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NUCLEONIC ASPECTS OF THE LINUS IMPLODING BLANKET*

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Nucleonic analyses have been performed for the Naval Research Laboratory's imploding-liner fusion reactor concept called LINUS. Mixtures of Pb and LiPb were used for the liquid metal liner (blanket), with blanket thickness, LiPb fraction, and Cd poisoning concentration being varied in scoping studies. Investigated responses were tritium breeding ratio, neutron leakage from the liquid liner to permanent reactor structure, and time-dependent nuclear heating of the liner and permanent structure. Tritium breeding ratio was as high as 1.8 for blankets sufficiently thick (~ 1 m) to reduce leakage to the permanent structure to tolerable levels. Approximately 98.4% of the energy is deposited in the blanket within 10 μs, providing confidence that the heating of LINUS's blanket will occur while it is mechanically secure.

INTRODUCTION

For some years there has been discussion of controlled thermonuclear fusion using imploding-liner flux compression to produce plasmas in magnetic fields of over 100 tesla. A conceptual design of a fusion reactor based upon an imploding liquid metal liner has been proposed at the Naval Research Laboratory.[1] Technical motivation and details of the concept, called the LINUS reactor, are given in Ref. 1; this paper is confined to those features impacting nucleonic aspects of the design.

As a calculational model, we can consider the reactor as an infinite cylinder with a plasma radius during maximum D-T burn of ~ 0.1 m. Outboard of the plasma are various liquid combinations of lithium and lead, which are parameterized in the nucleonic studies. The thickness of this liquid blanket was also a parameter, varying from 0.8 to 1.7 m. Outside the blanket are a cylinder block and pistons, which are used to impart rotational energy to overcome hydrodynamic (Rayleigh-Taylor) instabilities on the inner surface of the liquid blanket. In the model, this cylinder block/piston region (referred to below generically as the "cylinder block") is represented by a 0.15-m-thick stainless steel region.

During feasibility studies, several nucleonics issues needed to be addressed. These included:

(1) the requirements on blanket thickness and lithium concentration, in order to have a net tritium breeding ratio greater than unity,

(2) the need to minimize neutron and gamma-ray leakage into the cylinder block, in order to limit energy deposition and activation in that region, and

(3) the time dependence of the energy deposition in the blanket.

This paper summarizes the results from studies of these problems.

EQUIVALENT STEADY-STATE CALCULATIONS

For consideration of integral responses such as tritium breeding, activation, and total energy deposited per pulse, time-independent calculations are adequate. The latter two responses can then be adjusted for various duty-cycle times. Our first objective was to devise a LINUS blanket which

*Work performed under the auspices of the U. S. Department of Energy.

would be as thin as possible, yet recover most of the thermonuclear energy inboard of the cylinder block.

Initial scoping studies have been performed to determine the breeding potential of LiPb + Pb alloys when used in an imploding liner. The technological interest in such alloys stems from the need to breed tritium from lithium, while at the same time having a high-density and relatively incompressible liner. Lead is a desirable material from inertial and compressibility considerations, as well as for its low chemical reactivity. Alloys of lead and LiPb with less than 1.0 mole lithium per mole of lead have been found to be sufficiently unreactive for use as shields and collimators,[2] for example. Thus, such alloys are considered to be satisfactory, from a reactiveness viewpoint, for imploding liners.

Nucleonics calculations first were performed to find an envelope of parameters in which acceptable tritium breeding could be achieved. At the same time, neutron leakages from the blanket were computed, along with energy deposition in both the blanket and cylinder block for one configuration. The leakages then provide an approximate measure of heating and radiation damage to the cylinder block and mechanical constraints outboard of the liquid imploding liner. All neutron and gamma-ray transport calculations were based upon the one-dimensional cylindrical model proposed by Turchi and Robson.[1],[3] Parameters studied for their effect on breeding ratio and neutron leakage were:

(1) blanket thickness,
(2) lithium concentration in LiPb + Pb mixtures, including some inner layers of pure lithium,
(3) ^{6}Li concentration in lithium, and
(4) cadmium "poisoning" concentration in lead.

