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MILESTONE REPORT

DESIGN OF A CADMIUM SHIELD IN THE TANGENTIAL CHANNEL OF THE JSI TRIGA REACTOR

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Abstract:

An enhancement of the utilization of the existing Large object irradiation device installed in the Tangential Channel of the JSI TRIGA reactor will be achieved by the installation of a thermal neutron shielding device. The device will comprise a cadmium foil which will reduce the activation of samples created by the incident thermal neutrons, and hence significantly simplify the manipulation of irradiated samples.

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Executive summary

Within the framework of the AIDA 2020 collaboration project, a Large object irradiation facility was designed, manufactured and installed in the Tangential Channel of the JSI TRIGA reactor to allow irradiations of objects of lateral dimensions of up to 12 cm in a relatively intense fast neutron flux, of the order of 10^{11} n $cm^{-2}s^{-1}$.

An enhancement in the utilization of the existing Large object irradiation device installed in the Tangential Channel of the JSI TRIGA reactor will be achieved by the installation of a thermal neutron shielding device. The device will comprise a cadmium foil which will reduce the activation of samples induced by incident thermal neutrons, and hence significantly simplify the manipulation of irradiated samples.

This document reports the activities conducted to reach a conceptual design of the shielding device.

1. INTRODUCTION

In the framework of the EURO-LABS project, an enhancement of the utilization of the existing large object irradiation device installed in the Tangential Channel of the JSI TRIGA reactor will be achieved by the installation of a thermal neutron shielding device. The device will comprise a cadmium foil which will reduce the activation of samples due to incident thermal neutrons, and hence significantly simplify the manipulation of irradiated samples. As the cadmium foil will be activated during reactor operation with the shielding device in use, a strategy for safe handling and storage of the device needs to be formulated. This report presents the computational support needed for the device design, the device optimization, and outlines the conceptual device design.

2. EXISTING LARGE OBJECT IRRADIATION FACILITY IN THE JSI TRIGA REACTOR

The JSI TRIGA reactor in Ljubljana, Slovenia, is a 250 kW, light water, pool type research reactor, extensively used for education and training, irradiation of samples for neutron activation analysis (biological and geological samples), irradiation of materials for fusion reactors, experimental testing of nuclear instrumentation sensors (fission and ionization chambers and self-powered neutron detectors - SPNDs), testing and validating nuclear data, computer code benchmarking, research and development of radiation resistant electronic components, etc. The reactor is a reference centre for neutron irradiation testing of semiconductor radiation detectors used in the large experimental facilities at CERN and elsewhere.

In the framework of the AIDA 2020 collaboration project, a Large object irradiation facility was designed, manufactured and installed in the Tangential Channel of the JSI TRIGA reactor, the objective of which is to allow irradiations of objects of lateral dimensions of at least up to 12 cm in a relatively intense neutron flux, of the order of 10^{12} n $cm^{-2}s^{-1}$.

The requirements for the irradiation device were to enable easy insertion and withdrawal of samples, to allow for on-line irradiation testing of electronic components, i.e. the provision of cable and coolant line feedthrough capability, and to ensure adequate shielding from neutron and gamma radiation originating from the reactor core. Additionally, no modifications to the Tangential Channel were admissible. A key role of the irradiation device was to ensure protection of the interior channel components, especially the water-tight stainless-steel manifolds which join the sections of the channel located inside the reactor pool.

The installation and commissioning of the irradiation device was completed in November 2016. Measurements of the neutron flux were made; the achievable total neutron flux levels at full reactor power inside the device were of the order 2.6 10^{12} n cm^{-2} s^{-1}, the achievable 1 MeV neutron NIEL equivalent flux is 3.9 10^{12} n_{eq} cm^{-2} s^{-1} [1]. The device has since enabled numerous irradiation tests of sensors and electronic components. Figure 1 displays a drawing of the JSI TRIGA reactor and highlights the Tangential Channel and the shielding device location, Figure 2 displays a photograph of the outer radiation shielding components of the irradiation device and Figure 3 displays a schematic drawing of the irradiation device within the Tangential Channel.

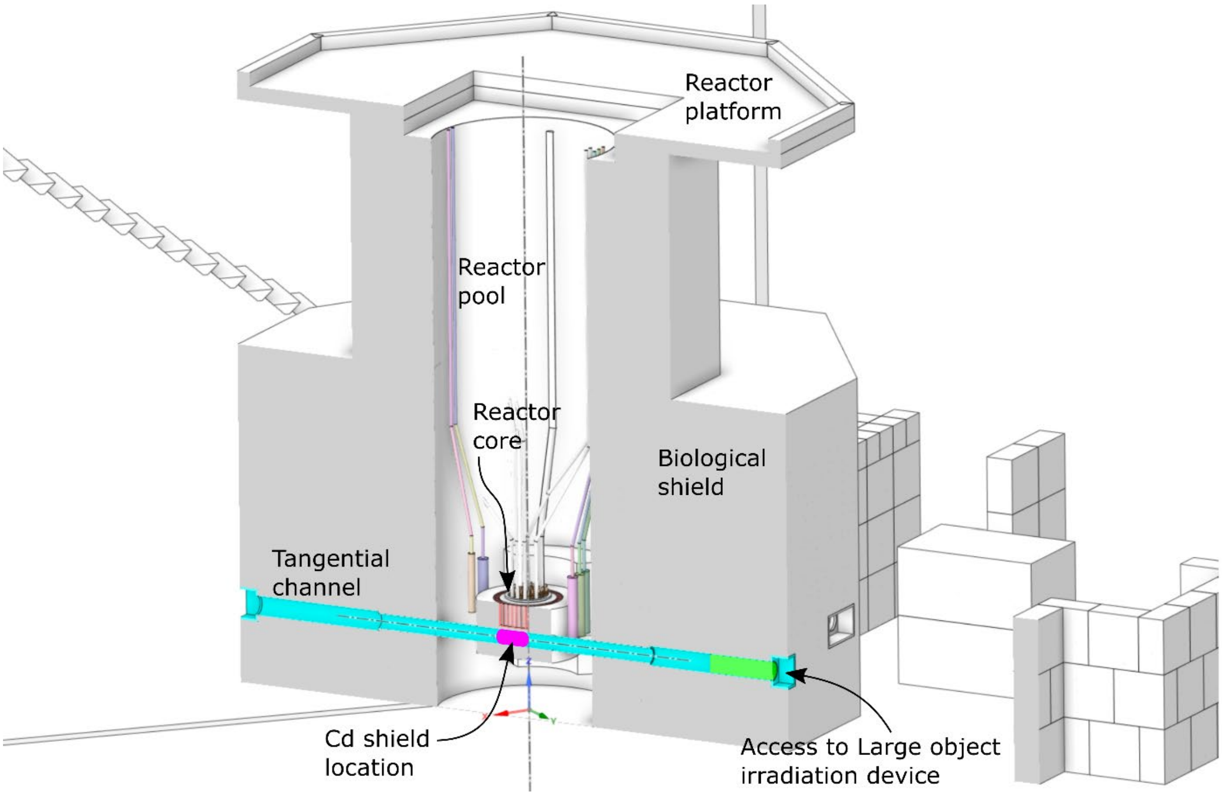

Figure 1: Schematic drawing of the Large object irradiation device in the reactor core.

Figure 2: Photograph of the outer radiation shielding components in the reactor hall.

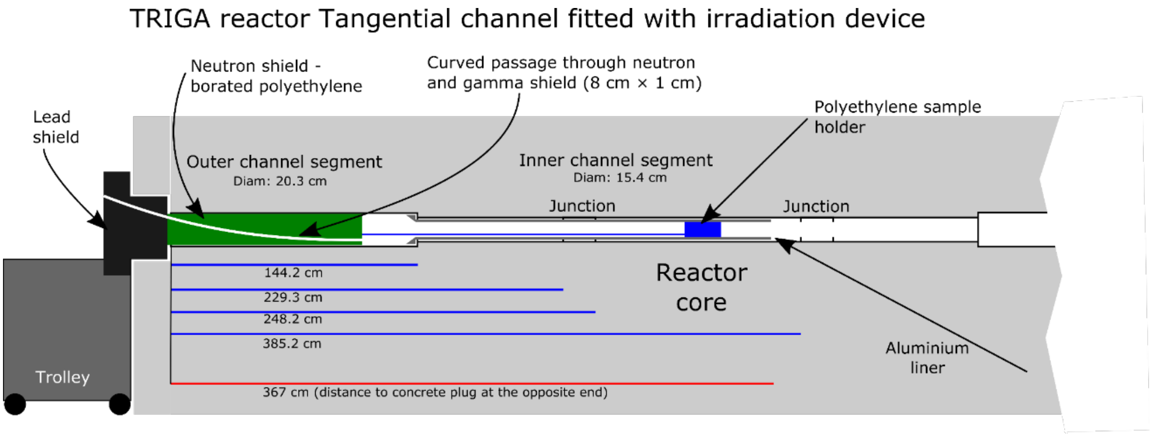

Figure 3: Schematic drawing of the Large object irradiation device in the reactor core.

