

PROPERTY CORRELATIONS FOR  
LITHIUM, SODIUM, HELIUM, FLIBE AND WATER  
IN FUSION REACTOR APPLICATIONS

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Abstract

General correlations for some properties of lithium, sodium, helium, flibe and water are presented for a range of conditions possible in fusion reactor applications. In particular, density, thermal conductivity, specific heat capacity, viscosity, vapor pressure and electrical resistivity correlations are given. The variation between the suggested correlations and available data is generally less than 20%.

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Abstract

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P.Gierszewski et al, "Property Correlations for Lithium, Sodium, Helium, Flibe and Water in Fusion Reactor Applications"  
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1) Table 1, page 2

References for helium melting temperature and critical temperature are Ref.8.

References for flibe are Ref.11 for melting temperature, and Ref.12 for boiling temperature.

2) Eqn.(2), page 3

$$k = 35. + 0.019 T \quad \text{NOT} \quad 35. - 0.019 T$$

3) Eqn.(14), page 6

$$= \dots + 1.668 \times 10^{-16} (T - 273.)^3 \quad \text{NOT} \quad \dots 1.668 \times 10^{-10} \dots$$

4) Figure 3a, page 9

Density graph: Right vertical axis corresponds to 1.0 MPa, NOT 0.1 MPa.

Property Correlations for  
Lithium, Sodium, Helium, Flibe and Water  
In Fusion Reactor Applications

1. Introduction

A wide variety of fluids are of interest as fusion reactor coolants. In this report, general correlations are presented for important properties of lithium, sodium, helium, flibe and water under conditions expected in fusion reactor applications. In particular, density, thermal conductivity, specific heat capacity, viscosity, vapor pressure and electrical resistivity correlations are given. Table 1 gives general critical point and phase change data.

The suggested property equations are largely based on graphical compatibility with available data. More complex equations were obtained from trial-and-error calculations using multiple linear regression. Suggested uncertainty bands are not based on reported experimental errors or other absolute sources, but are intended to provide a rough measure of the scatter of the data and/or the accuracy of fits to reliable data.

SI units are used in the correlations: temperature (T) in K, pressure (p) in Pa, density ( $\rho$ ) in  $\text{kg/m}^3$ , thermal conductivity (k) in W/m-K, specific heat capacity ( $c_p$ ) in J/kg-K, viscosity ( $\mu$ ) in kg/m-s, and electrical resistivity ( $\eta$ ) in  $\Omega\text{-m}$ .

TABLE 1: Critical Point and Phase Change Data [4]

Property	Lithium	Sodium	Helium	Flibe <sup>+</sup>	Water
Atomic weight	6.940	22.991	4.003	32.8	18.016
Melting temperature* (K)	453.7	371.0	0.95 [8]	732 [11]	273.1
Boiling temperature* (K)	1615.	1151.2	4.21	1700 [12]	373.1
Critical temperature (K)	3800.	2500.	5.25 [8]	---	647.1
Critical pressure (MPa)	97.0	37.0	0.229	---	22.1
Critical density (kg/m <sup>3</sup> )	100.	180.	69.3	---	318.

\* At 0.101 MPa

<sup>+</sup>Peritectic flibe, 67.2 mole % LiF

2. Lithium [1,2,3,4]

Property data for liquid lithium are correlated by the curves shown in Figures 1a, b, c and d. The lower bound on lithium's useful operating temperature range is its melting point, while the upper bound is partially based on chemical incompatibility with potential structural materials and partially on its vapor pressure. Lithium is a low pressure coolant because of its high boiling point temperature even at low pressures. Correlations presented here are thus suggested for the range 500 to 1600 K and 0.1 to 1.0 MPa.

$$\rho = 563. - 0.101 T \quad (5\%) \quad (1)$$

$$k = 35.0 - 0.019 T \quad (15\%) \quad (2)$$

$$c_p = 4640 - 0.885 T + 3.91 \times 10^{-4} T^2 \quad (2\%) \quad (3)$$

$$\mu = 0.0312 \exp(253/T) / T^{0.7368} \quad (30\%) \quad (4)$$

Eqns.(1) and (2) are from Ref.[1] , while Eqns.(3) and (4) are fits to data from Ref.[4]. The accuracy of these equations is limited by the scatter in the data itself. The suggested error ranges are indicated beside the equations and on the figures, and are simply based on the graphical spread of the temperature-dependent data. There is large variation between reported viscosity correlations. Ref.[1] gives two equations, one exactly a factor of ten smaller than Eqn.(4). Ref.(2) gives a curve for viscosity which is much higher than the other data, and also reports a correlation (valid over a very limited range) which is consistent with the recommended correlation.

No pressure dependence is included in these correlations since it is expected to be small and since no data were available. Ref.[4] does give pressure variation for lithium vapor thermal conductivity and specific heat as less than 60% and 10%, respectively, over 0.1 to 0.5 MPa and temperatures up to 2000K. The variation in liquid properties should be

much less and within the suggested error ranges.

Also, Ref.[2] suggests the following correlation for vapor pressure:

$$p = 1.33 \times 10^{10} \exp(-1.88 \times 10^4 / T) \quad (20\%) \quad (5)$$

which agrees with Ref.[4] to within about 20%.

Ref.[5] gives electrical resistivity as:

$$\eta = 1.507 \times 10^{-7} + 2.416 \times 10^{-10} T + 4.071 \times 10^{-14} T^2 - 1.819 \times 10^{-17} T^3 \quad (5\%) \quad (6)$$

which agrees with Ref.[2] within 5%.



