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Neutron Production Enhancements for the Intense Pulsed Neutron Source

E. B. Iverson, J. M. Carpenter, T. L. Scott, M. E. Miller, L. D. Peters, M. W. Schlueter
Intense Pulsed Neutron Source
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL USA 60439

The Intense Pulsed Neutron Source (IPNS) was the first high energy spallation neutron source in the United States dedicated to materials research. It has operated for sixteen years, and in that time has had a very prolific record concerning the development of new target and moderator systems for pulsed spallation sources. IPNS supports a very productive user program on its thirteen instruments, which are oversubscribed by more than two times, meanwhile having an excellent overall reliability of 95%. Although the proton beam power is relatively low at 7 kW, the target and moderator systems are very efficient. The typical beam power which gives an equivalent flux for long-wavelength neutrons is about 60 kW, due to the use of a uranium target and liquid and solid methane moderators, precluded at some sources due to a higher accelerator power.

The development of new target and moderator systems is by no means stagnant at IPNS. We are presently considering numerous enhancements to the target and moderators that offer prospects for increasing the useful neutron production by substantial factors. Many of these enhancements could be combined, although their combined benefit has not yet been well established. Meanwhile, IPNS is embarking on a coherent program of study concerning these improvements and their possible combination and implementation. Moreover, any improvements accomplished at IPNS would immediately increase the performance of IPNS instruments.

1 Enhancements In Progress

A number of enhancements to IPNS neutron production are already in progress. Design choices for these enhancements have largely been made, and engineering questions are all that remain to be answered, whether by experiment or calculation. These enhancements are relatively well-defined, with clearly demonstrable benefits. They include a re-designed booster target, based on experience with the booster target used from 1988–1991, re-designed solid methane moderators for use with the booster target, a moderator-reflector assembly designed for rapid moderator replacement, and experimental studies of minor moderator modifications.

1.1 New Booster Target

IPNS has operated with a depleted uranium target from 1981–1988 and since 1992. For three years, 1988–1991, we operated with a booster target composed of the same alloy of α-phase uranium enriched to 77% ^{235}U, and of the same physical design as the depleted target. This subcritical target had a multiplication factor k_{eff} of approximately 0.80, and resulted in neutron production of about two and one-half times the production rate with the depleted uranium target.

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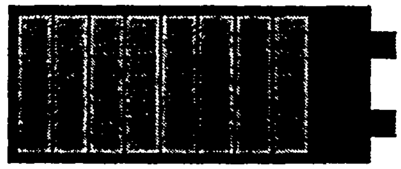

Figure 1: The IPNS target, composed of uranium disks cooled by water.

The booster target failed at approximately the expected end of its design life, as did the first depleted uranium target. Examination of the failed depleted uranium target indicated that the failure was due to anisotropic growth, caused by the rhombohedral α-phase crystal structure. A new booster target of enriched uranium with ten weight percent molybdenum in a cubic γ-phase was then designed which would be stable against anisotropic growth under irradiation. Stability and manufacturing methods for the U-10Mo alloy have been experimentally verified in the German SNQ study. The new target would have the same multiplication factor, and thus the same gain in neutron production, as the original booster target. The new booster target is predicted to have a significantly longer lifetime than the original booster target, which was nonetheless acceptable. The new target would be physically similar to the existing target.

There are a number of challenges to be met involving the use of an enriched booster target. Current Department of Energy policies require proof that highly enriched materials offer benefits which cannot be obtained by the use of materials of lower (less than 20%) enrichment. Detailed calculations demonstrating these benefits have been performed by Roger Blomquist of the Reactor Analysis division of ANL. If the booster target is to be combined with a beryllium reflector, the Safety Analysis Report will need to be modified slightly. Finally, use of the booster target will exacerbate the operational difficulties presently experienced in the solid methane moderators, discussed in greater depth below.

In spite of the benefits to be gained from the use a booster target, the penalties and challenges of its use have lead us to decide that it is simply not practical.

