Comparison of Liquid ISSECs

Li, Pb and Pb_4Li for Use in Laser Fusion Reactors; H.I. Avci and G.L. Kulcinski

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UWFDM-208

FUSION TECHNOLOGY INSTITUTE

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(Revised August 1977)

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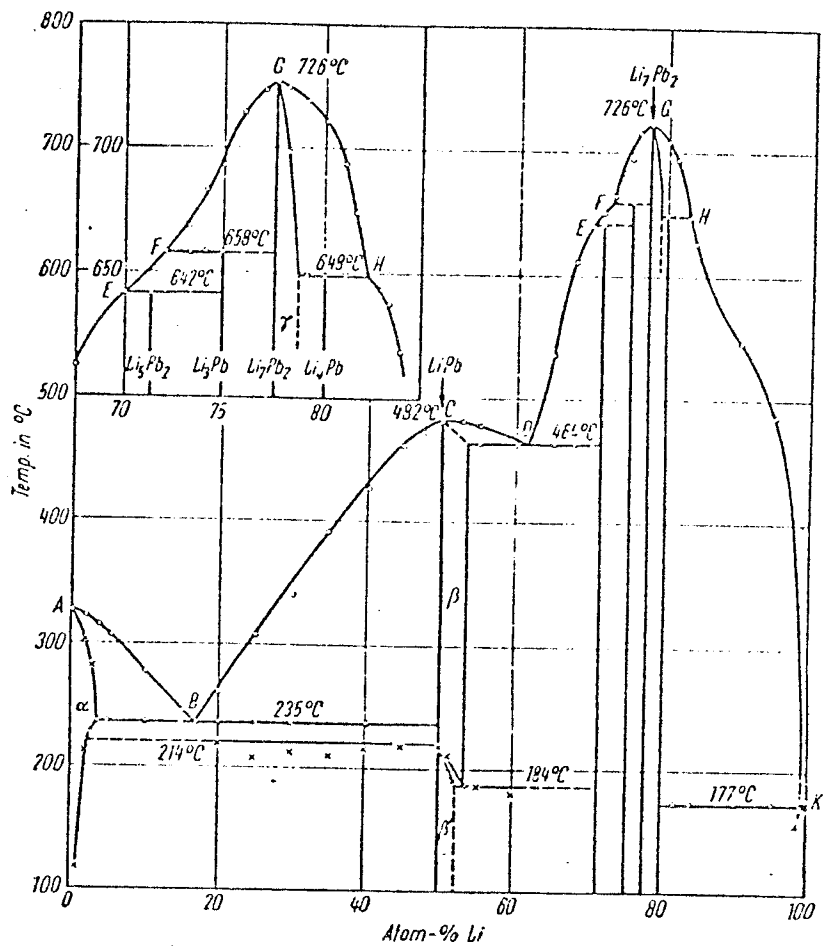
I.) Introduction

The idea of protecting the first walls of laser fusion reactors by a liquid lithium waterfall has been proposed by scientists at Lawrence Livermore Laboratory[1] and the consequences to the first wall studied in a recent University of Wisconsin report.[2] The concept involves a 'waterfall' of liquid Li (or Pb as suggested in reference 2) ranging in thickness from 0 to 100 cm dropping from the top of a laser fusion reactor to be collected at the bottom of the reaction chamber. The effectiveness of liquid ISSECs were assessed against the effectiveness of graphite or metallic ISSECs of previous studies,[3-6] and it was found that a liquid Pb ISSEC increases the total energy multiplication in the overall blanket, whereas, the breeding ratio is higher for a liquid Li ISSEC case.