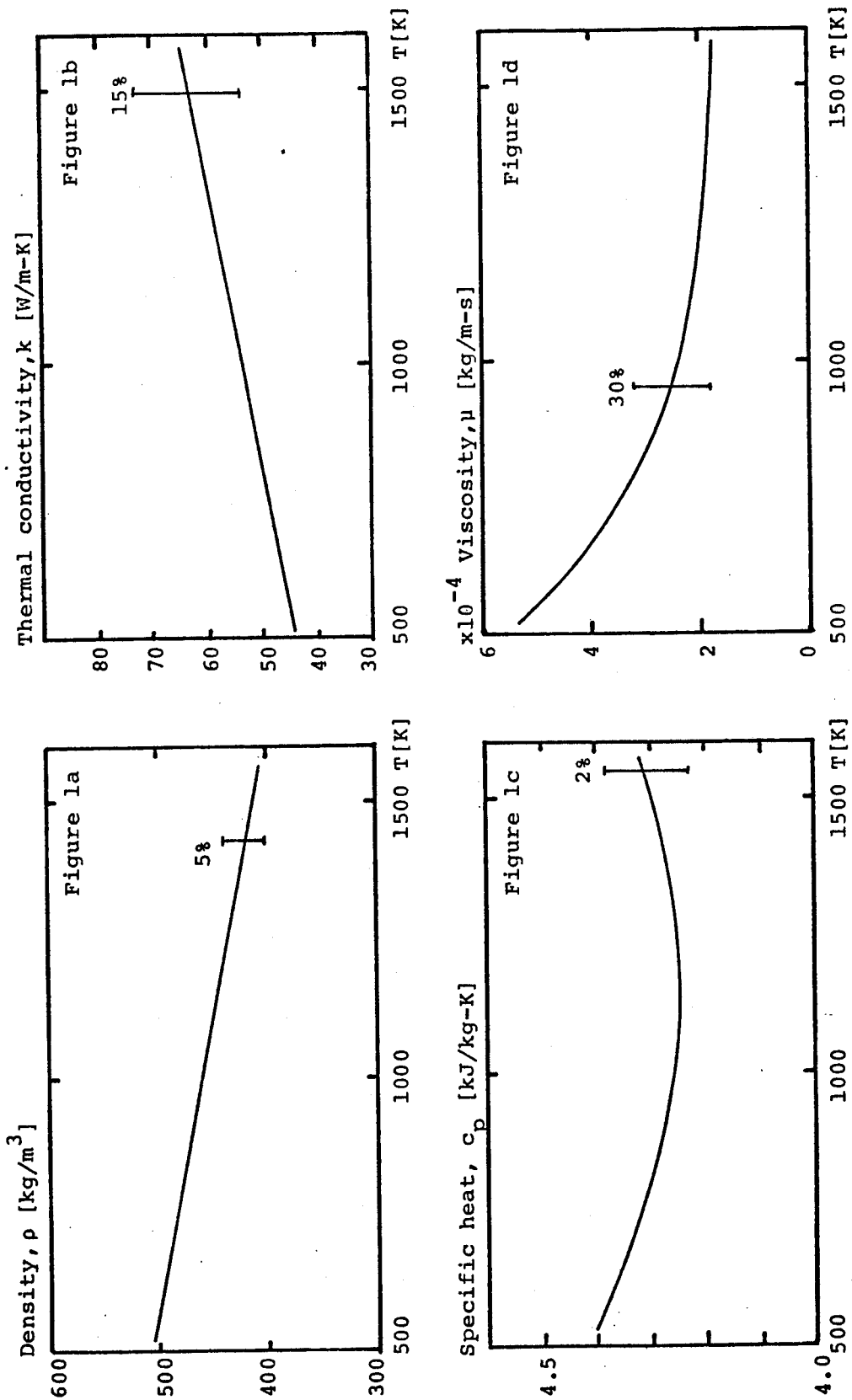


FIGURE 1: Property correlations for liquid lithium.

3. Sodium [2,3,4,6,7]

Property data for liquid sodium are correlated by the curves shown in Figures 2a, b, c and d. As with lithium, the temperature bounds are based on melting at the low end and boiling and chemical compatibility at the high end. Sodium is also a low pressure coolant. The following correlations are for 400 to 1500 K and 0.1 to 1.0 MPa.

$$\rho = 1004. - 0.2139 T - 1.105 \times 10^{-5} T^2 \quad (1.5\%) \quad (7)$$

$$k = 110. - 0.0645 T + 1.173 \times 10^{-5} T^2 \quad (5\%) \quad (8)$$

$$c_p = 1630. - 0.833 T + 4.62 \times 10^{-4} T^2 \quad (6\%) \quad (9)$$

$$\mu = 3.24 \times 10^{-3} \exp(508/T) / T^{0.4925} \quad (5\%) \quad (10)$$

Eqn.(7) is from Ref.[7], with a reported accuracy of 1.5%. All sources give virtually the same results for saturation density. Eqns.(8), (9) and (10) are from Ref.[6]. Again, no pressure dependence is given, nor is any reported.

Since sodium boils at 1150 K at 0.1 MPa, it is necessary to make sure that liquid properties are applicable. Ref.[7] gives the vapor pressure as:

$$p = 2.639 \times 10^9 \exp[-11485/T - 3.418 \times 10^5/T^2] \quad (1.5\%) \quad (11)$$

with a reported accuracy of 1.5%.

