CONF-9705113--1

SHIELDING AND NEUTRONIC OPTIMIZATION OF THE NATIONAL SPALLATION NEUTRON SOURCE (NSNS)*

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Presented at the
Simulation of Accelerator Radiation Environments (SARE-3)
KEK
Tsukuba, Japan

May 7-9, 1997

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*Managed by Lockheed Martin Energy Research Corporation for the U.S. Department of Energy under Contract No. DE-AC05-96OR22464.

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Abstract

Studies are now underway to establish initial design characteristics for the pulsed neutron source NSNS facility and to optimize the design. In this paper the methodology of calculation is presented together with the calculated facility characteristics. Optimization studies are discussed and initial results shown.

1. Introduction

The pulsed neutron source NSNS facility will start operation at 1 MW. An upgrade to 5 MW is planned. The facility consists of a linear accelerator, an accumulator ring and a target station with protons injected into the target station at an energy of 1 GeV. The subsequent spallation process then produces low energy thermal neutrons that may be used for a wide variety of experiments. In this paper initial calculations which simulate the spallation process and the moderation of the neutrons to low energy will be described. These calculations serve to establish facility characteristics and to allow optimization of the design. First the methodology and the validation of this methodology will be described together with the predicted performance. Neutron spectra and pulse widths, energy deposition, and results from damage calculations and target material studies will also be shown.

2. Methodology

Neutronics analyses were performed using a set of codes capable of handling all aspects of the neutral and charged particle transport. For the high energy calculations the computer code HETC [1] was used. When neutron energies fell to 20 MeV or less during the high energy transport, the neutron parameters were recorded and the transport of those neutrons was continued using the low energy code MCNP [2].

Two target station geometries have been used for the initial evaluation of the NSNS target system performance. The first was used for calculations which did not require a detailed representation of the outer target station structure such as the neutron flux leaving the moderator face and the energy deposition in the Hg target. This model had a Be reflector outer volume with dimensions of 900 mm x 900 mm x 1008 mm. The Be encloses a proton beam channel with dimensions 120 mm x 320 mm. A 640 mm long Hg target is placed at the end of this channel. The Hg target had a half cylinder on the front (where the proton beam enters) with radius of 50 mm. Downstream from the half cylinder was a section with rectangular cross section width of 300 mm and a height varying from 100 mm to 150 mm at the extreme downstream end. Moderators were 120 mm x 150 mm x 50 mm with the smaller dimension being the thickness (i.e., the distance measured perpendicular to the viewed moderator face) and the largest dimension being the height. A view of the first model from outside the Be reflector is shown in Fig. 1.

The second target station geometry was used for calculations that required the inclusion of the details of the outer structure to allow determination of activation and energy deposition in the outer shielding. The extreme outer layer of concrete in the model is shown in Fig. 2, together with an expanded section showing the beam tubes which cannot be seen on a scale which displays the outermost concrete structure. The second model with the outer concrete, Fe, SS vessel and the Ni and Be reflectors removed is shown in Fig. 3. The upper and lower beam tubes can be seen together with the Cd decoupler which surrounds the beam channels and the moderators. The neutron output from the moderator faces from the two models should give the same results if the two models are to be consistent. A comparison was made and there was agreement to within ~10%.

