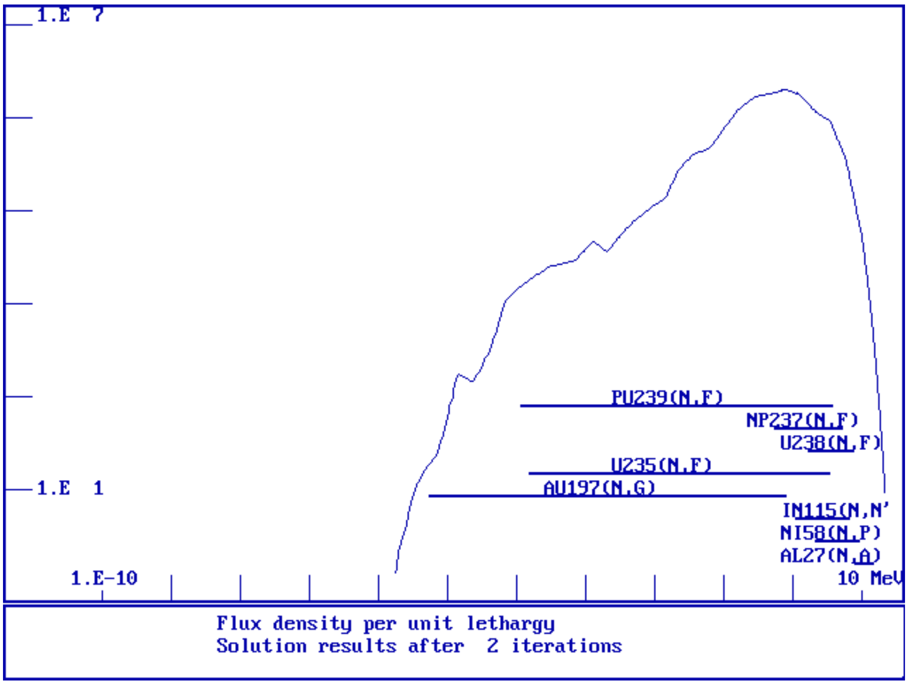


**Fig. 8.**

The ΣΣ system neutron field characteristics are:

- Spectrum mean energy: 0.865 MeV
- The neutron flux density reported to the monitor 2 signal (SU count rate): $\Phi/MON_2=(5.70\pm0.27)\times10^{10} n/m^2\cdot s\cdot cps$
- The available neutron flux densities ranges between
  $1.4\times10^{10} - 3.5\times10^{14}$ $n/m^2\cdot s$.

The neutron spectrum in the ΣΣ system placed in the TRIGA thermal column from INR is harder than the recommended ΣΣ spectrum, with a higher weight of the high energy neutrons, due to the reduced dimensions of our thermal column.

The spatial distribution of the neutron flux density inside the cavity created by the boron carbure shell was measured using Ni activation wires. The Ni wires have been placed on three perpendicular directions, sampled and measured for induced gamma activities after exposure. The measured flux density distributions are presented in Figure 9.