1.2 Solid Methane Moderators with Increased Neutron Yield

The C and H moderators are composed of solid methane, which displays a "burping" phenomenon under irradiation. This behavior is currently being controlled by an annealing procedure performed manually every two to three days during operations. Any increase in target yield, whether from a booster target or some other modification, will result in a shortening of the allowable time between annealing operations. The annealing procedure currently in use is to be automated, which will allow more flexibility in the annealing schedule, reduce manpower requirements, and reduce the operational down time for anneals. A task force has been assigned that is currently in the planning stage of this project with an estimated project completion of February 2000.

A cooperative research program with the Nuclear Engineering Department at Pennsylvania State University has been explored to study the behavior of solid methane under heavy neutron irradiation. This program is expected to provide insight into the dynamics of the spontaneous energy release and the hydrogen release and the associated pressure surge, possibly leading to techniques for controlling or mitigating the effect of radiation damage and/or resulting pressurization. This program is currently on hold. Finally, the moderator container may be amenable to redesign against fatigue effects based on calculation of the stresses resulting from the pressure surge associated with the burping phenomenon. This possibility has not yet been explored.

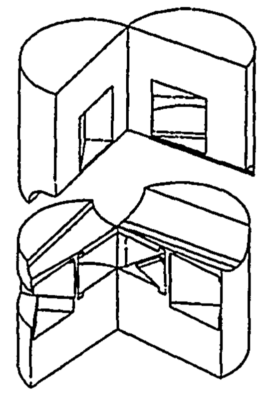

Figure 2: A "clamshell" reflector.

1.3 Rapid Moderator Replacement

The moderator and reflector assembly can be markedly improved to facilitate rapid moderator replacement. The present reflector assembly must be laboriously disassembled to provide access to the moderators, resulting in considerable time expenditure and radiation exposure. The use of "clamshell" reflector and shield plug assemblies, which would split open vertically to allow ready access to the moderators, would increase the availability of the moderator system, and reduce time and personnel irradiation during maintenance. Such a reflector design is on hold until resources become available to complete the design. A quick connection system for plumbing and wiring is also being designed to save operational down time and reduce personnel radiation exposure during moderator replacement. The design for the quick connect system is in progress with an estimated design completion of March 1999.

1.4 Grooved Moderator Reconfiguration

A program of Monte Carlo simulations directed toward optimizing the groove configurations of the C moderator was carried out at the University of Illinois, Urbana-Champaign under the direction of Professor Brent Heuser of the Nuclear Engineering Department. The results of these simulations indicate that exchanging the current solid methane moderator with horizontal grooves for a similar moderator with vertical grooves would increase the neutron intensity seen by the POSY instruments by a factor of 1.3–1.6. These simulations further predict that the neutron intensity at the SAD and SAND instruments, which also view the C moderator, would not be compromised. The vertical grooved moderator is currently being fabricated in Argonne shops, with an estimated completion date of March 1999.

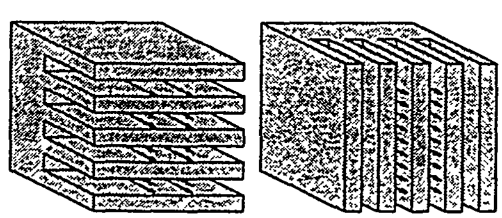

Figure 3: Grooved moderators from the POSY viewpoint.

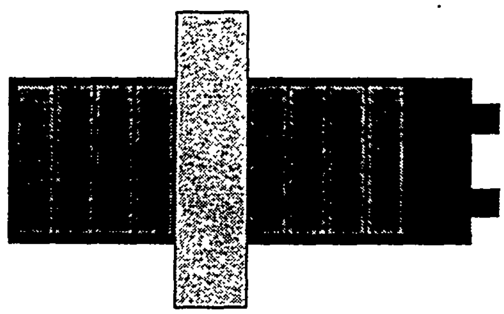

Figure 4: A split target with a tall moderator in the flux trap region.

1.5 Exotic Moderator Materials

Experimental studies of exotic moderator materials at Hokkaido University in Japan are in progress. The materials included in this study are partially deuterated liquid hydrogen (H_2+HD), partially deuterated liquid methane, and partially deuterated solid methane (CH_4+CH_3D). We anticipate improvements in the thermalization capabilities of these materials relative to the protonated versions, which would stem from the richer rotational levels of the asymmetric molecules. The benefit of such moderator materials include a roughly estimated gain of a factor of 1.2 in the intensity of long-wavelength neutrons. The materials to perform these experiments have been ordered, and should be received in October. The actual experiments will follow, according to the run schedule for the Hokkaido facility.