The primary objective of the testing activities performed at the JSI TRIGA reactor are irradiations with fast neutrons causing damage to materials and electronic components. A drawback of an irradiation device featuring an intense thermal neutron component is the activation of materials through reactions with thermal neutrons, which are not essential for the irradiation tests, and which cause unnecessary induced activities in the materials. This can represent an important constraint for the handling of irradiated samples and transferring irradiated samples to partner laboratories for post-irradiation analyses.

A cadmium shield is envisaged to enable a significant reduction in the thermal neutron flux within the Large object irradiation facility, while preserving the epithermal and fast neutron components in the neutron spectrum. The considered shielding device design is a cylindrical tube, open at both ends, supporting a cadmium foil. The considered cadmium foil thickness is 1 mm, which is sufficient to filter out the thermal neutron component (below 0.55 eV) to a large degree and therefore to significantly reduce the dominant activation of irradiated samples by thermal neutrons. During irradiations the samples will be placed within the cadmium shielding device.

3. MONTE CARLO CALCULATIONS

3.1. CALCULATIONS OF NEUTRON FLUX LEVELS AND SPECTRA

Calculations of the neutron spectra were performed using the state-of-the-art Monte Carlo particle transport code MCNP 6.2 [2] in conjunction with the ENDF/B-VIII.0 [3] nuclear data library. A detailed computational model of the JSI TRIGA reactor, validated for calculations of the multiplication factor, neutron flux distributions and neutron spectra, was used. A cadmium shield was modelled and the overall dimensions were varied to optimize the device design. Total shield lengths of 30 cm, 50 cm and 70 cm were considered. Figure 4 displays the Tangential Channel within the computational model of the JSI TRIGA reactor with a Cd shield modelled explicitly. Neutron spectra in 640 energy groups were calculated in the volume within the cadmium shield. Figure 5 displays the effect of the cadmium shield on the neutron spectrum for different shield lengths.

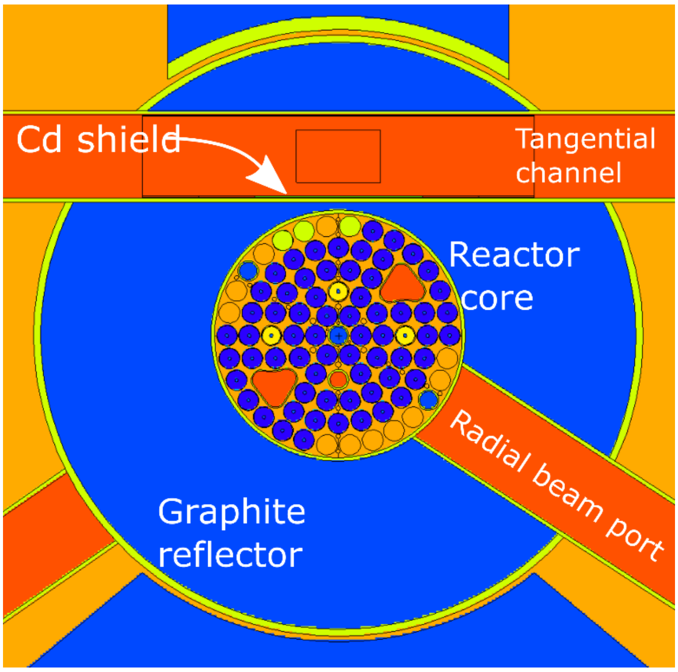

Figure 4: Top view of the computational model of the JSI TRIGA reactor

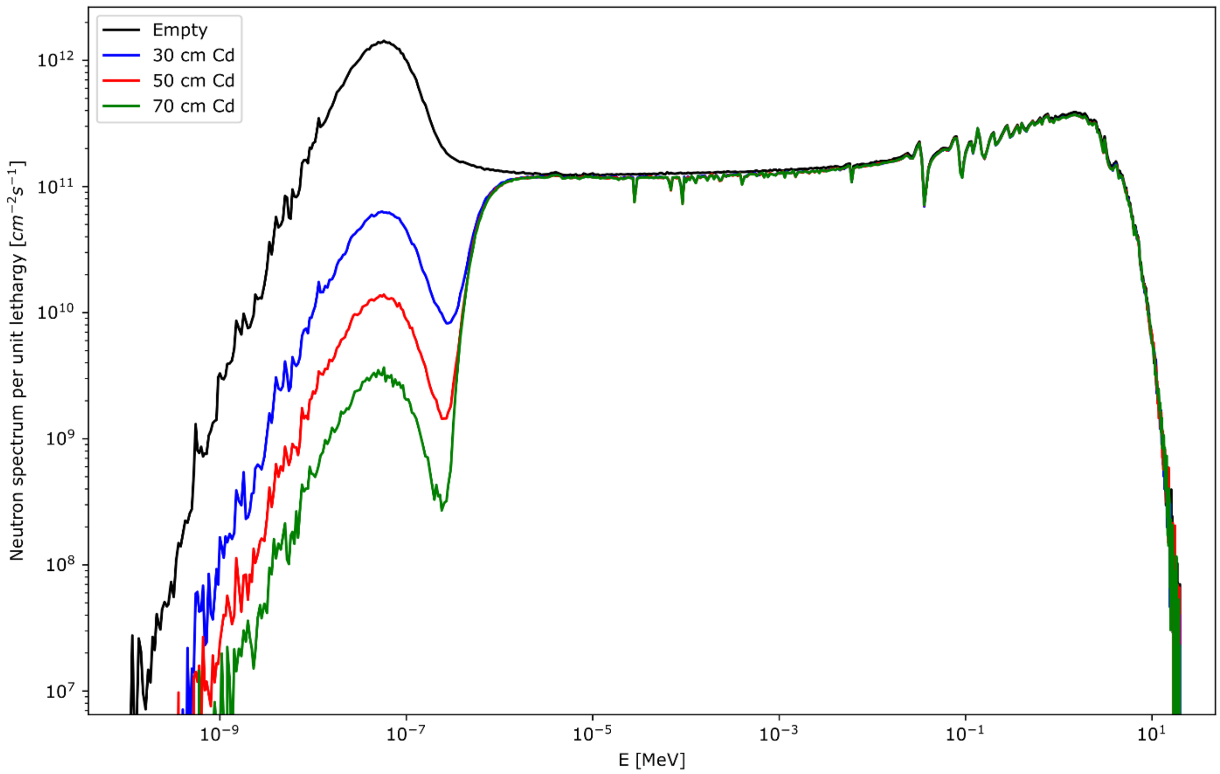

Figure 5: Neutron spectra in lethargy representation in the irradiation volume within the cadmium shield in the Large object irradiation device in the tangential channel of the JSI TRIGA reactor.

From the spectra displayed in Figure 5 it is evident that the cadmium shield introduces a sharp cut-off below 1 eV, absorbing the majority of all neutrons with lower energies. Additionally, increasing the length of the cadmium shield further decreases the neutron flux in the thermal energy range. Table 1 lists the calculated total neutron flux values in the thermal, epithermal and fast ranges for the different Cd shield lengths at full reactor power (250 kW). Table 2 lists the thermal, epithermal and fast flux fractions.

Table 1: Absolute thermal, epithermal, fast and total flux levels at full reactor power (250 kW)

Shield length [cm]	Thermal neutron flux (0 – 0.625 eV) [n cm^{-2} s^{-1}]	Epithermal neutron flux (0.625 eV – 100 keV) [n cm^{-2} s^{-1}]	Fast neutron flux (100 keV – 20 MeV) [n cm^{-2} s^{-1}]	Total neutron flux [n cm^{-2} s^{-1}]
No shield (reference)	1.23E+12	7.27E+11	4.94E+11	2.45E+12
30	6.26E+10	6.77E+11	4.76E+11	1.22E+12
50	1.87E+10	6.74E+11	4.76E+11	1.17E+12
70	9.76E+09	6.73E+11	4.76E+11	1.16E+12

Table 2: Thermal, epithermal and fast flux ratios.

Shield length [cm]	Thermal neutron flux ratio (0 – 0.625 eV) [%]	Epithermal neutron flux ratio (0.625 eV – 100 keV) [%]	Fast neutron flux ratio (100 keV – 20 MeV) [%]
No shield (reference)	50.2	29.7	20.1
30	5.2	55.7	39.1
50	1.4	57.7	40.7
70	0.8	58.1	41.1

3.2. CALCULATIONS OF THE 1 MEV DOSE RATE IN SILICON

Calculations of the 1 MeV neutron equivalent dose rates in silicon were performed using the ASTM-E722 standard flux to dose conversion factors [4]. Figure 6 displays the calculated 1 MeV silicon equivalent dose rates. The calculated results indicate that cadmium shields of the lengths considered account for a reduction in the 1 MeV silicon equivalent dose rates of approximately 4 - 5 % compared to the reference case with no cadmium shield.

