

**Summary of Thermo-Physical Properties of *Sn*,
And Compounds of *Sn-H*, *Sn-O*, *Sn-C*, *Sn-Li*, and *Sn-Si***

And

Comparison of Properties of *Sn*, *Sn-Li*, *Li*, and *Pb-Li*

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ABSTRACT

The APEX evaluation study has identified tin-lithium (Sn-Li) as a new liquid wall coolant for handling high wall loadings. The low vapor pressure of Sn-Li, which is about three orders of magnitude lower than that of lithium, minimizes the effects of material evaporation on the plasma performance for liquid wall designs. Furthermore, because the vapor pressure is dominated by lithium, the allowable operating temperature of the Sn-Li coolant is about 200°C higher than for lithium. The higher allowable operating temperature can result in an increase of coolant exit temperature and therefore, thermal efficiency. However, the compatibility of Sn-Li with structural materials needs to be assessed. Based on some limited experimental data, and our own thermodynamic model, Sn-Li will probably not be compatible with Ni-based and Fe-based alloys. However, V and Nb may be compatible up to about 900°C. Results of our thermodynamic analysis show that many non-metal structural materials, such as nitrides, carbides (including SiC) and some of the oxides are stable in Sn-Li at 773°K.

The APEX study has suggested a Sn-Li mixture of 75 at.% Sn and 25 at.% Li. A summary of thermo-physical data of pure Sn is presented here (10 Tables, and 8 Figures). Because of a lack of thermo physical data of Sn-Li coolants, some properties have, been estimated from pure Sn and Li using a simple rule of mixtures. In addition, some data of Sn-H, Sn-O, Sn-Li, and Sn-C systems are reported. In Section 3 the thermal conductivity, vapor pressure, electrical resistivity, surface tension, dynamic viscosity, and the density of three liquid coolants Sn, Li, and Pb-17 are compared.

We have developed a thermodynamic model to study the stability of non-metals in a Sn-25Li coolant. The model was applied to various oxides, nitrides, and carbides and the results are summarized here. It was found that almost all of the nitrides and carbides and most of the oxides are stable below 900°C and a lithium concentration of 25 at. %.

For purpose of completion, a literature survey was made to report on the number of publications in the area of fusion relevant corrosion and erosion research. Over the past 5 years, more than 75 papers have been published on these subjects. The list of publications is given in Section 5 and is organized in an alphabetical order by the author's name.

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Tin (Sn)

Tin is a silvery-white malleable metal, somewhat ductile, and has a highly crystalline structure. The element has two allotropic forms: gray, or α -tin, with a cubic structure, which changes at 13.2°C into white, or β -tin, the ordinary form of the metal. White tin has a tetragonal structure. When tin is cooled below 13.2°C, it changes slowly from white to gray. This change is affected by impurities such as aluminum and zinc, and can be prevented by small additions of antimony or bismuth. The conversion was first noted as growths on organ pipes in European cathedrals, where it was thought to be the devils work. This conversion was also speculated to be caused by microorganisms and was called "tin plague" or "tin disease" [1].

Tin resists distilled, sea, and soft tap water, but is attacked by strong acids, alkalis, and acid salts. Oxygen in solution accelerates the attack. When heated in air, tin forms SnO₂. It is, or was, used to plate steel, making "tin cans". Tin is used as a component in bell metals [1].

Uses for Sn [1]:

- Used to coat other metals to prevent corrosion or other chemical action (tin cans are made from tin coated steel)
- Alloying agent, important alloys include soft solder, fusible metal, pewter, bronze, bell metal, Babbitt metal, White metal, die casting alloy, and phosphor bronze.
- The chloride (SnCl₂·H₂O) is used as a reducing agent and as a mordant in calico printing.
- Tin salts sprayed onto glass are used to produce electrically conductive coatings. These have been used for panel lighting and for frost-free wind-shields.
- Window glass is made by floating molten glass on molten tin (float glass) to produce a flat surface (Pilkington process).
- A crystalline tin-niobium alloy is super-conductive at very low temperatures.
- Trialkyl and triaryl tin compounds are biocides - there is concern over their environmental effects. Tributyltin is the active ingredient in a type of antifouling paint used on ships.

Reference:

- [1] Mark Winter, "The University of Sheffield and Web Elements Ltd, UK" Document July 2000 (<http://www.webelements.com/>)

1. Thermo-Physical Properties of Sn

1. 1 Physical Properties of Metallic Tin

Tin has the largest number (10) of stable isotopes of any element, but also many unstable isotopes with half-lives ranging from 2.2 minutes to $\sim 10^5$ years:

Table 1: Stable and Unstable Isotopes of Tin [1]

<i>Stable Isotopes</i>			
	Abundance(%)		
^{112}Sn	0.95		
^{114}Sn	0.65		
^{115}Sn	0.34		
^{116}Sn	14.24		
^{117}Sn	7.57		
^{118}Sn	24.01		
^{119}Sn	8.58		
^{120}Sn	32.97		
^{122}Sn	4.71		
^{124}Sn	5.89		
<i>Unstable Isotopes</i>			
	Half-life	Mode of decay ¹	Decay energy (MeV)
^{108}Sn	9 m	EC	
^{109}Sn	18.1 m	β^+ , EC	
^{110}Sn	4.0 h	EC	
^{111}Sn	35 m	β^+ , EC	2.52
$^{113\text{m}}\text{Sn}$	20 m	IT, EC	0.079, 1.1
^{113}Sn	11.5 d	EC	1.02
$^{117\text{m}}\text{Sn}$	14 d	IT	0.317
$^{119\text{m}}\text{Sn}$	250 d	IT	0.089
$^{121\text{m}}\text{Sn}$	76 y	β^-	0.45
^{121}Sn	27 h	β^-	0.383
^{123}Sn	125 d	β^-	1.42
^{123}Sn	42 m	β^-	1.46
$^{125\text{m}}\text{Sn}$	9.7 m	β^-	2.39
^{125}Sn	9.4 d	β^-	2.34
^{126}Sn	$\sim 10^5$ y	β^-	~ 0.3
^{127}Sn	201 h	β^-	
^{127}Sn	4 m	β^-	~ 3.1
^{128}Sn	59 m	β^-	1.3
^{130}Sn	2.6 m		
^{131}Sn	3.4 m		
^{132}Sn	2.2 m		

¹EC: Electron Capture; IT: Isomeric Transition

Table 2: Physical Properties of Tin [1]

<i>Density</i>		
α -Tin	measured at 288K	7.29 g cm ⁻³
β -Tin	measured at 288K	5.77 g cm ⁻³
<i>Liquid</i>		
	measured at m.p.	6.968±0.005 g cm ⁻³
	measured at 600 K	6.70 g cm ⁻³
	measured at 1200K	6.29 g cm ⁻³
<i>Hardness</i>		
	(Moh scale)	1.5 –1.8
	at 293 K	3.9 HB
	at 373 K	2.3 HB
	at 473 K	0.9 HB
<i>Resistivity</i>		
α -Tin	measured at 293K	12.6 $\mu\Omega$ cm
β -Tin	measured at 273K	300 $\mu\Omega$ cm
<i>Young's modulus (at 293 K)</i>		
49.9 kN mm ⁻²		
<i>Bulk modulus (at 293 K)</i>		
58.2 kN mm ⁻²		
<i>Shear strength (at RM)</i>		
12.3 N mm ⁻²		

Table 3: Thermal Data of Tin [1]

Fusion point	231.9681 °C
Enthalpy of fusion	7.06 kJ g atom ⁻¹
Boiling point	2270°C
Enthalpy of vaporization	296.4 kJ g atom ⁻¹
Vapor pressure	
at 1096 K	10 ⁻⁵ mm Hg
at 1196 K	10 ⁻⁴ mm Hg
at 1315 K	10 ⁻³ mm Hg
at 1462 K	10 ⁻² mm Hg
at 1646 K	10 ⁻¹ mm Hg
at 1882 K	1 mm Hg
Specific heat (C _v) at 298 K	
α-Tin	215.5 J kg ⁻¹ K ⁻¹
β-Tin	223.3 J kg ⁻¹ K ⁻¹
Thermal conductivity at 273.2 K	
Polycrystalline	0.682 W cm ⁻¹ K ⁻¹
Coefficient of expansion at 273 K	
Linear	19.9 × 10 ⁶
Cubical	59.8 × 10 ⁶
Expansion on melting	2.3 %
Surface tension at melting point	544 mN m ⁻¹
Viscosity at melting point	1.85 mNs m ⁻²
Gas solubility in liquid tin	
oxygen at 809 K	0.00018%
oxygen at 1023 K	0.0049%
hydrogen at 1273 K	0.04%
hydrogen at 1573 K	0.36%

Reference:

- [1] P. G. Harrison, "Chemistry of Tin," Blackie, Glasgow and London, Chapman and Hall New York, 1989.

1.2 Specific Volume of Sn

The specific volume of tin, v (in cm^3/g), changes from 0.1444 at 300°C to 0.16554 at 1600°C [1]. Doge [2] tabulated the specific volume as a function of temperature between 200 and 1200°C (Fig. 1).

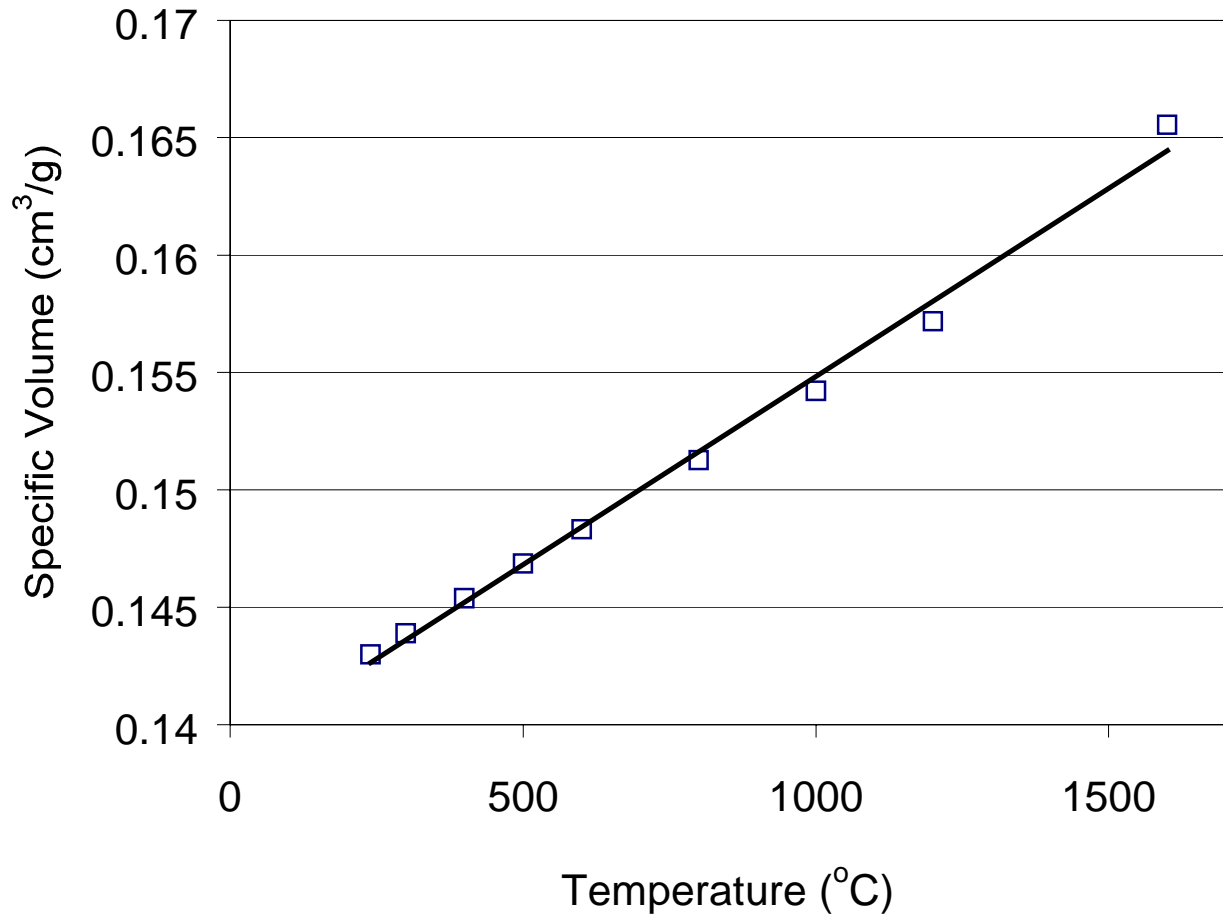


Figure 1: Specific volume of liquid Sn as a function of temperature (after Doge [2]).

References:

- [1] Y. Matuyama, Sci. Rept. Tohoku Univ. 18 (1929) 19/46, 28.
- [2] G. Doge, Z. Naturforsch. 21a (1966) pp. 266-269.

