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NUCLEAR STUDIES OF DIFFERENT TARGET SYSTEMS FOR THE EUROPEAN SPALLATION SOURCE (ESS)

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ABSTRACT

This paper summerizes nuclear simulation calculations to study various target concepts for the „European Spallation Source (ESS)" concerning a proton beam power of 5MW.For different target systems as rotating wheel targets,stationary targets and liquid metal targets results of beam energy - and target material investigations,induced radioactivity and afterheat production as well as usuable neutron fluxes are discussed.

1. Introduction

The simulation calculations were done using the HERMES code system [1] .This theoretical study here is directed towards assessing physics feasibility of discussed ESS target station concepts.The aim is to show the feasibility of the anticipated nuclear parameters,which will be necessary for the evaluation of the final design.

2. Beam Energy Studies

One of the first questions to us was which is the optimum proton beam energy in respect to a high thermal neutron flux in the moderators, to a long lifetime of target windows and target material, and in respect of necessary cooling power. From the experience of running spallation sources it was clear that proton beam energy should be in the energy range from 800 MeV up to 3000 MeV. In the beginning of the project we calculated a double wheel target (Fig. 1) and a double split target (Fig. 2) with three moderator positions with first moderator in front of the target, second moderator in flux trap position between target one and two, and third moderator behind second target. In Fig. 3 we can see a linear decrease of thermal neutron flux of the upstream moderator with increasing proton energy from 800 MeV up to 3000 MeV. The proton beam energy dependent thermal neutron flux in the intermediate moderator, decreases less with proton energy at a higher flux level. In contrary to neutron flux dependence

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in moderators above the thermal neutron flux in the downstream moderator increases with increasing proton beam energy. Around 1500 MeV proton beam energy fluxes of up- and downstream moderators have similar values. Therefore, from neutron flux calculations there is no strong tendency to a special proton beam energy and either energy should be good.

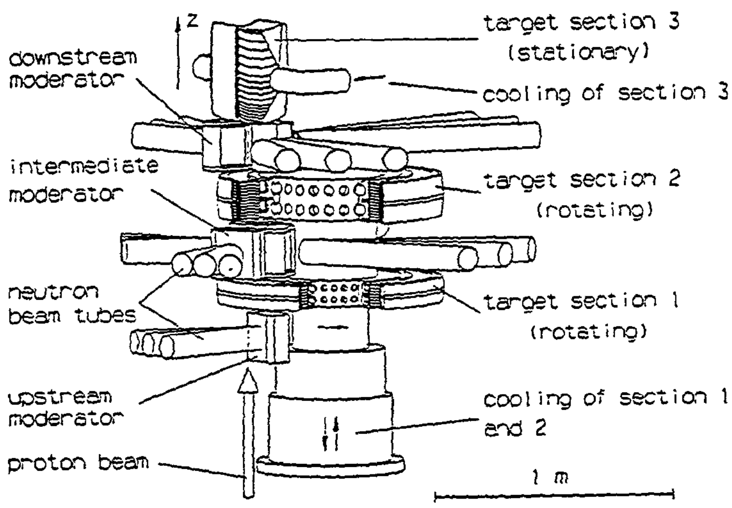

Fig. 1: Rotating double split target for vertical proton beam injection (rotation frequency 1 Hz)

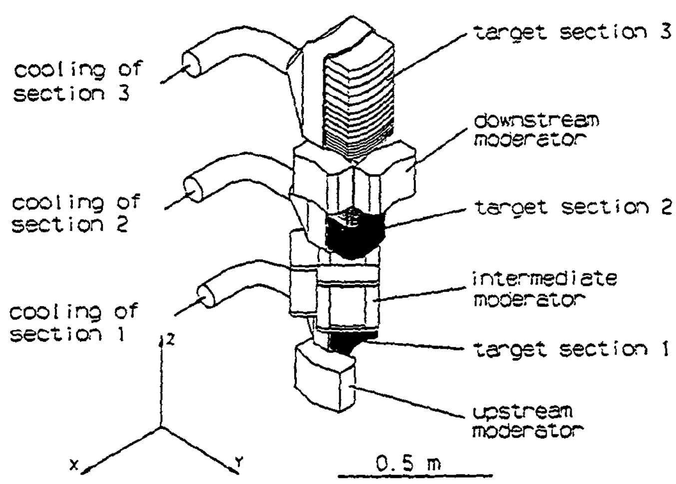

Fig. 2: Stationary double split target for vertical proton beam injection

Figure 4 shows the proton energy dependent power deposition in the first part of the split target and in the whole target. Between 800 MeV and 1600 MeV there is a strong decrease of power deposition which is much less versus higher proton energies. From this figure the proton beam for a target should not be far below 1500 MeV.

