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The Moroccan PGAA System: Design, Installation, and Challenges

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ABSTRACT

Among the instruments included in the Triga reactor's development plan, as envisaged by CNESTEN, is the installation of combined PGAA and NI instruments. Implementing this combined system, however, requires the mobilization of a multidisciplinary team and safety assessments. Indeed, given the complexity of this experimental device, these assessments should be carried out during all stages of the project in order to separate the modifications from the extensions. Two main stages are planned for the project, with the first being dedicated to implementing the PGAA system, and this is in turn divided over two sub-phases. The first of these sub-phases is dedicated to setting up a collimating device and primary beam shutter with filters to eliminate fast neutrons and gamma rays with high energy. The second sub-phase is concerned with setting up the neutron guide, a beam shaper, an irradiation box complete with the detection system, a beam stop, and the necessary instrumental and biological shielding. This paper summarizes the operational aspects involved in these two phases, the challenges that were encountered, and some views on how to overcome them.

1. INTRODUCTION

The Triga type reactors built by GA (General Atomics) are equipped with lateral channels (NB1, 2, 3 and 4) for setting up new nuclear equipment, and this is also the case at CNESTEN (*the Centre National de l'Energie, des Sciences et des Techniques Nucléaires*), which will use its reactor in the development of strategic programs in areas like the environment, archaeology, geology and industry [1 -3].

The applications that are envisaged in the coming years include neutron activation analysis, which will be achieved by employing prompt gamma ray activation analysis (PGAA) to determine the prevalence of elements in materials; non-destructive tests through neutron imaging (NI); and structural analysing materials through neutron diffraction (ND). The NI and PGAA equipment will coexist as two distinct modes around the NB1 channel. This enables them to benefit from the space available in front of this channel and make use of the same biological protective shielding, thus helping to reduce the associated expense.

Thus, two modes for the PGAA and the NI instruments will be available. Depending on the desired application, the appropriate items will be placed in the stream line of the beam [4]. However, in order to optimize the setup such that it will simultaneously meet the technological needs of both configurations, it was agreed that the installation of the two sets of instruments (PGAA and NI) should be divided over two stages, with the first stage itself being divided into two sub-phases. The first of these involves mounting the primary beam shutter and installing the collimator plug within the beam tube, while the second phase is dedicated to installing the other components, namely the neutron guide, irradiation box with a HPGe spectrometer, beam shaper, and beam stop with biological shielding.

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More specifically, the collimator's installation requires some preliminary study, mostly to evaluate its effect on the safety and controllability of the reactor [5-6]. In addition, an investigation is needed to learn how it will behave when exposed to irradiation over time and the consequences for radioactive waste disposal on dismantling it, as well as whether its insertion can be easily reversed when required.

The primary beam shutter, meanwhile, is an important element for ensuring safety, such that it must function at the same level as the plug originally supplied with the reactor. Its performance therefore needs to be evaluated, while its design needs to respect the physical constraints in the reactor hall. Critically, however, it must fulfil its safety requirements even in the event of external or accidental stresses [7].

In order to ameliorate the quality of the beam, two filter types, based on sapphire and bismuth, will be employed to reduce the fast component of the beam and attenuate the gamma radiation from the reactor core and surrounding materials, respectively. However, it is essential to optimize the lengths of these two filters to avoid losing excessive beam intensity [5].

2. CONCEPTUAL DESIGN

2.1. Collimator plug

The collimator enables a parallel beam to be generated at the beam tube exit, such that there is just a small angle of divergence with respect to the axis of the channel. A collimator typically comprises three primary materials: a neutron moderator, neutron absorber, and various other gamma radiation absorbers, primarily high-Z metals. For this reason, two materials based on lead and carbon steel were assessed for their suitability. Lead is widely utilized in the collimator elements at a number of facilities, such as at the College of Texas [7] and in the KFKI Budapest Research Reactor [8], while carbon steel has been used, for example, at the National Research Laboratory of Oak Ridge [9]. Unfortunately, pure lead has the disadvantage of being relatively soft, but this can be addressed by combining it with antimony at approximately 5% by weight to create a harder alloy. This important improvement facilitates the commissioning and stack-free decommissioning processes, but it can also influence measurement efficiency. Carbon steel, for its part, has issues in humid areas with chlorine hydrolase and/or rust, although both can be mitigated by coating the base material with nickel or chromium, and this will help to avoid corrosion from spreading inside the reactor vessel. This will be particularly important once the collimator is installed within the beam tube. These two materials (carbon steel and lead) were evaluated with two different layouts, with carbon steel being chosen as the most practical option in our case [5].

The two main blocks of the collimator are constructed from carbon-steel (item a in Figure 1) and high-density borated polyethylene (item c in Figure 1). A closing disc (item b in Figure 1), also made of carbon steel, and ensures the assembly is tight.