1.3 Density of Sn

The density of Sn has been reported by several authors and is shown in Figure 2. The most recent temperature dependence of the density of liquid tin was measured by Alchagirov et al. [1] between 610 and 700°K and are given by:

$$\rho(T) = 7374.7 - 676.5 \times 10^{-3} T \quad \text{kg} \cdot \text{m}^{-3} \quad (1)$$

The temperature coefficient of the density ($\Delta D/\Delta T$) for liquid Sn has been estimated using γ -ray absorption [2,3]:

$$\frac{\Delta D}{\Delta T} = 0.64 \times 10^{-3} \quad \text{g} \cdot \text{cm}^{-3}/^{\circ}\text{C} \quad (2)$$

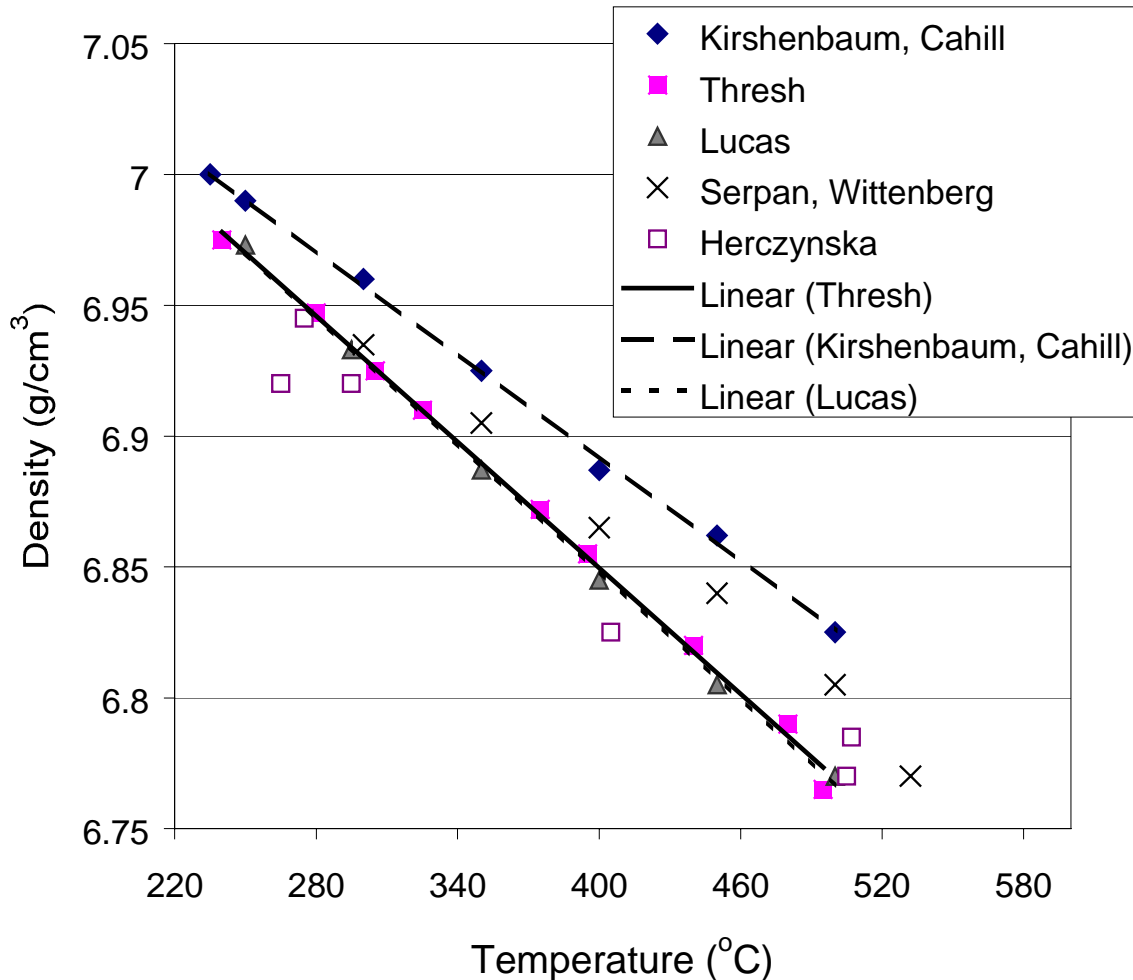


Figure 2: Density of liquid Sn as a function of temperature.

References:

- [1] B. B. Alchagirov, A. M. Chochaeva, "Temperature dependence of the density of liquid tin," High Temperature 38: (1) 44-48, JAN-FEB 2000
- [2] L. G. Berezkina, A. M. Yakobson, and Zavodsk L. 26 (1960) 171/2; Ind. Lab. [USSR] 26 (1960) 180/1.
- [3] V.A. Grosse, J. Inorg. Nucl. Chem., 22 (1961) pp. 23-31
- [4] D. Kirshenbaum, J. A. Cahill, Am. Soc. Metals Trans. Quart. 55 (1962) 844/8.

- [5] H. R. Thresh, A. F. Crawley, D. W. G. White, Trans. AIME 242 (1968) 819/22.
- [6] L. D. Lucas, Mem. Sci. Rev. Met. 61 (1964)1/24, 11.
- [7] C. Z. Serpan, L. J. Wittenberg, Trans. AIME 221 (1961) 1017/20.
- [8] E. Herczynska, Naturwissenschaften 47 (1960) 200/1.

1. 4 Volumetric expansion coefficient (γ) of liquid Sn:

Doge measured the volumetric expansion coefficient between 240 and 1200°C [1]:

$$\gamma = 105 \times 10^{-6}/^{\circ}\text{C} \quad \text{at } 240^{\circ}\text{C} \quad (3)$$

$$\gamma = 96 \times 10^{-6}/^{\circ}\text{C} \quad \text{at } 1200^{\circ}\text{C} \quad (4)$$

Widowski [2] measured the average expansion coefficient between 300 and 1600°C to be:

$$\gamma = 113 \times 10^{-6}/^{\circ}\text{C} \quad 300^{\circ}\text{C} < T < 1600^{\circ}\text{C} \quad (5)$$

References:

- [1] G. Doge, Z. Naturforsch. 21a (1966) pp. 266-269
- [2] E. Widowski, F. Sauerwald, Z. Anorg. Allgem. Chem., 192 (1930) 145/60, 150.

1. 5 Compressibility of Sn

The coefficient of compressibility χ is used to determine the modulus of compressibility, K ($=1/\chi$) [1]:

$$K = 4.6 \times 10^{11} \text{ dyn/cm}^2 \quad \text{at } 232^{\circ}\text{C} \text{ (} T_{\text{melt}} \text{ of Sn)}$$

χ has been reported for 232°C [2], 800°C [3], and 1200°C [2]:

$$\chi = 2.45 \times 10^{-12} \text{ cm}^2/\text{dyn} \quad \text{at } 232^{\circ}\text{C}$$

$$\chi = 2.8 \times 10^{-12} \text{ cm}^2/\text{dyn} \quad \text{at } 800^{\circ}\text{C}$$

$$\chi = 2.93 \times 10^{-12} \text{ cm}^2/\text{dyn} \quad \text{at } 1200^{\circ}\text{C}$$

References:

- [1] K. H. Schramm, Z. Metallk. 53 (1962) pp. 316-320.
- [2] S. I. Filippov, N. B. Kazakov, L. A. Pronin, Izv. Vysshikh Uchebn. Savedenii Chernaya Met. 9 (1066) 8/14.
- [3] C. M. Gittis, I. G. Mikhailov, Akust. Zh., 11 (1965) 434/7; Soviet Phys.-Acous. 11 (1965) 372/5.

1.6 Viscosity of liquid Sn

The dynamic viscosity, η (given in cP), has been reported between the melting temperature and 1000°C.

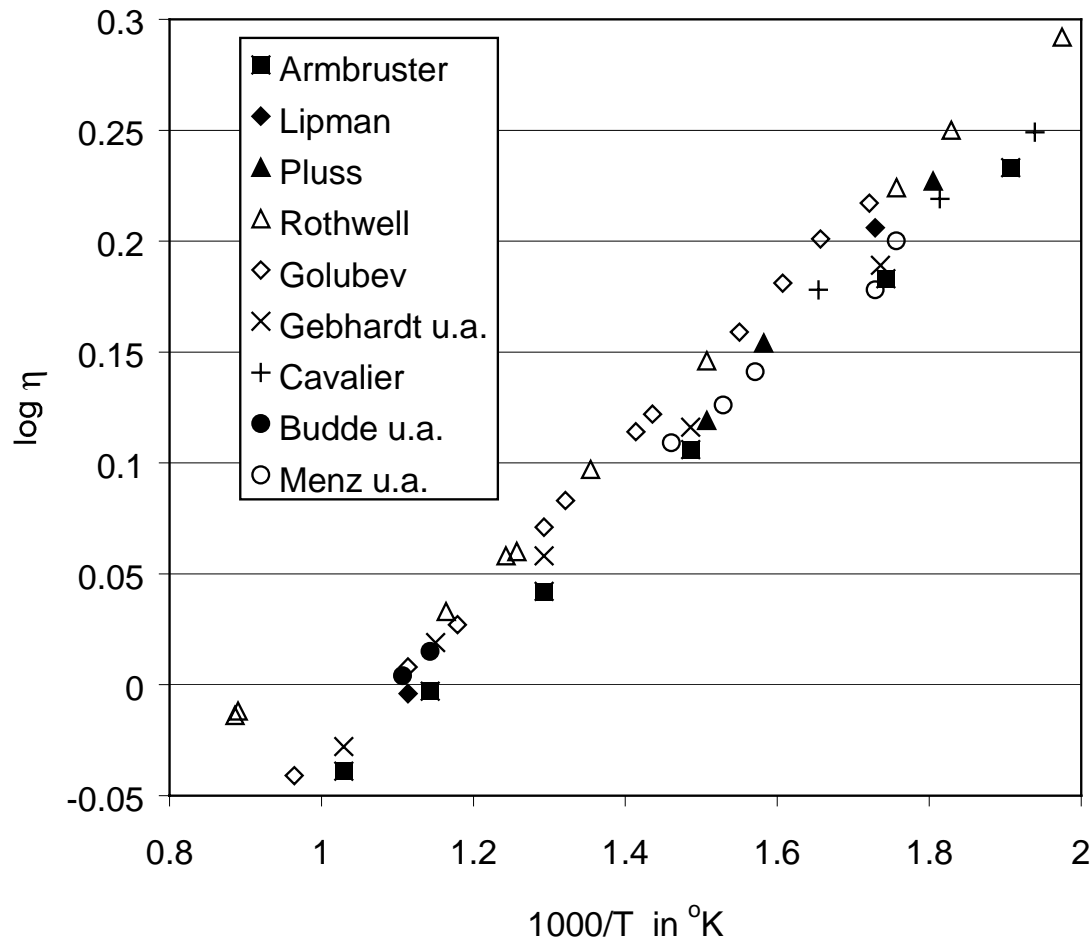


Figure 3: Dynamic Viscosity of liquid Sn as a function of temperature.

References:

- [1] J. C. Armbruster, Diss. Paris (1961) p. 1-78), M. Pluss, Z. Anorg. Allgem. Chem. 93 (1915) 1/44, 19):
- [2] M. S. Lipman, Zavodsk. Lab 16 (1950) 1349/54.
- [3] M. Pluss, Z. Anorg. Allgem. Chem., 93 (1915) 1/44, 19.
- [4] E. Rothwell, J. Inst. Metals 90 (1962) 38/94, 392.
- [5] F. Golubev, V. A. Petrov, Zavodsk. Lab. 7 (1938) 816/8.
- [6] E. Gebhardt, M. Becker, H. Sebastian, Z. Metallk., 46 (1955) 669/72.
- [7] G. Cavalier, Diss. Paris 1962 in: the Physical Chemistry of Metallic Solutions and Intermetallic Compounds, Bd. 2, 4 D, London 1959, p. 2/12, 7.
- [8] J. Budde, K. Fisser, W. Menz, F. Sauerwald, Z. Physik. Chem. (Leibzig) 218 (1961) 100/7, 105.
- [9] W. Menz, F. Sauerwald, K. Fischer, Acta. Met. 14 91966) 1617/23, 1620.

1.7 Thermal Conductivity of Liquid Sn:

The thermal conductivity of liquid tin was reported by Dutchak et al. [1]:

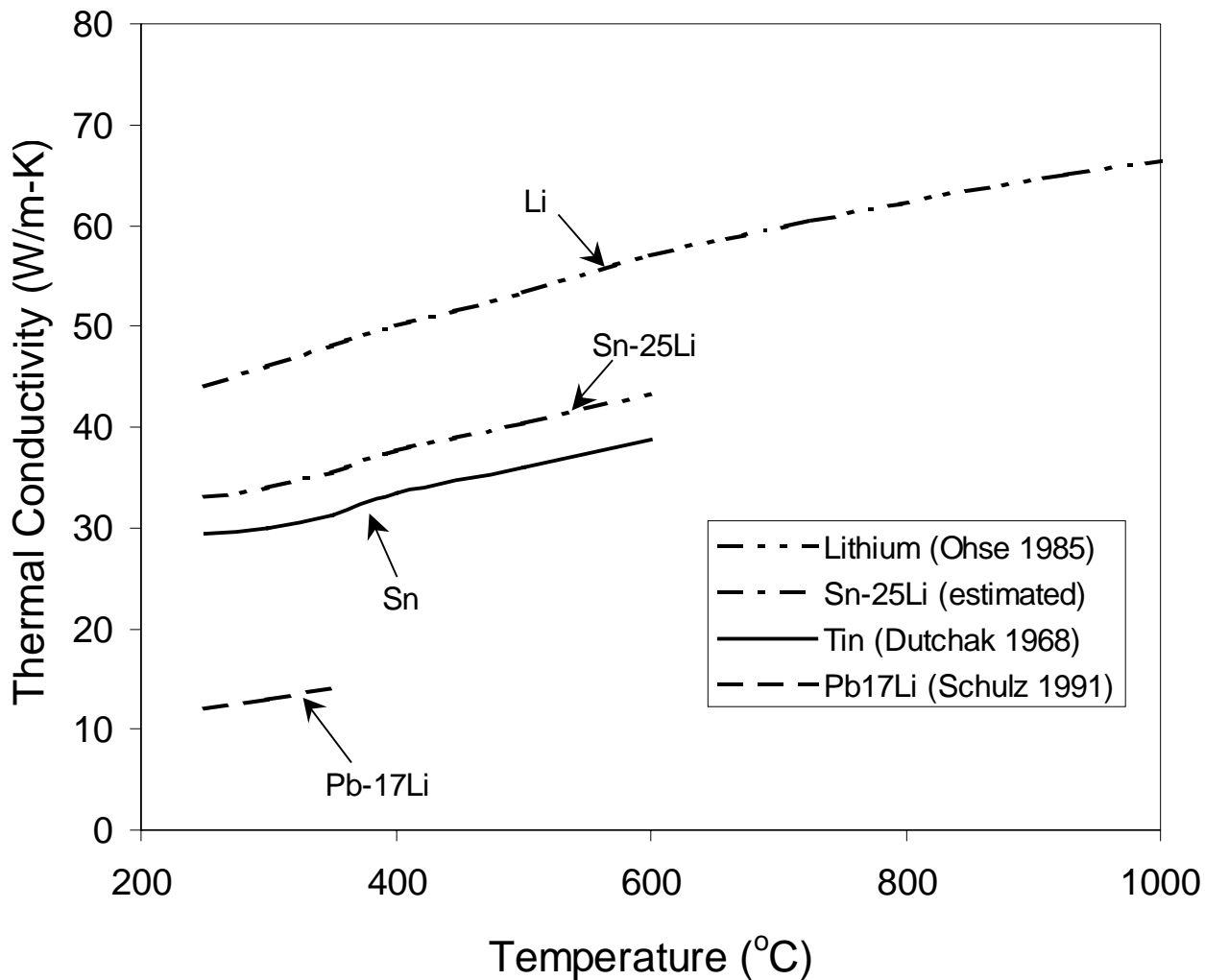


Figure 4: Thermal conductivity of liquid Sn as a function of temperature

Reference:

- [1] Ya. I. Dutchak, V. P. Osipenko, P. V. Panasyuk, *Izv, Vyssh. Zavedenii, Fiz*, 1968, No. 10, p. 154/C, C.A. 70[1969] No. 61918.
- [2] R. W. Ohse (Ed.) *Handbook of Thermodynamic and Transport Properties of Alkali metals*, Inter. Union of Pure and Applied Chemistry Chemical Data Series No. 30. Oxford: Blackwell Scientific Publ., 1985, pp. 987.
- [3] B. Schulz, *Fusion Eng. Design* 14 (1991) 199.

