

CHARACTERISTICS OF LONG-PULSE AND SHORT-PULSE SPALLATION-SOURCE TARGETS*

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INTRODUCTION

Generation of sharp neutron pulses is the desired output of a pulsed spallation neutron source (PSNS). These pulses should be approximately 10 μ s. wide at half maximum, and preserve as much of the original flux as possible. A proposed PSNS has been designed to operate at an average proton beam power of 5 MW. This source is described in a companion paper (Ludewig, 1996), and in a Brookhaven National Laboratory (BNL) report (BNL Report, 1994). Briefly, the PSNS consists of a heavy metal target, surrounded by a reflector, and a selection of moderators. The moderators are connected to beam tubes in which the neutrons are transported to the experimental stations. Reflectors are generally made of good moderating material, in which neutrons leaking from the target are slowed down by elastic scattering, prior to moderation. In the current study it is proposed to investigate the possibility of using reflectors which slow neutrons down by inelastic scattering rather than elastic scattering. In a purely inelastic scattering medium neutron pulses leaking from the heavy metal target will tend to preserve their original shape in both energy and time, since:

- 1) A relatively large loss in neutron energy following the first few inelastic interactions which bring the neutron pulse down to below the inelastic threshold,
- 2) Following this inelastic scattering phase there will be a relatively small amount of energy loss due to elastic scattering, since these nuclei are heavy and not very efficient moderators, and
- 3) The time structure is preserved because there are a relatively small number of scattering events involved in the slowing down process.

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The concept of using an inelastic scattering medium as a reflector is not new. Lead was studied as a reflector in connection with the SNQ project (Bauer, 1985), and measurements of its efficiency have been reported (Bauer, 1982). However, the inelastic scattering cross-section of lead has a comparatively high threshold of approximately 1 MeV, and thus the spectrum of inelastically scattered neutrons in a lead medium would have a pronounced peak at this energy. In this paper we propose to investigate the use of compounds which have inelastic scattering thresholds at lower energies. In this case, the pulse of neutrons entering the moderators will not have to undergo as many scattering event in the moderator to achieve a thermalized spectrum. The fluorine nucleus has an inelastic scattering threshold at approximately 100 keV, and thus compounds of fluorine will be investigated as possible reflectors or pre-moderators in a simple target, reflector and moderator system. Fluorine compounds of both lead and beryllium will be investigated in this study. Lead fluoride can be obtained commercially, either in crystalline or sintered form; and beryllium fluoride has been studied in connection with fusion reactor blankets.

Pulse broadening in energy, thus largely takes place in the moderating volumes located in the reflector. Slowing down in reflectors which are pure elastic scattering media cause the pulse shape to broaden in energy, and develop a low energy tail. This broadening is due to the very efficient slowing down power of the light nuclei characteristic of these materials.

In this paper we will examine the effect of different reflectors and proton pulse lengths on the neutron pulses in the moderators. This study will be carried out using a simple target configuration. In this way effects introduced by complicated target arrangements can be avoided. All the analyses presented in this paper were carried out

using the LAHET code system (LCS). This code system consists of two major modules:

- 1) LAHET, a modified version of the HETC intranuclear cascade code for evaluations above 20 MeV, and
- 2) HMCNP, a modified version of the well known MCNP transport code for calculations from 20 MeV down to thermal energies.

Both modules employ a combinatorial surface/cell specification of the problem geometry which permits modeling of the target configurations with minimal approximations. In addition, HMCNP employs nuclear data from the ENDF/B files in essentially unapproximated point-wise form which avoid the complications associated with generation of group cross sections.

In addition, the thermal-mechanical effects of the proton pulse length on the target will be discussed. These effects take the form of thermal stress enhancement due to shock waves which are generated when proton pulses length are comparable to the natural frequency of target elements.