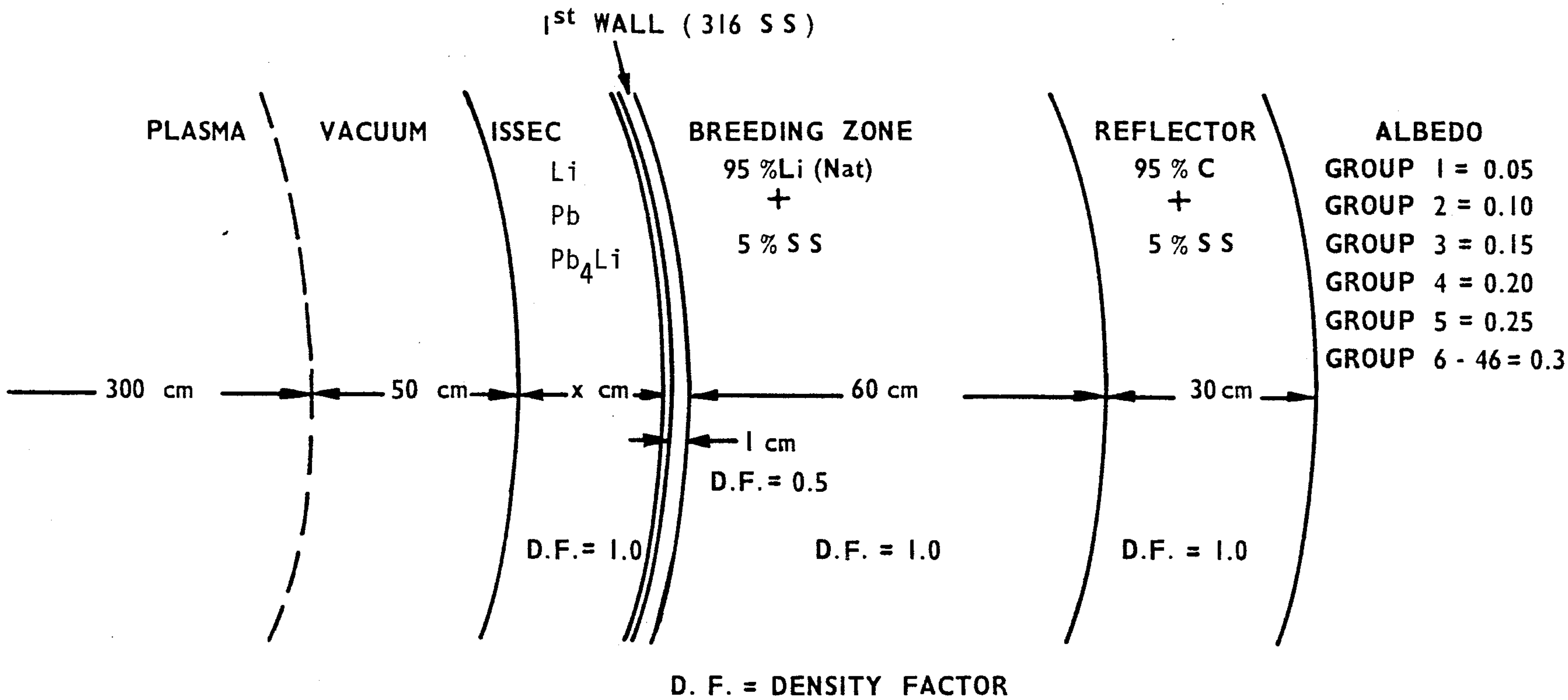
The purpose of this paper is to study the use of a lead-lithium compound as an ISSEC, utilizing both the high energy multiplication capability of lead and the high tritium breeding from lithium. The existence of a low temperature lead-lithium compound is evident from the Pb-Li phase diagram of Fig. I-1. There is a eutectic at 235°C which has the chemical composition of Pb_4Li. The effectiveness of Pb_4Li ISSEC will be compared to effectiveness of pure Li and Pb ISSEC cases. Since the calculational procedures and blanket geometry (Fig. I-2) are the same as for reference 2, they are not repeated here.



Pb-Li-Zustandsdiagramm.

Figure I-1

PHASE DIAGRAM FOR Pb-Li(7)



1 - DIMENSIONAL CYLINDRICAL BLANKET MODEL USED IN THIS STUDY

Figure I-2

II.) Results

The response of the first wall is analyzed with respect to three general categories:

A.) Damage parameters in the first 316 SS wall

B.) Overall breeding ratio

C.) Heat deposition profiles.

We will now consider each parameter separately.

A.) Damage Parameters

1.) Displacement damage

The effect of the various ISSEC thicknesses on the reduction in displacement damage in the 316 SS first structural wall is listed in Table II-1 and plotted in Fig. II-1.

The displacement damage after equal thicknesses of Li and Pb are roughly the same but for different reasons. The low moderating power of Li for high energy neutrons tends to maintain a rather hard neutron spectrum. Lead, on the other hand, is much more effective than Li in moderating high energy neutrons but its high (n,2n) and low absorption cross sections result in rather high flux of high energy (> 1 MeV) neutrons to the first wall. The net result is a coincidentally similar effect on the dpa rate with increasing ISSEC thickness. The addition of Li-6 to Pb counters the low absorption characteristics and hence the Pb_4Li alloy is even more effective than either Pb or Li by itself.

2.) Gas production

The reduction in the helium and hydrogen production rates with varying thicknesses of ISSEC are also given in Table II-1 and plotted for helium in Fig. II-2.

Table II-1

Summary of Radiation Damage in 316 SS First Wall Behind Various ISSECs

ISSEC Material	dpa/yr (1 MW/m^2)	Appm He/yr (1 MW/m^2)	Appm H/yr (1 MW/m^2)
None	10.1	218	470
	20 cm		
Li	5.4	82	210
Pb	4.8	14	37
Pb_4Li	4.0	13	35
	40 cm		
Li	2.8	32	96
Pb	2.6	1.8	5.4
Pb_4Li	1.6	1.5	4.4
	100 cm		
Li	0.5	2.0	10.5
Pb	0.4	0.004	0.4
Pb_4Li	0.1	0.002	0.012