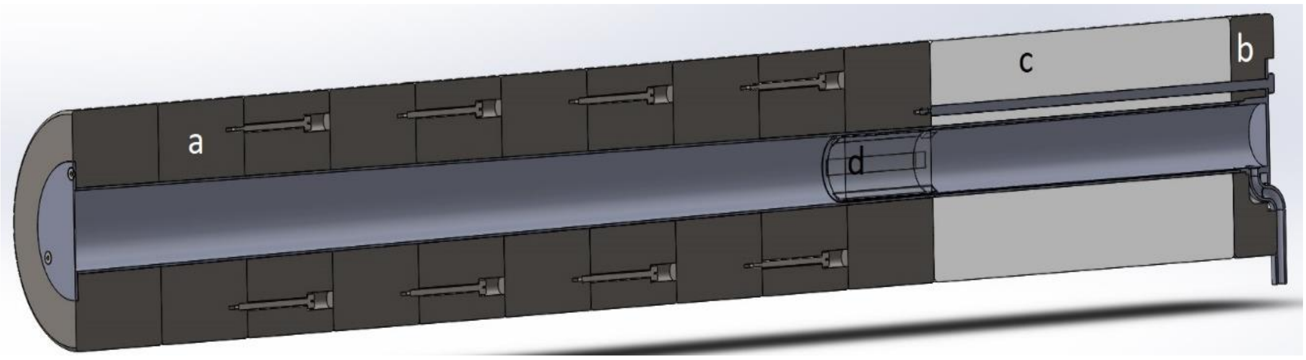

Fig. (1): Collimator plug—3D detailed design

2.2. Primary beam shutter

A primary beam shutter will open and close at the NB1 channel's exit to control the beam. Its correct operation in terms of controlling the rate of radiation attenuation is essential if an operator is to work in the experimental area under the applicable safety protocols.

Figure 2 illustrates the two positions of the shutter (i.e., open and closed). This component comprises two major elements: The first basically acts as a beam stopper, while the second serves as a collimator with an opening to let the beam pass through. The former is made from materials that are layered in such a way as to thermalize the fast and epithermal streaming neutrons that need absorbing and attenuate the residual gammas to an acceptable level that will ensure safety. Based on observations from similar experiments [10,11], the best candidate materials for this purpose are high-density polyethylene, borated polyethylene (80% by mass of B4C), carbon steel, and lead. The figure conveys how these materials are used laterally to eliminate the divergent beam, while the steel plates on the frame serve to provide further gamma protection.

When a beam is required, the open part of the shutter is moved into the neutron beam's path. Note that the aperture is optimized to maximize beam intensity for both PGAA and IN. In order to diminish the energetic gamma rays originating from the reactor's core, a bismuth filter of 10 centimetres in length is inserted into the open part of the shutter. An aluminium support houses this filter in order to guarantee that it is cooled to the temperature of liquid nitrogen. High-energy gamma rays can be significantly reduced by a bismuth filter like this [12].

Aluminium was selected as the assembly material to reduce the primary beam shutter's weight. Furthermore, to guarantee the shutter's stability, L-shaped plates were designed to securely hold the side shielding and its upper portion.

