Characterization of a Neutron Collimator for Neutron Radiography Applications.

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Abstract. At the ENEA TRIGA research reactor (Casaccia Research Center, Rome), a new neutron collimator has been designed and installed at the neutron tangential channel. This collimator, that is part of a neutron/X-ray facility for NDT analysis, was experimentally characterized and optimized in terms of thermal neutron flux, its spatial/energetic distribution, photon air KERMA and effective beam diameter. This paper shows the methodologies and the results of the experimental analysis that was carried out.

TRIGA RC-1 DESCRIPTION

The TRIGA Mark II nuclear reactor, named "RC-1" as Reactor Casaccia 1, was build in the early sixties from General Atomics, with original power of 100 kW, increased by the ENEA staff to 1 MW in 1967.

It is a pool thermal reactor having a core contained in an aluminium vessel and placed inside a cylindrical graphite reflector, bounded with lead shielding. The biological shield is provided by concrete having mean thickness of 2.2 m. Demineralized water, filling the vessel, ensures the functions of neutron moderator, cooling mean and first biological shield.

Reactor control is ensured by four rods: two shims and one safety fuelled follower rods, and one regulation rod.

Produced thermal power is removed by natural water circulation trough a suitable thermohydraulic loop comprehending heat exchangers and cooling towers. In Tab. 1 are listed some irradiation facilities.

Table 1.

Description	Neutron flux [n. cm-2 . s-1]
Rotating rack (40 positions)	$2.0\cdot10^{12}$
Pneumatic transfer system	$1.25\cdot10^{13}$
Central channel	$2.68\cdot10^{13}$
Thermal column collimator	$\sim1.0\cdot10^{6}$
Tangential piercing channel (w/o) collimator	$\sim1.0\cdot10^{8}$

The reactor and the experimental facilities are surrounded by a concrete shield structure. The core and the reflector assemblies are located at the bottom of an aluminium tank (190.5 cm diameter). The overall height of the tank is about 7 m, therefore the core is shielded by about 6 m of water. The core, surrounded by the graphite reflector, consists of a lattice of fuel elements, graphite dummy elements, control and regulation rods. There are 127 channels divided in seven concentric rings (from 1 to 36 channels per ring). The channels are loaded with fuel rods, graphite dummies and regulation and control rods depending on the power level required. One channel houses the start-up Am-Be source, while two fixed channels (the central one and a peripheral) are available for irradiation or experiments.

A pneumatic transfer system allows fast transfer from the peripheral irradiation channel and the radiochemistry end station.

The diameter of the core is about 56.5 cm while the height is 72 cm. Neutron reflection is provided by graphite contained in an aluminium container which is surrounded by 5 cm of lead acting as a thermal shield. The core components are contained within a top and bottom aluminium grid plates: the top grid has 126 holes for fuel elements and control rods and a central thimble for high flux irradiations. The reactor core is cooled by natural convention of the water in the reactor pool.

The fuel elements consist of a stainless steel clad (AISI-304, 0.05 cm thick, 7.5 g/cm^3 density) characterized by an external diameter of 3.73 cm and a total height of 72 cm end cap included. The fuel is a cylinder (38.1 cm high, 3.63 cm in diameter, 5.8 g/cm3 of density) of a ternary alloy uranium-zirconium-hydrogen (H-to-Zr atom ratio is 1.7 to 1; the uranium, enriched to 20% in 235U, makes up 8.5% of the mixture by weight: the total uranium content of a rod is 190.4 g, of which 37.7 g is fissile) with a metallic zirconium rod inside (38.1 cm high, 0.5 cm in diameter, 6.49 g/cm3 of density). There are two graphite cylinders (8.7 cm high, 3.63 cm in diameter, 2.25 g/cm^3 of density) at the top and bottom of the fuel rod. Externally two end-fittings are present in order to allow the remote movements and the correct locking to the grid.

The regulation rod has the same morphological aspect as the fuel rod: the only difference is that instead of the mixture of the ternary alloy Uranium-Zirconium-Hydrogen there is the absorber (graphite with powdered boron carbide). The control and safety rods are "fuel followed": the geometry is similar to that of the regulation rod with but in its bottom there is fuel element. The graphite dummies are similar to a fuel element but the cladding is filled with graphite. Fig.1 shows an horizontal section of the reactor.

