

CHAPTER 8: DATA BASE FOR LIQUID BREEDERS AND COOLANTS

Contributors

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8. DATA BASE FOR LIQUID BREEDERS AND COOLANTS**8.1 Liquid Breeders Properties (Li, PbLi, Flibe)**

The following figures and data sheets summarize the properties of liquid lithium, lead-lithium (Pb-17%Li), and $(\text{LiF})_n \cdot \text{BeF}_2$ (Flibe) coolants. The vapor pressure of Pb-Li was taken to be equal to that of pure Pb, due to the low activity of Li in Pb-17Li. The surface tension of Pb-Li was estimated using the procedure outlined by Buxbaum.

8.1.2 Physical Properties of Molten Natural Li

(temperature in degrees Kelvin)-Valid for $T = 455\text{-}1500$ K.

Melting Temperature: 454 K

Density [1]

$$\rho \text{ (kg/m}^3\text{)} = 278.5 - 0.04657 \cdot T + 274.6 (1-T/3500)^{0.467}$$

Specific heat [1; see also 2]

$$C_p \text{ (J/kg-K)} = 4754 - 0.925 \cdot T + 2.91 \times 10^{-4} \cdot T^2$$

Thermal conductivity [1]

$$K_{th} \text{ (W/m-K)} = 22.28 + 0.0500 \cdot T - 1.243 \times 10^{-5} \cdot T^2$$

Electrical resistivity [1]

$$\rho_e \text{ (n}\Omega\text{-m)} = -64.9 + 1.064 \cdot T - 1.035 \times 10^{-3} T^2 + 5.33 \times 10^{-7} T^3 - 9.23 \times 10^{-12} T^4$$

Surface tension [1]

$$\gamma \text{ (N/m)} = 0.398 - 0.147 \times 10^{-3} \cdot T$$

Dynamic viscosity [1] note: $\eta = \rho\nu$ where ν = kinematic viscosity (m^2/s)

$$\ln \eta \text{ (Pa-s)} = -4.164 - 0.6374 \ln T + 292.1/T$$

Vapor pressure [1]

$$\ln P \text{ (Pa)} = 26.89 - 18880/T - 0.4942 \ln T$$

8.1.3 Physical Properties of Pb-17Li

Melting Temperature: $T_M = 507$ K

Density [1]

$$\rho \text{ (kg/m}^3\text{)} = 10.45 \times 10^{-3} (1 - 161 \times 10^{-6} T) \quad 508\text{-}625 \text{ K}$$

Specific heat [1]

$$C_p \text{ [J/kg-K]} = 195 - 9.116 \times 10^{-3} T \quad 508\text{-}800 \text{ K}$$

Thermal Conductivity [1]

$$K_{th} \text{ (W/m-K)} = 1.95 + 0.0195 T \quad 508\text{-}625 \text{ K}$$

Electrical resistivity [1]

$$\rho_e \text{ (n } \Omega\text{-m)} = 10.23 + 0.00426 T \quad 508\text{-}933 \text{ K}$$

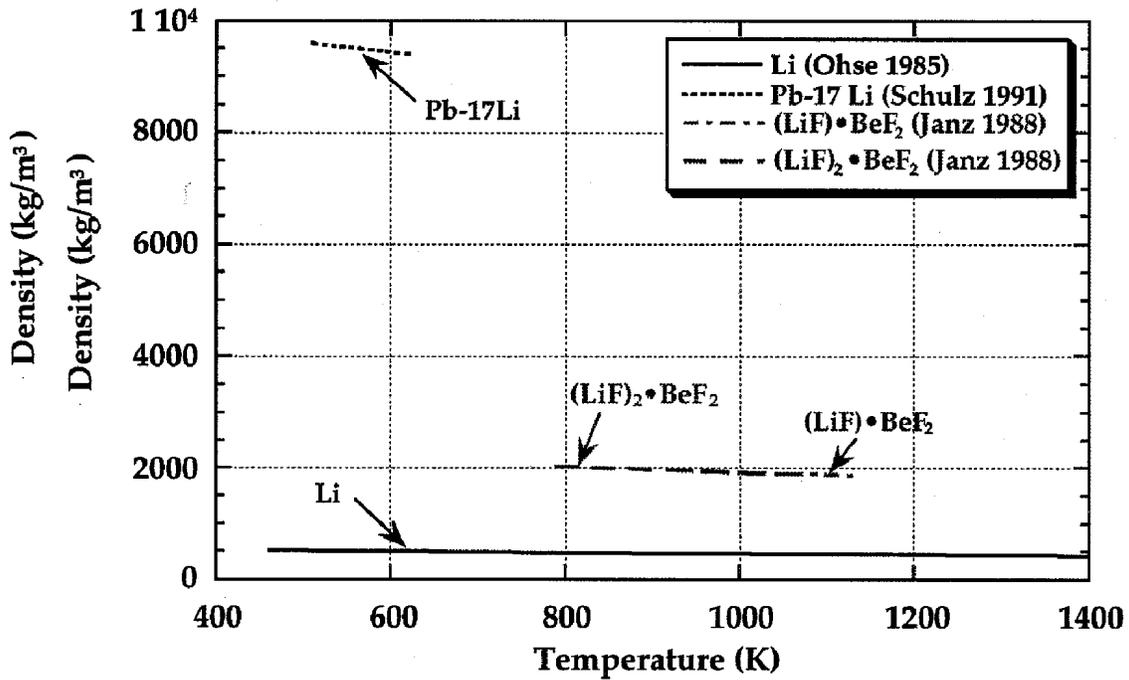
Surface tension [2,3]

$\gamma(\text{N/m}) = 0.52 - 0.11 \times 10^{-3} T$	520-1000 K
<u>Dynamic viscosity [1]</u>	
$\eta (\text{Pa} \cdot \text{s}) = 0.187 \times 10^{-3} \exp [1400./T]$	521-900 K
<u>Vapor pressure [2-4]</u>	
$P (\text{Pa}) = 1.5 \times 10^{10} \exp (-22900/T)$	550-1000 K

