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PRELIMINARY DESIGN STUDIES FOR AN IRIDIUM ROD TARGET AT THE BNL-AGS

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Abstract

The BNL-AGS is an intense source of 24 GeV protons. It is proposed to explore the potential to use these protons as the driver for a Pulsed Spallation Neutron Source target. The proposed target design is based on an edge cooled iridium rod concept - similar to the anti-proton production target which operated reliably at CERN under similar conditions. Lead, lead fluoride, and beryllium are investigated as possible reflector materials, and ambient temperature light water and 80 K light water ice are proposed as initial moderator materials. Both moderators are decoupled by cadmium containing moderator chamber walls. The small size of the target has the advantage that the moderators can be placed close to the target (resulting in a bright source), and since a large fraction of the radioactive inventory is contained in the iridium rod, removal and disposition of this inventory should be relatively simple and inexpensive.

INTRODUCTION

This paper outlines a pre-conceptual design study carried out on a solid iridium, Pulsed Spallation Neutron Source (PSNS) target for the BNL-AGS. The BNL-AGS accelerates protons to energies ranging from 1.5 GeV - 24 GeV in pulses, at a frequency of 0.556 Hz. Each pulse has 1.0(14) protons and consists of six bunches of 40 ns duration separated by 400 ns. Thus, each pulse is approximately $2\mu s$ long. At 24 GeV each pulse has an energy of 384 kJ and thus the energy per bunch is 64 kJ. It is possible to deliver the bunches to a target at a frequency of 30 Hz. The proton energy to be assumed in this study is 24 GeV, and the spot size on the target will be 0.5 cm in diameter. The conceptual target design is based on an operating target at CERN [1] used for the production of anti-protons. Briefly, this target consists of a solid iridium rod, surrounded by a graphite sleeve, which in turn is clad by a thin layer of titanium. The titanium clad is surrounded by a coolant passage filled with flowing light water. The outer containment of the CERN target is a titanium structure, designed to maximize the production of anti-protons. In the design considered for the AGS, it is assumed that the inner layers of the target remain the same as the CERN target (iridium rod, graphite layer, titanium clad, and cooling water), beyond this point the target design reflects its primary purpose - being a neutron source. Thus, the cooling channel is contained in an aluminum tube, a thick reflector surrounds the aluminum tube. Finally, a light water moderator is embedded in the reflector and a neutron beam tube is included in the design analysis in order to evaluate the potential performance of the source. Thus the material choices are based on the following:

1. Iridium has a high density (22.46 gm/cc), atomic number, and thermal conductivity, and is mechanically strong.

2. Graphite and titanium were chosen, based on the positive CERN target experience.

3. Light water cooling is efficient for the current application, and also can act as a pre-moderator of the neutrons leaving the target.

4. Aluminum is selected as the outer containment since it will minimize parasitic neutron capture and activation during operation.

Lead is chosen as the primary reflector material and light water as the moderator respectively, primarily because they are being proposed at advanced pulsed neutron sources [2,3]. The possibility of using other reflecting materials (beryllium, fluoride compounds ,and layered structures) and cryogenic moderators (liquid hydrogen, light water ice, and liquid or solid methane) will be investigated in subsequent studies. The assembly as described above is shown in Figures 1 - 3. Figures 1 and 2 show the overall configuration and Figure 3 shows a detail of the iridium target and surrounding structures. Dimensions of the most important target assembly features are given in Table 1.

Table 1 - Dimensions of target features.

Iridium rod	1.0 (OD) x 15.0 (L)
Graphite sleeve	0.7 (Thick) x 15.0 (L)
Titanium clad	0.2 (Thick) x 15.0 (L)
Cooling water channel	0.5 (Thick) x 15.0 (L)
Aluminum containment	0.2 (Thick) x 15.0 (L)
Front drift tube (void)	1.0 (OD) x 45.0 (L)
Back drift tube (void)	1.0 (OD) x 40.0 (L)
Moderator volume	12. X 5.0 x 12.0
Neutron beam tube (void)	8.0 (OD)

The parameters of primary concern in this paper are the energy deposition in the target (iridium rod), reflector and moderator (TRAM). In addition, the activation of the TRAM assembly will be estimated following operation for a specified time period. The neutron flux in the moderator will be estimated as a result of the above calculations. The above calculations will be carried out using the Monte Carlo codes LAHET version 2.83[4] and MCNP4B[5]. The activation estimates will be made using a modified version of the ORIGEN code[6] and the spallation product cross section library created for the CINDER-90 code[7].