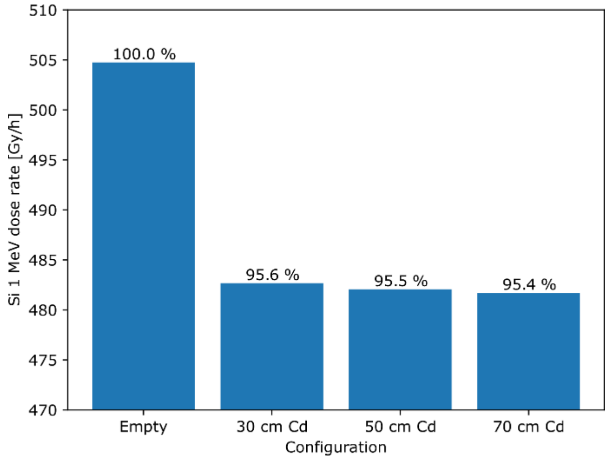

Figure 6: Calculated 1 MeV silicon equivalent dose rates (ASTM-E722) at full reactor power (250 kW).

3.3. CALCULATION OF THE DEVICE REACTIVITY EFFECT

The reactivity effect of experimental equipment (irradiation devices, samples, etc.) installed in the reactor represents an important constraint in the operating limits and conditions of the reactor [5]. Individual samples can have at most a reactivity effect of 0.25 $, or 175 pcm (1 $ = 700 pcm), while experiments can have at most a static reactivity effect of 2.5 $ or 1750 pcm or a dynamic reactivity effect of 1 $, or 700 pcm. The reactivity effect of the cadmium shield must be within the reactivity limits, i.e. static reactivity limit of 2.5 $ if the shield is kept in place during reactor operation or 1 $ if the cadmium shield is moved during reactor operation.

The effect of the shield on the reactivity of the reactor was determined by observing the effective multiplication factor k_{eff} obtained in the Monte Carlo calculations described previously. The reference value for the effective multiplication corresponded to a configuration without the cadmium shield and the control rods at positions corresponding to operation at full reactor power. Table 3 lists the calculated effective multiplication factors and the reactivity effect for cadmium shield lengths of 30 cm, 50 cm and 70 cm.

Table 3: Calculated effective multiplication factors and reactivity effect of Cd liners of different lengths.

Configuration	Effective multiplication factor	Reactivity effect [pcm]	Reactivity effect [$]
Reference – no Cd liner	1.06126 ± 0.00003		
Cd liner, length = 15 cm	1.05975 ± 0.00003	-151 ± 4	-0.22
Cd liner, length = 25 cm	1.05949 ± 0.00003	-177 ± 4	-0.25
Cd liner, length = 35 cm	1.05942 ± 0.00003	-184 ± 4	-0.26

From the calculated results it is evident that the presence of a Cd liner within the Tangential Channel does not have a considerable reactivity effect, well below the admissible dynamic reactivity effect for experiments of 1 $ (700 pcm) as per the operating limits and conditions.

3.4. CALCULATION OF ACTIVITIES AND DOSE RATES DUE TO THE CADMIUM SHIELD

Reactor operation with the cadmium shield in place in the Tangential Channel will lead to significant induced activities in the shield itself, which will pose an important constraint with the handling of the device. To support the device design and the formulation of an operation procedure with the cadmium shield in use, calculations were performed of the expected contact dose rate originating from the liner vs. cooling time. Three overall shield lengths were considered, corresponding to the calculations of the effect of the cadmium shield on the neutron spectrum within and the reactivity effect, as outlined in the previous sections: 30 cm, 50 cm, 70 cm. Reactor operation times of 5 h and 10 h at full reactor power (250 kW) were chosen. The calculations were performed using the JSI-developed calculation scheme JSIR2S [6], coupling Monte Carlo the MCNP code for particle transport calculations and the FISPACT-II [7] code for activation calculations. Figure 7 displays the calculated contact dose rates for cadmium shields of different lengths vs. time for full power operation times of 5 h and 10 h.

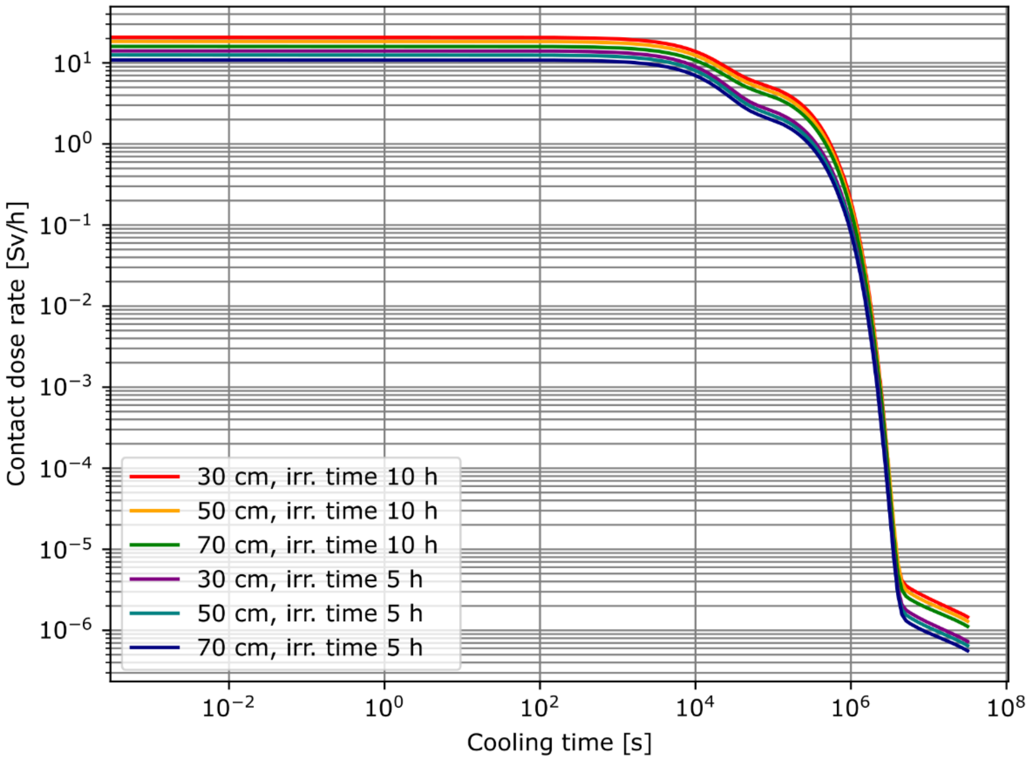

Figure 7: calculated contact dose rates for cadmium shields of different lengths vs. time for full power operation times of 5 h and 10 h.

It is evident that immediately after reactor operation the cadmium liner will become activated and that the expected contact dose rate will exceed 10 Sv/h. An appropriate cooling time will have to be observed for safe extraction and handling of the irradiated Cd liner. According to the operating limits and conditions, irradiated experimental equipment with a dose rate not exceeding 10 mSv/h at 1 m can be extracted from the reactor and handled in the radiation-controlled area. A conservative estimate of the cooling time after which the contact dose rate decreases to 10 mSv/h after a 10 h irradiation time is 20 days. The need for a cooling time in excess of several days after each use of the cadmium shield would considerably affect normal reactor operation. Therefore, to minimize the impact of the use of the cadmium shield on normal reactor operation, two shield positions within the Tangential Channel are considered:

- centered on the reactor core, when in use
- withdrawn from the vicinity of the reactor core, when not in use.

Withdrawing the shield from the vicinity of the reactor core will reduce its exposure to thermal neutrons by multiple orders of magnitude. Achieving an appropriate cooling time required before extraction will thus be possible without affecting normal reactor operation, with the shield located within the concrete biological shield of the reactor, effectively shielding radiation due to activation products.

3.5. CALCULATION OF ACTIVITIES AND DOSE RATES DUE TO THE CADMIUM SHIELD

Calculations of material activation and dose rates were performed to obtain indications of the effect of the cadmium shield and to support the device operation. The calculations were performed using the neutron spectra calculated with the MCNP code and an additional activation step using the FISPACT-II code. Figures 9 to 28 in the Appendix display the calculated time dependences of the specific activities in Bq/g and the contact dose rates in Sv/h after a 10 h irradiation time at full reactor power, for a selection of typical constituent materials of electronic components.

4. DEVICE DESIGN

The proposed design of the cadmium consists of three main components. An aluminium tube, machined to fit within the existing aluminium liner of the Large object irradiation device will serve as a structural component. It will consist of a tube with two flanges. A cadmium foil will be secured onto the outer surface of the tube in between the flanges. By this design, irradiated samples will not come in direct contact with the cadmium material. A flexible aluminium strip will be attached to the flange on the aluminium tube, enabling movement of the liner. The selected cadmium shield length, based on the results in the present report and practical considerations is 50 cm. Figure 8 displays the conceptual design of the shield.

