ICANS XIX,
19th meeting on Collaboration of Advanced Neutron Sources
March 8 – 12, 2010
Grindelwald, Switzerland

NEUTRONICS ANALYSES IN SUPPORT OF ROTATING TARGET DEVELOPMENTS AT SNS

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ABSTRACT

A second target station (STS) for Spallation Neutron Souce (SNS) very likely being operated in long-pulse mode is in the early design phase, will complement the ORNL neutron sources, which presently consist of a short-pulse spallation source and the HFIR research reactor. As an alternative to the stationary liquid metal target, a rotating target is being considered. Neutronics studies in support of a 3MW power 20 Hz repetition rate rotating target feasibility study funded through the laboratory LDRD program, was extended towards a 1.5 MW STS design. The scope of work included in-operation heat deposition rates in target structures for thermal and structural analyses, target radionuclide inventory for decay heat and safety analyses, lifetime estimations due to radiation-driven material damage of target and moderator components, moderator neutron performance and moderator cryogenic heatloads.

1. Introduction

With power levels of the new pulsed facilities achieving the megawatt power level, with newly planned spallation sources entering the multi-megawatt terrain and with no target vessel material in sight that might tolerate the radiation damage to extended DPA limits, the rotating target becomes again attractive as it allows to spread the radiation induced material damage around the circumference and the heating throughout the volume of a target disk and thus drastically extend the target life time.

A design concept for a rotating solid target that could accept a proton beam power of 3 MW in a SNS second target station (STS) has been developed as part of an ORNL/LDRD program [1] as an alternative to the liquid mercury target target design. Later the STS power level was defined to 1.5 MW, which initiated a redesign of the rotating target to adapt it to the lower power requirement. It is the 1.5 MW rotating target design we are reporting on in this paper.

In a white paper, a SNS second target station was proposed as a complementary facility to the first operating target station mainly focusing on highly intense cold neutron applications [2]. Target/moderator/reflector assembly (TMRA) optimization studies for this proposal arrived at a solution of two large-volume para-hydrogen moderators viewed in wing geometry on top and bottom of a flattened liquid metal target [3].

The same moderator suite was tuned to a rotating target with the intention to evaluate the neutronics effectiveness of a rotating target arrangement. Furthermore energy deposition rates in the target disk were provided for thermal and stress analyses that drove the engineering design [1]. Also energy deposition into the moderator systems was studied in the final TMRA, as well as target and moderator radiation-induced material damage. Finally decay-heat calculations were performed for identifying the heat sources for beam-off conditions and accident scenarios.

2. Design Requirements

The second target station (STS) will be optimized to produce the brightest cold neutron beams with a 1.3 GeV proton beam at 20 Hz. Large-volume supercritical para-hydrogen moderators at 20 K temperature were used to ease comparison to moderator performance. The question of proton pulse length between long-pulse (1ms) or short-pulse (1µs) mode is still open and will be driven by the performance of neutron instrumentation. The design must support 18 to 24 beamlines viewing the moderators positioned above and below the target. Decay heat loads must be determined and heat removal systems for the target under off normal conditions must be developed in conjunction with the facility safety assessment.

This study assumed tantalum clad tungsten as target because of good operating and fabrication experience with these materials at ISIS, Lujan Center and KENS. The tungsten bricks would be watercooled and contained within a stainless steel shell.

Preliminary evaluations indicated that a target diameter of 1 to 1.5 m would give lifetimes on the order of 5 to 8 years for 10 dpa on the window at 3 MW with low average heat loads. A disk diameter of 1.2 m was selected for this study starting with a tungsten depth of 300 mm. Rotation speeds of 30 to 60 rpm avoid overlapping of the proton beam induced energy deposition footprint in the target.

A flat proton beam profile was used for the design study with a beam footprint of 5400 mm^2 obtainable by rastering the one millisecond pulse in a rectangular region as proposed for the Material Test Station at Los Alamos National Laboratory [5] or by expanding the Gaussian shape linac beam with higher-order magnetical systems. It is only the latter version that would be feasible for flattening the proton profile in short-pulse mode.

2. Methods of Calculations

The neutronics design task is two-fold. Firstly, it is instrumental to find a target-reflector-moderator assembly (TMRA) that provides the best neutron output into beamlines. Secondly, neutronics data are needed to answer various engineering questions, like energy deposition data for subsequent thermal and structural analyses, the heat input of the moderator units for designing the cryogenic system, and material damage for component lifetime predictions. Ultimately both tasks are interwoven, since engineering establishes constraints that are folded back into further optimization studies.

