APEX Study
Memorandum MZY_APEX_98_2
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Title: Impact of Li-6 Enrichment of the Convective Layer on Damage and Heat Deposition Rate in the Vacuum Vessel

To: APEX Study Participants

From: Mahmoud Youssef, UCLA

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I. Introduction:

As a continuation to previous calculations (see APEX memo MZY_APEX_98_1), the impact of Li-6 enrichment inside the Convective layer (Lithium, Flibe) on the total neutron flux and damage rates at the inner surface of the vacuum vessel was studied. In addition, this impact was studied for the total heat deposited in the Convective layer, the V.V., and the blanket that follows the V.V. Figure 1 shows the calculational model used where the parameter L shown is the thickness of the Convective layer.

II. Results and Discussion
II.1 Total Flux and Damage Rates:

We recall, the damage parameter, R_o, for the case where no layer is flowing in front of the V.V. (i.e. L = 0 cm) is given in Table I for a wall load of 7 MW / m2. For a layer thickness L = 50 cm with natural Li-6, these parameters, R_{nat}, are given in Table II where drastic reduction occurs as a result of neutron slowing down in the Convective layer. The e-fold thickness (L_e: the thickness of the layer required to reduce each parameter by an order of magnitude) is estimated from the expression:

$$L_e = \frac{\ln 0.1}{\ln \frac{R_{nat}}{R_o}} \cdot x , \qquad (1)$$

where x is the physical thickness of the layer. These e-fold thicknesses are given in Table III for x = 50 cm.. As shown, L_e is much lower in case of Flibe due to its superior neutron moderation relative to the lithium layer. For the Flibe, it is ~ 25 cm for dpa, He-4, and H production rates and ~ 40 cm for the neutron flux. It is more than twice as much for the lithium layer in case of

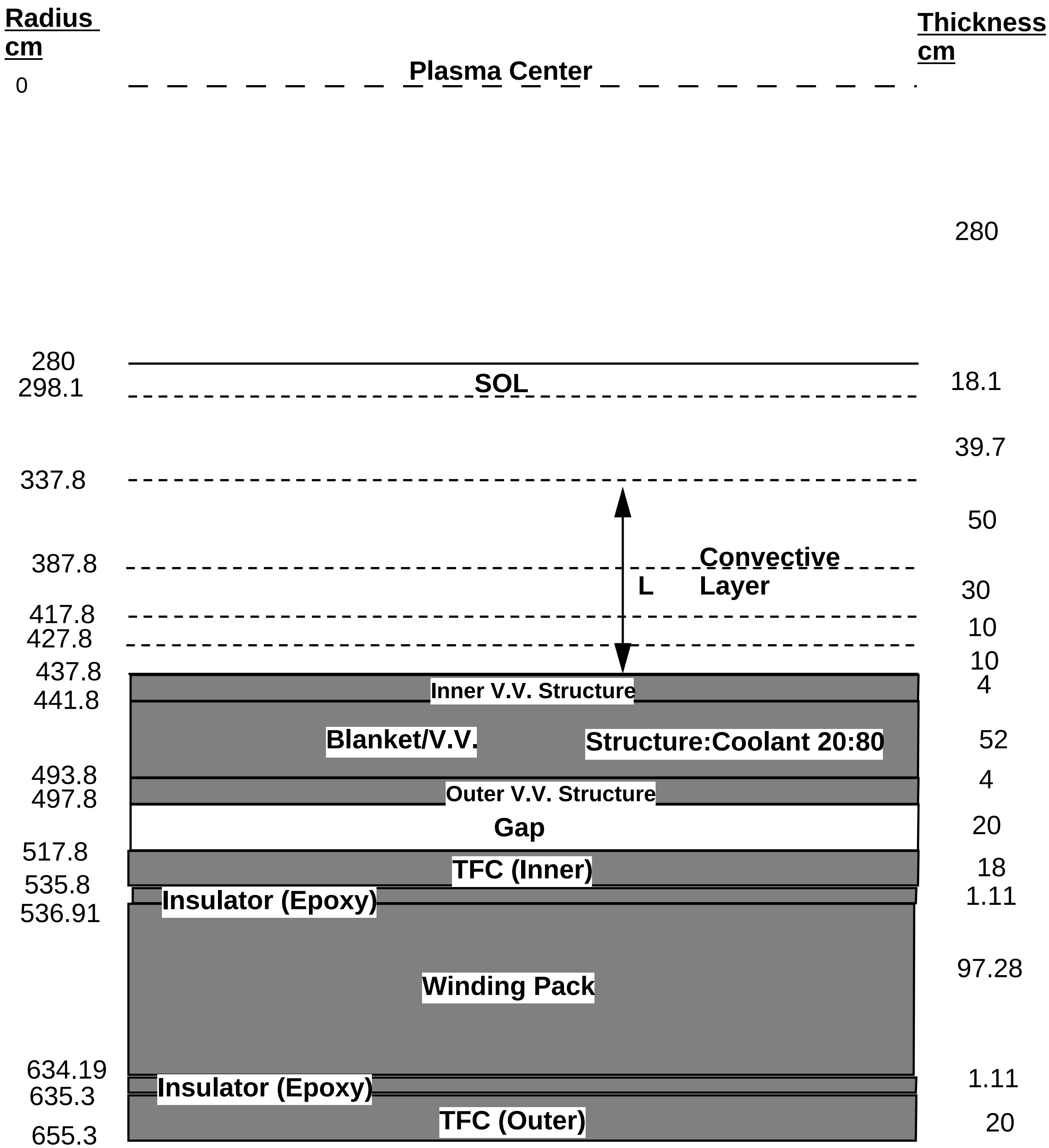


Fig. 1: One-Dimensional Geometrical Model (Cylinder)