8.1.4 Physical Properties of Molten Flibe (LiF)_n • (BeF₂)

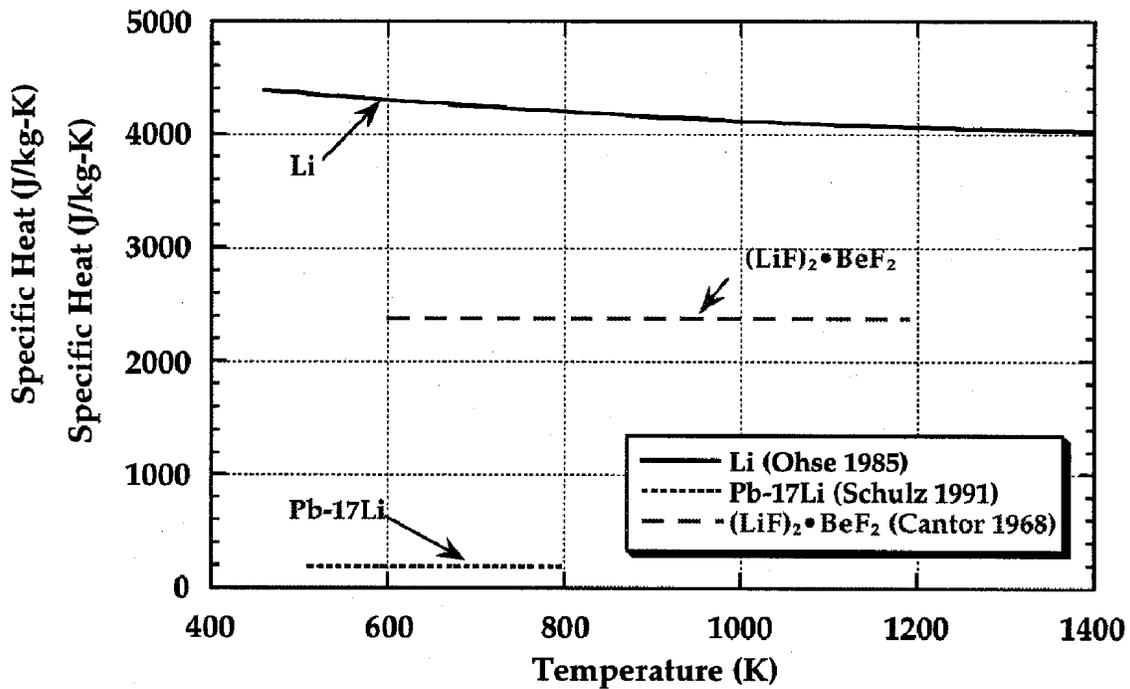
<u>Melting temperature [1]</u>		
$T_M(\text{K}) = 636 \text{ K}$	$n=0.88$	$(T_M=653 \text{ K for } n=1)$
$T_M(\text{K}) = 742 \text{ K}$	$n=2$	
<u>Density [2]</u>		
$\rho (\text{kg/m}^3) = 2319 - 424 \cdot T$	$n = 1$	930-1130 K
$\rho (\text{kg/m}^3) = 2413 - 488 \cdot T$	$n = 2$	800-1080 K
<u>Specific heat [3]</u>		
$C_p (\text{J/kg-K}) \approx 2380$	$n=2$	600-1200 K ?
<u>Thermal conductivity [3]</u>		
$K_{th} (\text{W/m-K}) = 1.0$	$n=2$	600-1200 K ?
<u>Electrical resistivity [2]</u>		
$\rho_e (\Omega\text{-m}) = 0.960 \times 10^{-4} \exp (3982/T)$	$n=1$	680-790 K
$\rho_e (\Omega\text{-m}) = 3.030 \times 10^{-4} \exp (2364/T)$	$n=2$	750-920 K
<u>Surface tension [2,4]</u>		
$\gamma (\text{N/m}) = 0.2978 - 0.12 \times 10^{-3} \cdot T$	$n = 1$	830-1070 K
$\gamma (\text{N/m}) = 0.2958 - 0.12 \times 10^{-3} \cdot T$	$n = 2$	770-1070 K
<u>Dynamic viscosity [2]</u>		
$\eta (\text{Pa} \cdot \text{s}) = 6.27 \times 10^{-6} \exp (7780/T)$	$n = 1$	680-840 K
$\eta (\text{Pa} \cdot \text{s}) = 5.94 \times 10^{-6} \exp (4605/T)$	$n = 2$	740-860 K
<u>Vapor pressure [3]</u>		
$P (\text{Pa}) = 1.5 \times 10^{11} \exp (-24200/T)$	$n = 2$	770-970 K