PROTON PULSE LENGTH IMPLICATIONS

In this section the effect of the proton pulse length and reflector type on the moderator neutron pulse length and relative amplitude will be outlined. In order to carry out this study a simple target arrangement will be considered. It will consist of the following components:

- 1) Cylindrical tungsten heavy metal target 15 cm OD x 100 cm L,
- 2) Cylindrical reflector surrounding the tungsten target 50 cm OD x 100 cm L,
- 3) Two moderators (light water and liquid hydrogen) embedded in the reflector.

A section through this target arrangement is shown on Figure 1. The proton energy in all cases will be 2 GeV. A Gaussian pulse shape with widths varying from $1.2(-6) \text{ s}$ - $1.0(-3) \text{ s}$ is assumed. The three different reflectors assessed in this study are:

- 1) Lead Fluoride (PbF_2),
- 2) Beryllium Fluoride (BeF_2),
- 3) Heavy Water (D_2O), and

The neutron slowing down mechanism in this selection of moderators varies from essentially all inelastic scattering (PbF_2), to purely elastic scattering (D_2O). Beryllium fluoride uses a mixture of both inelastic and elastic scattering for neutron slowing down. The inelastic scattering cross section for fluorine and lead are shown on Figure 2. Thus the inelastic slowing down scattering cross section for PbF_2 is finite over an energy range from 10 MeV to 0.1 MeV.

Neutron slowing down due to elastic scattering with PbF_2 is not very efficient, and is not expected to contribute much to the slowing down spectrum. Heavy water is the most efficient at slowing neutrons down by elastic scattering of the reflectors being considered.

Results of the analyses are shown on Table 1. From these results the following conclusions can be drawn:

- 1) The shortest proton pulses result in neutron pulses with the largest amplitudes for the H_2O moderator, regardless of reflector.
- 2) In the case of the liquid hydrogen moderator the neutron pulse length does not decrease monotonically, but stays approximately constant and then decreases in all cases. In addition, it should be noted that for the long pulse option a heavy water reflector yields the highest neutron pulse.
- 3) Lead fluoride reflector results in the largest neutron pulse amplitude, for both moderators considered.

The neutron pulse widths at half maximum for the light water moderator are shown on Table 2. These results show that using a PbF_2 reflector results in a neutron pulse width which is approximately 75% as narrow as a similar pulse using a D_2O reflector. The fractional difference between the pulses corresponding to a PbF_2 reflector and a D_2O reflector are shown on Figure 3. The fractional change is positive up to $1.0(-4) \text{ s}$, and then becomes negative, approaching -1.0. This result shows that the pulse corresponding to the PbF_2 reflector rises faster than that corresponding to the D_2O reflector. In addition, the result indicates that the pulse corresponding to the PbF_2 moderator dies away faster than the one corresponding to the D_2O reflector. Finally, a study was carried out of the effect of poisoning (^{10}B) the moderator on the neutron pulse width and the corresponding pulse amplitude. Various methods of reducing the pulse width have been studied in the past. These include the addition of a homogenous poison to the moderator, decoupling the moderator, or the addition of heterogeneous poisons. Of these methods the addition of a homogeneous poison is the least efficient since it results in a reduction of the amplitude of the peak (Fluharty, 1969). However, by comparing experimentally determined figures of merit (FOM) for various methods of shaping the neutron pulse; it was found that the addition of boric acid to light water was twice as good as an unpoisoned moderator and less than a factor of two (Fluharty, 1969) worse than the heterogeneously poisoned moderator. In addition, the difference in FOM for boric acid poisoned moderators and the heterogeneously poisoned moderators decreased with decreasing neutron energy. Based on these results, and the exploratory nature of the analysis the homogeneous method of poisoning the moderator was chose for investigation. These results are shown on Table 2 and Figure 4. The results shown in Figure 4 are integrated over the moderator volume and from .021 eV to .0253 eV.

