Revised per Referee's comments October 20, 1999

HEAT DEPOSITION, DAMAGE, AND TRITIUM BREEDING CHARACTERISTICS IN THICK LIQUID WALL BLANKET CONCEPTS

M.Z. Youssef and M.A. Abdou
School of Engineering and Applied Science
University of California-Los Angeles
(310) 825-2879, FAX (310) 825-2599, youssef@fusion.ucla.edu

Abstract

The Advanced Power Extraction (APEX) study aims at exploring new and innovative blanket concepts that can efficiently extract power from fusion devices with high neutron wall load. Among the concepts under investigation is the free liquid FW/liquid blanket concept in which a fast flowing liquid FW (~2-3 cm) is followed by thick flowing blanket (B) of ~40-50 cm thickness with minimal amount of structure. The liquid FW/B are contained inside the vacuum vessel (VV) with a shielding zone (S) located either behind the VV and outside the vacuum boundary (Case A) or placed after the FW/B and inside the VV (Case B). In this paper we investigate the nuclear characteristics of this concept in terms of: (1) attenuation capability of the liquid FW/B/S and protection of the VV and magnet against radiation damage, (2) profiles of tritium production rate and tritium breeding ratio (TBR) for several liquid candidates, and (3) profiles of heat deposition rate and power multiplication. The candidate liquid breeders considered are Li, Flibe, Li-Sn, and Li-Pb. Parameters varied are (1) FW/B thickness, L, (2) Li-6 enrichment, and (3) thickness of the shield.

1. **Introduction**

The main objective of the APEX study [Abdou 1] is to develop a concept that has the capability for a high neutron wall load and associated surface heat flux (>10 MW/m^2, >2 MW/m^2). A thick convective liquid layer that flows poloidally from the top, represents a liquid FW/Blanket and is among the several concepts under investigation [Ying 2]. Liquid-protected solid walls have been previously investigated [Christofilos 3, Moir 4-7]. The liquid layer copes with the high surface and neutron wall load and protects the blanket from excessive radiation damage. Because the liquid layer has low-atomic number, heat load from X-rays can deposit its energy over a measurable depth in the layer [Youssef 8] and thereby reduce the surface temperature. The candidate liquid breeders considered are lithium, (Li_2BeF_4), Li-Sn (25:75), and L17Pb83 (Li-Pb). The Li-Sn eutectic has lower vapor pressure than Li17Pb83. Low vapor pressure is an essential requirement for the flowing liquid layer facing the plasma to minimize its contamination [Sze 9].

In the Gravity and Momentum Driven (GMD) thick liquid FW/blanket concept, the fast flowing FW (~2-3 cm) is followed by thick flowing liquid blanket (B) of ~40-50 cm thickness with minimal amount of structure (no structure in these two layers is considered in the present analysis.) Effect of the magnetic field on the liquid FW/B and its impact on the heat transfer characteristics are addressed in Ref. 2. Tolerance to changes in the magnetic field and other MHD relevant issues are the subjects of an on-going investigation within the APEX research project. The liquid FW/B are contained inside the vacuum vessel (VV) with a shielding zone (S) located either behind the VV and outside the vacuum boundary (configuration A) or placed after the FW/B and inside the VV (configuration B). In this paper we investigate the advantage of protecting the solid walls following the liquid layer from neutron radiation damage and hence extending reactor components lifetime.

Other nuclear characteristics related to tritium breeding production and power deposition and multiplication are also investigated. Parameters varied are (1) FW/B thickness, L, (2) Li-6 enrichment, and (3) thickness of the shield. The 1-D modeling of the configurations considered is described in section 2 and 3. The attenuation characteristics of the various breeders investigated are also given in section 3. The concluding remarks from present work are described in section 4. The calculations were performed with ANISN code [Engle 10] along with 46:21 neutron-gamma multi group cross section data library based on FENDL-1 data base [Pashchenko 11] with an average neutron wall load of 10 MW/m^2 (a peaking factor of 1.4 is assumed in the APEX study). We note that the liquid FW/B is assumed to maintain its thickness in the poloidal direction (i.e. no account is taken for penetration) and therefore the 1-D model considered in the present work is appropriate under this assumption.

2. Configuration A: No Shielding inside the Vacuum Vessel

In this configuration, the vacuum vessel (VV) constitutes the vacuum boundary with 4 cm-thick walls and inner zone (52 cm-thick) with structure:coolant ratio of 20:80. The convective layer investigated in this case is 50 cm-thick and forms the liquid FW/B zone inside the VV with no structure. The TF coil casing and the winding pack of the magnet follow the VV. Two combinations are considered: lithium as the breeder/coolant with V-4Cr-4Ti (V-alloy) structure and Flibe with ferritic steel (FS).

2.1 Tritium Breeding

The profiles of total tritium production rate (TPR) are shown in Fig. 1 as a function of Li-6 enrichment. Most of the contribution to TPR comes from breeding in Li-6. The TPR at deep locations in the Flibe/FS system are 1-2 orders of magnitude less in the interior zone of the VV compared to the values in the Li/V-alloy system. This is due to the superior moderating power of the Flibe. This is seen from Fig. 2. At 14 MeV, the neutron mean free path (MFP) is ~ 16 cm in Li and 7 cm in Flibe. At all energies above ~ 3 eV, the MFP in lithium is much larger than those in Flibe by as much as an order of magnitude whereas at the thermal energies (below 1 eV) the MFP in lithium is a factor of ~6-8 lower than in Flibe. Thus, the lithium layer is much more "transparent" to high-energy neutrons and much less "transparent" to low-energy neutrons as compared to the Flibe. These features have also direct impact on the damage parameters in a solid wall that follows the liquid layer.