COMPARISON OF THE DENSITY OF LIQUID COOLANTS

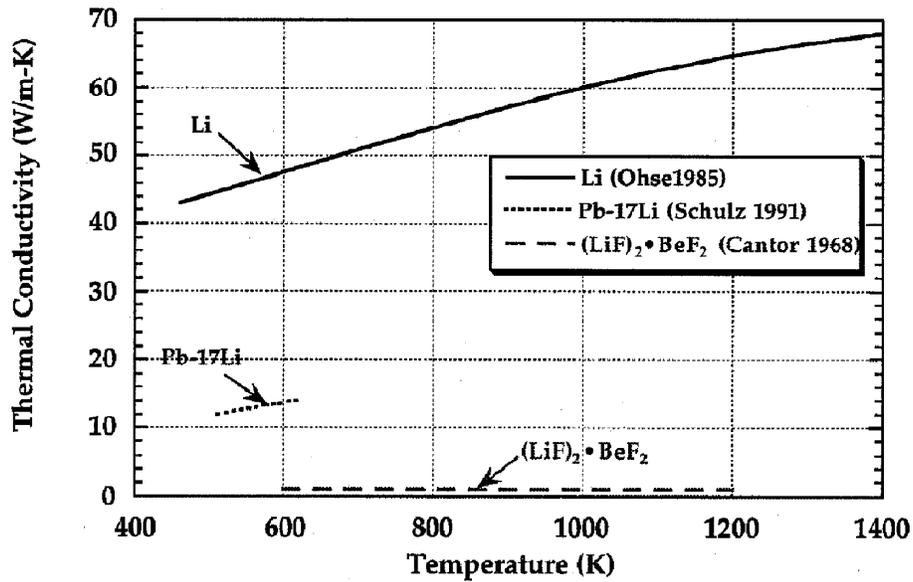


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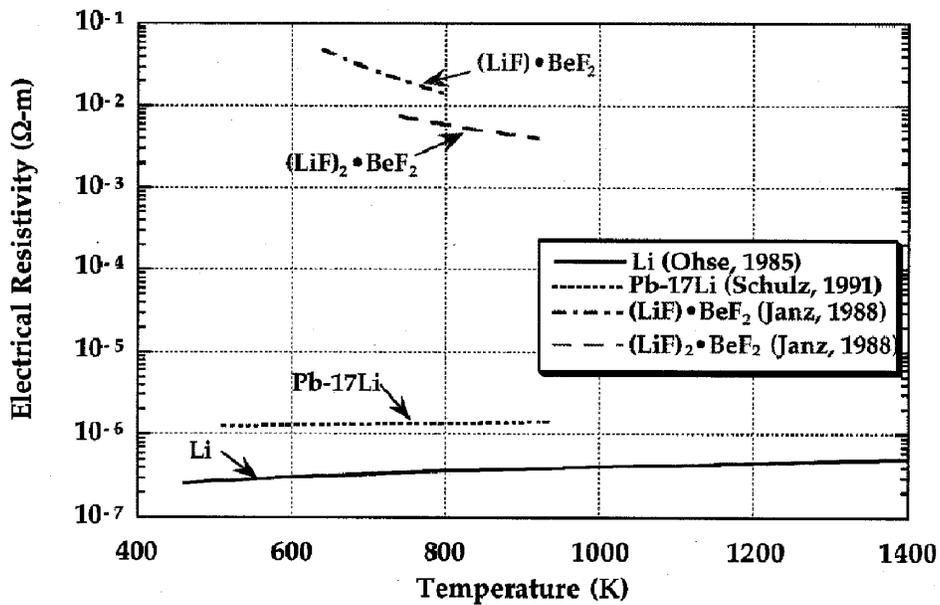
COMPARISON OF THE SPECIFIC HEAT OF LIQUID COOLANTS



