*ICANS-XI International Collaboration on Advanced Neutron Sources*
*KEK, Tsukuba, October 22-26, 1990*

# ENRICHED *vs* NON-ENRICHED *vs* NON-FISSILE TARGETS FOR PULSED SPALLATION NEUTRON SOURCES

J. M. Carpenter
Intense Pulsed Neutron Source
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439

## ABSTRACT

Numerous options exist among alternatives for target material and design of the neutron producing target in pulsed spallation neutron sources. This report surveys the advantages, disadvantages and limitations of some of the alternatives, including discussions of neutron yields, delayed neutron backgrounds, source pulse widths, source-to-moderator coupling, materials performance, fabrication problems, safeguards and security and hazards questions.

## I. Introduction

The purpose of "Booster" targets for pulsed neutron sources is to increase the intensity of the available neutron fluxes, above what is available from the primary neutron-producing interactions. The basic idea is to provide additional neutrons by fission in a target consisting at least in part of fissile material, which is a subcritical multiplying assembly. The pulse width demanded of the source depends on the uses to which the moderated beams are to be put, since moderation to different energies broadens the primary source pulse by an amount which is roughly proportional to the wavelength used, and by the width of the proton pulse which excites it. As will become clear below, booster targets designed to provide good resolution for measurements with eV neutrons, must operate as "fast" subcritical assemblies, that is, the fission process must be propagated by fast neutrons. If uses are confined to thermal neutrons, boosters with limited gain may be "intermediate spectrum" subcritical assemblies. For strictly cold neutron applications, low-gain "thermal" or "epithermal" subcritical assemblies may be appropriate. By way of limiting the discussion, I do not address variable reactivity boosters or reactivity pulsed reactors.

Figure 1 shows schematically the relationships among booster types classified according to the mean energy causing fission, $<E>_F$, appropriate for different applications using conventional time-of-flight instruments (as opposed to "time-modulated" sources and instruments).