We investigated the power deposition in the target plates in an area of radius 1cm around the proton beam axis. Figure 5 shows a power deposition of 11 kW/cm**3 in the first two target plates. This power deposition is reduced by a factor of two by increasing the proton beam energy from 800 MeV to 1600 MeV. A further doubling of the proton energy gives less reductions than factor two for the power deposition.

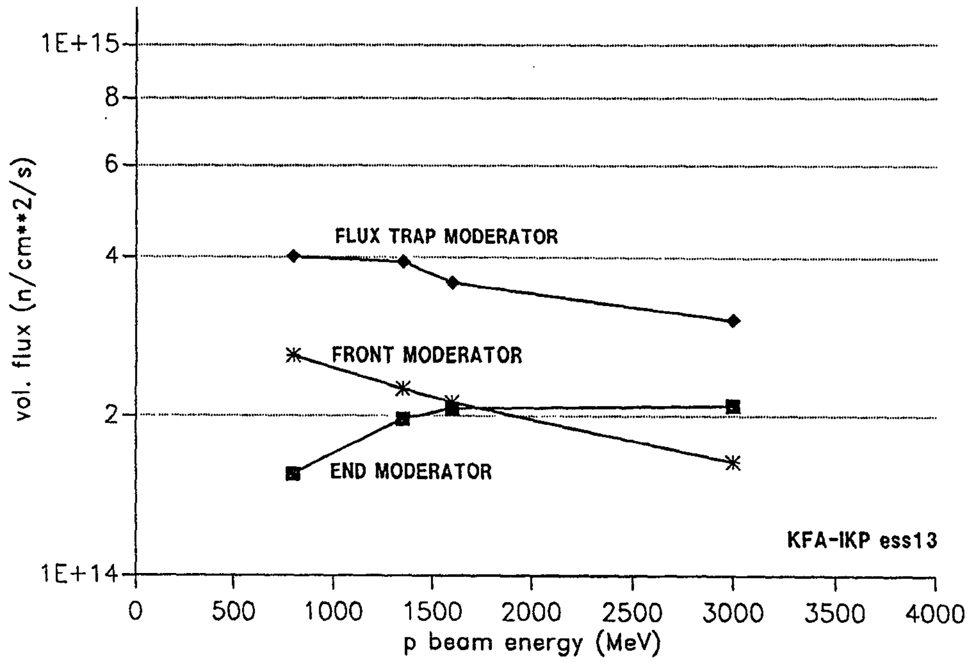

Fig. 3: Thermal neutron fluxes in moderators as a function of incident proton energy

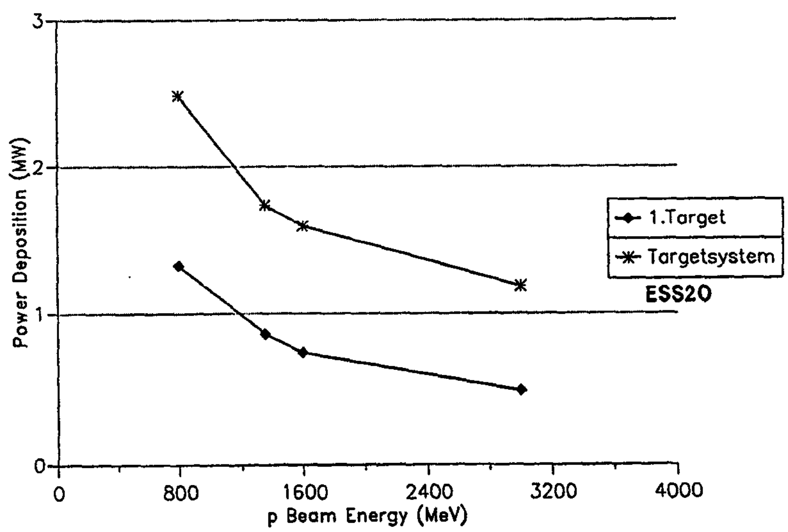

Fig. 4: Energy deposition in target systems as a function of incident proton energy