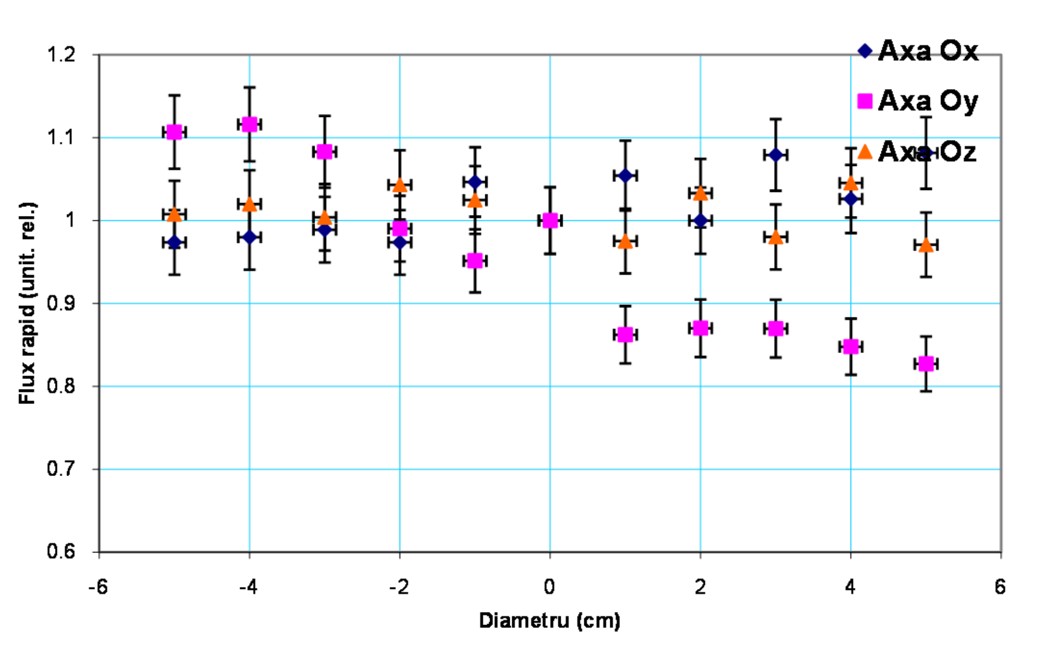


**Fig. 9.**

The flux density distribution on the longitudinal axis (*Oy*) shows a gradient, determined by the cavity and the thermal column flux density gradient. On the other two axes (vertical and transverse) the flux density distributions are almost flat.

As presented above, there are some discrepancies between the recommended ΣΣ spectrum and the neutron spectrum from the ΣΣ system placed in the Romanian TRIGA-SSR thermal column. There are no major discrepancies in the spectral shape, and as long as it is know and justified, the reference character of the irradiation facility is not affected.

## 4. Neutron field characterizations in the ACPR Reactor central channel

The main experimental facility of the TRIGA-ACPR pulsed reactor is the 9" diameter dry channel, which occupies the central part of the core. In this large, dry cavity, experiments can be exposed to a fast neutron fluency of $10^{15}$ n/cm$^2$ in a single pulse, or to a fast neutron flux on the order of $10^{12}$ n/cm$^2$·s in steady-state operation. The reactor is capable of continuous steady-state operation at power levels up to 500 kW, limited by heat removal through natural convection. The central channel may be accessed via the off-set tube, without biological shielding removal. The usual operation of the ACPR core dose not involves core modifications as function of experiments, like in the case of the SSR stationary reactor. For this reason the neutron energies distribution (spectrum) does not suffer modifications in time, being also reproducible. It is the reason for which this irradiation facility has been chosen for reference measurements and for neutron absorber screens qualification. This project is in progress in the frame of the European FP 6. A consistent neutron field characterization was required for this purpose, based on computation and measurements as well as by the thermal column irradiation facilities presented above.