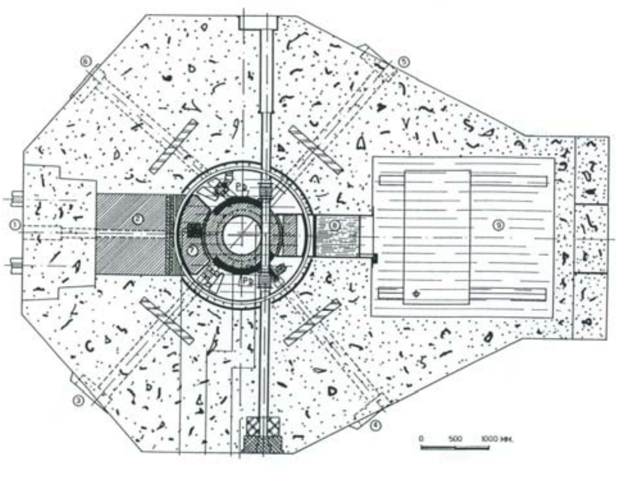

FIG. 1.

The reactor is mainly utilized for training, radiochemistry and NDT activities. With neutron activation and radiochemical treatments, several short lived radiopharmaceutical are produced. In recent times processes for beta-emitters production (90Y, 166Ho) are patented based on radioisotope link to solid bio-absorbable particles. Their promising pre-clinical trials are running for brain tumors therapy.

A small home made neutron tomography system is operating at the thermal column. The facility is based on a neutron collimator with a measured L/D ratio of 44, a circular aperture of 4 cm as diameter, a neutron flux of 5•106 n cm-2 s-1 with Cd ratio of about 3. A cooled CCD (192x165 pixels) and an intensifier for light from a NE426® scintillator with traditional optical coupling ensure the imaging with a typical acquisition time of about 5 s/frame. A complete set of 200 tomographic projections is acquired in about 1000 seconds.

The limitation in diameter allows to examine small objects. To encompass this limitation, the new facility at TP2 tangential channel is going to put in operation: its effective diameter of about 18 cm and a new CCD system will improve radiography and tomography capabilities.

NEUTRON COLLIMATOR ON TANGENTIAL CHANNEL

The neutron collimator placed in the tangential channel is represented in Fig.2. It consists in an anticorodal pipe with two different diameters (to reduce streaming), closed at both ends and filled with

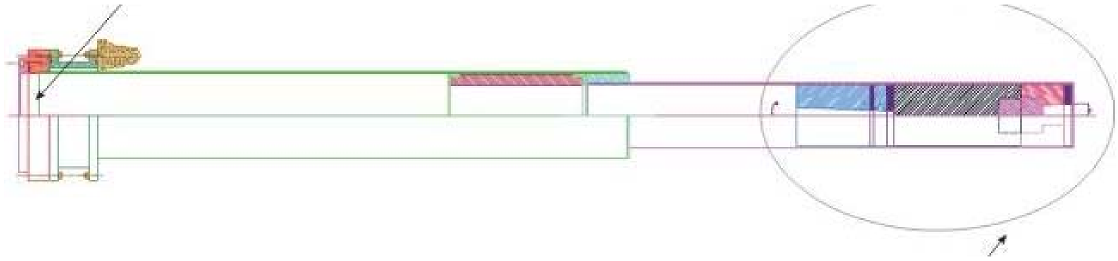

FIG. 2.

air or nitrogen.

At the inner end (near the reactor core) there is an active multi-material filter that contribute to form the shape and the characterization of the neutron beam.

The filter is shown in Fig. 3. It is constituted by a sandwich of various materials:

- Lead : to reduce gamma-radiation;
- Borated Polyethilene : to absorb (eliminate) neutrons with trajectory external to the beam shape;
- Iron : to reduce secondary-gamma radiation due to boron neutron capture;
- Polyethilene : to thermalize neutrons.

The red part of the filter was alternatively filled with Graphite or Bismuth in order to evaluate if some of these materials could improve the performances of the collimator : Bismuth to absorb gamma-radiation and Graphite to thermalize more neutrons.

