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Thermal and Fast Neutron Measurement in the STU Mini Labyrinth Experiment

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Abstract: The Mini Labyrinth experiment is a neutron and gamma shielding experiment constructed at the Slovak University of Technology in Bratislava (STU). The STU Mini Labyrinth consists of NEUTRONSTOP shielding, blocks of moderators, various neutron sources, a graphite prism, and the detector handling robot. It was designed for research and education purposes, while several experiments are also available online or a hybrid form. There have been several versions of the Mini Labyrinth developed, while currently the V3 version is available. This paper presents the methodology to effectively perform thermal and fast neutron measurements using a PuBe neutron source. In the experiment presented in this paper also active and passive detectors were used, and moderator materials were investigated to slightly shift the neutron spectrum. As for active detectors, the SNM-11 boron coated corona detector was used. Among passive detectors the CR-39 track detectors were investigated. The measurements were carried out in two configurations and the results were evaluated by simulations using the SCALE6 system.

Keywords: *Mini Labyrinth, Radiation protection, SCAL6, CR-39, SNM-11.*

I. INTRODUCTION

The Slovak University of Technology in Bratislava (STU) is a modern educational institution, consisting of 8 faculties, among which, one of the most successful in terms of education as well as research and development is the Faculty of Electrical Engineering and Information Technology (FEI). One of its leading institutes, the Institute of Nuclear and Physical Engineering (INPE) has been involved in research activities related to the use of different types of neutron sources, their application and shielding. The available Pu-Be, Am-Be and Cf-252 radioisotope neutron sources are regularly used as part of the education process and in international research projects, such as ENEEP or PADINE-TT, in which various hands-on experiments were performed on site but also online. There are 16 laboratories operated at INPE, such as the Laboratory of Reactor Physics, Mössbauer Spectrometry Laboratory, Positron Annihilation Spectrometry Laboratory of the Supercomputer Applications Centre. In addition, a new Laboratory of Neutron Applications is being developed, where a DD type neutron generator will be installed, and all neutron-physics related experiments will be under the same roof.

In this paper we are introducing the Mini-Labyrinth radiation shielding benchmark experiment, inspired by the ALARM-CF-AIR-LAB-001 ICSBEP [1] experiment, and built to be used for educational and research purposes. The Mini-Labyrinth experiment was started to

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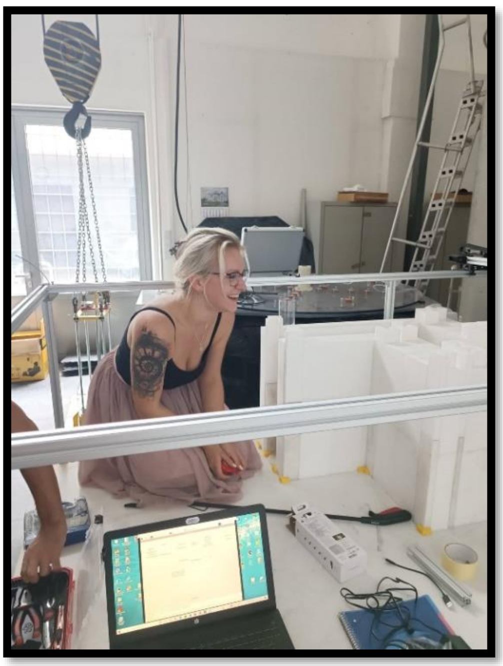
be developed in 2019, as part of the international project “Experimental and simulation shielding studies of materials used in radiation protection” in cooperation between STU, the Brno University of Technology (BUT) from Chechia and the Vinča Institute of Nuclear Sciences from Serbia. The initial V1 configuration was a set of NEUTRONSTOP shielding blocks with a dimension of 96x60x25 cm and was placed on a reinforced particleboard desk. This configuration made possible of inserting a neutron source to one specific position equipped with a tank of light-water moderator. The results of the V1 configuration presented in [2] showed, the single light-water tank is not sufficient to create thermal neutron spectrum, therefore the new V2 configuration was created with the same dimensions of the Mini-Labyrinth, however a solid graphic prism was placed on the same desk which allowed loading the neutron source inside the graphite and therefore creating almost ideal thermal neutron spectrum. The results of the V2 Mini Labyrinth can be found in [3].