dpa, He-4 and H production rates (~ 76 cm, 51 cm, and 55 cm respectively) and as much as 105 cm for neutron flux.

Table I: Values of Neutron Flux and Damage Responses, R_0, with Convective Layer L = 0 cm (Bare Vacuum Vessel)

Case	Flux (n/cm2.sec)	DPA (dpa/yr)	He-4 (appm/yr)	H (appm/yr)
Li/V4Cr4Ti	3.46×10^{15}	242.38	300	6.71×10^{3}
Flibe/FS	4.15×10^{15}	203.64.	867.7	3.81×10^{3}

Table II: Values of Neutron Flux and Damage Responses, R_{nat}, with Convective Layer L = 50 cm (natural Li6 Enrichment)

Case	Flux (n/cm2.sec)	DPA (dpa/yr)	He-4 (appm/yr)	H (appm/yr)
Li/V4Cr4Ti	1.16×10^{15}	53.62	31.23	8.37×10^{2}
Flibe/FS	2.35×10^{14}	3.89	9.25	3.76×10^{1}

Table III: E-fold Thickness for Neutron Flux and Damage Responses, L_e, (Convective Layer L = 50 cm, natural Li6)

Case	Flux (n/cm2.sec)	DPA (dpa/yr)	He-4 (appm/yr)	H (appm/yr)
Li/V4Cr4Ti	106	76	51	55
Flibe/FS	40	29	25	25

The Li-6 enrichment (l) has been varies as l (%) = 7.42% (natural), 25%, 50% and 90% for the case of layer thickness L = 50 cm. As l increases, the neutron spectrum at the surface of the inner V.V. wall gets more depleted in the low-energy neutron component as a result of absorption in Li6 via Li6(n,a) reactions. Figures 2-3 show the neutron spectrum at the V.V. as a function of Li6 enrichment, l. Since He-4 and H production rates are mainly driven by high-energy neutrons, the decrease in these damage parameters is not as large as in the case of DPA rate (occurs at all energies) and total neutron flux. This is particularly more noticeable in the case of Flibe layer. Figures 4-5, show these parameters on a linear scale with Li6 enrichment where we can notice slight change in DPA, He-4 and H production rates due to Li6 increase in the Flibe layer.

Fig. 2: Neutron Spectrum at the Inner Surface of the Vaccum Vessel as a Function of Li-6 Enrichment (Lithium, L= 50 cm)

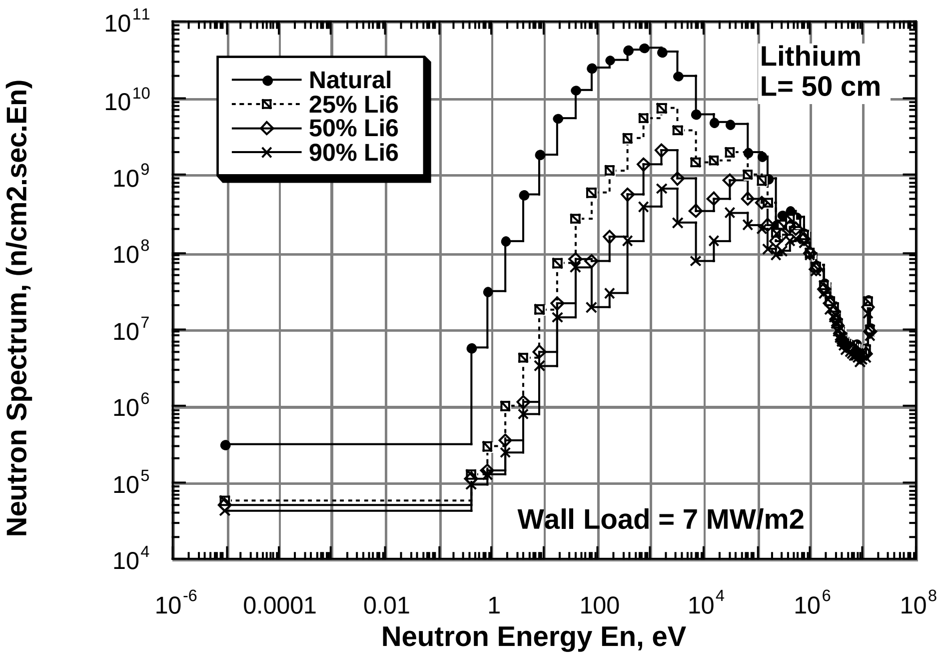


Fig. 3: Neutron Spectrum at the Inner Surface of the Vaccum Vessel as a Function of Li-6 Enrichment (Flibe, L= 50 cm)