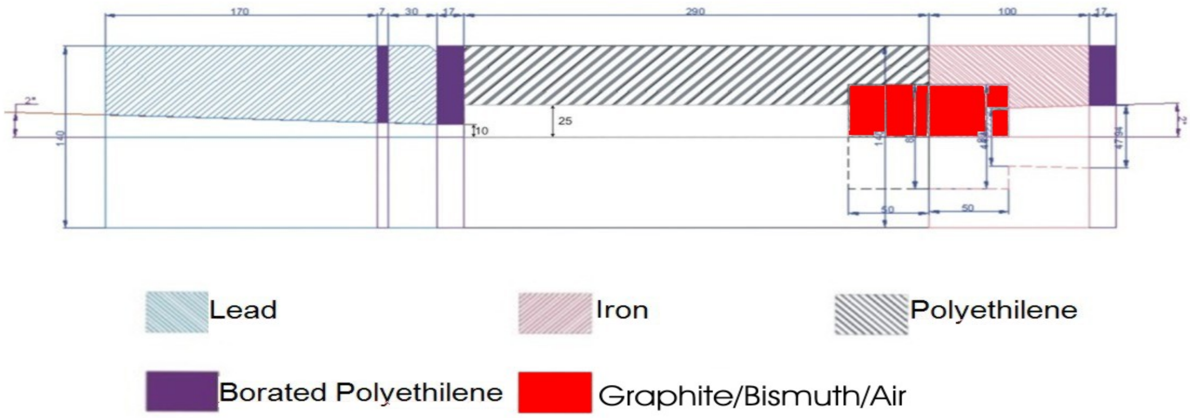

FIG. 3.

OPTIMIZATION PROCEDURES

The optimization of the collimator was carried out taking into account three main characterization parameters: the Cadmium Ratio, the gamma background and the L/D Ratio.

The activation analysis, by means of some gold foils placed in strategical positions, was used in order to determine the spatial and energetical distribution of the neutron flux and the value of the Cadmium Ratio. To do that, two different exposure of gold were made: with and w/o cadmium capsules.

The Cadium Ratio allows the evaluation of the “level of thermalization” of a neutron beam. In particular the Cadium Ratio is defined as:

$$RCD = \frac{\varphi_{th} + \varphi_{epi-fast}}{\varphi_{epi-fast}}$$

Where φ_{th} represents the thermal flux and $\varphi_{epi\text{-}fast}$ the flux in epithermal/fast zone.

The gamma flux was evalued using some TLD devices that were applicated at the external face of the collimator. In the case of our facility, as the neutron channel is located in tangential position with respect the reactor core, the gamma flux is lower than in the case of a radial channel (a value of the gamma ratio n/gamma > 10^5 is considered a good value). In any case we performed a tentative of reduction by means the positioning of a Bismuth Filter.

Fig. 4 shows the TLD and Gold Foils experimental layout in corrispondence of the external wall of the collimator.

FIG. 4.

The quality of a neutron radiography depends on many factors in particular: the length of the collimator L, the collimator inlet diameter D and the L/D ratio, represents some fundamental parameters useful to define the geometrical characteristics of the beam (attenuation, divergence), and the effects connected to focusing of the radiographic image.

The Kobayashi method allows to determine the L/D ratio by measuring the intensity of the neutrons transmitted across an appropriate cadmium plate (Kobayashi plate) and impressed over an imaging device (in our case we used an imaging plate). The layout of the equipmet used is represented in Fig. 5.

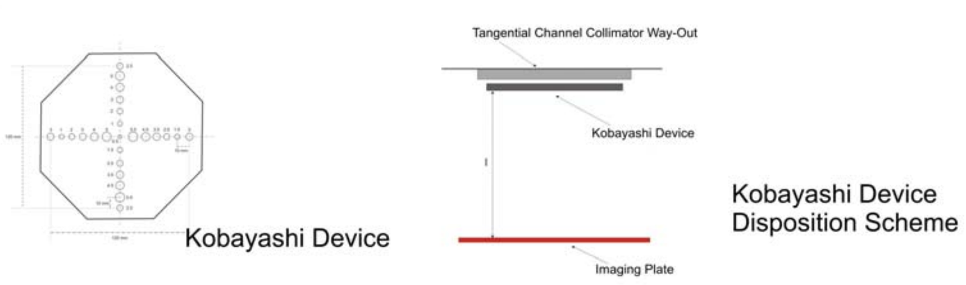

FIG. 5.