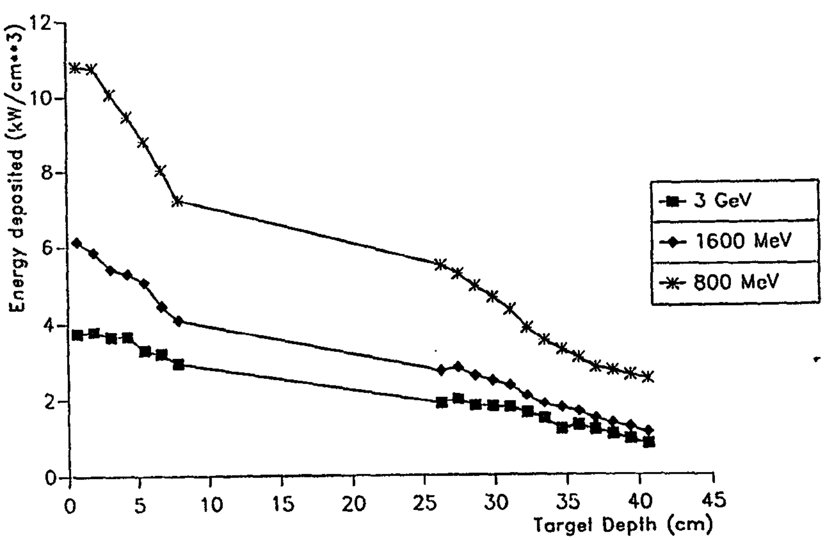

Fig. 5: Energy deposition in target plates in an area of radius 1cm around beam axis

Each proton pulse of a 5 MW at 50 Hz machine contains an energy of 100 kJ which is introduced into the target. This produces a space dependent temperature jump in the target material. In Fig.6 the temperature jump is plotted for the first W-Target plate as functions of proton beam diameter in an area of radius r = 1 cm for three proton energies. We see for a gaussian shaped circular proton beam (σ = 2.5) truncated at diameter 10 cm a temperature jump of 40 K, 25 K, and 15 K for 800 MeV, 1600 MeV, and 3000 MeV, respectively.

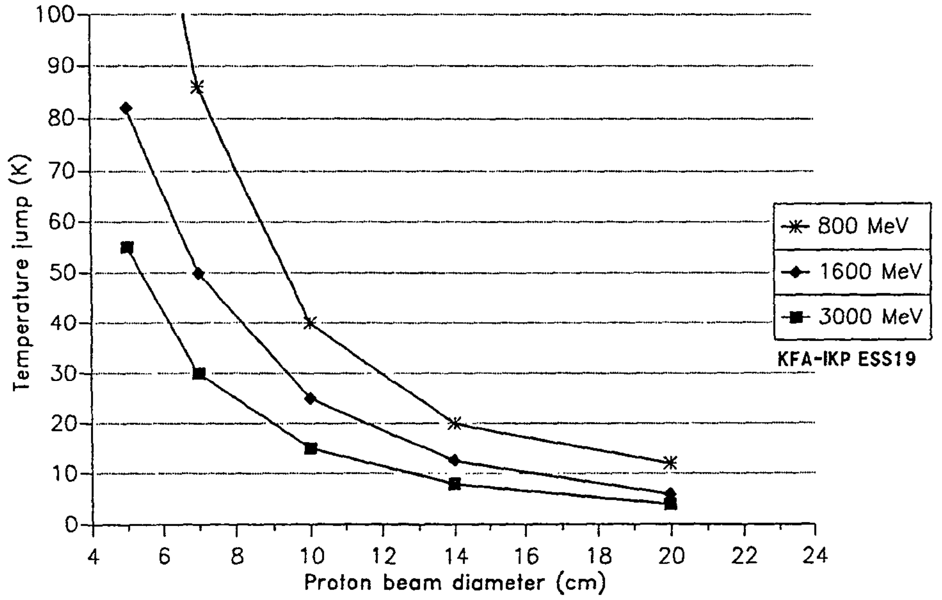

Fig. 6: Temperature jump in tungsten target as a function of proton beam diameter for different beam energies around beam axis