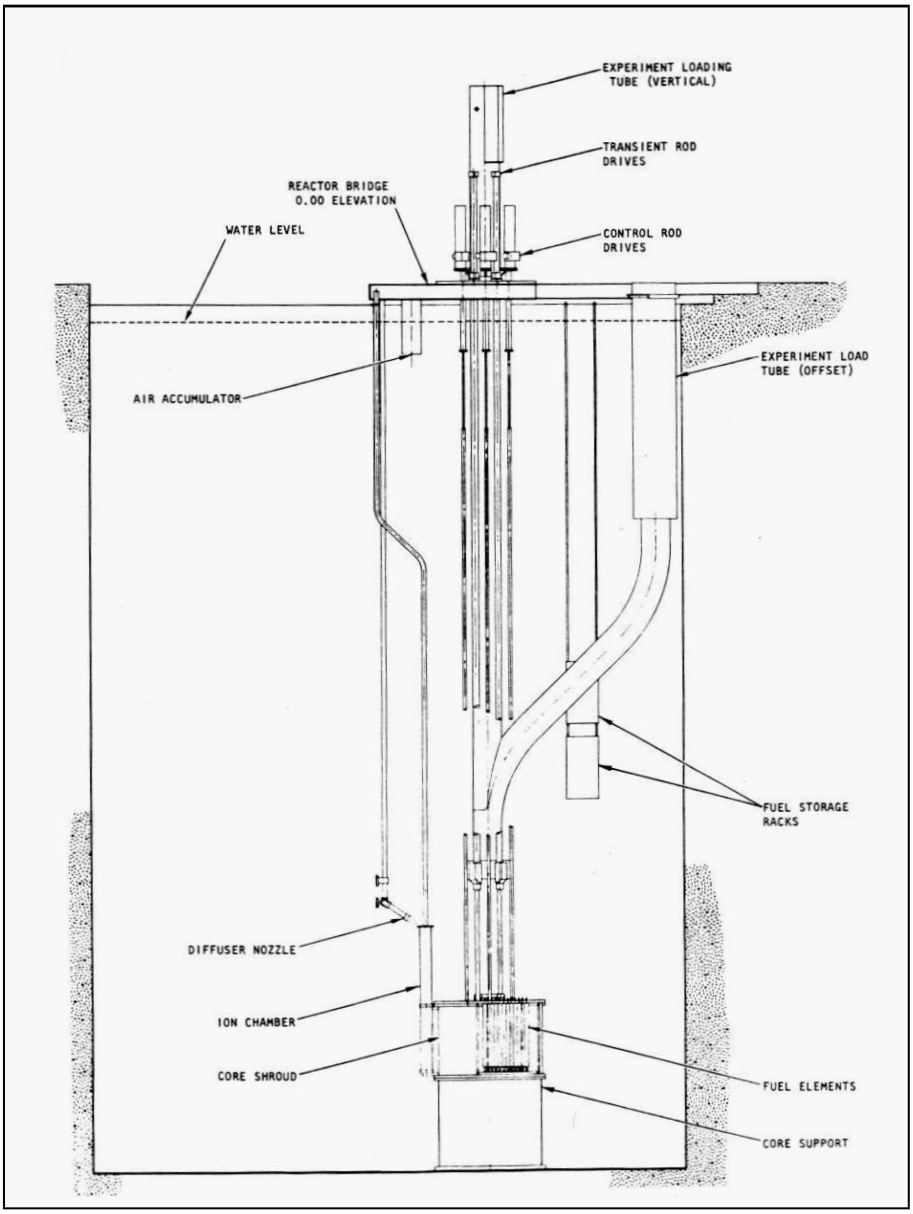


**Fig. 10.**

Figure 10 presents the assembly of the ACPR core with the dry central channel and off-set tube.

For MCNP computation the complete core model was implemented. Neutron energy distribution and axial distributions of the fast and thermal flux densities have been computed.

The computation have been validated and completed with activation measurements (foils and wires) aimed to absolute flux and spectrum determination, using unfolding procedures and axial distribution flux densities measurements.

**Fig. 11.**

For the activation detectors exposure the aluminium detector holder presented in Figure 11 was used. This holder dose not perturbs the neutron field and can be introduced in the central channel via a lateral off-set channel. For irradiation monitoring a Silver SPND (Self Powered Neutron Detector) has been placed at the core margin, as near as possible, in the first free positions from the core grid.

The monitor signal records (current measured during the detectors exposure) have been used for irradiation normalization and stored as reference values for future studies. Practically, like in the case of the thermal column reference facilities, the neutron flux density is reported to the local monitor records, the reactor power indicated on the console being affected by other parameters.

The solution spectrum obtained by measured reaction rates unfolding is presented in Figure 12. The solution is obtained after 6 iterations, with a standard deviation of the measured reaction rates from the computed reaction rates less than 4%, and with a very small spectrum adjustment produced by unfolding. The small magnitude of the spectrum adjustment validates the computations validity.