The experimental characterization of the collimator was carried out either by measuring the values of the parameters in the collimator “as it is” (totally filled by air) either evaluating an optimization using some “filters” located in an appropriate zone of the collimator (red zone in fig. 3).

RESULTS

The final results of the analysis can be summarized by the following figures 6,7 and 8.

In Fig. 6 is represented the radial trend of the thermal flux at the outer surface of the collimator in the 3 different adopted configuration. The most important thing that can be noticed is that radial distribution of the flux is not to much uniform (in every case) and can be improved. Otherwise we have to stress that the diameter of the beam is quite large and the result obtained can be considered good. Both the filters (Bismuth and Graphite) reduce the value of the thermal neutron flux.

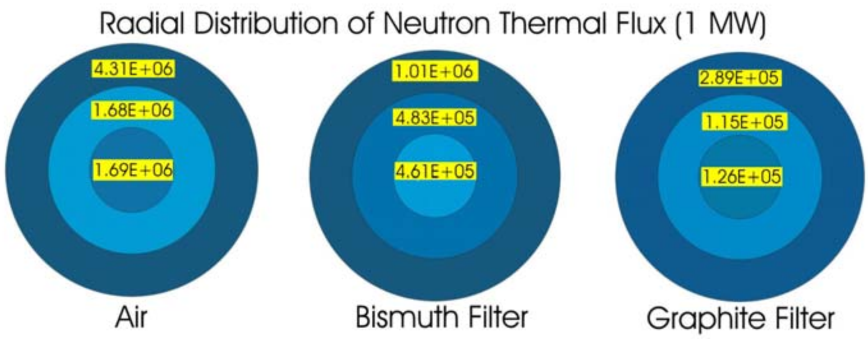

FIG. 6.

In Fig. 7, that shows the Cadmium Ratio, we can see that the graphite has a great effect in order to increase the CR. In any case, as shown in the previous figure, the absolute value of the thermal flux decreases.

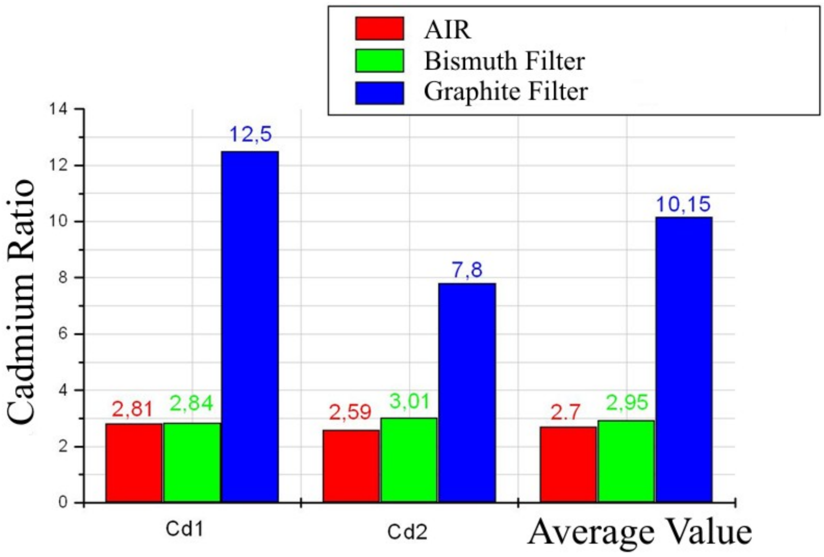

FIG. 7.

Fig. 8 below shows the profiles obtained by exposure of Kobayashi device and useful to calculate the Critical Diameter dc.