1. 8 Surface Tension of Sn:

A large scatter in the value of the surface tension, γ (in *dyn/cm*), exists. The scatter is potentially due to measurement techniques and to the impurity levels of the liquid Sn. Results are summarized in Fig. 5:

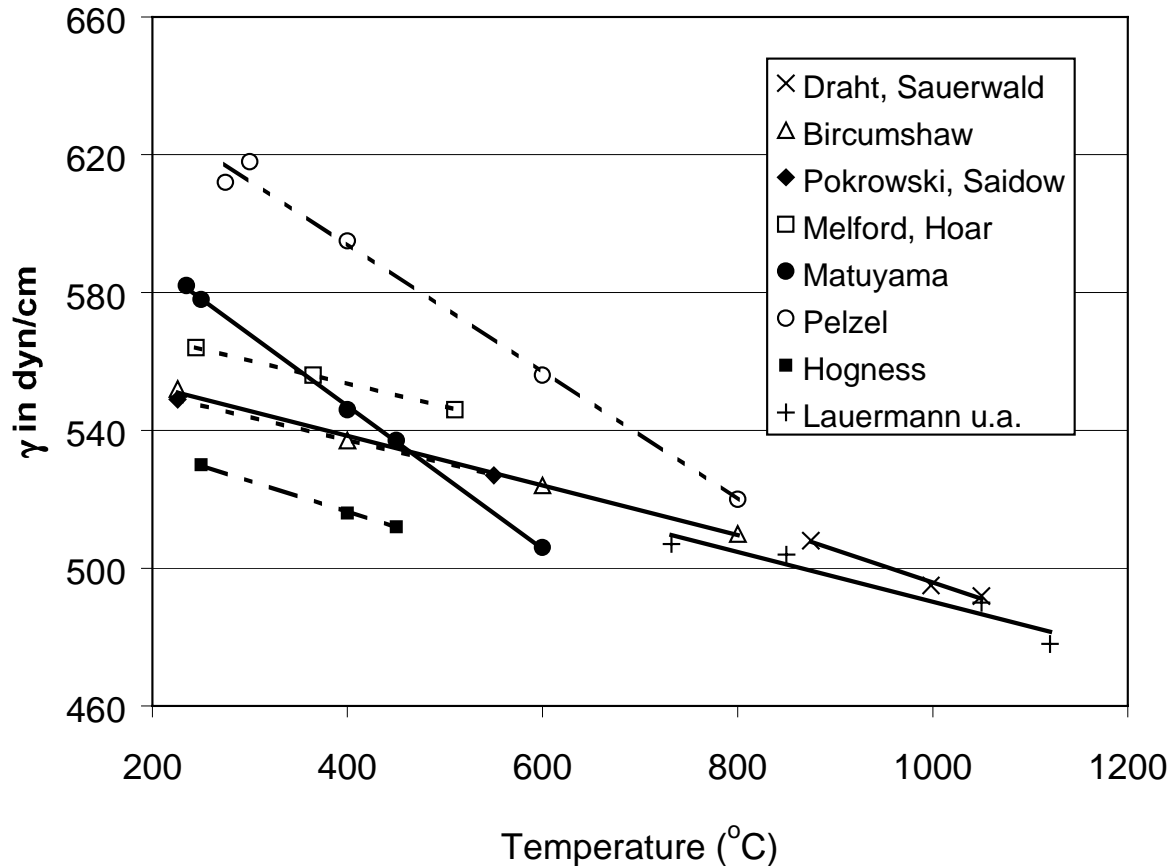


Figure 5: Surface tension of liquid Sn.

References:

- [1] G. Draht, F. Sauerwald, Z. Anorg. Allgem. Chem. 162 (1927) 301/20, 304.
- [2] L.L. Bircumshaw, Phyl. Mag. 17 No. 7 (1934) 181/91, 186.
- [3] N. L. Pokrovskii, m. Saidov, Fiz. Metal. i Metalloved. 2 (1956) 546/51, 550.
- [4] D. A. Melford, T. P. Hoar, J. Inst. Metals 85 (1956/57) 197/205, 201.
- [5] Y. Matuyama, Sci. Rept. Tohoku Univ. I 16 (1927) 555/62, 559.
- [6] E. Pelzel, Berg-Huttenmann. Monatsh. Monta., Hochschule Leoben 93 (1948) 248/54, 252.
- [7] T. R. Hogness, J. Am. Chem. Soc. 43 (1921) 1621/8, 1625.
- [8] Lauermann, G. Metzger, F. Sauerwald, Z. Physic. Chem.[Leibzig] 216 (1961) 42/9, 43).

1.9 Vapor Pressure of Sn

Mass-spectroscopy of Sn-vapor shows the presence of positive ion-clusters: Sn_2 , Sn_3 , Sn_4 , Sn_5 and Sn_6 [1]. The vapor pressure of Sn between 500°C and 1200°C has been measured [2] and is shown in Fig.6. Measurements between 800°K and 2940°K were reported by Honig [3]. For a limited temperature range between 1424 and 1638°K the following expression can be used for the vapor pressure [4]:

$$\lg p_k = 5.471 - 15730/T \quad (p \text{ in atm, } T \text{ in } ^\circ\text{K}) \quad (6)$$

$$\lg p_T = 5.810 - 16160/T \quad (p \text{ in atm, } T \text{ in } ^\circ\text{K}) \quad (6)$$

where the p_k indicates measurements using the Knudson effusion method, and p_T a torsion-based method. Given the spread of experimental data, Nemeyanov derived a general expression for the vapor pressure [5] as:

$$\lg p = -9.32188 - 14023.92/T - 8.8122 \times 10^{-4}T + 5.6201 \lg T \quad (7)$$

where the pressure is in *atm* and the applicable temperature range is $1424 < T < 1753$ °K.

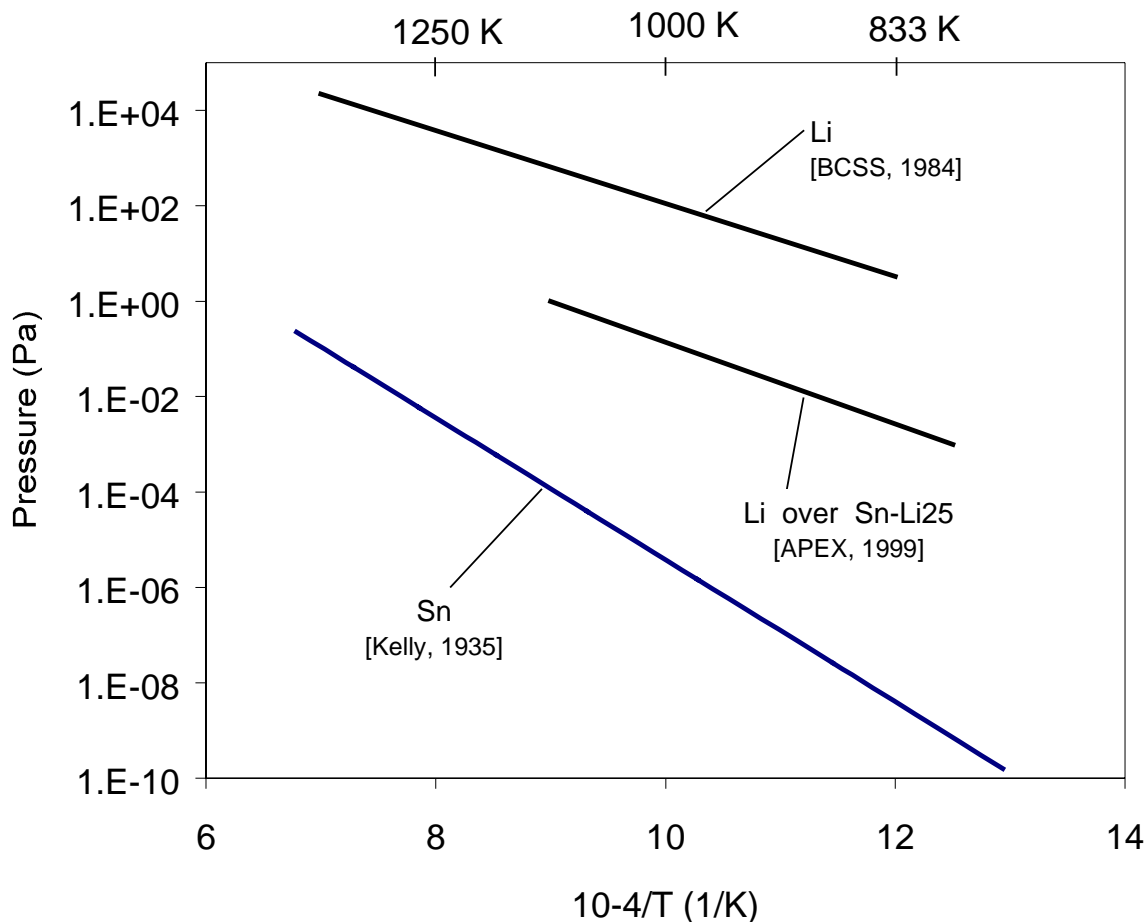


Figure 6: Vapor pressure of Sn as a function of temperature.

References:

- [1] (G. Kohl, Z. Naturforsch. 9a (1954) 913/8, 918).
- [2] K. K. Kelly, U.S. Bur. Mines Bull. Nr. 383 (1935) 1/132, 105.
- [3] R. E. Honig, D. A. Kramer, RCA Rev. 30 (1969) 285/305, 297.
- [4] L. Brewer, R. F. Porter, J. Chem. Phys. 21 (1953) 2012/3.
- [5] A. N. Nesmeyanov, Dablenie Para Khimicheskikh Elementov, Moskva 1961, p. 231,369; Vapour Pressure of the Elements, London 1963, P. 273, 445.
- [6] M. Abdou, et al., "On the Exploration of Innovative Concepts for Fusion Chamber Technology: APEX Interim Report," University of California School of Engineering and Applied Science, UCLA-ENG-99-206, Nov. 1999.
- [7] M. Abdou, et al., "Blanket Comparison and Selection Study Final Report," Argonne National Laboratory Report, ANL/FPP-84-1, Vol. 2.,1984

1. 10 Boiling Point of Sn

At 760 Torr the boiling point of Sn has been measured [1] to be:

$$T_{\text{boil}} = 2780 \pm 20 \text{ }^\circ\text{K} \quad (8)$$

A boiling point values of 3000°K has been reported [2]. It is speculated that the spread in boiling point may be caused by the formation of complex gases.

References:

- [1] D. T. Stull, G. C. Sinke, Thermodynamic Properties of the Elements, Washington 1956, p. 33.
- [2] L. L. Quill, The Chemistry and Metallurgy of Miscellaneous Materials, Thermodynamics, New York – Toronto – London 1950, p. 33.

1. 11 Heat of Sublimation (L_s) and Vaporization (L_v):

The heat of sublimation at 298°K and 232°C have been reported to be [1]:

$$L_s = 71.9 \pm 2.0 \text{ kcal/mol at } 298^\circ\text{K:} \quad (9)$$

$$L_s = 71.9 \pm 1.5 \text{ kcal/mol at } 232^\circ\text{C} \quad (10)$$

The heat of vaporization [2] is given by:

$$L_v = 70.8 \pm 1.5 \text{ kcal/mol at } 2623^\circ\text{C} \quad (11)$$

The melting temperature and the boiling temperature were reported to be 232°C and 2623°C, respectively.

References:

- [1] A. W. Searcy, R. D. Freeman, J. Am. Chem.Soc. 76 (1954) 5229/32.
- [2] O. Kubaschewski, W. L. Wvans, C. B. Alcock, Metallurgical Thermochemistry,4. Aufl., Oxford 1967, p. 385.

1. 12 Critical Pressure (p_c), Temperature (T_c), and Volume (V_c)

These were reported by Searcy and Freeman [1] and Gates [2]:

$$\begin{aligned}p_c &= 524 \text{ atm} \\T_k &= 5809^\circ\text{K} \\V_c &= 264.9 \text{ cm}^3/\text{mol}\end{aligned}$$

References:

- [1] A. W. Searcy, R. D. Freeman, J. Am. Chem. Soc. 76 (1954) 5229/32.
- [2] D. S. Gates, G. Thodos, A.I.Ch.E. (Am. Inst. Chem. Engrs.) J 6 (1960) 50/4.