All one-dimensional transport calculations were performed with the discrete-ordinates transport code DTF-IV[4] in an S_8-P_3 mode, using the LASL/CTR coupled cross-section library for 25 neutron and 21 gamma-ray groups. The cylindrical model has a 0.1-m-plasma region, representative of the stage of implosion at which the maximum thermonuclear burn occurs. Outboard of this is the imploding LiPb + Pb liquid liner of varying thickness and composition, followed by a 0.15-m structure of type 316 stainless steel (i.e., the cylinder block).

The first parametric set of one-dimensional discrete-ordinates transport calculations considered a homogeneous blanket using natural lithium and 50 w/o LiPb in the mixture. This concentration was chosen, based upon several considerations, including a liquidus curve[5] showing a rapid increase in the melting point (from ~ 743 K to ~ 993 K) as the atomic percent of lithium exceeds about 60. Also, it was expected intuitively, and later verified, that high lithium concentrations are not necessary for effective breeding. According to Ref. 2,* the density of the LiPb + Pb mixture is given by

$$\rho_o^{-1} = \frac{a}{11.9} + \frac{b}{7.86}, \tag{1}$$

where a and b are the weight fractions of Pb and LiPb, respectively. At 723 K, the assumed operating temperature for the blanket, the density is given by[3]

$$\rho = 0.92\ \rho_o. \tag{2}$$

From these equations, it appeared that the best attenuation of the primary 2.25-pJ (14-Mev) neutrons, and the most neutron multiplication by (n,2n) reactions in lead, would occur at lower concentrations of LiPb. Although thinner neutron multipliers made of lead have been analyzed previously,[6] this is the first time thick (~ 1-m) lead blankets have been studied. Early calculations quickly showed that tritium breeding ratios greater than unity could be achieved with blankets much less than 1 m thick, using natural lithium,

*Equation (1) from Ref. 2 has an apparent error, so exponents (-1) have been deleted from the right-hand side of that equation.

but neutron leakages were intolerably high at these thicknesses. This effect is caused by the high neutron multiplication in lead (almost a factor of two, as can be seen for low values of f_w(LiPb) in Fig. 1), combined with a low-absorption cross section for lead at all neutron energies. For example, 2.25-pJ neutrons have a total nonelastic cross section of 250 fm^2 (2.50 b), of which 216 fm^2, or 86%, is attributable to the (n,2n) reaction cross section. Because neutrons lose an inconsequential energy increment upon elastic scattering with a high atomic mass nucleus such as lead, almost all spectrum softening in the lead is caused by (n,2n) reactions with the accompanying neutron multiplication.

A reference blanket thickness of 1 m was then chosen, and the breeding and leakage characteristics were investigated as a function of f_w(LiPb), the weight percent of LiPb in the LiPb + Pb alloy. Figure 1 shows the results of this study. Clearly, the tritium breeding ratio is more than adequate for all values of f_w(LiPb) in the range [0.05,1.0]. The curve labeled T_7 shows the $^7Li(n,n't)^4He$ component of the total tritium breeding ratio. It is therefore clear that most of the breeding is in ^6Li, with considerable enhancement from the secondary (n,2n) neutrons from lead. The neutron right leakage from the blanket into the cylinder block, denoted L_2 on Fig. 1, varies inversely with f_w(LiPb), but is still unacceptably high for reasonable values of f_w(LiPb); i.e., values less than about 0.5 weight fraction LiPb.

Using the results of the parametric study shown in Fig. 1, it was decided to choose f_w(LiPb) = 0.5, the maximum practical value from melting point considerations.[5] Next, an alloying