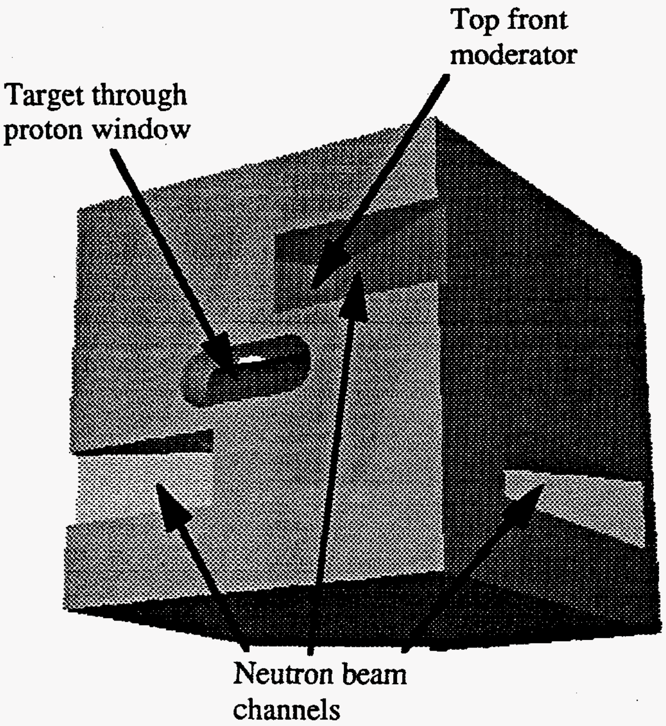

Fig. 1 Outside of target model 1.

