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A Conceptual Design Study of Target-Moderator-Reflector System for JAERI 5 MW Spallation Source

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Abstract

The fundamental design concept of the JAERI 5 MW spallation source is proposed with some new ideas on the target-moderator-reflector system. Extensive optimization efforts have been devoted, mainly from the neutronic point of view and various important information have been obtained with various technical issues associated with the present concept. The concept was reviewed by comparing the predicted performance with those of the other projected intense sources. Although the engineering feasibility to realize some of the important parameters optimized here are still under examination or R&D, the performance at the present stage is satisfactory to justify the present concept.

1. Introduction

As a next-generation neutron source the construction of a 5 MW class intense spallation neutron source is under planning at Japan Atomic Energy Research Institute (JAERI). The neutron source program is the most important part of the Neutron Science Project in JAERI with the nuclear energy application program (R&D of accelerator-driven nuclear-transmutation-system). The project includes R&D and the construction of a high-power proton (P/H^-) accelerator of about 8 MW in total beam power. After extensive discussions a basic design concept of the neutron source facility, especially of the target station and the target-moderator-reflector system, has almost settled. Based on the basic concept and various requirements, the effects of various source parameters, such as the target material/shape/size, type of moderators with their various parameters, target-moderator coupling, reflector material/size, etc. on the neutronic performance, including pulse characteristics, are being studied.

Although the optimization studies of parameters are still continuing, the present concept has to be justified by comparing the predicted performance with the optimized parameters at the present stage, to those in other high power spallation sources.

Another important issue is the energy deposition in cryogenic moderators : How to minimize the deposition and how to realize the required H_2 flow rate. In an intense pulsed spallation source this issue is equally serious to the target problem, since the moderator volume is rather small (about 0.5-0.7 litters) and the total energy deposition is in a range of several kW with a much higher local deposition rate near the target.

The present paper describes the proposed basic concept and overviews the present status of the design studies with various technical issues on the JAERI 5 MW spallation source, especially focused on the optimization with some new ideas.

2. Outline and basic concept of JAERI 5 MW spallation source

2.1 Accelerator

The main accelerator proposed for the Neutron Science Project is a superconducting P/H^- linac of the following specifications;

Proton energy	1.5 GeV
Peak beam current	30 mA
Total beam power	8 MW
Beam power for spallation source	5 MW at 50 Hz (finally) 1.5 MW (early stage).

A superconducting linac was chosen for the common use (multipurpose use) of a high power accelerator with other research fields, mainly of the nuclear technology (accelerator-driven nuclear-energy-system). How to efficiently utilize the proton beam of such a modest peak current (30 mA) for an intense spallation source is the most important issue in the JAERI spallation source project. After extensive discussions we decided to put priority at a short pulse spallation source (SPSS) with a long pulse spallation source (LPSS) in the second priority. For an SPSS compressor ring(s) is indispensable which is more expensive and technically challenging. In order to accumulate the proton beam into compressor ring(s) up to a level corresponding to 5 MW at 50 Hz, the charge exchange injection over a long pulse duration of about 3.7 ms becomes indispensable due to a modest peak current, which shall be compared to 105 mA in the ESS project. In order to overcome the technical difficulties associated with the conventional charge exchange injection method utilizing stripping foils, a new method which utilize undulators and a laser beam for ionizing H^0 beam has been proposed by Y. Suzuki [1]. It is expected to promote R&D works on this idea by an international collaboration.

2.2 Target station

After extensive discussions we reached at a basic concept for the neutron source facility and the target station [2]. Important items are as follows;

(1). A horizontal beam injection;
(2). One target station and one experimental hall at the early stage, but finally two sets;
(3). The first target station acceptable the full power (5 MW at 50 Hz);
(4). Four moderators on one target (the first target station);
(5). All moderators at the highest luminosity position on the target;
(6). As many neutron beams as possible (design goal: acceptable more than 40 instruments including packed beam extractions and multiple use of one beam by several instruments (as in a guide hall at a high-flux reactor);
(7). Equal number of beams for experiments utilizing cold, thermal and epithermal neutrons (tentative decision);
(8). Each neutron beam viewing a fixed moderator (no flexibility for viewing a different moderator, which is effective to increase the total number of the beam and simplify the design of beam shutters, beam windows, etc.)
(9) Minimum angular occupation around the target station for the proton beam injection (upstream) and for the target remote handling (down stream) in order to increase the number of

available beams;

(10). The smallest target void vessel or crypt in order to minimize leakage fast and high-energy neutrons around the slow neutron beams;

(11). Beam shutters of an ISIS type (simple up-down movement);

(12). Target remote handling cell downstream; Not decided yet for the cryogenic moderator handling (upward or downstream);

3. Basic concept for target-moderator-reflector system

Based on the concept described above we reached at a concept for the target-moderator-reflector system [2], which is described below.

3.1 Target

The major considerations and decisions are as follows;

(1). The use of a mercury target due to the reasons discussed later;

(2). Adopting a flat beam and a flat target as shown in Fig. 1, from a neutronic point of view (optimal flatness is discussed later);

(3). Assuming the maximum acceptable proton-current-density on the target to be 48 $\mu A/cm^2$, judging from the integrity of the target beam window under the proton irradiation;

(4). Assuming a beam current density distribution as close as an uniform distribution from the neutronic and mechanical points of view (A Gaussian profile is not acceptable. A Moffet or, at least, a parabolic distribution is acceptable. A perfect uniform distribution, rectangular distribution, is not acceptable due to a higher stress in the beam window by the pressure wave.);

(5). Assuming the minimum beam size determined by (3) and (4);

(6). Assuming the smallest lateral target dimensions, beam size plus 1.5 cm to up and down directions (towards moderators) and 2 cm to the left and right directions, in order to maximize the target-moderator coupling (the engineering feasibility must be considered separately);

3.2 Moderator and reflector

3.2.1 Choice of moderators

Since we assumed that one third of the total available angles around the source is allocated to each field of experiments utilizing cold, thermal or epithermal neutrons (basic concept (7) in