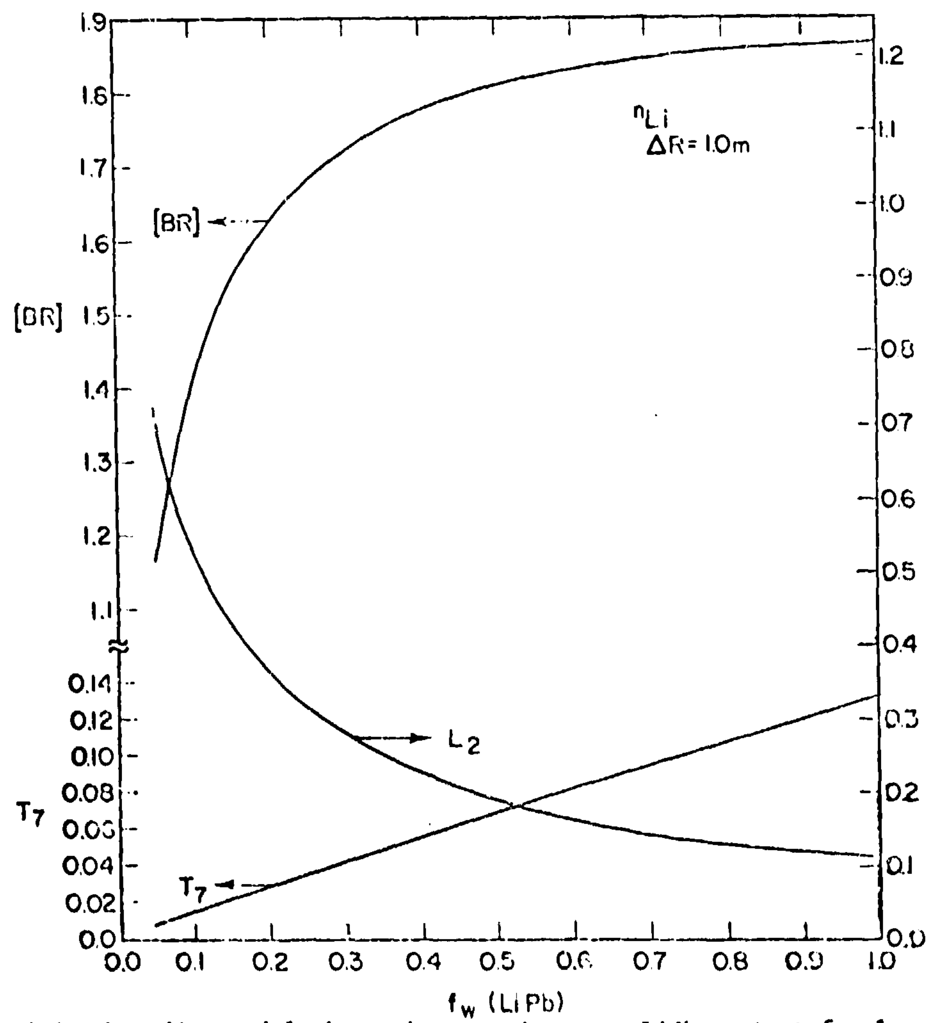

Figure 1. Tritium breeding and leakage characteristcs vs LiPb content for 1-m-thick blanket.

element for the LiPb was sought which would have the properties of (1) alloying with LiPb + Pb without seriously altering mechanical and chemical properties, especially melting point, and (2) providing a neutron poison to control the extraordinarily high tritium breeding ratio, while decreasing the leakage. Unfortunately, the leakage spectrum for the reference case peaks at ~ 10 fJ (6×10^4 eV), as can be seen in Fig. 2. This figure shows the spectrum, normalized to a unit D-T neutron source rate per cm along the cylindrical axis. The blanket thickness, R, is 1.0 m, and the spectrum is taken at 0.005 m inward from the outer surface of the blanket; namely, at R = 1.095 m. Recall that the plasma region, and thus the neutron source region, is 0.1 m in radius. The spectrum at the inboard portion of the blanket has a similar peak at ~ 20 fJ, but with an additional large peak at ~ 2.25 pJ (14 MeV), as shown in Fig. 3. No suitable poison could be found which would efficiently absorb neutrons in the keV region and satisfy the other criteria, so cadmium was selected as a trial material because of its otherwise desirable chemical/alloying properties. Figure 4 shows the relative ineffectiveness of cadmium in reducing leakage, as well as its effective competition with ^{6}Li for absorption of low-energy neutrons. The abscissa in Fig. 4 is the isotopic fraction of cadmium, as a fraction of total lead atoms. Possible colloidal suspension of materials other