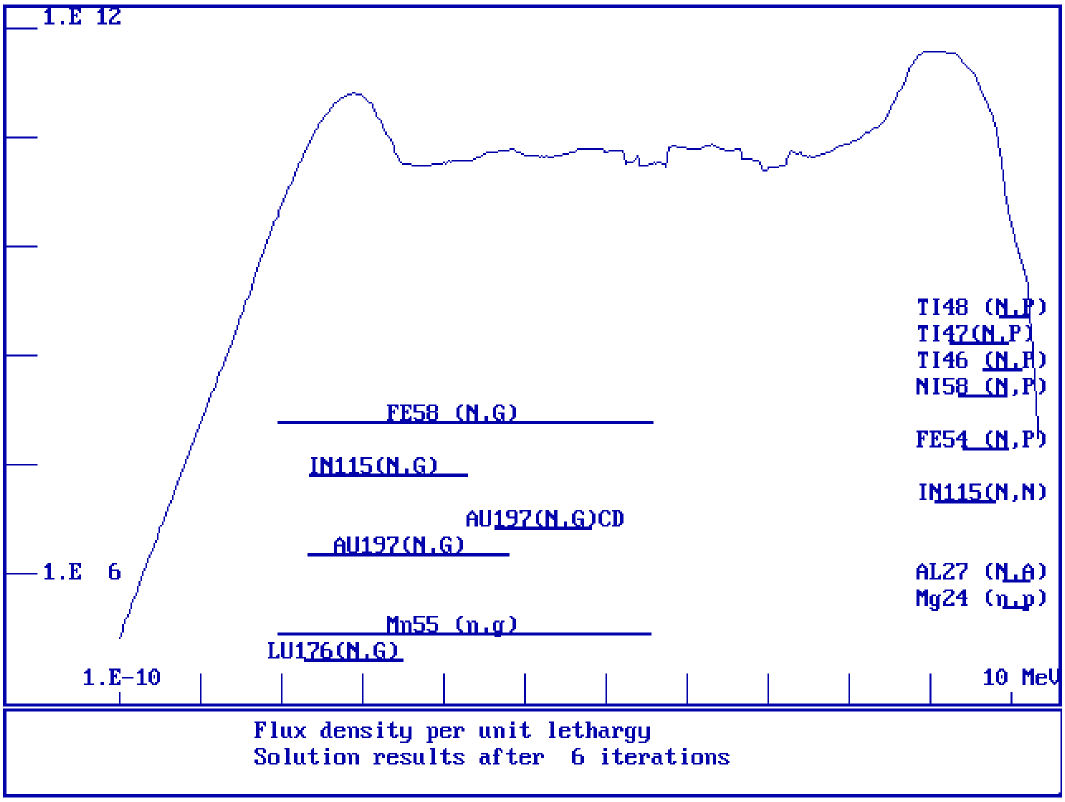


**Fig. 12.**

The $k_{eff}$ value obtained by using the real configuration ($k_{eff} \approx 1$) for the control rods confirms also the modeling validity, reproducing exactly the real geometry and material composition.

It is a hard spectrum, the high energy neutrons ($E$ > 1MeV) having a weight of 27%. The measured value of the neutron flux density is 2.4 $10^{12}$ n/cm$^2$·s corresponding to a monitor current of 4.398 nA, namely 5.46 $10^{11}$ n/cm$^2$·s/nA. The measurement has been performed at 100 kW reactor operating power.

Figures 13 and 14 shows the computed and measured thermal and fast neutron flux densities axial distributions. The measured data fits well the computation results.