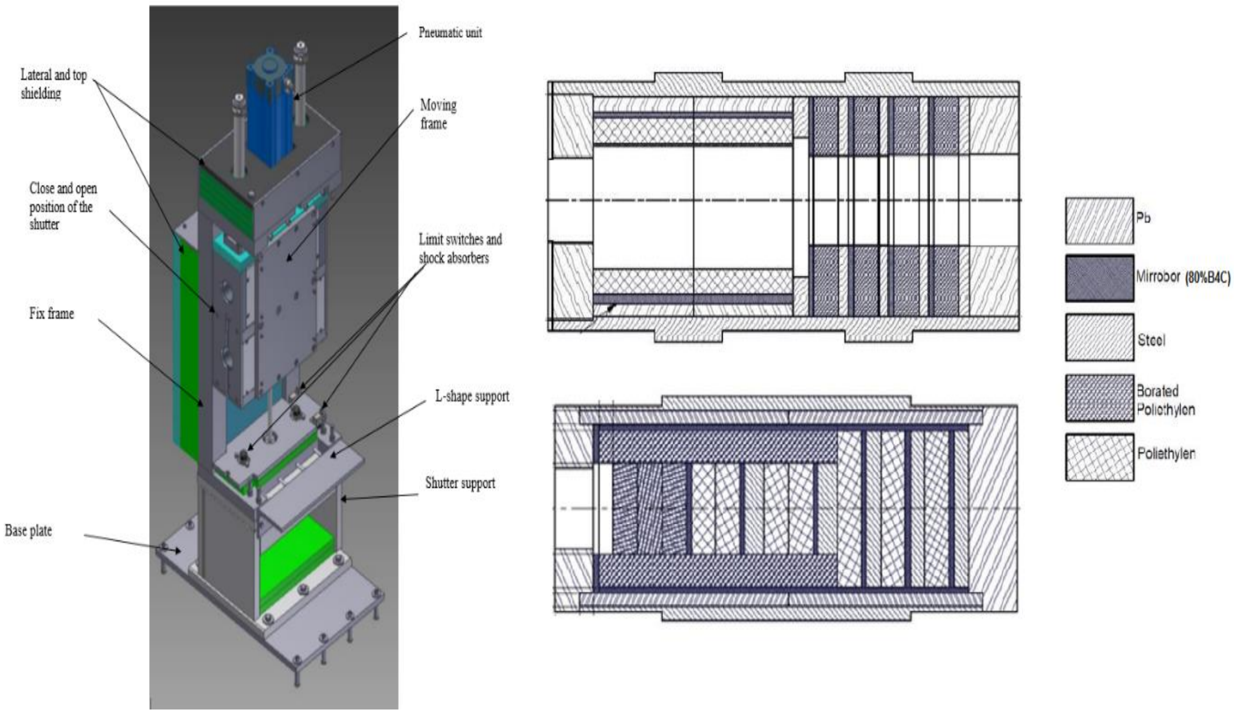

Fig. (2): The primary beam shutter's detailed design (left); the design and material composition of the aperture for the collimator and the shutter beam's stop (right)

2.3. Filters

At the carbon steel block's outer aperture, an aluminium tube is used to provide support for the sapphire filter's holder (item d in Figure 1), which has the capacity to host two grade B1 (Al_2O_3) sapphire filter units of 5cm each (Figure 3). Based on previous research studies, this grade of sapphire was selected for its appropriate neutron-transmission qualities. Moreover, the choice of length made it possible to achieve an approximately eightfold improvement in the thermal-to-fast-neutron and thermal-to-epithermal ratios [5].

Fig. (3): A sapphire filter segment that is 5 cm in length with a 5cm diameter

2.4. Neutron guide

With a cross section of 10cm (H) by 2.5cm (W), four super mirror guide units of 100cm each, which were manufactured by Mirrotron Ltd.[13], are used to transport the neutron beam (see Figure 4) to the irradiation box for PGAA analyses. The Ni/Ti-coated Borkron NBK-7 (Schott) superpolished glass used for the four faces of the guide units is known for its high degree of radiation resistance, such that its neutron fluence reaches 2×10^{18} n/cm2.

2.5. Beam shaper

It was necessary to shrink the beam's cross section, so a beam shaper is employed to supply the sample with a beam that has a cross section of the order of 1x1cm rather than the 2.5 × 10cm beam that leaves the neutron guide. The shielding to limit the scattering of radiation was optimized based on the MCNP model depicted in Figure 5.

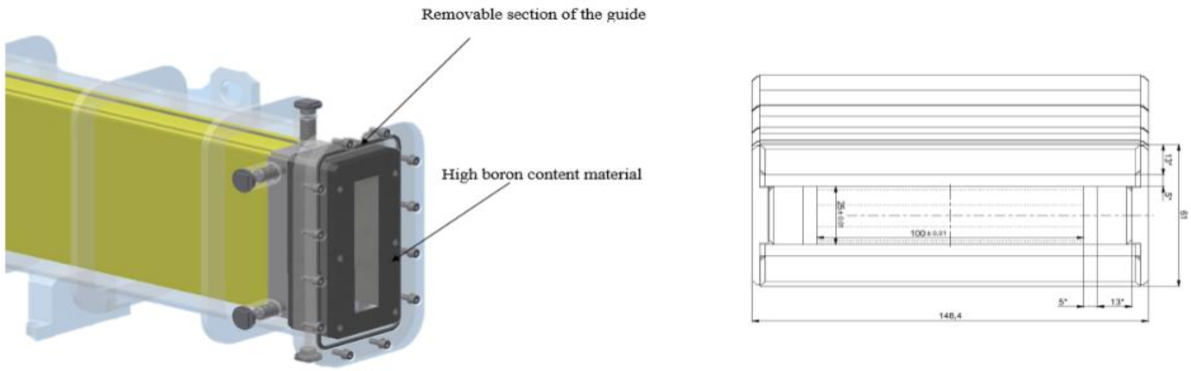

Fig. (4): Design for the neutron guide's integrated neutron protection (left) and its internal cross section (right)