ENERGY DEPOSITION

The energy deposition in the various volumes of the TRAM assembly is required to complete its mechanical design. This determination takes account of the coulomb losses due to interaction of the primary protons and secondary charged particles, nuclear recoil and gamma rays due to π° decay and

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de-excitation of residual nuclei. The gamma rays resulting from the last two mechanisms are transported from their point of creation in the MCNP calculation. In addition, energy deposition due to neutron slowing down and thermalization are included in the MCNP calculation. The latter component is particularly important in the moderator and cooling water volumes. The energy deposition calculated by the above method will be expressed as MeV/p, and is averaged over the volume of interest (reflector, moderator etc.), only the iridium rod is sub-divided into smaller volumes in order to improve the spatial description of the energy deposition. Each sub-division in the iridium rod is 3 cm long. Results of the above calculation are shown in Table 2.

Table 2 - Energy deposition in volumes of interest

Volume	Energy deposition	
	MeV/p	Watts*
Iridium vol. 1	954.0	3975.0
Iridium vol. 2	1140.0	4750.0
Iridium vol. 3	868.0	3617.0
Iridium vol. 4	715.0	2979.0
Iridium vol. 5	504.0	2100.0
Graphite sleeve	250.0	1042.0
Titanium clad	87.0	363.0
Cooling water	57.0	24.0
Aluminum containment	40.0	167.0
Moderator	71.0	296.0
Lead reflector (radial)	1226.0	5108.0
Lead reflector (back)	4325.0	18021.0

* Note: Current = 1.0(5)/24(9) x 6.21504(18) = 2.5896(13) p/s ; also 1 MeV/s = 1.60206(-13) W
Watts = MeV/p x 2.5896(13) x 1.60206(-13) = MeV/p x 4.1487

It is seen that the total TRAM assembly absorbs approximately 43.25 % of the primary proton energy. The iridium rod absorbs approximately 18 % and the lead reflector 23 %. In the case of the reflector the volumes are relatively large and the specific energy deposition is low, thus cooling should not be difficult. In the case of the iridium rod, estimates of the cooling requirements at an average beam power of 100 kW indicate a maximum temperature (~ 680°C) well below the melting point of iridium (due to the short conduction path and good thermal conductivity) for reasonable values of the heat transfer coefficient (5000 W/m^2-K) between the water and the titanium clad. However, due to the short proton pulse width (~ 2μs) and the relatively small volume of the target, enhancement of the thermal stresses due to thermo-mechanical shocks may be limiting in the above design, even though the CERN target operated satisfactorily under similar conditions.

TARGET ACTIVATION

The generation of radioactive nuclides (spallation products) and their decay following machine shutdown was estimated for the above TRAM configuration. It was assumed that the machine operates continuously for 10 days at an average beam power of 100 kW. The radioactivity in the TRAM following this period of operation was estimated, and subsequently allowed to decay for 1 day, 7 days, and 30 days following shutdown.

The spallation product mass distribution was estimated using the LAHET Code System. This is similar to the fission product mass distribution following a fission process. The neutron energy spectrum was estimated using the MCNP4B code. A one-group cross section library was created for each spallation product nuclide by collapsing an appropriate multi-group cross section library using the neutron spectrum determined by MCNP4B. The multi-group library used for this purpose was the 63-group compilation used with the CINDER-90 code. This library contains the nuclear data for 3400 nuclides. The one-group data and the nuclear decay data for the spallation products of interest are then used in an appropriately modified version of the ORIGEN code to track the creation, destruction, and decay of the spallation products in the neutron flux while the machine is running, and following shutdown. The original ORIGEN code is routinely used to calculate the activity in nuclear reactor cores due to fission products; the present version was developed at BNL for application to spallation systems.

