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The Development of Sn-Li Coolant/Breeding Material for APEX/ALPS Applications

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ABSTRACT

A Sn-Li alloy has been identified to be a coolant/breeding material for D-T fusion applications. The key feature of this material is its very low vapor pressure, which will be very useful for free surface concepts employed in APEX, ALPS and inertial confinement fusion. The vapor is dominated by lithium, which has very low Z. Initial assessment of the material indicates acceptable tritium breeding capability, high thermal conductivity, expected low tritium solubility, and expected low chemical reactivities with water and air. Some key concerns are the high activation and material compatibility issues. The initial assessment of this material, for fusion applications, is presented in this paper.

I. INTRODUCTION

The APEX (Advanced Power Extraction)(1) and ALPS (Advanced Limiter-divertor Plasma-facing Systems)(2) are two new programs in the U.S. to investigate the possibility of handling very high wall loading by the blanket (APEX) and the divertor (ALPS) regimes. The ability to handle high heat flux and high neutron wall loading can reduce the size and cost of the nuclear island and increase the attractiveness

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of fusion. The other requirements of fusion, such as tritium breeding, reliability, safety and efficient power conversion also have to be satisfied.

One approach for handling high wall loading is to have the coolant directly facing the plasma. Such a system will reduce concerns associated with a solid first wall, and remove the resistance to heat transfer by a solid first wall. Material sputtering is not life limiting for a liquid wall. While we are assessing the possible effect of material evaporation to the plasma performance, we are also developing concepts to minimize the evaporation rate.

The Sn-Li alloy has been identified for such application. The vapor pressure of Sn-Li is about a factor of 1000 lower than that of lithium at the same temperature.(3) Also, the vapor pressure is dominated by lithium. With the same vapor pressure, the allowable Sn-Li temperature is about 200°C higher than that of lithium. This higher allowable temperature significantly enlarges the design window of Sn-Li, compared to that of pure lithium. Also, the coolant exit temperature of the Sn-Li blanket can be much higher than that for the lithium blanket, resulting in a higher thermal conversion efficiency.

A key issue is to determine a structural material that will be compatible to Sn-Li at high temperature. Both Fe-based and Ni-based alloys will probably not be compatible with Sn-Li. However, Nb is reported to be compatible to Sn up to 850°C.(4) Since V is so metallurgically similar to Nb, there is some possibility that V will be compatible to Sn-Li, maybe to a lower temperature than 850°C. Also, many nonmetals, such as graphite, are reported to be compatible with Sn, up to 1000°C.(4) Therefore, there is some possibility that SiC maybe compatible to Sn-Li. Some material compatibility screen tests will be required to determine which structural materials can be used with Sn-Li at high temperature. Some effort at ANL is underway to produce Sn-Li that can be distributed to researchers interested in investigating Sn-Li.

II. PHASE DIAGRAM

Figure 1 shows the phase diagram of Sn-Li.[5] To have a low Sn-Li vapor pressure, and low lithium chemical activity, the mole fraction of lithium has to be as low as possible. However, to increase tritium breeding ratio, the lithium mole fraction has to be as high as possible. Also, the melting temperature of Sn-Li has to be reasonable. With all these considerations, the lithium mole fraction is selected to be 20 to 25%, with 25% as the reference value. The melting temperature of Sn75-Li25 is 599K.

III. Sn-Li VAPOR PRESSURE

Three separate measurements of Sn-Li vapor pressure have been found in the literature.[3,6,7] The most detailed results can be found in Reference 3. This experiment was carried out at 1200°C, which is beyond the temperature of interest for fusion. Table 1 summarizes the experimental results from Reference 3. The following conclusions can be derived from this table:

1. With lithium atom fraction of 0.25, the lithium vapor pressure is about 1 torr at 1200°C. This lithium vapor pressure is about a factor of 1000 lower than the pure lithium vapor pressure at the same temperature.
2. The chemical activity of lithium is very low. Due to the low chemical activity, it can be expected that the tritium solubility and chemical reactivities with air and water will be very low. This is very similar to the case of Pb-Li.

3. The activity of tin is about 0.7. Therefore, the tin vapor pressure is about 70% of the vapor pressure of pure tin. Since the vapor pressure of tin is so low, the vapor pressure is dominated by lithium. This is very different to the case of Pb-Li, whose vapor pressure is dominated by Pb.

Figure 2 summarizes the vapor pressure measurement results from the three references. Again, the Sn-Li vapor pressure is about a factor of 1000 lower than pure lithium at temperatures as low as 800K.