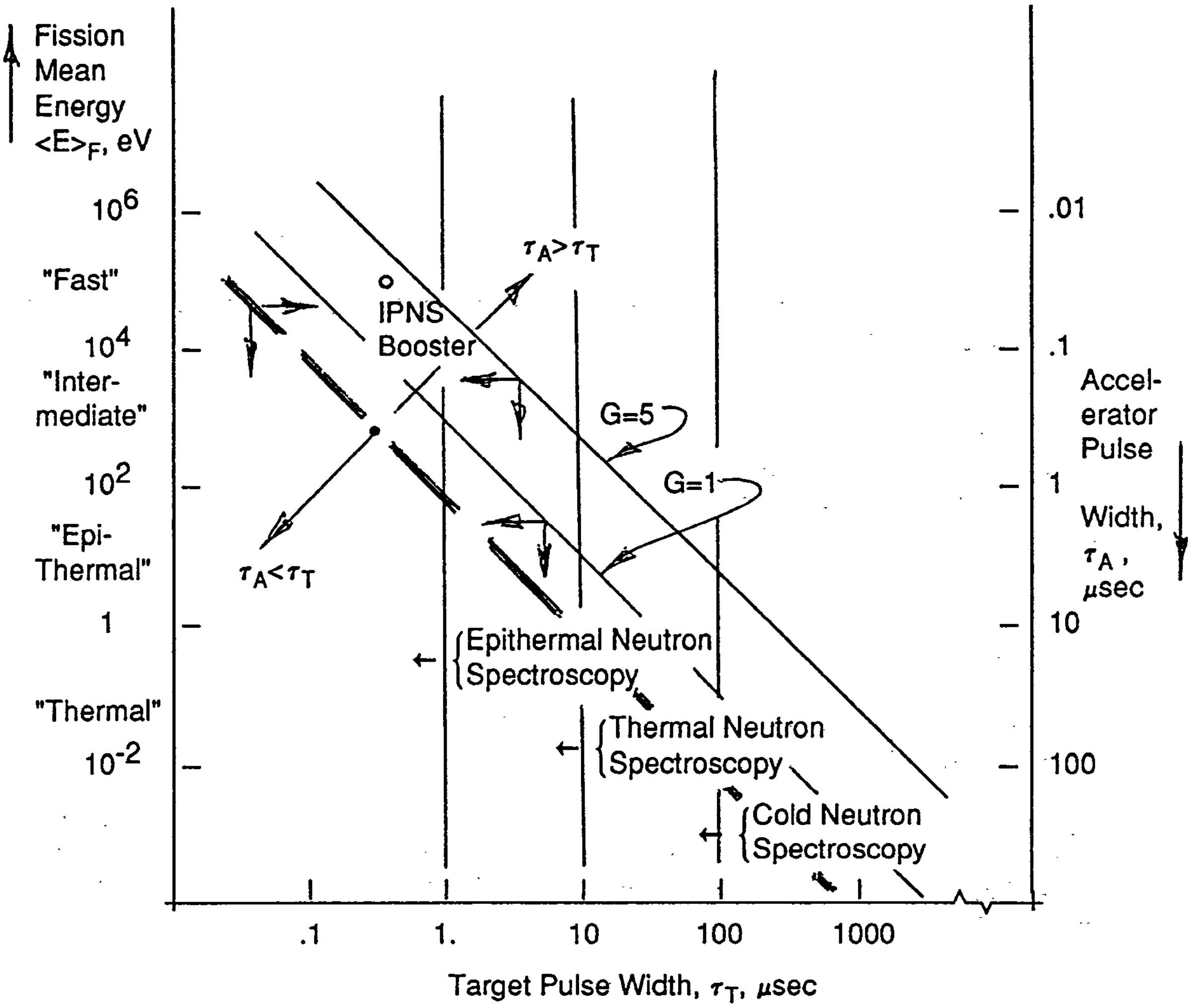

*Figure 1. Relationship between the mean energy causing fission, $\langle E\rangle_F$, and the pulse width, $\tau_T$, of subcritical booster assemblies. Two lines are shown, for no amplification, $G = 1$, and for a gain factor of 5. Regions shown define the pulse width requirements for efficient, conventional time-of-flight spectroscopy of epithermal, thermal and cold neutrons, assuming that appropriately designed moderators are provided; for example thermal and cold neutron spectroscopy are possible if $\tau_T$ is less than about 10 μ sec, but epithermal neutron spectroscopy is inefficient. The heavy line $\tau_T = \tau_A$ delineates the region in which the target pulse width is greater than the accelerator pulse width; the overall source pulse is dominated by whichever is greater.*

Figure 2 shows the IPNS Booster Target, which was described in our earlier report[1]; the configuration is typical of "Fast" subcritical assemblies, consisting mostly of fuel with little coolant. Note the surrounding decoupling layer of $^{10}$B-copper.

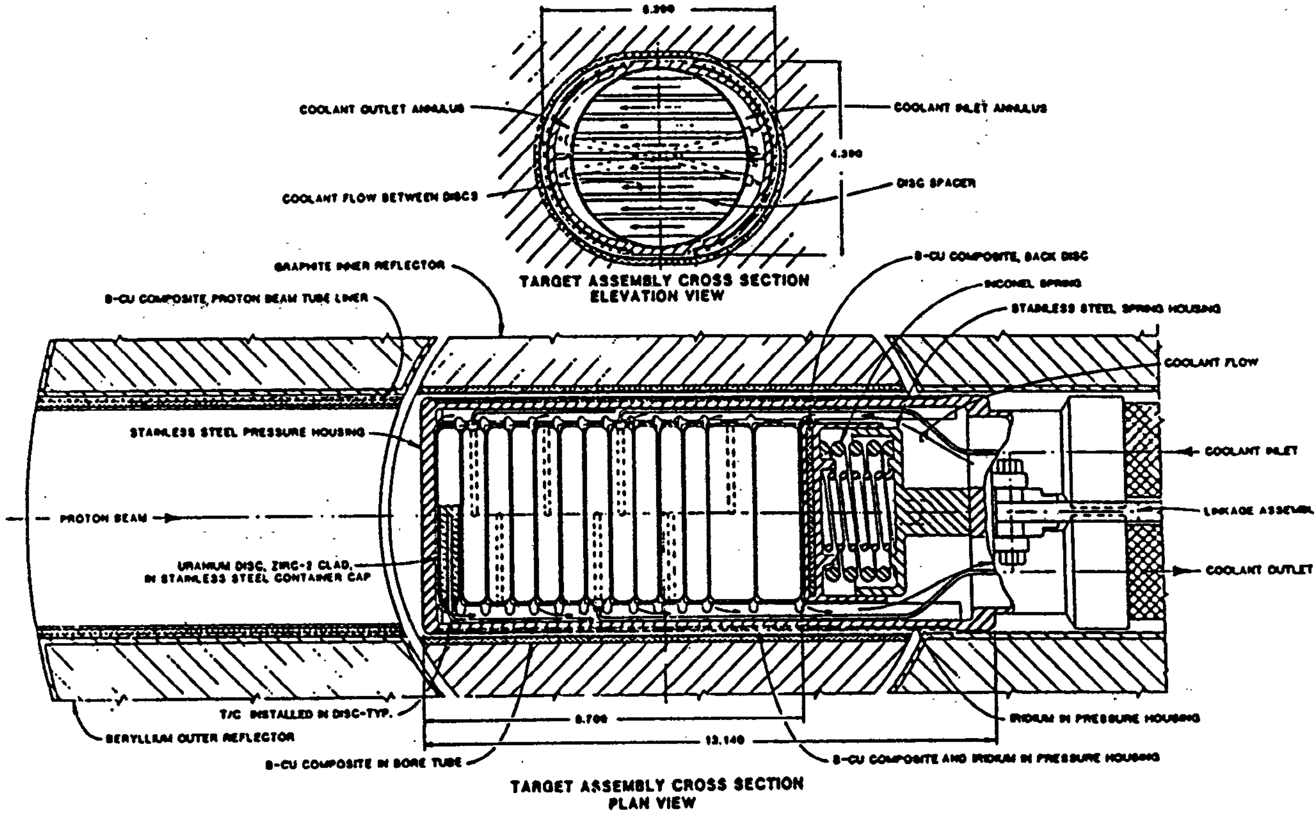

*Figure 2. The IPNS Enriched Uranium Booster Target.*

## II. Neutron Production, The Primary Source

Figure 3 shows Fraser's well-known data on the primary spallation neutron yield (the global number of neutrons escaping the target per incident particle) from thick targets of heavy materials irradiated by protons; these are well correlated by the relationship

$$Y(E_p,A) = 0.1(E_p - .12 \text{ Gev})(A + 20) \quad \text{(nonfissionable materials)} \qquad (1a)$$

$$= 5.0(E_p - .12 \text{ Gev}) \quad (^{238}U) \qquad (1b)$$

($E_p > .2$ GeV). The yield for $^{238}U$ is about twice what would be calculated for nonfissionable material, because of fissions induced above the roughly 1. MeV threshold. (The distinction among the terms is traditional--"nonfissionable" having no appreciable fission cross section for neutrons of MeV energies or below; "fissionable" having appreciable fission cross section for neutrons of MeV energies, above some threshold; and "fissile" having appreciable fission cross section for neutrons extending to low energies.)