The radial integrated TPR as one moves across the system is shown in Fig. 3 for various Li-6 enrichment. The total TBR is the value obtained at radius R=493.8 cm from plasma center (outer boundary of the inner VV zone). The local TBR is thus ~ 1.74 and ~ 1.24 in the Li/V-alloy and Flibe/FS system, respectively. In both systems, the TBR decreases by increasing Li-6 enrichment. This feature is true in our case where we have thick (50 cm) liquid layer on both the inboard (IB) and outboard (OB). Since there is no structure or neutron multiplier (e.g. Be), the increase in Li-6 enrichment leads to a decrease in Li-7(n,n,α)t reactions and hence less neutron population in the system. If a structural material were to be present in the liquid layer, it would have moderated neutrons via inelastic scattering processes where they can be absorbed in Li-6, leading to an increase in TBR [Youssef 12]. The decrease in TBR with Li-6 enrichment is more pronounced in lithium than in Flibe. Going from natural Li to 90 %Li-6 leads to ~32% and ~10% decrease in the local TBR in the Li/V and Flibe/FS system, respectively. Note also that the TBR in Flibe is much less than in lithium system. At natural Li, the TBR in Flibe/FS system (1.24) is ~ 30% less than in the Li/V-alloy system (1.74). The local TBR in the Flibe/FS system appears marginal to account for losses due to penetrations, prediction and design uncertainties, radioactive decay, etc. The TBR in the Li layer keeps rising with increasing layer/blanket thickness whereas it saturates much faster in the Flibe case but to a much lower value. This makes satisfying T self-sufficiency even harder in the Flibe case. This can only be confirmed from 3-D analysis when a complete design for the thick liquid FW/B concept is finalized; which is not the case yet. For natural Li-6 enrichment, ~44% and ~64% of the total TBR is accumulated at a depth of 20 cm in the Li and Flibe layer, respectively. About 90% of the total TBR is reached at a depth of ~67 cm and ~40 cm in Li and Flibe, respectively.

2.2 Heat Deposition

The profiles for the heat deposition rates across the Li/V-alloy and Flibe/FS systems were generated as a function of the Li-6 enrichment. Because of the higher moderation power of the Flibe, less neutrons and gamma rays reach the back locations and hence lower heating rates occur with steeper profiles. At natural Li, the maximum power density in the liquid layer is ~60 MW/m^3 (Flibe) and ~40 MW/m^3 (Li). (Note: power density from surface heating and comparison to nuclear heating is discussed in Ref. 8.) The power multiplication factor (PM) is defined as the ratio of the total power deposited in the system to the incident neutron power. At natural Li, PM is ~1.18 (Li/V) and ~ 1.13 (Flibe/FS). The corresponding integrated power deposited in the system per unit height in the poloidal direction is ~2.27×10^2 MW/m and 2.17×10^2 MW/m, respectively. The fraction of the total power deposited in the system as a function of depth throughout the system is shown in Fig. 4. At natural Li, ~47% and ~70% of the total power is deposited in the first 20 cm of the convective layer. About 90% of the total power is deposited within the depth of 35 cm (Flibe/FS) and ~60 cm (Li/V).

3. Configuration B: Shielding Behind the Liquid FW/Blanket

In this configuration, a shielding zone is introduced behind the liquid FW/B and inside the vacuum vessel. The dimensions adopted for the 1-D radial build of the inboard (IB) and outboard (OB) are those of the ARIES-RS design [Najmabadi 13]. The liquid FW is 2 cm-thick and represents a fast-flowing layer whereas the slow-flowing layer constitutes the blanket and is 40 cm-thick. A solid back wall of 4 cm-thickness follows the liquid FW/B zone. A shielding zone of 50 cm is located behind the solid back wall and is assumed to have the structure to breeder (coolant) ratio of 60:40. In all cases considered, the VV walls are 2 cm-thick and made of 316SSLN and the interior is 16 cm-thick (IB) and 26 cm-thick (OB) with 316SSLN structure cooled with water (structure:water ratio of 80:20). Note that the coolant in the shield zones is the liquid breeder under consideration while water is used only inside the VV as a coolant. The TF coil casing and winding pack followed the VV and were considered in the IB and OB side. In the following we focus on two combination of breeder/structure, namely, Flibe/FS and Li-Sn/FS.

3.1. Tritium Breeding Ratio and Power Multiplication

The TBR is low (0.43) for Li-Sn with natural Li. It increases rapidly with increasing Li-6 enrichment and reaches a value of ~ 1.32 at 90% Li-6 enrichment (~200% increase, see Fig. 5). In the Flibe case, TBR is the largest at natural Li (~1.22, 1.24 in configuration A above) and it decreases with Li-6 enrichment (~10% decrease at 90%Li-6 enrichment). This decrease is a characteristic feature for the thick liquid Flibe for the reasons described earlier. The sharp increase in TBR of Li-Sn breeder with Li-6 enrichment leads to a noticeable decrease in the power multiplication, PM (from 1.52 to 1.32, ~13% decrease at 90%Li-6). The PM is noticeably larger in the case of Li-Sn due to the large absorption in Sn via Sn(n,γ) reactions, which in turn leads to larger gamma-ray flux, and hence larger contribution from gamma-ray heating (particularly at low Li-6 enrichment) as can be seen from Fig. 6. In addition to its low vapor pressure, the large PM with Li-Sn breeder adds an additional advantage since the thermal efficiency of the power core can be improved.

The profiles for the heat deposition rate in the case of Flibe/FS system are shown in Fig. 7 (OB side) for 10 MW/m^2 average neutron wall load and with natural Li, the maximum heating in the Flibe liquid, and the solid back wall is ~70 MW/m^3 and ~8 MW/m^3 whereas the heating rates in the VV wall, the casing of the TF coil and the winding pack are 0.04, 0.0004, and 0.00003 MW/m^3. The heating rates in the casing of the TF coil and the winding pack on the IB side are higher by an order of magnitude.

3.2. Attenuation Characteristics of Several Liquid Breeders and Damage to Solid Walls

The impact of the convective layer thickness, L, on the damage parameters in the solid back wall has been studied for several breeders. For comparison purposes, ferritic steel is assumed to be the structural material of the solid back wall and in the shield zone. Figure 8 to Fig. 9 show the DPA rate (DPA/FPY) and the helium production rate (appm/FPY) as a function of liquid layer thickness and for Li, Flibe, Li-Sn, and Li-Pb.