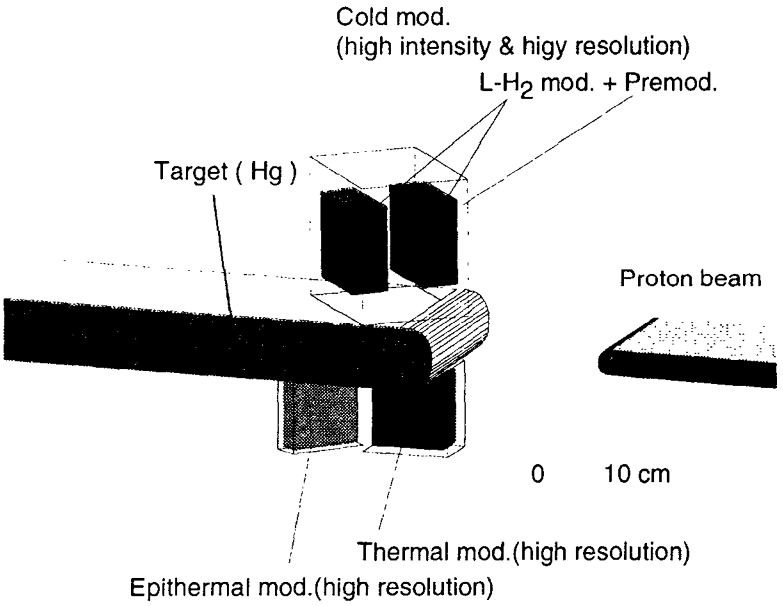

Fig. 1 Illustration of target and moderator layout

section 2.2), the required angular coverage for each kind of moderator(s) becomes about 100 degrees [2], which cannot be covered by one viewed surface, but two viewed surface becomes indispensable. For a moderator having only one viewed surface, two such moderators are required. Thus, four moderators as listed in Table 1 are considered.

Cold neutron moderator: For a cold neutron source we adopted a coupled composite moderator composed of liquid-hydrogen or supercritical hydrogen (H_2) plus hydrogenous premoderator (practically H_2O) at ambient temperature (sometimes called a coupled H_2 with premoderator), which has been developed to provide a higher time-integrated and simultaneously a higher peak cold neutron intensity than a conventional decoupled H_2 or solid methane moderator [4-6]. This moderator can satisfy high-intensity experiments such as SANS, reflectometry, etc. in which the time-integrated intensity is important [7], together with high-resolution experiments in which the peak intensity is essential [7]. We assumed two such moderators since this moderator has only one viewed surface.

Thermal neutron moderator: For high-resolution thermal neutron experiments we assumed a decoupled H_2 moderator with a interleave poison sheet, since a decoupled solid or liquid methane moderator so far been successfully used cannot be utilized at MW sources. R&D of a mixed moderator for this purpose (for example, [8]) will require a long period. Optimization studies on a decoupled poisoned H_2 moderator is under progress.

At the present stage of the design work we are not thinking to install a high-intensity thermal neutron moderator, since high-resolution thermal neutron experiments are much more promising than high-intensity ones at SPSS.

Epithermal neutron moderator: For a high-resolution epithermal-neutron-moderator we are assuming an H_2O moderator of an appropriate thickness, tentatively 3 cm thick. The optimal thickness will be determined after extensive discussions by users on the most interesting energy range in future science.

3.2.2 Moderator layout

Figure 2 shows moderator layout we proposed; two coupled composite moderators above the target and two decoupled moderators, one poisoned H_2 and one H_2O, below the target. In order to make it possible to put two coupled moderators at the highest luminosity region on the target, we proposed an idea of sharing a backside premoderator as shown in Fig. 2. Similarly we put two decoupled moderators such that both can take the best place by positioning them adjacently each other. One concern with this configuration was a possible cross talk between

Table 1 Main parameters of moderators

Purpose	High-resolution & high-intensity cold neutrons	High-resolution thermal neutrons	High-resolution epithermal neutrons
Main moderator	H_2	Poisoned H_2	H_2O
size (cm^3)	12 x 12 x 5	10 x 10 x 5	10 x 10 x 3
Moderator temp.	20 K	20 K	Room temp.
Premoderator	H_2O (2.5 cm thick)	Non	Non
Coupling	Coupled	Decoupled	Decoupled
Cut - off energy	--	1 eV	1 eV
Angular coverage	50°×1	50°×2	50°×2
No. of viewed surface / moderator	2 / 2	2 / 1	2 / 1

two adjacent viewed surfaces. However, it was confirmed by a simulation that such cross talk will not be important.

The neutronic performance of this configuration will be discussed later.

3.2.3 Reflector

We assumed a reflector as shown in Fig. 2 as a reference size (80^{W} x 160^{H} x 120^{L} cm^{3}) and compared the performance with a smaller one (60^{W} x 140^{H} x 90^{L} cm^{3}) to discuss the required size, especially for coupled moderators. Each reflector has neutron-beam extraction holes as shown in Fig. 2.

4. Optimization

4.1 Calculation

Calculational model was essentially the same as the model shown in Fig. 2. When the size of the target or a moderator, or the bottom premoderator thicknesses were changed, the positions of moderators and beam extraction holes were also changed accordingly. All the inside surface of the beam extraction holes in the reflector for the decoupled moderators were covered by liners made of B_4C. The thickness of the decouplers and the liners was fixed at 3 mm and a