By sub-dividing the TRAM into its components, and further sub-dividing the iridium target rod, it is possible to determine a space dependent radioactive inventory using the above approach based on the spatially varying neutron energy spectrum. The results of this analysis are shown in Table 3.

Table 3 - TRAM component activation
(Curies)
(Following 10 days of operation at a power of 100 kW)

Component	0 days	1 day	7 days	30 days
Iridium cell 1*	970	346	104	51
Iridium cell 2	1762	563	155	64
Iridium cell 3	1677	533	144	60
Iridium cell 4	1015	366	98	45
Iridium cell 5	800	305	75	35
Graphite	130	4	4	3
Titanium	84	42	13	3
Cooling water	37	0.5	0.3	0.2
Aluminum	80	3	--	--
Moderator (water)	25	0.2	0.2	0.1
Reflector (radial)	8086	2756	510	62
Reflector (back)	19830	6351	1200	167

* cell 1 closest to proton entry point - all cells 3 cm long.

The above calculations indicate that the bulk of the activity is confined to the iridium target and the lead reflector. Only the cooling water will pass out of the TRAM assembly to an intermediate heat exchanger. In the event of an accident only the activity associated with the cooling water should contribute to the source term, since the remaining activity should be confined to the TRAM assembly. The following are the major contributors to the radioactive inventory, by volume:

1. Iridium rod - Immediately following shutdown of the machine the major radioactive nuclides are a selection of isotopes of the elements from Tc to Pt, Br to Zr, and Ga to As; the primary contributor being Ir-194. After 30 days of decay/cooling the activity is primarily due to Ir-192, Ir-190, Ir-189, Os-191, Os-185, Re-183, W-181, and W-178.

2. Lead reflectors - Following shutdown the radioactivity in the lead reflectors is due to isotopes of Mn to Bi; with the primary contributors being Tl-195 to Tl-206.After 30 days of decay/cooling the primary activity is due to Bi-205, Tl-204, Tl-202, Hg-203, Au-195, Pt-188, Ir-189, Ir-188, Os-185, Re-183, W-181, W-178, and Ta-178.

The decay gamma-rays from these two volumes have a similar distribution in energy. In both cases the distribution has two peaks, and a monotonic decrease as the energy either increases or decreases. In the case of lead these two peaks occur at 0.1 MeV and 0.35 MeV, and in the case of iridium they occur at 0.06 MeV and 0.8 MeV. In order to determine the gamma-ray flux leaking from the surface of these volumes a transport calculation will have to be carried out in which these distributions are treated explicitly as sources. Since these materials have high values of "Z", they are self-shielding and thus only a fraction of the activity would leak out. Furthermore, the leakage spectrum will be biased in the high energy direction.

MODERATOR NEUTRON FLUX

The neutron flux averaged over the moderator volume was calculated for a number of candidate reflector types. In addition to the lead reflector, lead fluoride, and beryllium were considered as reflecting materials. Fluorine compounds are of potential interest as reflectors because the inelastic scattering cross section for fluorine has a relatively low threshold (~ 100 keV), compared to that for heavier nuclides (~ 1 MeV) [8]. This low threshold will efficiently slow source neutrons down to the threshold energy before they enter the moderator. The disadvantage of lighter nuclides in the reflector is the reduced neutron production due to a lower number of spallation reactions, and the lower (n,2n) cross section (except for beryllium and heavy water). A comparison of the neutron flux (ϕ (n/cm^2-s-p-eV)) in an ambient temperature water moderator in the thermal range (up to 1.0 eV) is shown in Figure 4 for the reflectors mentioned above. It is seen that the beryllium reflected system has the highest peak flux while lead has the lowest. The peaks for all the reflector types occur at the same energy (~ 0.025 eV).