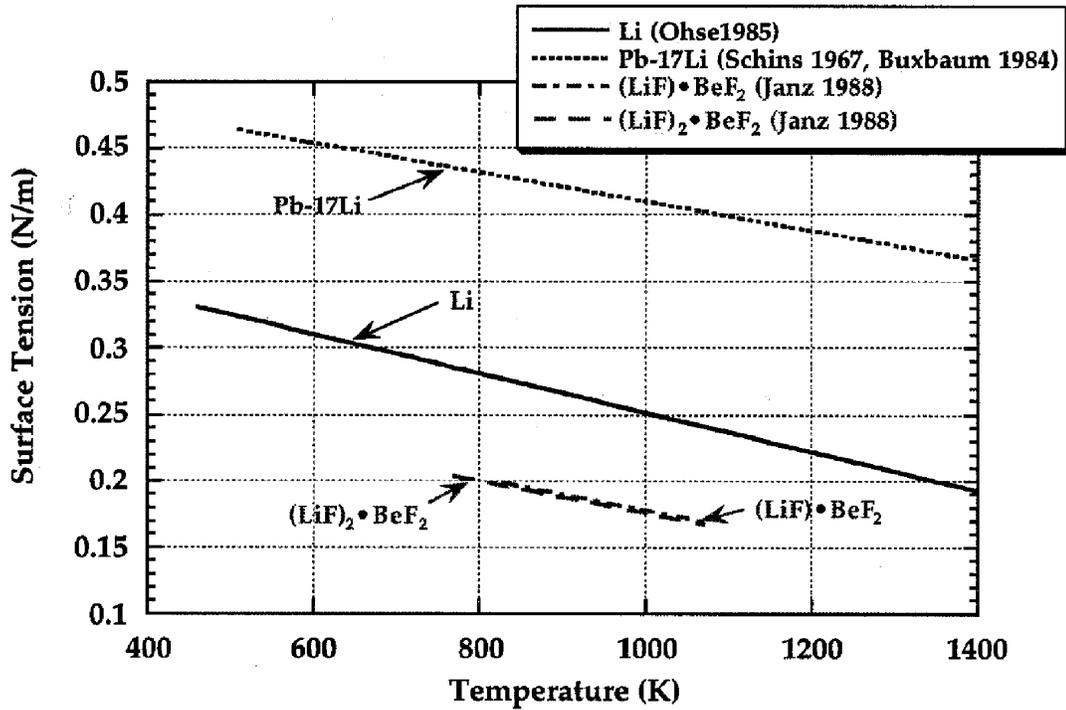
COMPARISON OF THE THERMAL CONDUCTIVITY OF LIQUID COOLANTS



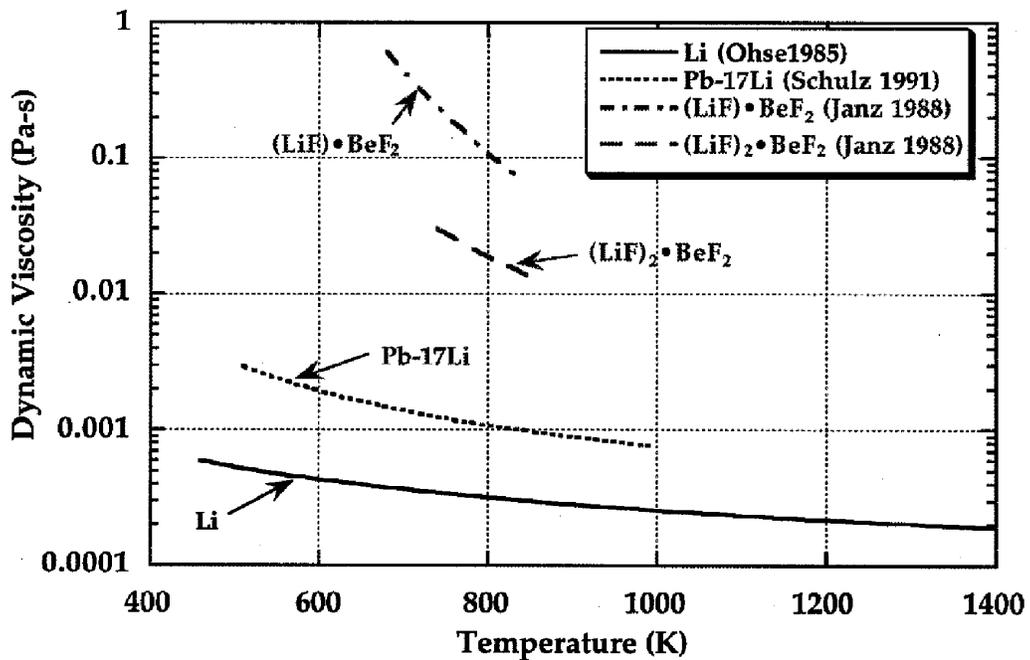
COMPARISON OF THE ELECTRICAL RESISTIVITY OF LIQUID COOLANTS

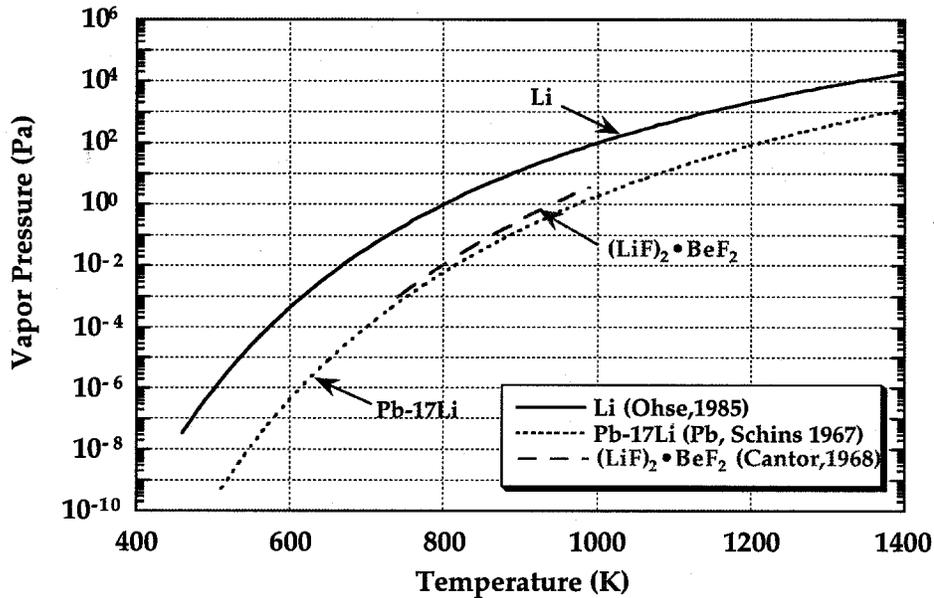


COMPARISON OF THE SURFACE TENSION OF LIQUID COOLANTS



COMPARISON OF THE DYNAMIC VISCOSITY OF LIQUID COOLANTS



COMPARISON OF THE VAPOR PRESSURE OF LIQUID COOLANTS**References to Section 8.1**First Equation:

- [1] R.W. Ohse (Ed.) Handbook of Thermodynamic and Transport Properties of Alkali Metals, Intern. Union of Pure and Applied Chemistry Chemical Data Series No. 30. Oxford: Blackwell Scientific Publ., 1985, pp. 987.
- [2] C.B. Alcock, M.W. Chase, V.P. Itkin, J. Phys. Chem. Ref. Data 23 (1994) 385. Physical Properties of Pb-17Li

Second Equation:

- [1] B. Schulz, Fusion Eng. Design 14 (1991) 199.
- [2] H.E.J. Schins, Liquid Metals for Heat Pipes, Properties, Plots and Data Sheets, JRC-Ispra (1967)
- [3] R.E. Buxbaum, J. Less-Common Metals 97 (1984) 27.
- [4] H. Feuerstein et al., Fusion Eng. Design 17 (1991) 203.

Third Equation:

- [1] K.A. Romberger, J. Braunstein, R.E. Thoma, J. Phys. Chem. 76 (1972) 1154.
- [2] G.J. Janz, Thermodynamic and Transport Properties for Molten Salts: Correlation equations for critically evaluated density, surface tension, electrical conductance, and viscosity data, J. Phys. Chem. Ref. Data 17, Supplement 2 (1988) 1.
- [3] S. Cantor et al., Physical Properties of Molten-Salt Reactor Fuel, Coolant and Flush-Salts, ORNL-TM-2316 (August 1968).
- [4] K. Yajima, H. Moriyama, J. Oishi, Y. Tominaga, J. Phys. Chem. 86 (1982) 4193.

8.2 Liquid Breeders Properties (Sn-Li)

8.2.1 Introduction

One approach for handling high wall loading is to have the coolant directly facing the plasma. 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 as a new material for such application. The vapor pressure of Sn-Li is about a factor of 1000 lower than that of lithium at the same temperature.⁽¹⁾ 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.⁽²⁾ 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.⁽²⁾ 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.

8.2.2 Phase Diagram

Figure 8.2.1 shows the phase diagram of Sn-Li.⁽³⁾ 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.