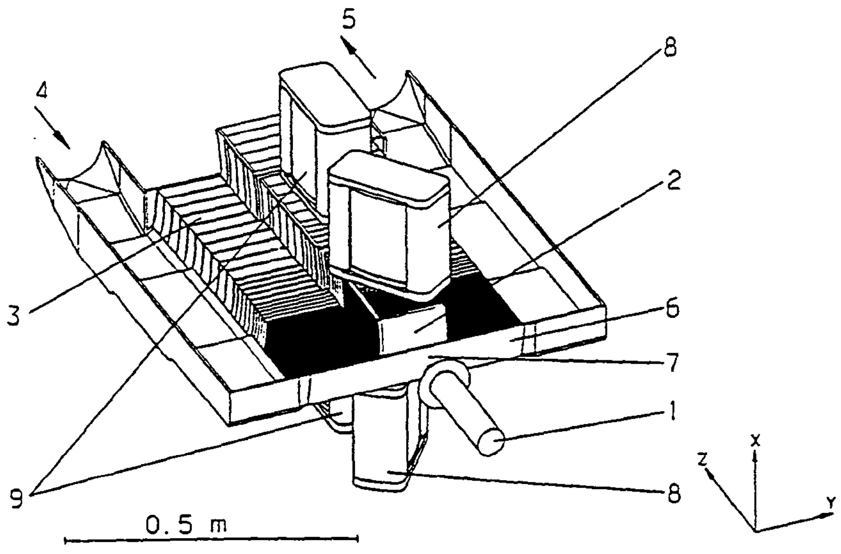

Fig. 7: Reference 5 MW ESS target with moderators

(1: proton beam, 2: target plates, 3: wing reflctor plates, 4: coolant inlet, 5: coolant outlet, 6: target vessel, 7: beam window, 8: cold moderator, 9: room temperature moderator)

The double wheel split target Fig. 1 and the stationary split target (Fig. 2) from neutronical point of view do not differ much from one another. The rotating target has the advantage that irradiation damages and heat loads of beam window and target plates are considerably lower by a factor of 50 and this means a longer lifetime by a factor of 50. The advantage of the stationary target is the lower fabrication cost. As reference target a non-split stationary target as depicted in Fig. 7 was chosen(see details in Ref. [2].
(ESS reference proton beam energy is 1.334 GeV)

3. ESS Reference Energy Studies

The reference 5 MW target (see Fig. 7) is horizontal, non-split and cooled by H_2O. It consists of three stacks of slightly 1D-bent rectangular plates. The centre stack, made of tantalum as reference material, acts as the target, the two other stacks on its left and right side integrated in the target are part of the reflector and are manufactured of nickel. All stacks are cooled by the same water stream in y-direction. The described target plate configuration has the front (x-y-plane) dimension of 120 x 400 mm^2 which increases to 160 x 400 mm^2 to allow for the scattering of the proton beam. The length (z-direction) of solid target material is 580 mm and, due to the cooling gaps between the plates, the overall length of the target is 690 mm. The rest of the nickel reflector, not shown in Fig. 7, encloses the target inside the volume of 900 x 800 x 1050 mm^3 (x,y,z).The ESS proton beam energy was choosen to 1.334 GeV.

To achieve the same heat flow on the surface of each target plate their thicknesses are increased in bundles of five plates from 2.6 mm up to 30 mm. The total number of plates in each stack is 55. Because of the thickness variation the water content in the cooling gaps decreases from 22% in the first cooling gap down to 8% in the last .The average water content in the target is 10%. The beam window is part of the target container and will be 2D-curved.

To simulate the transport of hadrons and to estimate particle fluxes, energy deposition and induced radioactivity the HERMES code system [1] has been used. First neutron flux estimations for the 5 MW target have been performed under the condition that all four moderators were H_2O-moderators at room temperature. For these calculations the target material was tungsten to compare the results with of the SNQ study [3]. A detailed 3D-geometry configuration of the target has been considered. In Table 1 neutron yields per proton for the reference target with tungsten as target material are compared to various target systems of the SNQ study [3].

Targets and moderators which have been studied in the SNQ project have been compared for their average thermal neutron flux with a similar fast moderator at the ESS target. The average ESS thermal neutron flux differs by less than 5% from that of the corresponding SNQ value, for a 5 MW beam power.