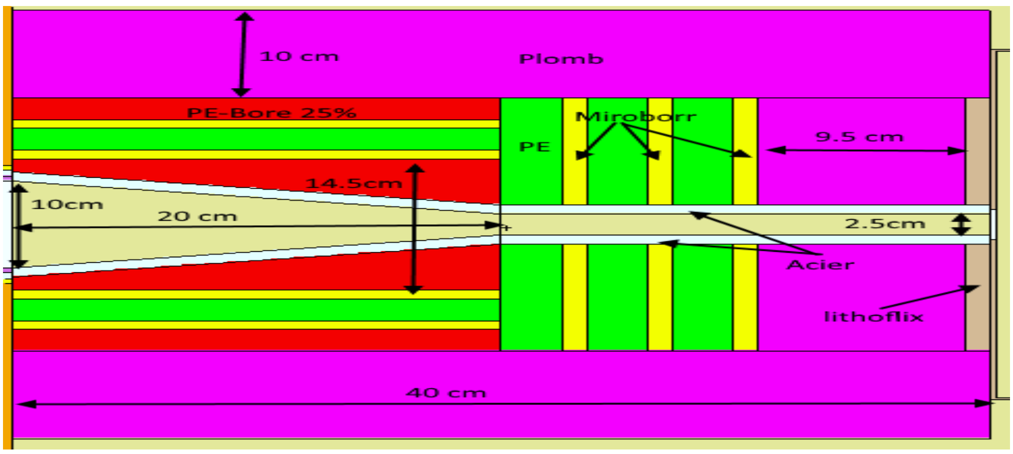

Fig. (5): MCNP model for the beam shaper's configuration for a 2.5 x 2.5cm cross section

2.6. Irradiation chamber and detection system assembly

Thanks to the open top of the sample holder, the aluminium irradiation box can be extracted to reduce background noise during PGAA measurements. This box features an integrated detection system and instrumental shielding, while the base system was designed to facilitate excellent tightening precision. The assembly can be removed while maintaining a sample–detector distance of approximately 20cm.

The Compton background noise is reduced thanks to an assembly containing a ring of anti-Compton BGO (bismuth germanium oxide), as well as a BGO annular catcher that surrounds the low-background, high-purity germanium (HpGe) detector that was fabricated by Canberra Co., as shown in Figure 6.

2.7. Beam stop

The beam stop is an essential component for eliminating the neutron flux once it has travelled through the sample. As such, it operates in principle in a manner similar to that of the primary beam shutter when in its closed position, and as such, it has no need for an aperture, because it needs to be closed permanently. It comprises plates arranged in such a manner that they together thermalize and absorb almost all the neutrons and gamma radiation within the beam. The fact that both the PGAA and IN instruments will be operating within the same beam was taken into account, and several arrangements were investigated to find an optimal configuration for both tools.

3. SAFETY ASSESSMENTS

3.1. Heating-distribution calculation

The expected increase in the collimator's temperature was determined based on an evaluation of the way in which heat is transferred to the collimator through radiation emitted by the reactor core. Of the many potential operating routines for the reactor that could be analysed to determine the thermal behaviour of the steel collimator, an extreme case was chosen whereby the reactor is operated continuously for a month at the nominal power of 2 MW. Figure 7 plots how collimator's temperature varies over the period in question. The maximum increase was insignificant after 720 hours of irradiation under a fluence rate of $\varphi_{0,n} = 8.14\,.\,10^9 n.cm-2.s-1$ and $\varphi_{0,g} = 9.10^9 n.cm-2.s-1$ for neutrons and gammas, respectively, with it being only approximately 0.6 K. A rapid temperature drop of approximately 0.3 K then occurs once the reactor is shutdown, as is evident in the same figure [6].

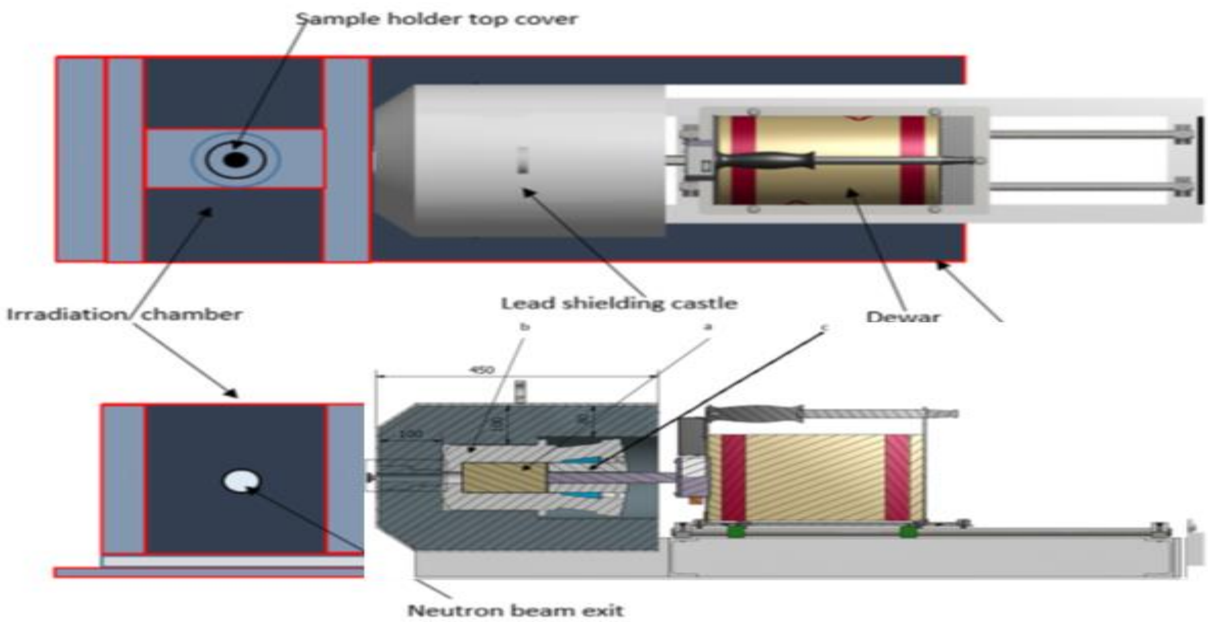

Fig. (6) : Different views for the base platform, with these showing the irradiation box and the detection system together with its related shielding: (a) HpGe, (b) BGO, and (c) a BGO annular catcher