Ref.[7] also gives correlations for vapor density and heat capacity:

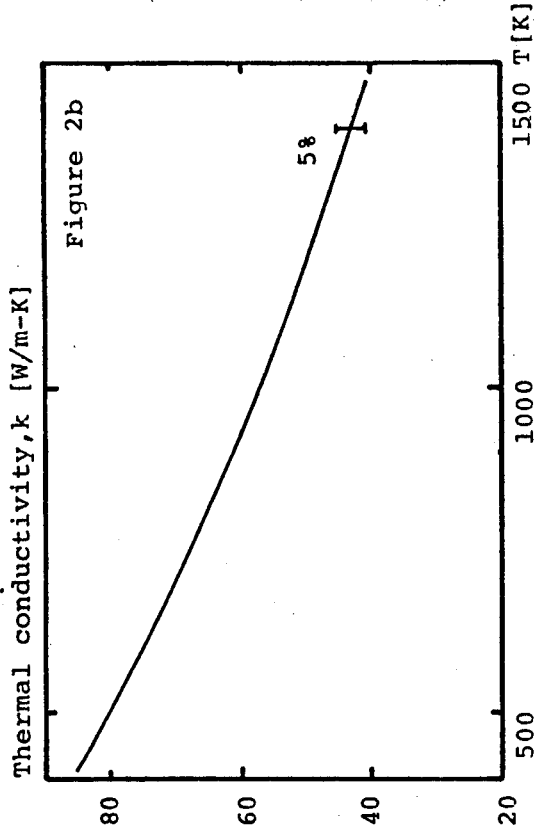
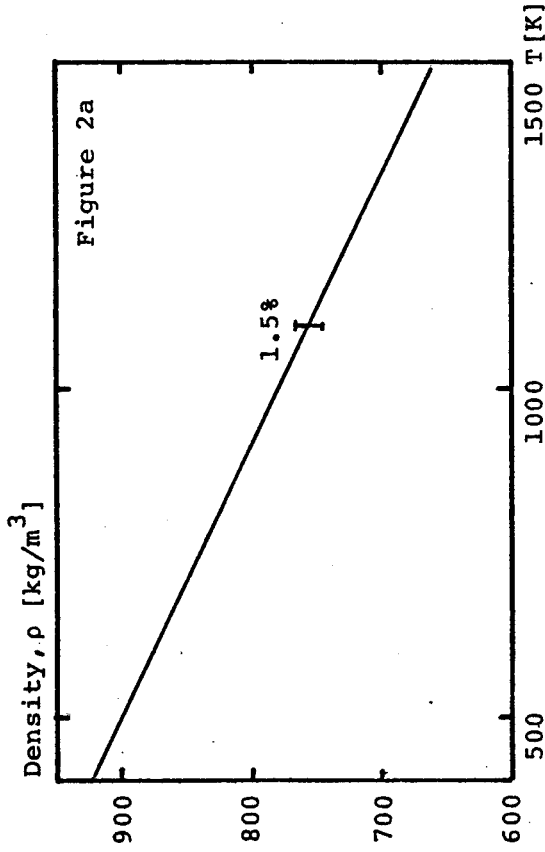
$$\rho = p (4144/T - 7.446 + 0.01377 T - 1.083 \times 10^{-5} T^2 + 3.890 \times 10^{-9} T^3 - 4.922 \times 10^{-13} T^4) \quad (1.5\%) \quad (12)$$

$$c_p = 2141. - 22.40 T + 7.979 \times 10^{-2} T^2 - 1.062 \times 10^{-4} T^3 + 6.787 \times 10^{-8} T^4 - 2.113 \times 10^{-11} T^5 + 2.583 \times 10^{-15} T^6 \quad (1.5\%) \quad (13)$$

Ref.[6] gives electrical resistivity as:

$$\eta = 6.142 \times 10^{-8} + 3.505 \times 10^{-10} (T-273.) + 5.690 \times 10^{-14} (T-273.)^2 + 1.668 \times 10^{-10} (T-273.)^3 \quad (7\%) \quad (14)$$

which agrees with Refs.[2] and [3] within 7%.



7.

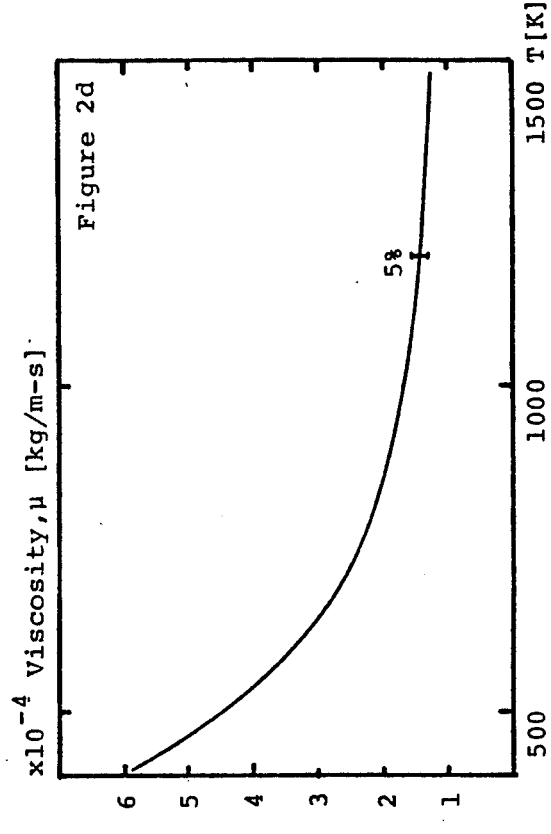
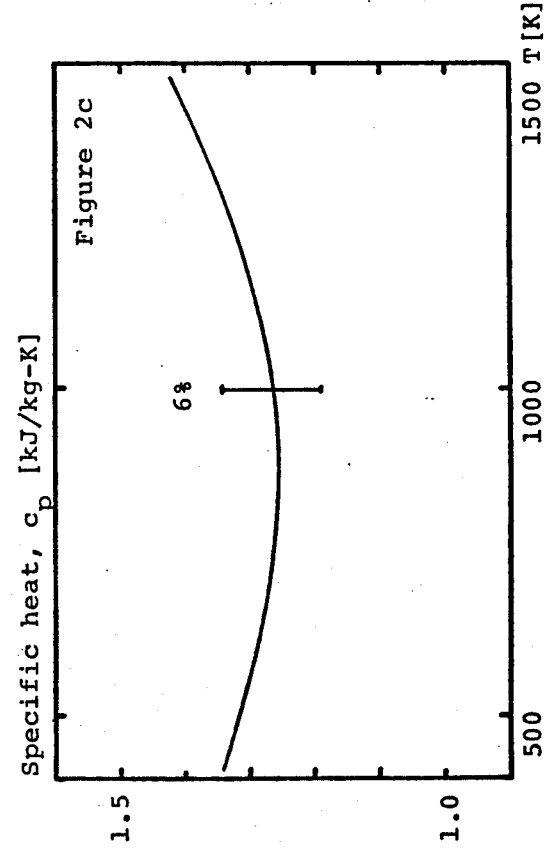