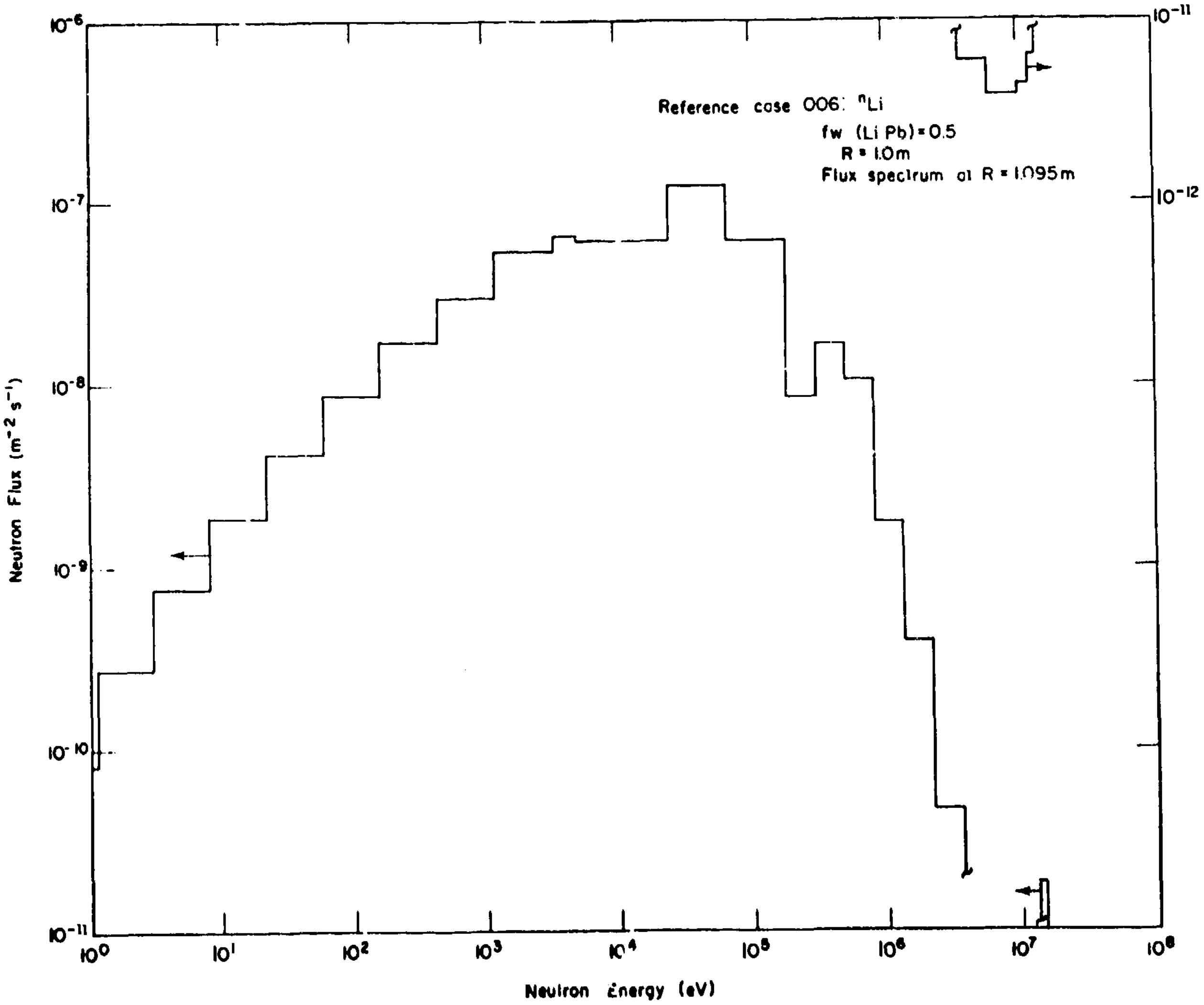

Figure 2 Leakage neutron spectrum for reference blanket (normalized to 0.01 neutron per m along the cylindrical axis).