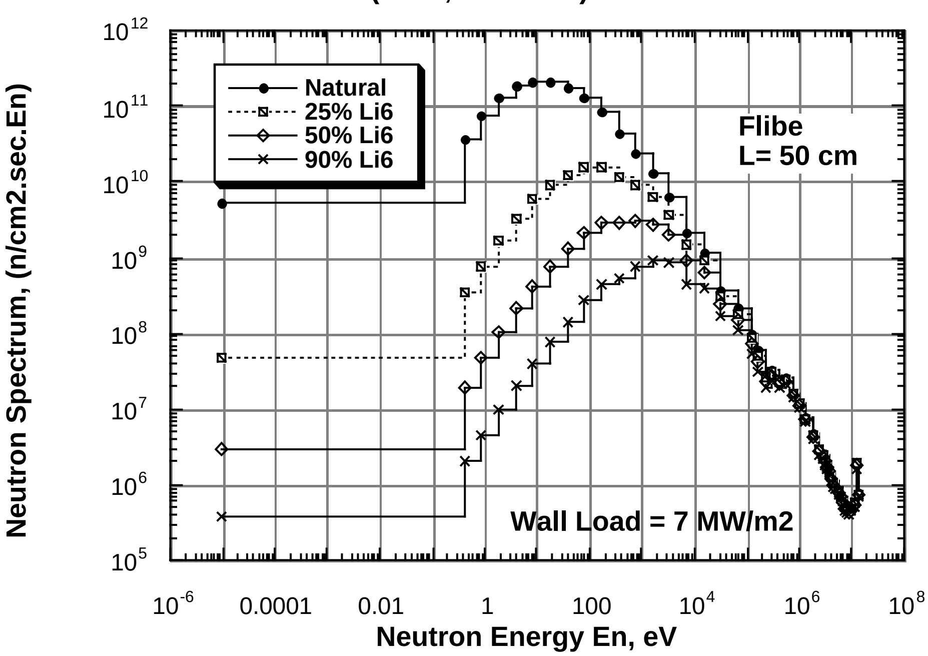


Fig. 4: Total Neutron Flux and DPA Rate (DPA/yr)
at the Inner Surface of the Vaccum Vessel
As a Function of Li-6 Enrichment

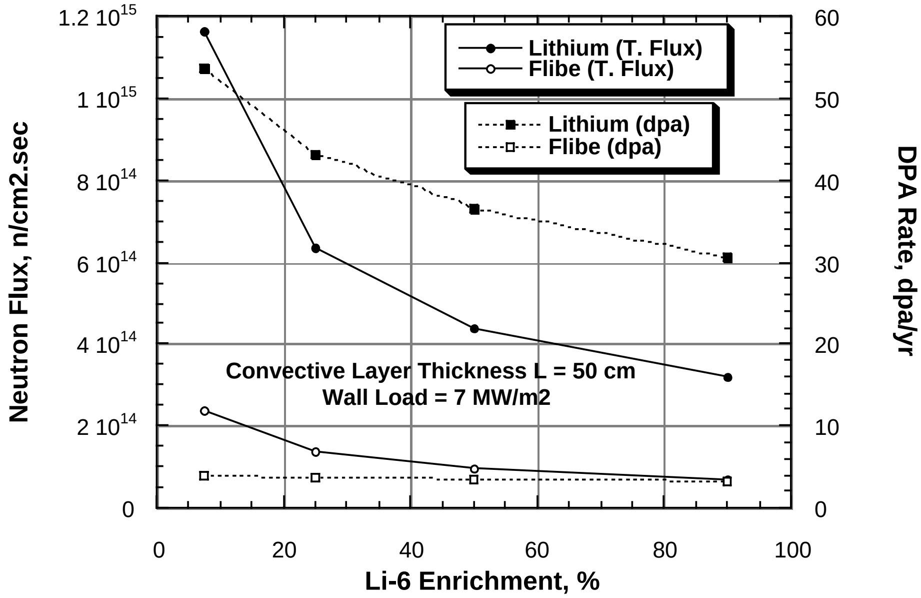
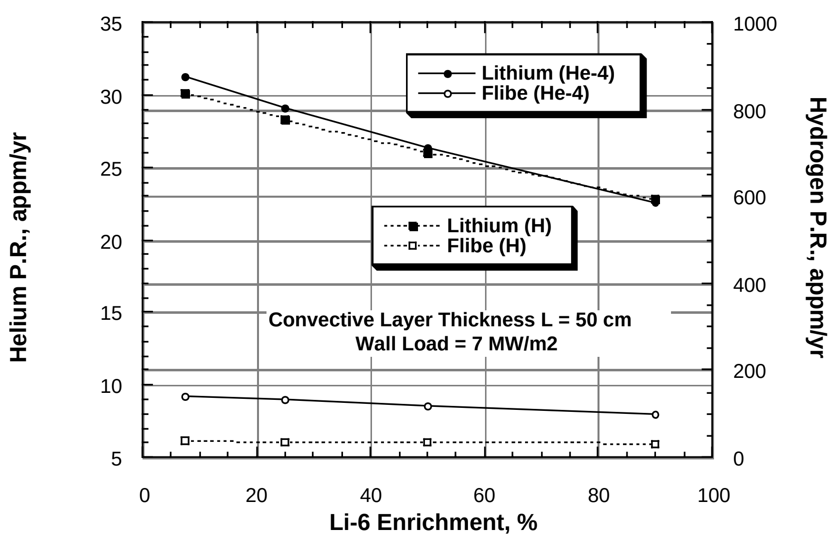