All multi-particle transport analyses were performed with MCNPX version 2.5.0 or 2.6.0 using default settings of physics parameters [6]. Global optimizer strategies applying Bayesian algorithms were applied for the neutron performance optimization of the TMRA [3]. The analyses of buildup and decay of radionuclides, estimates of activity and decay heat was performed with the CINDER'90 code package [7].

3. Neutronics Performance

Extensive studies were performed for a second SNS target station optimized for high-intensity cold neutron fluxes on a liquid target. In these studies, a TMRA configuration of two large volume cylindrical para-hydrogen moderators positioned on top and bottom of a flat target in wing configuration and surrounded by a layer of ambient light water and by a beryllium reflector emerged as the optimum solution considering the 18-24 beam ports the moderators have to serve. Beam lines view the cold source at three ports at viewing areas of 100 mm width and 120 mm height.

This TMRA configuration was used as baseline substituting the liquid mercury target by the rotating target and optimized to the different target. Tantalum clad tungsten was

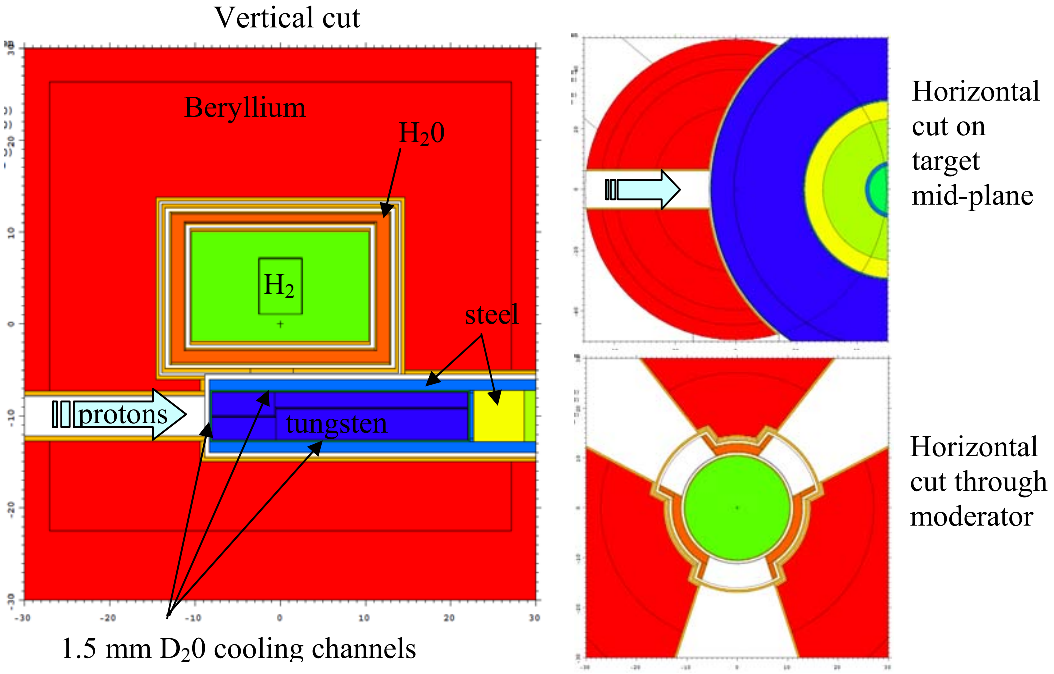


Fig. 1: Target, moderator, reflector assembly (TMRA) of a STS based on a rotating target.

considered as first choice target material for its high atomic mass and high density and availability, but also for the experience base as spallation target. Scoping studies of energy deposition and heat removal lead to a design with a bulk tungsten ring of 600 mm outer and 350 mm inner radius backed on the inside by a steel hub. The bulk tungsten would be edge-cooled by forced water flow in the radial direction and across the front face. A central cooling water channel as needed for the 3 MW LDRD design could be eliminated because of the reduced power level.

Figure 1 shows the layout of the final optimized TMRA with a para-hydrogen moderator height and diameter of 120 mm and 220 mm, respectively, pre-moderator thicknesses of 13 mm, 15 mm and 9 mm, at the bottom, top and radially, respectively, with a target height of 53 mm. The optimal moderator axis position arrived at 520 mm distance from the rotating target axis.