Without the liquid layer (bare wall), the helium and hydrogen production rates in the solid back wall are comparable in the four breeders. However, Li-Pb gives larger DPA rate and hence smaller He-4/DPA ratio (~8.7) as compared to the value with the other breeders (~10-11). As L increases, the reduction in the damage parameters varies among the four breeders. The lithium is the weakest material in moderating the neutron energy. The reduction in DPA rate is less than an order of magnitude for L=42 cm while the reduction in He-4 and H production is about an order of magnitude. The attenuation characteristic of the Li-Pb breeder for the DPA rate is similar to Li. However, the Li-Pb is superior to the other breeders in reducing the He-4 and H production due to its larger attenuation power to high-energy neutrons though (n,2n) and (n,inelastic) reactions. Because of the smallest He-4 production and the largest DPA rate with the Li-Pb, the He-4/DPA ratio is the smallest (~0.3) at L=42 cm (Li; ~7, Flibe: ~6, Li-Sn: 2). The attenuation characteristics of the Flibe and Li-Sn are similar for the helium and hydrogen production. However, the Flibe gives the best attenuation to the DPA rate since it is capable of attenuating both the high- and low-energy neutrons.

From Figs. 8 and 9, one can estimate the 10-fold thickness, L_{10}, defined as the required thickness of the layer to reduce a particular response by an order of magnitude. This thickness is given in Table I. For He-4 and H production, L_{10} ~22 cm with Flibe and Li-Sn and L_{10} ~18 cm with Li-Pb. Twice as much thickness is required in the Li case. As for the DPA rate, larger thickness is required. It is ~26 cm and ~36 cm for the Flibe and Li-Sn but much larger thickness (~58 cm) is required with the Li and Li-Pb breeders.

At L=42 cm, the DPA rate in solid back wall is ~26, 3.6, 9.5, and 30 DPA/FPY, with the Li, Flibe, Li-Sn, and Li-Pb liquid layer. If 200 DPA is considered as the limit at which the wall and shield zone require replacement, the lifetime of these components would be 7.7 year, 56 year, 21 year, and 7 year, respectively. Clearly the presence of a Flibe layer made these components last the lifetime of the plant (30 year). In the case of Li-Sn, one replacement may be required after ~20 years but 3-4 replacements may be needed in the case of Li and Li-Pb breeders.

Damage to the VV walls was also estimated as a function of the shield thickness for a liquid FW/B of 42-cm thickness. With the Flibe and Li-Sn breeders, the10-fold attenuation length of the shield is ~20 cm, and 30 cm, respectively (shorter than pure liquid due to presence of FS). The DPA rate in VV walls is ~ 0.01, and 0.1 DPA/FPY with Flibe and Li-Sn, respectively. Over 30 years plant lifetime, the accumulated DPA are below the 200 dpa limit [Zinkle 15] which makes the VV also a lifetime component for both breeders. The He-4 production rate is ~0.02 appm/FPY with both breeders. The accumulated value after 30 years is ~0.6 which is below the 1 appm limit [Zinkle 15] for the VV to be reweldable. It should be noted that this component lifetime assessment is based on the 1-D model applied here where a continuous liquid FW/B is assumed in the poloidal direction. Higher damage rates in the back solid wall and the VV are expected near radial penetrations that can be obtained from 3-D analysis. Since there is no finalized design for the thick liquid FW/B concept that addresses all the liquid wall issues, we rely here on scoping results obtained from the 1-D analysis.

4. Concluding Remarks

The gravity and momentum driven (GMD) thick liquid FW/Blanket concept under investigation within the APEX study for high power density extraction can offer several advantages over conventional blanket concepts. The present work shows that drastic reduction in the damage parameters at the solid wall following the liquid layer can be realized. For ~42 cm layer, ~ two orders of magnitude reduction in the helium and hydrogen production is achieved with either Flibe or Li-Sn liquid breeder (thinner thickness of ~36 cm with Li-Pb). Twice as much thickness however is required with lithium due to its poor attenuation characteristics. With this thickness, and based on the 200 DPA damage limit for replacement, using Flibe can make the solid back wall/shield a lifetime component. With the Li-Sn liquid wall, only one replacement may be needed during the lifetime of the plant (30 years) but 3-4 replacements may be needed in the case of Li and Li-Pb breeders. The vacuum vessel is also a lifetime component with the Flibe and Li-Sn liquid layers. In addition, it was shown from radioactive hazard and waste viewpoint that they can be reduced in the FW/blanket zone by ~ two–three orders of magnitude upon the inclusion of the thick liquid layer [Youssef 14]. As for breeding capability, it is shown that the tritium breeding ratio, TBR, with the Li and Flibe breeders is the highest at natural Li-6 and is the largest in the Li case; an inherent property for these breeders in liquid FW concepts. The Li-Sn breeder gives larger TBR than Flibe at 90%Li-6 but marginal for both breeders which may require a neutron multiplier (confirmation of tritium self-sufficiency with these breeders can only be obtained from 3-D analysis when a complete conceptual design is developed for the thick liquid FW/B concept in tokamaks). The power multiplication is the largest in the Li-Sn case, which could improve the thermal cycle with this new breeder that exhibits low vapor pressure, an additional advantage for deployment in liquid FW/B concepts.

Figure Captions:

Fig. 1: Profiles of the Total Tritium Production Rate a Function of Li-6 Enrichment

Fig.2: Mean Free Path of Neutrons in Lithium, Flibe, and Li17Pb83 as a function of Neutron Energy

Fig. 3: The Integrated Tritium Production Rate as a Function of Depth in the Convective Liquid Layer and for Various Li-6 Enrichment

Fig. 4: Fraction of the Integrated Power Deposited as a Function of Depth in the Convective Liquid Layer and for Various Li-6 Enrichment

Fig. 5: The Tritium Breeding Ratio, TBR, and Power Multiplication, PM, as a Function of Li-6 Enrichment

Fig. 6: Total Power Deposited in the System and Contribution from Neutron and Gamma-ray Heating

Fig. 7: The profiles of Heat Deposition Rate in the Outboard of the GMD Liquid FW/Blanket concept

Fig. 8: The DPA Rate in the Solid Back Wall as a Function of the Liquid Layer Thickness

Fig. 9: The Helium Production Rate in the Solid Back Wall as a Function of the Liquid Layer Thickness

Table I: The 10-Fold Thickness, $L_{10,}$ of the Liquid Layer

Parameter	Li/FS	Flibe/FS	Li-Sn/FS	Li-Pb/FS
DPA (dpa/FPY)	~58	~26	~36	~56
Helium Production (appm/FPY)	~46	~22	~21	~18
Hydrogen Production (appm/FPY)	~44	~22	~22	~19

References

[1] M. A. Abdou and the APEX Team, Exploring novel high power density concepts for attractive fusion systems", Fusion Engr. & Design 45 (1999) 145-167.