1. 13 Heat Capacity of Sn

The heat capacity at the melting point (232°C) has been reported to be $C_p = 7.10 \text{ cal}/(\text{mol}\cdot^\circ\text{K})$ [1]. Raising the temperature to 800°C reduces the heat capacity from 7.10 to $C_p = 6.87 \text{ cal}/(\text{mol}\cdot^\circ\text{K})$. An expression for the heat capacity as a function of temperature was given as [1]:

$$C_p = 9.97 - 9.15 \times 10^{-3}T + 6.5 \times 10^{-6}T^2 \quad [\text{cal}/(\text{mol}\cdot^\circ\text{K})] \quad (11)$$

References:

- [1] T. W. Chapman, Mater. Sci. Eng. 1 (1966) 65/9

1. 14 Electrical Resistivity (ρ) of liquid Sn

At the melting temperature the electrical resistivity (ρ) of Sn doubles from the solid value of $\rho_s = 22.8 \mu\Omega\text{-cm}$ to the liquid value of $\rho_l = 48.0 \mu\Omega\text{-cm}$ [1]. However, there is a large scatter in the reported data of ρ (see the Fig. 7).

The following temperature dependent correlations have been reported (ρ in $\mu\Omega\text{-cm}$; T in $^\circ\text{C}$):

$$\rho(T) = 40.88 + 0.0272 \times T \quad \text{for } T < 315^\circ\text{C} \quad (12)$$

$$\rho(T) = 41.16 + 0.0263 \times T \quad \text{for } T > 315^\circ\text{C} \quad (13)$$

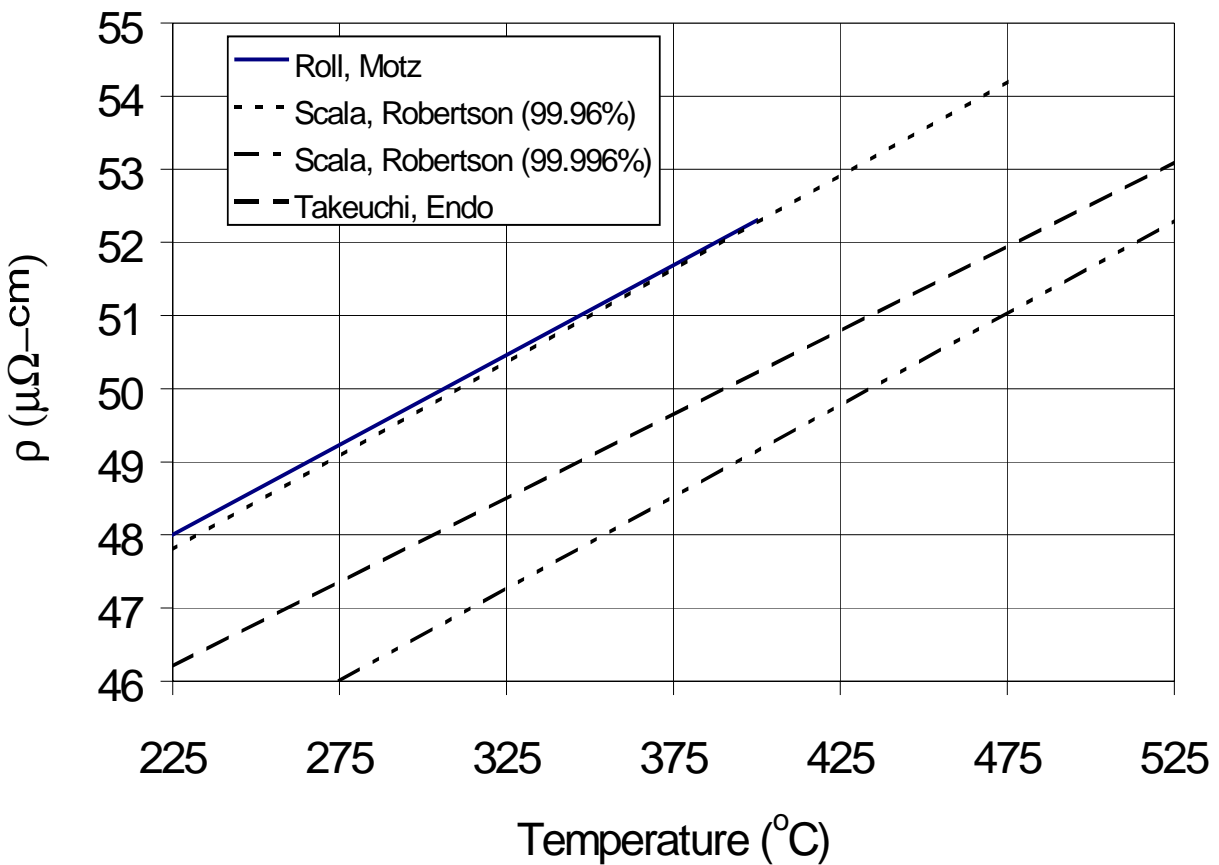


Figure 7: Electrical resistivity of liquid Sn as a function of temperature.

References:

- [1] A. Roll, H. Motz, Z. Metallk. 48 (1957) 272/80, 274.
- [2] E. Scala, W. D. Robertson, J. Metals, 5 (1953) Trans. 197, p. 1141/7, 1144.
- [3] S. Takeuchi, H. Endo, Trans. Japan Inst. Metals 3 (1962) 30/5.
- [4] H. A. Davis, J. S. L. Leach, Phys. Chem. Liquids 2 (1970) 1/12, 5.
- [5] P. D. Adams, Diss. Univ. of London, 1964.

2. Thermodynamic Properties of Sn

2.1 Enthalpy, Specific Heat, and Entropy of Sn-Vapor

Thermodynamic values of enthalpy, specific heat, and entropy were determined spectroscopically assuming, that Sn-vapor obeys the ideal gas law [1-3].

Table 4: Thermodynamic Values of Sn-Vapor

Temperature (°K)	$H^\circ - H^\circ_{298.15}$ (kcal/mol)	C°_p (kcal/mol-°K)	S° (kcal/mol-°K)
298	0	5.08	40.24
400	535	5.47	41.79
600	1747	6.66	44.22
800	3179	7.57	46.28
1000	4735	7.91	48.01
1400	7866	7.62	50.65
1800	10805	7.09	52.20
2200	13555	6.69	53.88
2600	16178	6.44	54.98
3000	18717	6.27	55.89
3200	19964	6.199	56.29
3400	21198	6.139	56.66
3600	22420	6.086	57.01
3800	23633	6.038	57.34
4000	24836	5.995	57.65
4400	27218	5.919	58.22
4800	29573	5.859	58.73
5200	31907	5.815	59.20
5600	34228	5.791	59.63
6000	36543	5.790	60.02

References:

- [1] [D. R. Stull, G. C. Sinke, Thermodynamic Properties of the Elements, Washington 1956, p. 209.
- [2] R. Hultgren, R. L. Orr, P. D. Anderson, K. K. Kelly, Selected Values of Thermodynamic Properties of Metals and Alloys, NY – London, 1963, p. 262.
- [3] J. S. Gordon, ADI-6930 (1961) 1/3.

2. 2 Heat of Dissociation, Reaction Enthalpy, and Ionization Potentials of Various Tin-Compounds

L. V. Gurvich, et al., [1], reported the heat of dissociation, reaction enthalpies, and ionization potentials of various tin compounds. The heat of dissociation D_o° (kcal/mole) is defined as:

$$D_o^\circ(R_1 - R_2) = \Delta H_{fo}^\circ(R_1) + \Delta H_{fo}^\circ(R_2) - \Delta H_{fo}^\circ(R_1R_2) \quad (14)$$

where $\Delta H_{fo}^\circ(R_i)$ is the enthalpy of formation at 0°K and R_i is reactant i .

Table 5: Heat of Dissociation of Sn-Compounds

Compound	D_o (kcal/mole)
Sn ₂	46 ± 4
SnAg	32 ± 5
SnAu	60 ± 4
SnCu	42 ± 4
SnBr	80 ± 1
SnBr ⁺	80 ± 12
SnCl	98 ± 4
SnF	112 ± 3
SnF ⁺	112 ± 12
SnH	60 ± 3
SnI	55 ± 2
SnO	126 ± 2
SnO ⁺	53 ± 15
SnS	110.2 ± 0.8
SnS ⁺	55 ± 12
SnSe	95 ± 8
SnSe ⁺	40 ± 12
SnTe	75.0 ± 1.0
SnTe ⁺	36 ± 12

Table 6: Reaction Enthalpies of Sn-Compounds

Reaction	ΔH_{f0} (kcal/mole)	ΔH_{f298} (kcal/mole)
$\text{SnO} = \text{Sn} + \text{O}$	126 ± 2	127
$(\text{SnO})_2 = 2\text{SnO}$		66 ± 4
$(\text{SnO})_3 = (\text{SnO})_2 + \text{SnO}$		69 ± 6
$(\text{SnO})_4 = (\text{SnO})_3 + \text{SnO}$		71 ± 7
$(\text{SnO})_4 = 2(\text{SnO})_2$		74 ± 9
$\text{SnF} = \text{Sn} + \text{F}$	112 ± 3	112
$\text{SnF}_2 = \text{SnF} + \text{F}$		105
$(\text{SnF}_2)_2 = 2\text{SnF}_2$		41
$(\text{SnF}_2)_3 = (\text{SnF}_2)_2 + \text{SnF}_2$		30
$\text{SnCl} = \text{Sn} + \text{Cl}$	98 ± 4	98
$\text{SnCl}_2 = \text{SnCl} + \text{Cl}$		81
$\text{SnBr} = \text{Sn} + \text{Br}$	80 ± 1	80
$\text{SnBr}_2 = \text{SnBr} + \text{Br}$		74
$\text{SnI} = \text{Sn} + \text{I}$	55 ± 10	
$\text{SnI}_2 = \text{SnI} + \text{I}$		66 ± 10
$\text{SnS} = \text{Sn} + \text{S}$	110.2 ± 0.8	111.1
$\text{Sn}_2\text{S}_2 = 2\text{SnS}$		49 ± 5
$\text{Sn}_2\text{S}_2 = \text{Sn}_2 + \text{S}_2$		126 ± 6
$\text{SnSe} = \text{Sn} + \text{Se}$	95 ± 5	
$\text{Sn}_2\text{Se}_2 = 2\text{SnSe}$		46.5 ± 0.4
$\text{Sn}_2\text{Se}_2 = \text{Sn}_2 + \text{Se}_2$		119 ± 10
$\text{SnTe} = \text{Sn} + \text{Te}$	75.0 ± 1.0	75.6
$\text{SnTe}_2 = \text{SnTe} + \text{Te}$		48.9 ± 3.0
$\text{SnTe}_2 = \text{SnTe} + 1/2\text{Te}_2$		17.5 ± 0.3
$\text{SnTe}_2 = \text{Sn} + \text{Te}_2$		61.7 ± 2.0
$\text{Sn}_2\text{Te}_2 = \text{SnTe}_2 + \text{Sn}$		73.6 ± 8.0
$\text{Sn}_2\text{Te}_2 = 2\text{SnTe}$		46.9 ± 6.0
$\text{Sn}_2\text{Te}_2 = \text{Sn}_2 + \text{Te}_2$		90 ± 8
$\text{SnWO}_4 = \text{SnO} + \text{WO}_3$	136 ± 15	
$\text{Sn}_2\text{WO}_5 = \text{SnO} + \text{SnWO}_4$	66 ± 15	

Table 7: Ionization Potentials of Sn-Compounds

Compound	Ionization Potential (eV)
SnO	10.5 ± 0.5
Sn ₂ O ₂	9.8 ± 0.5
Sn ₃ O ₃	9.8 ± 0.5
Sn ₄ O ₄	9.2 ± 0.5
SnH ₄	9.2 ± 1.0
Sn ₂ H ₆	9.0 ± 0.3
SnF	7.4 ± 0.5
SnF ₂	11.5 ± 0.5
SnCl	6.6 ± 0.5
SnCl ₂	10.2 ± 0.5
SnCl ₃	9.5 ± 0.5
SnCl ₄	11.5 ± 0.5 12.10 ± 0.05
SnBr	7.4 ± 0.5
SnBr ₂	10.0 ± 0.4
SnBr ₃	9.1 ± 0.5
SnBr ₄	10.6 ± 0.4 11.0 ± 0.1
Sn ₂ F ₄	10.5 ± 0.5
Sn ₃ F ₆	10.5 ± 0.5
SnS	9.7 ± 0.5
Sn ₂ S ₂	9.4 ± 0.5
SnSe	9.7 ± 0.5
Sn ₂ Se ₂	9.8 ± 0.5
SnTe	9.1 ± 0.5

References:

- [1] L. V. Gurvich, et al., "Heat of Dissociation of Chemical Bonds and Ionization Potentials," Published by Nauka, Moskow, 1974.

2. 3 Thermodynamic data of Sn-Silicates

Enthalpy of formation (ΔH), free energy of formation (ΔG) in kcal/mol and entropy of formation (ΔS) in cal/mol- $^{\circ}K$ between 298 and 1500 $^{\circ}K$ have been estimated [1]:

Table 8: Thermodynamic Data for Sn-Silicates

Compounds	$-\Delta H_{298}$	$-\Delta G_{298}$	ΔS_{298}
SnSiO ₃	270	252	24.19
Sn ₂ SiO ₄	301.2	283.38	34.93

References:

- [1] D. E. Wilcox, Ind. Eng. Chem. 55 No.7 (1963) 32/9, 37.

2. 3. 1 Specific heat (c_p) of Sn-Silicates as a function of temperature

For SnSiO₃ [1]:

$$c_p = 24.06 + 9.32 \times 10^{-3}T - 2.35 \times 10^{-5}T^2 \quad \text{cal/mol-}^{\circ}K \quad (15)$$

and for Sn₂SiO₄:

$$c_p = 33.026 + 14.31 \times 10^{-3}T - 2.09 \times 10^{-5}T^2 \quad \text{cal/mol-}^{\circ}K \quad (16)$$

References:

- [1] V. A. Gorochovskii, E. A. Kregius, V. A. Vlasov, T. B. Dashkevich, Izv. Akad. Nauk SSSR Neorgan. Materialy 7 (1971) 2033/5; Inorg. Materials (USSR) 7 (1971) 1810/2.

2. 4 The Sn-H System

At room temperature, molten Sn does not absorb any H₂ [1]. At 1000 $^{\circ}C$ 100 g Sn will dissolve 1.77 cm³ of H₂ [2]. Between 1150 and 1300 $^{\circ}C$ no dissolution of H₂ in liquid Sn is observed, based on monitoring the H₂ pressure [3]. However, hydrogen pressures above 10 Torr indicate some dissolution of H₂ [4]. Atomic hydrogen reacts with Sn and forms SnH₄[5].