Fig. 5: Helium and Hydrogen Production Rates (appm/yr)
at the Inner Surface of the Vaccum Vessel
As a Function of Li-6 Enrichment



Least-square curve fitting was performed to the curves shown in Figures 4-5 to derive expressions for neutron flux and damage rate parameters as a function of Li6 enrichment, l. Linear curve fitting was applied to DPA, He-4, and H production rate for the Flibe layer and He-4 and H rates for the lithium layer. Quadratic form was used for the neutron flux for the Flibe layer case and DPA rate for the lithium layer case since the variation with "l" in these parameters is not linear. As for the neutron flux in the lithium layer case, power form (R_l = mo

l^{m1}) is applied which gives the lease square errors. The curve fitting forms and the values of the fitting coefficients are given in Tables IV and V, respectively.

Table IV: Curve Fitting Type for Neutron Flux and Damage Responses, R_l, as a Function of Li-6 Enrichment, l

Case	Flux (n/cm2.sec)	DPA (dpa/yr)	He-4 (appm/yr)	H (appm/yr)
Li/V4Cr4Ti	$R_l = mo\ l^{m1}$	$R_l = mo + m_1 l + m2\ l^2$	$R_l = mo + m_1 l$	$R_l = mo + m_1 l$
Flibe/FS	$R_l = mo + m_1 l + m_2 l^2$	$R_l = mo + m_1 l$	$R_l = mo + m_1 l$	$R_l = mo + m_1 l$

Table V: Coefficients of Curve Fitting for Neutron Flux and Damage Responses, R_l (Convective Layer L = 50 cm)

Case	Flux (n/cm2.sec)	DPA (dpa/yr)	He-4 (appm/yr)	H (appm/yr)
Li/V4Cr4Ti	mo = 3.3235×10^{15} m1 = -0.5189	mo = 57.302 m1 = -0.60135 m2 = 3.4046×10^{-3}	mo = 31.806 m1 = -0.10461	mo = 853.49 m1 = -2.9369
Flibe/FS	mo = 2.6667×10^{14} m1 = -5.4268×10^{12} m2 = 3.5989×10^{10}	m o = 3.928 m1 = -9.3046×10^{-3}	mo = 9.3486 m1 = -0.015506	mo = 37.986 m1 = -0.062724

Assuming the largest possible increase in Li6 enrichment of l = 90%, the values of the parameters under consideration are given in Table VI as obtained from neutron transport and from fitting curves (in parentheses).

Table VI: Values of Neutron Flux and Damage Responses, R_l, with Convective Layer L = 50 cm (90% Li6 Enrichment) (Values in Parentheses are obtained from Curve Fitting)

Case	Flux (n/cm2.sec)	DPA (dpa/yr)	He-4 (appm/yr)	H (appm/yr)
Li/V4Cr4Ti	3.18×10^{14} (3.22 x 1014)	30.59 (30.76)	22.54 (22.39)	5.93×10^{2} (5.89 x 102)
Flibe/FS	6.77×10^{13} (6.98 x 1013)	3.11 (3.09)	7.96 (7.95)	3.24×10^{1} (3.23 x 101)

The percentage decrease in these parameters is given Table VII from both direct and curve fitting calculations. As shown, the change in DPA, He-4, and H production rates is only ~ 15-20% in the Flibe layer case although the change in the neutron flux in much larger (~ 70%). On the other hand, these changes are large in the lithium layer case; being ~ 30% for He-4 and H production rates, 42% for DPA rate and 72% for the neutron flux.

Table VII: % Decrease in Neutron Flux and Damage Responses, R_l, with Convective Layer L = 50 cm (90% Li6 Enrichment) (Values in Parentheses are obtained from Curve Fitting)

Case	Flux (n/cm2.sec)	DPA (dpa/yr)	He-4 (appm/yr)	H (appm/yr)
Li/V4Cr4Ti	72.6 (72.3)	42.9 (42.6)	27.8 (28.3)	29.1 (29.7)
Flibe/FS	71.2 (70.4)	20.0 (20.6)	13.9 (14.0)	13.8 (14.0)

The above observations apply as well to the e-fold thickness as a function of Li6 enrichment. Figures 6-7 show these thicknesses for the parameters under consideration. For a given Li-6 enrichment, l, the e-fold thickness, L_e, is obtained from Eq. (1) with x= 50 cm and R_l replaces R_{nat}. Table VIII lists these thicknesses for 90% Li6 enrichment (with comparison to the natural enrichment case). The e-fold thickness hardly changes for DPA, He-4 and H production rates in the Flibe case (only reduction by ~ 1 cm) by going from natural lithium to 90% Li6. The e-fold thickness decreases by ~ 10 cm, 7 cm, and 8 cm for DPA, He-4 and H production rates in the lithium layer case with larger reduction (~58 cm) for the neutron flux.