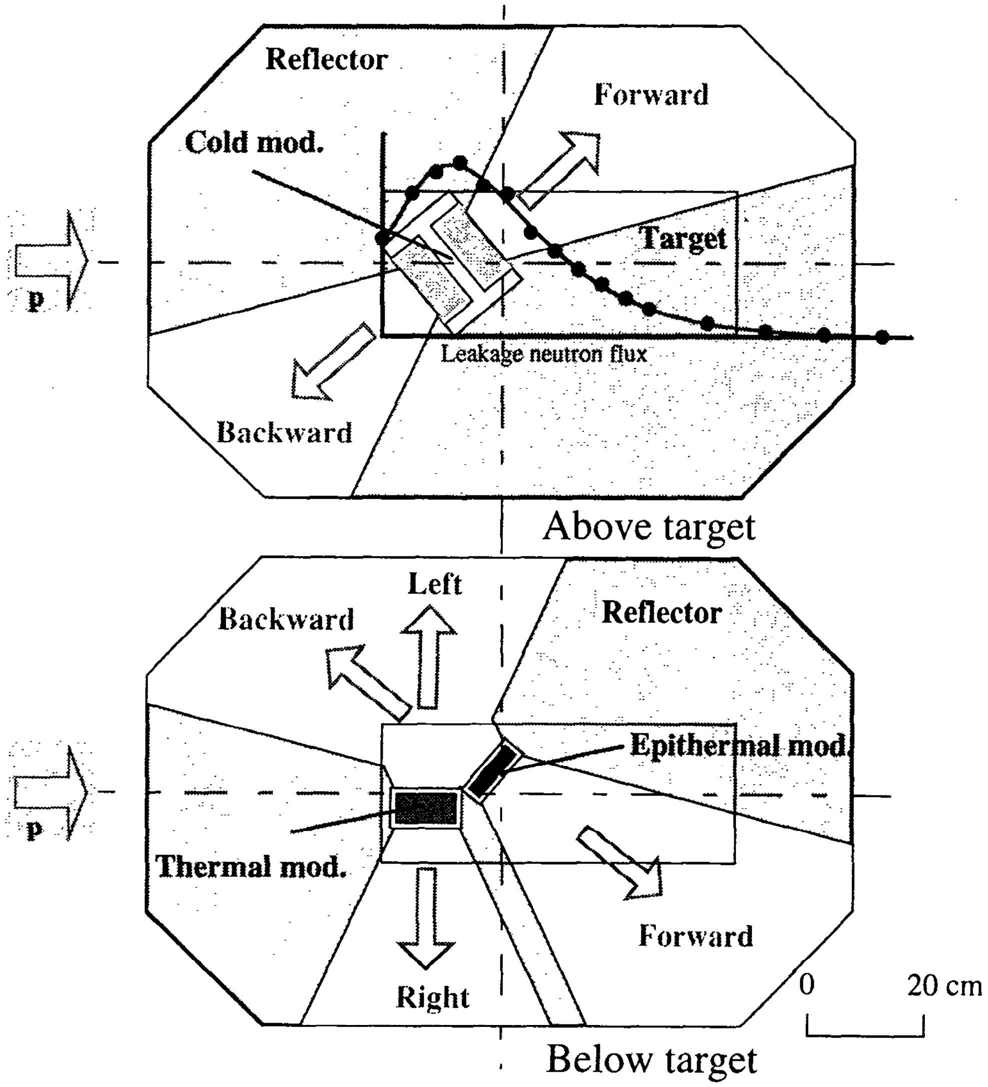

Fig. 2 Layout of target-moderator-reflactor system

required cut-off energy was controlled by adjusting the number density of B_4C. The cut-off energy was tentatively fixed at 1 eV.

In the case of a water cooled solid target, a homogeneous mixture of the metals and the coolant was assumed as usual. The target and moderator vessels were also treated as homogenous mixtures, including metals, cooling water and void of 1 cm thick in total for both vessels.

Codes, cross sections and the number of protons used for the present calculations are almost the same as those described at the separate article in this ICANS [9].

4.2 Choice of target material and shape

Assuming that the use of a liquid metal target is indispensable, we compared mercury (Hg) and lead bismuth (Pb-Bi) as a target material from the neutronic point of view. To understand the bare target neutronics the leakage neutron intensities at 2 cm from the target surface towards moderators were calculated for the two different target materials of various shapes and sizes. The lateral dimensions of the targets were automatically determined from the assumed proton beam size (beam size plus 1.5 cm up and down directions, and plus 2 cm to the left and the right directions). The results are shown in Fig. 3. An Hg target gives always a higher intensity than a Pb-Bi target of the same geometry. A flat target (of a rectangular cross section) provides a higher intensity than a cylindrical one under the same condition in the maximum proton current density (48 $\mu A/cm^2$, i.e., the same beam cross sectional-area). Since Hg has a larger slow neutron absorption cross section, the final decision shall be done after comparing slow neutron intensities.

Figure 4 shows leakage neutron distributions on the five different horizontal regions for flat targets. Although the maximum intensity is approximately comparable of different flatness, the flatter one provides a larger high luminosity region (horizontally).

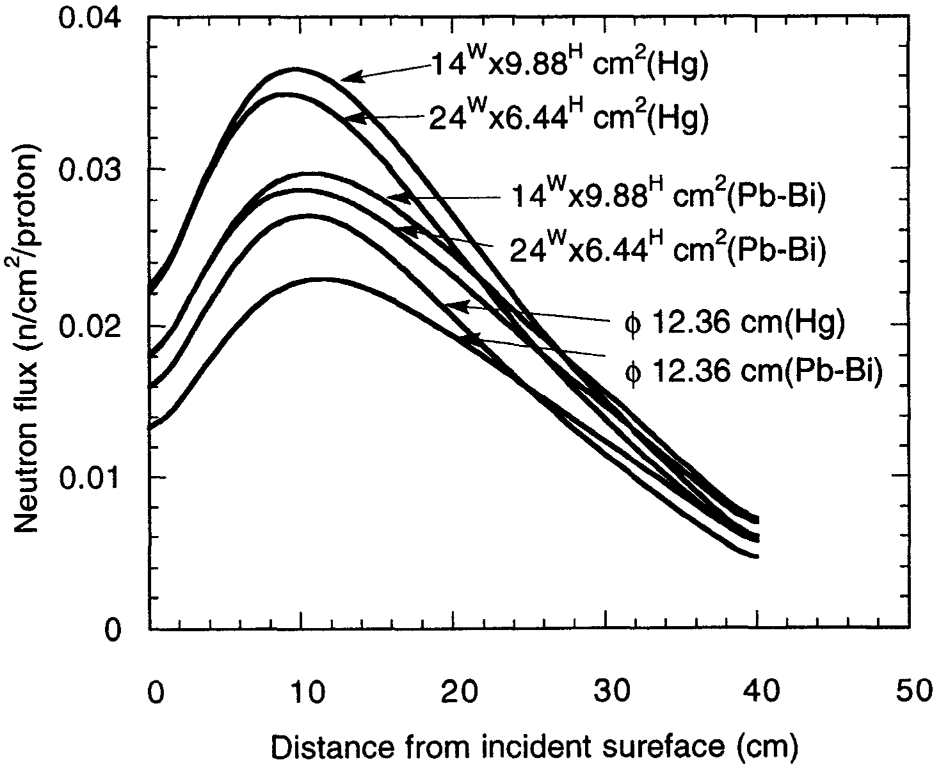

Fig. 3 Spatial (axial) distribution of leakage neutron intensities from various targets