* $1.2(-6) = 1.2 \times 10^{-6}$

Table 2 shows the variation in the width, amplitude, and time of the peak with the increased addition of ^{10}B . The amount of ^{10}B added to the light water moderator is measured in units of water absorption. Thus, enough ^{10}B is added to the moderator to equal ten times and fifty times the original absorption cross section of light water. It is seen that the pulse width can be reduced from 8.0(-5) s to 1.0(-5) s. However, the pulse amplitude is reduced by approximately a factor of five at the same time.

The neutron energy spectrum integrated over the respective volumes of the target (tungsten), reflector (lead fluoride), and moderators are shown in Figures 5 - 8. It is seen that the tungsten target neutron energy spectrum peaks at approximately .44 MeV with a tail extending to 20.0 MeV. The spectrum in the reflector peaks at .022 MeV - .066 MeV with a lesser peak at 1.2 MeV. However, its fairly tight structure in energy is the result of the inelastic slowing down mechanism characteristic of this reflector. In the light water moderator there is a broad peak at approximately 0.057 eV. Finally, in the liquid hydrogen moderator there is a pronounced peak at 0.009 eV.

Finally, the temporal variation of the integrated neutron flux which corresponds to the maximum neutron pulse amplitude in the various components is shown in Figures 9 and 10 for two proton pulses (1.2(-6) s and 1.0(-3) s). It is seen that for the short proton pulse, the neutron pulse in the heavy metal target and the reflector are clearly separated from the pulses in the moderators. In the case where a longer proton pulse is used the neutron pulses in the heavy metal target and heavy water moderator essentially overlap.

In addition to affecting the neutron pulse width, the proton pulse width also has implications for the mechanical performance of the target. The length of the proton pulse determines the time during which the energy in the pulse is deposited in the target. This in turn determines the rate at which the target temperature rises. If this rise is extremely rapid a stress wave can be generated, which enhances the steady state thermal stresses due to temperature gradients. This dynamic problem arises from the inability of the target elements to expand in unison with the temperature rise because of mass inertia.

This problem has been recognized by various investigators (Burgreen, 1962, Sievers, 1974, Conrad, 1994). Time dependent stresses for spheres subjected to temperature pulses of various duration have been studied (Burgreen, 1962), and can be characterized by the following relationship:

$$\sigma = E \alpha \Delta T F(t)$$

where,

- E = Young modules
- α = Coefficient of thermal expansion
- ΔT = Temperature increase
- $F(t)$ = Function of time

The variation of $F(t)$ with time determines the magnitude of the thermal-mechanical stress enhancement. It has been shown (Burgreen, 1962) that the value of $F(t)$ is a strong function of T_p/T_f , where:

- T_p = Period of the temperature pulse
- T_f = Fundamental period of the sphere

For values of T_p/T_f less than unity the stress enhancement at the center of the sphere can become extremely large. These stresses have no shear components, and are purely compressive in nature. The maximum stress enhancement for $T_p/T_f=1$ is estimated to be approximately 3.7. The tungsten sphere diameter chosen in the current BNL target design (BNL Report, 1994) is based on $T_p/T_f=1$, thus a modest stress enhancement is expected during operation with a proton pulse width of 1.4 micro-sec. However, the spheres are expected to survive many pulses without a fatigue failure.

Other target components such as windows and internal target structures are also subject to the same transient stresses. By examining the expression for the transient stresses it is seen that they can be minimized, for a given proton pulse width by minimizing ΔT or α . The value of ΔT can be minimized by choosing a material which absorbs a small fraction of the proton beam energy. These materials are characterized by a low value for the number of electrons per unit volume. Alloys with a low expansion coefficient α have been created, i.e. "Invar" a nickel alloy. Thus the transient thermal stresses can be minimized by judicious choice of materials.