[2] A. Ying, et al, Free surface heat transfer and innovative designs for thin and thick liquid walls, Proc. 5th International Symposium on Fusion Nuclear Technology, ISFNT-5, Rome, Italy, Sept. 19-24, 1999, to appear

[3] N.C. Christofilos, Design for high power density astron reactor, J. Fusion Energy, 8 (1989) 97

[4] R.W. Moir, Liquid first wall for magnetic fusion energy configuration, Nuclear Fusion 37, No. *4*, 1997

[5] R.W. Moir, Liquid wall inertial fusion energy power plants, Fusion Eng. Des. 32-3, (1996) 93

[6] R.W. Moir, Rotating liquid blanket for torsional fusion reactor, Fusion Eng. Des. 5, (1987) 269

[7] R.W. Moir, The logic behind thick liquid-walled fusion concepts, Nucl. Eng. Des. 29 (1995) 344.

[8] M.Z. Youssef, N. Morley, and A. El-Azab, X-rays and volumetric heat deposition and tritium breeding issues in liquid-protected FW in high power density devices, Fusion Tech., 34 (1998) 697-705

[9] Dai-Kai Sze, et al., "Sn-Li, a New Breeding Material for Fusion", presented at the 5th APEX Study Meeting, November 2-4, 1998, University of California at Los Angeles (1998)

[10] W. W. Engle, ANISN: A one dimensional discrete ordinates transport code with anisotropic scattering, Report K-1693, Union Carbide Corporation, 1967

[11] A.B. Pashchenko, "Completion of FENDL-1 and Start of FENDL-2," INDC(NDS)-352, IAEA Nuclear Data Section, International Atomic Energy Agency, March 1996

[12] M.Z. Youssef and C. Wong, Neutronics performance of high-temperature refractory alloy helium-cooled blankets for fusion application, , Proc. 5th International Symposium on Fusion Nuclear Technology, ISFNT-5, Rome, Italy, Sept. 19-24, 1999, to appear

[13] F. Najmabadi, et al., "Overview of the ARIES-RS Reversed-Shear Tokamak Power Plant Study", Fusion Engr. & Design, 38 (1997) 3-35

[14] M.Z. Youssef, Damage indices in He-cooled refractory metal FW/blanket concept-comparison for solid and liquid walls, The APEX6 Workshop, February 16-19, University of California, Los Angeles, 1999

[15] S. Zinkle, private communication, Oak Ridge National Laboratory, United States, 1999.