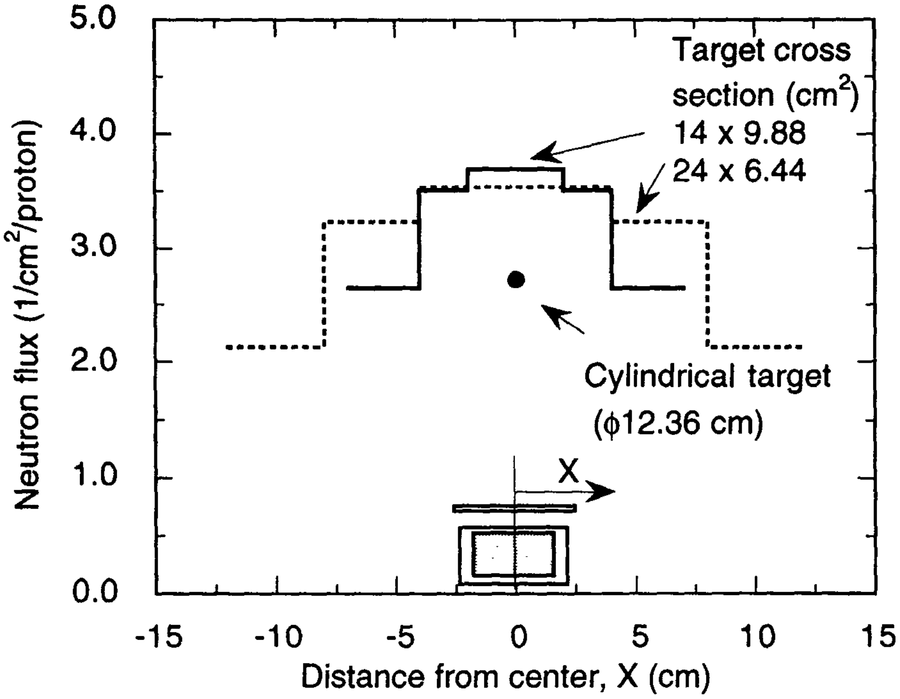

Fig. 4 Spatial (lateral) distributions of leakage neutron intensity from flat Hg targets

4.3 Target shape and size

The effects of the target shape and size on slow neutron intensities were studied. Some results for the case of the Hg targets with a Pb reflector are shown in Fig. 5, where slow neutron intensities from various moderators are compared for various beam sizes and shapes (in terms of the aspect ratio, b/a, where a and b are the horizontal and the vertical beam sizes, respectively). The target sizes and shapes are automatically defined from these values. Note that the data indicated by open circles are for a reduced beam current density (two third of the assumed maximum acceptable value), which corresponds to a larger beam size, accordingly a larger target size. Judging from this result, one important conclusion comes out: the slow neutron intensity is almost unchanged for a large variety of the beam aspect ratio, b/a, and for a different (larger) target size. **This fact will provide a larger flexibility for the target engineering.** This is a rather surprising result for Hg targets, since Hg target has been considered to act as a sort of a large decoupler due to a larger slow neutron absorption cross section. The reason will be due to the fact that a flatter (a smaller b/a) target gives a wider maximum luminosity region on the target than a less flat one as shown in Fig. 4, but absorbs more slow neutrons, canceling the former effect.

4.4 Effect of reflector

The effects of the reflector material and the size on slow neutron intensities and pulse shapes were studied. The intensities calculated with a Be reflector of the same size as the Pb reflector are also plotted in Fig. 3 (for the case of b/a=3.44/20). The Be reflector gives higher time-integrated intensities (J's) for all moderators, especially for coupled composite moderators, compared to the Pb reflector. Figure 6 compares time distributions (pulse shapes) of cold neutrons at 2.1 meV (2.0-2.2 meV) from the reference coupled composite moderator in the Be and the Pb reflectors.

The result shows that although a Be reflector can provide a higher integrated intensity with a