The neutron pulse shape for a representative energy was determined for an ambient temperature moderator (room temperature light water), and a cold moderator (80 K light water using a proton free gas scattering kernel). These two determinations were carried out for both lead and lead fluoride reflectors. The neutron pulse is shown in Figures 5 and 6 for the energy ranges 0.02 eV - 0.025 eV for the ambient temperature moderator, and for the energy range 0.005 eV - 0.01 eV for the cold moderators respectively. It is seen that in both cases the configuration with a lead fluoride reflector has a more intense neutron pulse (~ 15 % increase). The above result may be due to the relatively rapid slowing down due to inelastic processes (one or two collisions rather than many) to a lower energy (~ 100 keV) rather than the higher energy customarily associated with lead (~ 1 MeV).

The total flux averaged over the moderator volume was found to be highest for the lead reflected case (~ 20% higher than for the beryllium reflected case). However, in the thermal range the beryllium reflected configuration exhibits a higher flux. Furthermore, it has been found [2,3] that beryllium reflected pulsed neutron sources have pulse decay time constants which are approximately twice as large as those using lead reflectors for coupled moderators. In the case of decoupled moderators the decay constants will be closer in magnitude. In addition, the heat deposited in the moderator for a lead reflected configuration has been found [3] to be approximately double that for a similar configuration using beryllium as a reflector. In order to increase the source performance due to the enhanced neutron production of a heavy nuclide reflector and the potential advantage of efficient slowing down of fluorine, a compound containing both components, or a layered structure will have to be designed.

ESTIMATES OF THE OPERATING STRESSES

The operating stresses in a PSNS target will be due to the cyclic heating of heavy metal, and may be enhanced by thermal-mechanical shock waves. A steady state thermal stress was estimated based on the thermal analysis presented above. Assuming that the elastic modulus of iridium is 517 (9) N/m², the thermal expansion coefficient is 6.8 (-6) /K, and the temperature rise across the rod target is determined to be 110°C, an average thermal stress of 4.0(8) N/m² results. This value is approximately two thirds of the ultimate strength of iridium (6.0(8) N/m²). According to a study carried out by P. Sievers [9] the thermal-mechanical shock enhancement of the average thermal stress can be estimated, and for rods is given by:

$$\sigma_\phi/\sigma_a = \sigma_r/\sigma_a \leq 6r/ct$$

where

c = velocity of sound (5.3(3) m/s for iridium)
r = radius of rod (0.005 m)
t = pulse duration (2.0(-6) s)
σ_ϕ and σ_r are the maximum azimuthal and radial stresses respectively
σ_a = average thermal stress

For the proposed target the value of 6r/ct is seen to be approximately 3.0. This implies the maximum stress in either the radial or azimuthal directions will be approximately twice the ultimate strength of iridium. A sectioned (either axially, azimuthally or both) rod structure will have to be designed to partially relieve the stress build up. A sectioned target design has been proposed for the solid metal target to be used in the AUSTRON project [10].

CONCLUSIONS

The following conclusions can be drawn from this study:

1. The BNL-AGS with an edge cooled solid iridium target is potentially a bright neutron source.

2. A similarly designed target has operated reliably at CERN under comparable conditions, indicating that a design based on a solid iridium rod encased in a graphite sleeve and clad by titanium should contain any shock induced failure of the iridium rod. The same mechanism will allow the target to potentially survive the thermal-mechanical shocks expected in the above application.

3. Both lead and lead fluoride are suitable reflectors - with lead fluoride yielding more intense neutron pulses.

4. Residual radioactivity is confined primarily to the iridium rod and lead reflector - cooling water will be the only pathway out of the TRAM area.

   - Iridium activity reduces by approximately a factor of 30 after one month.
   - Lead activity reduces by approximately a factor of 100 after one month.