As the value of T_p/T_f increases beyond unity the stress wave problem is reduced. This increase can be effected by increasing the length of the proton pulse or decreasing the fundamental period of the target element. Decreases in the value of T_f are determined by the size of the target element and the velocity of sound in the target material. Thus decreases in T_f are limited by physical propoerties and component size. A value of $T_p/T_f=4$ results in essentially no stress enhancement due to thermal mechanical effects. This implies that increasing the proton pulse to approximately 7 micro-sec, for the current particle bed target design, would essentially eliminate the transient stress problem.

CONCLUSIONS

The following conclusions can be drawn from this comparative study of proton pulse lengths and their effects on the neutron pulses:

- 1) The result of using a short proton pulse lengths (~ 1.0(-6) s) are:
 - 1.1) Moderator neutron pulses with larger amplitudes,
 - 1.2) Neutron pulses which have a narrower width at half maximum; and which rise faster, and die away faster,
 - 1.3) Neutron pulses in the heavy metal target and reflector

which do not overlap the neutron pulse in the moderator.

- 2) The use of longer proton pulses ($\sim 1.0(-3)$ s) are:
 - 2.1) Removal of the thermal-mechanical shock enhanced stresses in the target components,
 - 2.2) Potentially more reliable operation and the possibility of a larger number of target design options.

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TABLE 1. NEUTRON PULSE HEIGHT
(Relative Unites) / P

**LEAD FLUORIDE REFLECTOR
MODERATOR**

Proton Pulse (s)	H ₂ O (0.0253 eV)	LH ₂ (0.00405 eV)
1.2 (-6)	3.5 (.007)	0.59 (.011)
5.0 (-5)	2.9 (.010)	0.62 (.013)
5.0 (-4)	0.96 (.014)	0.29 (.016)
1.0 (-3)	0.53 (.016)	0.18 (.018)

**BERYLLIUM FLUORIDE REFLECTOR
MODERATOR**

Proton Pulse (s)	H ₂ O (0.0253 eV)	LH ₂ (0.00405 eV)
1.2 (-6)	2.4 (.009)	0.56 (.012)
5.0 (-5)	2.2 (.012)	0.56 (.014)
1.0 (-3)	0.43 (.017)	0.18 (.018)

**HEAVY WATER REFLECTOR
MODERATOR**

Proton Pulse (s)	H ₂ O (0.0253 eV)	LH ₂ (0.00405 eV)
1.2 (-6)	1.6 (.010)	0.48 (.013)
5.0 (-5)	1.5 (.014)	0.49 (.015)
1.0 (-3)	0.38 (.018)	0.25 (.015)

* 1.2 (-6) = 1.2×10^{-6}

TABLE 2. NEUTRON PULSE WIDTH AT HALF MAXIMUM
(s)

**LIGHT WATER MODERATOR
REFLECTOR**

Proton Pulse Width	Lead Fluoride	Heavy Water
1.2 (-6)	8.0 (-5)	1.3 (-4)
1.0 (-3)	6.2 (-4)	8.0 (-4)

EFFECT OF POISON ON MODERATOR PERFORMANCE
LEAD FLUORIDE REFLECTOR
LIGHT WATER MODERATOR

Poison Concentration (In multiples of H ₂ O abs.)	Width (s)	Relative Amplitude	Time of Peak (s)
1.0	8.0 (-5)	3.5 (.007)	1.9 (-5)
10.0	2.5 (-5)	2.3 (.010)	1.3 (-5)
50.0	1.0 (-5)	0.8 (.033)	7.6 (-6)