In this configuration, the time-integrated cold neutron flux of energies below 5 meV in a beam line at 10 meter distance viewing a 100×120 mm^2 area of moderator is approximtelly $6.67 \cdot 10^{-8}$ n/cm^2/proton and 17% higher compared to that of a TMRA driven by a mercury target. Changing the heavy water coolant in the rotating target assembly to light water reduces the neutron performance only by 2%.

A comparison of time-averaged neutron brightness of the STS moderator against the moderators at the first SNS target station is shown in Fig.2, illustrating that STS will provide a factor of 5 higher cold neutron fluxes to the instruments. A comparison with regard to the mercury driven STS shows a gain of 17% in time-integrated brightness, a gain of approximately 25% in peak brightness both in short-pulse and long-pulse mode all in favor of the rotating target configuration. The higher gains for the peak brightness compared to the time averaged brightness comes by the fact that the large target disk acts as a decoupler of the bottom half of the reflector shortening the short-pulse pulse widths in the rotating target configuration. In long-pulse mode this effect means a faster ramp-up and ramp-down of the pulses losing fewer neutrons in the pulse tails.

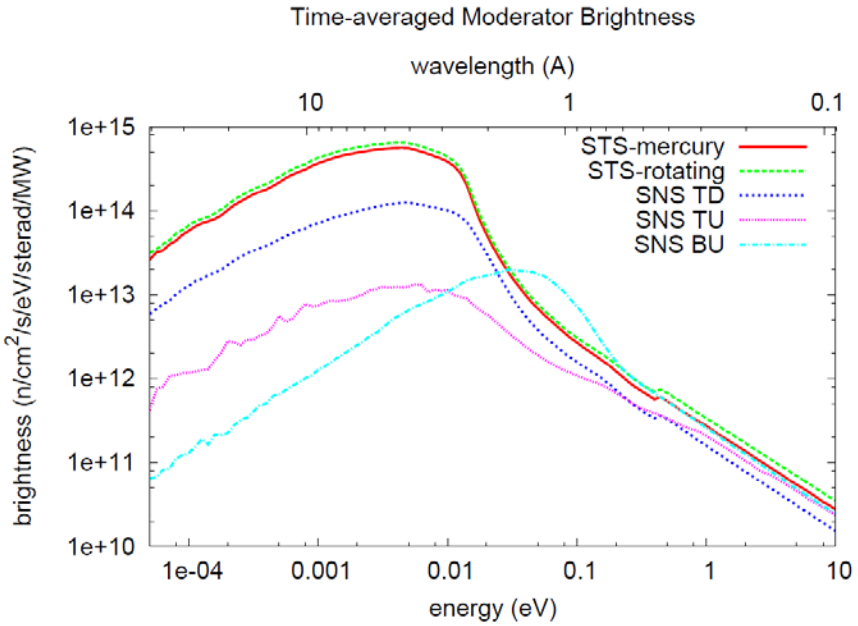


Fig. 2: Neutron brightness of second SNS target station (STS) compared to performance of the top upstream (TU) and top downstream (TD) supercritical hydrogen moderators and the bottom upstream (BU) ambient water moderator of the first SNS target station.

4. Radiation-induced Material Damage

For the optimized configuration, the material damage of key components was assessed folding DPA cross sections [8] with neutron and proton fluxes. Results are summarized in Table I. While the rotating target structures spend only a fraction of the operations time in the high flux zone, the moderator structures are exposed permanently to severe radiation fields. Hence it is not surprising that the moderator structures exhibit more than a factor of 10 higher dpa rates resulting in shorter life times and higher frequency of exchange than the rotating target structure. For a 10-DPA-limit on the steel target vessel, the lifetime would be 11 years while the moderators at a 20-DPA-limit for Al6061 would likely need to be replaced about once every 2 years at 5000 hours of beam time per year.

Table I: Estimated dpa values in STS key components based on 1.5MW power and 5000 hours of operations per year.