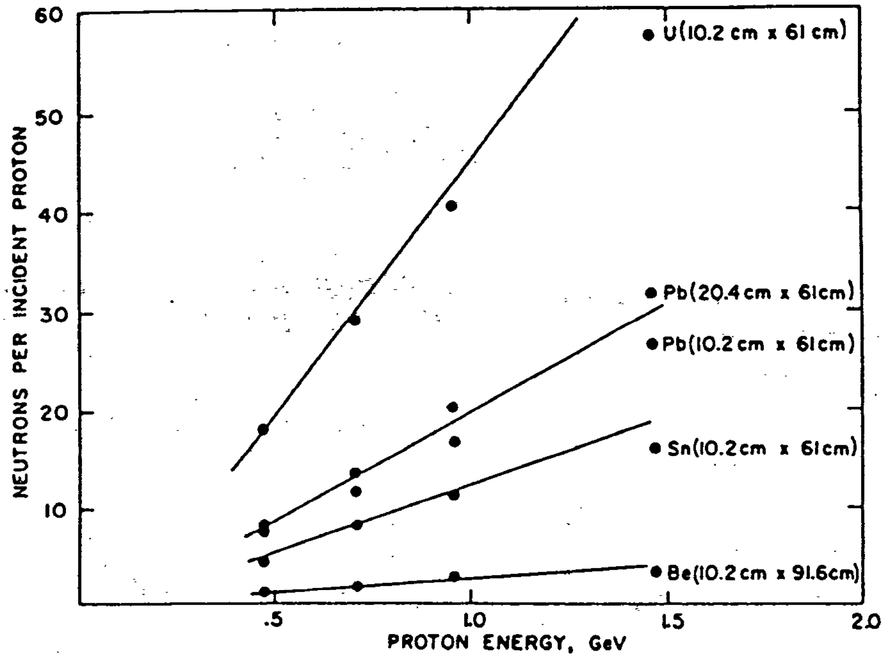

*Figure 3. Measured global neutron yields vs proton energy, for various target materials. (from Fraser, et al[3])*

The primary neutron producing reaction provides an externally-controlled source, either to be utilized directly or as a source which drives a multiplying, subcritical assembly, which is integral with the primary source. In the case of booster targets, it is important to recognize that the primary neutrons produced in the volume of the target are multiplied, some of which leak out and represent the source driving the moderators.

LANSCE uses a W target; other eligible non-fissionable target materials are Ta, Pb and Bi--liquid Pb is the target material in SINQ and the TRIUMF source. $^{238}$U is used as fissionable, but non-fissile target material in ISIS, KENS and IPNS; Th, $^{237}$Np and $^{240}$Pu have similar threshold fission properties. $^{233}$U, $^{235}$U and $^{239}$Pu are appropriate booster target materials insofar as their fission properties are concerned. Table I below summarizes the relevant attributes of some target materials.

Table I

Nuclear Properties of Some Target Materials for Pulsed Neutron Sources[a]

| Material | $\Sigma_f$(~1.MeV), barns | Fission Threshold Energy, $E_{th}$, MeV | Delayed Neutron Fraction, $\beta$ | Fission Yield, $\bar{\nu}$ |
|---|---|---|---|---|
| | | Fissionable, Non-fissile | | |
| Th | .13 | 1.6 | .022 | 2.3 |
| $^{238}$U | 0.52 | 1.35 | .0157 | 2.6 |
| $^{237}$Np | 1.4 | 0.8 | ? | 2.4 |
| $^{240}$Pu | 1.5 | 1.0 | .0026 | 3.3 |
| | | Fissile | | |
| $^{233}$U | 1.9 | --- | .0027 | 3.0 |
| $^{235}$U | 1.3 | --- | .0065 | 2.7 |
| $^{239}$Pu | 1.95 | --- | .0021 | 3.1 |

a Mostly from ANL-5800[2].

Yields corresponding to Equation (1b) for fissionable materials other than $^{238}$U may have been calculated or measured, but are not known to me; these depend on target size and geometry, but are not strong functions of the size of the target. Yields and the time structure of the pulses for booster targets depend very strongly on the density, enrichment of the fissile isotope, composition in terms of moderator, fuel, reflector and decoupler and on the spatial configuration of the target, and have to be computed for rather exact descriptions of the target. Beyond the question of global leakage neutron yields, there is the question of the coupling to the surroundings and moderators; this is addressed below.

While several of the materials represented in Table I have superior nuclear properties to U, practical metallurgical questions dictate the use of Uranium--which, in view of the fact that pulsed source targets are worked quite hard, is difficult enough even given the very large base of experience with that metal and its alloys. In the case of the fissile materials, the question of supply dictates the use of $^{235}$U. However, in view of these superiorities, in particular the fraction of delayed neutrons, materials other than U may eventually come to the fore.