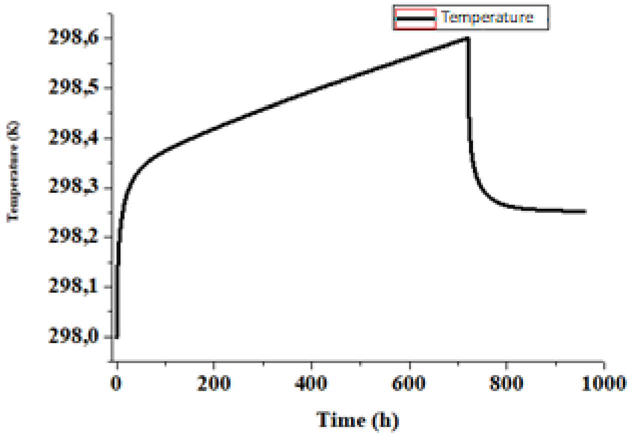

Fig. (7): How the collimator temperature varies over 720 hours of irradiation (Note that the baseline (t=0) temperature was 298.00 K).

In the context of a comparison to validate the selection of carbon steel over alternative types of steel commonly used in nuclear installations, Figure 8 shows the temperature variation for carbon steel (E235) and stainless steel (304L) at various degrees of gamma radiation and neutron fluence. The results reveal how these materials perform differently, with carbon steel having a temperature that is 16.9% lower than that of the stainless steel. Moreover, a linear variation manifests in carbon-steel alongside an increasing combined fluence rate ($\varphi_0 = \varphi_{0,n} + \varphi_{0,g}$).