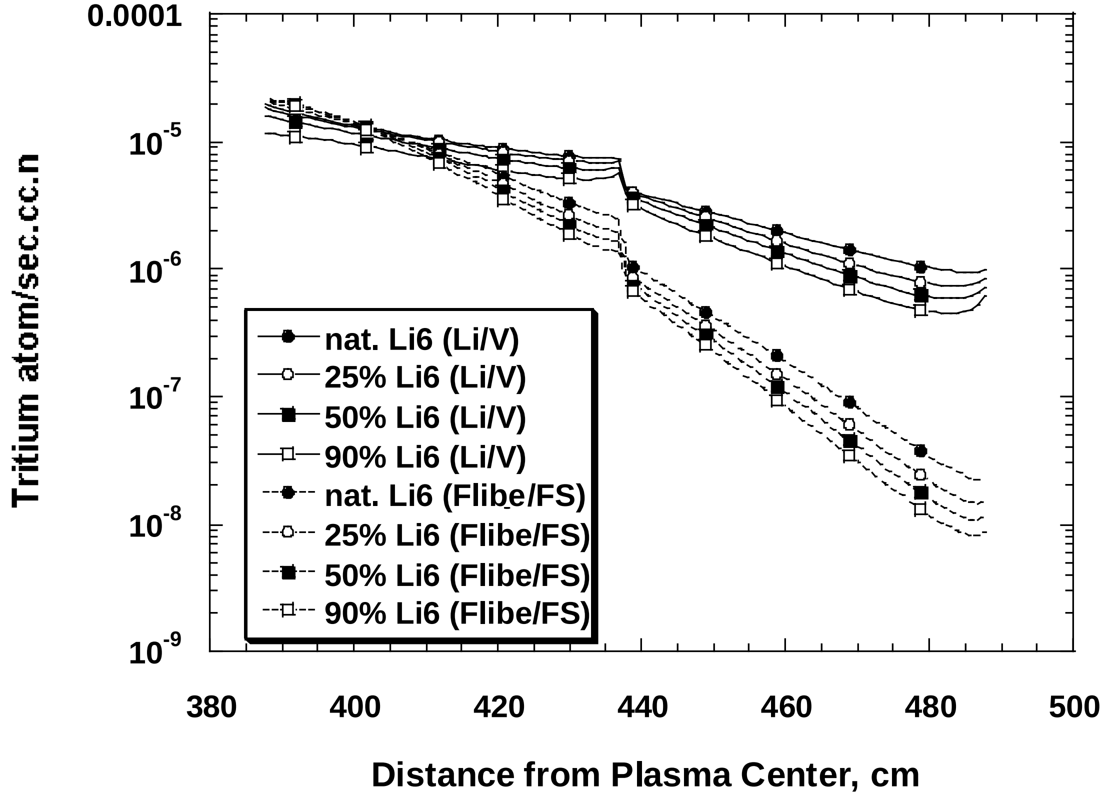

Fig. 1,

HEAT DEPOSITION, DAMAGE, AND TRITIUM BREEDING CHARACTERISTICS IN THICK LIQUID WALL BLANKET CONCEPTS

M.Z. Youssef and M.A. Abdou

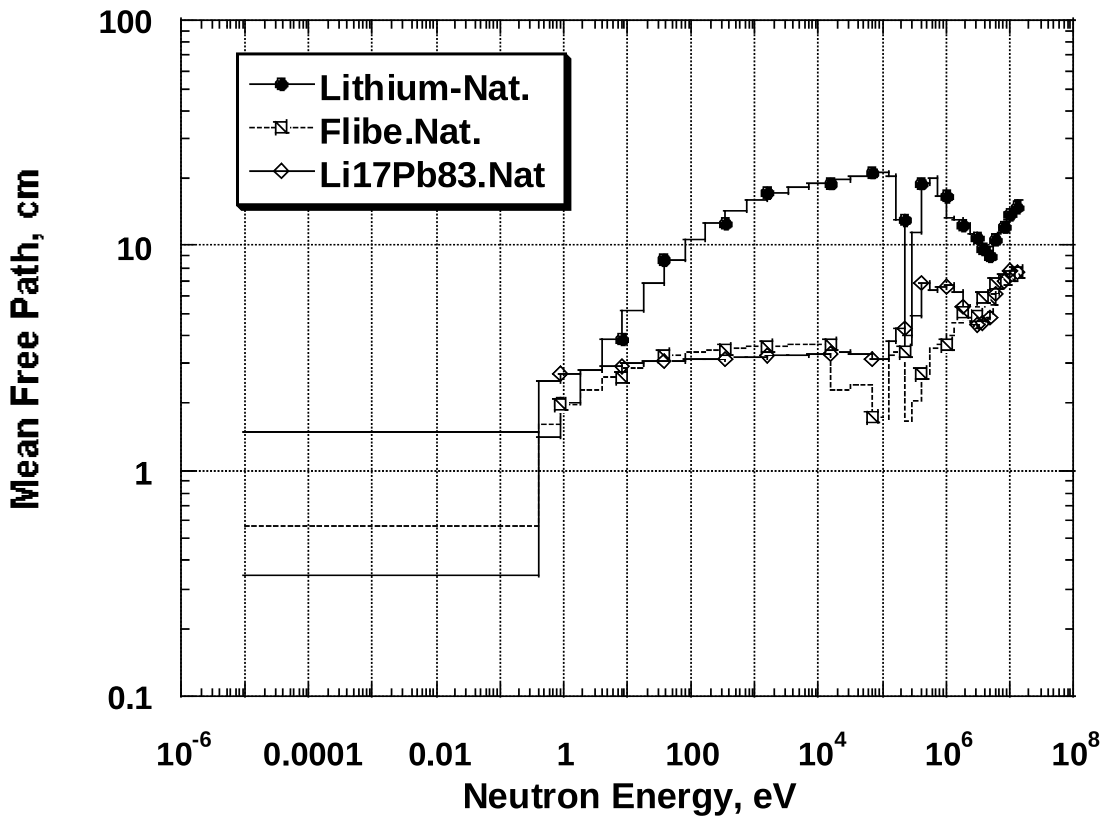

Fig. 2.

HEAT DEPOSITION, DAMAGE, AND TRITIUM BREEDING CHARACTERISTICS IN THICK LIQUID WALL BLANKET CONCEPTS

M.Z. Youssef and M.A. Abdou

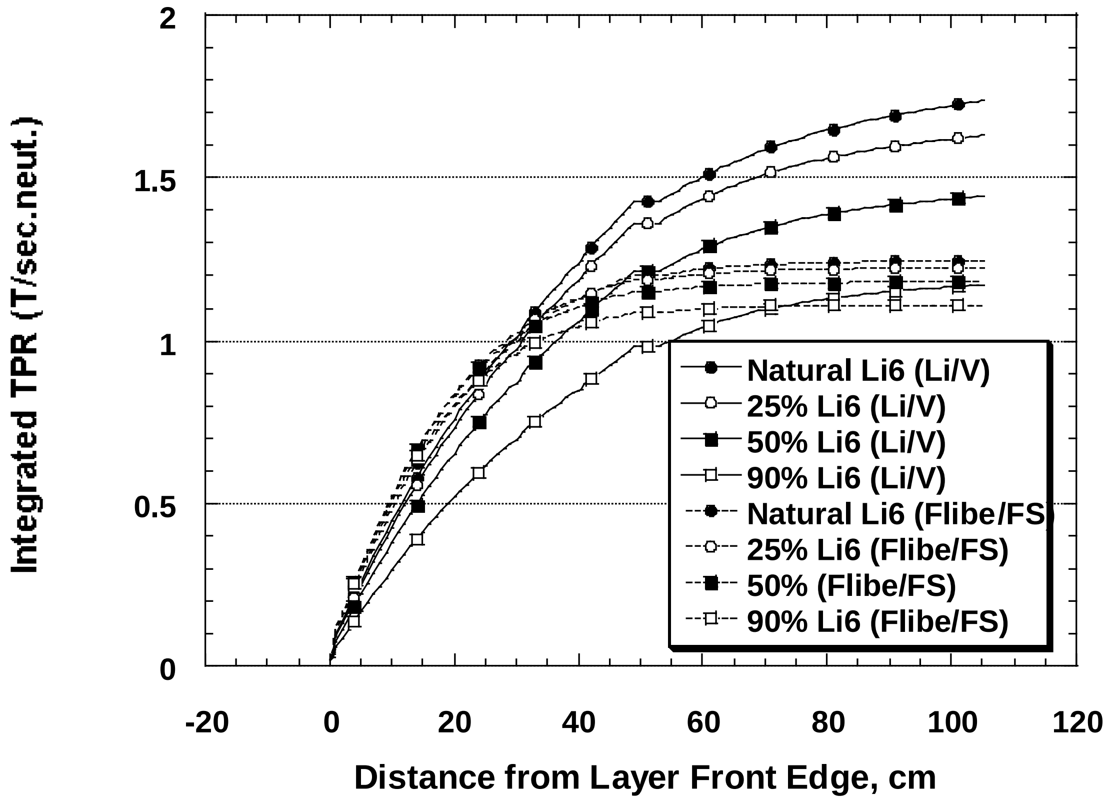

Fig. 3.