## III. Booster Target Kinetics

Two aspects of the time dependence of booster target behavior are important, namely the prompt pulse width and the delayed neutron response. The number of neutrons n(t) in the system at time t, in a subcritical multiplying assembly responding to an instantaneous externally-controlled source is described by a simple lumped-parameter theory which illustrates the main points,

$$\dot{n}(t) = n(k(1 - \beta)-1)/\ell + \lambda c + N_o\delta(t)$$

$$\dot{c}(t) = nk\beta/\ell - \lambda c \qquad (2)$$

where k is the multiplication constant ($k < 1$ in a subcritical system), $\beta$ is the delayed neutron fraction, $\ell$ is the prompt generation time, $c(t)$ is the number of delayed neutron precursors, $\lambda$ is the average decay constant of delayed neutron precursors and $N_o$ is the number of neutrons introduced by the external source at $t = 0$. Equations 2 assume that the external source produces no delayed neutron precursors. The solution by Laplace transform methods is straightforward,

$$n(t) = N_o\{(s_1 + \lambda)e^{s_1 t} - (s_2 + \lambda)e^{s_2 t}\}/(s_1 - s_2) \qquad (3)$$

where

$$s_{1,2} = {}^1/_2\{(\Delta k - k\beta)/\ell \pm [(\Delta k - k\beta)^2/\ell^2 + 4\Delta k\lambda/\ell]^{1/2}, \qquad (4)$$

and $\Delta k = k - 1$ (< 0). Since in a fast booster

$$\Delta k/\ell >> \lambda,$$

approximate values of $s_1$ and $s_2$ are

$$s_1 \approx (\Delta k - k\beta)/\ell \qquad (5)$$

and

$$s_2 \approx -\lambda\Delta k/(\Delta k - k\beta). \qquad (6)$$

The two terms represent the prompt response ($s_1$) and the delayed neutron response ($s_2$).

The total number of neutrons disappearing (some leak out: these are the ones we are interested in!) with the prompt pulse is proportional to

$$N_p = 1/\ell\int_0^\infty dt(\text{first term in eq 5})$$

$$= N_o(-1/(\Delta k - k\beta)) \qquad (7)$$

and the prompt neutron gain factor is

$$G_p = N_p/N_o = -1/(\Delta k - k\beta). \qquad (8)$$

The total number of delayed neutrons disappearing after the source pulse is, with the same proportionality as $N_p$

$$N_D = 1/\ell\int_0^\infty dt\,(\text{second term in eq 5})$$

$$= (k\beta/\Delta k)N_o/(\Delta k - k\beta) = \beta G_P(G_P - 1)N_o/(1 - \beta G_P) \qquad (9)$$

(increasing as the square of the prompt gain) and the ratio of the number of delayed neutrons to prompt neutrons is

$$R_{D/P} = N_D/N_P = -k\beta/\Delta k = \beta(G_P - 1)/(1 - \beta G_P). \qquad (10)$$

The delayed neutron background as a fraction of the prompt signal increases linearly with the prompt gain. (In a steady reactor, exactly critical, ($\Delta k = 0$), $R_{D/P} \to \infty$; all the neutrons are delayed neutrons in the present sense.) The total gain is

$$G_T = (N_P + N_D)/N_o = -1/\Delta k = G_P(1 - \beta)/(1 - \beta G_P) \qquad (11)$$

and the delayed-to-total ratio is

$$R_{D/T} = -k\beta/(\Delta k - k\beta) = \beta(G_P - 1)/(1 - \beta). \qquad (12)$$

The width of the prompt pulse is proportional to the prompt gain,

$$\tau_P = \ell G_P. \qquad (13)$$

For representative values of the parameters, (roughly as in the IPNS Booster)

$\ell$ = 68. nanosec,
$\Delta k$ = -0.2,
$\beta$ = .006
$\lambda$ = 1. sec.

$$\tau_P = |1/s_1| = 340.\ \text{nanosec}$$

and

$$|1/s_2| = 1.02\ \text{sec.}$$

The width of the prompt pulse, 340. nanosec, is considerably greater than the generation time $\ell$; the delayed neutron pulse is so long that in, say, 30 Hz operation, the delayed neutrons appear essentially constant in time.

Roughly, for the IPNS Booster ($k = 0.80$), $G_T = 4.85$ and $\epsilon_D = R_{D/T} = .03$.

This simple analysis does not deal with the coupling of the source to different eigenfunctions (modes) of the neutron distribution, which have different multiplication constants, nor with the coupling of the target to moderators, which varies from mode to mode. On these accounts, the actual gain factor expected for beams from the IPNS booster is about 3.0 or 3.5 (determined from Monte Carlo calculations for a single moderator); figure 4 shows the calculated spectra emerging from the IPNS "H" moderator, for the depleted uranium target and for the Booster target. Measured neutron beam intensities per unit of proton current increased on average by a factor × 2.5 over their values with the depleted uranium target. The delayed neutron fraction has been measured, with the result $\epsilon_D = 0.0283$ [4].