IV. LITHIUM CHEMICAL REACTIVITY

As seen from Table 1, the activity of lithium in Sn-Li is very low. Based on similar information from Pb-Li, it can be expected that the chemical reactivities between Sn-Li and air/water will be rather low. Also, similar to Pb-Li, Sn will act as heat sink for the heat of reaction generated when there is Li reaction with air or water.

An experimental program has been initiated at University of Wisconsin to assess the chemical reactivities, as well as pressure and temperature changes, between Sn-Li and air/water.

V. TRITIUM SOLUBILITY

Since the low chemical activity of lithium in Sn-Li, the tritium solubility in Sn-Li, from the effect of lithium is expected to be low. Sn has much higher tritium solubility than Pb and, therefore, will dominate tritium solubility in Sn-Li. With no tritium solubility in Sn-Li information available, it is recommended that we assume that the tritium solubility in Sn-Li is the same as the tritium solubility in Sn. The Sivert's constant of hydrogen solubility in Sn is 3 appm H in metal/torr$^{1/2}$.

VI. MATERIAL COMPATIBILITY

Table 2 shows results from static corrosion experiments between Sn and different structural materials.[4] It is clear that the only structural materials which maybe compatible with Sn at fusion relevant temperatures are refractory metals and nonmetals. An interesting observation is that Nb is compatible with Sn up to 850°C. There is no data between V and Sn. But since V is so similar to Nb, there is some possibility that V can be compatible with Sn. Most nonmetals tested are reported to be compatible with Sn to high temperature.

There are no experimental results from Sn-Li and structural material compatibility tests. The only indication is that Reference 3 used Ta as the material for the crucible for the vaper pressure measurement. Therefore, it can be implied that Ta is compatible to Sn-Li up to 1200°C.

VII. THERMOPHYSICAL PROPERTIES

The thermophysical properties for Sn-Li have not been measured. The material properties for Sn can be used for the time being for Sn-Li. Table 3 shows the material properties for lithium, Sn and Pb.[5]

VIII. TRITIUM BREEDING

A 1-D tritium breeding calculations has been done to estimate the tritium breeding capability of a Sn-Li blanket (9). The (n,2n) cross section of Sn is similar to that of Pb, but the capture cross section is larger. Therefore, the breeding capability of Sn-Li is not as high as that of Pb-Li. It is judged that the tritium breeding is marginal. A detailed 3-D calculation needs to be done to include the detailed design of the blanket. If additional breeding is required, a thin layer of Be can be added to assure sufficient breeding. The calculated results of tritium breeding are shown on Figure 3. The Sn-Li breeding capability is compared to that of Pb-Li in the same figure.

IX. CONCLUSIONS

A new breeding material for D-T fusion has been proposed. The key advantage of this new breeding material is the very low vapor pressure, which is dominated by lithium. Therefore, this material is well suited for open channel applications such as APEX, ALPS, and inertial confined fusion. It is expected to have low chemical reactivties with air and water, and have moderately low tritium solubility. Recent experimental results show it has excellent thermal conductivity.

The tritium breeding capability is marginal for a conventional blanket. Detailed tritium breeding calculations are being done to resolve this issue. Also, safety assessment is being done to assess the activation due to the Sn, and its impact on safety.

Some preliminary experimental work has been planed in the US, which include Sn-Li preparation, sputtering measurements, chemical reactivities with air and water, vapor pressure measurement, as well as small scale experiments on the material capability tests.

X. REFERENCES

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Table 1. Experimental Data for Lithium and Calculated Results for Tin in Lithium-Tin System at 1200°C

Atom Fraction Lithium in Liquid	Total Lithium Vapor Pressure, torr	Monatomic Lithium Vapor Pressure, torr	Activity of Lithium	Activity Coeff of Lithium	Activity Coeff of Tin	Activity of Tin
0.100	0.266	0.266	1.09×10^{-3}	0.0109	0.994	0.895
0.200	0.705	0.705	2.89×10^{-3}	0.0144	0.947	0.758
0.296	1.62	1.62	6.63×10^{-3}	0.0233	0.817	0.574
0.300	2.41	2.41	9.87×10^{-3}	0.0328	0.695	0.486
0.400	4.84	4.83	0.0198	0.0496	0.553	0.332
0.500	9.2	9.2	0.0377	0.0754	0.388	0.194
0.600	19.1	18.9	0.0775	0.129	0.195	0.0780
0.700	46.2	45.3	0.186	0.266	0.0517	0.0155
0.800	90.0	86.6	0.354	0.442	0.0108	0.00216
0.900	195	180	0.739	0.821	2.57×10^{-4}	2.57×10^{-5}