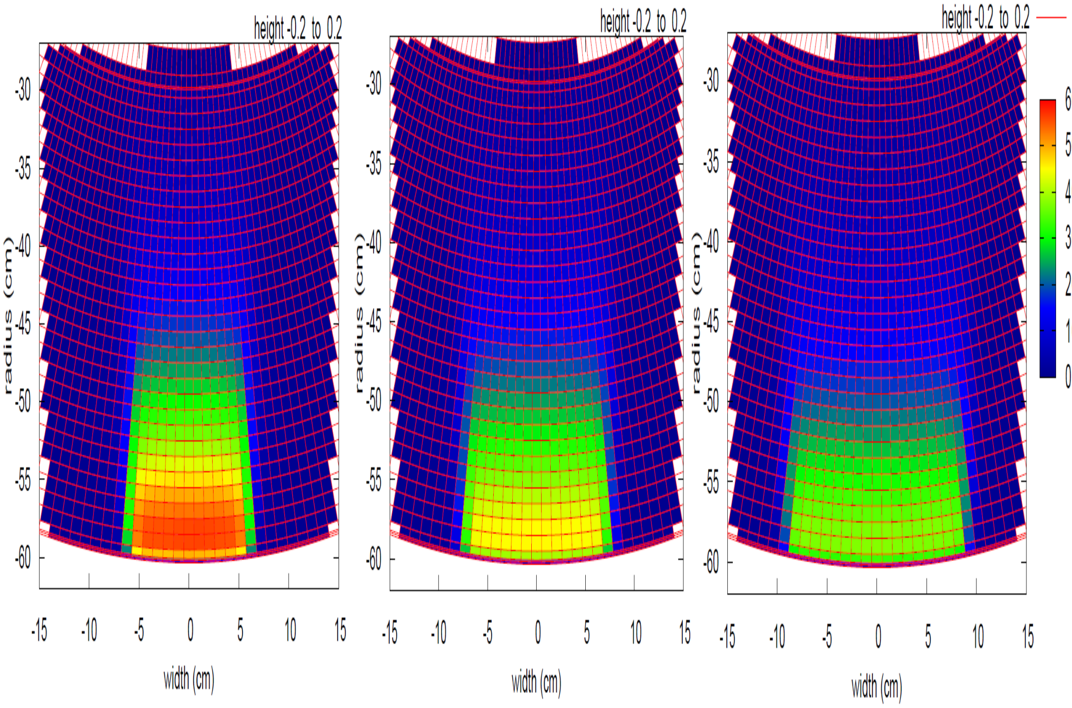
Component	**Flat beam**
Target vessel (SS316)	0.91 dpa/yr
Tantalum cladding	1.14 dpa/yr
Tungsten bulk	1.40 dpa/yr
Moderator structure (Al6061)	12 dpa/yr

5. Target Energy Deposition

Radiation induced energy deposition in the target and moderator assemblies was assessed for the optimized TMRA as a basis for subsequent thermal and structural analyses and for estimating the cooling capacity of the moderator cryogenic systems.

The fraction of 61% of the incident beam energy is deposited into the target structure, the balance is deposited in the surrounding moderator, reflector and shielding or invested into the binding energy of secondary particle production of the spallation interactions. The peak energy deposition in the target structure reaches 57 J/cc/pulse in the bulk tungsten for a proton beam width of 123 mm, and drops to 46 J/cc and 39 J/cc for proton beam widths of 152 and 184 mm, respectively.

Peak time-averaged heating is approximately 37 W/cc versus the 1140 W/cc heating if the target was stationary for 123 mm beam width.



beam width 123 mm beam width 152 mm beam width 184 mm

Fig. 4: Energy deposition rates (J/cm^3) in a horizontal slice of the rotating target in beam centerline. Cases of flat beam profiles with height 44 mm and various beam widths are compared.

6. Moderator Energy Deposition

Table II summarizes and compares the heating in the moderator components for 1.5 MW power delivered by a proton beam of 123 mm width, and also lists values for an equivalent moderator system at a mercury target.

However, larger differences with about 33% higher heating of the cryogenic part and 92% higher heating in the ambient part of the moderator are found comparing to the moderator at a mercury target. The origin of the increased heating driving the size and expense of the refrigerating systems needs further investigation.

Table II: Time-averaged heating in moderator components normalized to 1.5 MW beam power for cylindrical moderators at a rotating target and for an equivalent system at a mercury target.

Component	**Heating (W)**	
	Rotating tungsten target	Mercury target
H2 moderator	4600 W	3450 W
H2-vessel	1100 W	825 W
H2O pre-mod	8050 W	4600 W
Pre-mod vessel	2400 W	1200 W
Moderator hull	3200 W	1700 W

7. Reduction Measures for Moderator DPA and Heating

Mechnisms were sought for reducing the moderator peak DPA and heatloads.

Two measures were invesitgated: firstly to increase the gap between moderator and target, and secondly to increase the width of the proton beam. While both measures targeted the peak DPA rate, only first measure effected the moderator heatload.