HEAT DEPOSITION, DAMAGE, AND TRITIUM BREEDING CHARACTERISTICS IN THICK LIQUID WALL BLANKET CONCEPTS

M.Z. Youssef and M.A. Abdou

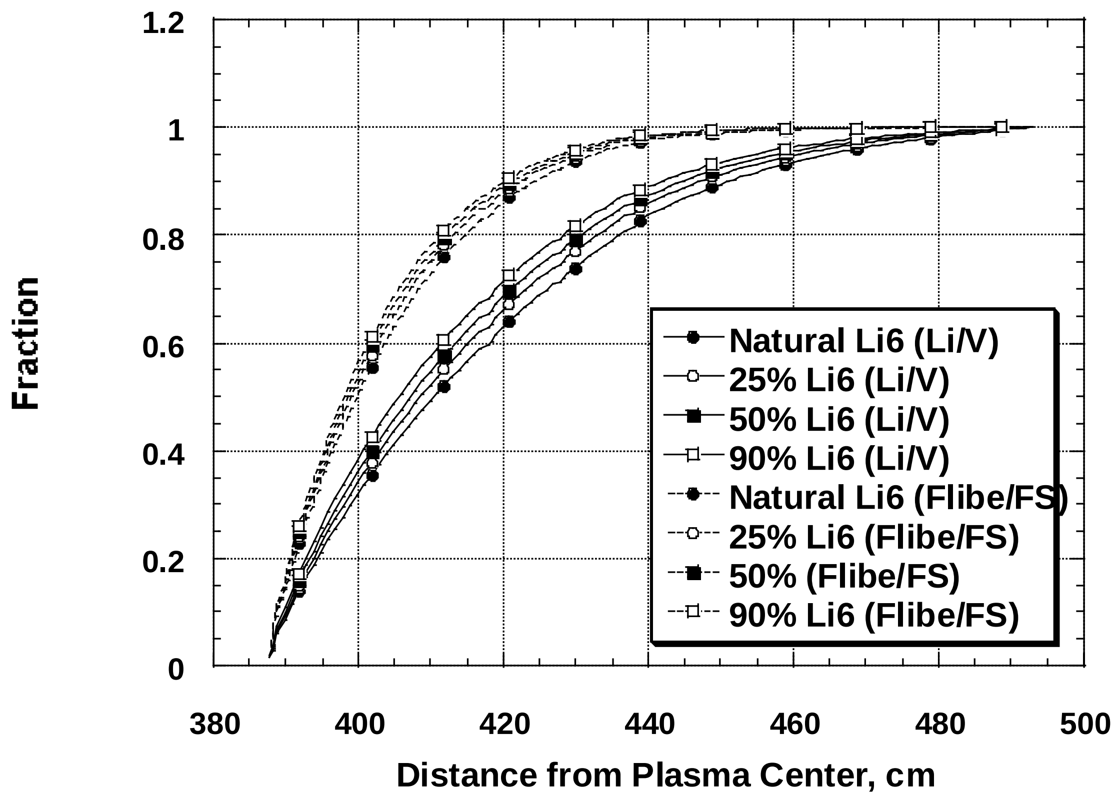

Fig. 4.

HEAT DEPOSITION, DAMAGE, AND TRITIUM BREEDING CHARACTERISTICS IN THICK LIQUID WALL BLANKET CONCEPTS

M.Z. Youssef and M.A. Abdou

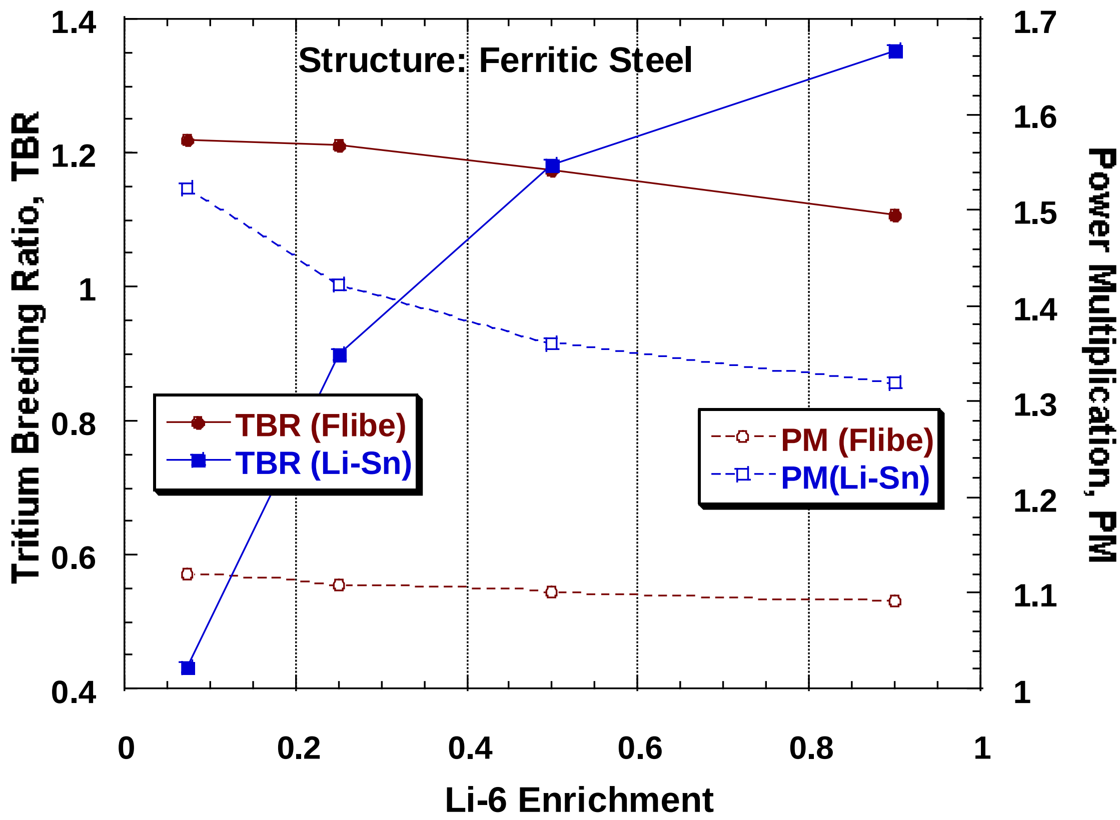

Fig. 5.