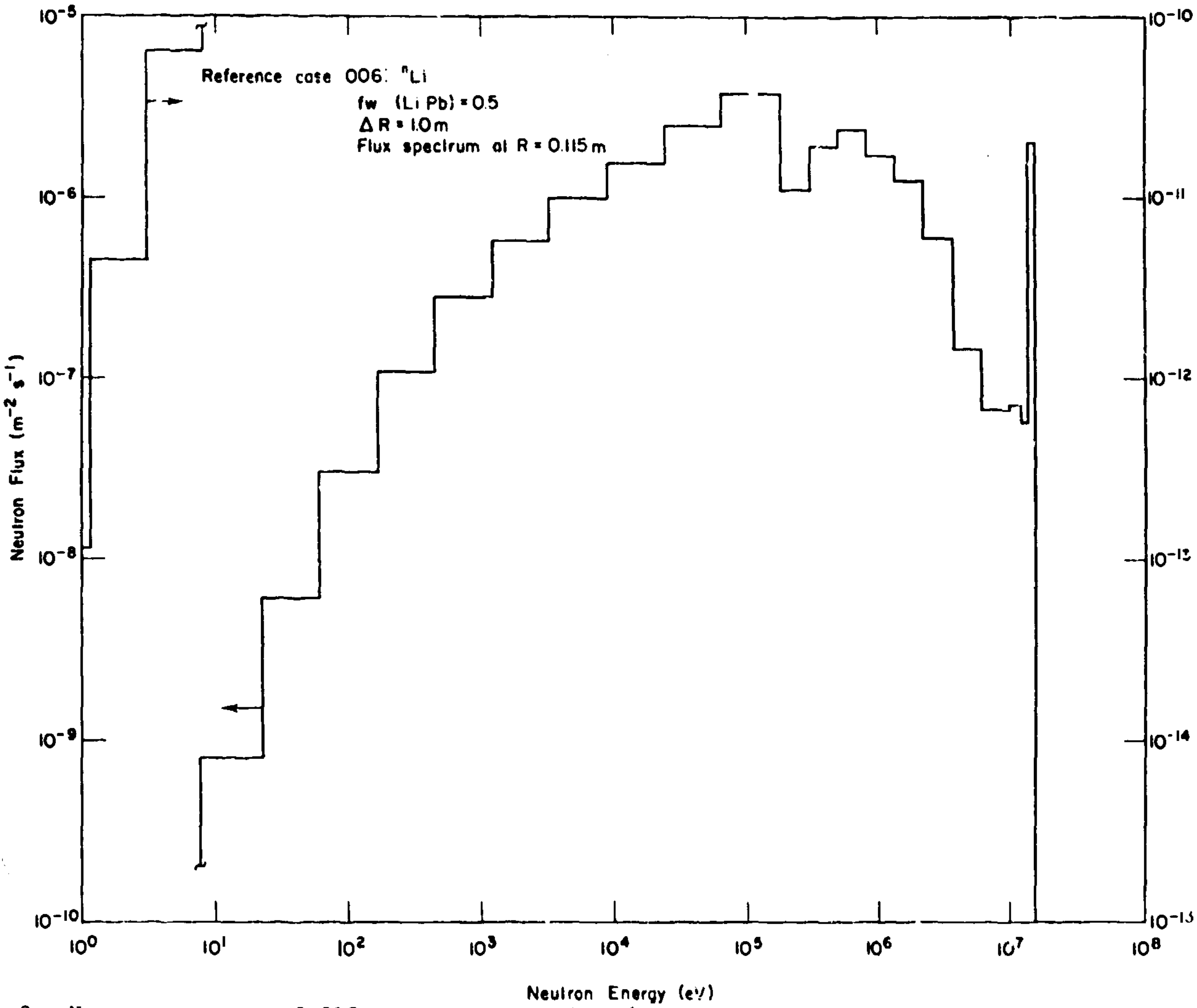

Figure 3. Neutron spectrum 0.015 m into the blanket (normalized to 0.01 neutron per m along the cylindrical axis).

than cadmium might prove more effective and should be explored in any further conceptual design studies.