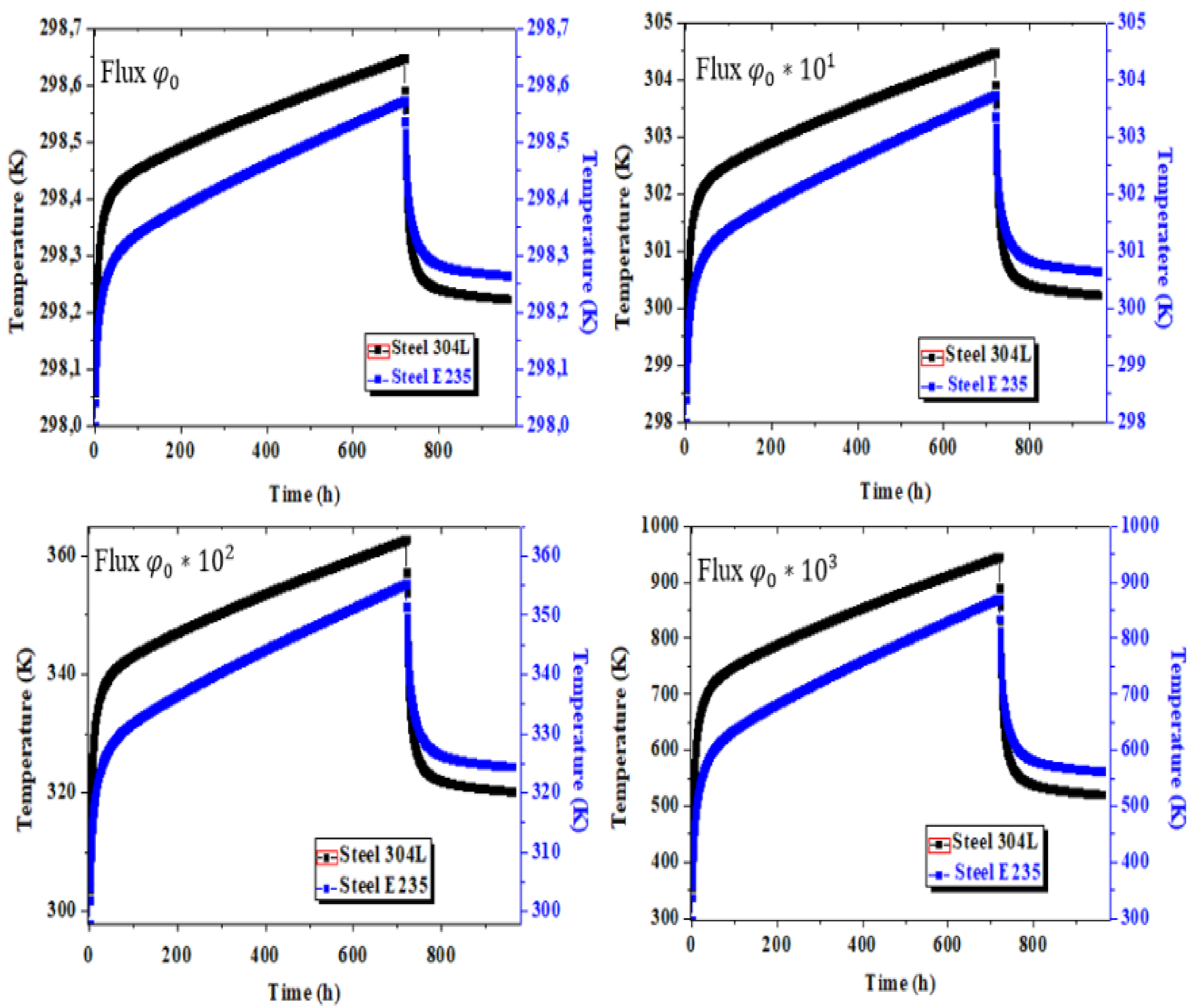

Fig. (8): The change in the temperature of the two materials at the most exposed ring of the collimator, shown as a function of the fluence rate

3.2. Swelling effect

The next step was to examine the rate that the carbon steel collimator would deform under irradiation in the NB1 channel in terms of the dose rate, as measured by displacement per atom (dpa), experienced by the collimator. Moreover, the enlargement resulting from the expected increase in temperature is also considered. We reasonably assumed that the swelling manifests only in the radial direction. The curve plotted in Figure 9 represents the dose rate experienced along the collimator in dpa/s, and it shows that the most exposed ring receives a dose rate of the order of $1.2\ 10^{-12}\ dpa/s$. The presence of the high-density borated polyethylene component triggered an increase in the background noise, thus explaining the slight hump towards the right end of the curve.

The increase in temperature is at most 1K, which in turn leads to swelling of 3.31E-3%. As expansion is only considered for the radial direction, this means that the external radius of the collimator increases by only 4.58 µm.

Combining this with the swelling caused by the dose rate, we can conclude that the collimator's radius will increase by about 5 µm (Figure 10), which will not cause issues at decommissioning, provided that the clearance between the beam tube and the collimator is between 0.5 and 1 mm.

3.3. Induced radioactivity within the collimator plug

Any device being considered for use in a nuclear facility needs the degree of radioactivity that will be induced after exposure to the neutron beam to be assessed. This in turn allows radioactive waste storage services to develop suitable procedures in advance for storing and handling the generated waste. To perform this evaluation, the radioactivity generated in the collimator was considered for an extreme scenario, such that over 10 years, the reactor operates at its maximum nominal power for one-month-on, one-month-off cycles. The induced radioactivity for this 120-month period is presented in Figure 11. The greatest induced radioactivity, which was of the order of 2Ci, was observed at the most exposed ring of the collimator.

As mentioned above, the collimator comprises 10 10-cm-long rings (Figure 12), so the induced radioactivity was calculated separately for each of these. It was therefore found that the induced radioactivity does not exceed 7.5 Mbq/g for the ring closest to the reactor core, while the rings located at the other are exposed to activity more than 300 times lower.

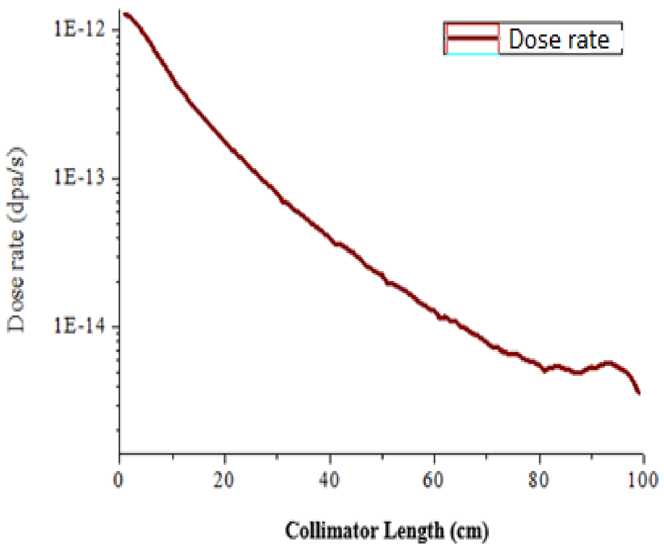

Fig. (9): How the dose rate (dpa/s) varies at different points along the steel collimator