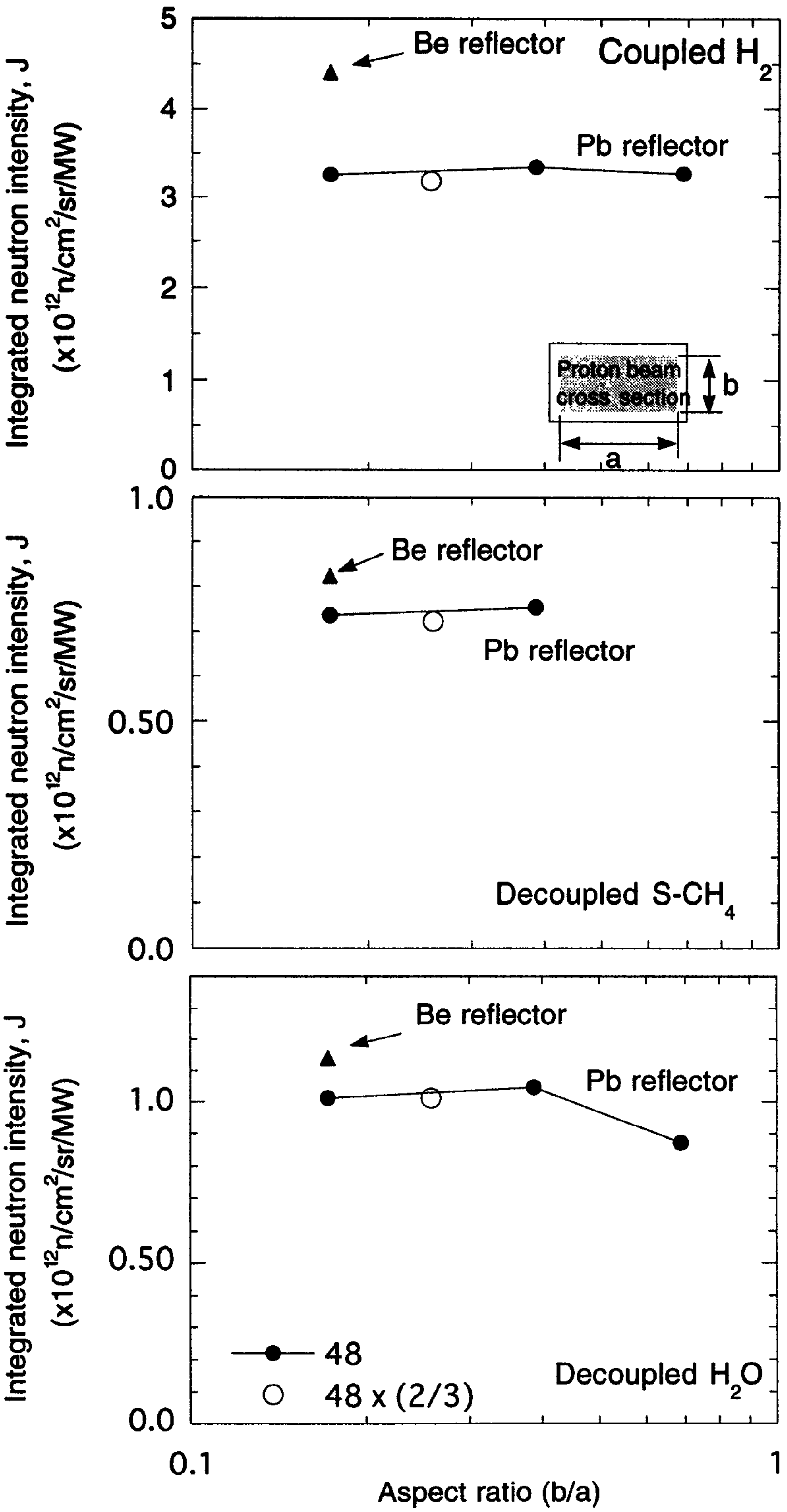

Fig. 5 Beam aspect-ratio dependence of integrated neutron intesity, J, from various moderators

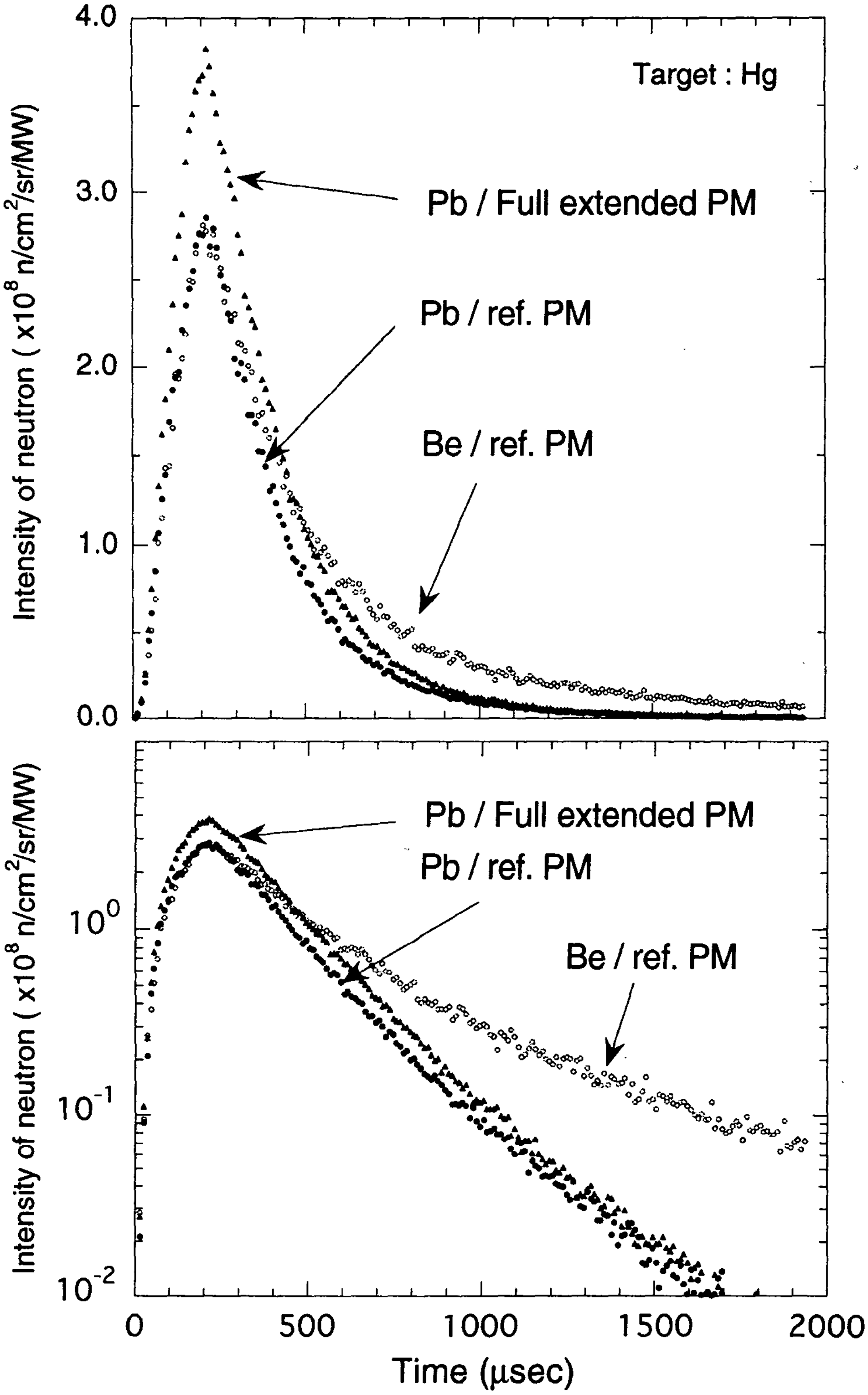

Fig. 6 Time distributions of neutron at E=2.0-2.2 meV from coupled composite moderators

lower energy deposition, as described later, than a Pb reflector, if we compare the pulse characteristics, the latter with an optimized premoderator, as described in a separete article [9], gives much higher peak intensity with a narrower pulse width than the former. This suggests the superiority of a Pb reflected system as far as the neutronic performance is concerned. The integrated cold neutron intensity from a Be reflected system will also increased to some extent by adopting a similar fully extended premoderator. However the gain factor by this will not be as large as in the case of the Pb reflected system. Such comparison is under progress.