It turned out that the 25 cm height of the Mini Labyrinth is not sufficient to effectively manage the radiation doses of the operation personnel during the experiments, therefore the STU team decided to perform another upgrade of the Mini Labyrinth and the V3 version was created. This version consists of the same materials but have 50 cm height. The solid graphite block is installed on movable plates that ease its modifications and provide flexibility in selecting the neutron source position. In addition, the detector handling robot was developed and installed, which is remotely controlled, moves on an aluminium platform around the measurement desk and is capable of 3D detector positioning with a precision of 0.5 cm. Photos of the V3 version of the Mini Labyrinth are shown in Fig. 1 and some partial results of the first measurement activities can be found in [4].



(a) Setting up the experiment

(b) Detector handling robot

Fig. 1. Photos of the V3 version of the Mini Labyrinth experiment

It should be noted that there is a special version of the Mini-Labyrinth being developed, designated as V4. It is a version equipped with shielding materials to minimize the doses during student exercises, as the Mini Labyrinth experiment has been included in the set of mandatory students´ exercises as part of the BSc subject „Materials of Nuclear Power Plants“. This version has been designed for education purposes only, therefore it is beyond the scope of this paper. Interested readers may find some partial results of experiment using the V4 configuration in the recent publication of our team [5].

II. METHODOLOGY

A. Measurement configurations

As it was explained above, in this paper the V3 configuration of the Mini Labyrinth is examined, especially the V3-50-L sub-configurations. The geometry of the V3 configuration is shown in Fig. 2.

It consists of 6x12x25 cm C-shape NEUTRONSTOP shielding blocks (polyethylene with B-10), plastic source holder, graphite prism, and radiation detectors. In the V3-50-L case, the neutron source is placed from the left, from the corridor of the labyrinth. There is a possibility to insert the source from the right, into the adjustable cavity inside of the graphite prism, which allows thermal neutron measurements. This case would have the V3-50-R ID, however, has not been set up so far. The measurement zones in the recent V3-50-L configuration of the Mini Labyrinth are shown in Fig. 3. As it can be seen the neutron source is installed from the left and there is a possibility to use a plastic tank filled with light-water moderator to soften the neutron spectrum. The measurements explained in this paper were conducted using Pu-Be radioisotope neutron source with the emission rate of 1.1E+07 n/s.