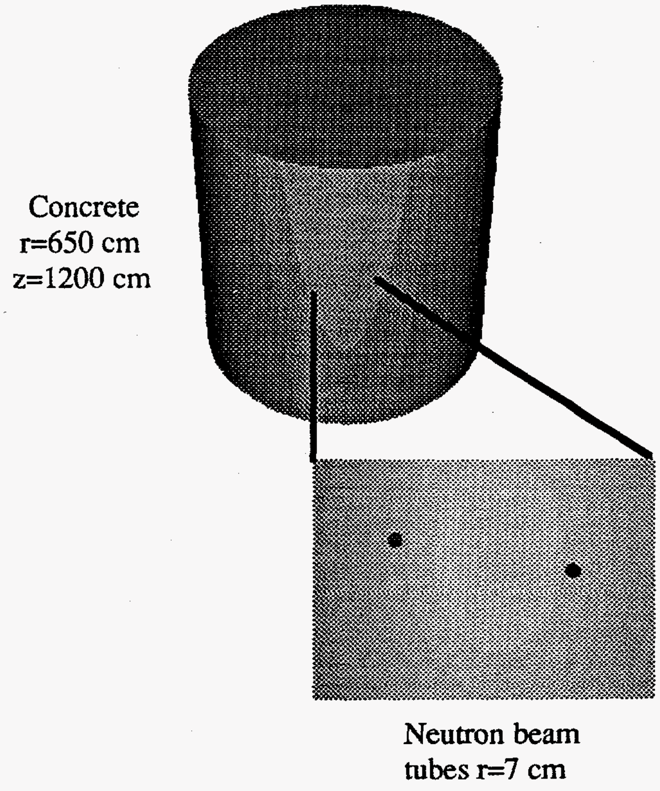

Fig. 2 Outside of target model 2

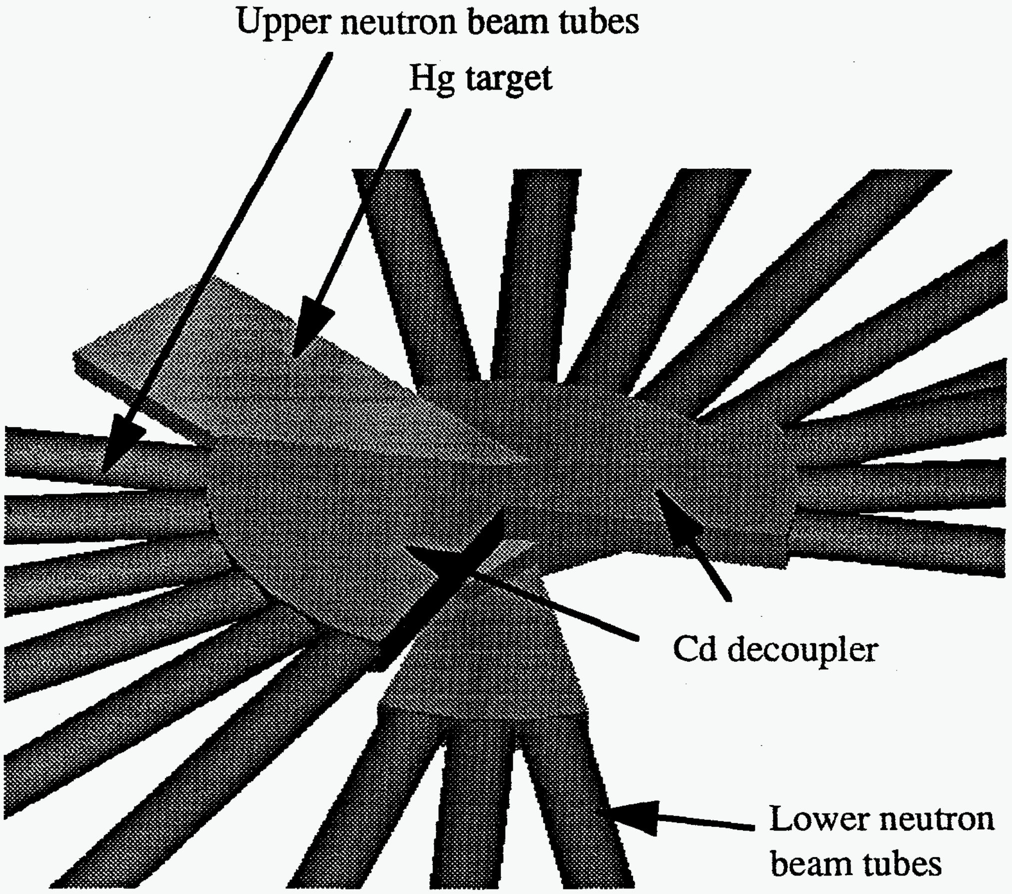

Fig. 3 Model 2 with concrete, Fe, SS vessel, Ni and Be reflectors removed.

3. Validation of the calculations

Neutron fluxes leaving a moderator face with an energy of 1 eV are approximately independent of moderator properties, and the fluxes for energies less than 1 eV are independent of the value at 1 eV if they are normalized to the 1 eV value[3,4]. It is thus possible to compare neutron fluxes for energies less that 1 eV to fluxes from existing devices if they are properly normalized. The 1 eV values for devices such as NSNS for which no experimental data exists can then be compared to values from other calculations or to scaled values. A comparison of properly normalized pulses (neutron current versus time) is shown in Figs. 4, 5, and 6. Target model 1 was used. The calculated results from this study are compared to the experimental measurements from Ref. [5]. The first comparison, shown in Fig. 4, is for neutrons with a wavelength of 3.94 Å coming from the face of a coupled 20 K liquid H_2 moderator. The agreement is generally good except for differences in the tail of the pulse. However, as noted in the figure, a graphite reflector was used when the experimental data was taken and a beryllium reflector was used for the calculations. For coupled moderators the tail is determined primarily by the reflector material and configuration. Thus the differences in the tail region of Fig. 4 can be understood. The comparisons shown in Figs. 5 and 6 are for decoupled moderators which have been neutronically isolated from low energy (less than ~.5 eV) neutrons. Comparisons at 3.94 Å (Fig. 5) and at 9.87Å (Fig. 6) are shown. In both cases the data and the calculational results are in good agreement. In Table 1, a comparison of 1 eV currents is made between NSNS, ESS [6], a LANL proposed device [7], a ANL proposed device [8], and with the scaling calculations discussed in Ref. [3]. The NSNS current was found using target model 1. All the results shown in this table are either for a 1 MW source or are scaled to 1 MW. All are comparable as should be the case. It is claimed that the comparisons discussed in this section are sufficient to establish the credibility of the present neutronics study.

Table 1. Comparison of the calculated NSNS neutron currents at 1 eV with other designs and a scaling calculation

Design	J(1 ev)
NSNS	5.0×10^{13}
ESS (Scaled from 5 MW)	4.0×10^{13}
LANL (1 MW Proposal)	5.0×10^{13}
IPNS-U (Upgrade Proposal)	4.0×10^{13}
Scaling	5.0×10^{13}
(Units: n/sr-sec-eV-180cm^2-1 MW)	