FIGURE 2: Property correlations for liquid sodium.

4. Helium [4,8,9,10]

Property data for gaseous helium are correlated by the curves shown in Figures 3a, b, c and d. The temperature and pressure bounds are based on structural limits for materials in contact with the helium and on practical ranges for high heat transfer rate helium coolant in power systems. The correlations, then, are for 400 to 1600 K and 0.1 to 10. MPa.

$$\rho = 4.80 \times 10^{-4} p/T \quad (4\%) \quad (15)$$

$$k = 0.0640 + 3.23 \times 10^{-4} T - 3.13 \times 10^{-8} T^2 \quad (5\%) \quad (16)$$

$$c_p = 5190. \quad (1\%) \quad (17)$$

$$\mu = 8.33 \times 10^{-6} + 4.16 \times 10^{-8} T - 5.30 \times 10^{-12} T^2 \quad (4\%) \quad (18)$$

Eqn.(15) is the ideal gas law. It agrees with Refs.[4] and [10] to within 4%, with the poorest match at high pressures. Eqn.(16) fits the data in Refs.[4], [8], [9] and [10] to within 5%. The variation with pressure is less than 2%, with maximum variation at lower temperatures. Eqn.(17) agrees with Refs.[4] and [10] to 0.5%, and the older data of Ref.[9] to 1%. Eqn.(18) matches Refs.[4],[8],[9] and [10] to about 4% and the pressure variation is less than 0.5%.

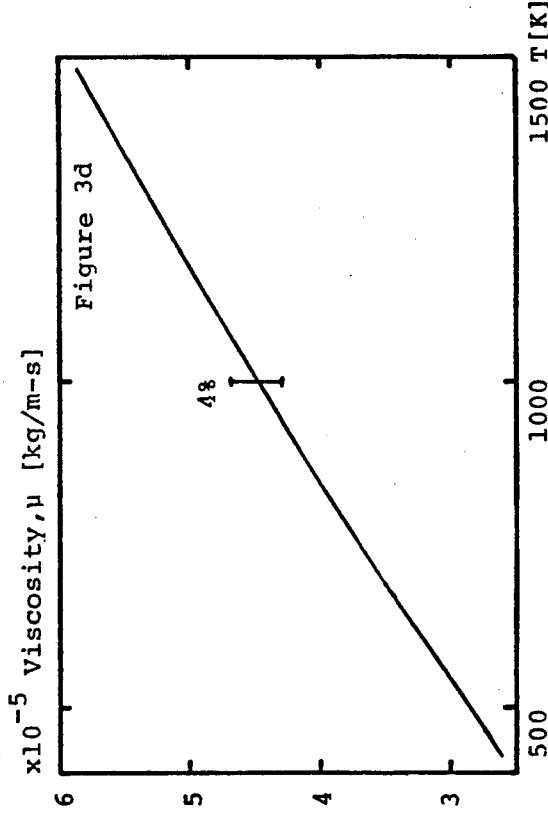
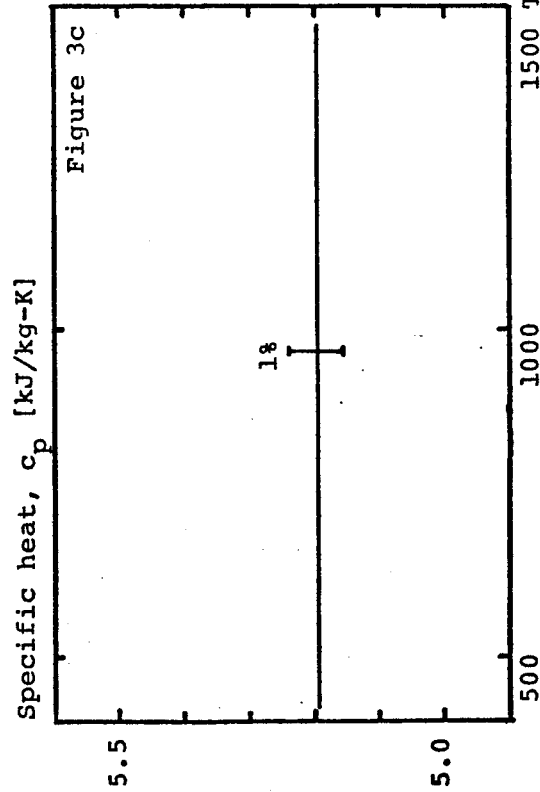
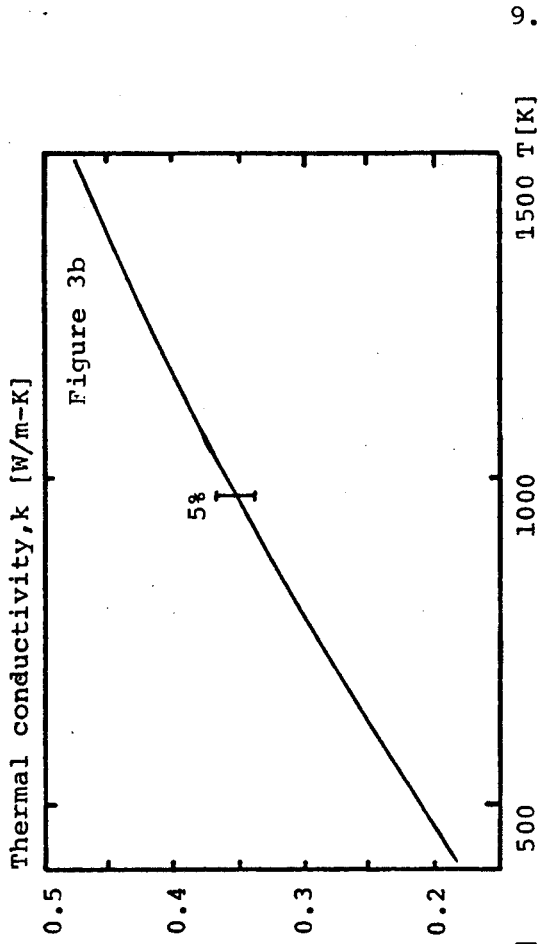
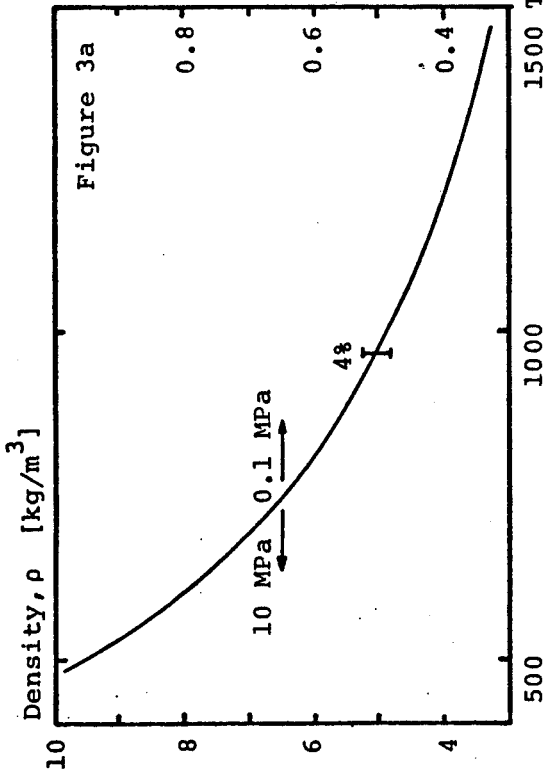