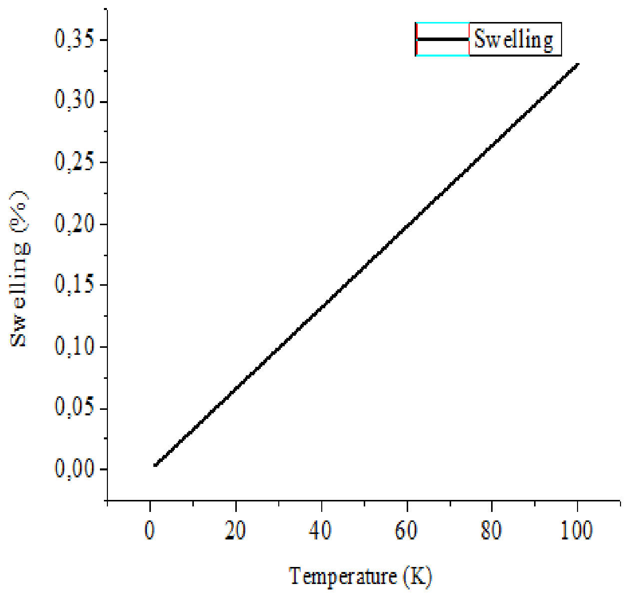

Fig. (10): The degree of swelling caused by thermal expansion

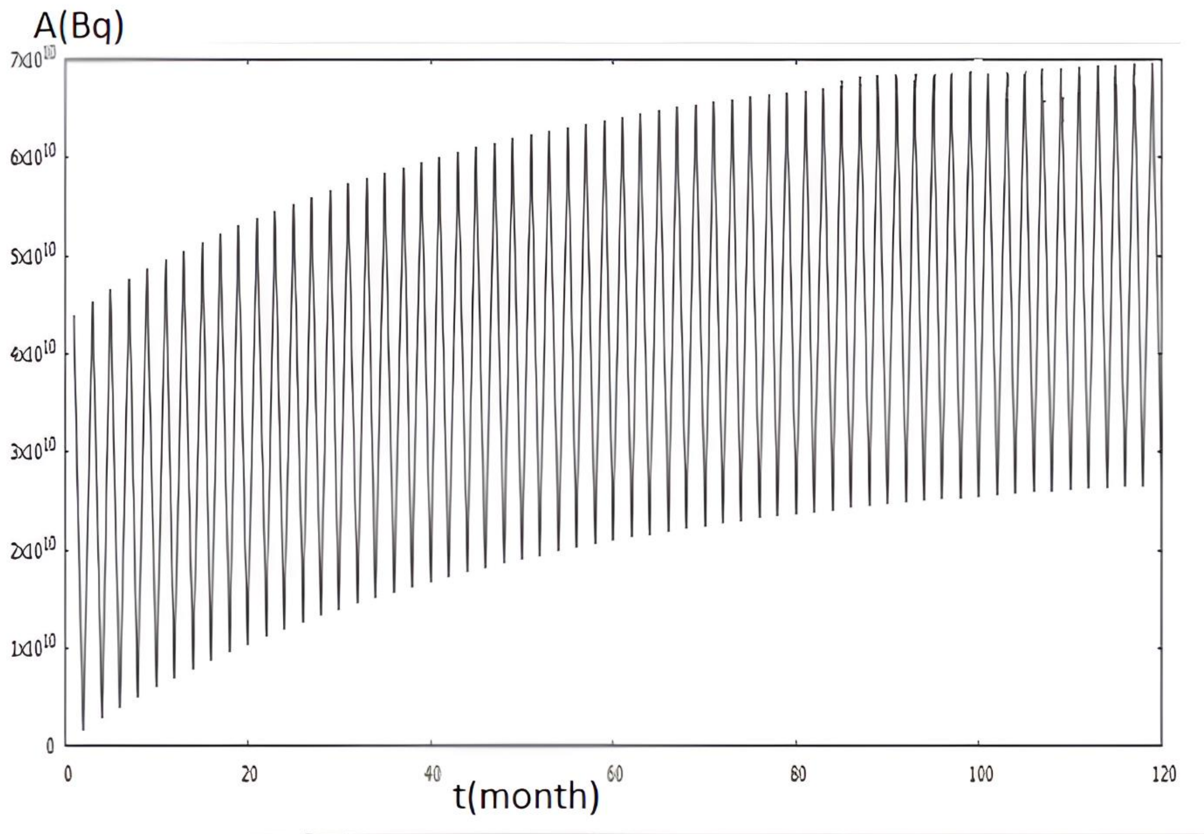

Fig. (11): Induced radioactivity in the carbon steel over 10 years of alternate-month reactor operation