Table 9: Hydrogen Solubility.

Temperature ($^{\circ}C$)	H ₂ (cm ³) /100 g Sn	References
800	0.3	[6]
1000	1.77	[7]
1000-1300	0.02 – 0.43 (at 1 atm)	[8]

References:

- [1] A. Sieverts, Z. Elektrochem. 16 (1910) 707/13, 708.
- [2] K. Iwase, Sci. Rept. Tohoku Imp. Univ. I 15 (1926) 531/66, 543.
- [3] R. Schafer. W. Klemm, J. Pract. Chem. [4] 5(1(58) 233/41, 240.
- [4] E. Bauer, R. Brunner, Helv, Chi, Acta 17 (1934) 958/69.
- [5] T. G. Pearson, P. L. Robinson, E. M. Stoddart, Proc. Roy. Soc. [London] A 142 (1933) 275/85, 280.
- [6] L. L. Bircumshaw, Phil. Mag.[71] 1 (1926) 510/22, 513.
- [7] K. Iwase, Sci. Rept. Tohoku Imp. Univ., 15 (1926) 531/66, 544.
- [8] M. B. Bever, C F. Floe, Trans. AIME, 156 (1944) 149/59.

2. 4. 1 Absorption of Hydrogen

At room temperature, molten Sn does not absorb any H₂ [1]. At 1000°C 100 g Sn will dissolve 1.77 cm³ of H₂ [2]. Between 1150 and 1300°C no dissolution of H₂ in liquid Sn is observed, based on monitoring the H₂ pressure [3]. However, hydrogen pressures above 10 Torr indicate some dissolution of H₂ [4]. Atomic hydrogen reacts with Sn and forms SnH₄[5].

References:

- [1] A. Sieverts, Z. Elektrochem. 16 (1910) 707/13, 708.
- [2] K. Iwase, Sci. Rept. Tohoku Imp. Univ. I 15 (1926) 531/66, 543.
- [3] R. Schafer. W. Klemm, J. Pract. Chem. [4] 5(1(58) 233/41, 240.
- [4] E. Bauer, R. Brunner, Helv, Chi, Acta 17 (1934) 958/69.
- [5] T. G. Pearson, P. L. Robinson, E. M. Stoddart, Proc. Roy. Soc. [London] A 142 (1933) 275/85, 280.

2. 4. 2 H₂-Adsorption

Measurements of the surface tension of Sn in a low pressure H₂-atmosphere showed that the number of adsorbed H₂-molecules is about 10% the total number of surface Sn-atoms. Results of statistical thermodynamic calculations have estimated the adsorption energy to be about:

$$E_{adsorp} = 12.67 \text{ kcal/mol}$$

which is similar to the adsorption energy of di-atomic gas molecules on solid metal surfaces [1].

References:

- [1] M. Ishigura, Mem. Int. Sci. Ind. Res. Osaka Univ., 8 (1951) 78/82.

2. 4. 3 H₂-Diffusion Coefficient

The diffusion coefficient of H₂ in liquid Sn is larger than that of H₂ in liquid Ag, Cu, and Ni [1].

References:

[1] E. M. Sacris, N. A. D. Parlee, Met. Trans., 1 (1970) 3377/82.

2. 4. 4 Reduction of Sn by atomic hydrogen

Glow discharge experiments in the presence of dilute H₂-gas have shown the production of SnH₄ only in the presence of hydrocarbons (catalytic reactions).

2. 4. 5 The SnH and SnD Molecule

Based on the size difference of 0.532 Å between the atomic radius and the radius of the outer orbit, Pollitzer [1] concludes that the H-atom has to overcome a larger barrier to attachment to Sn than to metals in the I and III group.

Significant detail is available on the electron configuration, the rotational and vibrational constants and the inter-nuclear distances of the SnH and SnD molecules.

The dissociation energy has been calculated to be:

$$E_{diss} = 2.7 \text{ eV}$$

References:

[1] P. Pollitzer, J. Phys. Chem., 70 (1966) 4041/4.

2. 4. 6 Solubility of the gas composition H₂-CO-CO₂

The solubility of the gas composition H₂-47, CO-45, CO₂-0.8 (vol. %) was measured between 1000° and 1300°C.

Temperature (°C)	H ₂ -CO-CO ₂ (cm ³) /100 g Sn	Ref.
1000-1300	5 – 12	[1]

References:

[1] S. B. Delachanal, Compt. Rend. 148, 1909) 561/4.

2.5 The Sn-Li System

Li_2SnO_3 is a stable crystalline solid above 1000°C .

Table 10: Formation Temperature and Stability of $\text{Li}_2\text{SnO}_3^*$

Compounds	Formation Temp. ($^\circ\text{C}$)	Stability of $\text{Li}_2\text{SnO}_3^*$	References
SnO_2 ; Li_2O	800	α -Phase: stable below 800°C β -Phase: stable above 1000°C	[1]
SnO_2 ; Li_2OC_3	1000	α -Phase: stable below 800°C β -Phase: stable above 1000°C	[2]

* Li_2SnO_3 is formed from the solid compounds with an approximate molar fraction of 1;1.05, by heating at the formation temperature for about 10 hr.

Li_2SnO_3 is luminescent when exposed to UV-rays (2537 \AA), or α -rays (Po-based 5.6 MeV α 's). TiO_2 activated Li_2SnO_3 can be used as a neutron scintillator, because the α -energy from the ${}^6\text{Li}(n,\alpha){}^3\text{H}$ reaction is of the same range as the α 's from Po.

Li_2SnO_3 is stable in H_2O or methanol. Equimolar mixtures of Li_2O and Li_2SnO_3 heated at 360°C show no sign of dissolution, however, between 450 and 900°C partial formation of Li_8SnO_6 has been reported [1,3]. (Li_8SnO_6 is stable up to 1000°C but melts at 1050°C [5]).

References:

- [1] D. Rade, Diss. Karlsruhe T. H. !958, p. 60
- [2] F. Hund, G. Lang, Naturwissenschaften 38 (1951) 502/3.
- [3] W. Pucall, Silicat-Z., 2 (1914) 65/76.
- [4] D. Rade, Diss. Karlsruhe T. H. !958, p. 64/6.

2.6 The Sn-C System

2.6.1 Solubility

Liquid Sn dissolves only trace amounts of C [1]. For all practical applications, Sn and C are immiscible. Estimates of solubility are given as [1]:

$$\lg x_c = -13800/T + 0.315 \quad (17)$$

where x_c is the mole fraction of C and T is in $^\circ\text{K}$.

References:

- [1] O. Ruff, B. Bergdahl, Z. Anorg. Allgem. Chem., 106 (1919) 76/94, 91.

2. 6. 2 The Sn-C Molecule

The binding energy of the a Sn-C molecule has been estimated to be [1]:

$$E_{\text{bind}} = 60 \text{ kcal/mole}$$

The vibration frequency (ω) of this molecule has been reported to be between 944.4 and 1021 cm^{-1} . [2,3].

References:

- [1] M. L. Huggins, J. Am. Chem. Soc., 75 (1953) 4123/4, 4125.
- [2] Y. P. Varshni, Z. Physik. Chem. (Leibzig), 204 (1955) 188/93, 191.
- [3] P. L. Goodfriend, Can. J. Phys. 45 (1967) 3425/7.

2. 6. 3 The SnCO₃ Molecule

The enthalpy of formation of SnCO₃ has been estimated to be [1]:

$$\Delta H_{298} = -177 \text{ kcal/mole}$$

and that of the formation of Sn(HCO₃)₂ has been estimated to be [1]:

$$\Delta H_{298} = -353 \text{ kcal/mole}$$

and the partial pressure of CO₂ for a hypothetical carbonate of Sn [Sn(CO₃)₂] has been estimated to be [2]:

$$\lg p_{\text{CO}_2} = -895.T + 9.803 \quad (p \text{ in atm; } T \text{ in } ^\circ\text{K}) \quad (18)$$

A related molecule, Sn(HCO₂)₂ has an enthalpy of formation given by:

$$\Delta H = -209 \pm 15 \text{ kcal/mole}$$

Although this compound (Tin-formiate) is stable in air and in vacuum, it does dissociate when heated between 198 and 200°C, without first melting.

References:

- [1] D. E. Wilcox, Ind. Eng. Chem., 55 No. 7 (1963) 32/9, 3.
- [2] E. Erdos, Collection Czech. Chem. Commun., 27 (1962) 2152/67, 2165.

2. 7 The Sn-Si System

Investigations of Sn-Si compounds have been reported only sporadically, with most of the attention given to the SnO-SiO₂ system. Thermodynamic measurements indicate the existence of the Sn₂SiO₄ compound, which can be prepared by melting the two oxides [1,2].

Tin and Si form, what is called a “degenerative” eutectic near the melting temperature of Sn (232°C). For all practical purposes, Si is considered insoluble in liquid Sn at low temperatures. However, the solubility of Si in Sn at 1100°C is about 10 at.%, but increases as the melting temperature of Si (1417°C) is reached [1].

The solubility of Sn in solid Si (k_{Sn-Si}) at 800°C and up to 1412°C has been measured as [3]:

$$\begin{aligned}k_{Sn-Si} &= 6.5 \times 10^{-4} \text{ at } 800^\circ\text{C} \\k_{Sn-Si} &= 6.5 \times 10^{-2} \text{ at } 1412^\circ\text{C}\end{aligned}$$

The enthalpy of mixing at 50 at. % is given by [4]:

$$\Delta H = 1.300 \text{ kcal/g-atom}$$

and for solid Sn in liquid Si, it is [5]:

$$\Delta H = 9.160 \text{ kcal/g-atom}$$

References:

- [1] S. Tamaru, Z. Anorg. Allgem. Chem., 61 (1909) 40/5, 41.
- [2] W. Johnson, M. Hansen, AF-TR-6383 (1951) 1/133, 21, 76; N. S. A. 5 (1951) No. 6757.
- [3] F. A. Trumbore, C. R. Isenberg, E. M. Porbansky, Phys. Chem. Solids 9 (1959) 60/9, 63.
- [4] W. Ptak, Arch. Hutnictwa, 1 (1956) 53/97, 91.
- [5] G. M. Kuznetsov, S. K. Kuznetsova, Izv. Akad. Nauk SSSR Neorgan. Materialy 2 (1966) 643/9; Inorg. Materials (USSR) 2 (1966) 555/60, 557.

2. 7. 1 Diffusion of Sn in Solid Si and Si in Liquid Sn

Between 800°C and 1200°C the diffusion zone of Sn in solid Si rises with increasing temperature. Above 850°C the diffusion rate increases exponentially from 100 nm. The activation energy for Sn diffusion in Si has been estimated to be 7.3 kcal/mole [1,2] and for Si in liquid Sn it is 5 kcal/mole.

References:

- [1] V. N. Lozovskii, A. I. Kalinyuk, V. I. Buddo, Tr. Novocherk. Politekhn. Inst. (1970) No. 208, p. 50/4.
- [2] V. N. Lozovskii, A. I. Kalinyuk, Fiz. Kondens. Sred., (1969/70) 87/90.

2. 7. 2 The Sn-Si Molecule

The binding energy of the hypothetical Sn-Si molecule has been estimated to be [1]:

$$E_{\text{bind}} = 37.0 \text{ kcal/mole at } 300^\circ\text{K}$$

The vibration frequency (ω) of this molecule has been estimated to be between 555.6 and 608 cm^{-1} [2,3].

References:

- [1] P. Manca, Phys. Chem. Solids 20 (1961) 268/73, 269.
- [2] Y. P. Varshni, Z. Physik. Chem. (Leibniz) 204 (1955) 188/93, 191.
- [3] P. L. Goodfriend, Can. J. Phys. 45 (1967) 3425/7.

2. 8 Sn and Oxygen

In dry air, Sn is stable against oxidation at room temperature [1]. The time to develop a layer of oxide (yellow discoloration) has been estimated to be about 3.8×10^8 years [2].

A relative humidity of 80% increases the oxidation rate by about 50% compared with that in dry air [3]. In the presence of H_2O , Sn shows distinct discoloration after 100 days, and in flowing air, oxidation becomes visible within 14 days [4]. Oxidation in humid air results in the formation of an oxide layer, which prevents further oxidation at room temperature. A rise in temperature increases the oxidation rate.

The oxide, which forms with pure O_2 between 0°C and 200°C is a $\alpha\text{-SnO}$ [5]. Above 280°C both SnO and SnO_2 form, while above 390°C only SnO_2 will form [6]. When Sn powder with an average diameter of 2.5×10^{-6} cm is molten at 505°C a 50 Å thick SnO layer is formed [7].

2. 8. 1 Low Pressure Oxidation

At low pressures, 2×10^{-4} Torr, oxidation results only in the formation of SnO regardless of the temperature. At a higher pressure of 5×10^{-3} Torr SnO forms up to a temperature of 400°C . With an increase in temperature, SnO_2 starts to form, and above 630°C only SnO_2 forms [8].

2. 8. 2 Oxidation Mechanism:

The oxidation of Sn starts with the formation of oxide-nuclei, which were measured to be of the order of $2 \times 10^6 \text{ cm}^{-2}$ at an oxygen pressure of above 1 torr. These nuclei consist of oriented $\alpha\text{-SnO}$ platelets, which grow until they cover about 80% of the surface area. This phase constitutes the fasted oxidation rate. Following the coalescence of the

platelets, a logarithmic growth rate sets in, which is dictated by the rate of diffusion of liquid Sn to the surface between the platelets. The rate of diffusion of Sn through the space between the platelets is slow, because of the formation of cavities, which act as diffusion barriers to Sn.

At 220°C and an oxygen pressure of 10 torr, about 1/3 of the surface layer consists of these cavities [9]. The presence of these cavities is responsible for the logarithmic oxidation rate instead of a common parabolic rate. At oxygen pressures below 0.1 Torr the formation of α -Sn dendrites instead of platelets is observed.