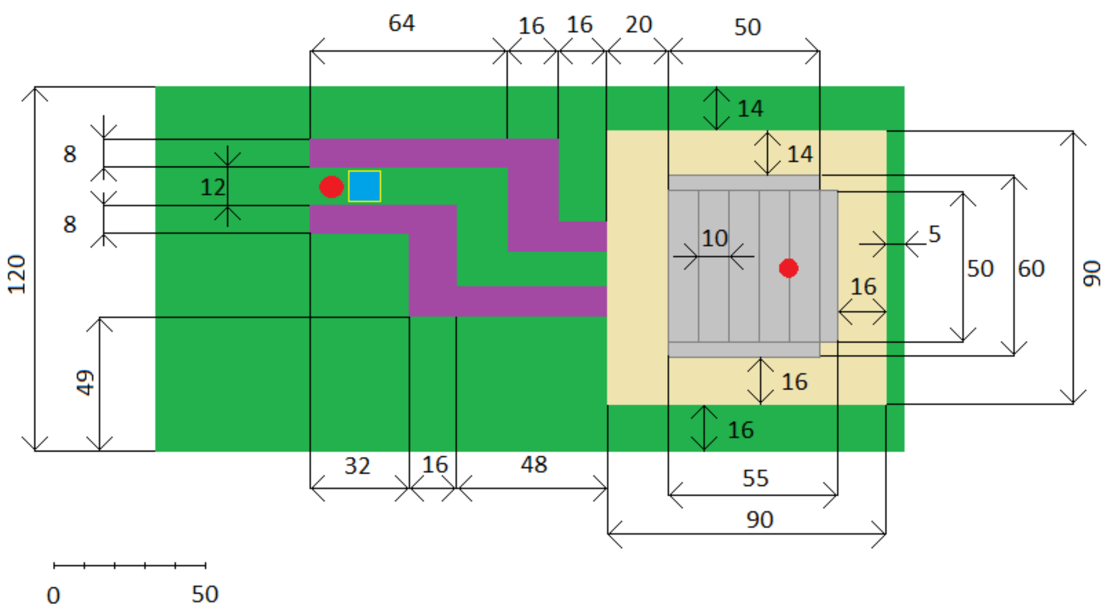


Fig. 2. Top vie of the V3 configuration of the Mini Labyrinth

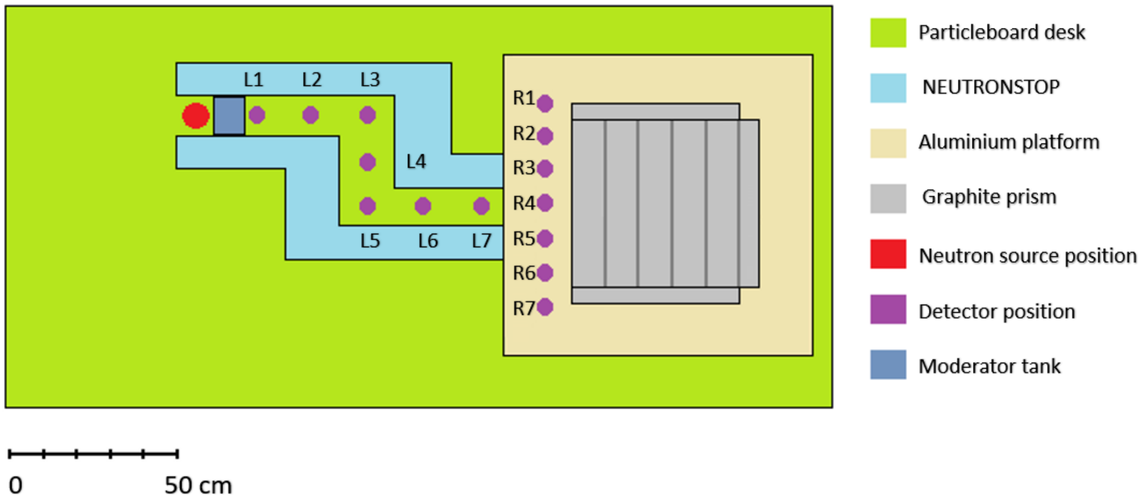


Fig. 3. Illustration of measurement positions in the V3-50-L configuration

Using the V3-50-L configuration of the Mini Labyrinth shown in the figure above, two separate measurements were performed, designed as Experiment 1 and Experiment 2. The conditions and parameters of the experiments are summarized in Table I.

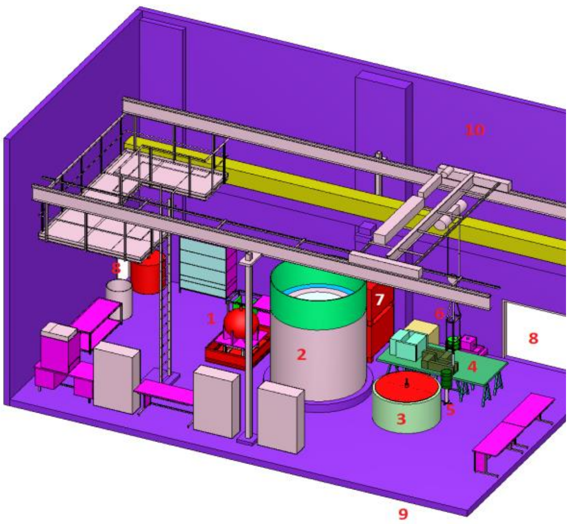
Table I. Overview of the experiments

	Experiment 1	**Experiment 2**
Neutron source	Pu-Be 1.1 1.1E+07 n/s	
Extra moderator	N/A	H_2O (T=300K)
Detector type	TASTRAK CR-39	SNM-11
Number of detectors	16 x 7 (stationary)	1 (movable)
Measurement time	23 h	3 x 15 min / position
Measurement positions	L1 - L7	R1 - R7
Neutron energies of interest	E > 100 keV	E < 0.625 eV
Measured quantity	H*(10)	Count rate
Evaluation method	SCALE6 volume detectors	SCALE6 meshtalies