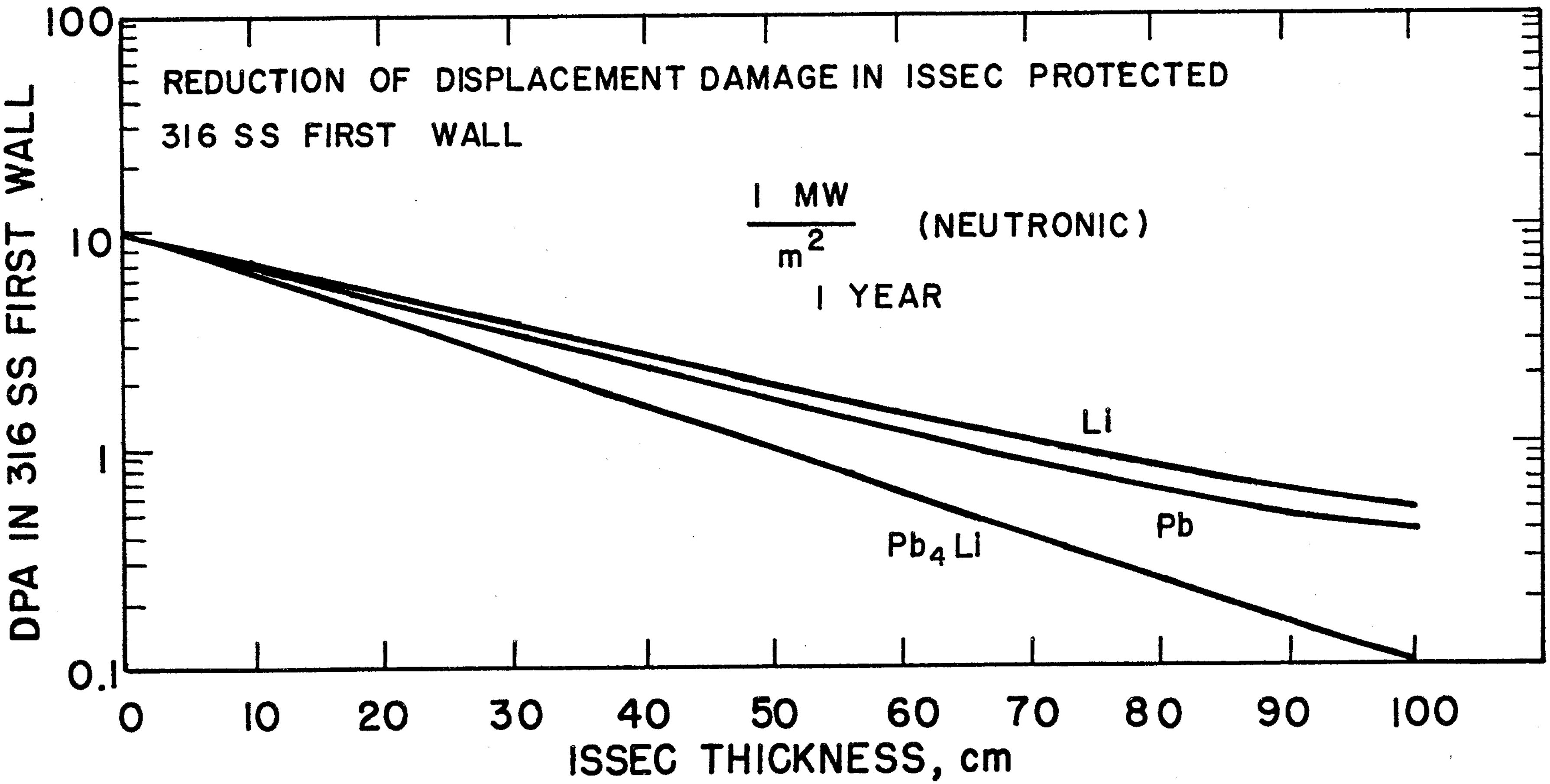
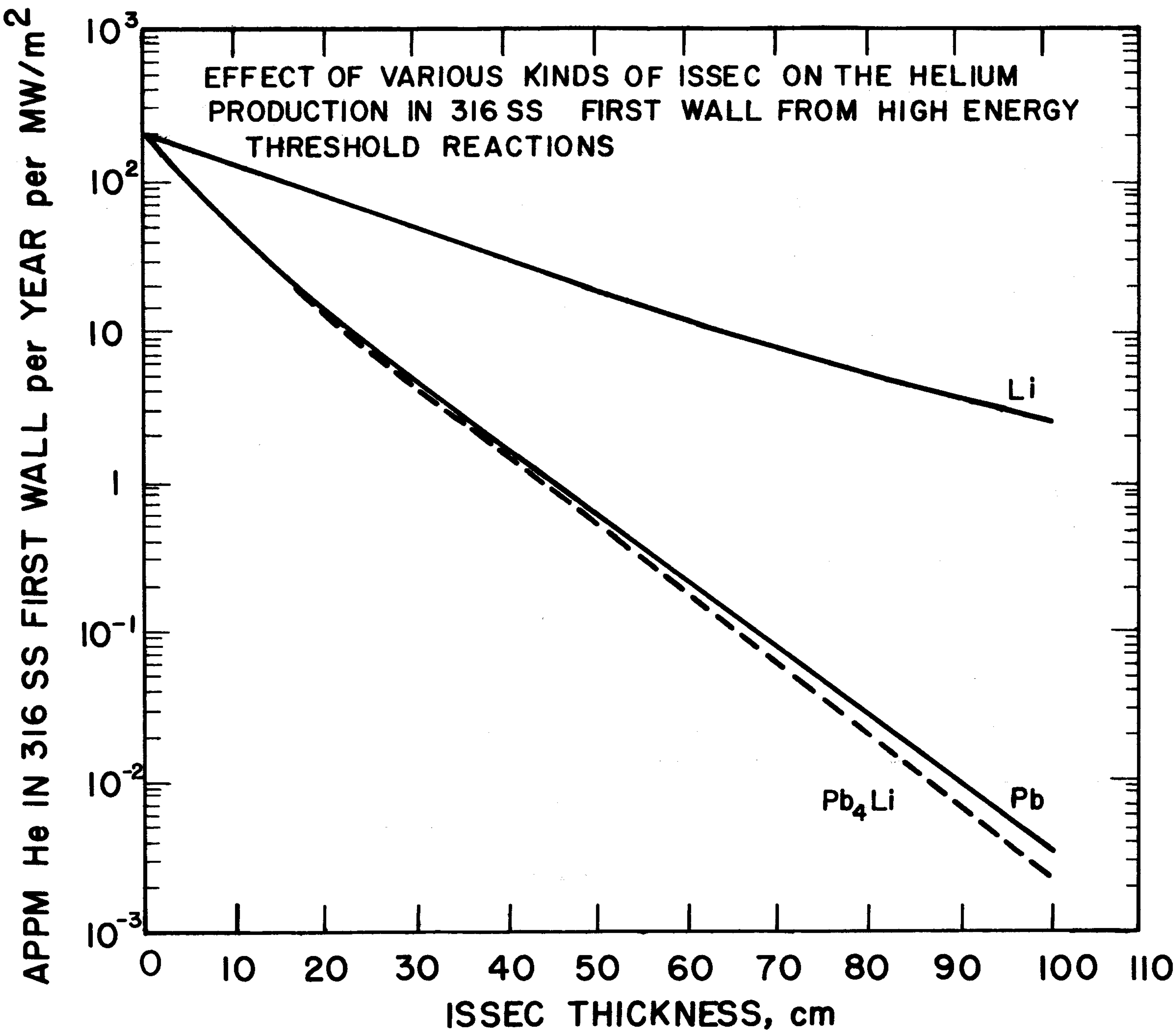