2 Computational Studies of Potential Enhancements

A number of possibilities for potential enhancement of the neutron production at IPNS are being investigated by computational Monte Carlo studies. The benefits of these design changes are in general less precisely known, and such calculations will provide a useful assessment of their value to IPNS, as well as to the pulsed neutron community in general.

2.1 Split Target

The present target system is composed of a set of eight zircalloy-clad uranium disks, cooled by water. Each disk is four inches in diameter and one inch thick. These disks are spaced one-sixteenth of an inch apart, and the moderators are centered along the length of the target assembly. By "splitting" the target, i.e., separating two of the intermediate disks by a larger space, it is conceivable that the intensity gains from appropriately positioned moderators could reach a factor of three over the present target arrangement. A split target could be employed with either the new booster target design, or with the present depleted uranium design. The space between the two halves of the split target might be useful as a flux-trap moderator. The flux-trap moderator could be "tall," i.e., oblong, in such a way that it provides more neutrons to those instruments which would not suffer from the reduced angular resolution in the vertical dimension. This design is similar to that which forms a central part of the current upgrade at the Manuel Lujan, Jr., Neutron Scattering Center.

2.2 Squat Target

Japanese experience at KENS indicates that a target which presents an oblong cross section to the oncoming proton beam may result in large intensity gains—greater than a factor of two in some cases. This cross section would have the major axis comparable to the diameter of the present circular target. If premoderators (discussed below) were found to provide an additional benefit, use of the oblong target at IPNS

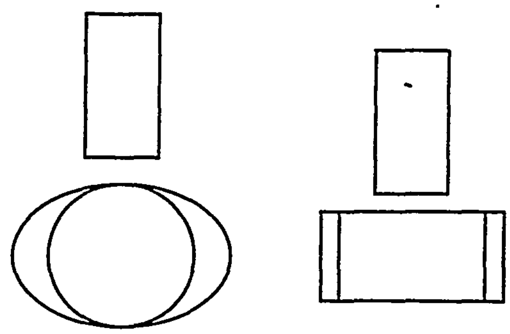

Figure 5: A squat target (right) allows moderators to be closer to the target itself.

might not require moving the moderators (and thus the neutron beam-lines). The new target might further require modifying the incident proton beam, either in position or footprint. Implementation of the squat target might require moving some or all of the neutron beam-lines and instruments up or down.

2.3 Combined C and H Moderators

The three moderators (C, F, and H) now in use serve twelve neutron beam-lines. Six of these beam-lines view the F moderator, beneath the target; three view the C moderator, also beneath the target; and three view the H moderator, above the target. Combining the functions of the C and H moderators could enhance the beam intensity available from all moderators by as much as a factor of 1.5, due to the increase reflector efficiency which would result.

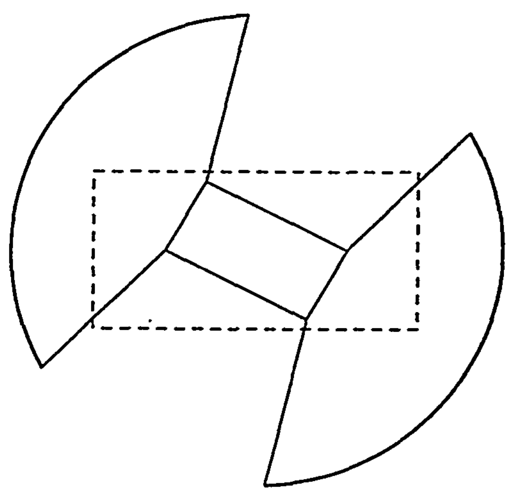

Figure 6: Combining the functions of the C and H moderators.