A design breeding ratio which will allow for data uncertainties and multidimensional effects, is ~ 1.1. Very little provision for blanket structure or inhomogeneities need be made, because by its intrinsic nature the imploding liquid blanket is homogeneous and without internal structure. From Fig. 4 it can be inferred that significant poisoning can be tolerated in a 1-m-thick blanket, so blanket leakages to the cylinder block of ~ 0.1 appear achievable if materials such as tantalum or tungsten can be introduced in the blanket. As noted above, the large excess of neutrons in the blanket is due almost exclusively to (n,2n) reactions in lead, which almost double the initial neutron population. For example, from Fig. 4 at f_1 (cadmium in lead) = 0.0 the breeding ratio is 1.81 and the leakage from the blanket (L_2) is 0.187. Even ignoring other absorptions in the blanket, one has 1.997 "neutrons" per D-T neutron. It can also be concluded from Fig. 4 that most neutrons which leak from the blanket into the cylinder block (L_2) continue on through the cylinder block and escape (L_3). The fraction of neutrons absorbed in the cylinder block (approximately L_2-L_3) is only about 0.03 at a Cd isotopic fraction in Pb of 0.1. This fraction absorbed in the cylinder block is approximately 25% of the neutrons leaking from the blanket into the cylinder block. Again, consideration of the blanket leakage spectrum in Fig. 2 explains the relative transparency of the cylinder block to the leakage neutrons. Neutron absorption in the cylinder block is primarily due to resonance

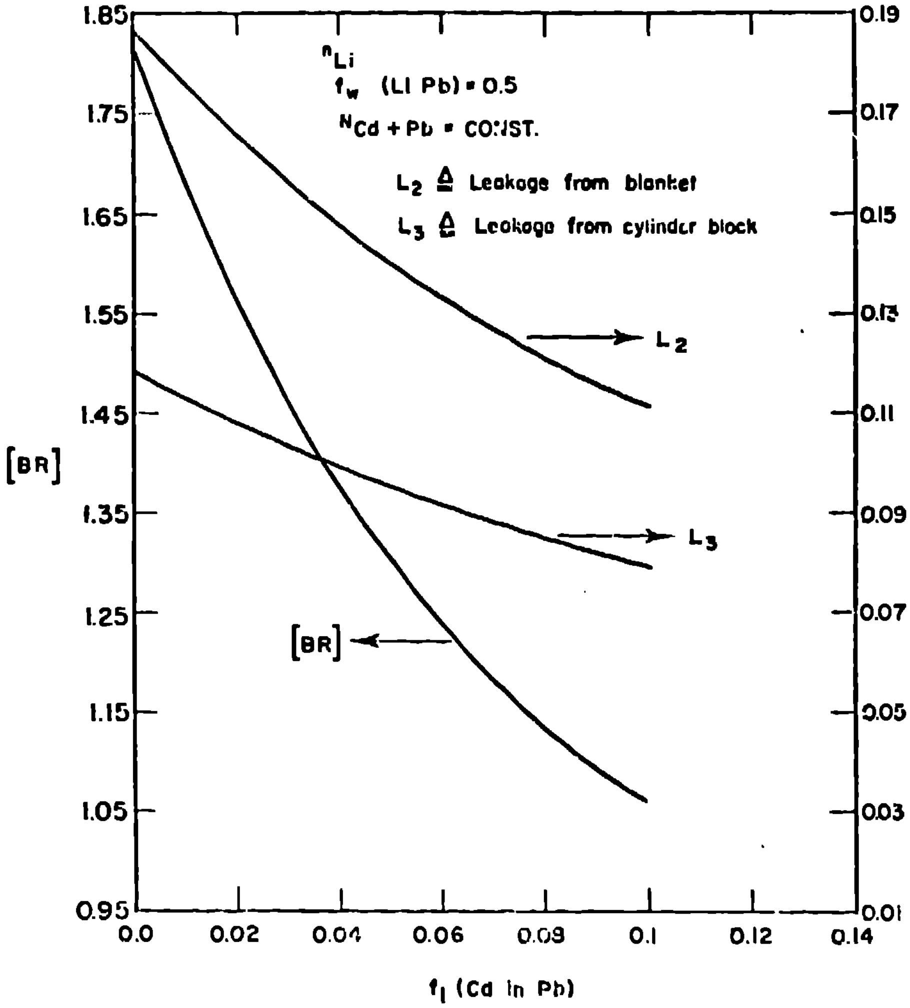

Figure 4. Effect of Cd substitution for Pb on breeding and leakage characteristics.

capture in iron at ~ 160 aJ (1 keV), and in fact, almost half of the absorptions occur in neutron energy group 17, which encompasses 72.6 to 198 aJ.