The results are shown in the graphs of Fig. 5. Increasing the gap from 5 mm to 15 mm decreases the peak material damage about 17% at only 2% losses of neutron performance. This measure also reduces the moderator heatload of the cryogenic and ambient parts about 9% and 25%, respectively. Increasing the proton beam width by 50% reduces the neutron performance by only 3% at a reduction of the peak moderator dpa of 21%, and an obvious reduction in the peak target energy deposition of 66%.

7. Target Decay Power

The decay power of the target structure was determined assuming 10 years continuous operation at 1.5 MW power feeding MCNPX calculated neutron flux and isotope production rates into the nuclear inventory analyses.

The timeline of the resulting decay power is shown in Fig. 6 for the target disk including tungsten blocks, 1-mm-thick tantalum cladding, steel vessel and hub summing up to 17 kW at shutdown following 10 years of operations at 1.5 MW. A significant quantity of decay power is observed in the tantalum cladding, which dominates the total decay power one hour after shutdown. The problem is even more severe with increased thickness of the tantalum cladding increasing the total decay power from 17 kW for 1 mm cladding to 23 kW at 2 mm as shown in Fig. 7.

Generally, in a tungsten/tantalum target assembly the decay power is governed by isotopes generated by thermal neutron absorption reactions at the target/moderator and target/reflector interfaces rather than by spallation reactions, creating peaking in the local decay energy deposition rates close at the cooling channels. A simulation of the decay gamma transport showed that 90% of the decay gamma power (or 93% of the total decay power) is deposited within the target assembly.

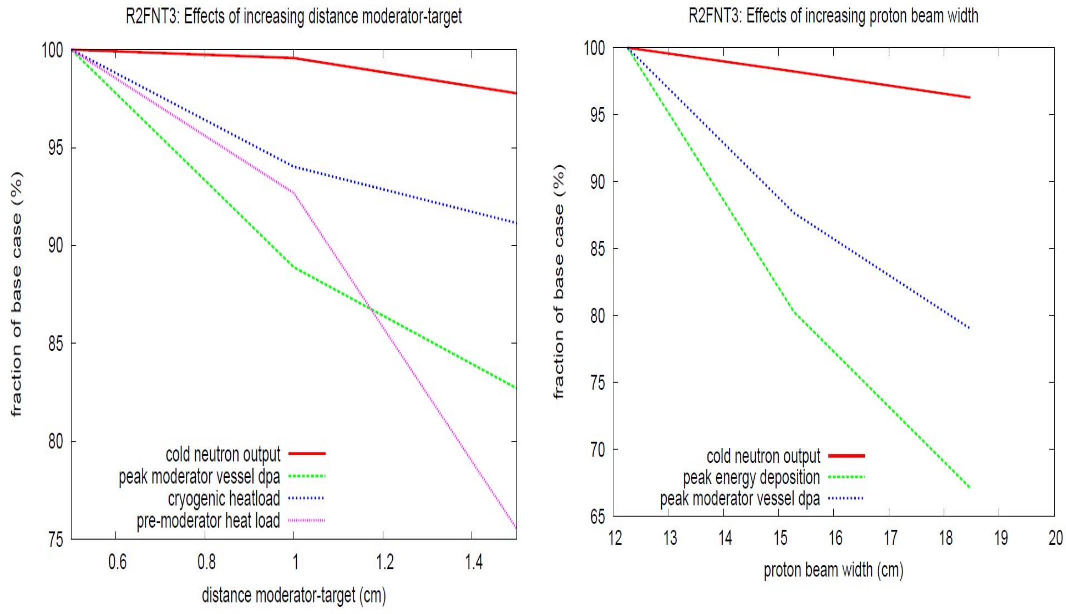


Fig. 5. Neutron performance, moderator heating and peak moderator DPA due to an increase of the gap target-moderator, and due to an increase of the proton beam width.