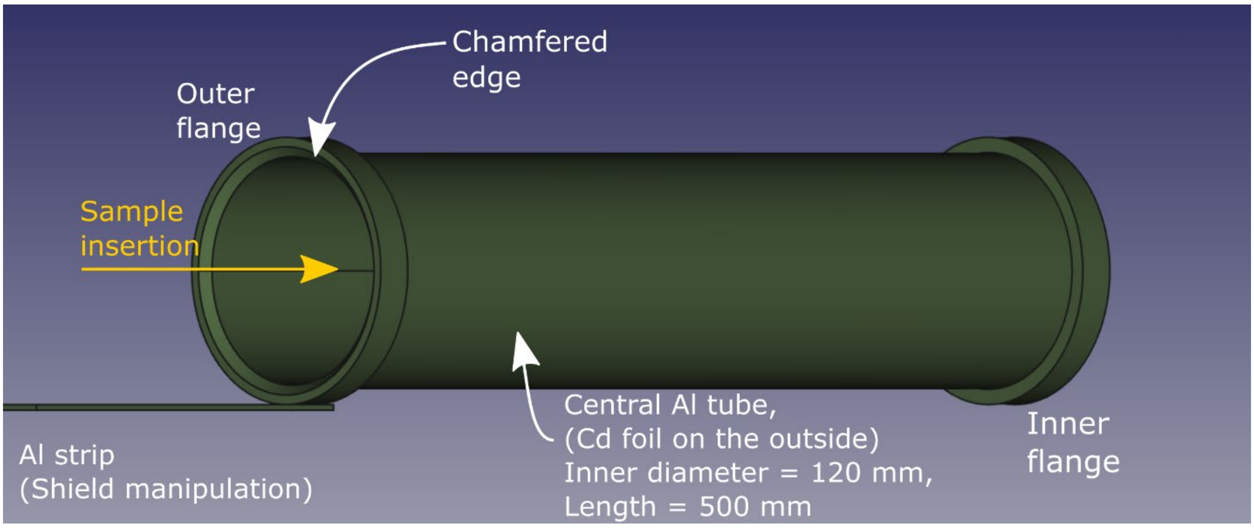

Figure 8: Conceptual design of the Cd shield.

Samples to be irradiated will be mounted onto a polyethylene holder and inserted into the cadmium shield. To facilitate insertion, the flanges on the cadmium shield will have pronounced chamfers. After irradiation the cadmium shield will be partially withdrawn to limit further activation and achieve an appropriate cooling time. When not in use, it will be possible to store the cadmium shield within an existing concrete shield designed for storage of the inner concrete / steel plugs of the reactor beam ports.

5. Summary and conclusions

This report presents the computational support needed for the design of a cadmium shield device aimed at reducing material activation in samples irradiated in the Large object irradiation facility in the JSI TRIGA reactor due to thermal neutrons. Quantities relevant for the device design and operation were calculated using the Monte Carlo particle transport code MCNP and the material activation code FISPACT-II, coupled in the JSIR2S code. The main results can be summarized as follows:

- The cadmium shield as envisaged will significantly reduce the magnitude of the thermal neutron flux in the Large object irradiation facility, and therefore material activation due to incident thermal neutrons.
- The cadmium shield will have a minor effect on the epithermal and fast components in the neutron spectrum, as well as on the 1 MeV silicon equivalent dose.
- The cadmium shield will have a low effect on the reactivity of the reactor, well below the admissible dynamic reactivity effect for experiments.
- The cadmium shield will become activated after irradiation. An appropriate cooling time before extraction of the shield will be achieved by partial withdrawal of the shield into an area with a significantly lower thermal neutron flux.
- Material activation calculations for typical constituents of electronic components were performed to support the use of the cadmium shield.

A conceptual design of a cadmium shield has been achieved with the desired properties and compatibility with the operation of the JSI TRIGA reactor.

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APPENDIX

Figures 9-28 display the calculated time dependence specific activity and contact dose rates for typical constituents of electronic devices after a 10-h irradiation at full reactor power (250 kW).

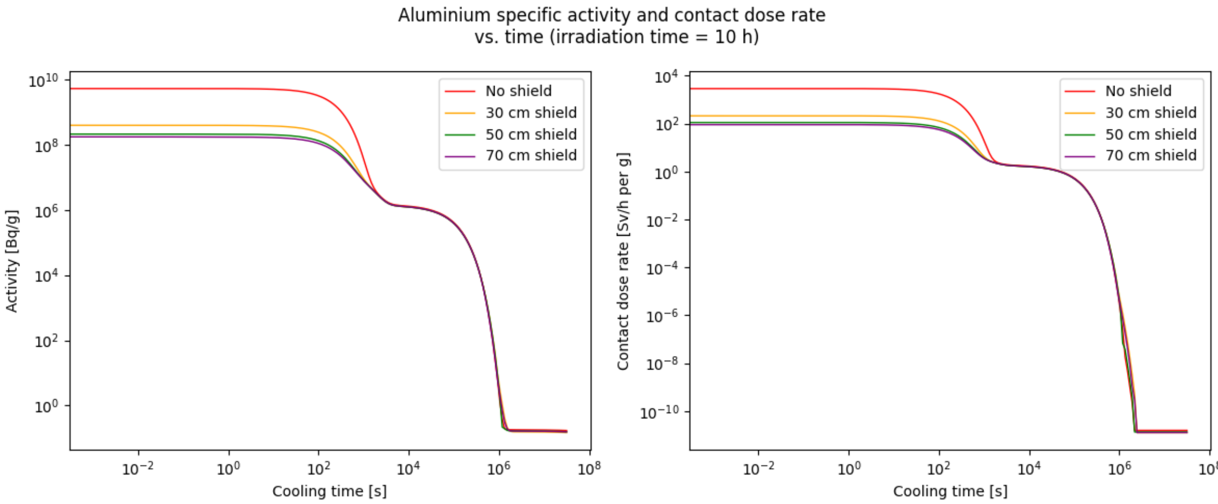

Figure 9: Aluminium specific activity and contact dose rate vs. time.

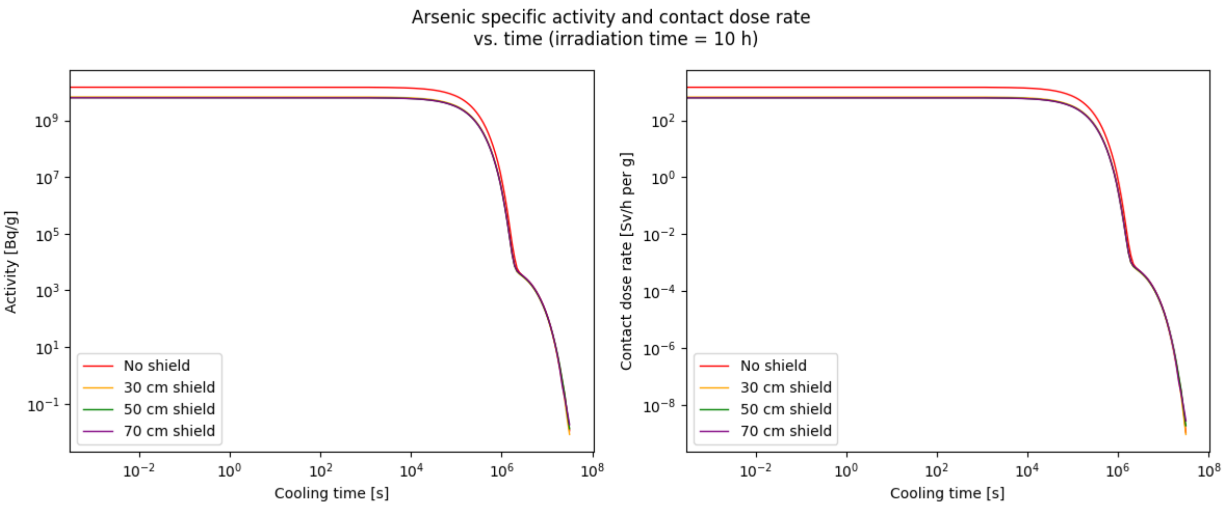

Figure 10: Arsenic specific activity and contact dose rate vs. time.

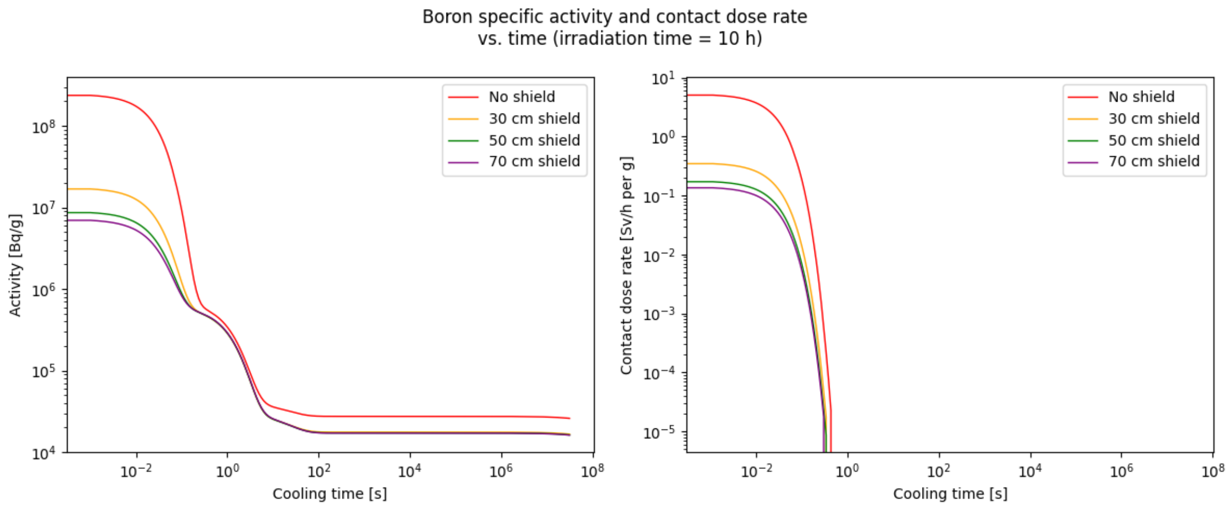

Figure 11: Boron specific activity and contact dose rate vs. time.