FIGURE 3: Property correlations for gaseous helium.

5. Flibe [11,12,13,14,15,16]

Flibe is a  $\text{LiF-BeF}_2$  salt compound. Property data for the molten state are roughly correlated by the curves shown in Figures 4a, b, c and d. There is some dependence on the LiF fraction. Practical interest in flibe concentrates between its peritectic and eutectic points (67 and 47 mole % LiF, respectively<sup>[11]</sup>) where the melting point is lowest. The correlations presented are limited by available data to 600 to 1200 K. Little variation over 0.1 to 1.0 MPa is expected, although no data were found.

$$\rho = 2330. - 0.42 T \quad (4\%) \quad (19)$$

$$k = 1.0 \quad (20\%) \quad (20)$$

$$c_p = 2380. \quad (20\%) \quad (21)$$

$$\mu = 1.16 \times 10^{-4} \exp(3760/T) \quad (22)$$

Eqns.(19) to (21) are from peritectic flibe data but correlate the general data with the given uncertainty ranges. The largest variation is in viscosity where the agreement over 47% to 69% LiF is only within a factor of ten, but over 66 to 69% the match is within 40%.

Ref.[12] gives the vapor pressure and electrical resistivity of peritectic flibe as:

$$p = 1.46 \times 10^{11} \exp(-24180/T) \quad (23)$$

$$\eta = 1/(0.60 T - 310.) \quad (24)$$

The melting temperature varies with LiF concentration over 47 to 67 mole % LiF roughly as<sup>[11]</sup>:

$$T = 1940 x - 1260 x^2 - 1 \quad (1\%) \quad (25)$$

where x is mole fraction LiF.