REDUCTION OF DISPLACEMENT DAMAGE IN ISSEC PROTECTED
316 SS FIRST WALL
1 MW / m2 (NEUTRONIC)
1 YEAR
Li
Pb
Pb4Li
DPA IN 316 SS FIRST WALL
100
10
1
0.1
0
10
20
30
40
50
60
70
80
90
100
ISSEC THICKNESS, cm

Figure II-1

Figure II-2


EFFECT OF VARIOUS KINDS OF ISSEC ON THE HELIUM
PRODUCTION IN 316 SS FIRST WALL FROM HIGH ENERGY
THRESHOLD REACTIONS
APPM He IN 316 SS FIRST WALL per YEAR per MW/m²
ISSEC THICKNESS, cm
Li
Pb
Pb₄Li
10³
10²
10
1
10⁻¹
10⁻²
10⁻³
0
10
20
30
40
50
60
70
80
90
100
110

Comparing Figures II-1 and II-2, one can see that the relative effectiveness of all three ISSECs is greater for reducing the helium generation rates in the first wall than it is for reducing displacements. The second thing to notice is that while both Pb and Li are essentially the same in reducing the displacement damage in the first wall, a Pb ISSEC reduces the helium production in 316 SS much more than does a Li ISSEC of the same thickness. The reason for this is that the energies of most of the neutrons coming from the (n,2n) reactions of Pb are below the threshold values for the (n,2n) reactions in steel. The effectiveness of the liquid Pb_4Li ISSEC in reducing the helium production in the 316 SS first wall is a little higher than that of pure Pb.

B. Breeding Ratio

Table II-2 lists the breeding in ISSEC and the blanket behind for various thicknesses of the three liquid ISSECs considered. Fig. II-3 shows the total breeding ratio in the system as a function of ISSEC thickness. Also shown in Fig. II-3 is the breeding in just the ISSEC for Li and Pb_4Li ISSEC cases. It can be seen from that figure that the overall breeding ratio initially increases in all three cases. It saturates in Li and Pb_4Li cases after about 30 cm of ISSEC thickness but it starts to decrease after about 30 cm of thickness in the case of Pb. The breeding ratio in just the ISSEC itself goes over 1.0 in Li and Pb_4Li ISSECs after about 30 and 50 cm thicknesses, respectively. The significance of this is that one can do all the breeding inside the reaction chamber with Li and Pb_4Li ISSECs and there is no need to breed tritium behind the first solid wall.

C. Energy Extraction

Total energy absorbed in the ISSEC plus the blanket per neutron born in DT is plotted in Fig. II-4 as a function of ISSEC thickness. The

Table II-2

Summary of Tritium Breeding Data in Liquid ISSEC Systems

ISSEC	Thickness cm	Tritium atom per incident neutron: Breeding in ISSEC	Breeding in Blanket	Overall Breeding Ratio
Li	0	---	1.50	1.50
	20	0.758	0.950	1.71
	40	1.177	0.645	1.82
	100	1.740	0.200	1.94
Pb	0	---	1.50	1.50
	20	---	1.68	1.68
	40	---	1.64	1.64
	100	---	0.92	0.92
Pb_4Li	0	---	1.50	1.50
	20	0.244	1.455	1.70
	40	0.740	0.990	1.73
	100	1.580	0.150	1.73