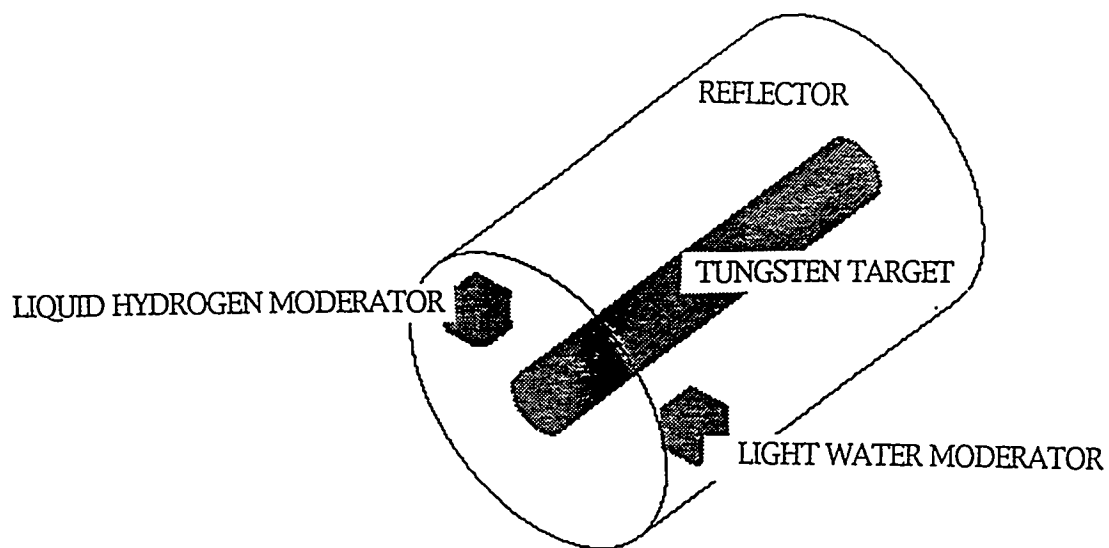


Figure 1. Simple Target Configuration

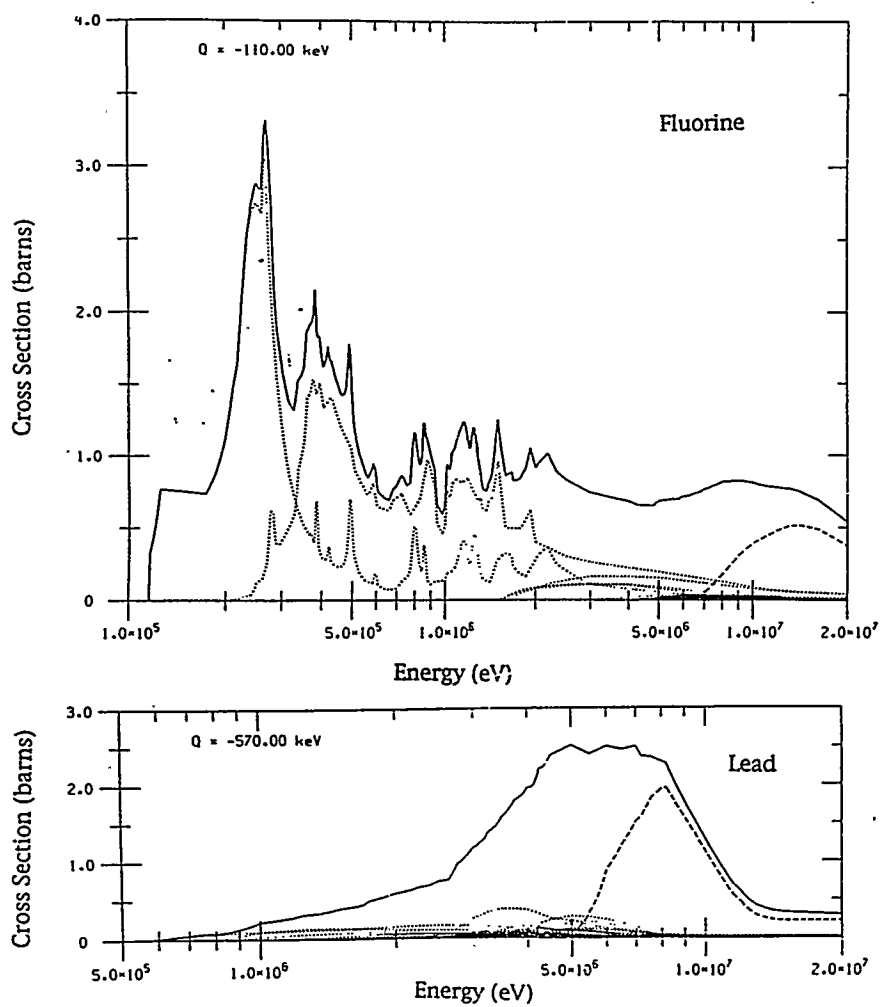


Figure 2. Inelastic Scattering Cross Section for Fluorine and Lead

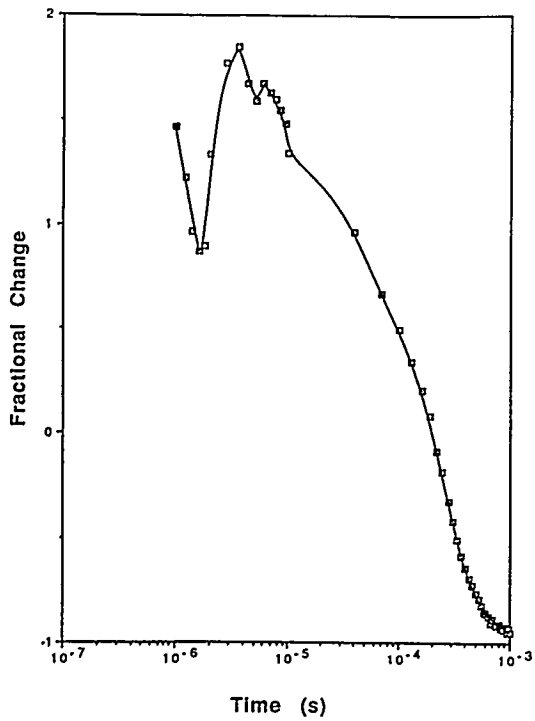