8.2.3 Sn-Li Vapor Pressure

Three separate measurements of Sn-Li vapor pressure have been found in the literature.^(1,4,5) The most detailed results can be found in Reference 1. This experiment was carried out at 1200°C, which is beyond the temperature of interest for fusion. Table 8.2.1 summarizes the experimental results from Reference 1. 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.

- 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 from the case of Pb-Li, whose vapor pressure is dominated by Pb.

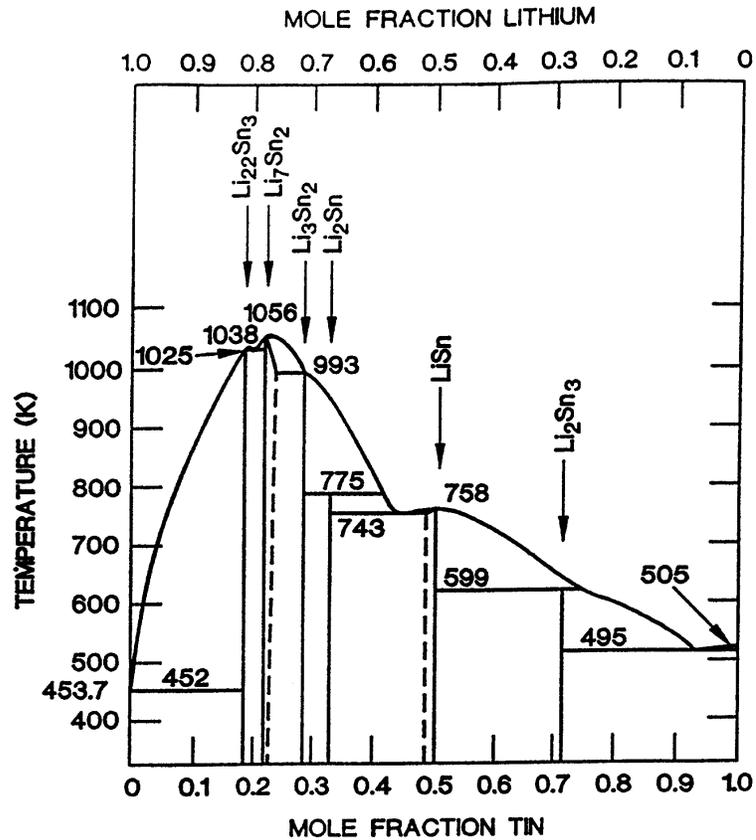


Figure 8.2.1. Sn-Li Phase Diagram

Figure 8.2.2 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.

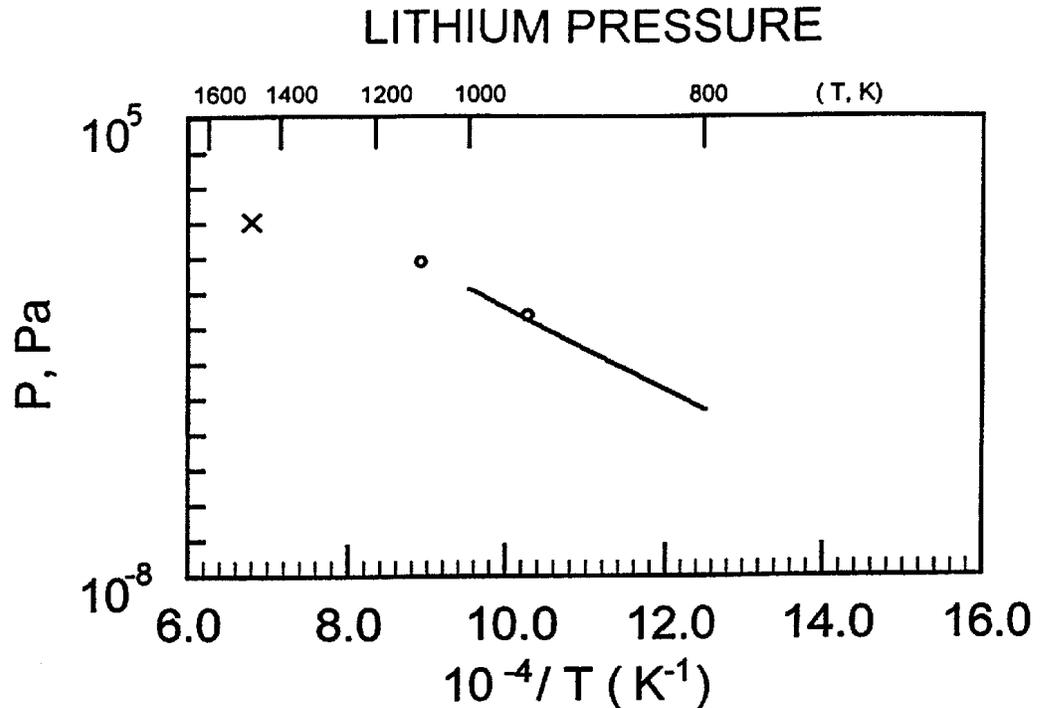


Figure 8.2.2. Lithium Vapor Pressure Over 75 Sn-25 Li

8.2.4 Lithium Chemical Reactivity

As seen from Table 8.2.1, 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 the University of Wisconsin to assess the chemical reactivities, as well as pressure and temperature changes, between Sn-Li and air/water.

8.2.5 Tritium Solubility

Due to 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 Sievert's constant of hydrogen solubility in Sn is 3 appm H in metal/torr^{1/2}.

Table 8.2.1. 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}

8.2.6 Material Compatibility

Table 8.2.2 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 temperatures.

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 vapor pressure measurement. Therefore, it can be implied that Ta is compatible to Sn-Li up to 1200°C.

8.2.7 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 8.2.3 shows the material properties for lithium, Sn and Pb.⁽³⁾

8.2.8 Tritium Breeding

A 1-D tritium breeding calculations has been done to estimate the tritium breeding capability of a Sn-Li blanket. 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 8.2.3. The Sn-Li breeding capability is compared to that of Pb-Li in the same figure.

8.2.9 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 reactivities 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.