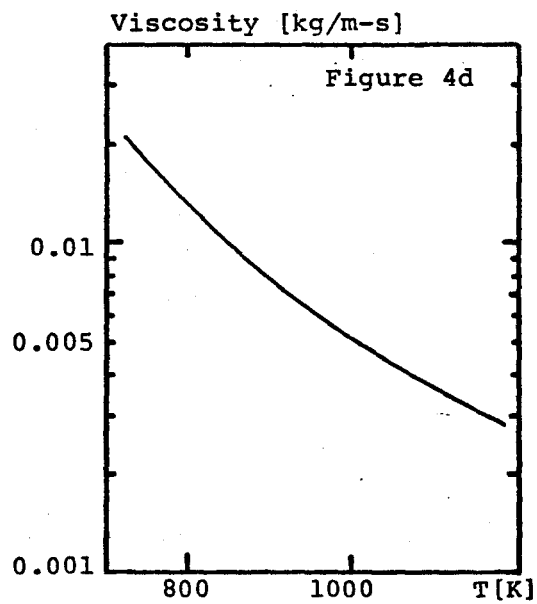
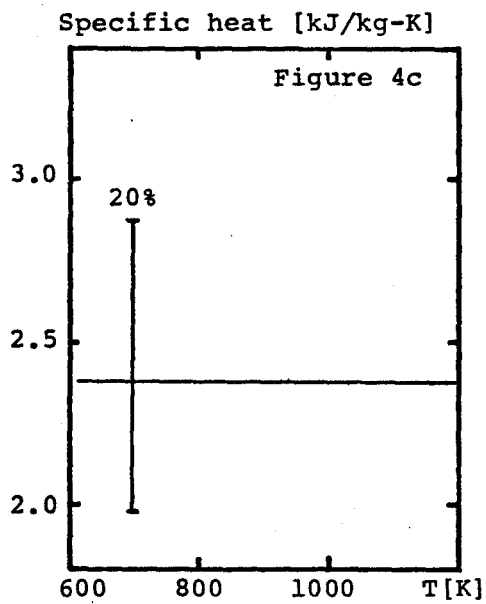
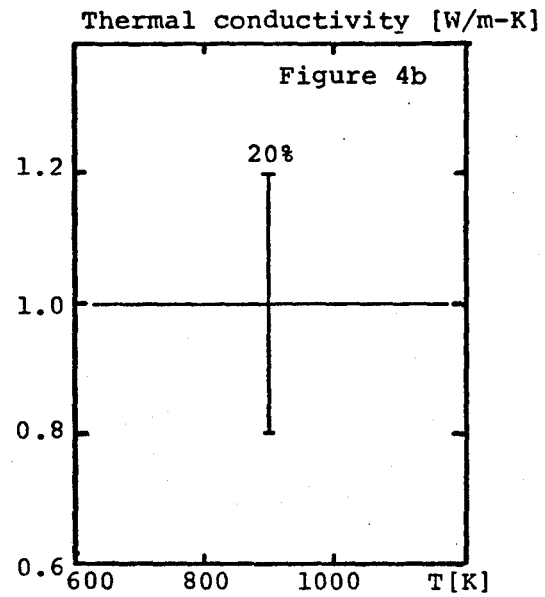
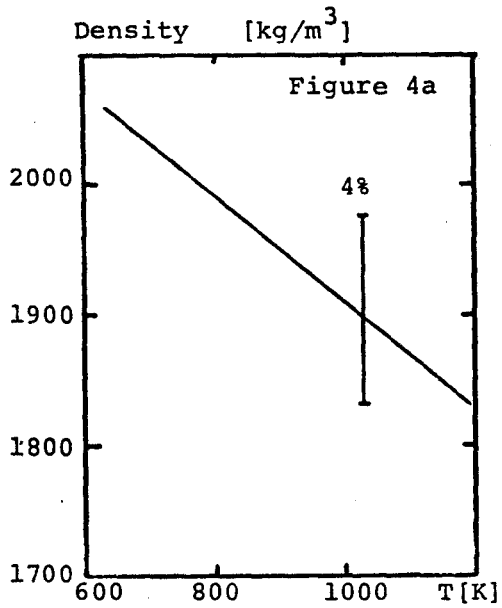


FIGURE 4: Property correlations for molten flibe.

6. Water [4,8,17]

Property data for water and steam are correlated by the curves in Figures 5 and 6 respectively. The useful range of these correlations is at least 300 to 640 K and 1 to 15 MPa.

$$\rho_l = -4276. + 53.24 T - 0.1953 T^2 + 3.097 \times 10^{-4} T^3 - 1.824 \times 10^{-7} T^4 \quad (6\%) \quad (26)$$

$$\rho_v = 0.576 + p (2.483 \times 10^{-5} - 1.410 \times 10^{-12} p) + (p/T) (-2.616 \times 10^{-2} + 1.016 \times 10^{-9} p + 7.589/T) \quad (20\%) \quad (27)$$

$$k_l = 0.686 + 7.3 \times 10^{-10} p - 5.87 \times 10^{-6} (T-415)^2 \quad (5\%) \quad (28)$$

$$k_v = -7.210 \times 10^{-3} + p (8.309 \times 10^{-8} + 2.818 \times 10^{-15} p) + T (6.740 \times 10^{-5} + 3.895 \times 10^{-8} T) + pT (-2.854 \times 10^{-10} - 4.067 \times 10^{-18} p + 2.417 \times 10^{-13} T) \quad (5\%) \quad (29)$$

$$c_{pl} = 4028. + 128.8/[1-T/650] + 4.674/[1-T/650]^2 \quad (6\%) \quad (30)$$

$$c_{pv} = 2709. + (p/T) (-8.594 \times 10^{-1} - 2.378 \times 10^{-7} p) + 1.062 \times 10^{-3} T + 1.686 \times 10^{-4} p/T - 277.2 T^2/p \quad (25\%) \quad (31)$$

$$\mu_l = 25.3/[-8.58 \times 10^4 + 91. T + T^2] \quad (7\%) \quad (32)$$

$$\mu_v = 11.4/[1.37 \times 10^6 - 844. T - T^2] \quad (20\%) \quad (33)$$

Eqn.(26) is from saturation density data. Eqn.(27) fits superheated vapor density from 300 to 650 K and 1 to 15 MPa within 20%, with poorest match at 1 MPa. For 0.1 MPa, this equation consistently overestimates the density by a factor of 2.5. Eqn.(28) is from the THERMIT<sup>[18]</sup> program where it is said to be within 5% for 273 to 573 K and up to 15 MPa. We find it fits the data in Ref.[17] to within 2% over 300 to 650 K and 0.1 to 15 MPa. Eqn.(29) fits superheated vapor data in Refs.[4] and [17] to within 5% over 373 to 650 K and 0.1 to 15 MPa. It is an improvement over the corresponding equation in THERMIT which has a maximum error of about 10% at high pressure and superheat. The liquid heat capacity is a fit to saturation data, but the variation for subcooled properties