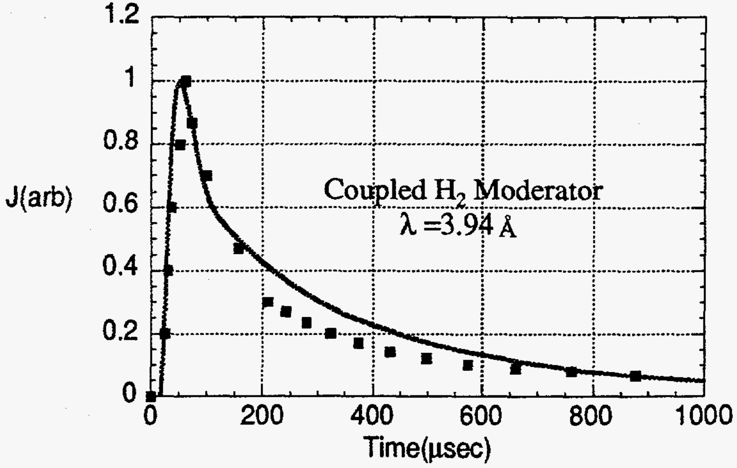
Comparison Between NSNS (Line-Be reflector) and Experiment (Squares-Graphite reflector)

Fig. 4 Comparison between NSNS calculated results and experimental data [5] for 3.94 Å neutrons from a coupled H_2 moderator

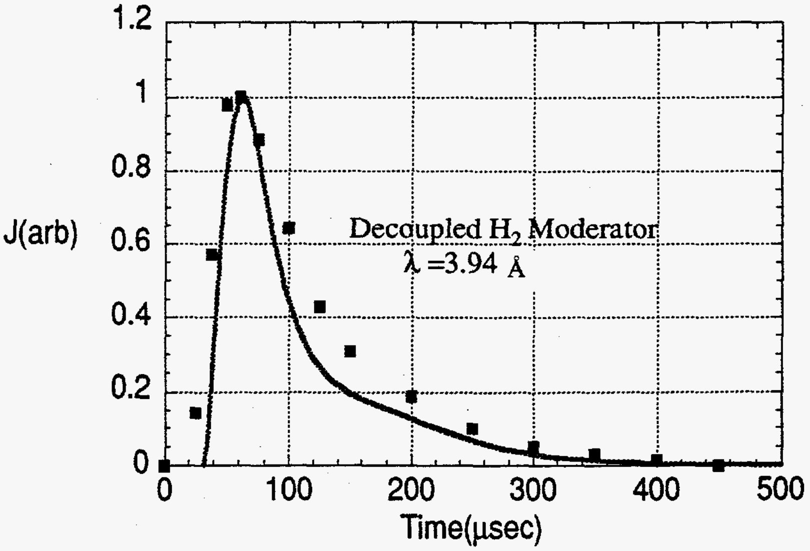
Comparison Between NSNS(line) and Experiment (Squares)

Fig. 5 Comparison between NSNS calculated results and experimental data [5] for 3.94 Å neutrons from a decoupled H_2 moderator

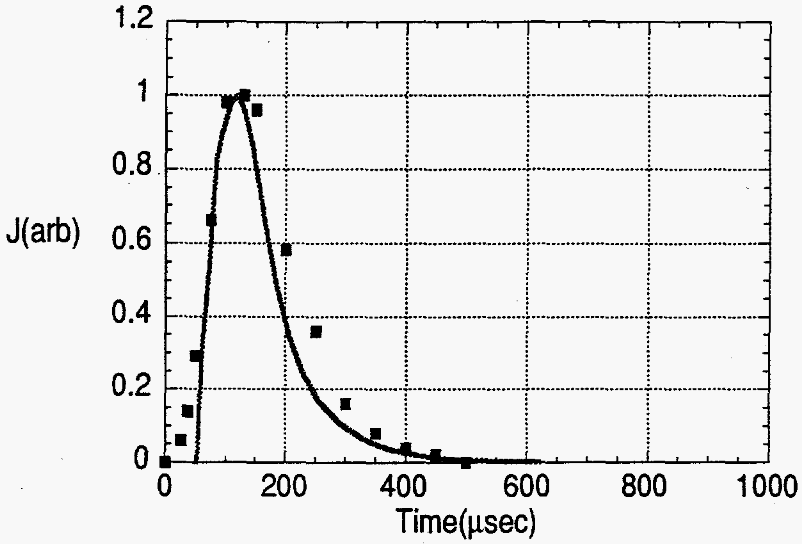

Fig. 6 Comparison between NSNS calculated results and experimental data [5] for 9.87Å neutrons from a decoupled H_2 moderator