Table 1: n/p values for various targets

target	n/p 1100 MeV	n/p 1334 MeV
SNQ: U_{dep}-H_2O-Al	33.1	40.2
SNQ: Pb-H_2O-Al	21.5	26.0
SNQ: W-H_2O-Al	23.4	28.4
SNQ: W_{solid}	25.6	31.1
ESS: W^*	-	31.5

Table 2: Comparison of thermal neutron fluxes in fast moderators of the SNQ and ESS for 5 MW proton beam power

target	$\Phi_{thermal}$ [n/(cm^2·proton)]	$\Phi_{thermal}$ [n/(cm^2·s)]
SNQ: U_{dep}-H_2O-Al	$2.6 \cdot 10^{-2}$	$7.5 \cdot 10^{-14}$
SNQ: Pb-H_2O-Al	$1.6 \cdot 10^{-2}$	$4.5 \cdot 10^{14}$
SNQ: W-H_2O-Al	$1.8 \cdot 10^{-2}$	$5.1 \cdot 10^{14}$
SNQ: W_{solid}	$2.0 \cdot 10^{-2}$	$5.6 \cdot 10^{14}$
ESS: W^*	$2.1 \cdot 10^{-2}$	$4.9 \cdot 10^{14}$

One should take into account that the flux values of Table 2 depend on the chosen target-moderator-reflector geometry and should be taken as first approximations of the expected neutron flux.

4. Target Material Studies of Tantalum,Tungsten and Mercury Targets

4.1 Usuable Neutron Fluxes

Based on the above discussed scoping calculations we compared the nuclear properties of three target material candidates, namely tantalum, tungsten, and mercury using the target geometry given in Fig. 7. For optimal positioning of the moderators it is important to know the distribution of the neutron flux density along the surface of the target. In Fig. 8 for bare reference targets (Ta- and W- with water cooling; and Hg-filled,-only with mercury-) we show the surface leakage current distributions of neutrons below energies of 20 MeV as a function of target depth. The tantalum target delivers the lowest neutron current. In the maximum of the neutron current distribution W and Hg target give same values but downstreams the Hg target produces higher currents.

Figure 9 shows for lead-reflected target systems that the tantalum target delivers the lowest neutron current. A tungsten target gives a neutron current which is about 20% higher in the maximum. The highest neutron currents at the target surface are produced by the mercury target and are more than 30% higher compared to the tantalum target. Especially along the target surface the current gradient in case of Hg is lower than in case of the W target. This means that the downstream moderators receive an even higher percentage of neutrons in case of mercury.

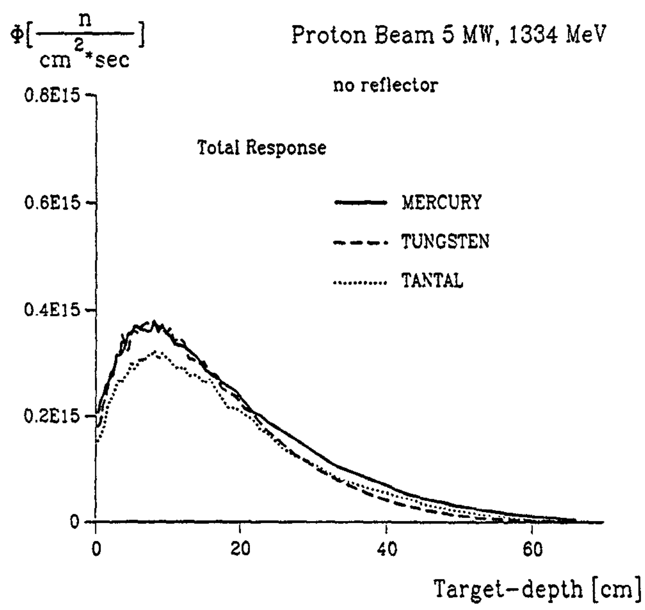

Fig. 8: Leakage distributions for neutrons below 20MeV of bare reference targets

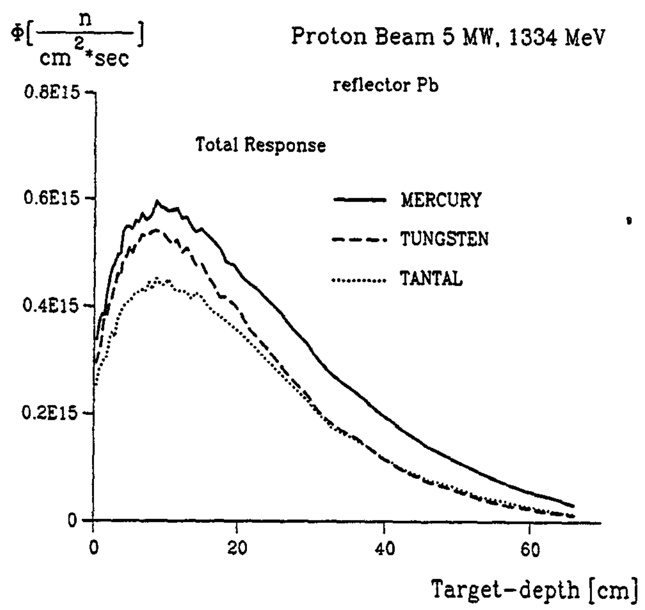

Fig. 9: Leakage distributions for neutrons below 20MeV of reflected reference targets