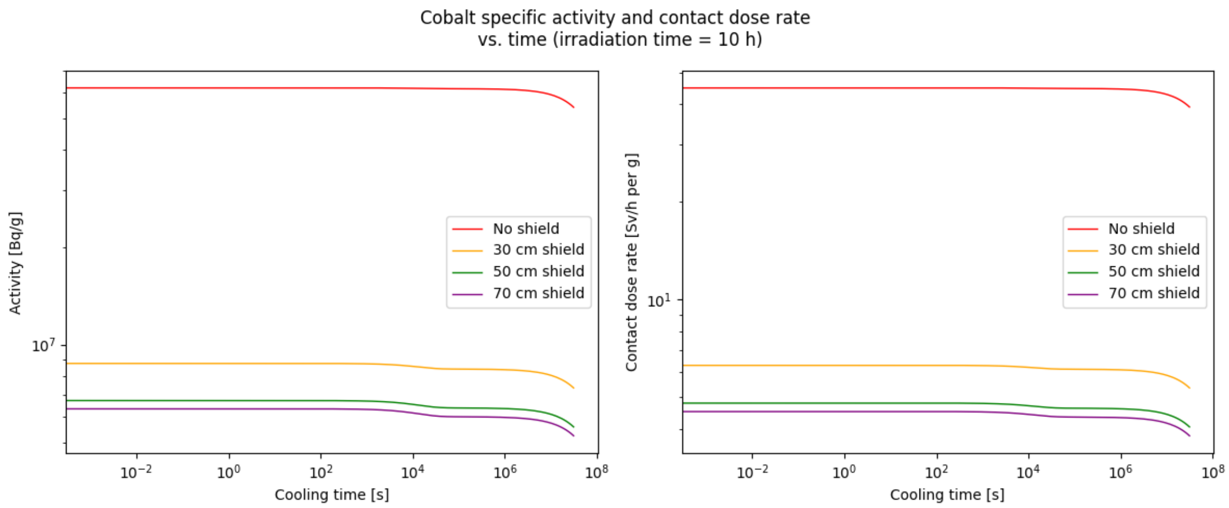

Figure 12: Cobalt specific activity and contact dose rate vs. time.

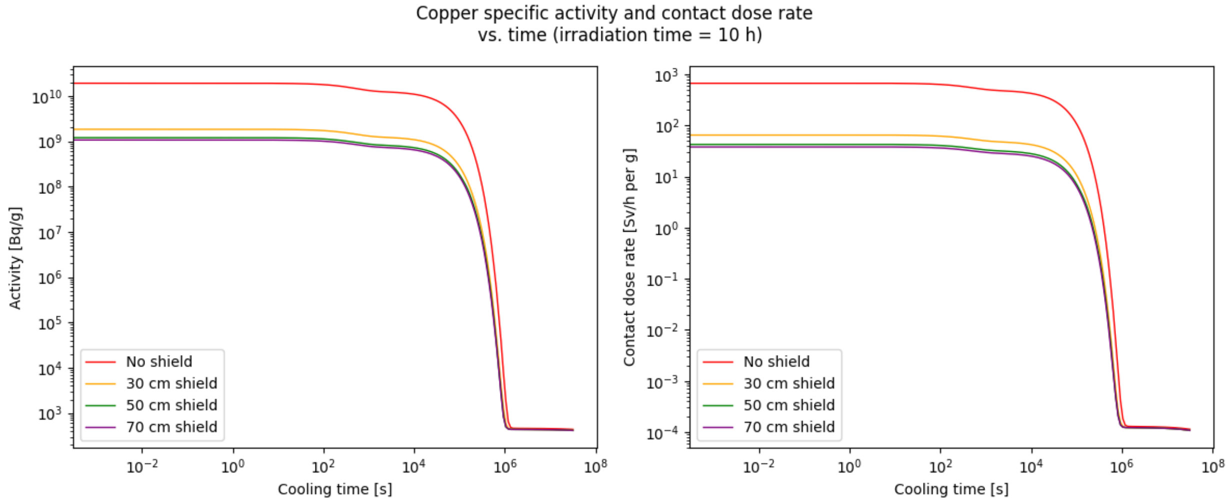

Figure 13: Copper specific activity and contact dose rate vs. time.

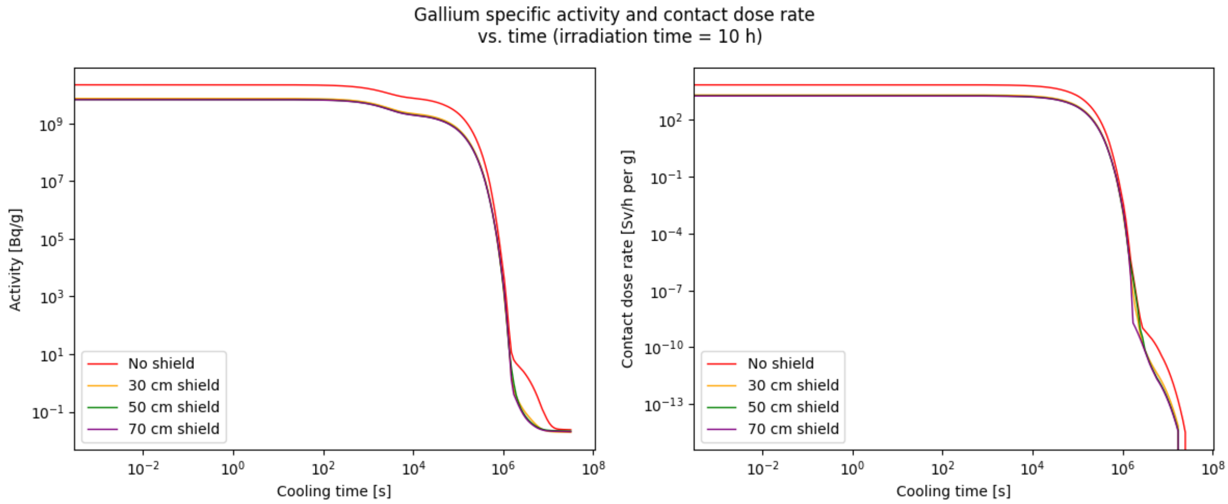

Figure 14: Gallium specific activity and contact dose rate vs. time.

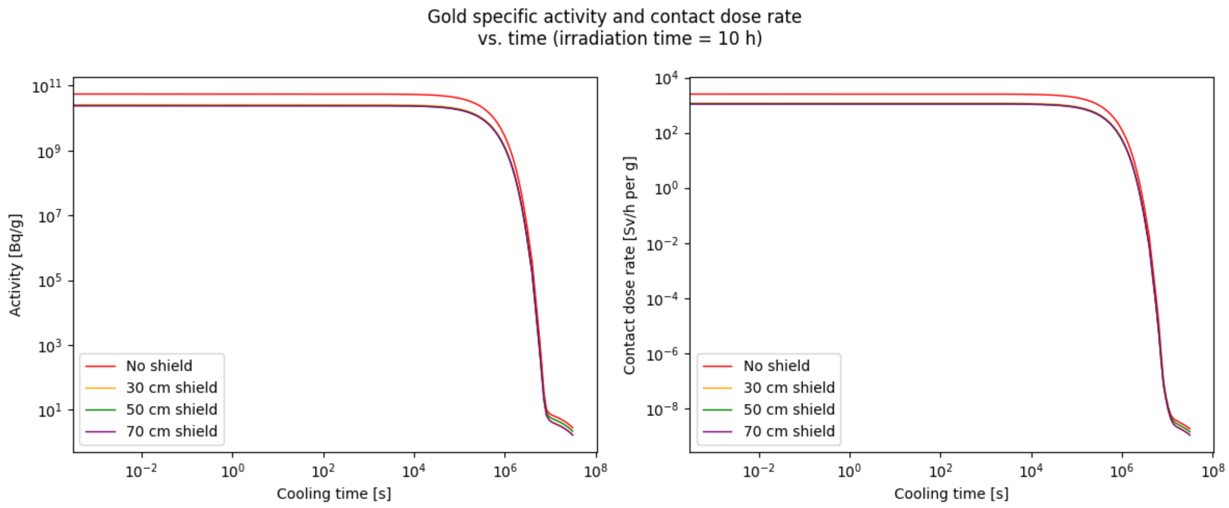

Figure 15: Gold specific activity and contact dose rate vs. time.