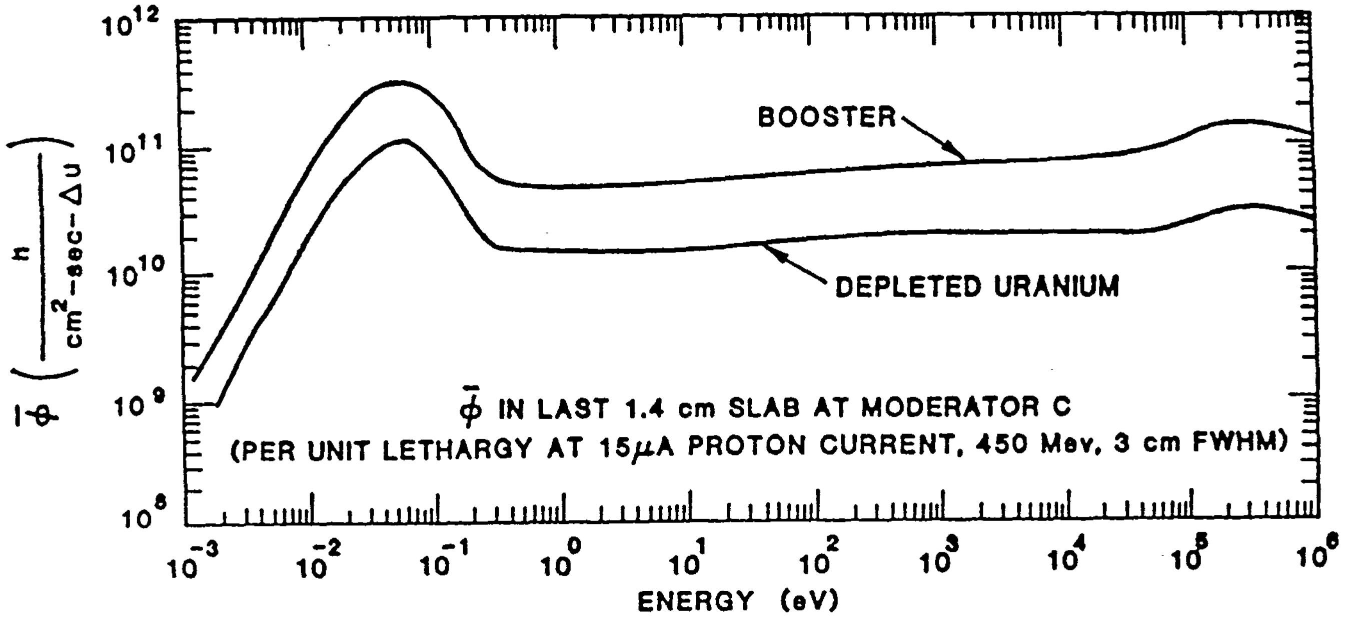

***Figure 4. Time-and-spatial average scalar neutron flux in the IPNS "H" moderator, computed for the depleted and enriched uranium targets.***

Reviewing the properties of the fissile isotopes in Table I, $^{233}U$ and $^{239}Pu$ are superior to $^{235}U$, both in view of their higher cross sections (less fissile material would be needed to achieve a given gain) and in view of their lower delayed neutron fractions.

The discussion above deals only with delayed neutrons appearing from fission-generated precursors. In systems containing $D_2O$ as coolant or Be as reflector, gamma rays above the relevant thresholds produce photoneutrons. These may be prompt fission gammas from the target, capture gammas from structural decoupling and poisoning materials, and activation gammas from activated components. Depending on their origins, these have different time dependence and importance in the neutron beams; some may be quick and important, as for example capture gammas produced by capture of moderator neutrons, or of reflector neutrons. As long-term delayed neutrons, these appear typically at a lower rate than delayed fission neutrons. Estimation of the photoneutron effects requires coupled gamma ray and neutron transport calculations. No source can be expected to be free of delayed neutrons; although their number may be small in sources with W or Ta targets, the measurements are easy and it is advisable to determine $\epsilon_D$ experimentally.

Delayed fission neutrons emerge from their resting parent nuclei in two-particle decays, and therefore exhibit discrete line spectra. Typical energies are in the range .1 - 1. MeV, while fission neutrons and the low-energy component of spallation neutrons have continuous evaporation spectra approximately proportional to $\sqrt{E}e^{-E/T}$, with $T \approx 1.3$ MeV. Photoneutrons have a spectrum that depends sensitively on the gamma ray energy spectrum and on the photoneutron cross section as a function of gamma ray energy.

Certain rare, light spallation product nuclei exhibit beta-delayed neutron emission, for example, $^{9}Li \rightarrow {^{9}Be^*}$ ($T_{1/2}$ = .17 sec), $^{9}Be^* \rightarrow {^{8}Be} + n$. (This is the same state that gives neutrons in $^{9}Be(\gamma,n)$.) Others, such as $^{12}Be \rightarrow {^{12}B^*}$ ($T_{1/2}$ = .011 sec), $^{12}B^* \rightarrow {^{11}B} + n$ exist which have short half lives and would appear as a time-varying delayed neutron background in repetetively-pulsed sources; as far as I know, none of these have been observed in pulsed spallation sources.

There are actually numerous species of fission-produced delayed neutron precursors, which are typically classed in groups having similar half-lives. Table II shows the relative abundances and half-lives of precursors from $^{235}U$ fast fission.

Table II

Relative Abundances and Half-lives of
Delayed Neutron Precursors from $^{235}U$ Fast Fission[b]

| Group | Relative Abundance $a_i$, % | Halflife $T_{1/2i}$, sec | Decay Constant $\lambda_i$, $sec^{-1}$ |
|---|---|---|---|
| 1 | 3.8 | 54.5 | .0127 |
| 2 | 21.3 | 21.8 | .0317 |
| 3 | 18.8 | 6.0 | .115 |
| 4 | 40.7 | 2.23 | .311 |
| 5 | 12.8 | .496 | 1.40 |
| 6 | 2.6 | .179 | 3.87 |

average decay constant = $\langle\lambda\rangle$ = .435 $sec^{-1}$
$T_{1/2eff} = \ln(2)/\langle\lambda\rangle$ = 1.6 sec.

b from ANL 5800[2].