Figure 3 - Fractional Change in Pulse Amplitude

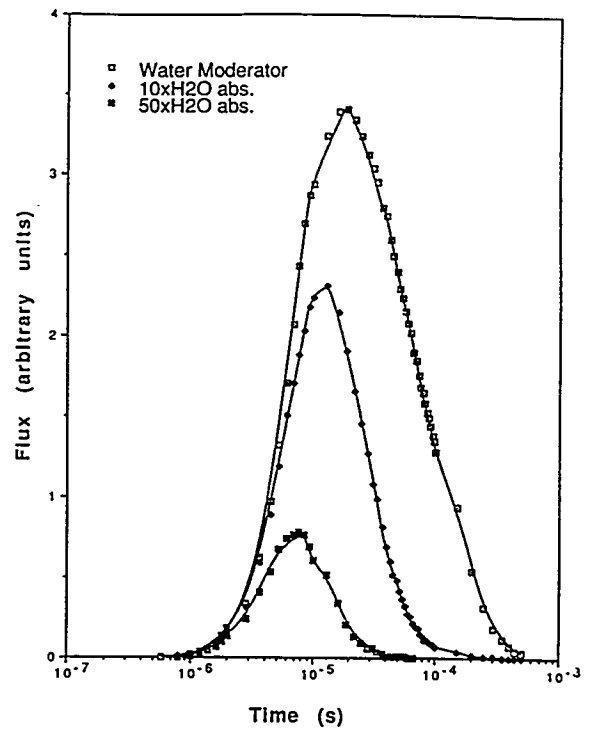


Figure 4 - Neutron Pulse In Light Water Moderator

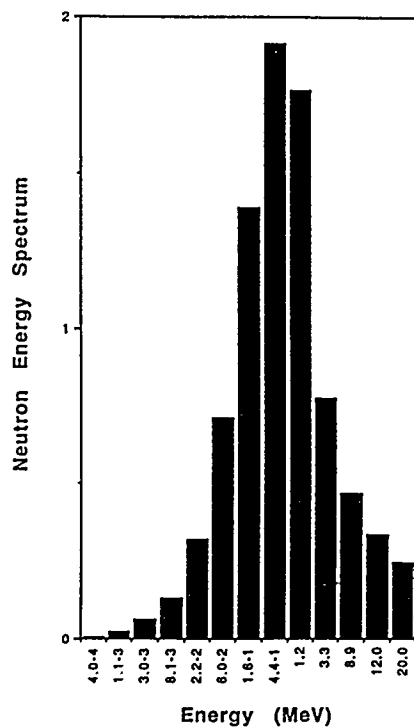


Figure - 5 Neutron Energy Spectrum in Tungsten Target