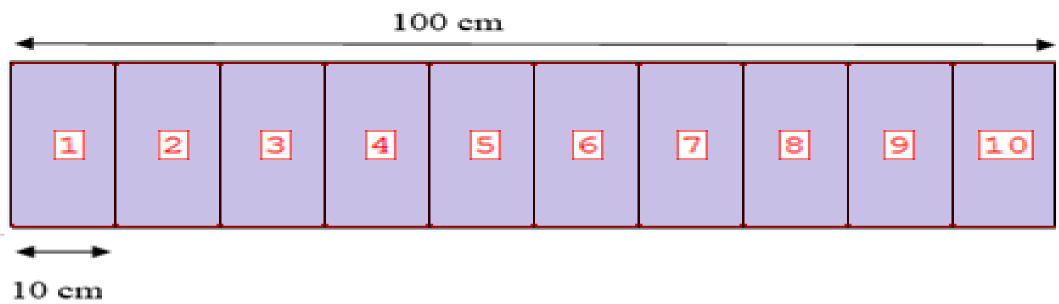

Fig. (12): The collimator plug's ten rings of carbon steel

3.4. Beam shutter

As described earlier, the primary beam shutter comprises two main blocks. The first is dedicated to stopping the neutron flux, and this comprises borated-PE and a succession of five sandwiches of polyethylene, Mirrobor, and steel enveloped by lead. The second block then allows the neutron beam to pass through an aperture with a radius of about 2.5cm. The bismuth filter is placed at the entry to this section to eliminate any photons and reduce any epithermal and fast neutrons that may be present in the beam. Several assessments were performed using the Monte Carlo method in multiple shutter positions in order to investigate the intensity and type of the neutron flux in each region. The neutron distribution was calculated based on the type of the neutrons (thermal, epithermal, and fast) [7], and the results show that in its closed state, the primary beam shutter can stop 97% of neutrons, as shown in Figure 13. It also reduced the gamma dose produced by the neutron–matter interaction by up to 0.183 mSv/h and the reactor source gamma dose by up to 3.57 mSv/h.

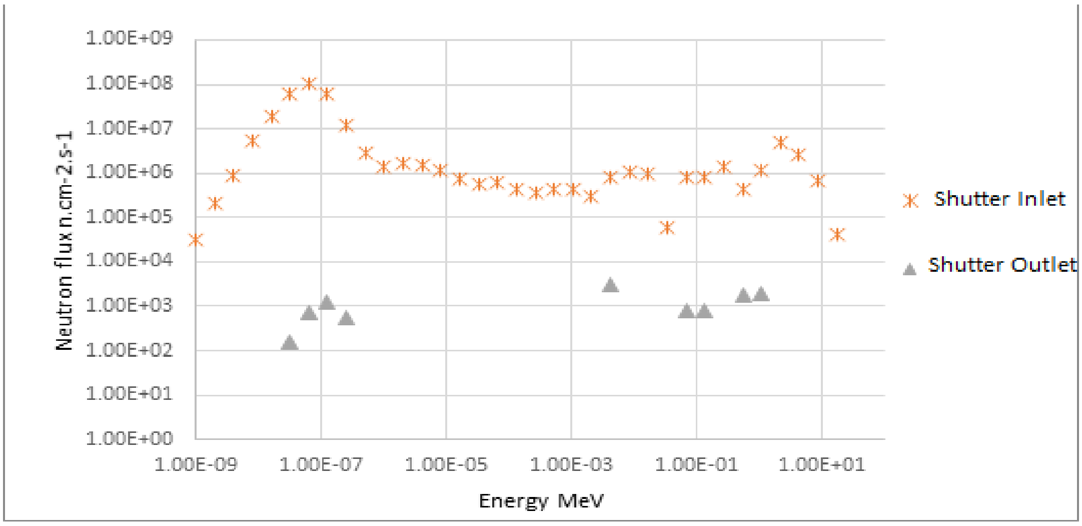

Fig. (13): The energetic distribution of the neutron flux at the closed beam shutter's inlet and outlet

4. CONCLUSION

This work presents an overview of the approach that was adopted for deploying the combined PGAA/NI system in the NB1 channel of the CENM's Triga reactor. The use of each particular mode requires specific components to be positioned in the channel. Space limitations and ease of use by operators have led to certain components being switched vertically and others horizontally, all while satisfying the requirement of each instrument. In the first phase, the implementation of the PGAA system involves installing the 4 m supermirror guide, the beam shaper, the irradiation box with its associated detection system, and the beam-stop.

The evaluation informed us that the temperature increase in the collimator was insignificant at no more than 1K, even after a long period of irradiation (10 years of alterative monthly operation) at a nominal reactor power of 2MW. This allows us to conclude that the introduction of the collimator will not degrade the safety and performance of the reactor. In order to avoid chemical corrosion and chlorine hydrolase, the collimator was coated with a layer of nickel. The swelling induced by increasing temperature and dpa dose rate is extremely low, so the collimator will largely retain its original dimensions throughout its service life. Thus, the clearance between the beam tube and the collimator was also taken into consideration to ensure there would be no blockage issues. Moreover, peak activity in the collimator does not exceed 2Ci, so the chosen configuration, with carbon steel being adopted for the collimator material, is the most appropriate option for good PGAA performance and a smooth decommissioning.

Finally, the primary beam shutter was shown to be effective at replacing the reactor's default neutron beam plug, even though it is also allowed the neutron beam to be safely used whenever necessary. For safety purposes, temporary shielding will be used to isolate the shutter from the reactor hall, pending the implementation of the second phase.

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