In case of the Experiment 1, the neutron source was used without the extra moderator and the positions L1-L7 were investigated. Passive CR-39 type solid state track detectors were used, which were irradiated all at the same time, for 23 h and were analysed and evaluated using the TASLIMAGE [6] system. The TASTRAK CR-39 [7] detectors measured the ambient dose equivalent of neutrons H*(10). These detectors ware able to detect neutrons with energy above approximately 100 keV and the minimal dose of 0.1 mSv. In case of Experiment 2, the source was placed in the same position, but the moderator tank was filled with light-water at room temperature and the positions R1-R7 were investigated. The measurement of the neutron count rate was performed using the SNM-11 B-10 coated corona detector. The length of the detector was 30 cm and the diameter 1.8 cm, and it was moved to each measurement position by the remote detector handling robot. Each position was measured separately, 3 x 15 mins with and without a Cd cover. In the first step, the measurement was performed with a Cd tube on the SNM-11 detector to cut the thermal part of the spectrum down. In the second step, the Cd cover was removed from the detector, to measure neutrons of all energies and the measurement was repeated without moving the detector. The count rate from thermal neutrons was calculated as a difference between the results with and without the Cd cover. The results from the detector were evaluated using the custom-made four channel analyser. This analyser collects the signal from 1024 bins, each bin representing 7 mV, and the EMConfig software, obtained from the NUVIATECH company. The used analyser made possible using different levels of discrimination. For this experiment bins 31 – 2024 were used, the first 30 were omitted.

B. Simulation model

To verify the experimental results a 3D model of the laboratory, where the Mini Labyrinth experiment is located, was created in the SCALE6 system [8]. This model is showed in Fig. 4.



1 Manganese bath for neutron emission rate measurements

2 SUR reactor vessel

3 Vessel with liquid moderators for neutron fermi age measurements

4 Mini-Labyrinth

5 Certified NuDet neutron detector

6 Crane with source loading mechanism

7 IBC containers

8 Exit to the corridor

9 Exit to the yard

10 Walls

Fig. 1. SCALE6 model of the laboratory with the Mini-Labyrinth

The model was created using the GeeWiz sequence of SCALE6 and the graphic plot was created using the KENO3D tool. The model was developed in a way that it could be used in several modules of the SCALE6 system. For the evaluation of experimental results, the Monaco code from the MEVRIC sequence was used. The experiment was modelled as a coupled N-P problem, however only the neutron results were used for the evaluation. The Pu-Be neutron source was modelled as a cylinder with a diameter and height equal to 2 cm. Uniform spatial and directional distribution was used. The defined neutron and gamma spectra of the source, as sampled in the SCALE6 system, are shown in Fig. 5. For the neutron part a smooth function with a total emission rate of 1.1E+07 n/s was used. The gamma part was defined through 3 discrete energies, 3.43 MeV, 3.94 MeV and 4.44 MeV, with the probabilities of 0.32, 0.4 and 0.28 and the total emission rate of 7.15E+06 p/s. As it can be seen, the SCALE6 system translated the discrete energies into a smooth function. For the calculations standard 27n18g ampx multi group cross-sections, processed based on ENDF/B-VII.1 [9] evaluated data, were used.