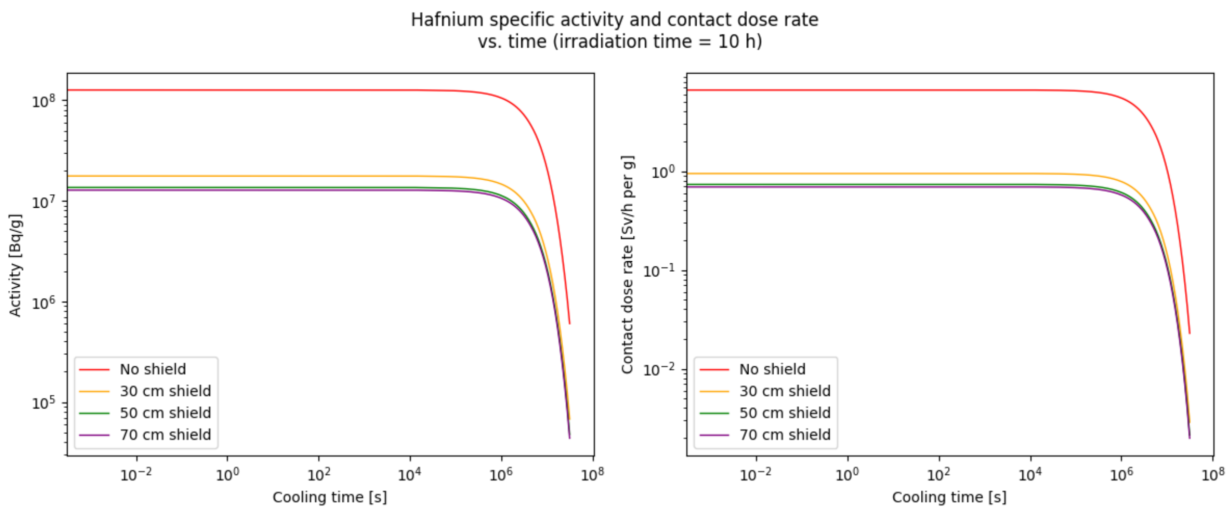

Figure 16: Hafnium specific activity and contact dose rate vs. time.

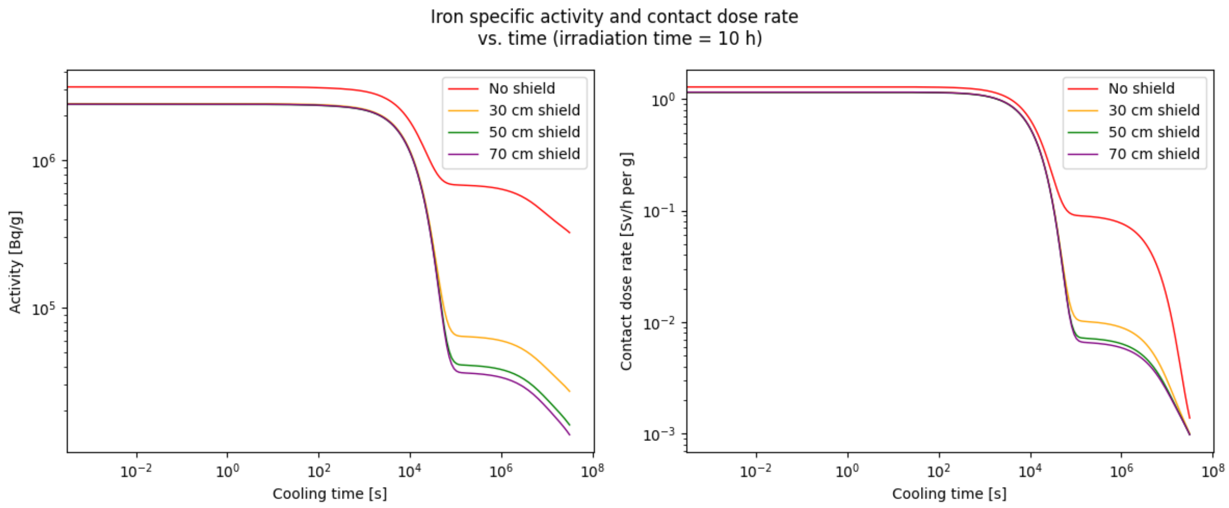

Figure 17: Iron specific activity and contact dose rate vs. time.

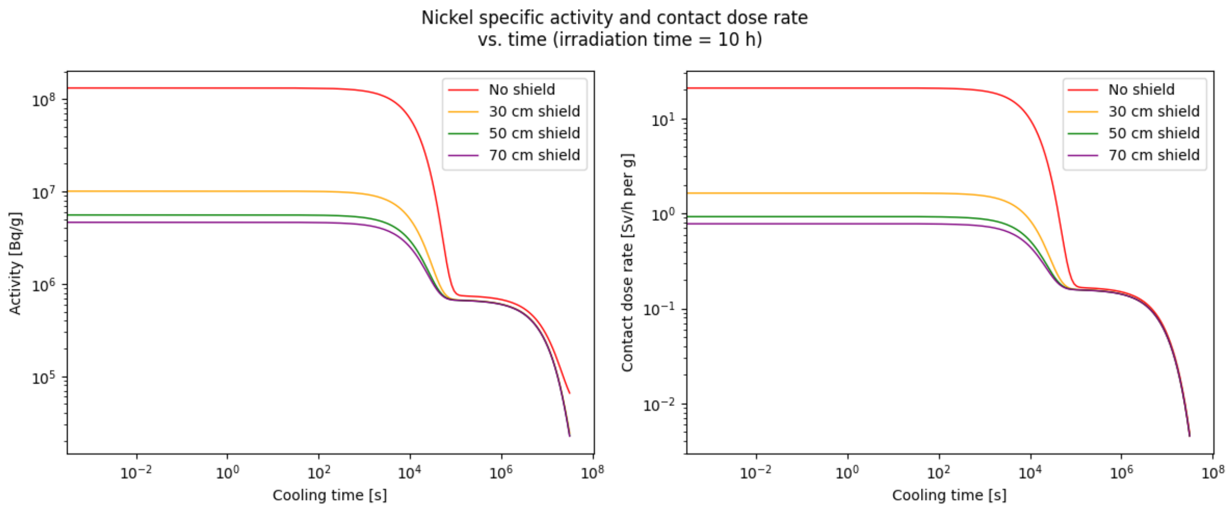

Figure 18: Nickel specific activity and contact dose rate vs. time.

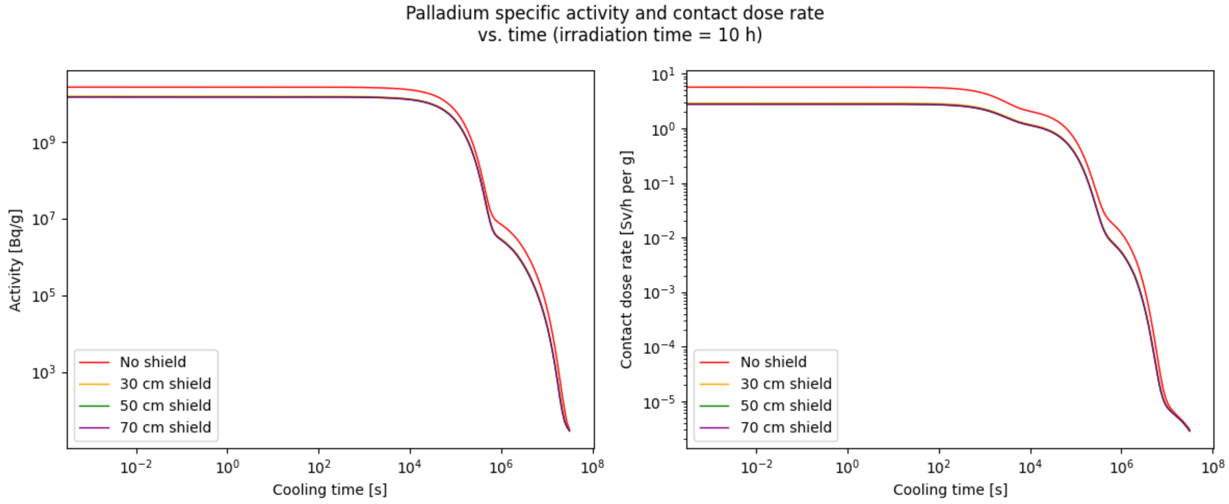

Figure 19: Palladium specific activity and contact dose rate vs. time.