Table 2. The Static-Corrosion Resistance of Materials to Liquid Tin

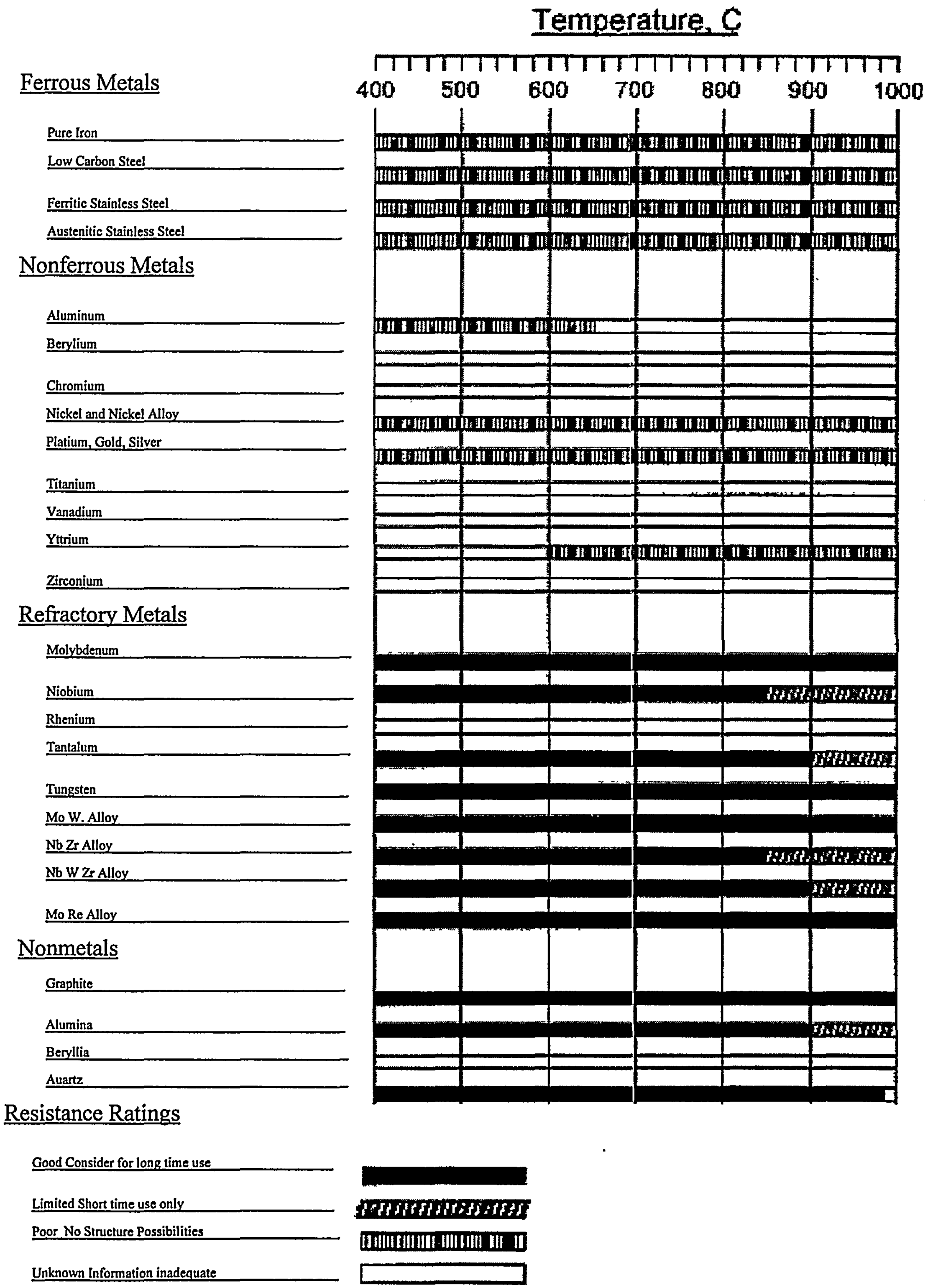

Table 3. Material Properties for Lithium, Pb and Sn

	Sn	Pb	Li
Temperature at P=1 Torr,C	1492	987	745
Density, Kg/m3	6800	10400	500
Heat capacity, kj/kg-C	0.32	0.16	4.2
K, kw/m-C	0.034*	0.016	0.038
Viscosity, cp	1.2	2.0	0.5
Elec. Resis. Mic-ohms /cm	60	100	50

*Thermal conductivity of Sn-Li is recently reported to be 0.05 kw/m-C (8).