Of considerable interest in any blanket design is the spatial distribution of nuclear heating (neutron and gamma-ray) in the blanket and structure, as well as the volume integral of the energy. Figure 5 presents the spatial distribution of neutron plus gamma-ray energy deposition in the reference blanket and cylinder block. There is a decrease of over two decades in the blanket, with a small gamma-ray heating peak at the outer boundary. Values given in Fig. 5 are normalized to a unit D-T neutron in the plasma region per cm length of the cylinder. For a wall loading of $\overline{I}_w$ MW/m^2, where the primary D-T neutron current is $4.44 \times 10^{17}\ \overline{I}_w\ m^{-2}s^{-1}$, the renormalized source would be

$$S_L(cm^{-1}s^{-1}) = 4.44 \times 10^{17}\ \overline{I}_w\ A/L$$
$$= 2.79 \times 10^{15}\ \overline{I}_w\ .$$

Here A/L is the wall area per unit length (m^2/cm). Normalized to a cycle-time averaged wall loading of $\overline{I}_w$ = 1.0 MW/m^2, the maximum heating in the blanket and the cylinder block are 5.0 and 2.8 x 10^{-2} MW/m^3, respectively. Also, the integrated total heating in the blanket is 2.807 pJ per D-T neutron; and similarly in the cylinder block, 0.073 6 pJ. Thus the energy multiplication of the 2.25-pJ D-T neutrons is 1.248 in the blanket, and 1.280 in the combined blanket and cylinder block. The latter is the equivalent of 18.0 MeV deposited energy per D-T neutron. The normalization to $\overline{I}_w$ = 1.0 MW/m^2 does not imply that this is a realistic reactor value. Actual wall loadings