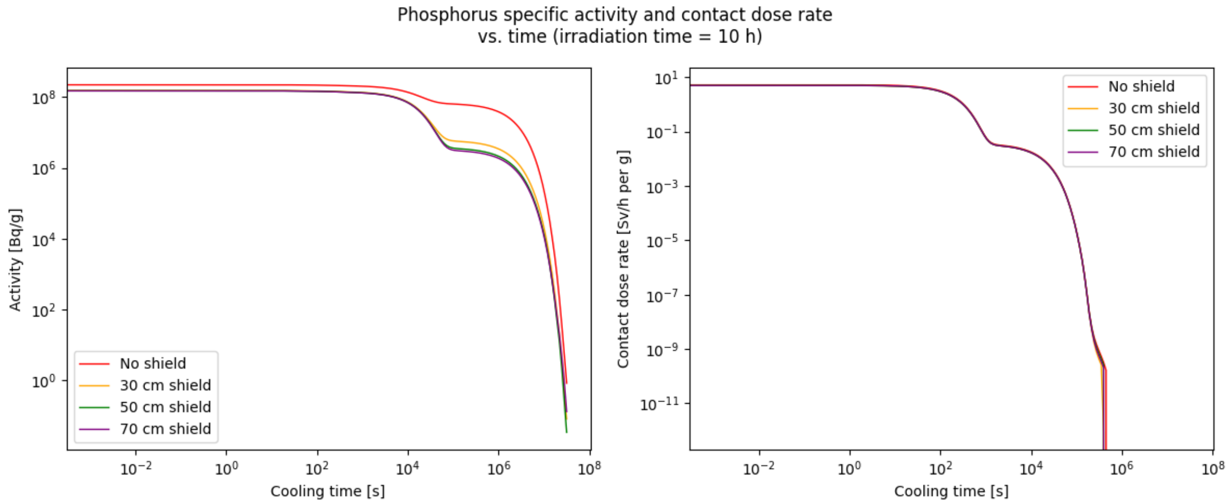

Figure 20: Phosphorous specific activity and contact dose rate vs. time.

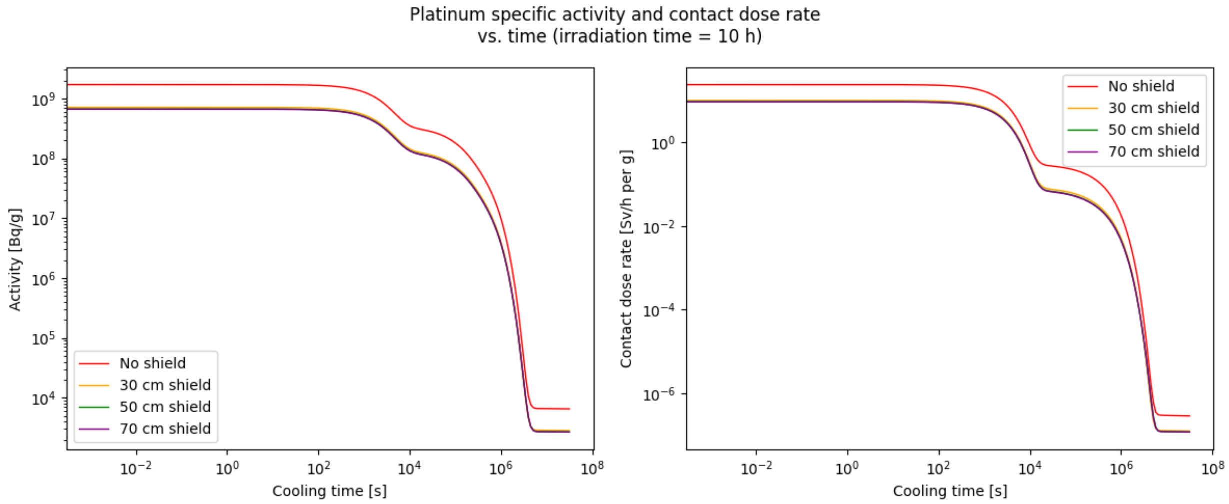

Figure 21: Platinum specific activity and contact dose rate vs. time.

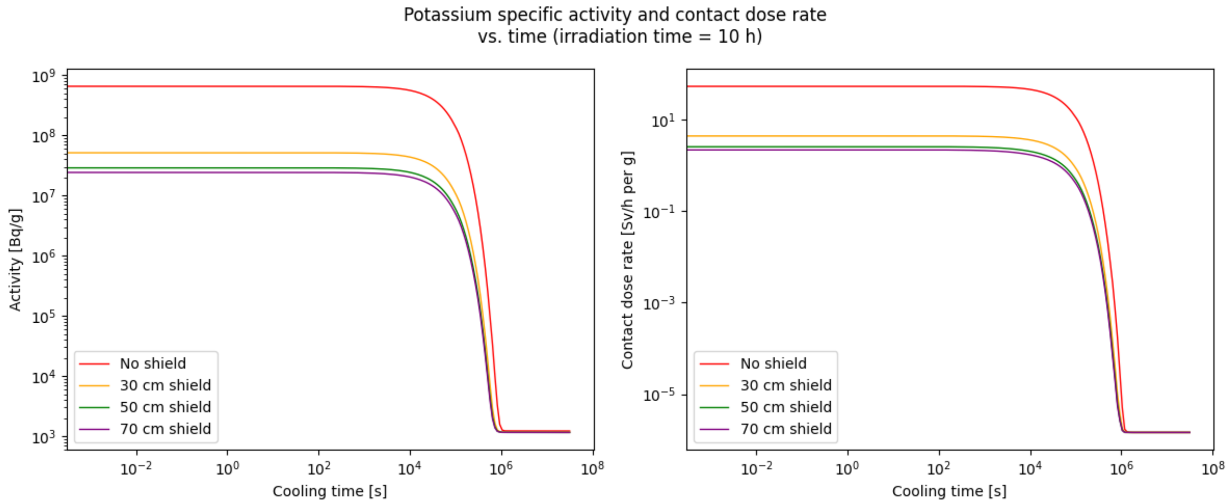

Figure 22: Potassium specific activity and contact dose rate vs. time.

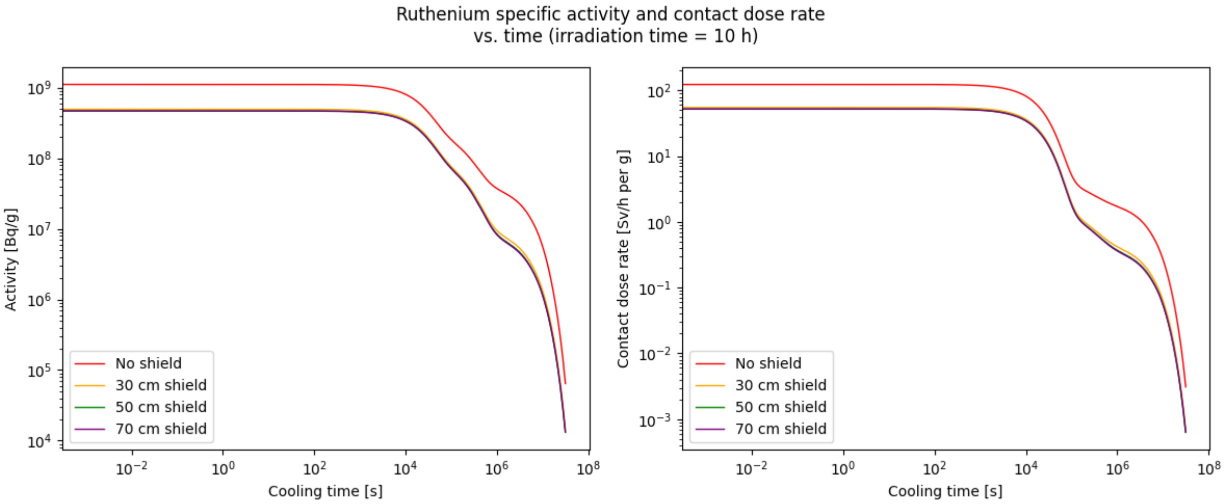

Figure 23: Ruthenium specific activity and contact dose rate vs. time.

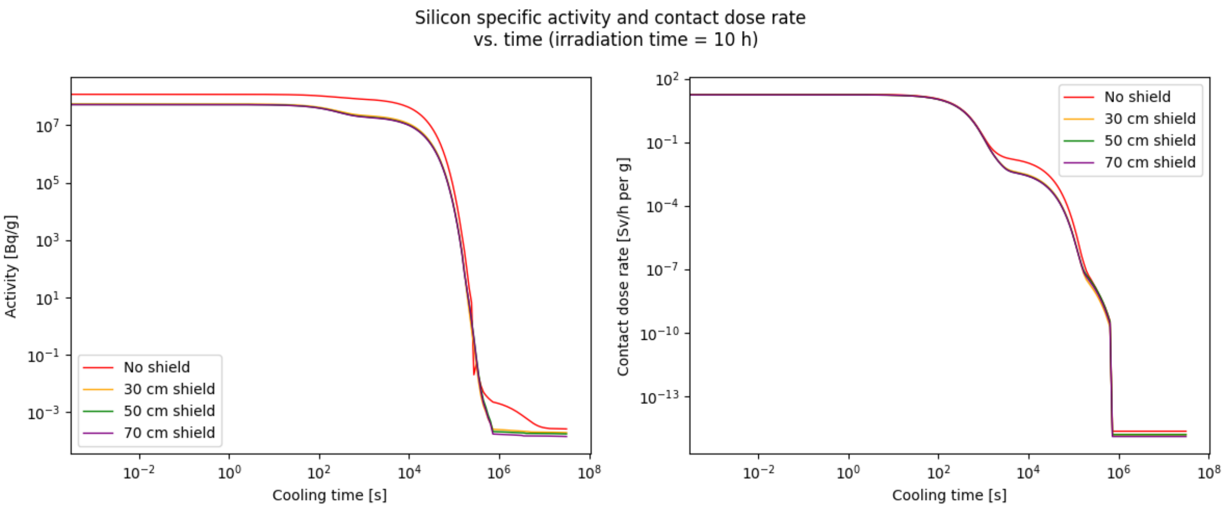

Figure 24: Silicon specific activity and contact dose rate vs. time.