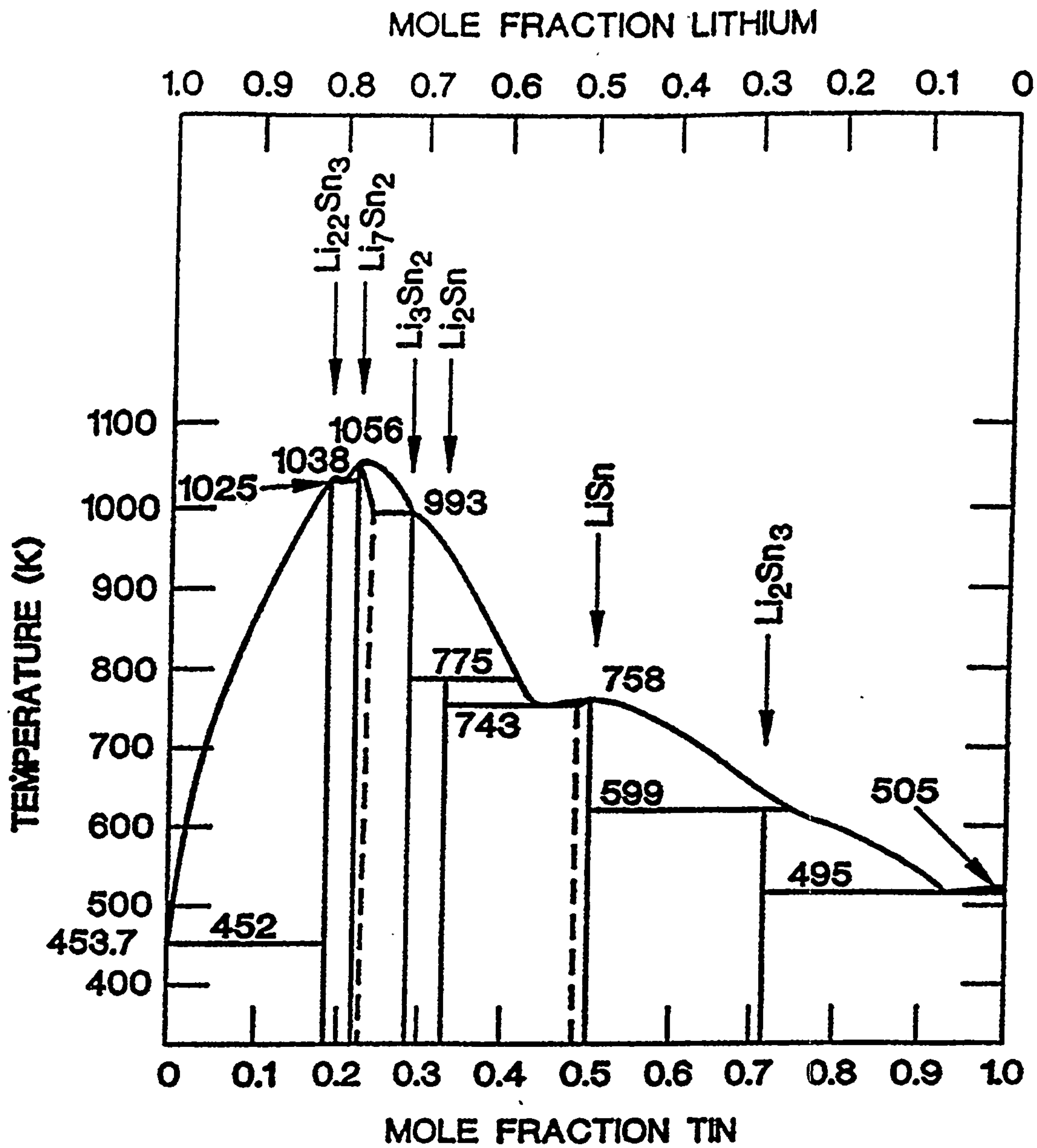

Figure 1. Sn-Li Phase Diagram

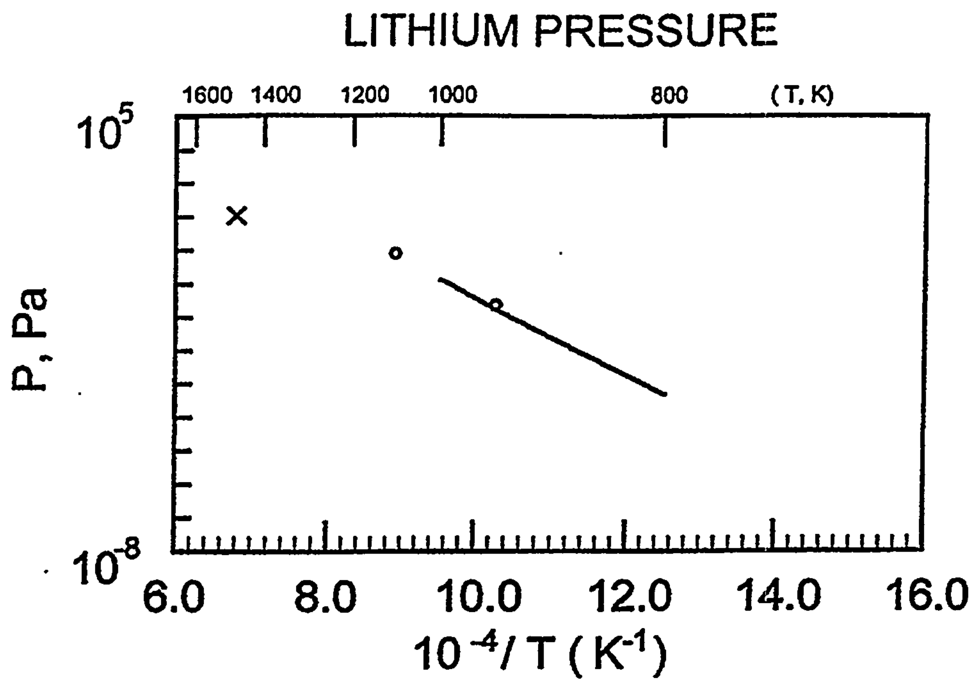