5. Due to the small size of the target, its eventual disposal is potentially simple compared to larger target designs.

ACKNOWLEDGMENTS

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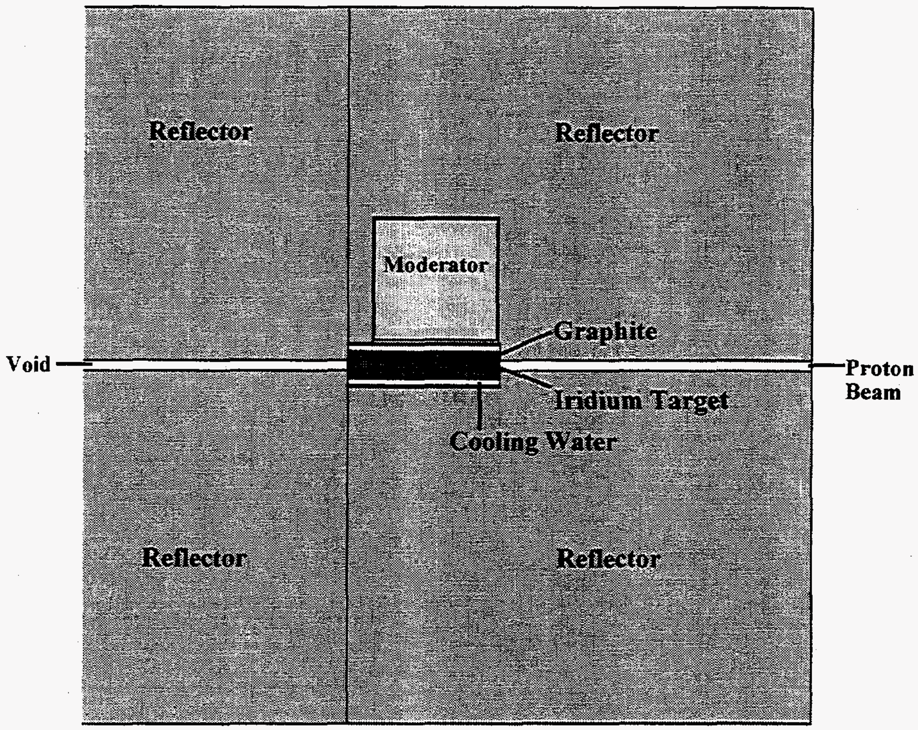

Figure 1 - TRAM Assembly
(Iridium Solid Target Configuration)

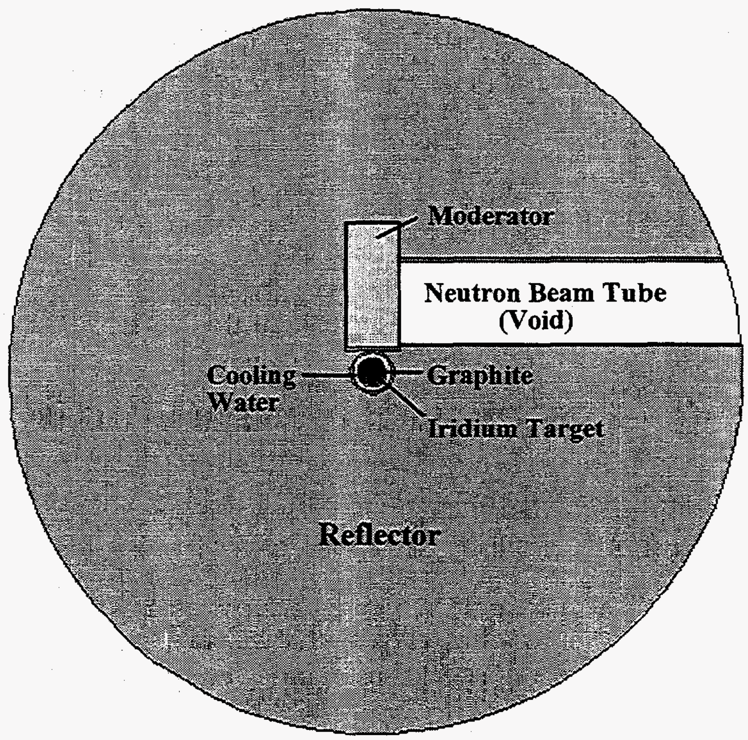

Figure 2 - TRAM Assembly
(Iridium Solid Target Configuration)