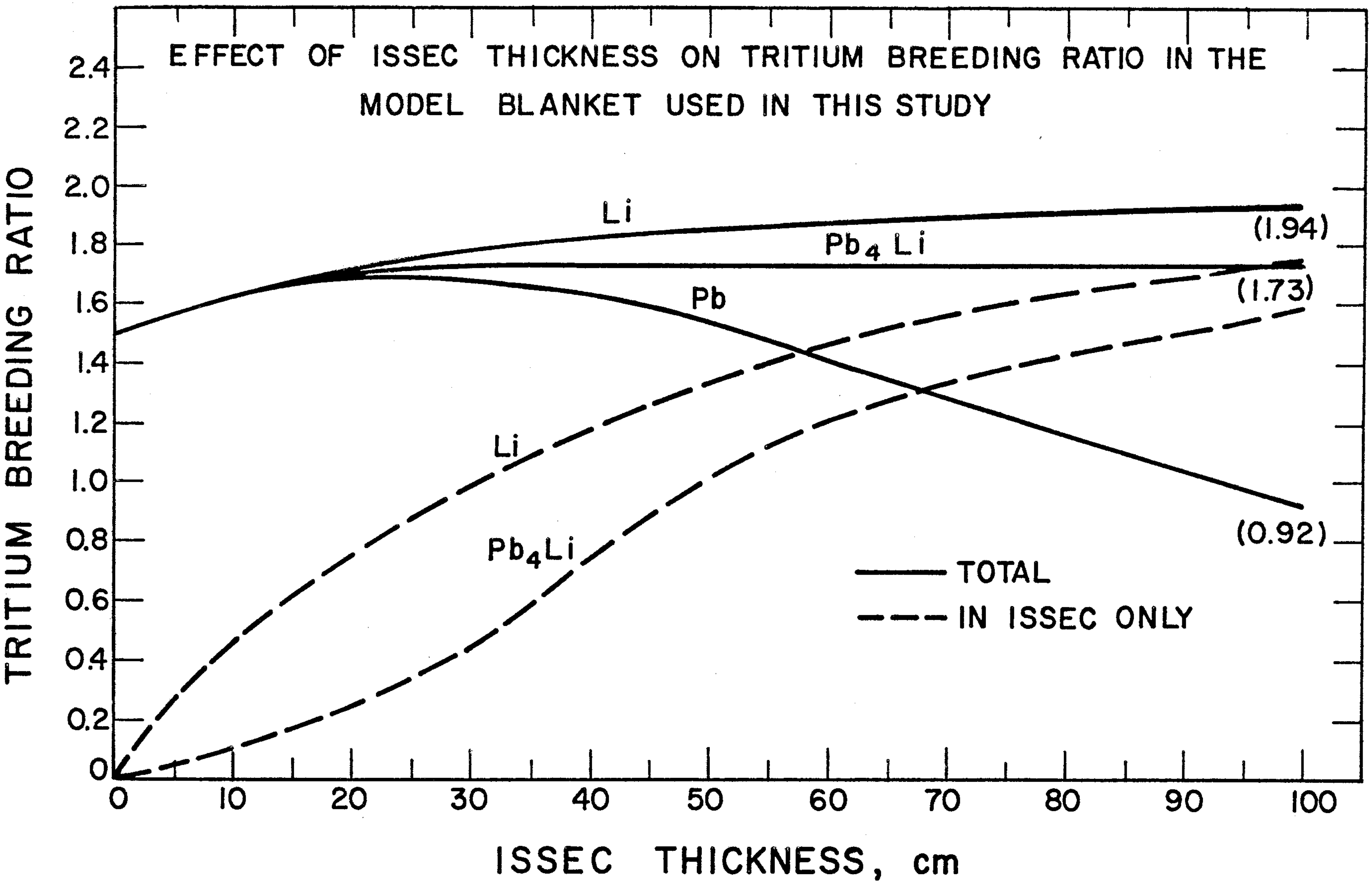

EFFECT OF ISSEC THICKNESS ON TRITIUM BREEDING RATIO IN THE
MODEL BLANKET USED IN THIS STUDY
TRITIUM BREEDING RATIO
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
Li
Pb4 Li
Pb
Li
Pb4Li
(1.94)
(1.73)
(0.92)
TOTAL
IN ISSEC ONLY
0
10
20
30
40
50
60
70
80
90
100
ISSEC THICKNESS, cm