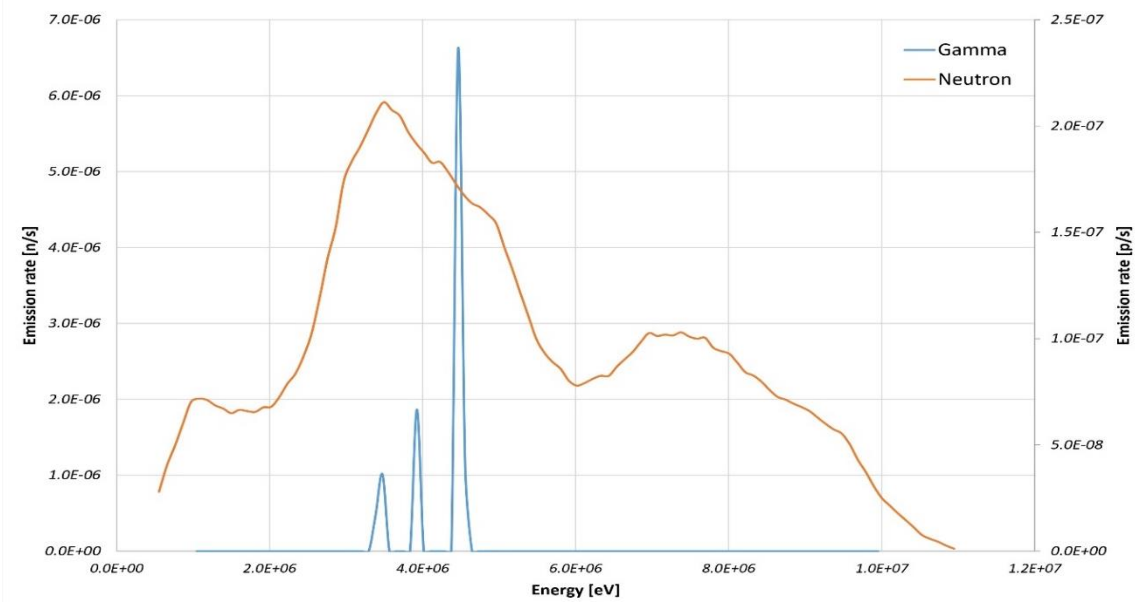


Fig. 2. Neutron and gamma spectrum of the Pu-Be source

As Experiment 1 and Experiment 2 used a slightly different neutron source setup, both experiments were simulated separately, but using the same statistics. The collection of neutron results in the defined positions (L1-L7 and R1-R7 according to **Error! Reference source not found.**) was performed in the following way:

- *Experiment 1:*
    - In SCALE6 H*(10) was calculated based on ICRU-57 [10] as average from 16 detectors per each position.
    - The CR-39 detectors were evaluated using TASLIMAGE to obtain H*(10) and calibrated using NUDET-ENE.
    - Comparison of H*(10): SCALE6 point detector Vs. CR-39 was done
- *Experiment 2:*
    - The neutron count-rates were measured by SNM-11
    - The neutron flux was calculated through meshtallies in SCALE6 and converted to count rate through the volume of detector
    - Comparison of count rates was done: SCALE6 Vs. SNM-11

III.RESULTS

A. Experiment 1

In Experiment 1, CR-39 passive solid-state detectors were used. As the active scannable surface of theses detectors is only 1 cm^2, it was necessary to install 16 detectors in each measurement positions. The TASLIMAGE system creates 80 digital images per detector, thus 1280 images were available for analyzes in each position. The detectors were placed in 8 pairs, numbered from K to Z while each pair represents a different specific height in the Mini Labyrinth. The illustration and the photo of the CR-39 detector holder and the numbering scheme in Experiment 1 is shown in Fig. 6.

As each detector pair represents a different position, it was useful to compare the results for different pairs and combinations of pairs. In our case the averages were calculated for 3 combinations of detectors:

- K-Z: Average from all 16 detectors
- O-V: Average from 8 the detectors
- Q-T: Average from central 4 detectors

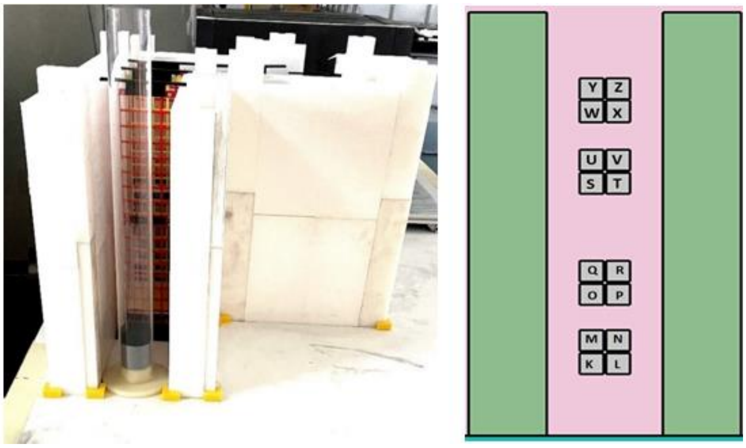


Fig. 3. Photo and illustration of the CR-39 detector holder in Experiment1 [3]