Table VIII: E-fold Thickness for Neutron Flux and Damage Responses, L_e, (Convective Layer L = 50 cm, 90% Li6) (Values in Parentheses are obtained at Natural Li-6)

Case	Flux	dpa	He-4	H
Li/V4Cr4Ti	48 (106)	56 (76)	44 (51)	47 (55)
Flibe/FS	28 (40)	28 (29)	24 (25)	24 (25)

Fig. 6: Required e-fold Thickness of Convective Layer for Neutron Flux and DPA rate at the Inner Surface of the Vaccum Vessel As a Function of Li-6 Enrichment

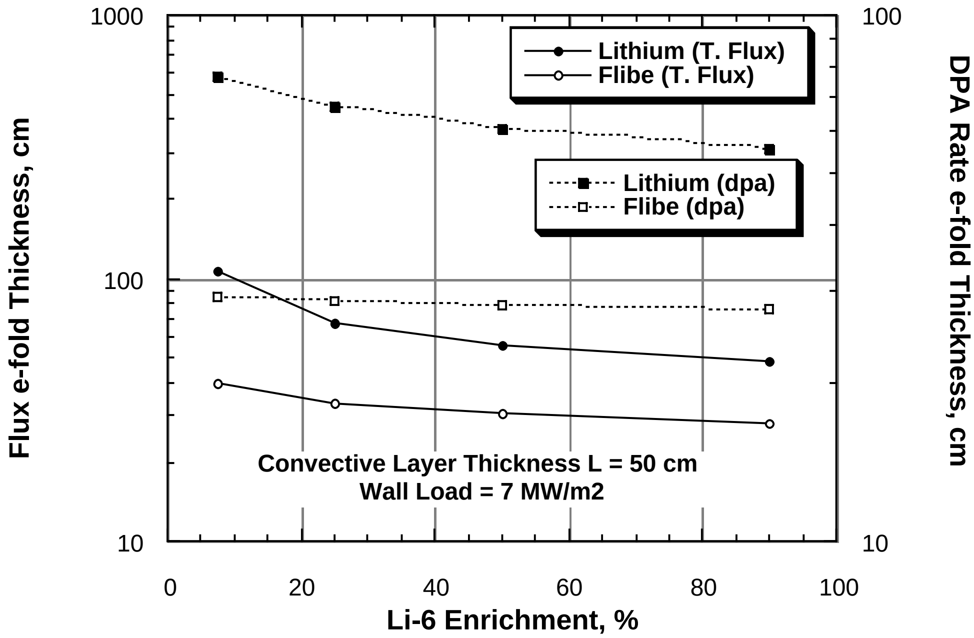
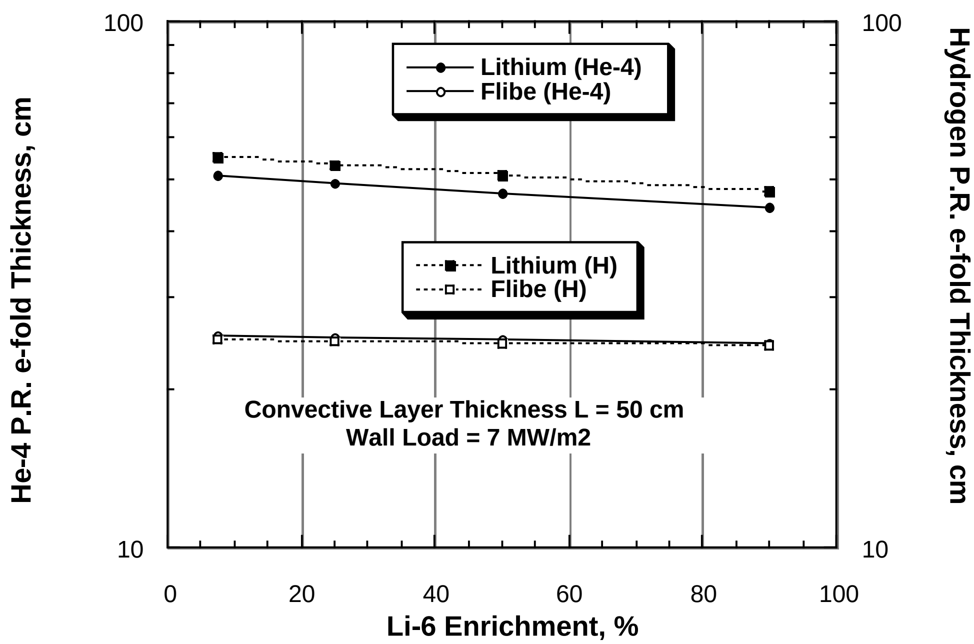