Figure II-3

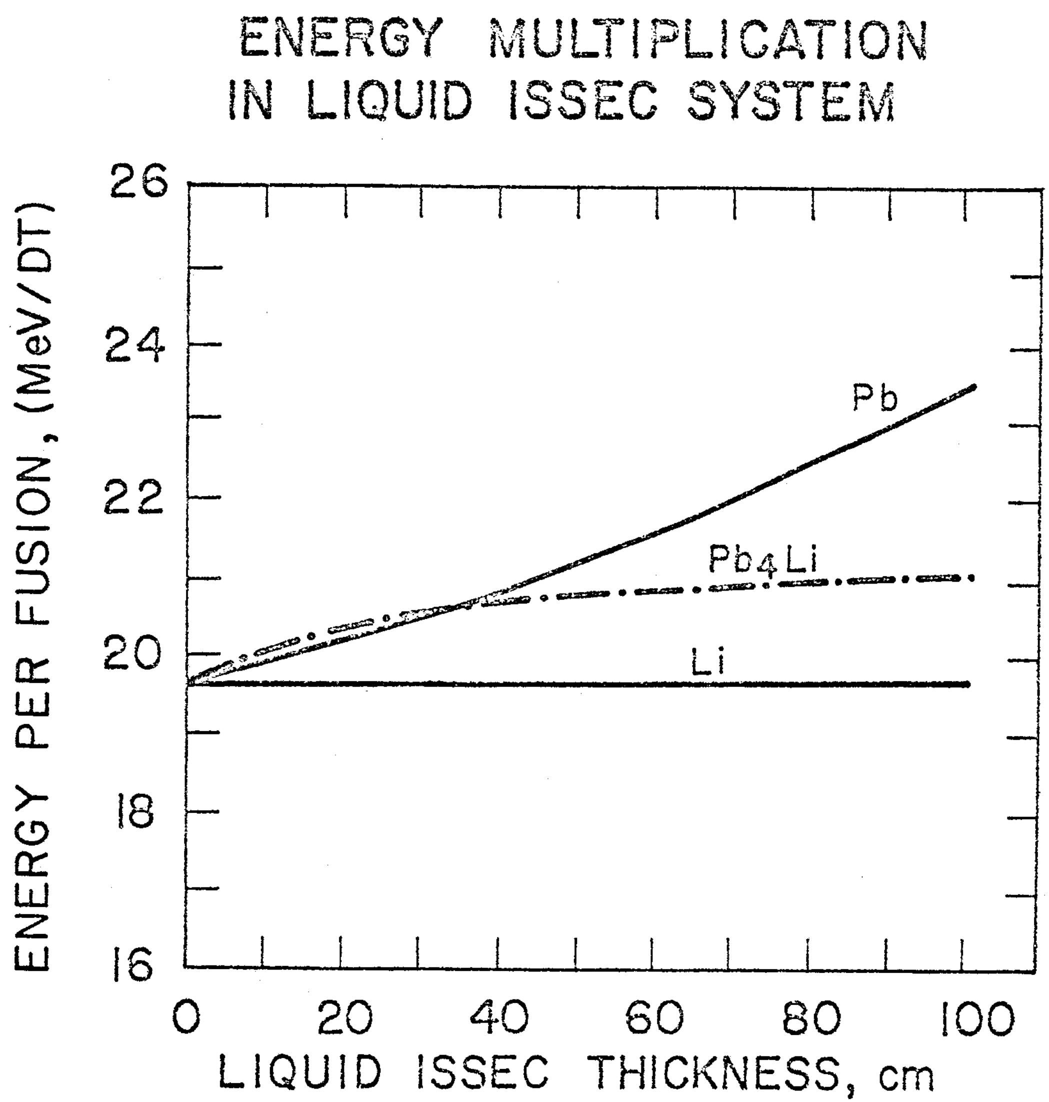

ENERGY MULTIPLICATION
IN LIQUID ISSEC SYSTEM
ENERGY PER FUSION, (MeV/DT)
26
24
22
20
18
16
0
20
40
60
80
100
LIQUID ISSEC THICKNESS, cm
Pb
Pb4 Li
Li

Figure II-4

total heating in the blanket without any ISSEC protection is 19.6 MeV/n, and it stays surprisingly constant as the thickness of the Li ISSEC is increased. On the other hand, the total heating in the Pb_4Li ISSEC system initially shows a large increase, but after about 30 cm thickness, it levels off at ~21.0 MeV/n, a value in between that of pure Li and Pb.

The fraction of heat absorbed in the liquid ISSEC (including charged particles) is plotted in Fig. II-5, and it shows that for thickness of 20-30 cm, the ISSEC zone will generate > 50% of the heat. The fraction of heat collected in ISSEC is always greater with Pb_4Li ISSEC than with pure Li and Pb. Ninety (90) percent of heat in a liquid Pb_4Li ISSEC system is deposited in about 77 cm of ISSEC and only 2% of the total heat is left for the blanket behind a 100 cm liquid Pb_4Li zone. Proportionately less energy is absorbed in the Pb ISSEC because of the breeding behind the first wall. About 20% of the total heat generated in that system remains to be collected in the blanket even after a 100 cm thick ISSEC zone.

The absolute amount of heat deposited in Pb_4Li ISSEC is also always greater than both in Pb and Li. At 50 cm thickness, for example, the amount of heat absorbed in the ISSEC is 16.0 MeV/n for Pb_4Li, 15.2 MeV/n for Li, and 12.8 MeV/n for Pb. At 90 cm ISSEC thickness 17.6 MeV/n is deposited in both Li and Pb ISSECs but the amount of heat absorbed in Pb_4Li ISSEC is 19.8 MeV/n. At 100 cm thickness the amount of energy deposited in ISSEC per neutron born in DT plasma is 20.6 MeV for Pb_4Li, 18.8 MeV for Pb and 18.1 MeV for Li.