2. 8. 3 Solubility of Oxygen in Liquid Sn

The rate of solution of oxygen in molten Sn at 536°C, 600°C, and 700°C is 10^{-8} , 7×10^{-8} , and 10^{-7} g/h, respectively, and the solubility limit at each of these temperature is 6×10^{-6} , 2×10^{-4} , and 6×10^{-4} at. % of oxygen, with the formation of SnO₂. The partial enthalpy and entropy of solution of oxygen in Sn per g-atom oxygen is [10]:

$$\Delta H = -43870 \pm 1000 \text{ cal/g-atom}$$

$$\Delta S = -15.74 \pm 1.10 \text{ cal-g/atom-}^\circ\text{K}$$

Oxygen dissolves in Sn atomically between 780°C and 1180°C and the enthalpy of solution and entropy are then given by [11,12]:

$$\Delta H^\circ = -46060 \text{ cal/g-atom}$$

$$\Delta S^\circ = -11.98 \text{ cal-g/atom-}^\circ\text{K}$$

References:

- [1] M. Traube, Ber. Deut. Chem. Gas. 18 (1885) 1877/1885.
- [2] G. Tammann, W. Koster, Z. anorg. Chem. 123 (1922) 196/224, 208.
- [3] S. C. Britton, K. Bright, Metallurgia 56 (1957) 163/8.
- [4] L. Kenworthy, Trans. Faraday Soc. 31 (1935) 1331/45, 1333.
- [5] C. Luner, Trans. AIME 218 (1961) 13/24, 21.
- [6] G. Shimaoka, I. Yamai, J. Chem.Soc. Japan Pure Chem. Sect. 76 (1955) 965/7.
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- [9] W. E. Boggs, P. S. Trozzo, G. E. Pellissier, J. Electrochem. Soc. 108 (1961) 13/24.
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- [11] W. A Fischer, Arch. Eisenhuttenw. 38 (1967) 422/9, 428.
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2. 9 The SnO-SiO₂ System

The system SnO – SiO₂ exhibits a eutectic at 865°C with a concentration of 66.1 wt% SnO. A concentration of 54.6 wt. % SnO results in melting at 1160°C. Dissolution of SiO₂ by liquid SnO results in the formation of Sn-silicate above 1040°C. Between 1200 and 1250°C, the mixture of molten SiO₂ and SnO results in the formation of Sn₂SiO₄, which is a black crystalline substance. SnSiO₃, which forms around 900°C, has a gold-yellow appearance [1,2].

The activity of SnO (a_{SnO}) in SnO-SiO₂ melts has been determined as a function of SnO molar fraction at 1000, 1050, 1100, and 1150°C [3].

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2. 10 General Literature on Corrosion of Sn with Metals:

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3. Comparison of Thermo-Physical Properties between Sn, Li, and Pb-Li

The thermal conductivity, electrical resistivity, surface tension, dynamic viscosity vapor pressure, and density of Sn, Li, and Pb-17Li are summarized in the following figures.

3.1 Thermal Conductivity of Coolants

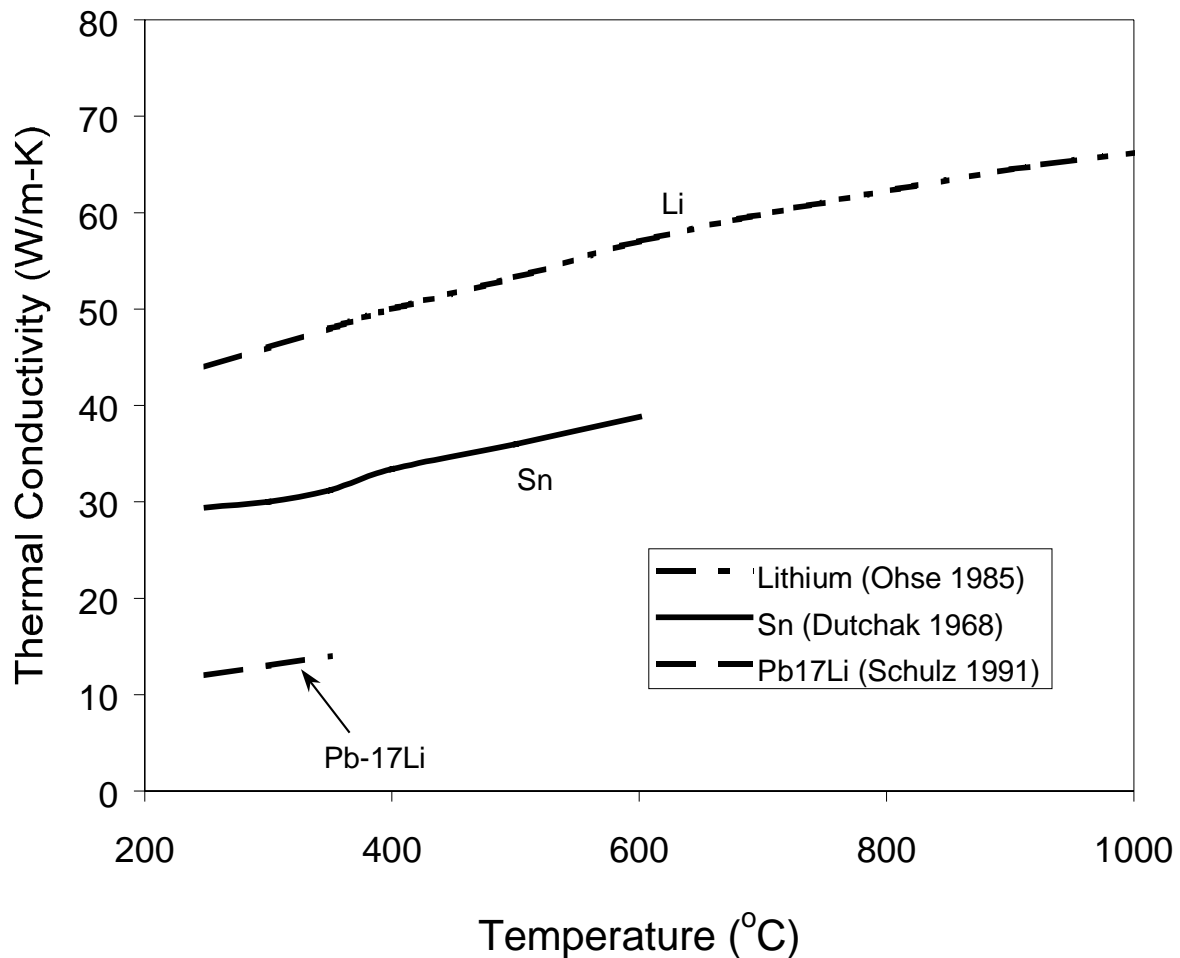


Figure 8: Comparison of thermal conductivity of Sn, Li, Pb-17Li, and Sn-25Li.

References:

- [1] B. Schulz, Fusion Eng. Design 14 (1991) 199.
- [2] R. W. Ohse (Ed.) Handbook of Thermodynamic and Transport Properties of Alkali metals, Inter. Union of Pure and Applied Chemistry Chemical Data Series No. 30. Oxford: Blackwell Scientific Publ., 1985, pp. 987.
- [3] Ya. I. Dutchak, V. P. Osipenko, P. V. Panasyuk, Izv, Vyssh. Zavedenii, Fiz, 1968, No. 10, p. 154/C, C.A. 70[1969] No. 61918.

3.2 High-Temperature Thermal Conductivity of Sn

The rule of mixtures is used to estimate the thermal conductivity of Sn-25Li. High-temperature (>600°C) thermal conductivity data for Sn is estimated using the Wiedeman-Franz equation, which relates the thermal conductivity of metals to their electrical resistivity:

$$k_{th} = LT/\rho + k_o \quad (\text{W/mK})$$

where L is the Lorentz constant ($2.44 \times 10^{-8} \text{ W}\cdot\Omega/\text{K}^2$), ρ is the electrical resistivity ($\Omega\cdot\text{m}$), and k_o is constant in W/mK . The best fit of the Wiedeman-Franz equation to the given data for liquid Sn is with $k_o = 0 \text{ W/mK}$ (see Figure below).

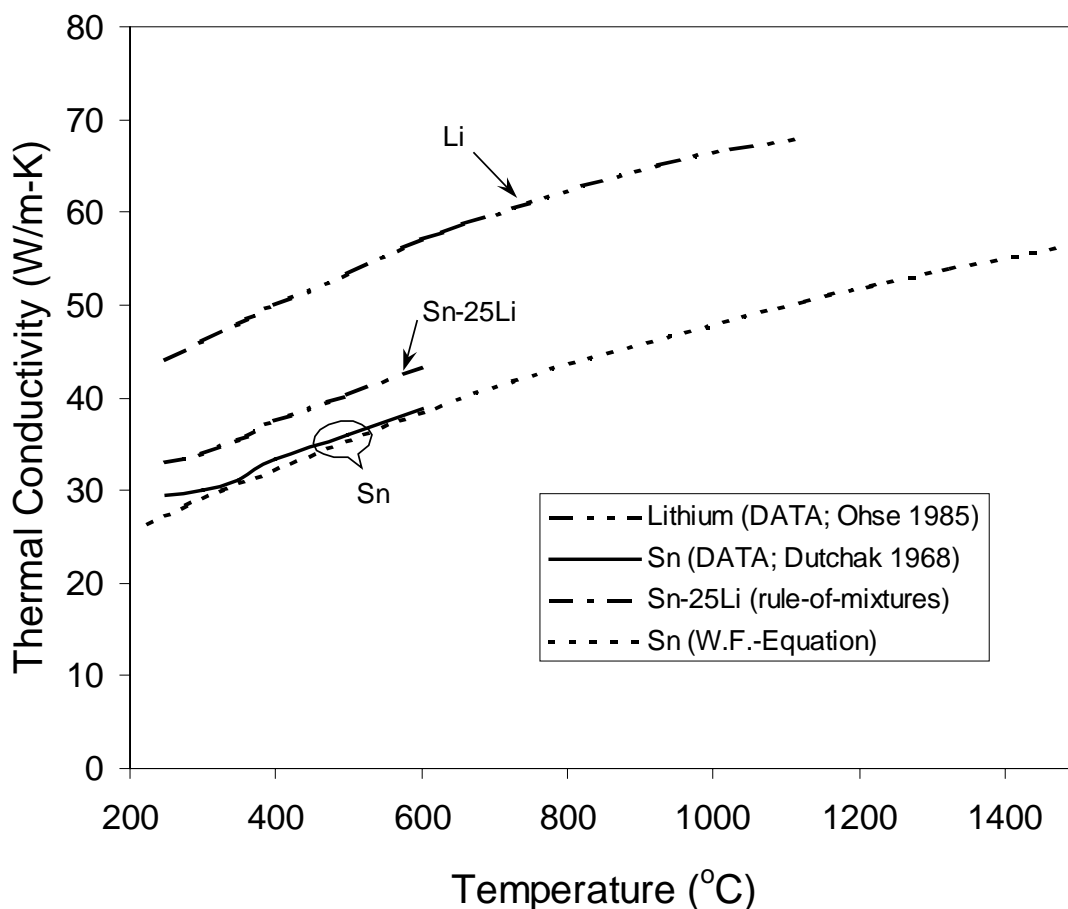


Figure 9: Extrapolated thermal conductivities of liquid Sn and Sn-25Li..

References:

- [1] R. W. Ohse (Ed.) Handbook of Thermodynamic and Transport Properties of Alkali metals, Inter. Union of Pure and Applied Chemistry Chemical Data Series No. 30. Oxford: Blackwell Scientific Publ., 1985, pp. 987.
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3.3 Electrical Resistivity

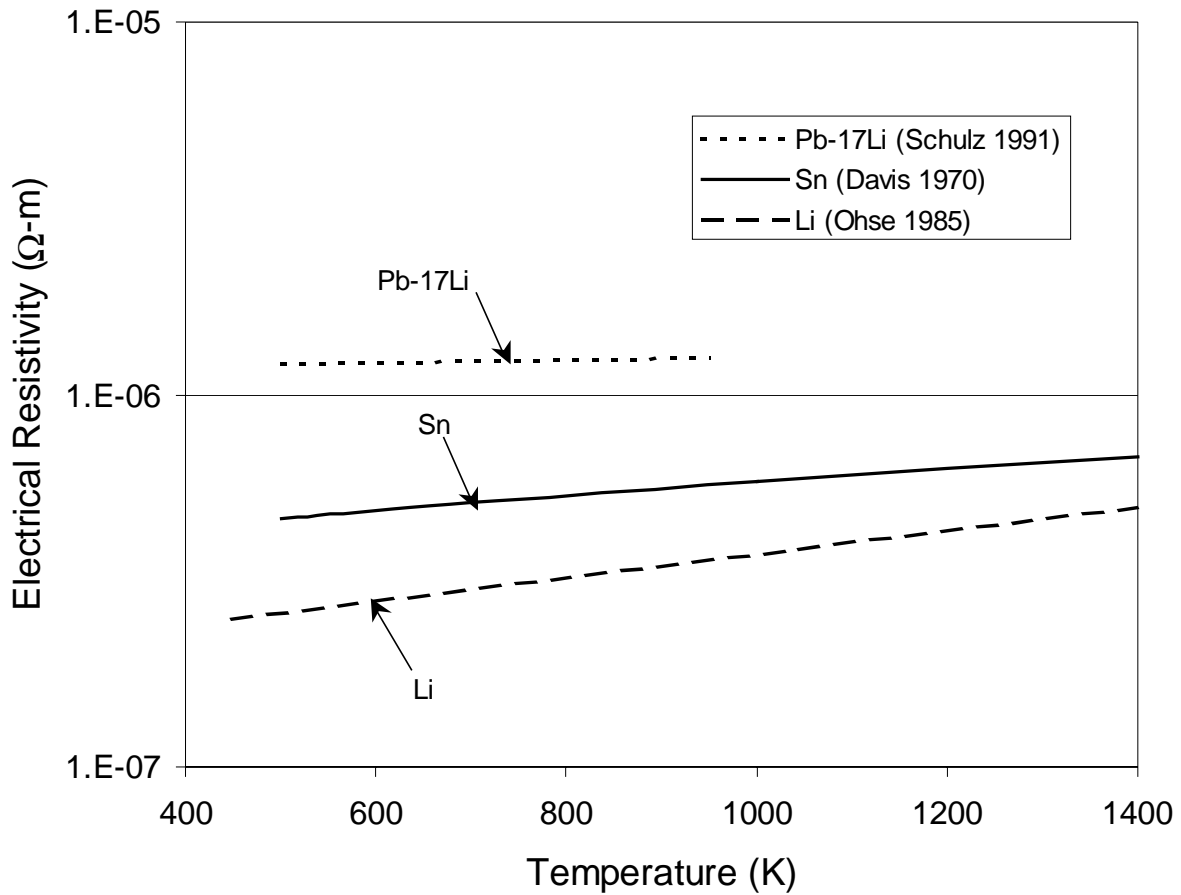


Figure 10: Electrical resistivity of liquid Sn, Pb-17Li, and Li.