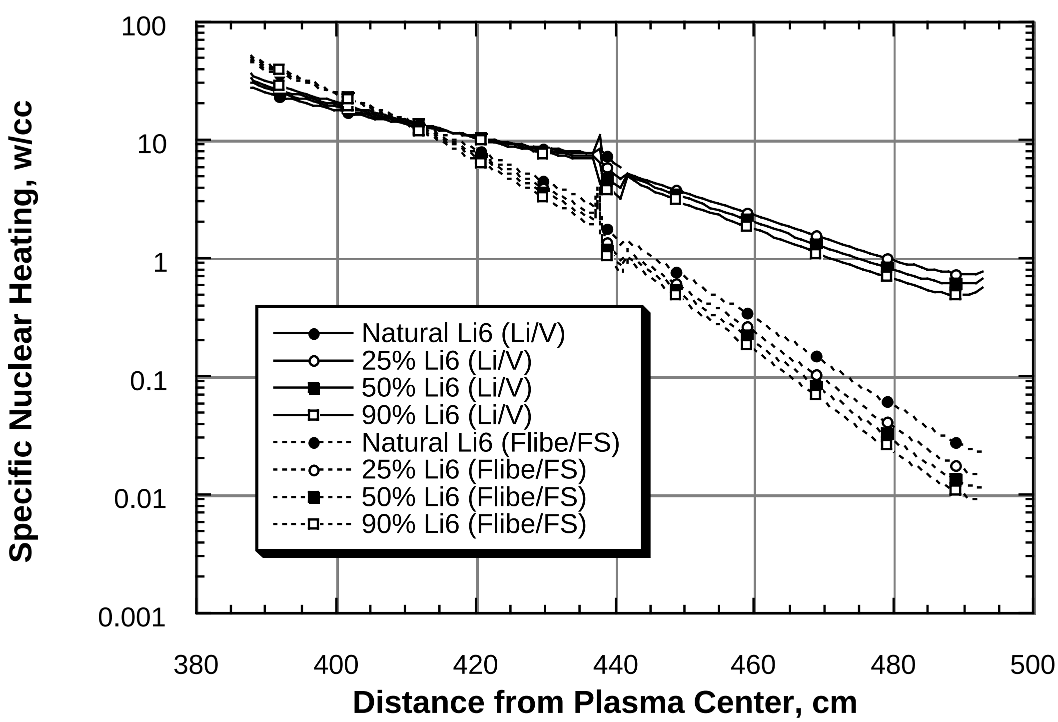
Fig. 7: Required e-fold Thickness of Convective Layer for Helium and hydrogen Production Rates at the Inner Surface of the Vaccum Vessel As a Function of Li-6 Enrichment



II.2 Total Heat Deposition

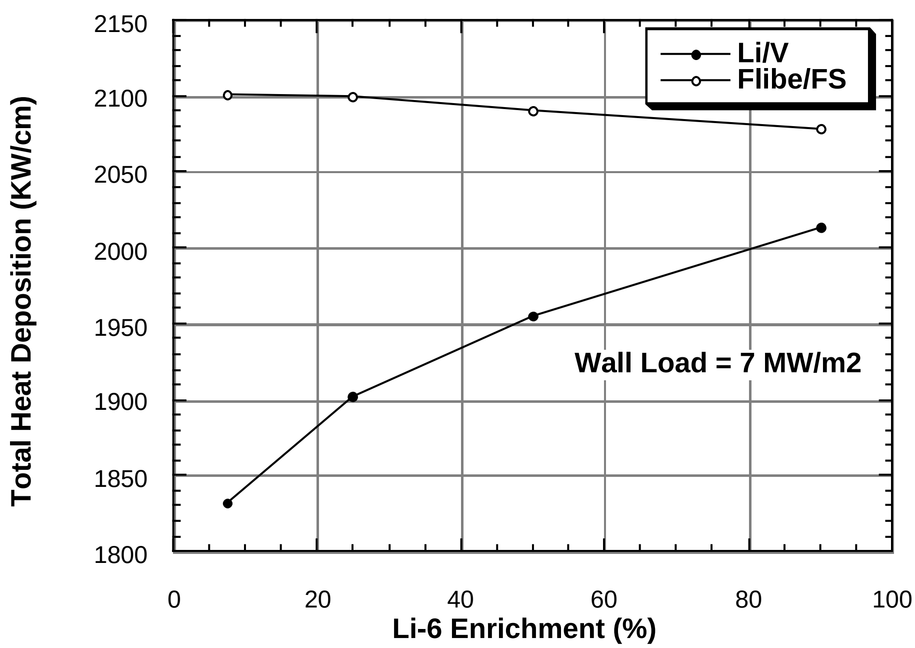
Increasing Li-6 enrichment enhances the reaction Li-6(n,a) which is exothermic with Q-value of ~ 4 MeV. This tends to increase specific heat rate at the front locations of the Convective layer. Since neutrons are more likely to be absorbed in these front locations as Li-6 enrichment increases, the number of neutrons reaching the back locations inside the Convective layer (and at all locations behind the Convective layer) is decreased with an adverse consequence on heat deposition rate at these locations. The decrease in heating rate at these back locations is more pronounced in the case of Flibe/FS due to the additional slowing down of neutrons through inelastic collisions with fluorine and beryllium at the front locations. This effect can be seen from Figure 8 which shows the specific nuclear heating in the Convective layer, inner wall of the V.V. and the blanket.