is less than 2%. Eqn.(30) is in error by less than 6% for temperatures between 300 and 643 K. Since no data was available near the critical point where the specific heat capacity rises to infinity, the error is uncertain between 643 and 647 K. Eqn.(31) for superheated vapor heat capacity agrees with Ref.[4] to within 25% for 1 to 15 MPa, and to within 50% for 0.1 MPa. Eqns.(32) and (33) are also from THERMIT. The stated accuracy is 6% for 273 to 623 K and 3% for 373 to 623 K, respectively. Over 0.1 to 15 MPa and 300 to 650 K, these correlations agree with Ref.[17] to within 7% and 20%.

The vapor pressure of water can be calculated through an equation taken from THERMIT:

$$p = 5.157 \times 10^{-5} (T-255.2)^{4.484} \quad (1\%) \quad (31)$$

over 0.1 to 15 MPa.

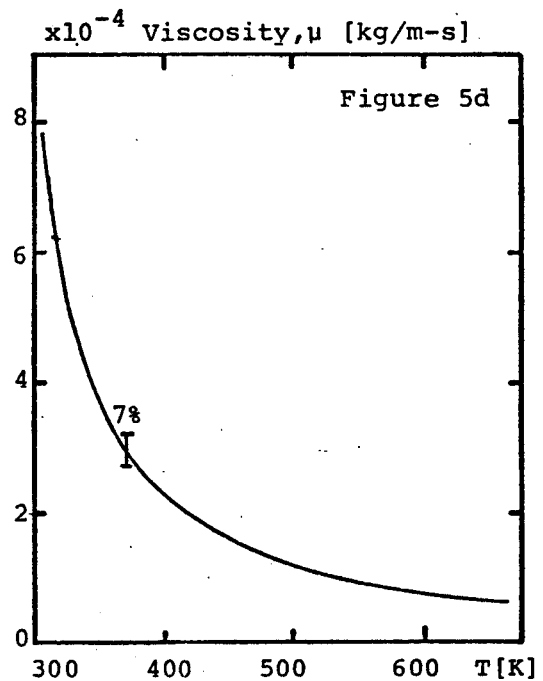
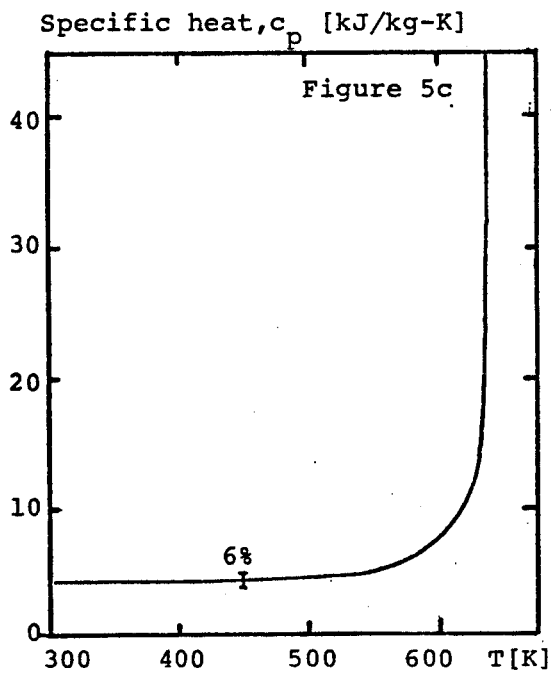
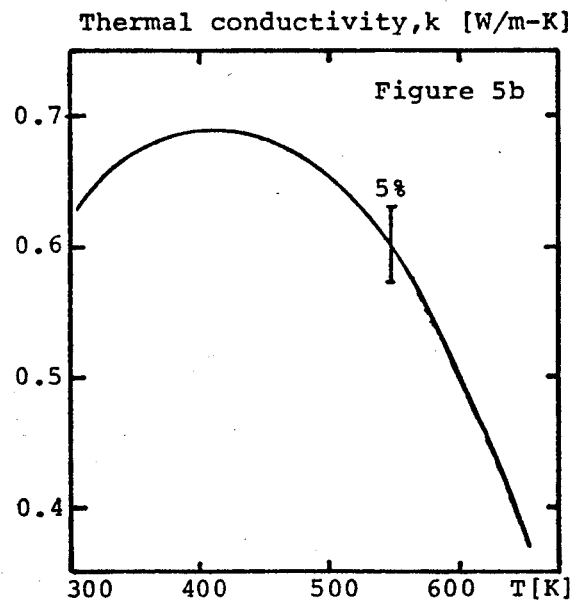
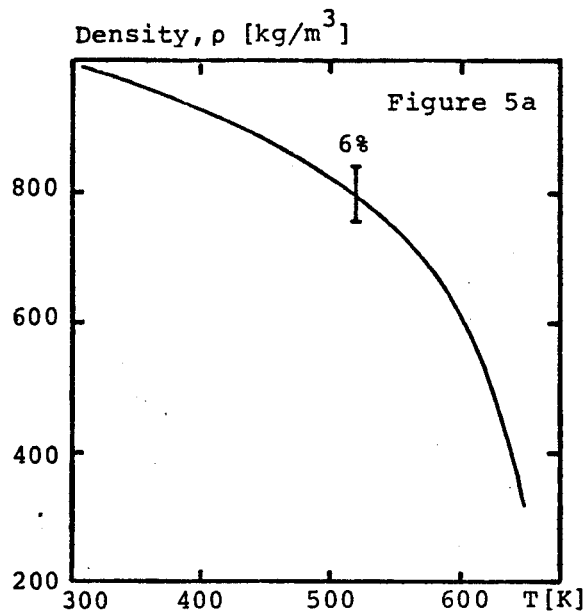


FIGURE 5: Property correlations for liquid water.