References:

- [1] B. Schulz, Fusion Eng. Design 14 (1991) 199.
- [2] H. A. Davis, J. S. L. Leach, Phys. Chem. Liquids 2 (1970) 1/12, 5.
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3.4 Surface Tension

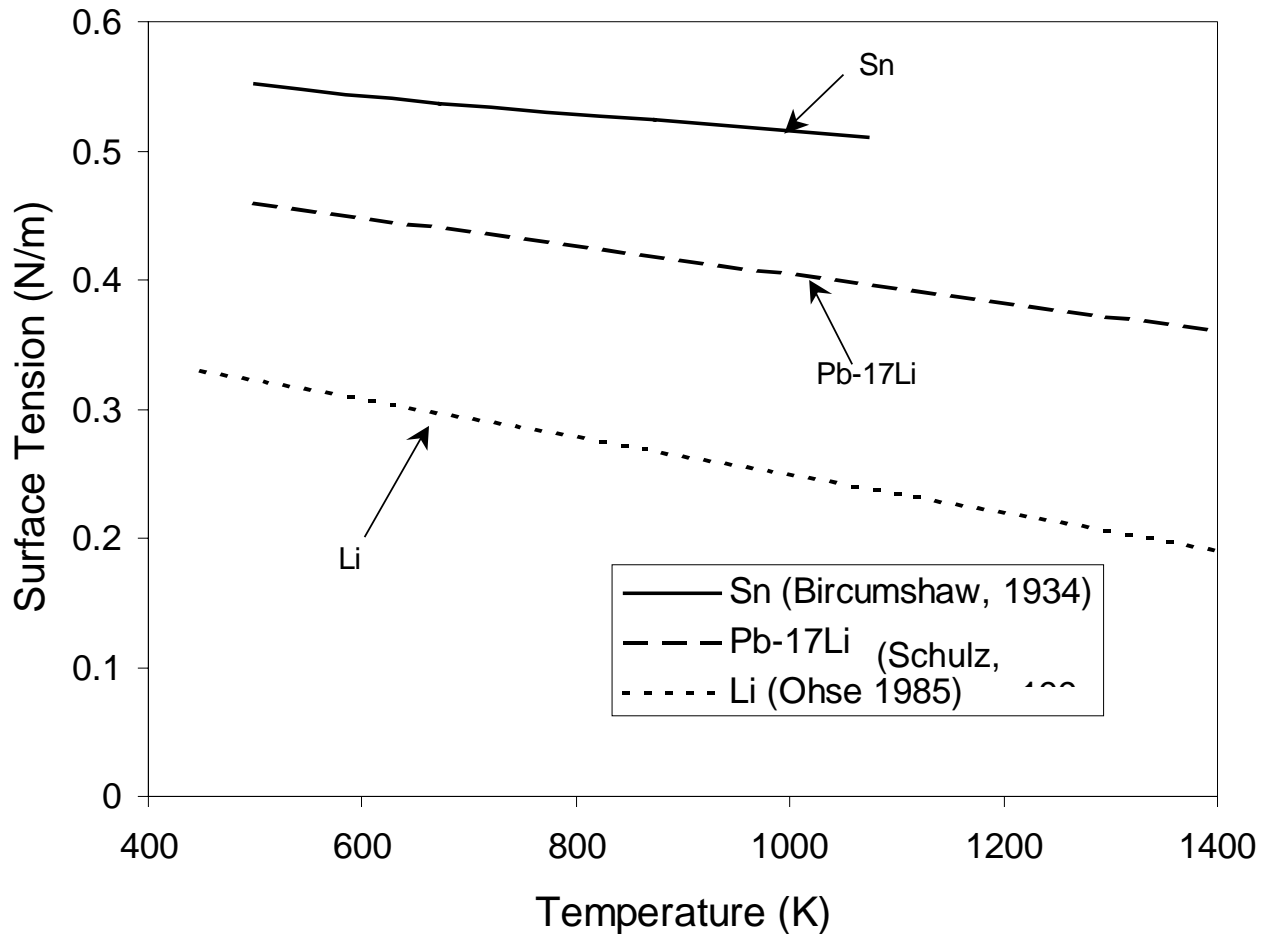


Figure 11: Comparison of surface tension of liquid coolants

References:

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- [2] B. Schulz, *Fusion Eng. Design* 14 (1991) 199.
- [3] R. W. Ohse (Ed.) *Handbook of Thermodynamic and Transport Properties of Alkali metals*, Inter. Union of Pure and Applied Chemistry Chemical Data Series No. 30. Oxford: Blackwell Scientific Publ., 1985, pp. 987.

3.5 Dynamic Viscosity

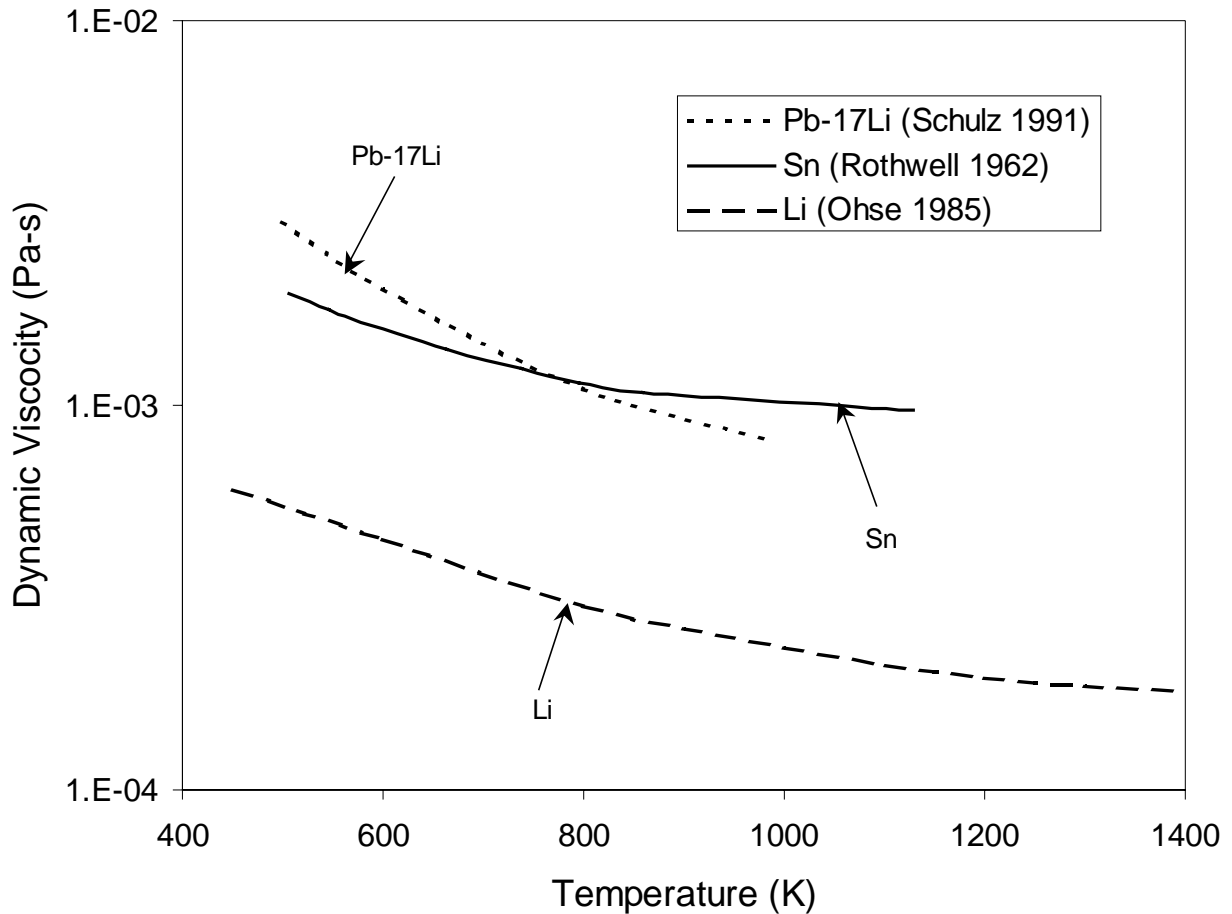


Figure 12: Comparison of the dynamic viscosity of liquid coolants.

References:

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3.6 Vapor Pressure

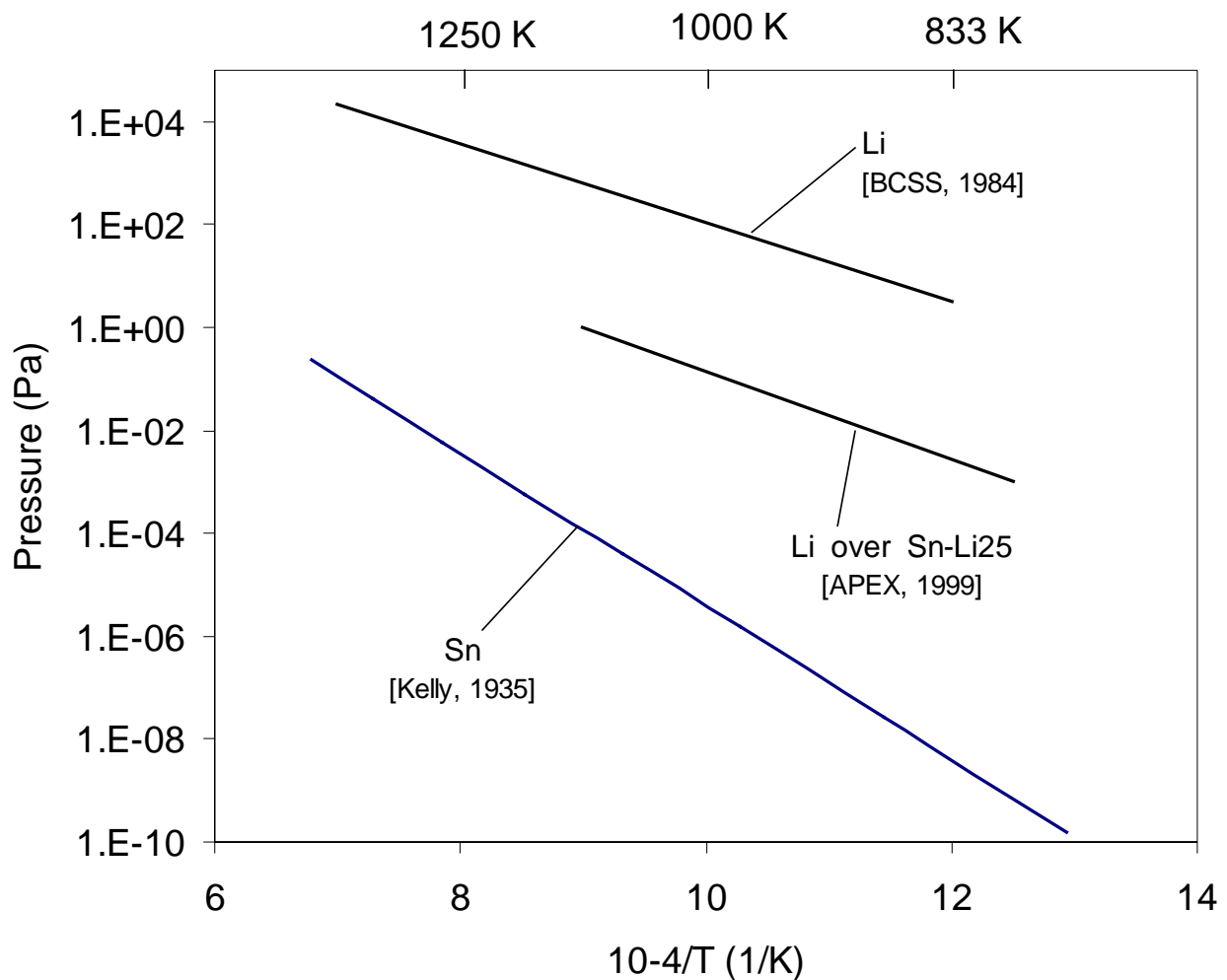


Figure 13: Comparison of the vapor pressure of liquid coolants.