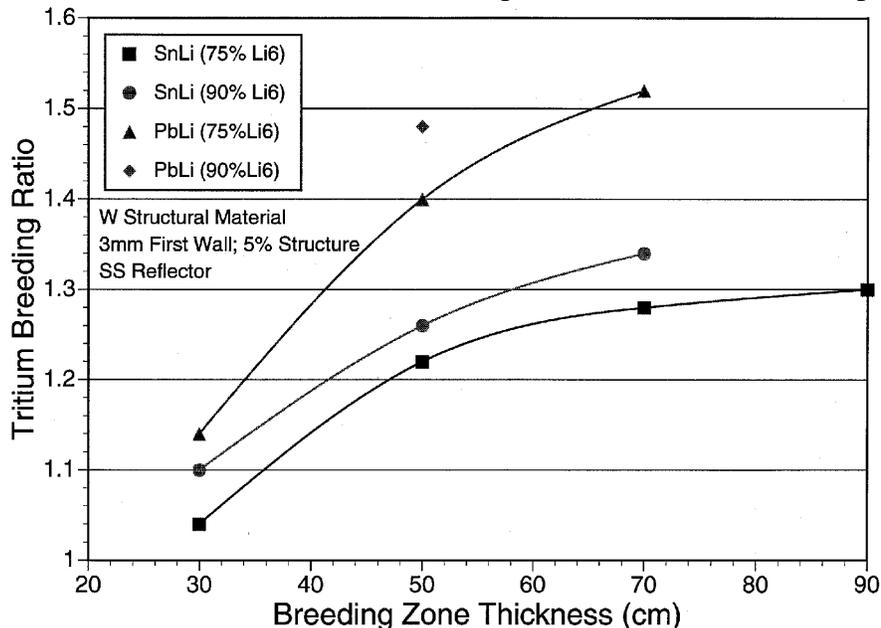
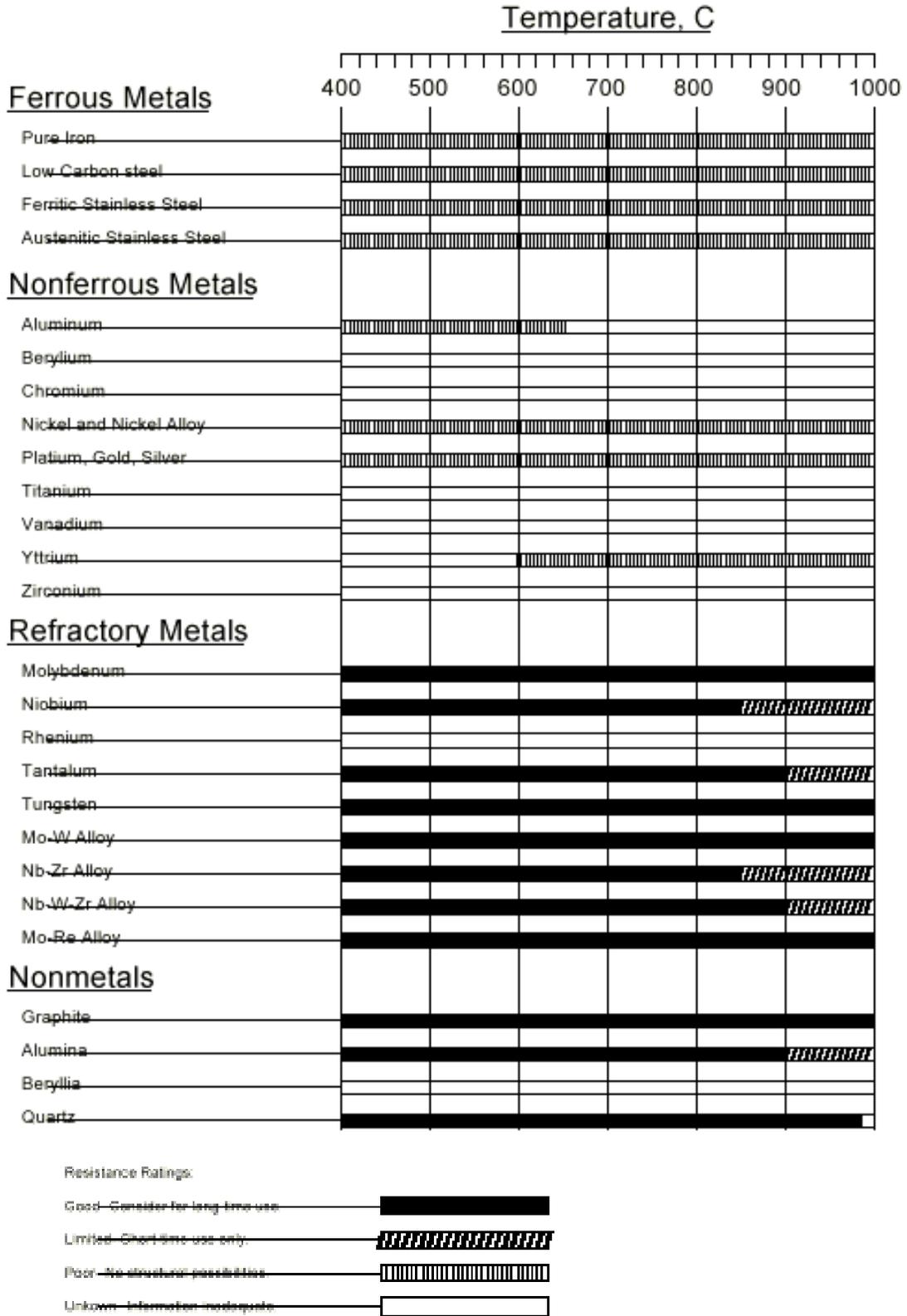


Figure 8.2.3. Tritium Breeding in Sn-Li and Pb-Li Blankets

Table 8.2.2. The Static-Corrosion Resistance of Materials to Liquid Tin



Reference to Section 8.2

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2. R.F. Mattas and the ALPS team, ALPS-Advanced Limiter-Divertor Plasma-Facing Systems, to be presented at the ISFNT-5, Rome, Italy, September, 1999.
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6. P. Baradel, et. Al., Rev. Int. Haute Temper. Et Refract. 8(1971)201.
7. M.S. Foster, et. Al., J. Phys.Chem. 70(1966)3042.
8. R. Nygren, Sandia National Laboratory, private communication.