Fig. 8: Specific Heat Deposition Rate (w/cc)
(Wall Load = 7 MW/m2)



The total heat deposited in the Convective layer, the inner wall of the V.V. and in the blanket is shown in Figures 9-11, respectively, as a function of Li-6 enrichment and per unit height (1 cm) of each zone shown in the 1-D model of Figure 1. Within the 50 cm-thick Convective layer, the heat deposited in the Flibe is ~ 15% larger than in the case of lithium layer at natural Li-6 enrichment and ~ 3% larger at 90% enrichment. The increase in heat deposition in the lithium layer case is due to the enhancement in the Li-6(n,a) reaction whereas the slight decrease in the Flibe case is due to the decrease in neutron population through the Be(n,2n) reactions and inelastic collisions with fluorine as the Li-6(n,a) reaction increases which competes with these high-energy reactions.

Fig. 9: Total Nuclear Heating per unit Hight (KW/cm)
Versus Li-6 Enrichment
(Convective Layer - 50 cm-Thick)



Due to the superior moderation power of the Flibe layer, the neutrons reaching the V.V. and blanket and depositing their energies at these locations are much less than in the lithium layer case. As shown in Figure 10, heat deposited in the inner wall of the V.V. is larger by a factor of ~ 4 and ~ 2.8 in the lithium layer case than in the Flibe layer case at natural and 90% Li-6 enrichment, respectively. This is also true in the blanket zone where the heat deposited in the lithium layer case is larger by a factor of ~ 7 and ~ 8.3 than in the Flibe layer case at natural and 90% Li-6 enrichment, as can be seen from Figure 11. Note that heat deposited in the V.V. and the blanket in the Flibe layer case decreased by ~ 36% and 40%, respectively, as Li-6 enrichment increased from natural to 90%. The decrease in the lithium layer case for the same change in Li-6 enrichment is ~50% and ~33%.

Fig. 10: Total Nuclear Heating per unit Hight (KW/cm)
Versus Li-6 Enrichment
(Inner Wall of V.V. - 4 cm-Thick)

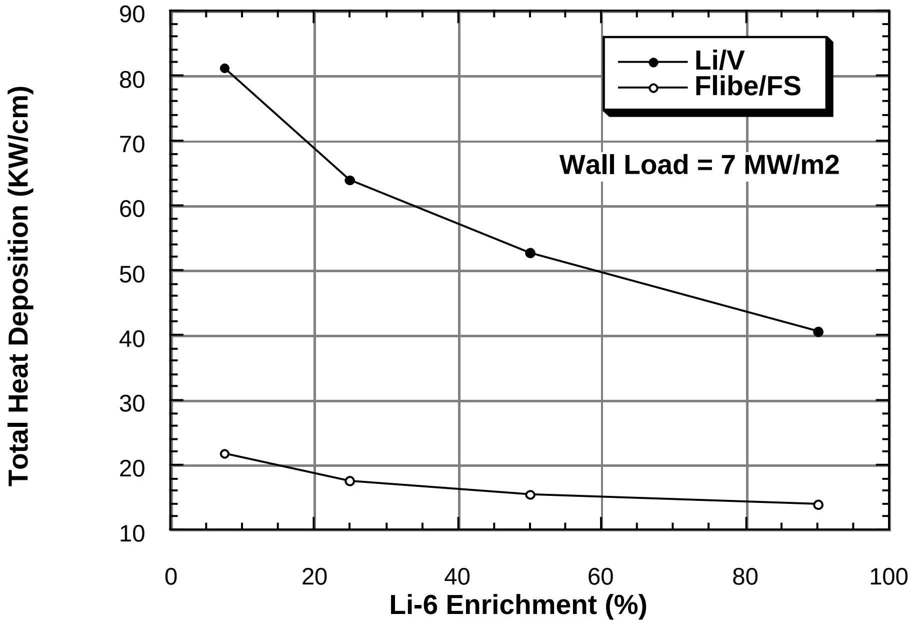
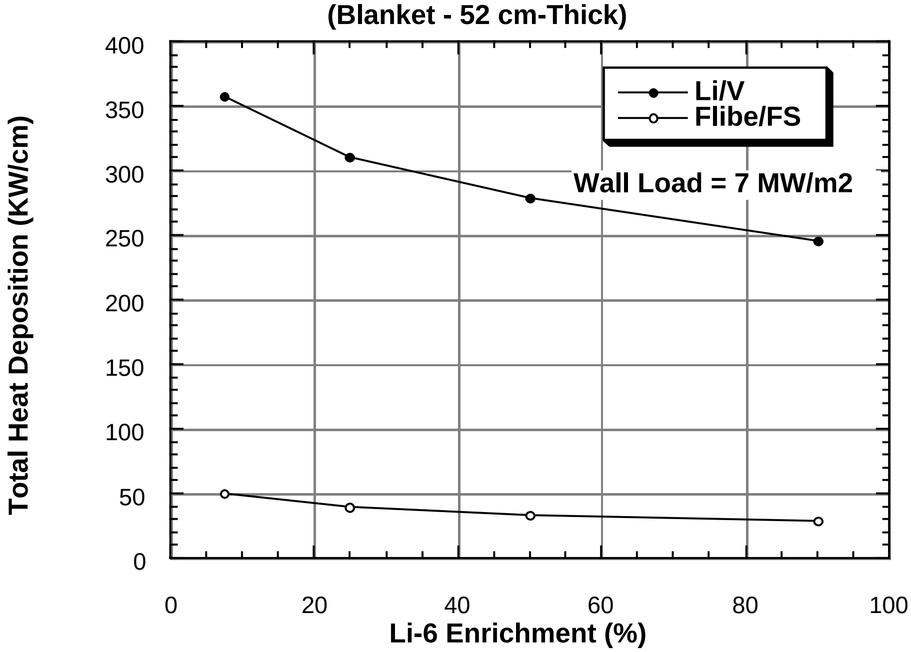