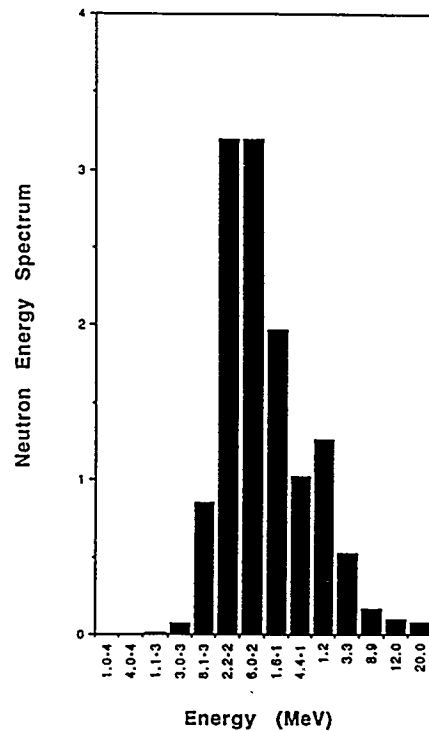


Figure 6 - Neutron Energy Spectrum in Lead Fluoride Reflector

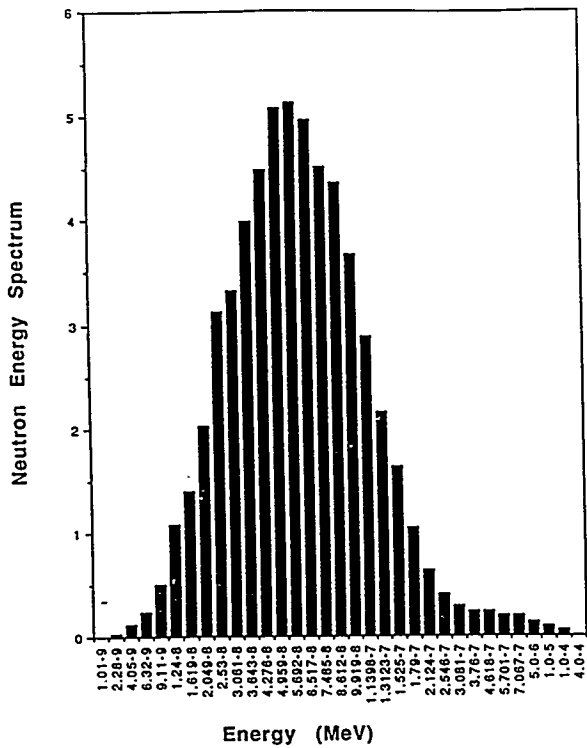


Figure 7 - Neutron Energy Spectrum in Light Water Moderator

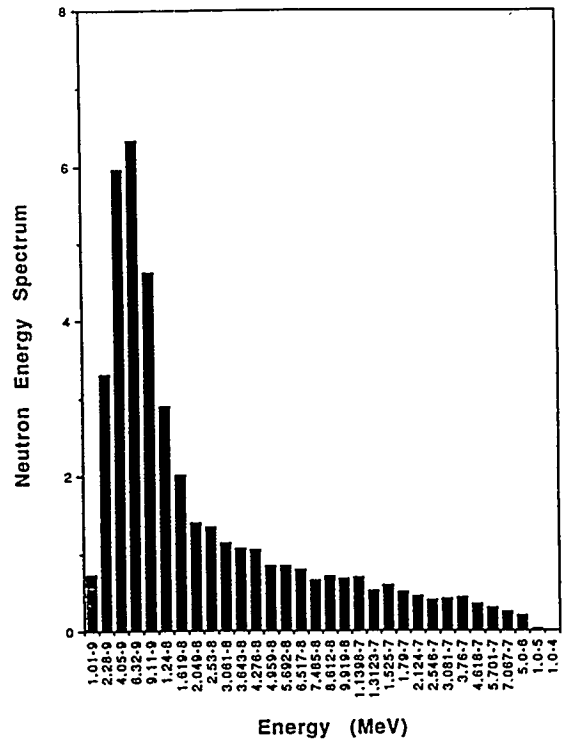