2.4 Solid Methane F Moderator

Of the current moderators, the C and H moderators are composed of solid methane at 30 K, while the F moderator is composed of liquid methane at 110 K. Replacing the moderator material in the F moderator with solid methane would increase the intensity of longer wavelength neutrons by a factor of six, although reducing the intensity at intermediate wavelengths by a factor of two. This reduction is partially countered

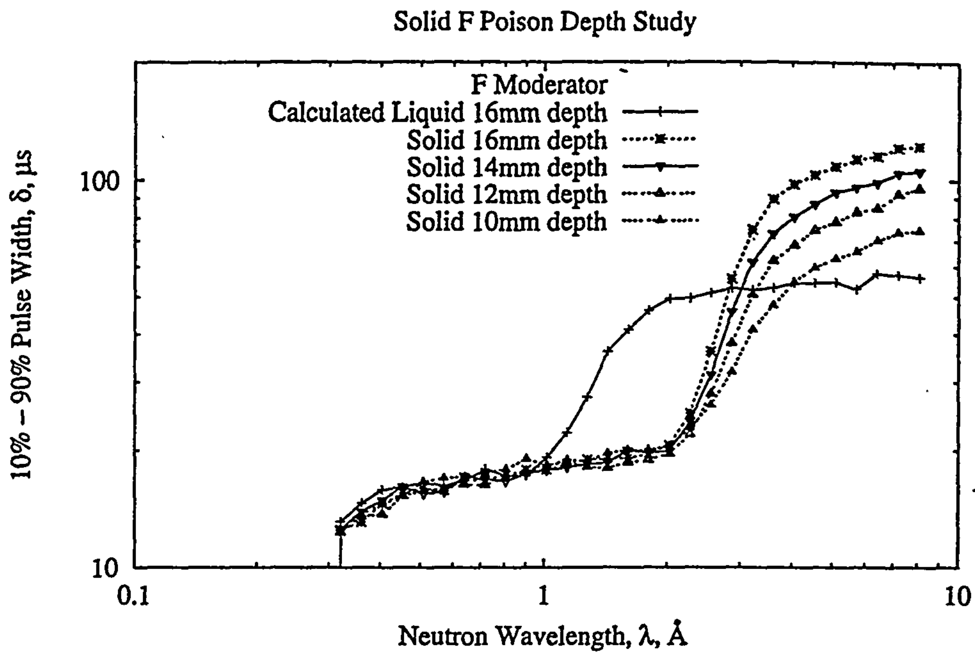

Figure 7: Pulse widths as a function of poison depth for a solid methane F moderator, as compared to the present liquid methane moderator.

by an improvement (reduction) in the pulse resolution of a factor of 0.8 at intermediate wavelengths, and 0.9 at shorter wavelengths. The interest in such a proposal stems from the ever-present desire to have more long-wavelength neutrons.

2.5 Pre-Moderators

In the present moderator-reflector configuration, there is neither moderating nor reflecting material between the target and the moderators. The use of "pre-moderators," moderating material at room temperature placed between the target and the viewed moderator, would reduce cooling requirements on the cryogenic moderators; especially important if other IPNS improvements were to increase the neutron yield of the target system, requiring more frequent annealing of the solid methane moderators. Calculations performed as part of a Japanese study have further indicated the possibility that pre-moderators would result in intensity gains in the neutron beams.

2.6 Composite (Pre)Moderators

Typical moderators at pulsed neutron sources are, like those at IPNS, poisoned with a heterogeneous layer of neutron absorbing material. This layer provides a more advantageous pulse shape to the neutron beam. Moderators which employ more complex arrangements and more diverse materials offer the ability to tailor the neutron spectrum and increase the neutron intensity. Such composite moderators may also provide the possibility of duplicating the 100 K spectrum available from a liquid methane moderator without using liquid methane, which suffers serious radiation-induced decomposition at higher heat loads.

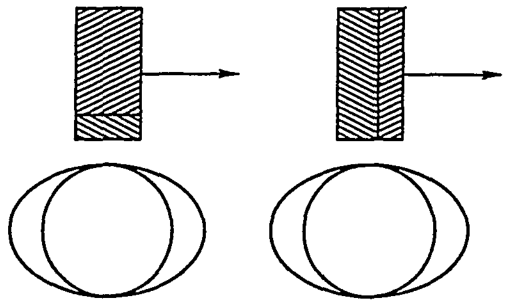

Figure 8: A pre-moderator (left) and a composite moderator.