HEAT DEPOSITION, DAMAGE, AND TRITIUM BREEDING CHARACTERISTICS IN THICK LIQUID WALL BLANKET CONCEPTS

M.Z. Youssef and M.A. Abdou

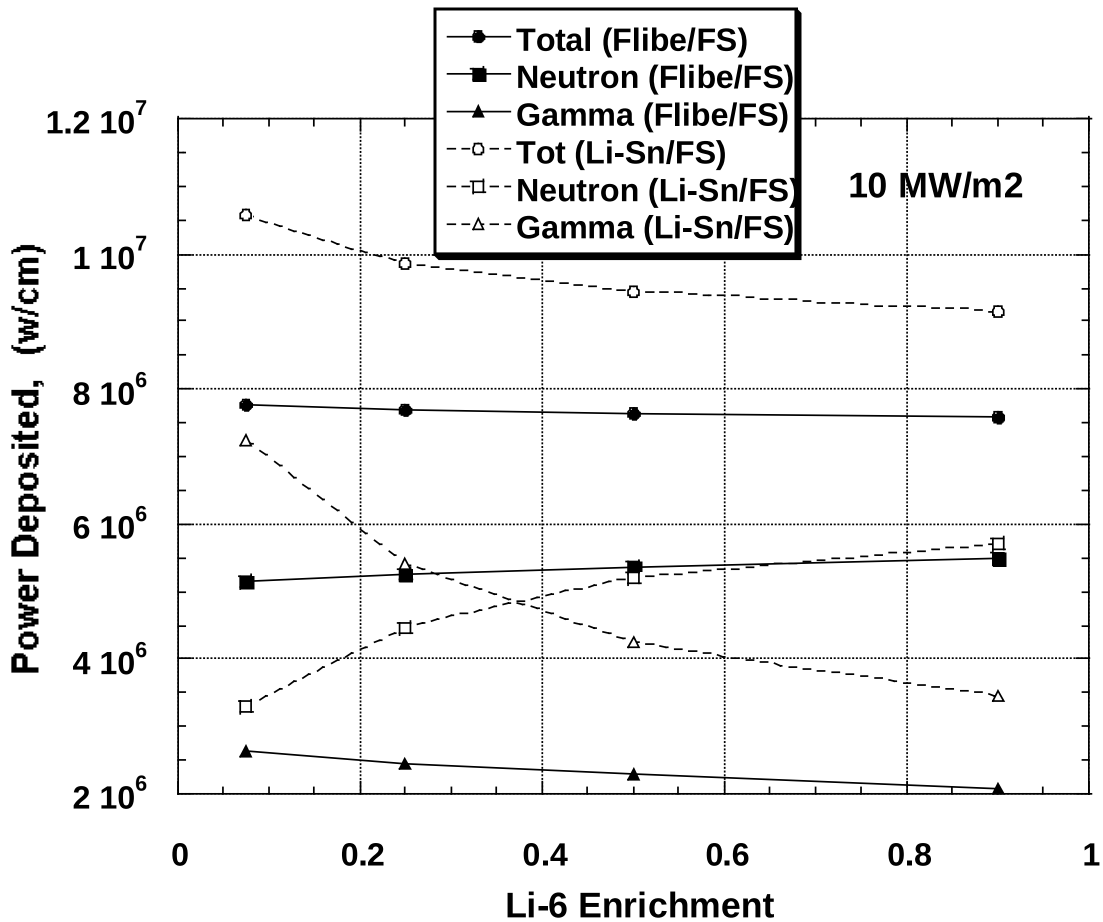

Fig. 6.

HEAT DEPOSITION, DAMAGE, AND TRITIUM BREEDING CHARACTERISTICS IN THICK LIQUID WALL BLANKET CONCEPTS

M.Z. Youssef and M.A. Abdou

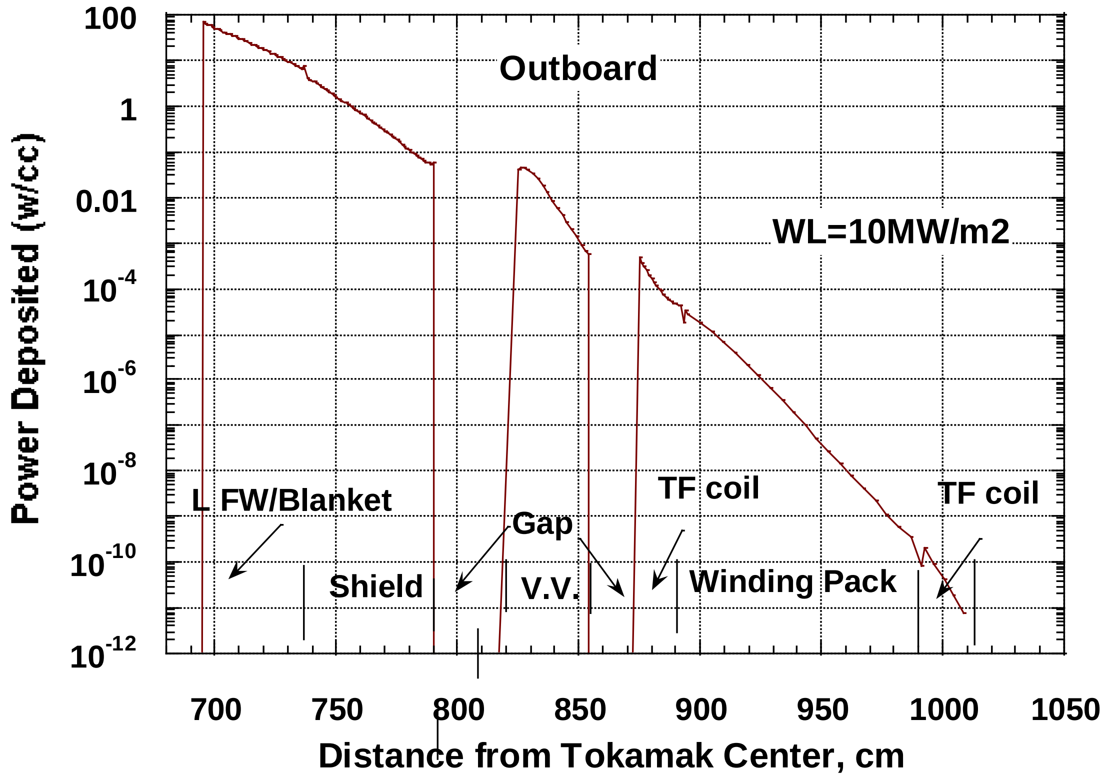

Fig. 7.