The comparison of measured and simulated ambient dose equivalents representing 23 h irradiation is shown in Fig. 7. The values shown in the figure are the average values with the ± 1σ combined uncertainty resulting from the measurement or the simulation and the averaging process. In case of the SCALE simulation, 1.5 % nuclear data induced uncertainty was also considered. In case of all positions and methods, the difference between the calculated and measured quantities is less than the corresponding uncertainty, which is satisfactory. In terms of averaging methods, the best agreement was found for the 4 detectors close to the neutron source (Q – T). Regarding the measurement positions, the lowest discrepancy was achieved for L2 and L5, and the largest for L7, which is caused by the low neutron flux in this position. Further improvements will be required to decrease the uncertainty of the measurement and to analyse the effects of neutron source anisotropy.

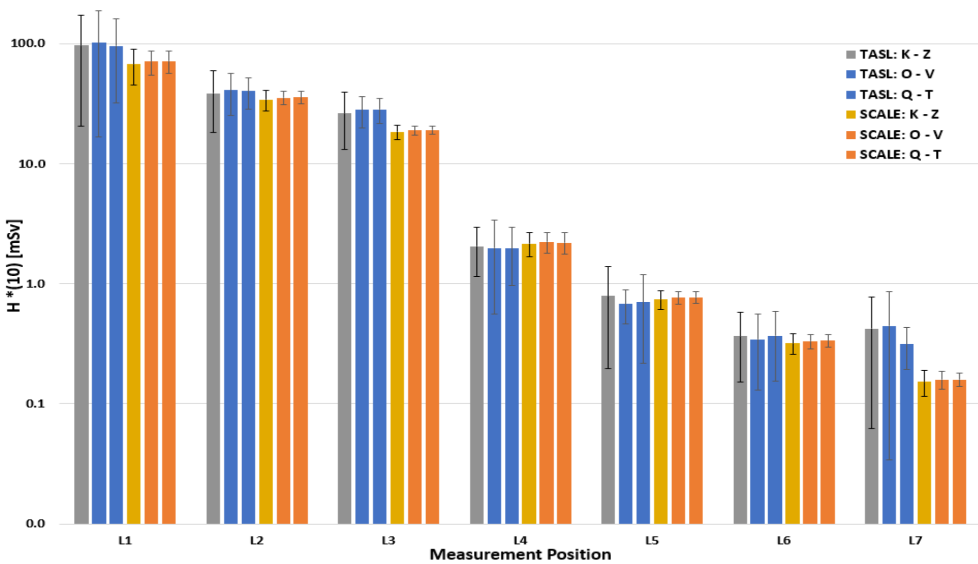


Fig. 7. Comparison of measured and simulated values of H*(10) in experiment 1

B. Experiment 2

In Experiment 2 the focus was on comparing the performance of the SNM-11 detector with SCALE6 based on the measurement of the count rate of thermal neutrons. We also focused on investigating the effect of extra light-water moderator. As the response of the SNM-11 detectors is proportional to the B-10(n,α)Li-7 reaction, we assumed that small moderation of neutrons would increase the detector responses. The results of the measured and simulated thermal neutron count-rates are shown Fig. 8, where the ID "Air" represents a case without light-water moderator and the ID "H2O" with light-water moderator. As before, the values shown in the graph are average values with the ±1σ combined uncertainty, including the uncertainty resulting from averaging the measured results and the uncertainty resulting from the nuclear data. The average values of measured quantities were calculated from the 1 min. integrals of measured count rates. In SCALE, the count rate was normalized from the thermal neutron flux.