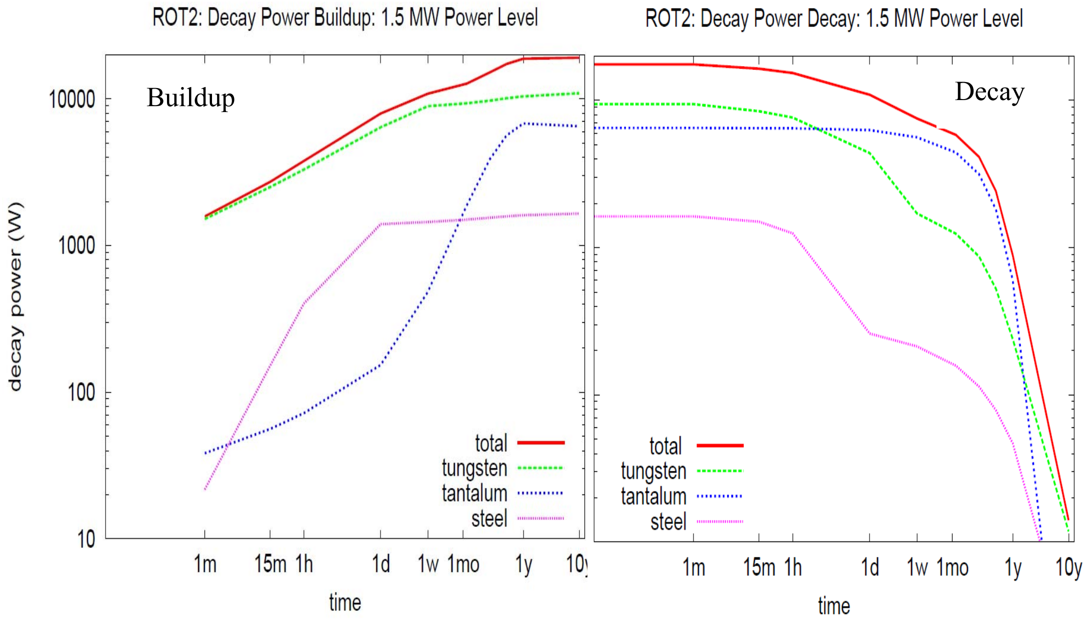


Fig. 6: Integral decay power of rotating target with 1 mm thick tantalum clad tungsten bricks after 10 years irradiation at 1.5MW.

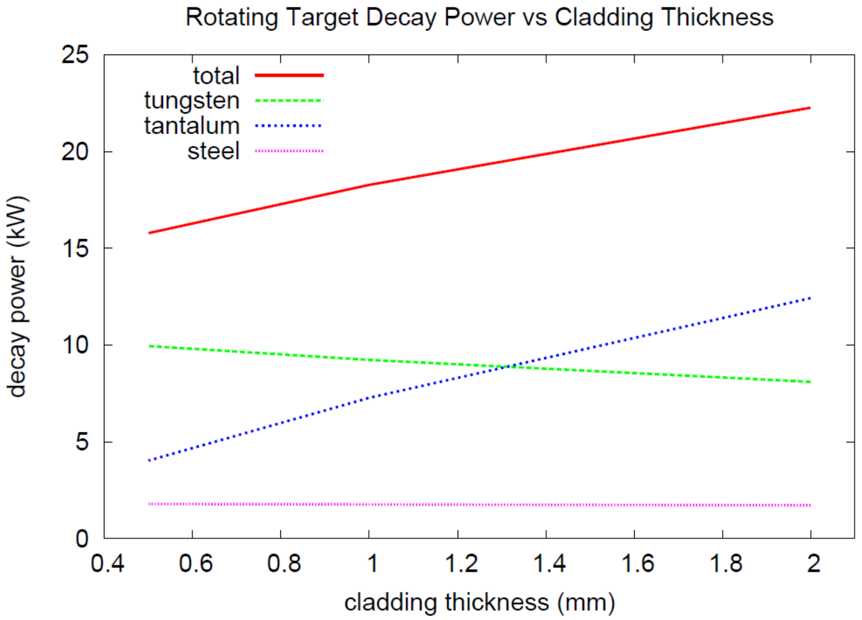


Fig. 7: Variation of decay power with tantalum cladding thickness immediately after shutdown after 10 years of operations at 1.5MW.

4. Conclusions

Moderator performance comparisons of the cylindrical para-hydrogen moderator at rotating tungsten and liquid mercury targets show 10-20% advantages for the rotating target configuration. With this increased neutron performance comes an increased moderator energy deposition of about 25% in the cryogenic parts and 60% in the ambient water parts. Target lifetimes of 15-18 years are feasible from the material radiation damage viewpoint assuming 1 MW beam power. The stationary moderators, however, accumulate damage at all proton pulses and therefore have lifetime limits of 3 MW-years for their target nearest aluminium structures. We could show that distance to target and size of proton footprint influence the moderator DPA damage and their proper adjustment may increase the moderator life time significantly. For an overall evaluation of the rotating target option, we want to refer to another paper of this conference [4].

5. References

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