2.7 Decoupler Materials

The present moderators are all decoupled from the rest of the moderator-reflector assembly by 0.5 mm thick layers of cadmium. Changing the decoupler material to gadolinium or some other neutron absorber exhibiting a different energy dependent cross section would result in a different balance between lengthened tails in the neutron pulse structure and neutron intensity. This balance might further be influenced by cooling the reflector assembly, which is presently at ambient temperature. Figure 9 shows an approximate time-average neutron spectrum in the reflector, $F(E)$, and the fraction of neutrons transmitted by decoupling layers of Cd and Gd. Actual attenuation of isotropically distributed neutrons is greater than shown, computed for normally incident particles. The decoupler must exclude long-lived neutrons from the Maxwellian (low-energy) part of the spectrum, yet should pass epithermal (higher energy) neutrons which fall off rapidly. The gadolinium decoupler passes more epithermal neutrons than does the cadmium, at the expense of broadening the pulse in the moderator.

2.8 Reflector Material

The target and moderators are contained within a large two-region reflector assembly, currently composed of beryllium and graphite. Changing the inner reflector material from graphite to beryllium would result in greater intensity in the neutron beams from some or all of the moderators. Rough calculations indicate that this gain in intensity would be of the order of a factor of 1.15.

2.9 Larger Moderators

The present moderators have viewed surfaces with dimensions of ten by ten centimeters. Enlarging the viewed face of the moderator from ten by ten centimeters to, for example, twelve by twelve centimeters

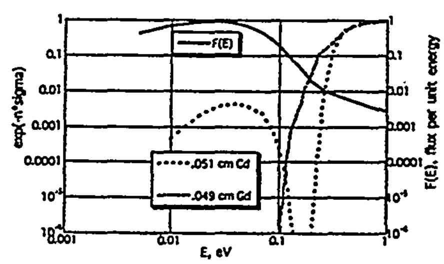

Figure 9: The neutron spectrum in reflector compared to decoupler transmission fractions.

would provide a gain in neutron intensity at the cost of angular resolution.

2.10 Exotic Moderator Materials

The experiments previously described (concerning exotic moderator materials) taking place at Hokkaido University should be accompanied by computational analysis of the potential benefit of these materials. As mentioned above, these partially deuterated moderator materials—$H_xD_{2-x}(\ell)$, $CH_xD_{4-x}(\ell)$, and $CH_xD_{4-x}(s)$—offer the possibility of gains of a factor of 1.2 in intensity for longer wavelength neutrons. The primary obstacle to calculation of the moderating capabilities of these materials is the lack of knowledge of their scattering kernels at cryogenic temperatures.

3 Long-Term Enhancements

Finally, there are some long-term possibilities for study. These concepts would require a considerable amount of study before they could be determined to be feasible, and their benefits are not well characterized. The knowledge and experienced gained would be enormously useful to the pulsed neutron source community, and they would require a great deal of additional study prior to implementation.

3.1 Intermediate Spectrum Booster

The present design for a sub-critical booster target uses primarily ^{235}U, deriving most of the neutron multiplication from fast neutron induced fissions. A booster target which relied more upon fissions induced by neutrons of lower intermediate energies accomplished by including more coolant/moderator might require lower enrichment uranium for the target material. A target composed of lower enrichment uranium would provide a solution to the political difficulties surrounding the use of highly enriched uranium.

3.2 Circulating Solid Methane Moderator

One of the difficulties described previously concerning the use of solid methane as a moderator material is that, while solid methane is neutronically superior to any other material presently used, its behavior under radiation exposure leads to gas evolution and attendant "burping"—sudden surges in temperature and pressure resulting in often permanent structural damage to the physical structure of the moderator assembly. While there are other avenues of exploration intended to counter this problem, one attractive concept is the use of *circulating* solid methane in a moderator. Several systems have been proposed, including small particles of solid methane suspended in liquid hydrogen. Development of a circulating solid methane moderator would have considerable benefit to the entire pulsed neutron community. This concept is presently under active development by various members of the ACoM collaboration (the collaboration for Advanced Cold Moderators); this collaboration and its work are discussed elsewhere in these proceedings.

4 Summary

IPNS has a history of innovative developments in spallation neutron production for neutron scattering. The new efforts described herein will continue to improve the state-of-the-art neutron scattering research that takes place at IPNS, and will benefit companion efforts underway elsewhere in the country and throughout the world.