The neutronic performance with a smaller Pb reflector was compared to that with the reference size one. The result shows that in the case of a Pb reflector the time-integrated intensities are more or less lower than those of the reference size case, especially for a coupled composite moderator.

4.5 Moderator position relative to target

The effects of the relative position of a moderator to the target on time-integrated intensities (J's) were studied changing the position of the target in the fixed moderator-reflector configuration. This is nearly equivalent to that the moderators were moved as a set relative to the target. The relative position was changed by 5 cm upstream and downstream from the reference position. The intensities from various moderators at the three positions are plotted in Fig. 7 for the case of the Pb-Bi target with the Pb reflector of the reference size. Judging from this result, it can be said that the present moderator layout at the reference position is almost at the optimal, not only in the sum of the intensities from the two moderators above and below the target, respectively, but also for each moderator, i.e., all moderators are positioned at the first class sheet as envisaged. More exactly speaking, the optimal position for the set of two coupled composite moderators is about X = -5 cm. This conclusion will be true also for other combination of target and reflector. The intensities with the reference Hg target combined with a Pb and a Be reflector are also plotted in the figure only at the reference position.

5. Nuclear heating in cryogenic moderator

The nuclear heating in cryogenic moderators is one of the most important technical issues in the design study of an intense spallation source. We calculated the energy deposition in the main cryogenic moderator (H_2) for various cases, a simple decoupled H_2 moderator, a coupled composite moderator with the reference premoderator and with fully extended premoderator. In all cases two different reflectors, Be and Pb, were compared. The results on the total energy depositions are summarized in Table 2 and the spatial distributions are compared in Fig. 8. The

Table 2 Total energy deposition in cryogenic moderators

Case	Moderator	Moderator size (cm^3)	Reflector	Premoderator	Heat deposition (kW)
(1)	Composite*	12 x 12 x 5	Pb	PM (2.5 cm)	2.79
(2)	Composite*	12 x 12 x 5	Be	PM (2.5 cm)	2.06
(3)	Composite*	12 x 12 x 5	Pb	Full (3.5 cm)**	1.94
(4)	Decoupled H2	10 x 10 x 5	Pb	non	3.95
(5)	Decoupled L-CH4	10 x 10 x 5	Pb	non	5.77
(6)	Decoupled L-CH4	10 x 10 x 5	Be	non	4.68