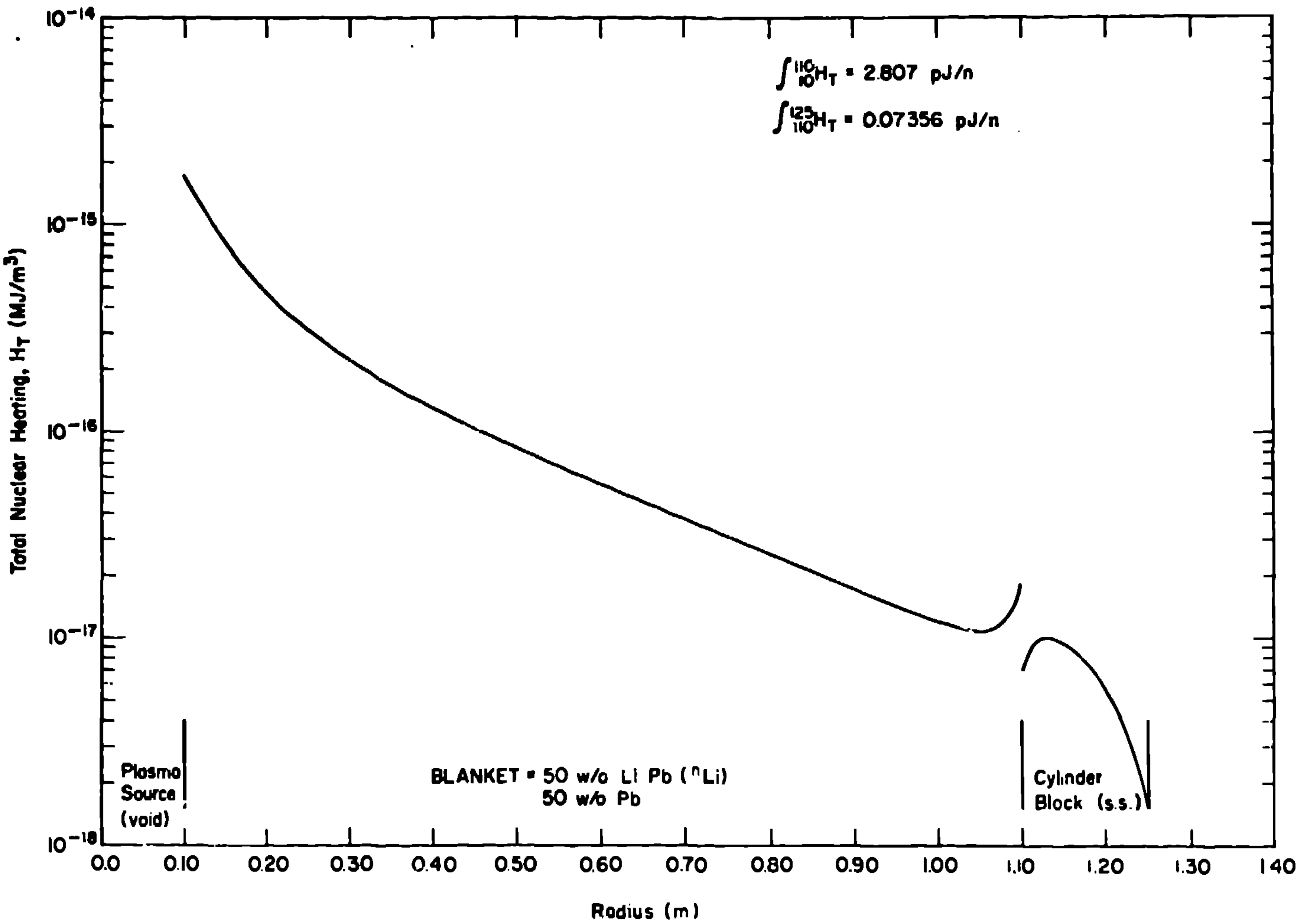

Figure 5. Spatial distribution of neutron plus gamma-ray energy deposition in reference blanket and cylinder block.

would depend upon plasma engineering considerations as discussed in Ref. 1, but almost certainly would be much higher than 1 MW/m^2 (e.g., 15 MW/m^2 at the permanent structure in one reactor configuration[1]).

TIME-DEPENDENT CALCULATIONS

An important consideration in the thermal-mechanical stability of the imploding liner in the time scale over which the nuclear energy is deposited in the blanket. Rough estimates were first made by simple slowing-down calculations,[7] and by comparison with time-dependent calculations for laser fusion reactors.[8] From the time-independent discrete-ordinates transport calculations it was determined that most of the absorption occurs in the 0.1- to 10-fJ (~ 10^3- to 10^5-eV) energy region. Based upon results from Ref. 7 and a slowing down time calculation* in lithium, an upper limit of ~ 10 μs can be inferred for the energy deposition time. From Ref. 8, the time is known to be > 0.1 μs. Time-dependent Monte Carlo calculations, using the MCNG code,[9] indicate that 81.4% of the total energy is deposited in < 0.5 μs, 8% from 0.5 to 2.0 μs, 6% from 2.0 to 5.0 μs, and 3% from 5.0 to 10.0 μs. Analysis of these

*The slowing-down time in lithium from 2.25 pJ to 800 aJ is given by

$$t = \frac{\sqrt{2m}}{\xi\Sigma_s}\left(\frac{1}{\sqrt{E_1}} - \frac{1}{\sqrt{E_0}}\right),$$

where $\xi_{Li} \simeq 0.263$ is the average lethargy increase per scattering collision, $\Sigma_s \simeq 2.4 \times 10^{-2}$ cm^{-1} is the average macroscopic scattering cross section, m is the mass of the neutron (g), E_0 is the initial neutron energy (ergs), and E_1 is the final neutron energy (ergs).

$t \simeq 3$ μs,

results shows that the energy is effectively absorbed before significant mechanical disruption of the blanket occurs. A rule-of-thumb criterion[3] used for energy absorption is that essentially all the energy should be deposited within < 10 μs, so a secure margin for error in the time-dependent Monte Carlo calculations still exists. These calculations show that only ~ 4% of the energy is deposited after 5 μs. Thus, it appears LINUS's blanket is mechanically secure for the lifetime of almost all nonleaking neutrons and gamma rays.

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