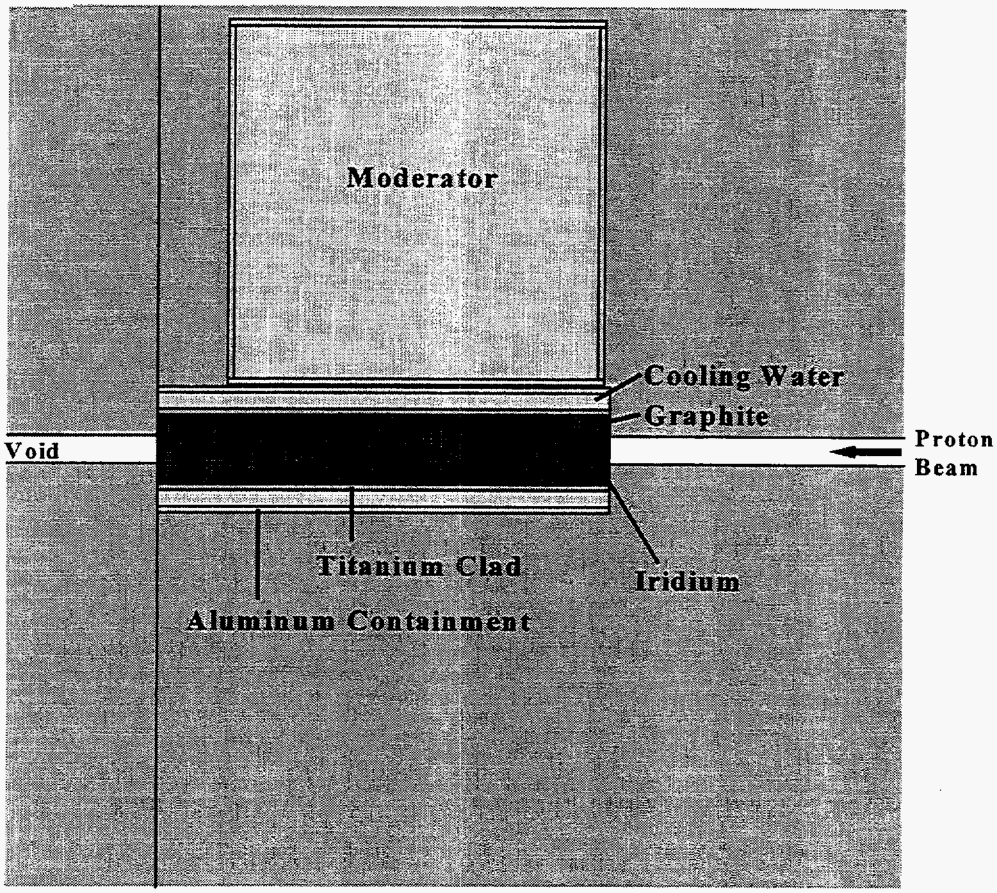

Figure 3 - Detail of Target

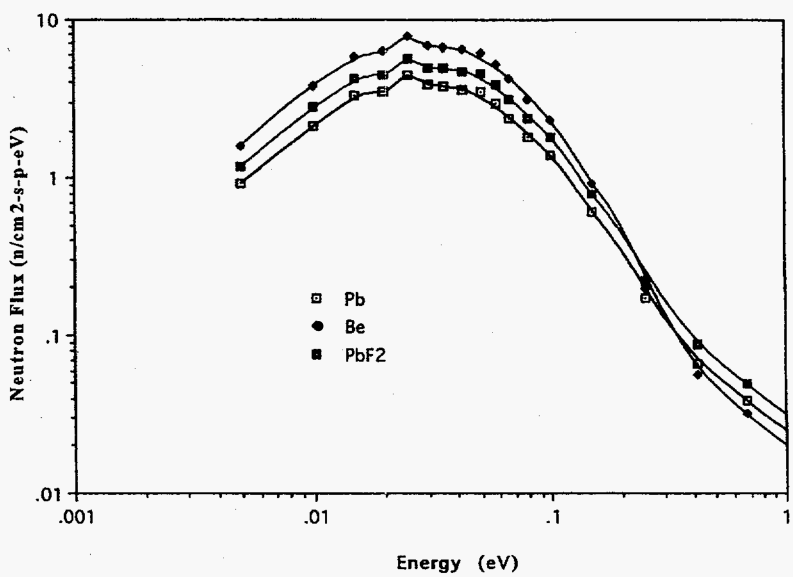

Figure 4 - Neutron Spectra Averaged Over Moderator Volume
(Ambient Temperature Light Water)