*Coupled composite moderator composed of H_2 + premoderator

** A fully extended premoderator with 3.5 cm thick bottom premoderator (see ref. [9])

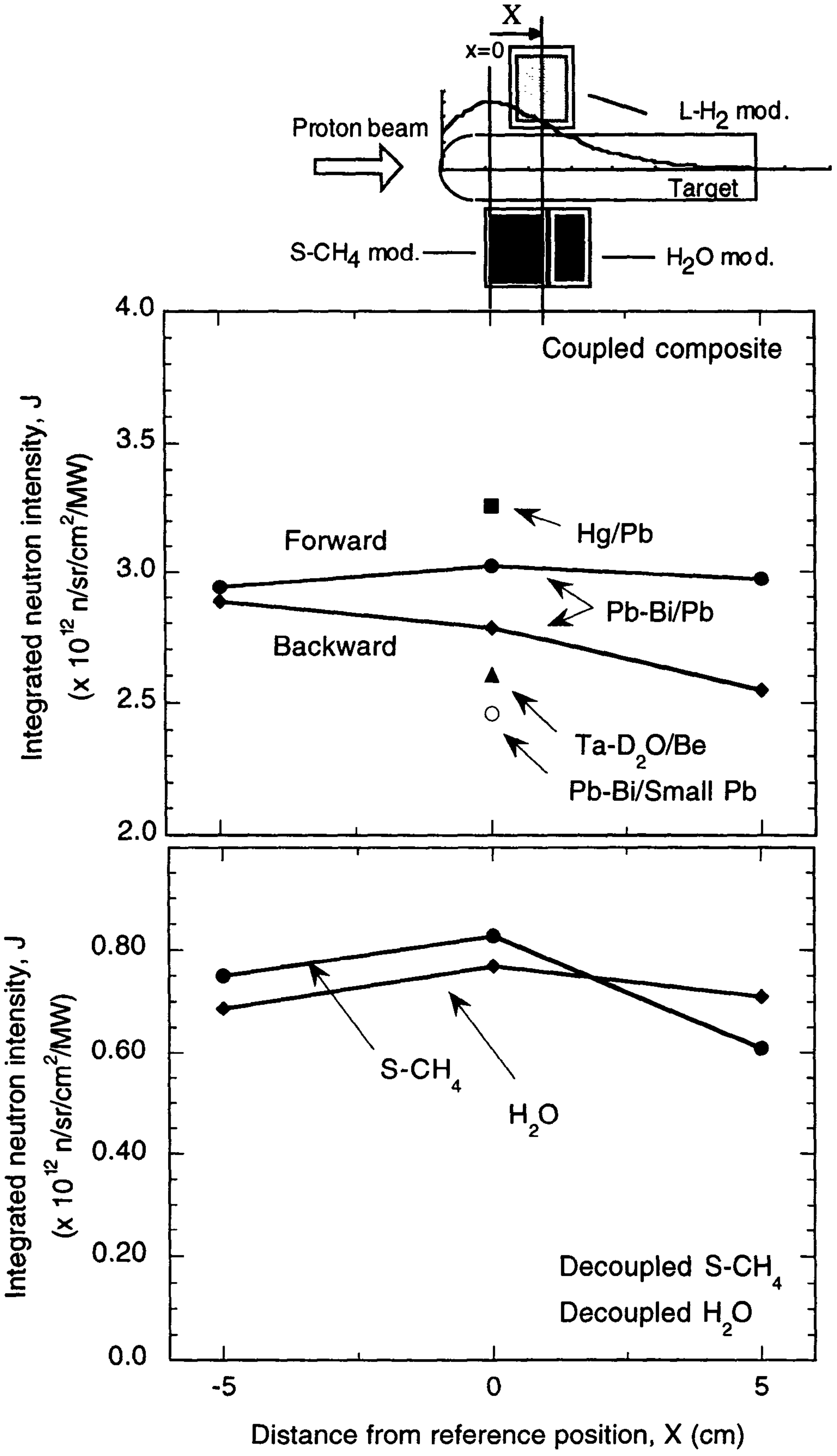

Fig. 7 Integrated neutron intensities, J's, from various moderators at three different positions

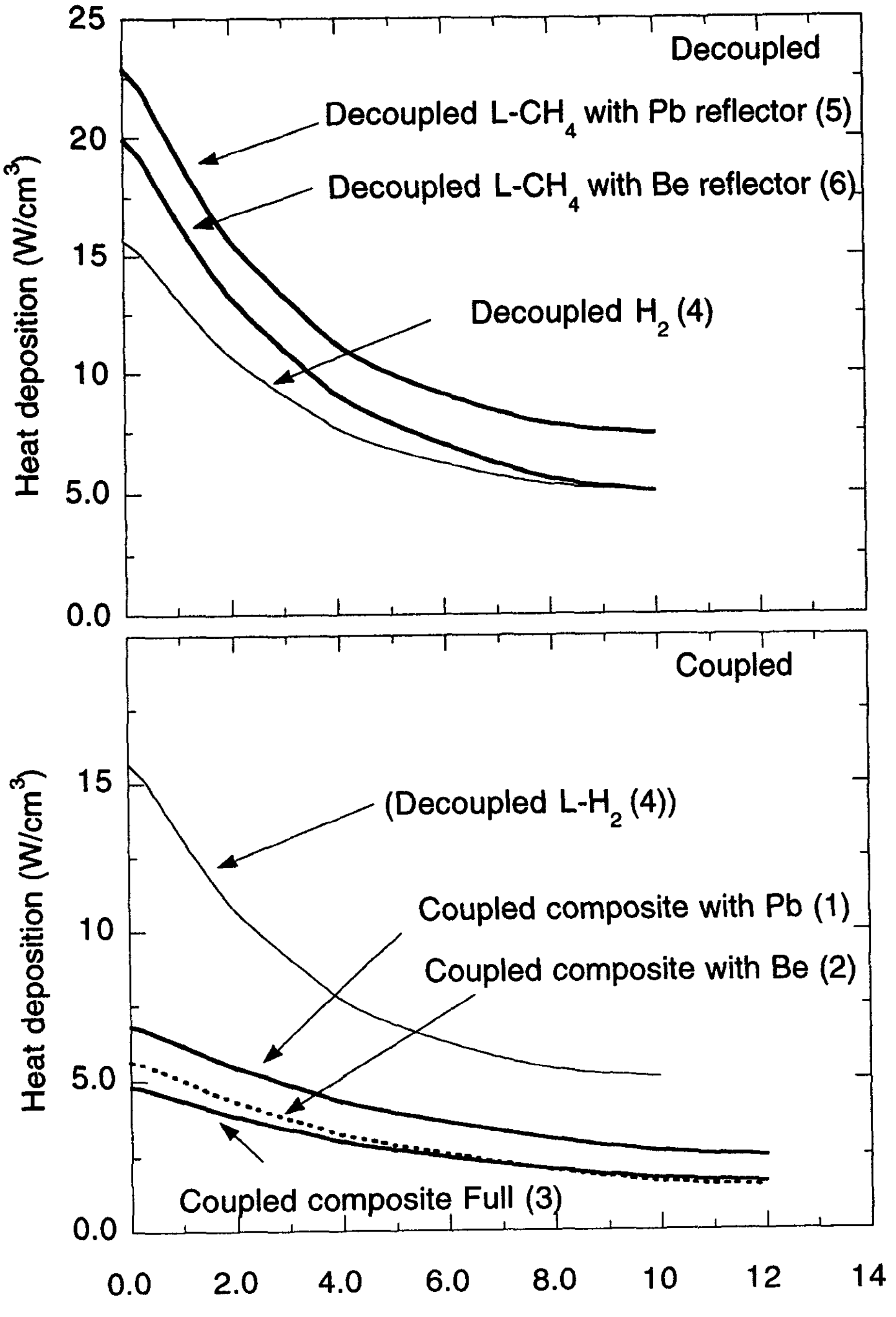

Fig. 8 Spatial distributions of heat deposition in cryogenic moderator as a function of distance from moderator bottom

energy deposition can be decreased by the use of a premoderator as already well known, but we found, with various efforts as described in the separate paper in this ICANS [9], a further reduction in the nuclear heating is feasible incorporated with a higher cold neutron intensity without sacrificing the pulse characteristics for example by the use of a fully extended premoderator. The choice of the reflector is another important issue. The energy depositions can be reduced to some extents by adopting a Be reflector, also as well known. However, the reduction rate at the hottest region close to the target is rather small as shown in Fig. 8. Note that even with a Pb reflector the energy deposition can be reduced to the same level as with a Be reflector by adopting a fully extended premoderator as described above.

