



3 4456 0274739 3

ORNL/TM-10622

ornl

**OAK RIDGE
NATIONAL
LABORATORY**

MARTIN MARIETTA

An Evaluation of Some Thermodynamic and Transport Properties of Solid and Liquid Lithium over the Temperature Range 200–1700 K

R. K. Williams
G. L. Coleman
D. W. Yarbrough

OAK RIDGE NATIONAL LABORATORY
CENTRAL RESEARCH LIBRARY
DEPARTMENT OF ENERGY
KNOX, TENNESSEE 37831
LIBRARY LOAN COPY
DO NOT TRANSFER TO ANOTHER PERSON
If you wish someone else to use this
report, send its name with report and
the library will arrange a loan

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes - Printed Copy A03; Microfiche A01

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ORNL/TM-10622
Distribution
Category UC-404

Metals and Ceramics Division

AN EVALUATION OF SOME THERMODYNAMIC AND TRANSPORT PROPERTIES
OF SOLID AND LIQUID LITHIUM OVER THE TEMPERATURE
RANGE 200-1700 K

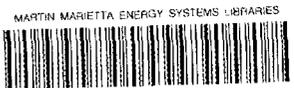
R. K. Williams, G. L. Coleman, and D. W. Yarbrough

Date Published - March 1988

NOTE: This document contains information of
a preliminary nature. It is subject to revision
or correction and therefore does not represent
a final report.

Prepared for the
Office of Space and Defense
Power Systems
AF 60 10 10 0

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400



3 4456 0274739 3

CONTENTS

LIST OF FIGURES	v
ABSTRACT	1
INTRODUCTION	1
DATA EVALUATIONS	2
DENSITY AND THERMAL EXPANSION	2
ENTHALPY, SPECIFIC HEAT, AND LATENT HEAT OF FUSION	5
VAPOR PRESSURE AND HEAT OF VAPORIZATION	7
COMPRESSIBILITY	9
SURFACE TENSION	9
VISCOSITY	9
ELECTRICAL RESISTIVITY	13
THERMAL CONDUCTIVITY	15
REFERENCES	18
APPENDIX. SUMMARY OF SELECTED PROPERTIES OF LITHIUM	23

LIST OF FIGURES

Fig. 1. Comparison of several experimental studies of the effect of temperature on the density of lithium	4
Fig. 2. Experimental data on the thermal expansion of solid lithium. <i>Source:</i> Y. S. Touloukian et al., "Thermal Expansion Metallic Elements and Alloys," pp. 186-189 in <i>Thermophysical Properties of Matter</i> , Vol. 12, IFI/Plenum, New York, 1975	4
Fig. 3. Effect of temperature on the specific heat of solid lithium. <i>Source:</i> Y. S. Touloukian and E. H. Buyco, "Specific Heat, Metallic Elements and Alloys," pp. 117-20 in <i>Thermophysical Properties of Matter</i> , Vol. 4, IFI/Plenum, New York, 1970	6
Fig. 4. Effect of temperature on the specific heat of solid and liquid lithium	6
Fig. 5. Comparison of two enthalpy-temperature curves for lithium	7
Fig. 6. Effect of temperature on the isothermal compressibility of lithium	10
Fig. 7. Comparison of four experimental determinations of the surface tension of lithium	10
Fig. 8. The effect of temperature on the viscosity of lithium as found by six investigators	12
Fig. 9. High temperature kinematic viscosity data for lithium. <i>Source:</i> N. A. Kalakutskaya, "Viscosity of Liquid Alkali Metals Potassium, Sodium, and Lithium, at High Temperature," <i>Teplofiz. Vys. Temp.</i> 6(3), 455-60 (1968)	12
Fig. 10. Experimental data for the electrical resistivity of lithium as compiled by Chi. <i>Source:</i> T. C. Chi, "Electrical Resistivity of Alkali Elements," <i>J. Phys. Chem. Ref. Data</i> 8(2), 339-438 (1979)	14
Fig. 11. Experimental values for the thermal conductivity of lithium. Note that the thermal conductivity units are W/cm·K, not W/m·K. <i>Source:</i> Y. S. Touloukian et al., "Thermal Conductivity Metallic Elements and Alloys," pp. 192-7 in <i>Thermophysical Properties of Matter</i> , Vol. 1, IFI/Plenum, New York, 1970	16
Fig. 12. Comparison of some compiled and experimental values for the thermal conductivity of lithium	17

AN EVALUATION OF SOME THERMODYNAMIC AND TRANSPORT PROPERTIES OF
SOLID AND LIQUID LITHIUM OVER THE TEMPERATURE RANGE 200-1700 K*

R. K. Williams, G. L. Coleman, and D. W. Yarbrough

ABSTRACT

Experimental data on the effects of temperature on the density, thermal expansion coefficient, specific heat, enthalpy, vapor pressure, compressibility, surface tension, viscosity, electrical resistivity and thermal conductivity of lithium were reviewed. Comparisons of original data with handbook values revealed some cases in which the latter values should probably be revised. Empirical equations describing the recommended property values are included.