Even though some of these groups have halflives of only a fraction of a second, all have halflives so long that delayed neutrons from these origins appear constant between pulses in practical pulsed sources (say, f > 20. Hz). This cannot be said of photoneutrons of certain origins, some of which may appear with short delays, both in booster targets and in non-multiplying targets.

## IV. Time Response, Decoupling

It is important in pulsed sources that the prompt pulse be narrower than the width of the moderated pulse from the moderators. Inasmuch as the moderated neutron spectrum is rich in epithermal neutrons, and many instruments capitalize on this, and because the primary source must serve all of the moderators, the primary source pulse width must be narrower than the narrowest required by any instrument. In IPNS this indicates so far the use of 10. eV neutrons (in GLAD, see elsewhere in these proceedings). In dense hydrogenous moderators, the pulse width is about 2/3 μsec FWHM at 10. eV. The simple analysis above indicates that the multiplied source pulse width for the booster target will be about .34 μsec, which is comfortably less than the requirement, but not by much.

This is achieved in IPNS by decoupling the target from its surroundings, using a boron layer designed for $e^{-1}$ attenuation of perpendicularly-incident neutrons of 100. eV. Without such decoupling, slow neutrons from the reflector and the moderators would participate in the multiplication process, significantly slowing down the response time (i. e. increasing $\ell$). Such decouplers are a necessary feature of pulsed booster targets designed to preserve pulse resolution at eV energies, even though they reduce somewhat the intensity of moderated neutron beams.

## V. Coupling of Source to Target and Surroundings

In highly symbolic form the Boltzmann equation describing multiplying assemblies is

$$\mathcal{H} n(\mathbf{r},\mathbf{v}) + S(\mathbf{r},\mathbf{v}) = 0 \qquad (14)$$

where

$$\mathcal{H} = \mathcal{L} + \mathcal{M}, \qquad (15)$$

and

$$\mathcal{L} n(\mathbf{r},\mathbf{v}) = -\mathbf{v}\cdot\nabla n(\mathbf{r},\mathbf{v}) - v\Sigma_{\text{total}}(\mathbf{r},\mathbf{v})\, v(\mathbf{r},\mathbf{v}) + \int d^3\mathbf{v} v' \Sigma_s(\mathbf{r},\mathbf{v}'\rightarrow\mathbf{v})\, n(\mathbf{r},\mathbf{v}') \qquad (16)$$

is the loss operator,

$$\mathcal{M} n(\mathbf{r},\mathbf{v}) = f(v)\int d^3\mathbf{v} v' \bar{\nu}(v')\, \Sigma_f(\mathbf{r},\mathbf{v}'\rightarrow\mathbf{v})\, n(\mathbf{r},\mathbf{v}') \qquad (17)$$

is the fission operator

and $S(\mathbf{r},\mathbf{v})$ is the external source density. The notation is the conventional reactor physics notation.

The task of analysis reduces to the problem of solving the eigenvalue equation

$$\mathcal{H}\Psi_n = \omega_n \Psi_n, \qquad (18)$$

with its adjoint

$$\mathcal{H}^+ \Psi_n^{\ +} = \omega_n^* \Psi_n^{\ +}, \qquad (19)$$

for which

$$\int \Psi_m^{\ +}(\mathbf{r},\mathbf{v})\, \Psi_n(\mathbf{r},\mathbf{v})\, d^3\mathbf{r} d^3\mathbf{v} = \delta_{mn}. \qquad (20)$$

Representing

$$n(\mathbf{r},\mathbf{v}) = \Sigma_n\ a_n\Psi_n(\mathbf{r},\mathbf{v}) \qquad (21)$$

and

$$S(\mathbf{r},\mathbf{v}) = \Sigma_n\ s_n\Psi_n(\mathbf{r},\mathbf{v}) \qquad (22)$$

Then

$$a_n = -(1/\omega_n)\int d^3\mathbf{r}d^3\mathbf{v}\Psi_n{}^{+}(\mathbf{r},\mathbf{v})S(\mathbf{r},\mathbf{v}), \qquad (23)$$

$$s_n = \int d^3\mathbf{r}d^3\mathbf{v}\Psi_n{}^{+}(\mathbf{r},\mathbf{v})S(\mathbf{r},\mathbf{v})$$
(24)

and

$$n(\mathbf{r},\mathbf{v}) = \Sigma_n\ (-1/\omega_n)s_n\Psi_n(\mathbf{r},\mathbf{v}). \qquad (25)$$

Now defining the multiplication constants $k_n$

$$(\mathcal{L} + \mathcal{M}/k_n)\Psi_n = (\mathcal{H} + (1-k_n)\mathcal{M}/k_n)\Psi_n \equiv 0, \qquad (26)$$

so that

$$\mathcal{L}_n \equiv \int\Psi_n{}^{+}\mathcal{L}\Psi_n = -\mathcal{M}_n/k_n \qquad (27)$$

where

$$\mathcal{M}_n \equiv \int\Psi_n{}^{+}\mathcal{M}\Psi_n \qquad (28)$$

and observing that if we order $k_n$'s so that $k_{n+1} \leq k_n$, (for subcritical systems, all$k_n$'s are less than 1.0), then

$$|\mathcal{L}_n| \geq |\mathcal{L}_{n+1}|. \quad (29)$$

So

$$n(\mathbf{r},\mathbf{v}) = \Sigma_n\ k_n/(1-k_n)s_n/\mathcal{M}_n\Psi_n(\mathbf{r},\mathbf{v}) \qquad (30)$$

$$= \Sigma_n\ 1/(1-k_n)s_n/(-\mathcal{L}_n\Psi_n(\mathbf{r},\mathbf{v}). \qquad (31)$$