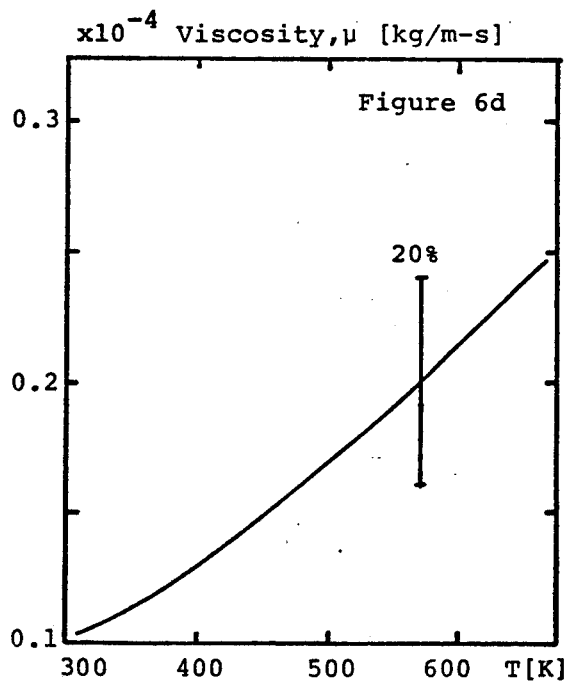
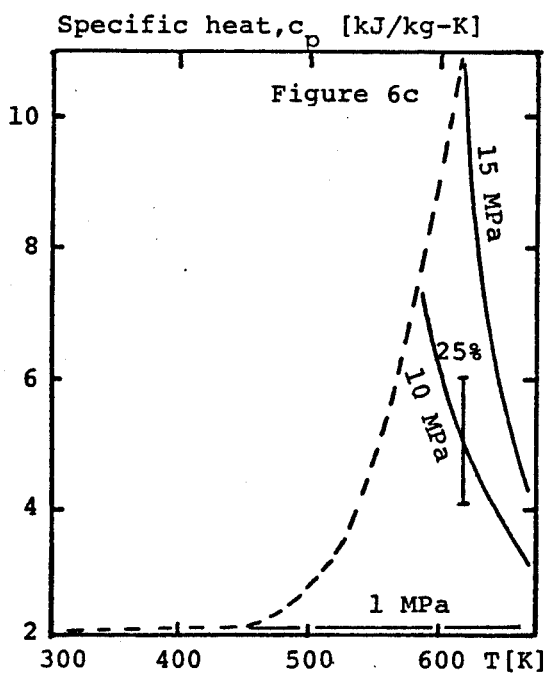
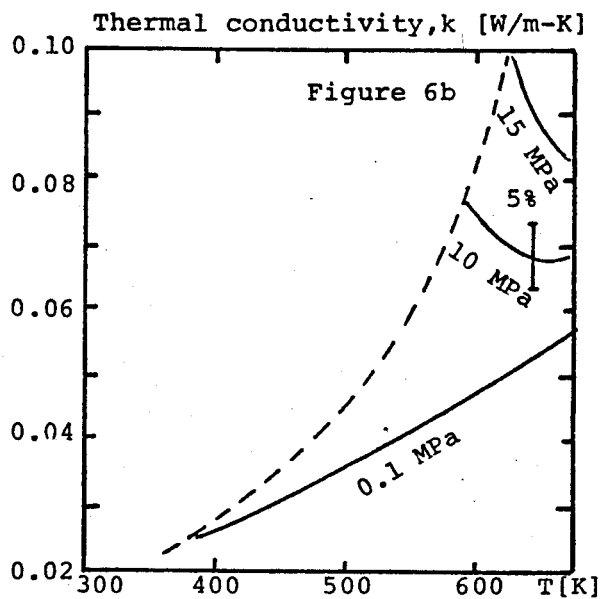
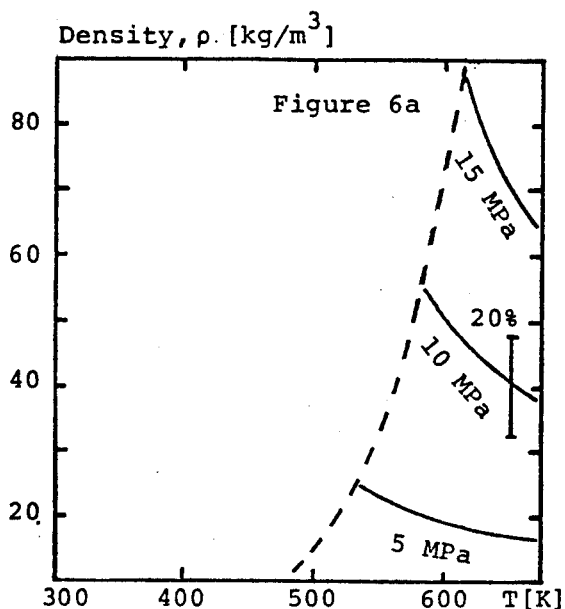


FIGURE 6: Property correlations for steam.

## 7. Summary

Density, thermal conductivity, specific heat capacity, viscosity, vapor pressure and electrical resistivity correlations are presented for lithium, sodium, helium, flibe and water under conditions expected in fusion reactor applications. The equations were extracted from other sources or derived from trial-and-error multiple linear regression fits. The variation between the suggested correlations and available data is generally less than 20%.

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