Figure 2. Lithium Vapor Pressure Over 75 Sn-25 Li

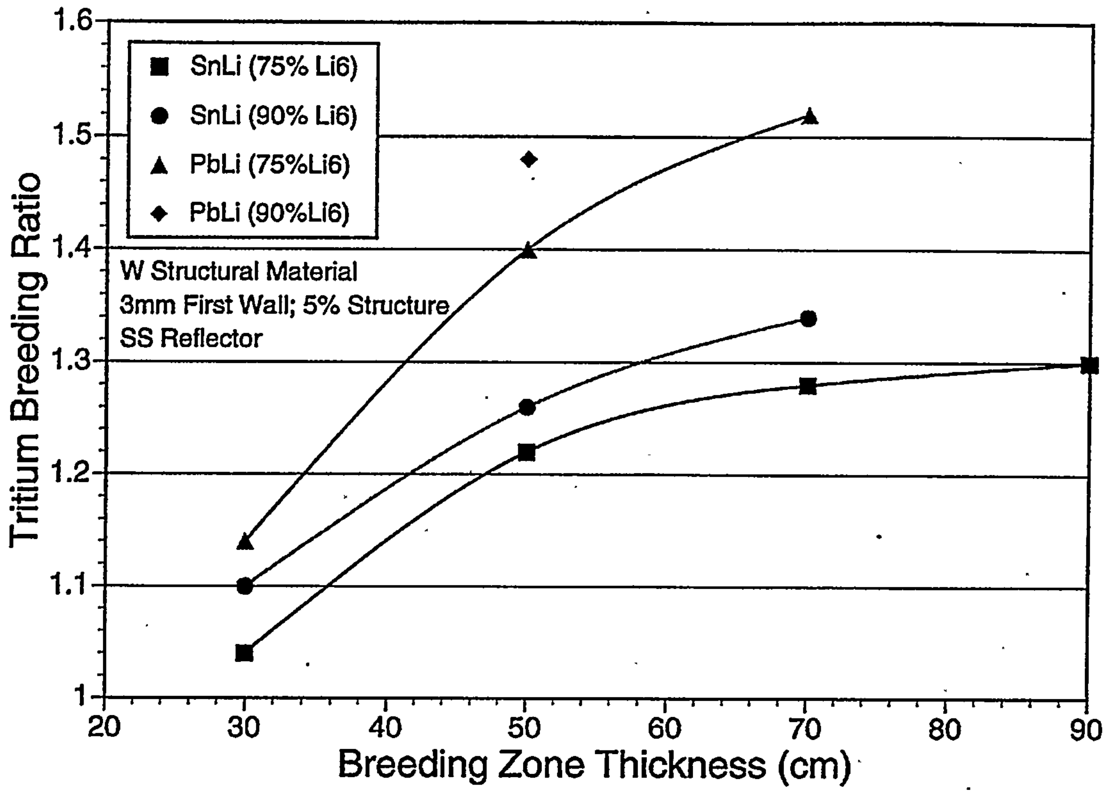

Figure 3. Tritium Breeding in SnLi and PbLi Blankets