Integrated source and neutron densities are

$$S_T \equiv \int S(\mathbf{r},\mathbf{v})d^3\mathbf{r}d^3\mathbf{v} = \Sigma_n s_n\int\Psi_n(\mathbf{r}<\mathbf{v})d^3\mathbf{r}d^3\mathbf{v} \equiv \Sigma_n s_n f_n$$
(31)

and

$$N_T \equiv \int n(\mathbf{r},\mathbf{v})\, d^3\mathbf{r}\, d^3\mathbf{v} = \Sigma_n k_n/(1-k_n)\, s_n f_n/\mathcal{M}_n \tag{32}$$

$$= \Sigma_n 1/(1-k_n)\, s_n f_n/(-\mathcal{L}_n)\,. \tag{33}$$

If the source is entirely proportional to the lowest eigenfunction,

$$S(\mathbf{r},\mathbf{v}) = S_{Fo}(\mathbf{r},\mathbf{v}) = \mathcal{M}\Psi_o(\mathbf{r},\mathbf{v}), \tag{34}$$

so that

$$s_n = S_T \delta_{no}/f_o \tag{35}$$

then

$$N_T = N_{Fo} \equiv k_o S_T/(1-k_o) \text{ and } N_T \propto k_o/(1-_{ko})\,. \tag{36}$$

This is case of the "single-mode" reactor, a description that applies when $k_o$ is very near to (but less than) 1.0 and the source distribution is similar to the fundamental eigenfunction. Otherwise and in general, since

$$f_{n+1}/(1-k_{n+1}) \le f_n/(1-k_n), \tag{37}$$

$$N_T < N_{Fo} \text{ and } N_T \not\propto k_o/(1-k_o)\,. \tag{38}$$

That is, in general, <u>the full source is not multiplied by the simple gain factor for the single-mode reactor</u>. Neither is the gain observed at a given point ($\mathbf{r},\mathbf{v}$) proportional to the simple gain factor. This is the usual situation in far-subcritical assemblies--no single eigenfunction dominates.

**Criticality Monitoring**

These last qualitative observations have a very significant impact on the design of procedures for measuring the fundamental multiplication constant, say during fabrication or handling (insertion and removal) of a multiplying target. Conventional reactor practice applies to situations in which the fundamental eigenfunction is dominant or nearly dominant, as in the approach to criticality. In the case of far-subcritical systems, say $k_o \approx .90$, the fundamental mode does not dominate, and many modes contribute to the total neutron density or flux at a position where it might be monitored. Procedures for monitoring $k_o$ must surely be devised to detect incipient criticality, $k \rightarrow 1.0$, for obvious safety reasons. However, the procedures must also **succeed,** in that **false indications of approach to criticality must be ruled out**.We suffered this problem in designing the insertion procedures for the IPNS Booster target; detailed calculation of the detector response is necessary to provide predictions of the monitored neutron density, if that is the procedure followed. Other methods, such as Rossi-$\alpha$ measurements suffer from comparable difficulties.

## VII. Power and Power Density

Producing neutrons by fission is less efficient than by spallation--about 190. MeV of sensible heat is deposited locally per fission. For $^{235}U$, at best $\bar{\nu} - 1 = 1.7$ neutrons per fission remain as potential leakage neutrons (one is needed to propagate the chain reaction), so that at best, about 112. MeV of heat must be removed to provide each leakage neutron. Pure spallation, on the other hand is endothermic so that slightly less than the proton beam energy appears as heat, with about 40. MeV of heat required to be dissipated to produce a neutron from Pb. Booster targets therefore must be designed to dissipate more heat than pure spallation targets to produce the same number of neutrons; for a 15 µA proton beam current and a $^{238}U$ target as in IPNS, the power increases from about 6 kW to about 53 kW.

This is not as bad as it seems in terms of the total power figures, since the power density distribution in booster targets is considerably smoother than in pure spallation targets, and the local power density determines the difficulty of heat removal. Figure 5 shows the computed power density distribution in the IPNS Booster Target.

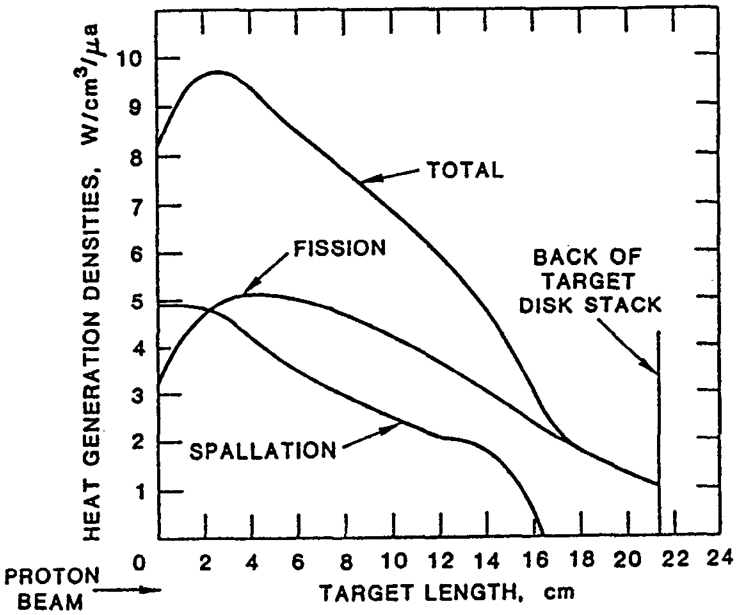

*Figure 5. The power density distribution in the IPNS Booster target.*

## VIII. Materials and Metallurgy

Since our last report, we have had to overcome numerous difficulties in the disk fabrication process; in the end, we have succeeded.