The following table (Tab. 3) shows a comparison of possible fast and thermal neutron fluxes averaged about the moderator volume.

Table 3: Fast and thermal neutron fluxes of Ta, W, and Hg targets

Target	Φ_{fast} [n/(cm^2 · s · 5 MW)] upstream Moderator	Φ_{fast} [n/(cm^2 · s · 5 MW)] downstream Moderator	$\Phi_{thermal}$ [n/(cm^2 · s · 5 MW)] upstream Moderator	$\Phi_{thermal}$ [n/(cm^2 · s · 5 MW)] downstream Moderator
Tantalum	$7.25 \cdot 10^{13}$	$2.30 \cdot 10^{13}$	$3.19 \cdot 10^{14}$	$1.52 \cdot 10^{14}$
Tungsten	$6.42 \cdot 10^{13}$	$2.14 \cdot 10^{13}$	$3.52 \cdot 10^{14}$	$1.67 \cdot 10^{14}$
Mercury	$8.21 \cdot 10^{13}$	$3.52 \cdot 10^{13}$	$3.91 \cdot 10^{14}$	$2.29 \cdot 10^{14}$

4.2 Induced Radioactivity and Afterheat Production

The procedure to calculate the radioactivity and afterheat in the different materials Ta, W, and Hg proposed as ESS target materials consists of using the HERMES system[1] to calculate the nuclide production rates caused by the spallation process and to generate the neutron source and then using MORSE[1] with the recently released cross section library MATXS11[4] to calculate the production rates caused by neutrons with energies below 15 MeV. All nuclide production rates are handed over to the nuclide generation and depletion code ORIHET[5], which calculates radioactivity and thermal power for different beam and decay times.

All calculations described here were performed for ESS beam energy 1.334 GeV and 5 MW proton beam power, i.e. for 3.748 mA beam current. The geometry used for the Monte Carlo calculations is described above. Because the reason of the study is the comparison of the different target materials Ta, W and Hg, we restrict ourselves to calculate the values of the target zones only, assuming that the activity and afterheat of the surrounding reflectors, moderators, and cooling systems are nearly the same for the different target materials. The nuclide generation and depletion was calculated for a full power beam time of 1 year and after shut down of the beam for decay times reaching from 1 day to 100 years. The results are given separately for those caused by spallation and those caused by neutrons with energies below 15 MeV.

The most interesting time with respect to problems of cooling and handling of the target is the time when the beam is shut down. The amount of radioactivity and thermal power for the three different targets is compared in Table 4. It can be seen that the activity and thermal power caused by spallation are nearly the same for all three targets, but the amounts caused by the low energy neutrons are quite different. Therefore the total amount of activity and afterheat is largest in the tantalum target, followed by the tungsten target. Here the mercury target shows the lowest values.

Table 4: Comparison of radioactivity and thermal power at shut down time for different targets for 5 MW proton beam power and 1 year full power operation

	Tantalum	Tungsten	Mercury
Radioactivity [Tbq]			
-total power	$4.55 \cdot 10^5$	$1.63 \cdot 10^5$	$1.10 \cdot 10^5$
-caused by spallation	$6.94 \cdot 10^4$	$7.73 \cdot 10^4$	$7.28 \cdot 10^4$
-caused by neutrons below 15 MeV	$3.85 \cdot 10^5$	$8.75 \cdot 10^4$	$3.67 \cdot 10^4$
Thermal power [kW]			
-total.power	56.9	15.40	9.21
-caused by spallation	8.94	8.75	7.21
-caused by neutrons below 15MeV	48.0	6.60	2.00

Next question is about the long term radioactivity and afterheat production with respect to storage and waste management. The time behaviour of the three targets is shown in Figs. 10 and 11. In Table 5 we give the total values for the time 100 years after shut down. It should be mentioned that the radioactivity and afterheat caused by the low energy neutrons have no importance for the long term behaviour of all targets. Therefore the total amounts given in Table 5 are caused by the spallation products only.