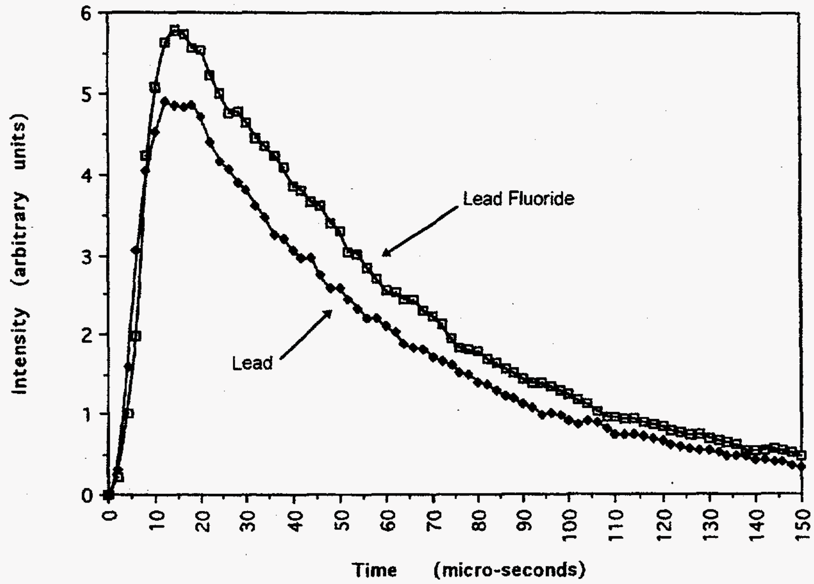

Figure 5 - Neutron Pulse in Moderator (.02 eV - .025 eV)
(Ambient Temperature Light Water)

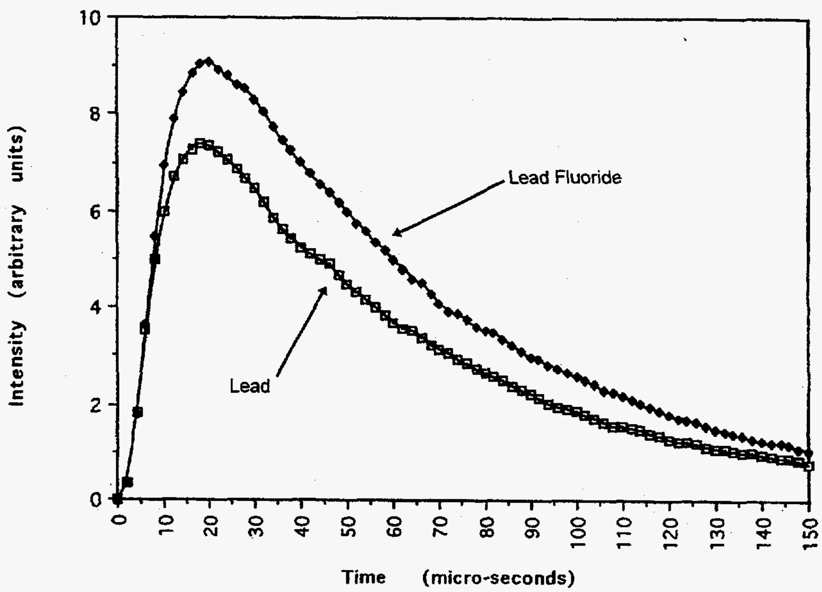

Figure 6 - Neutron Pulse in Moderator (.005 eV - .01 eV)
(80 K Proton Gas Model)