Two general areas of uranium target design relate to questions of metallurgy: bonding and texture.

Cleanliness is next to Godliness, they say. In relation to disk fabrication, cleanliness is next to Bondedness, and we found it necessary to develop a new regimen for cleaning surfaces and handling components in order to produce reliable Zircaloy-to-uranium bonds between the cladding and the target material.

The same is true of the gas in the Hot Isostatic Pressing (HIP) apparatus. We found it necessary to send our small HIP machine to Oak Ridge for the purpose, since outgassing from the insulation in the pressure chamber of the Oak Ridge device contaminated the parts sufficiently to degrade the cladding surface.

Because it was necessary to clamp the cladding cans tightly together prior to evacuation of the welding chamber, we found it necessary to provide special vents around the periphery of the circumferential electron-beam weld, in order to release the air from the clearance space between the clad and the uranium. Even the small amount of air that remained in that space after pumping on the welding chamber without the vents, prevented good bonding, we determined.

Special attention had to be devoted to controlling the electron-beam welding parameters. Although we obviously have found a method of producing reliable welds, we must admit that we still do not understand the microscopically observed pattern of recrystallization as it relates to the zone of fusion in the weld.

The cast uranium alloy has considerably greater metallurgical texture (preferred orientation) and grains larger than the depleted uranium target material with which we have had such good experience. These observations led us to an extensive neutron diffraction investigation to characterize the material; in the process we developed newly the capability for carrying out those studies at IPNS[4]. Having obtained our best characterization, we had much to puzzle out, as to how this will affect the target. Ultimately, we adjusted the diameter of the disks, and the range of travel of the compression spring, to account for our maximal estimates of anisotropic growth of the disks. Initially, we believed that this will limit the lifetime of the target to between 3½ and 5 years under current operating conditions. However, an ultrasonic examination program provided for in the design of the booster has shown, after two years of operation, that growth is taking place at a rate approximately 1/10th of the rate initially allowed for.

## IX. Safeguards, Security and Safety

Requirements for safeguards and security (e.g. antiproliferation) and safety vary locally, and can impose significant conditions on a booster target project. Any program intended to lead to installation of a fissile booster target should be launched with ongoing simultaneous efforts to comply with these regulations, obtain the associated approvals, and provide the needed documentation. The IPNS Booster Project profited immensely from this approach.

## X. Acknowledgements

We were greatly assisted in these materials assessments by Bill M^cDonnel of Savannah River National Laboratory, whose advice based on experience with metallic uranium reactor fuel was essential. Throughout, we enjoyed the helpful cooperation of our colleagues at Oak Ridge Y-12 Plant where the disk

processing was carried out. This work was performed under the auspices of the U.S. Department of Energy, Division of Materials Sciences, Office of Basic Energy Sciences, under Contract W-31-109-ENG-38.

## XI. Conclusions

First experience with the IPNS Enriched Uranium Booster target is encouraging. The intensity gained is approximately what was expected, and the main negative effect of the increased background of delayed neutrons (also consistent with expectations) seems so far to be able to be dealt with. A considerable body of information exists concerning the performance and operational problems of moderators, which enable the design of tailored moderators for many purposes. More development should be pursued to provide better moderators, especially cold moderators appropriate for use in high-power sources.

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Q(I.M.Thorson): Can you give us any indication of the relative importance of ($\gamma$, n) neutrons in D or Be, relative to delayed neutron problem?
Do any of the operating facilities see any significant background component that can be attributed to ($\gamma$, n) neutrons?

A(J.M.Carpenter): In reactors, photoneutrons are typically less than 10% of fission delayed neutrons; the situation in spallation sources is not known. It would be informative if measurements were made at LANSCE (W target) or ISIS (when Ta target is in place); even though the relative delayed neutron number may be quite small, it should be easily determined.

Q(N.Watanabe): You have 2.5 times more neutrons with 5 time more delayed neutrons. Is it correct? Why you have an effective gain factor 2.5 rather than $1 / (1-k_{eff}) = 5$? Is the heat distribution more flat compared to the depleted uranium target?

A(J.M.Carpenter): Yes, the average (many beams) gain is ×2.5. This differs from the simple $1 / (1-k)$ because all the source neutrons do not couple into the fundamental mode. The best distribution is in fact somewhat flatter.

Q(G.J.Russell): In the context of a several target station, have you considered sub-critical dynamic booster to help in the delayed neutron problem for $^{235}$U fuel? How do mechanical complexities stack-up against potential problems of substituting $^{239}$Pu for $^{235}$U vis-a-vis Health-Safety and Environments issues.

A(J.M.Carpenter): Yes, but only briefly (about 10 minutes in a project of 5 years' duration). The combination of mechanical complexity and potential criticality hazards makes such a proposition outside our capacity to deal with. Concerning use of $^{239}$Pu, the chemical and $\alpha$-activity problems, difficult in themselves, probably are outweighed by problems of metallurgy; if it is possible, Pu is metallurgically more difficult than U. This last comment is inapplicable if a "slow" booster were considered, which enables use of oxide fuel.