8.3 Evaporation Rates Versus Temperature

Evaporation rates are estimated for use as the source term for the edge plasma calculations to estimate the contamination of the core plasma by evaporation from the liquid wall in the context of the liquid wall magnetic fusion reactors.

Evaporation from a surface into a vacuum is given by the following relations, which depend only on mass and temperature of the liquid at the free surface:

$$J = \frac{n\bar{v}}{4}$$

$$\bar{v} = \sqrt{\frac{8kT}{\pi m}}$$

$$n = \frac{P}{kT}$$

$$J = \frac{P}{kT} \sqrt{\frac{8kT}{\pi m}}$$

where J is the evaporation rate in molecules per second per square meter.

Pressure in Pascals can be converted to Torr as follows:

$$P(\text{Pa}) = 133.3 \times P(\text{Torr})$$

The density, n, is the density that would be present at equilibrium when evaporation equals condensation. In our case, where the edge plasma is close to the liquid surface and absorbs all evaporating particles that strike it, the density never reaches the equilibrium value but is one half of it. That is all the particles are heading away from the liquid surface. When the edge plasma is not so close or when collisions occur the equilibrium density is approached and condensation begins to cancel out evaporation as will be discussed later. The concept of density away from equilibrium is not very useful and we will emphasize evaporation rates (number of molecules leaving the liquid per square meter per second). This is the quantity that goes into the edge plasma calculation

rather than either density or vapor pressure. From experimental data in the literature (Ref. 1-6) the equilibrium vapor pressure is given by the approximate equations below which are only temperature dependent:

$$P(\text{Torr}) = 10^{9.00045-104410/T} \dots \text{Li}_2\text{BeF}_4 \dots m_{\text{BeF}_2}$$

$$P(\text{Torr}) = 10^{9.134-978/T} \dots \text{LiBeF}_3 \dots m_{\text{BeF}_2}$$

$$P(\text{Torr}) = e^{17.46-2230/T} \dots \text{Li}_{17}\text{Pb}_{83} \dots m_{\text{Pb}}$$

$$P(\text{Torr}) = e^{18.4-1875/T} \dots \text{Li} \dots m_{\text{Li}}$$

$$P(\text{Pa}) = 10^{107.75-112033/T} \dots \text{Sn}_{80}\text{Li}_{20} \dots m_{\text{Li}}$$

The evaporating species is predominantly that given to the right of the pressure equation above. BeF_2 is 200 times LiF density⁵. Li should be 1000 times denser than Sn as can be seen from Fig. 8.3.1 where Sn density is shown at 800°C . Li evaporation will be primarily Li but also some Li_2 and Li_3 will be present. The equilibrium vapor pressure is plotted in Fig. 8.3.1.

We have plotted the vapor pressure for $\text{Sn}_{75}\text{Li}_{25}$ to compare it to $\text{Sn}_{80}\text{Li}_{20}$ showing the effect of the composition change, because of the interest in the APEX project of increasing the Li content to help tritium breeding. For Lead at 600°C the value lies just above that of $\text{Li}_{17}\text{Pb}_{83}$ and for tin at 800°C it is just below 10^{-5} Torr as shown in Fig. 8.3.1 from Ref. 4. For comparison we plot two values from Ref. 6 as circles and from Ref. 4 as dashes for Li . The equilibrium vapor pressure is plotted in Fig. 8.3.2 versus $1/T$. The equilibrium vapor density is plotted in Fig. 8.3.3. The evaporation rate of the various species is plotted in Fig. 8.3.4.

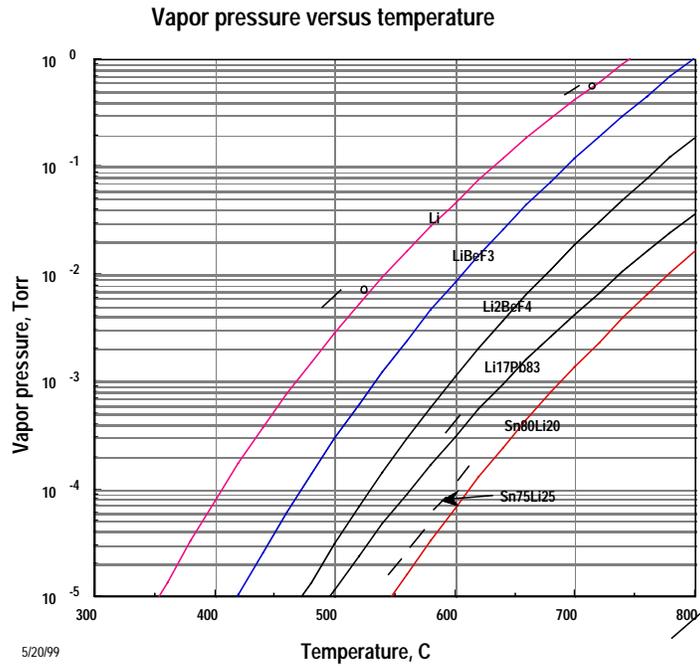


Fig. 8.3.1. Equilibrium vapor pressure for candidate liquids, plotted versus temperature in °C.