The level of the nuclear heating for a coupled moderator with premoderator is in an acceptable range even at the full power (5 MW at the full repetition rate of 50 Hz): it ranges from 2 to 2.8 kW. However, for a decoupled H_2 moderator, which we are thinking to use as a high-resolution thermal neutron moderator probably with an interleave poison sheet, the level becomes very high, especially in the case with a Pb reflector, which reaches at about 8 kW/liter. If we compare the power density, our value is a much higher than other sources due to full pulse use (50 Hz). Some important parameters on cryogenic moderators in various intense sources are compared in Table 3. The use of supercritical hydrogen, is, of course, indispensable. However, one important problem is a very high temperature rise of H_2 during the passage through the moderator chamber, even assuming a higher hydrogen flow rate of 2 liters per second, which is technically very ambitious for such a small moderator volume. The average temperature rise reaches at about 5.8 K. If we assume a possible flow disturbance such as a recirculation flow, a local temperature rise beyond the critical temperature may occur, resulting in the break of the supercritical state over the whole moderator and eventually in the destroy of the cryogenic moderator. Extensive studies how to prevent such flow instabilities has just started [9].

Table 3 Comparison of important parameters of cryogenic moderators in various neutron sources

	ISIS	HFIR	ANS	SNS	JAERI*
Energy deposition (total, kW)	0.4	0.6+1.4	15+15	2	3.95
Moderator volume (liter)	1.06		30		0.5 (1)
Average power density (kW/liter)	0.4		1		7.9
Volumetric flow rate (liters/sec)	0.5	1	30	1	2
Temperature rise (K)	1.1	3	2.3	3	2.9 (5.8)

* The values for pulsed spallation source are for a decoupled H2 moderator. Our value is for the case of (4) in Table 2. The values in parenthesis are for the case of 1 liter moderator volume.

6. Discussions and conclusions

How to judge or justify the present concept of the target-moderator-reflector? A direct comparison of the predicted performance based on the present model with those of other similar project will be the most persuasive way. Since the calculation methods are almost well established, such comparisons will be fair, provided that the model is realistic in engineering feasibility. Thus, neutron spectral intensities and time-integrated intensities (J's) from various moderators combined with an Hg target of a given size were calculated. An example of the results on cold neutron intensity obtained from the reference coupled composite moderator (in detail, see Fig. 1 of a separate paper presented at this ICANS [9]) coupled to the reference Be reflector is shown in Fig. 9 in a liner scale compared with reported values at a medium power SPSS (LANSCE Upgrade, about 160 kW [10]). From these results it can be said that the cold neutron intensity per MW of the present model is at least comparable to or higher than those in other project including a medium power one. The results justify the present concept of the target-moderator-reflector system as far as the neutronic performance is concerned. By adopting a fully extended premoderator an additional gain will be obtained also in the case of a Be reflected system, although the gain may not as large as in a Pb reflected system.

As described above, the superiority of a Pb reflector for coupled composite moderator has been proved in the case a fully extended premoderator : a higher peak cold neutron intensity with approximately a comparable time-integrated intensity, but with a narrower pulse width and a lower energy deposition compared to the reference Be reflected system. For decoupled moderators, the advantage of a Pb reflector is not clear. Extensive calculation on the time distribution of thermal and epithermal neutrons from decoupled moderators are under progress.

Next It was found that the slow neutron intensities are not strongly depend upon the target (Hg) geometry (size and aspect ratio), bringing about a large flexibility in the target engineering.

It also turned out that the energy deposition in a decoupled H_2 moderator is very high, especially in power density which requires a very high H_2 flow rete. To ensure the engineering feasibility to realize the optimized parameters, further R&D efforts are necessary.

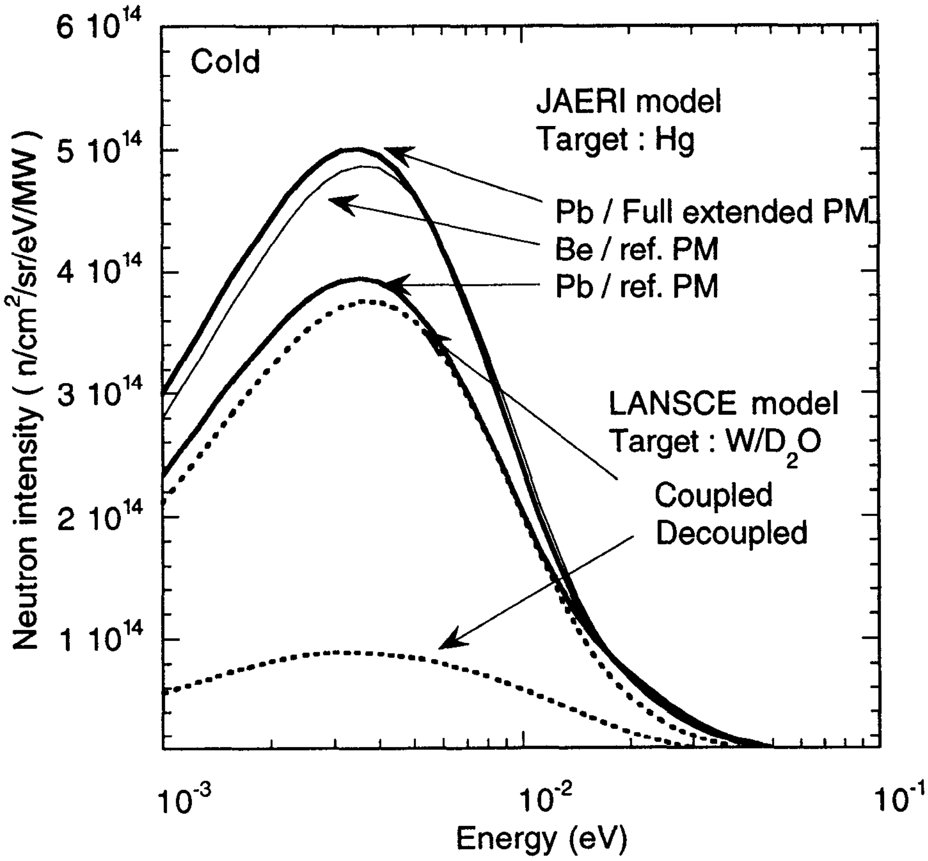

Fig. 9 Slow neutron spectral intensities for various moderator in a liner scale

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