Fig. 11: Total Nuclear Heating per unit Hight (KW/cm)
Versus Li-6 Enrichment
(Blanket - 52 cm-Thick)



Figures 12 and 13 summarize the total heat deposited in the Convective layer, the inner wall of the V.V. and the blanket for the case of lithium layer and Flibe layer, respectively. While the total heat deposited in the Flibe layer is ~ 15% and ~ 3% larger than the deposited heat in the lithium layer at natural and 90% Li-6 enrichment, the heat deposited in the V.V. and the blanket is factor 7-8 lower than in the lithium layer case.

Fig. 12: Total Nuclear Heating per Unit height V.S. Li-6 Enrichment (Li/V Case - Wall Load = 7 MW/m2)

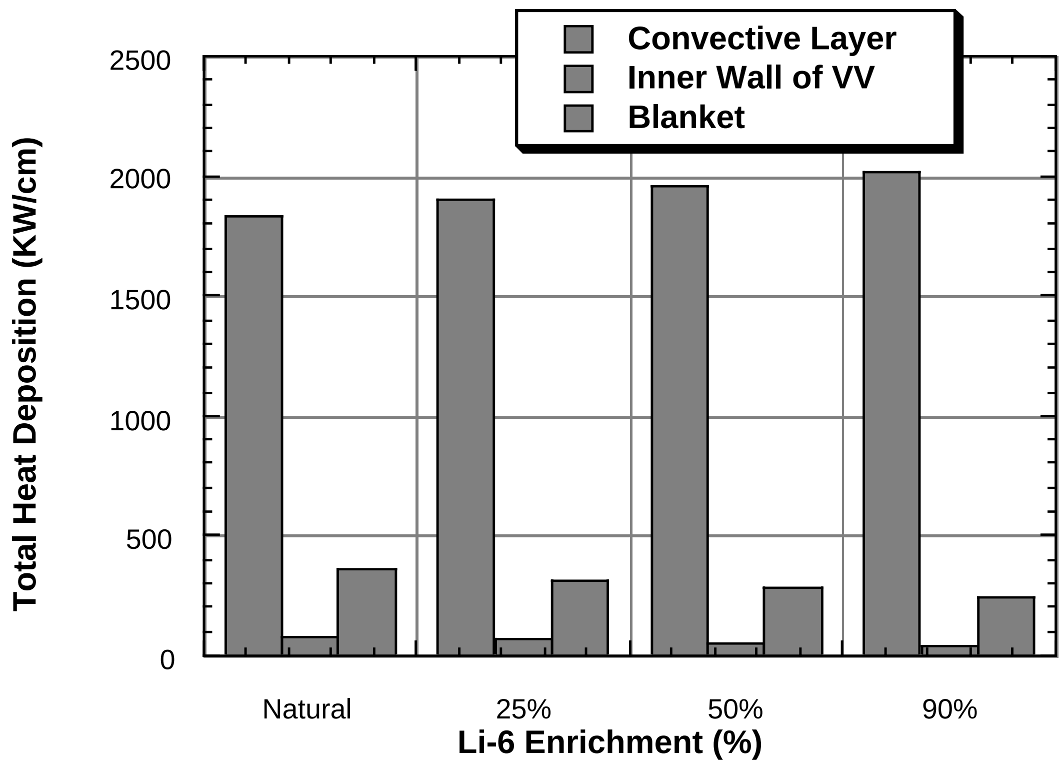


Fig. 13: Total Nuclear Heating per Unit height V.S. Li-6 Enrichment (Flibe/Ferritic Steel Case - Wall Load = 7 MW/m2)