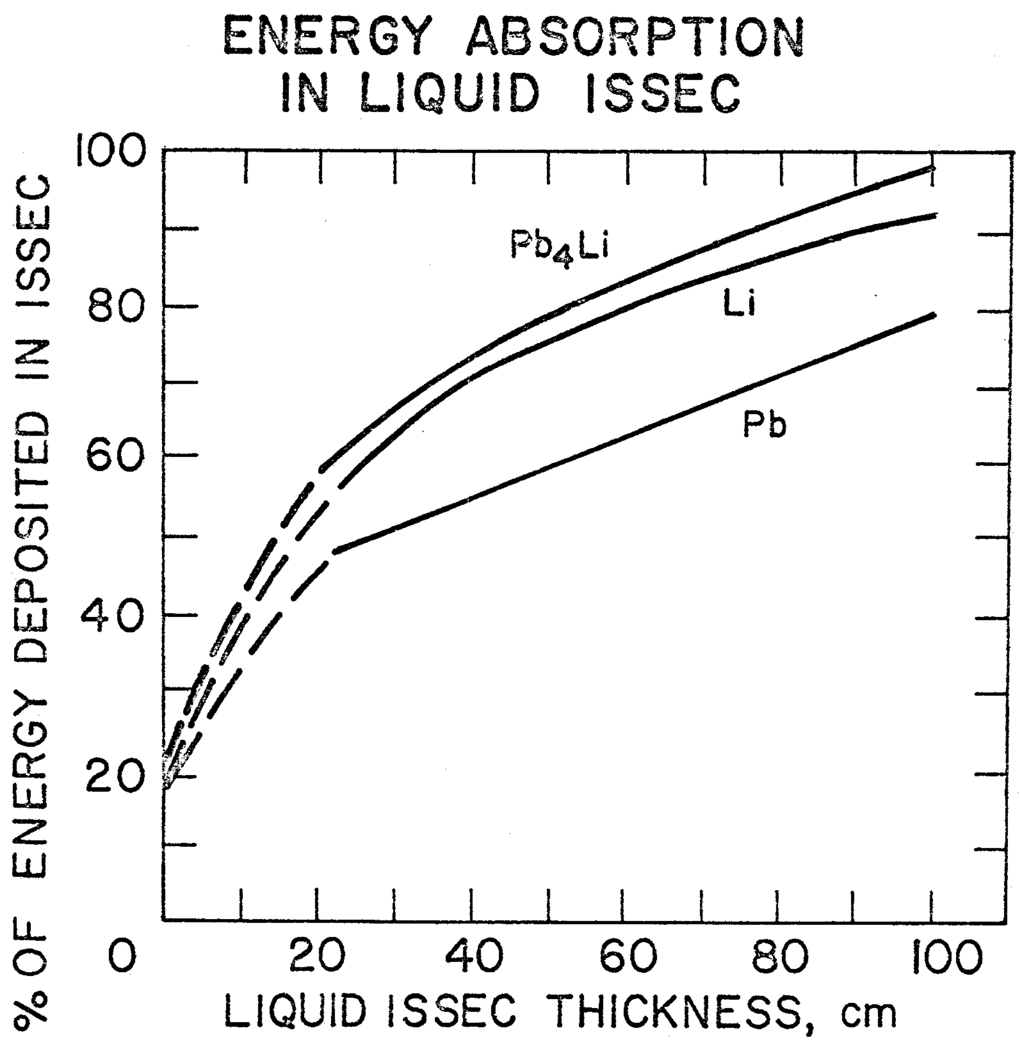

ENERGY ABSORPTION
IN LIQUID ISSEC
% OF ENERGY DEPOSITED IN ISSEC
0
20
40
60
80
100
LIQUID ISSEC THICKNESS, cm
Pb4Li
Li
Pb

Figure II-5

III.) Discussion

The estimated criteria for failure of a 316 SS first wall in a fusion reactor at three different temperatures (300°C, 500°C, and 600°C) were discussed in a previous report[2] and repeated in Table III-1. Assuming that we desire to have "permanent" first wall for 30 years of operation at a nominal wall loading of 5 MW/m^2 and a plant factor of 70%, we can use the information in Tables III-1 and II-1, and Figures II-1 and II-2 to estimate the required ISSEC thickness. The necessary ISSEC thickness is given in Table III-2. Taking the higher value of the two thicknesses associated with each ISSEC material at each first wall temperature in Table III-2 as the design limit, we list in Table III-3 what the other system parameters would be for that thickness of an ISSEC.

The required ISSEC thickness to reduce the dpa level to value desired at end of life (Table III-1) falls in the general range of 45-75 cm for Li and Pb and 35-50 cm for Pb_4Li. The requirements from the helium generation levels are generally more severe for Li and it is found that the ISSEC thickness must be much greater than 1 meter and probably on the order of 2 meters for 600° operation. At all three first wall temperatures and from both the dpa and appm He considerations, the required ISSEC thickness to extend the first wall lifetime to 30 years at 5 MW/m^2 wall loading at 70% plant factor is less for a Pb_4Li ISSEC than it is for Li ISSEC. From the displacement damage point of view, less thickness of Pb_4Li is required for full lifetime operation than for pure Pb, but from the helium production point of view the required ISSEC thickness is about the same for both materials.

It appears from Tables III-2 and III-3 that the main advantage of a pure Li ISSEC system is its high breeding ratio. Although all three systems have quite adequate overall breeding, only Li ISSEC shows an internal breeding ratio

Table III-1

Estimate of Damage Limitations in 316 SS Irradiated in a Fusion Neutron Spectrum

	Design Limit	
Temperature °C	dpa	appm He
300	200*	4000
500	150*	500*
600	100	10*

* Limiting Parameter

Table III-2

Summary of Liquid Metal ISSEC Thickness Required to Extend 316 SS First Wall Life to Reactor Life[a]

Temperature °C	Li		Pb		Pb_4Li	
	Required ISSEC Thickness-cm					
	dpa	He	dpa	He	dpa	He
300	52	37	47	12	37	12
500	58	~85	52	30	41	30
600	74	~200	67	67	50	65

(a) 5 MW/m^2 at 70% P.F. for 30 years. (1060 dpa, 22,900 appm He accumulated for an unprotected wall).