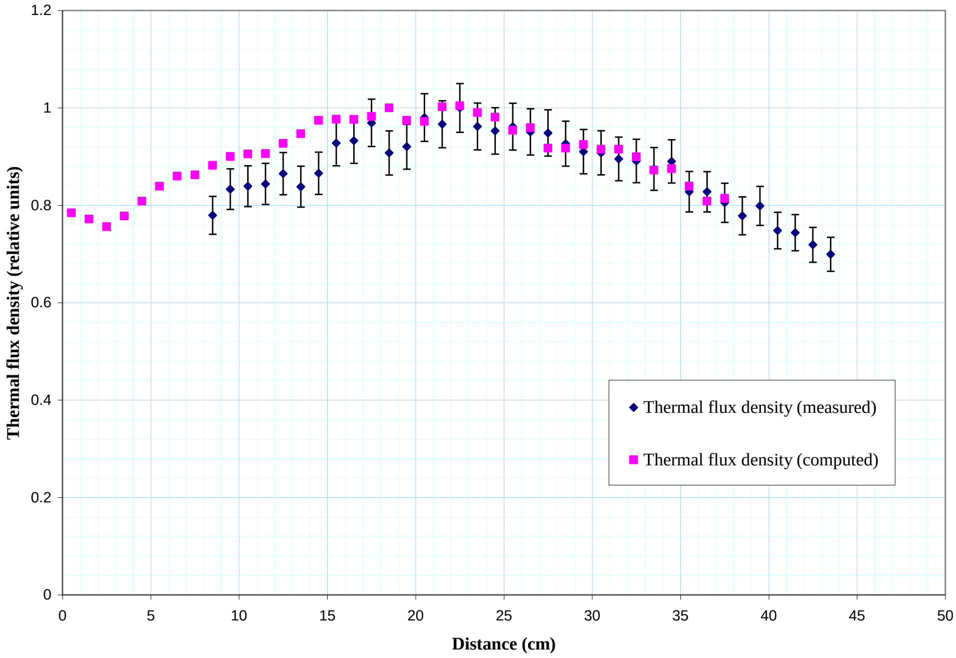


**Fig. 13.**

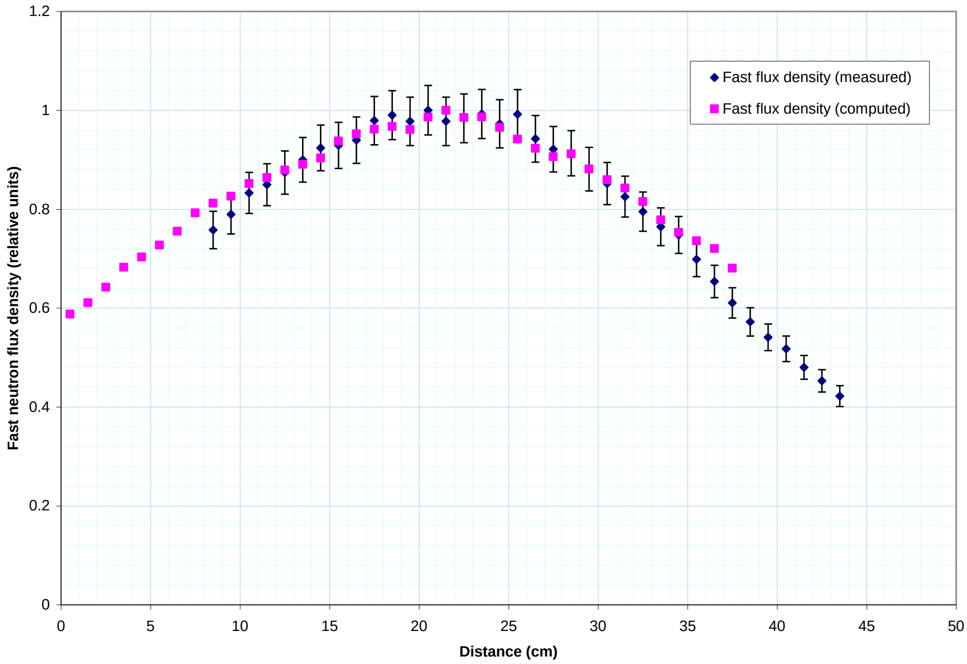


**Fig. 14**

Figure 15 shows the distribution of measured thermal and fast neutron flux densities absolute values. A specific particularity of the ACPR core can be observed: the thermal and fast flux densities distributions are not similar. In other words, the thermal and fast flux density's ratio shows significant changes along the central channel axis. This specific property of the experimental channel may be useful for applications which need a specific neutron spectrum.