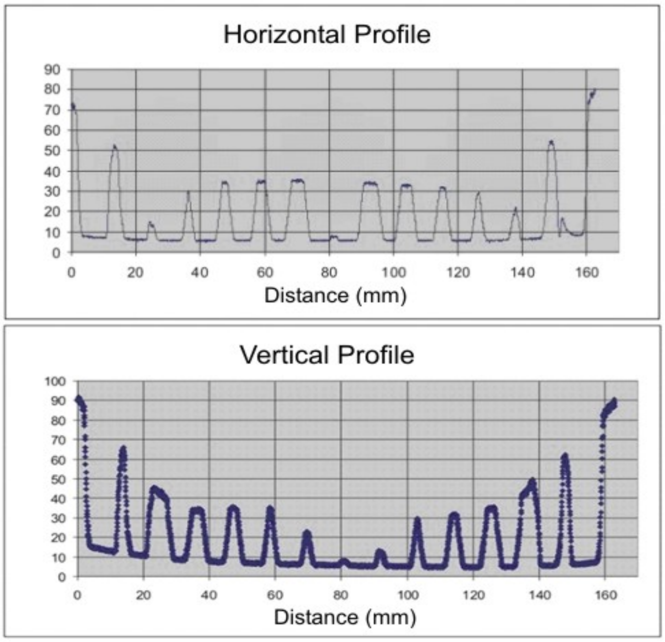

FIG. 8.

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The Critical Diameter allows, using the Kobayashi method, the calculation of the L/D ratio.

$$\frac{L}{D} = \frac{l}{dc} = \frac{220}{2.044} = 107.6$$

This ratio (see also fig.9) is useful to evaluate the unsharpnes of the neutron beam.

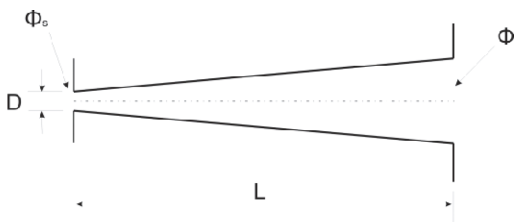

FIG.9.

The unsharpness U_g , in facts, is calculated by means of:

$$U_g = \frac{t}{(\frac{L}{D})}$$

Where t is the distance of the object from the imaging plane. Using this equation, and considering that the distance from the object till the imaging device plan could be

$$t = 150 \text{ mm}$$

we have that the unsharpness of the neutron beam is:

$$U_g = 0.14 \text{ mm}$$

it means that we could be able to discriminate, with our facility, geometrical details whose dimensions are greather than 0.14 mm.

CONCLUSION

The final results of the characterization and optimization of the neutron collimator installed at the Triga RC-1 tangential channel are summarized below:

Neutron Flux	=	$2.7 \bullet 10^6$ n cm^{-2} s^{-1}
CD Ratio	=	2.7
L/D	=	108
Gamma Background	=	2.5 mGy/h
Neutron/gamma	=	$8.3 \bullet 10^{-5}$ n cm^{-2} μSv^{-1}
Beam Aperture	=	2.8
Unsharpness @ 150 mm	=	0.14 mm
Beam Diameter	=	180 mm

These values show that the new channel constitute a great improvement with respect the previous Triga neutron facility installed at the thermal column and encourage to go on in the optimization and completation of the facility. Next step will be the design and optimization of the beam shutter and neutron/XRay imaging equipment installation.

REFERENCES

[1] Rosa R., Chirco., Neutron Radiography (7), Proceedings of the Sebenth World Conference, Rome Italy, September 15-21, 2002.

[2] Kobayashi H., Wakao H., Accurate measurement of L, D, and L/D for divergente collimators, ASTM E 803-81 1981.

[3] Burkhard Schillinger, Estimation andMeasurementof L/D on a Cold and Thermal Neutron Guide, Technische Universität. München Fakultät für Physik E21 D 85747 Garching Germany

[4] MacGillivray G.M., Neutron Radiography Collimator Design, Nray Service Inc. RR#1 Petawawa, Ontario, Canada.

[5] Kobayashi H., Beam Formation and Characterization for Neutron Radiography, Institute for Atomic Energy, Rikkyo University, 2-5-1 Nagasaka, Yokosuka, 240-0101 Japan.

[6] Tortorella D., Progettazione e verifiche sperimentali di un collimatore di neutroni presso il reattore TRIGA RC-1 dell'ENEA Casaccia, Tesi di laurea in Ingegneria Nucleare, DINCE Università degli studi di Roma "La Sapienza", 2001.

[7] Kobayashi H.,Basics ofImaging Plate forRadiograms,Institute for Atomic Energy, Rikkyo University, 2-5-1Nagasaka, Yokosuka, 240-0101 Japan, 2000.

[8] Giannini M., Festinesi A., Sangiovanni G., Storelli L., Galli G., Sistema rapido per radiografia neutronica digitale, DINCE Università degli studi di Roma "La Sapienza", 1995.