4. Performance of the neutron source

The expected peak and average neutron flux values for the reference (1 MW) NSNS target system are shown in Table 2 for moderators that are coupled, decoupled and both decoupled and poisoned. The NSNS flux is about six times larger than that for ISIS (160 kW) and about five times smaller than that for the proposed ESS (5 MW) . In the present design the decoupling is accomplished by surrounding the moderator with 1 mm of Cd. A 50 μm thick Gd poison plate is placed in the center of the moderator parallel to the viewed moderator face. A comparison of the pulsed NSNS neutron flux with the steady state values for HFIR and ILL is shown in Fig. 7. During the early phase of the NSNS neutron pulse, the generated flux is more than a factor of 10 brighter than for the reactors.

Table 2. Peak and average neutron flux values for the viewed moderator faces (n/cm^2-s)

	H_2O Moderator		H_2 Moderator	
	coupled	decoupled/ poisoned	coupled	decoupled/ poisoned
Flux (peak)	2.1x10^{16}	1.8x10^{16}	1.2x10^{16}	9.4x10^{16}
Flux (ave)	7.9x10^{13}	2.0x10^{13}	6.3x10^{13}	1.1x10^{13}

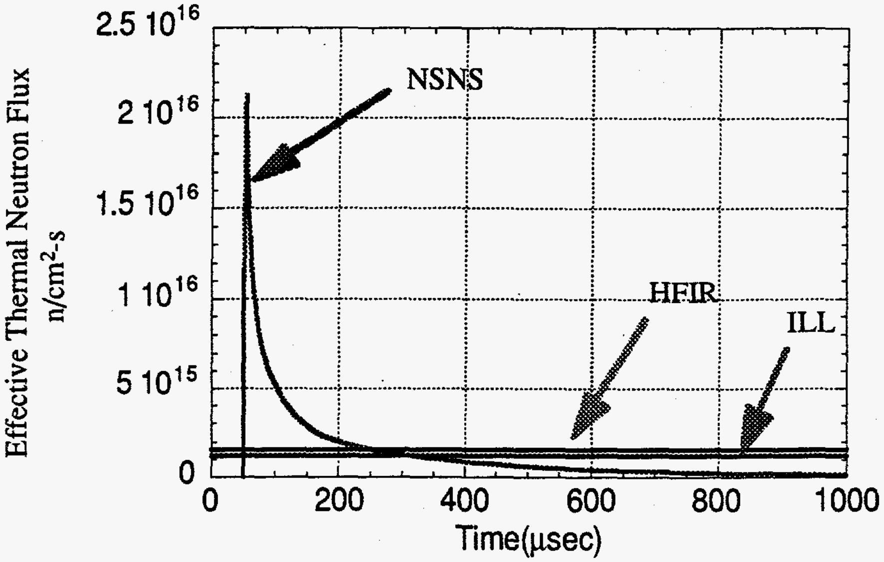

Fig. 7 Expected performance of NSNS compared to the HFIR and ILL reactors

5. Neutron Spectra and Pulse Widths

The thermal neutron spectra coming from the ambient water moderator face using target model 1 is shown in Fig. 8 along with the full-width-at-half-maximum (FWHM) pulse widths. At the top of Fig. 8, it is seen that the energy dependence of the current is the same at the highest energies shown in the figure with the decoupled current less than that for the coupled case as the energy decreases. At a lower energy the current for the decoupled and poisoned case becomes less than that for the decoupled case. This sequence is due to the lower cutoff energy of the gadolinium poisoning than the cadmium decoupler. The neutrons "see" the decoupling at a higher energy than the poison. The peak in the spectrum is at ~25 meV which is determined by the ambient water temperature. The bottom part of the figure shows that the width of the pulse is decreased at low energies by the decoupler and the poison. The expected direct relationship between a narrow pulse width and neutron intensity is apparent.

Information such as that shown in Fig. 8 allows instrument designers to make an initial estimate of appropriate instruments for the NSNS facility. For a more detailed instrument design the full pulse characteristics will be necessary. The long term pulse time dependence however remains somewhat subject to uncertainties due to its small amplitude.