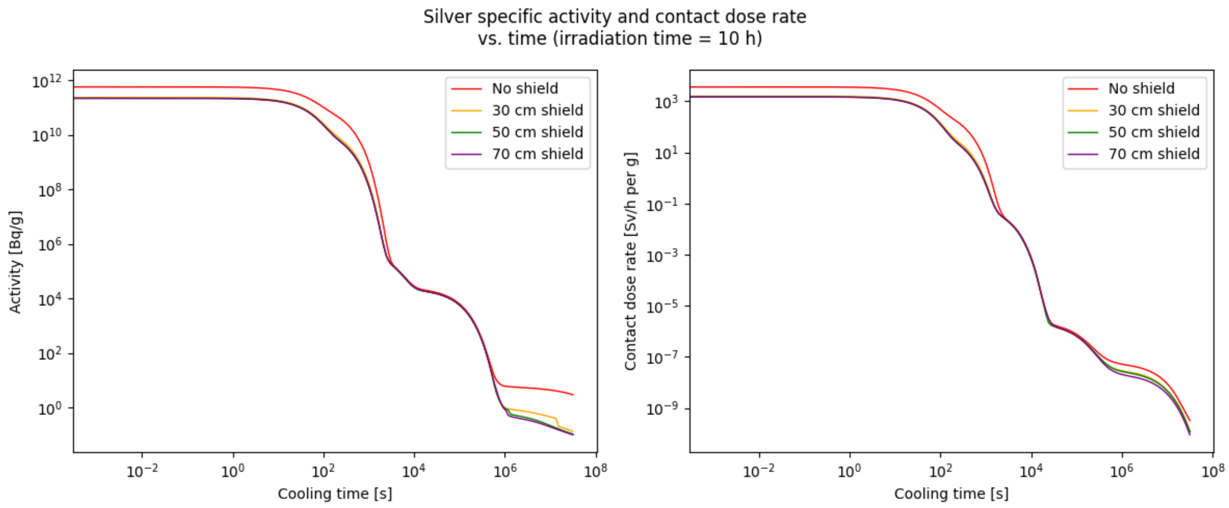

Figure 25: Silver specific activity and contact dose rate vs. time.

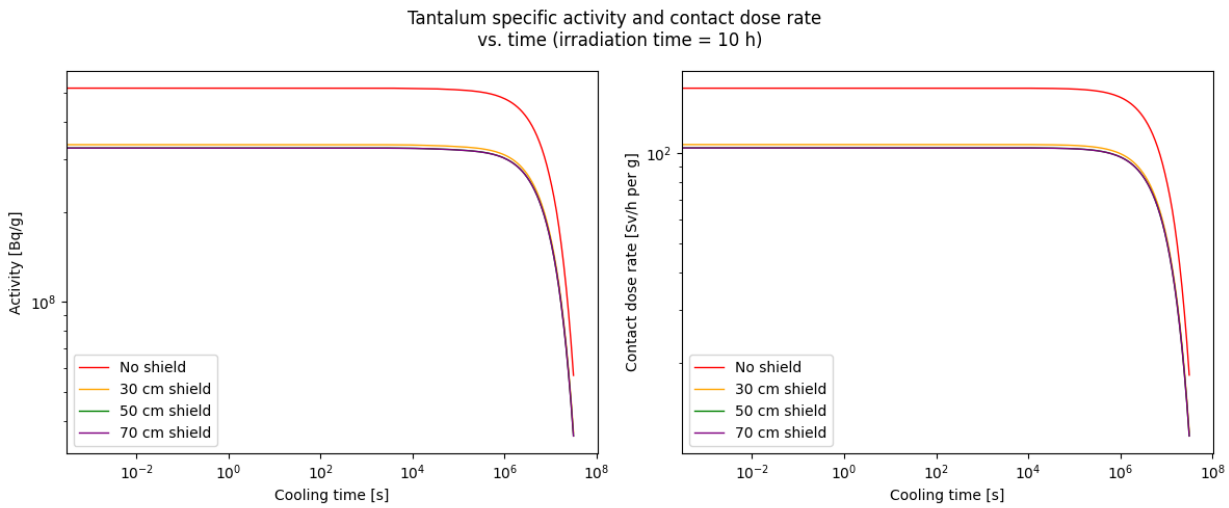

Figure 26: Tantalum specific activity and contact dose rate vs. time.

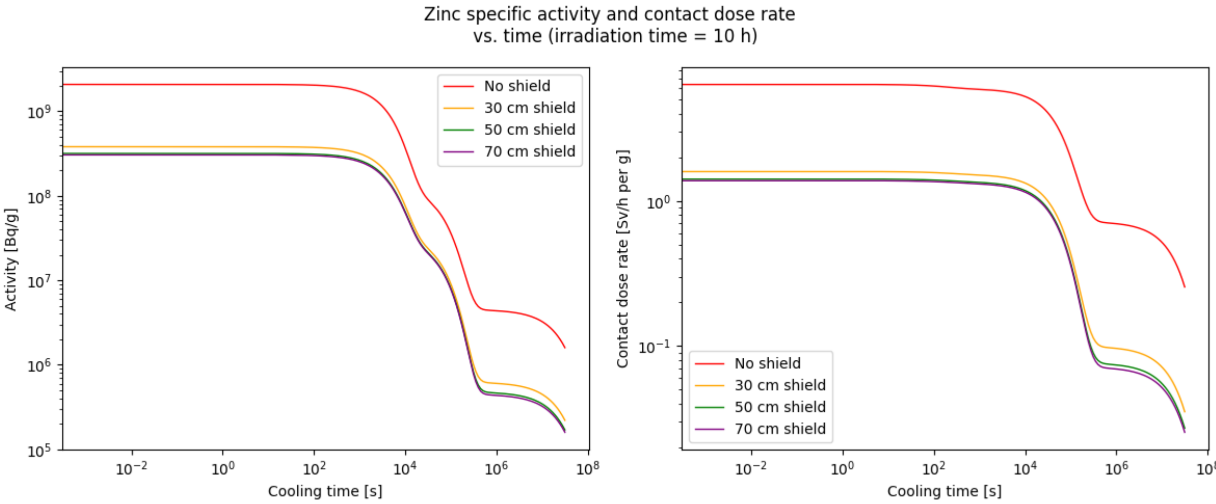

Figure 27: Zinc specific activity and contact dose rate vs. time.

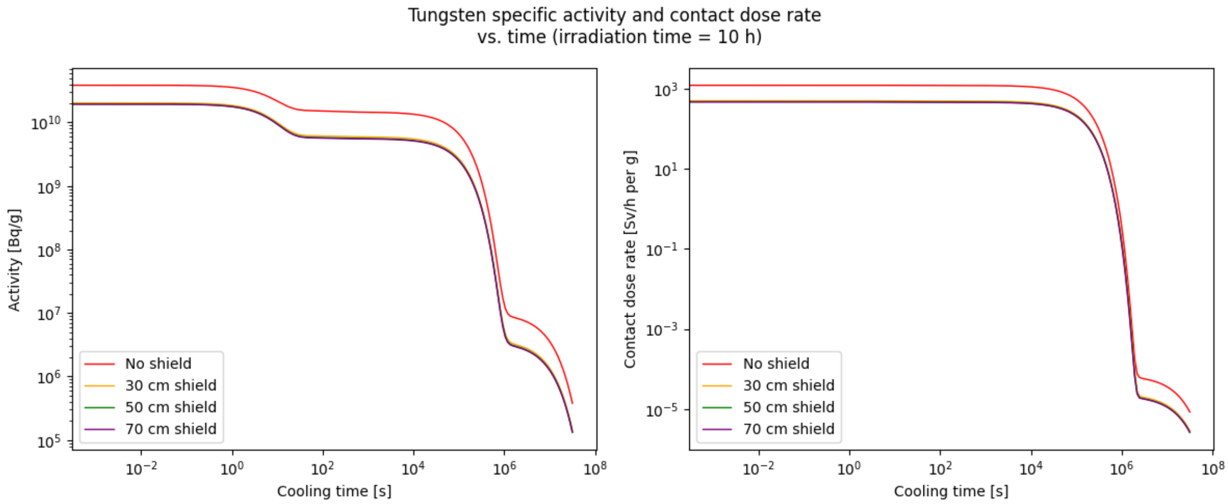

Figure 28: Tungsten specific activity and contact dose rate vs. time.