The results are showing a very good agreement between the measured and simulated neutron count rates in both setups (with and without moderator). The average deviation was 1.56 % in case without moderator and 1.73% with moderator. The largest discrepancy was found in position R4, and the lowest discrepancy in position R2. In all cases the discrepancy was lower than the statistical uncertainty. Regarding the use of extra moderator, it can be concluded that it partially fulfilled our expectations. The use of extra moderator increased the portion of thermal neutrons absorbed in all detector positions. The increase lies in the range of 5.42 % to 9.33 %. The largest increase can be seen in position R4, which is in front of the corridor of the Mini-Labyrinth, where the absorption on NEUTRONSTOP is minimal. Despite the increase of the count-rate of thermal neutrons, the uncertainty of the measurement is almost the same in both cases, therefore the improvement due to the use of light-water moderator is negligible. In the future, graphite and heavy-water moderator will be investigated to replace the light-water moderator. These materials will have comparable moderator properties and significantly lower absorption rate of thermal neutrons, but their use may not be economically feasible.

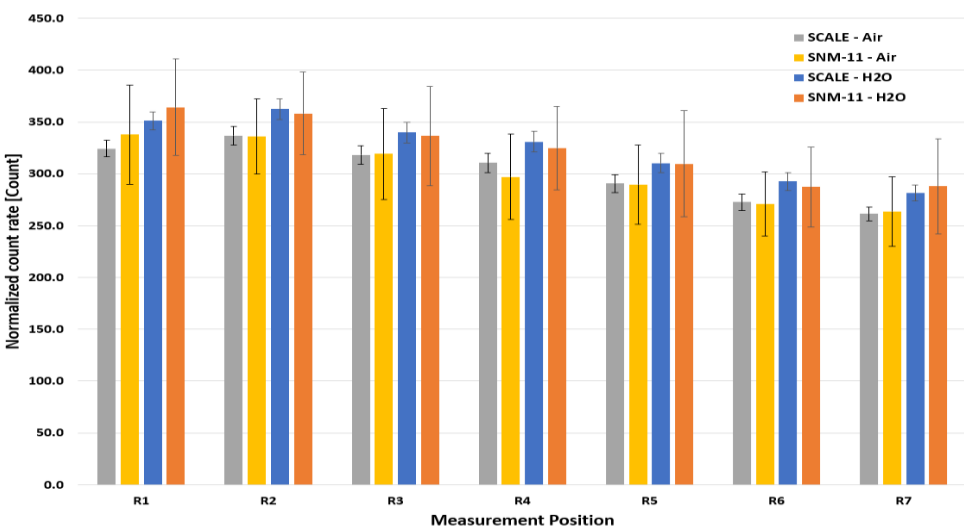


Fig. 8. Comparison of measured and simulated count rates in experiment 1

C. Estimation of the doses of the personnel

As the last set of results, the H*(10) ambient dose equivalent rates around the Mini Labyrinth workplace and in the laboratory are shown in Fig. 9 and Fig. 10. The results are showing that in the vicinity of the neutron source, the ambient dose equivalent of neutrons exceed 100 μSv/h, even though one layer of NEUTRONSTOP.