6. Energy Deposition

Target model 2 has been used to determine the energy deposition in the outer sections of the target station. This was needed to determine cooling requirements in the design of the reflector, shielding and vessel systems. The power deposited is shown pictorially in Fig. 9, which shows the fraction of the 1 MW initial proton beam power that is deposited in each target section. The power deposited in the moderators includes that deposited in the Cd decoupler liner associated with each moderator. The power shown as being deposited in the Hg target includes that deposited in the Hg itself together with that deposited in the mercury vessel and shroud. The fall off in deposition as the distance from the Hg increases is clearly seen, with ~90% of the power being deposited in the Hg and in the outer Ni reflector.

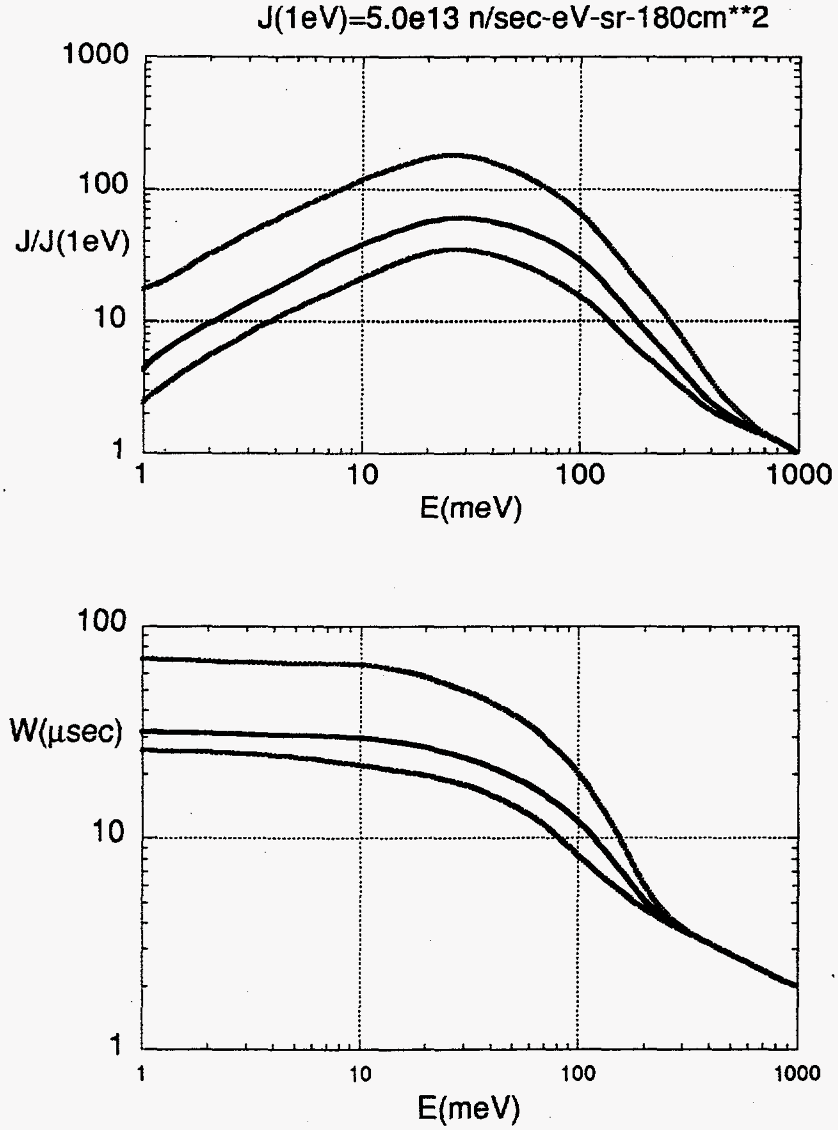

Fig. 8 H_2O moderator spectra and pulse widths (FWHM). For both plots the top curve is for a coupled moderator, the middle curve for a decoupled moderator, and the bottom for a decoupled-poisoned moderator.