Figure 8 - Neutron Energy Spectrum in Liquid Hydrogen Moderator

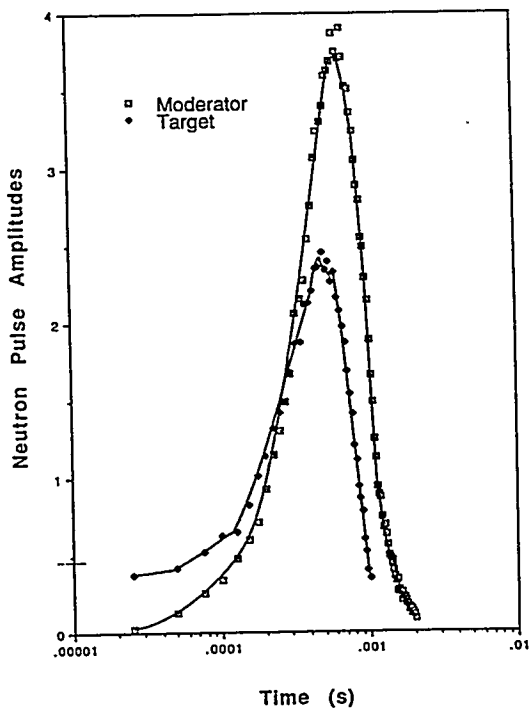


Figure 9 - Neutron Pulses for Long Pulse Option

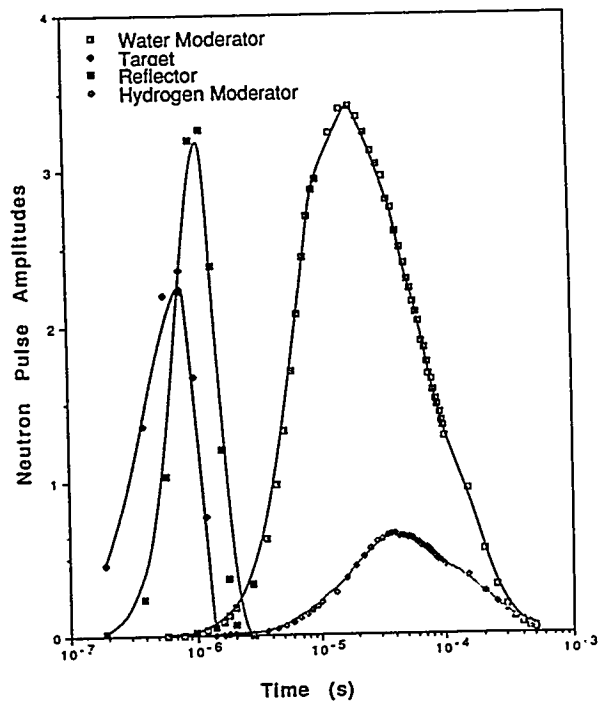


Figure 10 - Neutron Pulses for Short Pulse Option