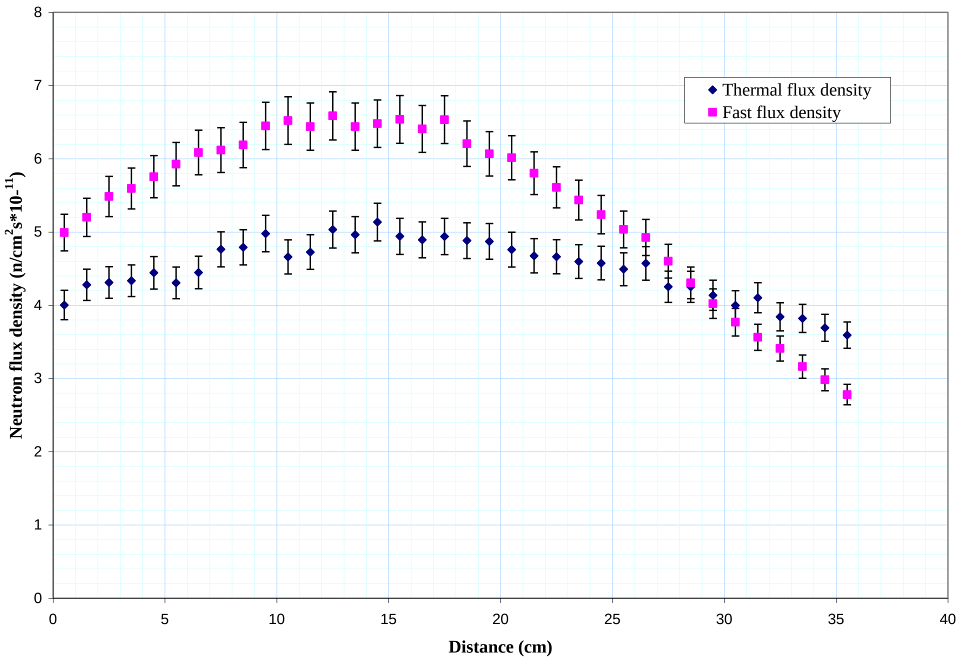


**Fig. 15.**

The knowledge of this distribution allows, with certain limits, choosing the position which offers the desired neutron spectrum (for low volume experiments). The use of moderator and/or neutron absorber shielding offers another possibility to modify the spectrum shape in order to satisfy certain requirements.

## Conclusions

The neutron reference spectra irradiation facilities development requires, beside the effective execution of the experimental arrangements, a high computational and experimental effort. This is necessary to certify that the neutron field characteristics are well know, with an acceptable uncertainty, to certifies that these parameters are well controlled and can be reproduced. A major requirement, warranty of reproducibility, represents the reporting of the interest values (neutron flux densities) to the local monitoring system (with sensors placed as near possible to the irradiation enclosure). The linearity of the thermal column monitoring system response has been checked. Figure 16 shows the linearity of monitor 2, checked by reporting to a fission chamber signal which has been placed into the thermal flux cavity.

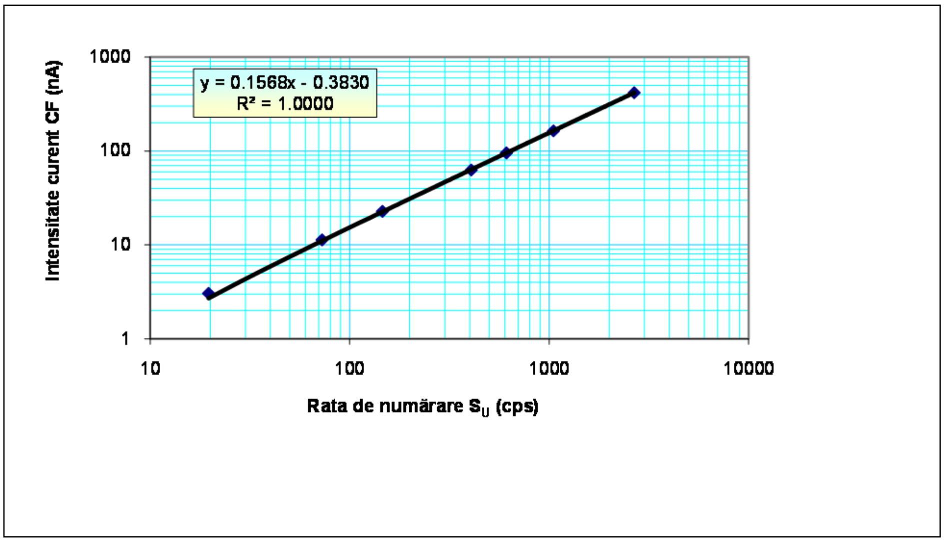


**Fig. 16**

The high quality of the linear regression confirms the monitor response linearity.

The computation and measurement results, the intercomparisons carried out, show that the neutron parameters related to the reference irradiation facilities are well known and controlled.

The formalities to recognize the thermal flux cavity as thermal flux density unit for National Standard are now in progress. This status will allow performing metrological testing of the apparatus measuring neutron flux densities and associated physical quantities (fluency, dose, dose rate). The main requirements are related to the traceability demonstration, as required by the Mutual Recognition Arrangement.

During the irradiation facilities development the traceability to similar systems developed at SCK/CEN Mol (Belgium) has been documented, but now these are not included in the MRA Annexes. As consequence, new intercomparisons are required and we decided to concentrate our efforts on the thermal flux cavity recognition. The ΣΣ facility dose not has similar facilities between the metrologicaly recognized ones, even the neutron spectrum being included in the IAEA recommendations.

Based on the above presented neutron characterization, the ACPR central dry channel will be used in the near future for neutron absorber screen qualification. This work is done in the frame of MTR+I$^3$ project founded by the Euratom FP6.

Also the large irradiation cavity will be used for Large Sample Neutron Activation Analysis developments (experimental devices and methodology) in the frame of the dedicated IAEA Coordinated Research Project.

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