Table III-3

Summary of Necessary Liquid ISSEC Thicknesses Required to Extend Useful Lifetime of 316 SS to 30 Years at 70% P.F. and 5 MW/m^2 Wall Loading

System Parameters

Temperature °C	Thickness cm	dpa/yr	Appm He/yr	$B.R.^T$	$B.R.^I$	MeV/n	% Energy in ISSEC
			Lithium				
300	52	6.67*	63	1.9	1.36	19.7	77
500	85	2.4	16.7*	1.9	1.66	19.7	89
600	~200	~0.02	~0.33*	~2	~2	19.7	~100
			Lead				
300	47	6.67*	2.8	1.58	---	21.0	59
500	52	5.0*	1.8	1.50	---	21.3	61
600	67	3.3*	0.33*	1.34	---	22.2	67
			Pb_4Li				
300	37	6.67*	7.0	1.73	0.62	20.6	71
500	41	5.0*	4.55	1.73	0.68	20.7	73
600	65	1.85	0.33*	1.73	1.24	20.8	85

*Design Limit

$B.R.^T$ --- Total Breeding ratio in system

$B.R.^I$ --- Breeding ratio in ISSEC only greater than one at ISSEC thicknesses less than 50 cm. If an ISSEC thickness of more than 50 cm is required, Pb_4Li is clearly superior to both Li and Pb in that it has higher percentage of heat deposited in ISSEC, it can breed internal to the first structural wall and with 65 cm thickness the first wall can run at any temperature less than 600°C and still meet its design criteria for a full lifetime operation.

There is an ISSEC thickness above which it probably makes no sense to run the first wall hot because there is very little heat to collect. For example it is entirely conceivable that one could collect the last 10% of the energy at 300°C and not suffer very greatly on overall efficiency. This could especially be true if the ISSEC increased the overall heating rate in the system as does Pb and Pb_4Li ISSECs. The limit at which 90% of total heat is deposited inside ISSEC is ~90 cm for Li, ~120 cm for Pb and ~77 cm for Pb_4Li.

The concept of 'cold' first walls and blankets has a great attractiveness because it would significantly reduce the complexity of the reactor design and perhaps even the tritium leakage.

One final point is worth noting about the ratio of helium production to displacement damage. The characteristic values for a fast fission reactor (EBR-II), a LWR (HFIR), a bare wall, and various thicknesses of Li, Pb, and Pb_4Li ISSECs are given in Table III-4.

It can be seen that whereas the helium to dpa ratio is very high in an unprotected first wall, it is very low in a fast fission reactor. This unfavorable ratio has been responsible for the lack of interest in using these facilities for test beds. On the other hand, placing approximately 68 cm of Pb or 75 cm of Pb_4Li in front of the first wall reduces that ratio to a value commensurate with the fast reactor. If the materials scientists knew that the first walls

Table III-4

Ratio of Helium Production to Displacement Damage in ISSEC System

ISSEC	Thickness-cm	Appm He/dpa in 316 SS
Li	20	15
	40	11
	100	4
Pb	20	2.9
	40	0.7
	68	0.1
	100	0.01
Pb_4Li	20	3.3
	40	0.94
	75	0.1
	100	0.02
Fusion	0	20
EBR-II	-	0.1
HFIR	-	~100

would experience such low ratios of gas to displacement damage in ISSEC protected fusion reactors, they could take advantage of the information generated in the fast reactor program and thereby save a lot of time and money for future design analysis.

IV.) Conclusions

It has been shown that either a 45-75 cm thick liquid, Li or Pb ISSEC or a 35-50 cm Pb_4Li ISSEC can reduce the displacement damage in the 316 SS first structural wall to such levels as to allow it to achieve a 'permanent' lifetime (~100 MW-yr/m^2) in a laser fusion reactor. Pb and Pb_4Li ISSECs are much more effective in reducing the helium production in the first wall than Li. The Pb ISSEC is the most effective in increasing the energy multiplication in the blanket, but Pb_4Li ISSEC has the highest percentage of heat deposited in the liquid ISSEC region.

Conclusions regarding each of the ISSEC materials considered are listed below separately:

Li:

---High breeding ratio, both overall and internal

---Least effective in reducing the helium production rates in the 316 SS first wall; therefore suitable for low temperature operation only

Pb:

---Increases the thermal output of the system by increased energy multiplication

---Effective in reducing the helium production in the 316 SS first wall

---Does not allow breeding internal to the first structural wall

---Double heat extraction scheme is required; both from the ISSEC and from the blanket behind the first wall

Pb_4Li:

---Increases the thermal output

---Effective in reducing the helium generation in the 316 SS first wall

---Most effective in reducing the displacement damage in the first wall

---For thicknesses greater than 50 cm breeding internal to the first wall is possible

---For the same thickness both the percentage and the absolute amount of heat deposited in ISSEC is highest

An overall conclusion to be obtained from this study is that the liquid ISSEC material that has the best overall characteristics is Pb_4Li and the thickness to be used is 50 to 75 cm.

Acknowledgement

This research was supported by a grant from the Energy Research and Development Administration, Division of Laser Fusion Energy, under Contract ES-77-S-02-4296.

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