References:

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- [2] M. Abdou, et al., "On the Exploration of Innovative Concepts for Fusion Chamber Technology: APEX Interim Report," University of California School of Engineering and Applied Science, UCLA-ENG-99-206, Nov. 1999.
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3.7 Density of Liquid Coolants

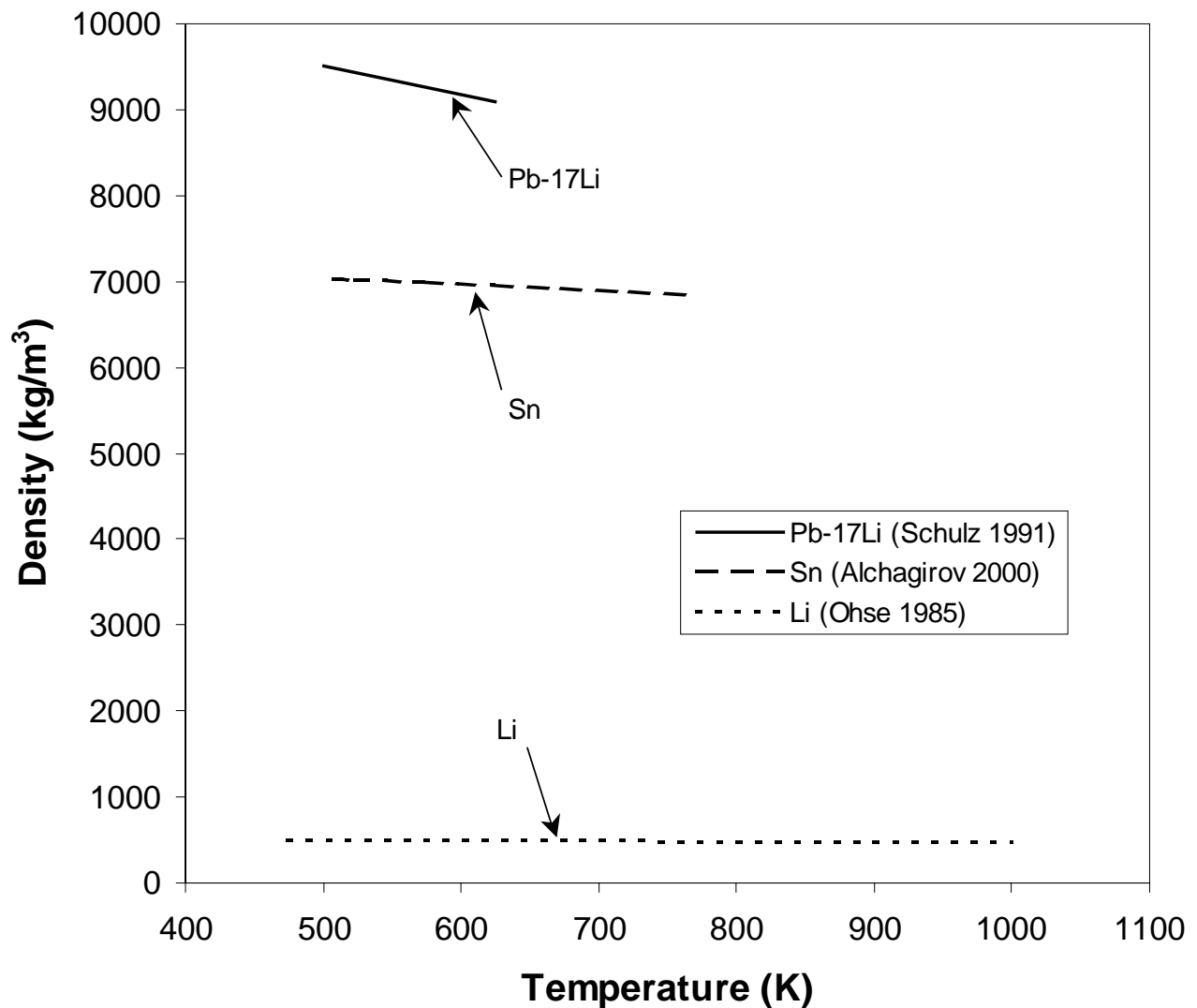


Figure 14: Comparison of the density of liquid coolants.

References:

- [1] B. Schulz, Fusion Eng. Design 14 (1991) 199.
- [2] R. W. Ohse (Ed.) Handbook of Thermodynamic and Transport Properties of Alkali metals, Inter. Union of Pure and Applied Chemistry Chemical Data Series No. 30. Oxford: Blackwell Scientific Publ., 1985, pp. 987.
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3. 8 Density of Liquid Sn-Li Mixtures

The rule of mixtures is used to estimate the density of liquid Sn-Li as a function of volume percent at 500°C.

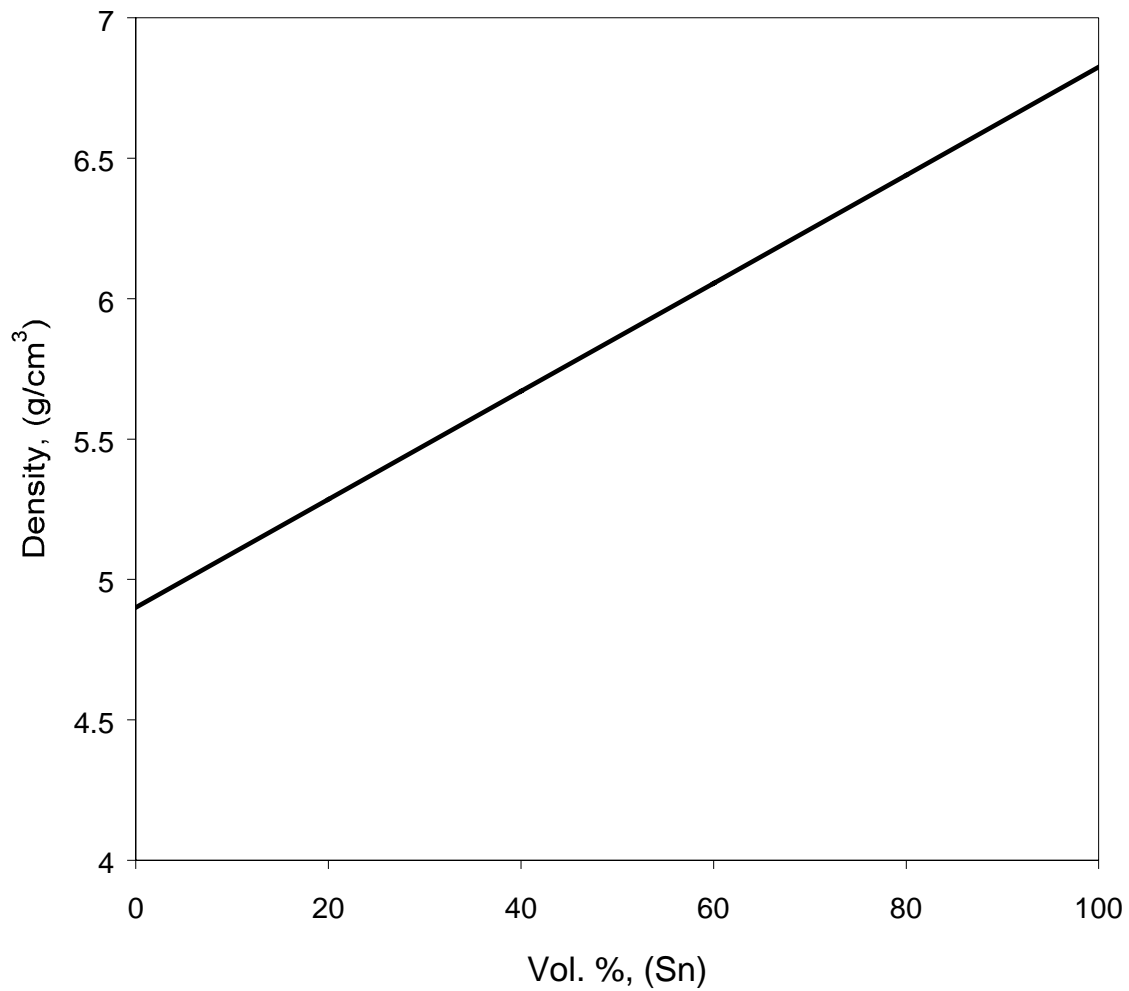


Figure 15: Estimated density of liquid Sn-Li at 500°C.

4. Chemical Compatibility of Ceramic Materials with Sn-Li

We report here on our investigation of the stability of non-metallic coatings and alloying phases in liquid Sn-25Li. First, the activity-temperature-composition relationship of lithium in Sn-Li was estimated. Next, thermodynamic calculations of dissolved solutes (O, C, H, and N) were performed to determine their chemical activity as a function of temperature and composition in saturated liquid Sn-Li. Using the activity of the solutes and the Gibbs free energy of formation of corresponding lithium salts (Li_2O , LiH , Li_3N , and Li_2C_2) the stability region of these salts was mapped out as a function of temperature and composition. Finally, the stability of ceramic materials in Sn-25Li at 773°K was estimated using the Gibb's free energy data of various oxide, nitride, and carbide ceramic materials.

The JANAF thermo-chemical tables were used for the formation Gibbs free energy data of lithium salts (Li_2O , LiH , Li_3N , Li_2C_2). It was found that the oxygen activity is low throughout the composition (20 to 80 at% Li) and the temperature range (500°C to 1500°C), therefore, Li_2O formation is favored. Thus, very low levels of dissolved oxygen can be expected in Sn-Li. Li_2C_2 was found to be stable at high temperatures above 900°C down to low Li-fractions (10%). Carbide coatings should therefore be resistant to dissolution in Sn-25Li. Lithium-nitride, Li_3N , formation is suppressed below 75% Li-fraction over the entire temperature range (500°C-1500°C), therefore, nitride coatings should also be resistant to dissolution. Lithium-hydride, LiH , activities are positive for almost all Li-fractions and the entire temperature range. Therefore, hydride salt formation is suppressed. This indicates, that tritium recovery from Sn-25Li should not pose a problem.

The nitrides are the most stable ceramics, followed by oxides, and then the carbides. However, among the oxides those of iron and nickel based alloys will probably not be stable. It can be assumed that iron and nickel based alloys will also not be preferred structural materials for Sn-Li. In summary, based on the solubility of O, N, H, and C in liquid lithium, the following stability results are found for nitride, oxides, and carbide-based coatings in Sn-25Li at 773°K (Fig. 18):

–Nitrides:

- At 500°C all of the considered nitrides are stable.
- ZrN is the most stable nitride.

–Oxides:

- The most stable oxides are: Sc_2O_3 and Y_2O_3
- Fe_2O_3 , NiO , and Cr_2O_3 decompose.
- All other considered oxides were found to be stable.
- TiO_2 SiO_2 marginally stable.
- B_2O_3 is unstable at Li-fractions above 0.2.

–Carbides

- All carbides including SiC were found to be stable (note: β - SiC is unstable in *pure* Li).
- ZrC is the most stable carbide.

The most stable ceramics are nitrides, followed by oxides, and then by carbides.

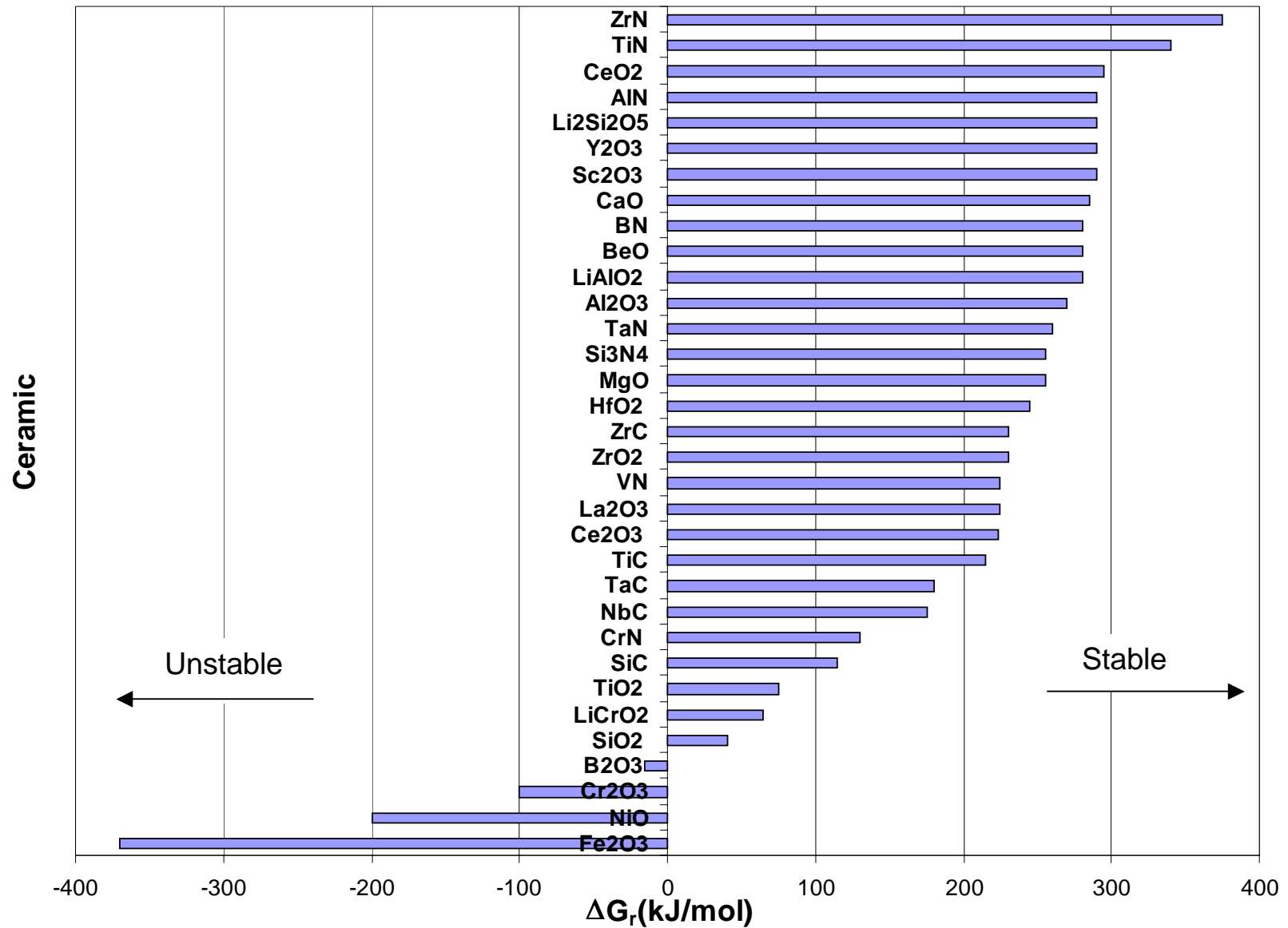


Figure 16: Calculated stability of various nitrides, carbides and oxides in liquid Sn-25Li at 773°K.

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- [5] Borgstedt, H.U., Glasbrenner, H., "Development of a direct insulation layer for a self-cooled liquid metal fusion reactor blanket.," *Fusion Engineering and Design, Fusion Eng. Des. (Netherlands)*, vol.27, (Third International Symposium on Fusion Nuclear Technology, Los Angeles, CA, USA, 26 June-1 July 1994.) 1995, p.659-62.
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¹ The list is by no means to be considered complete.

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