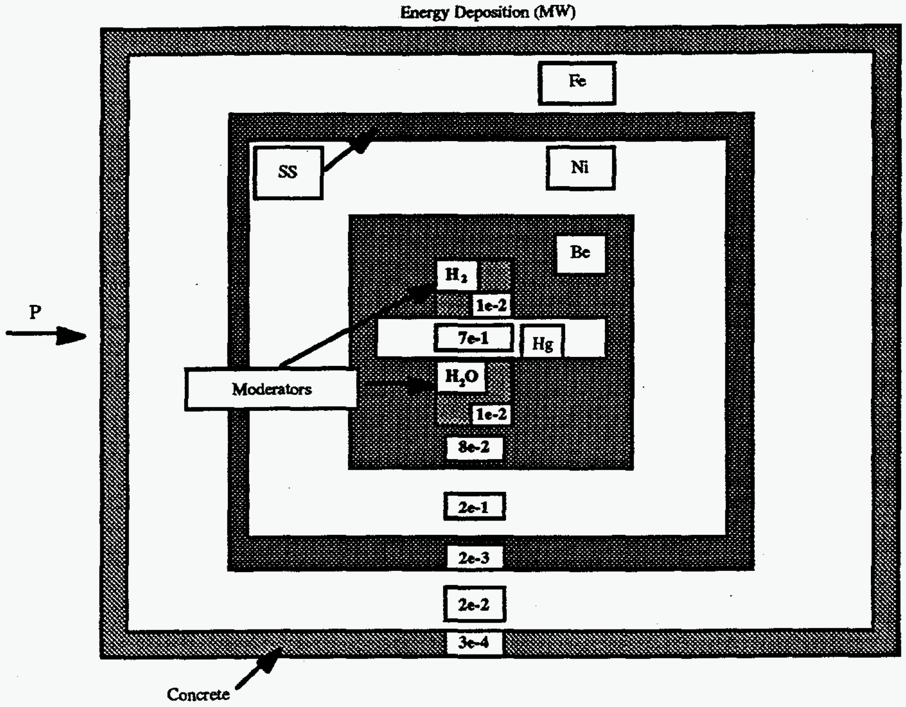

Fig. 9 Energy deposition in the NSNS target region

7. Target material trade studies

Neutronic comparisons were made between W, Ta, and Hg target materials. The spectra of neutrons coming from the face of a H_2O moderator is shown in Fig. 10 for each of these materials assuming 35% (by volume) cooling fraction of D_2O. The cooling is necessary for the two solid targets but is added in the case of Hg only for comparison. The neutron spectra with a Hg target with no assumed cooling fraction is also shown. The three materials are (within statistical uncertainties) equivalent when cooling is assumed. However when the unnecessary cooling is removed from the Hg target, it is clearly superior. Although not shown, the three materials are also equivalent when no cooling is assumed. Since the three materials are equivalent with the same cooling, and since the addition of cooling degrades the performance of all three materials it is clear that cooling requirements make Hg neutronically superior. The superiority of Hg is greater the greater the power since progressively more cooling is required as the power is increased.

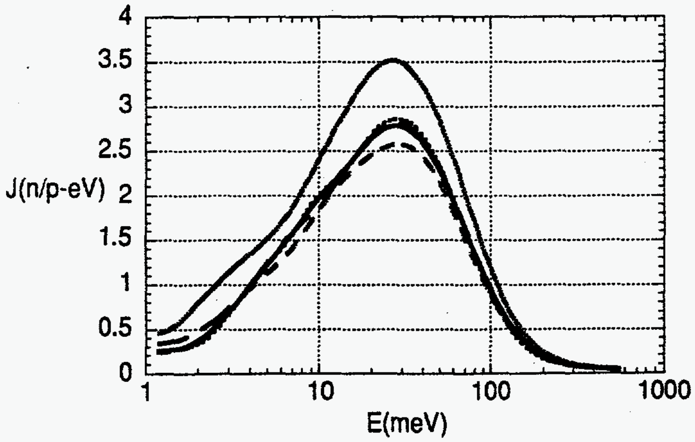

Fig. 10 Neutron current from a H_2O moderator with varying target material: Hg with no cooling (solid), Hg with D_2O (long dashed), Ta with D_2O (short dashed), and W with D_2O (dotted)

8. Discussion

The design of the NSNS target station is well underway. The optimization of facility parameters has started. Results have been presented which show the credibility of the methodology used, the predicted neutron output, energy deposition, material damage and the performance of various target materials have been presented.

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