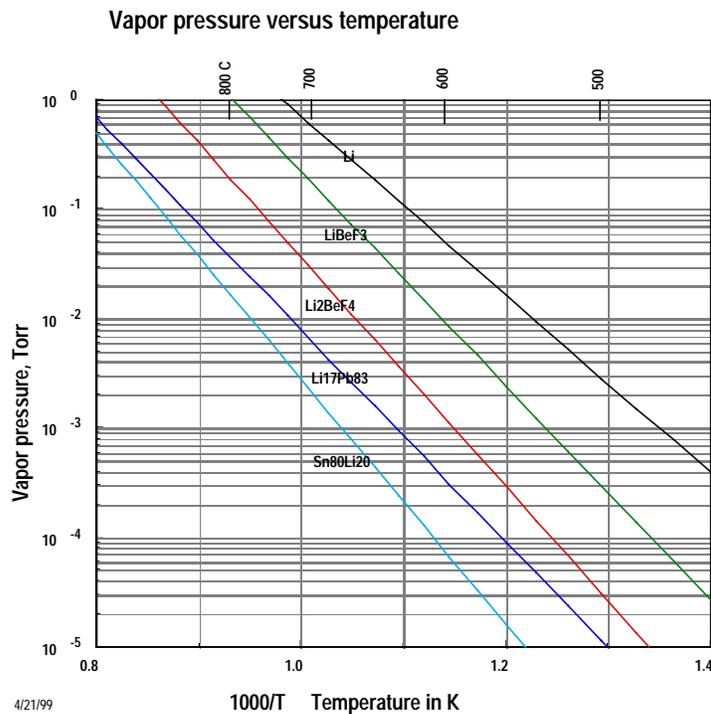


Fig. 8.3.2. Equilibrium vapor pressure for candidate liquids, plotted versus 1000/T.

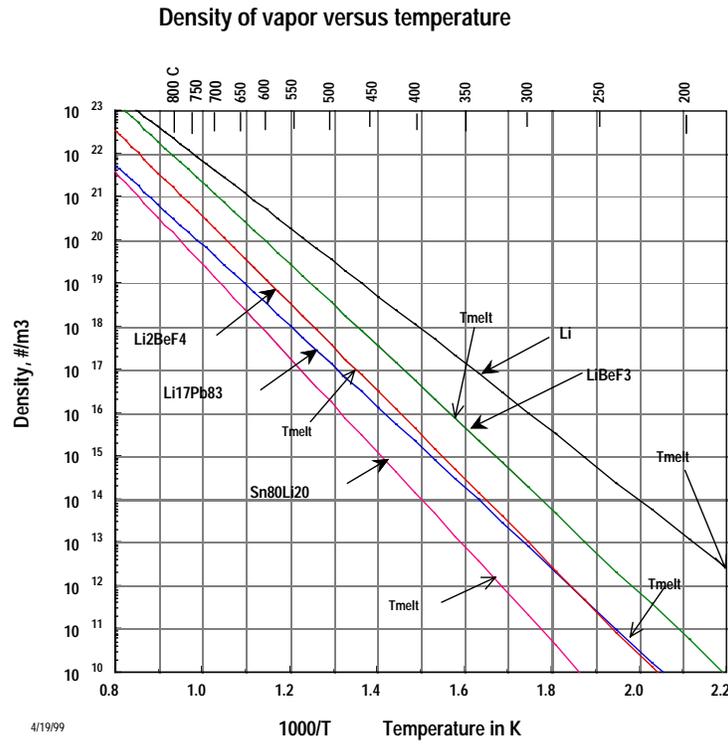


Fig. 8.3.3. Equilibrium density (vapor pressure) for candidate liquids.

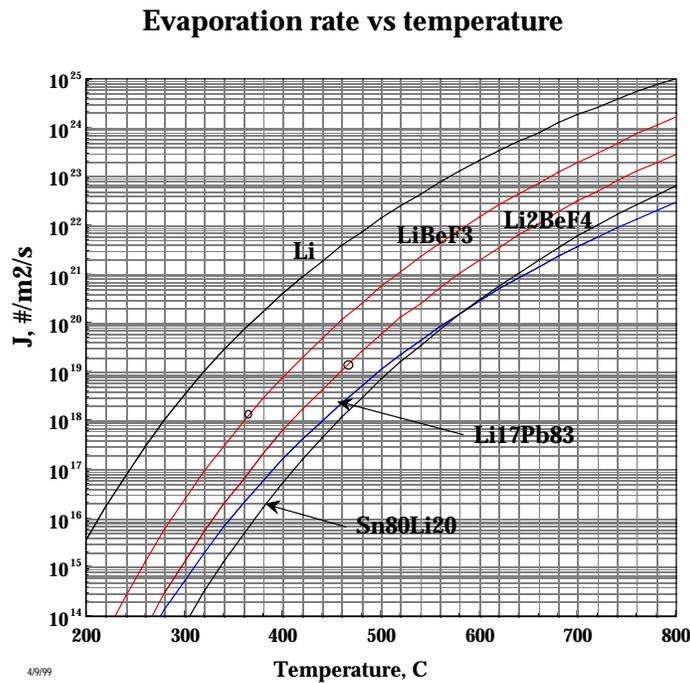


Fig. 8.3.4. Evaporation rates into vacuum for candidate liquids.

When evaporation becomes vigorous there are limiting effects which will become important for liquid wall magnetic fusion configurations and especially for liquid divertors where the evaporation is extra vigorous. These effects are: 1-collisional driven condensation of evaporated material, that is, evaporating molecules have collisions that return them to the liquid before they strike the edge plasma; 2-evaporative cooling, and 3-depletion of the volatile species at the surface. When condensation equals evaporation the latter two effects are absent. The first effect should start to become important above about 630 and 750°C for Flibe and $\text{Sn}_{80}\text{Li}_{20}$ and is expected to be especially important in the divertor. The second effect should be important for power fluxes of 1 MW/m² above about 920°C for Flibe. The third effect depends on molecular diffusion rates and of course turbulence and is never expected to be important.

References to Section 8.3

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2. S. Cantor, D. S. Hsu, and W. T. Ward, "Vapor Pressures of Fluoride Melts," in Reactor Chem. Div. Ann. Progr. Rept., Oak Ridge National Laboratory, Oak Ridge, Tenn., ORNL-3913, pp. 24-26 (1965). For Flibe.
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