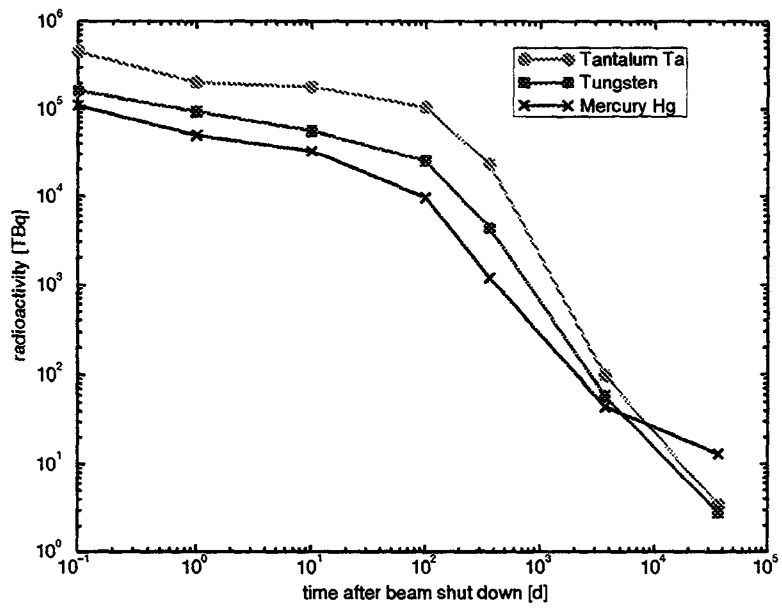

Fig. 10: Time behaviour of radioactivity in Tbq in Ta-, W-, and Hg- targets after 1 year full power operation

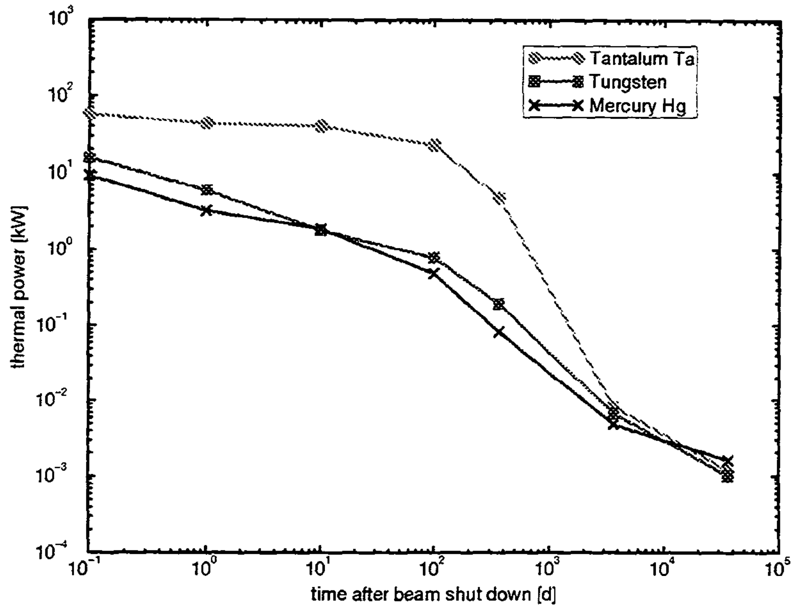

Fig. 11: Time behaviour of thermal power in kW in Ta-, W-, and Hg- targets after 1 year full power operation

Table 5: Comparison of total radioactivity and total thermal power after 100 years decay time for different targets for 5 MW proton beam power and 1 year full power operation

	Tantal	Tungsten	Mercury
Total Radioactivity [TBq]	3.40	2.83	13.00
Total Thermal Power [kW]	$1.16 \cdot 10^{-3}$	$9.94 \cdot 10^{-4}$	$1.58 \cdot 10^{-3}$

It should be mentioned that the nuclide data base of the code ORIHET is incomplete. We found that the nuclide production rate, which is generated by HETC and not treated by ORIHET, is less than 10 percent of the total production rate. The nuclides caused by low energy neutrons were entirely treated by ORIHET. Therefore the results of activity and thermal power caused by spallation should be increased by about 10 percent.

5. References

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