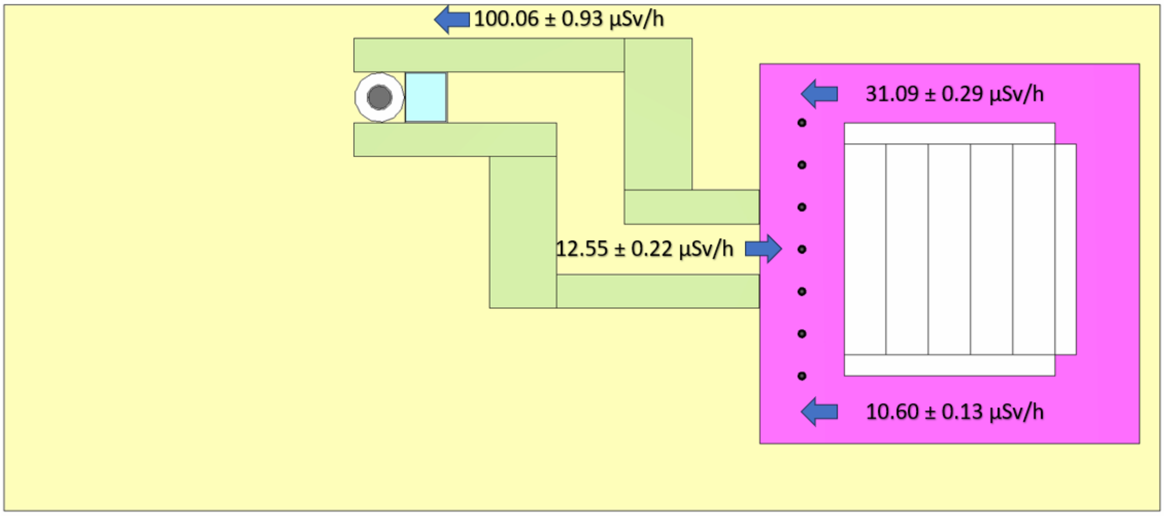


Fig. 4. Radiation doses around the Mini-Labyrinth

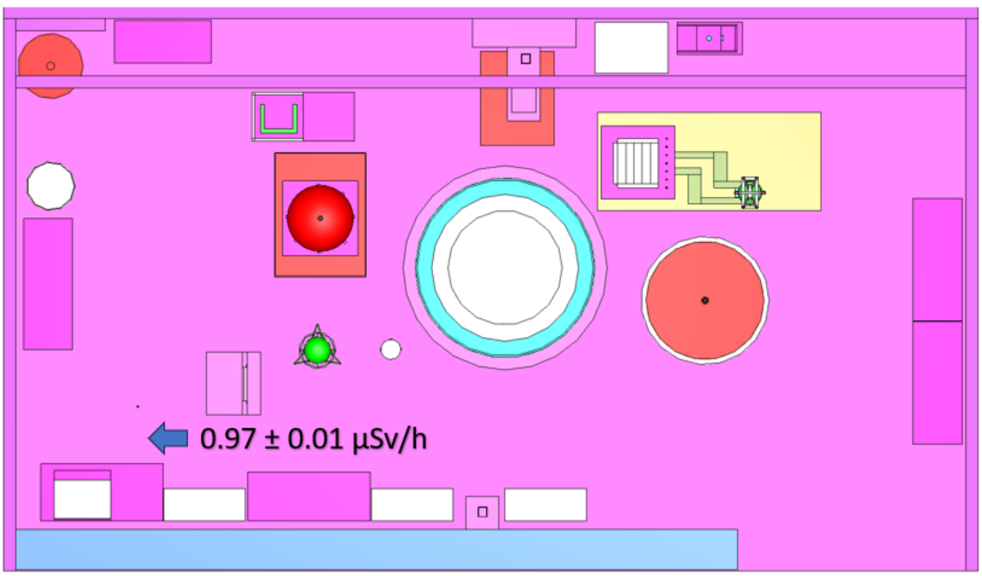


Fig. 5. Radiation doses at the measurement control panel

This is an important result, not only to minimize the time spent by the personnel close to the workplace but also to understand a potential failure of the electronic parts of the detector handling robot, because this equipment cannot be effectively shielded, nor the distance, neither the operation time cannot be significantly optimized. The only possible solution would be modifying the design of the robot and placing the control electronics and other sensitive parts father from the source. In terms of minimizing the doses of the operation personnel, it can be concluded that it is not recommended to stay closed to the measurement desk. The measurement should be controlled from a workplace situated behind the SUR reactor vessel, where the ambient dose equivalent is less than 1 μSv/h from neutrons and approximately 200 nSv/h from gamma radiation. During the experiments, these values were evaluated and confirmed by certified measurement tools.

IV. CONCLUSIONS

As result of long-term development activities of the research team from STU, the Mini Labyrinth radiation shielding benchmark experiment has been developed. This paper presents the results of two experiments designed to verify the measurement methods used though high-fidelity Monte Carlo modelling and simulations. The experiments presented her consists of measurements of fast end thermal neutron related quantities though passive CR-39 solid state track detectors and the SNM-11 boron coated corona chambers. The results concluded the measurement methodology, but also highlighted potential fields of improvement, mainly in the field of minimizing the measurement uncertainties and verifying the anisotropy of the used Pu-Be neutron source. The latest V3 and V4 configurations of the Mini-Labyrinth are ready for R&D and E&T purposes. In R&D field the investigation of unknown shielding materials could be application. In terms of E&T the Mini Labyrinth can be used as a hands-on exercise or as a tool to demonstrate basic radiation shielding principles by means of online or hybrid lectures.

ACKNOWLEDGEMENT

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