HEAT DEPOSITION, DAMAGE, AND TRITIUM BREEDING CHARACTERISTICS IN THICK LIQUID WALL BLANKET CONCEPTS
M.Z. Youssef and M.A. Abdou

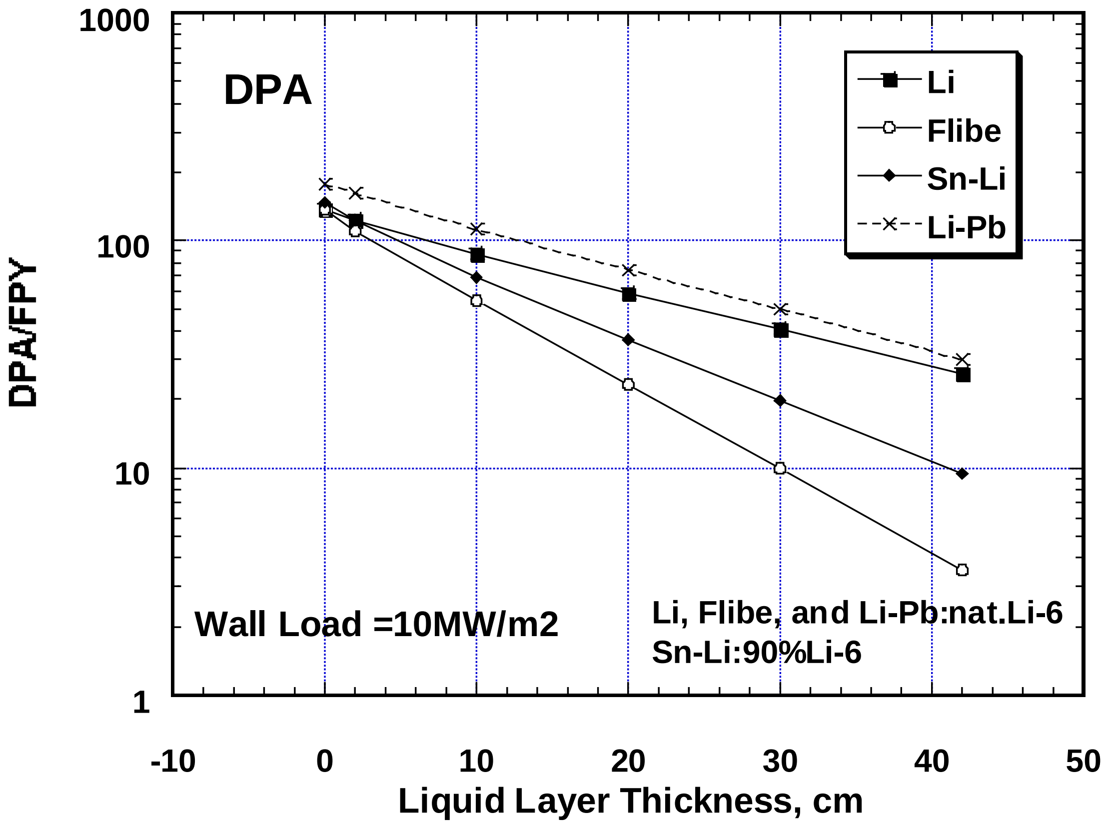

Fig. 8.

HEAT DEPOSITION, DAMAGE, AND TRITIUM BREEDING CHARACTERISTICS IN THICK LIQUID WALL BLANKET CONCEPTS
M.Z. Youssef and M.A. Abdou

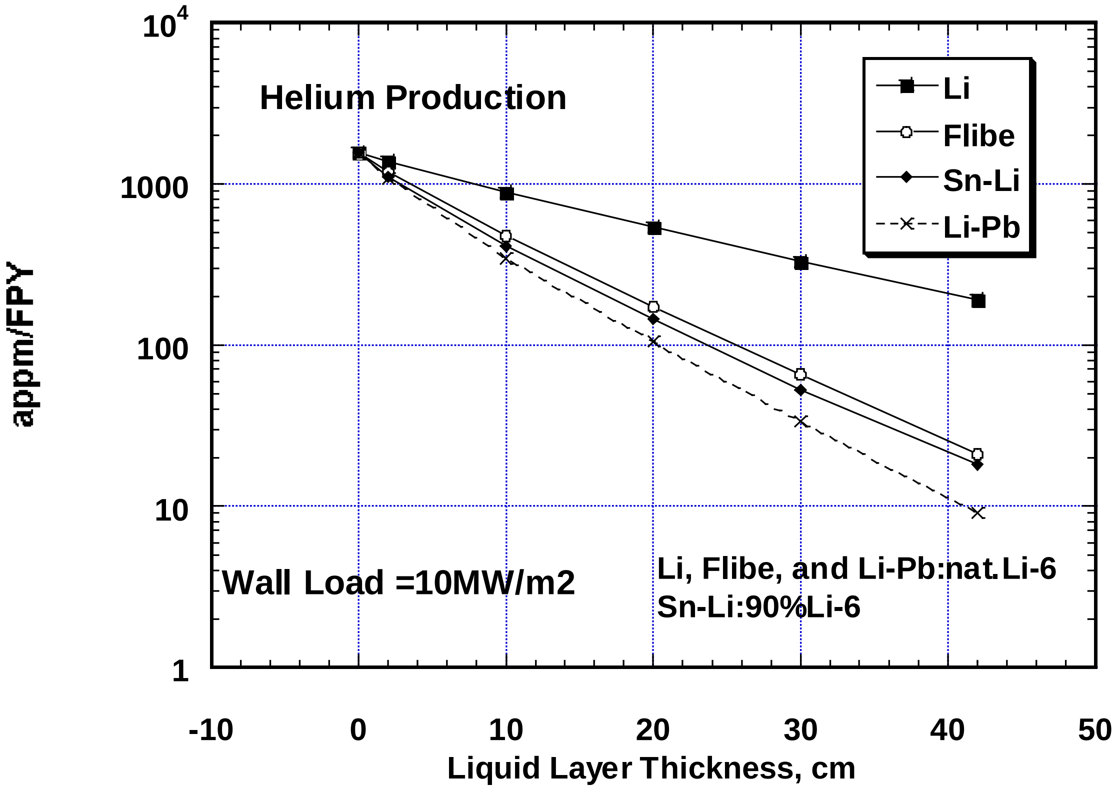

Fig. 9.

HEAT DEPOSITION, DAMAGE, AND TRITIUM BREEDING CHARACTERISTICS IN THICK LIQUID WALL BLANKET CONCEPTS

M.Z. Youssef and M.A. Abdou