INTRODUCTION

The purpose of this report is to present and document a set of reference thermophysical property values for solid and liquid lithium (Li). The values are required for an analysis of the stresses generated in starting or re-starting a lithium-cooled reactor from the frozen state, and the results are therefore presented in analytical as well as graphical form. The temperature range of interest, 200-1700 K, contains the melting point of Li, 453.7 K; and because the *Materials Handbook for Fusion Energy Systems*¹ contains information on the liquid phase, the primary need for the results was for the solid phase. The first step in making the calculation was to search *Chemical Abstracts* for pertinent references. This effort yielded about 40 titles, some of which were apparently not considered in previous surveys of the literature.^{2,3} Consequently, we reexamined the values in the *Materials Handbook for Fusion Energy Systems*¹ and have suggested some corrections.

*This research was sponsored by the Office of Space and Defense Power Systems, Office of Defense Energy Projects, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

Whenever possible, the data from the original work are shown graphically to give the reader some feel for the experimental uncertainties involved. The recommended values are stated as empirical equations, and the percent differences frequently quoted refer to the difference between values calculated from the equation and the best estimates of the property. This is not the experimental uncertainty associated with the property value. Finally, the authors want to emphasize that extrapolation of the property-temperature equations contained in this report can lead to serious errors. These empirical or semiempirical equations appear to be adequate for the 200–1700 K temperature range but should not be used outside the range. Extrapolating a power series containing a term proportional to T^{-2} to lower temperatures is no more justified than using expressions with T^2 terms above 1700 K. Design equations are given in the Appendix.

DATA EVALUATIONS

DENSITY AND THERMAL EXPANSION

The density-temperature relationship is based on the assumption that the density of Li is 0.5332 Mg/m^3 at 293 K, as stated in the *Materials Handbook for Fusion Energy Systems*.¹ Using the atomic weight and lattice parameter⁴ yields a density of 0.5334 Mg/m^3 . For the solid phase, the effect of temperature was included by using the volume change values recommended by Touloukian et al.⁵ The best values for solid Li are given, with an average difference of 0.01% by

$$D_S = 0.5633 - 8.898 \times 10^{-5}T - \frac{1.16}{T} \quad \frac{\text{Mg}}{\text{m}^3}, \text{ K} , \quad (1)$$

for $200 \leq T \leq 453.7 \text{ K}$.

This equation predicts that at the melting point, 453.7 K, the density of solid Li is 0.5204 Mg/m^3 .

Experiment shows that the density of liquid Li is 1.5 % less than that of the solid²; and, therefore, the density of liquid Li at the melting point equals 0.5126 Mg/m³. The density-temperature data⁶⁻⁸ are shown in Fig. 1. For the temperature range of interest, the density of liquid Li decreases linearly with increasing temperature as given in the *Materials Handbook for Fusion Energy Systems*¹:

$$D_L = 0.5584 - 1.01 \times 10^{-4}T \quad \text{Mg/m}^3, \text{ K} , \quad (2)$$

for $453.7 \leq T \leq 1700 \text{ K}$.

The thermal expansion data for solid Li are shown in Fig. 2 illustrating the experimental scatter. Volumetric thermal expansion coefficients derived from these data by Touloukian et al.⁵ fall within $\pm 2\%$ of the equation

$$\alpha_{vS} = \frac{d \ln V}{dT} = 1.968 \times 10^{-4} - \frac{6.724}{T^2} + \frac{1.413 \times 10^5}{T^4} \quad \text{K}^{-1} , \quad (3)$$

for $200 \leq T \leq 453.7 \text{ K}$.

This equation approximates the Debye integral, J_4 , at high temperatures.⁹ The expansion behavior of the liquid is derived from the density-temperature data, Eq. (2):

$$V(T) = \frac{m}{D(T)} . \quad (4)$$

Because the volumetric coefficient of expansion is

$$\alpha_{vL} = \frac{d \ln V}{dT} = \frac{d}{dT} \ln(0.5584 - 1.01 \times 10^{-4} T)^{-1} , \quad (5)$$

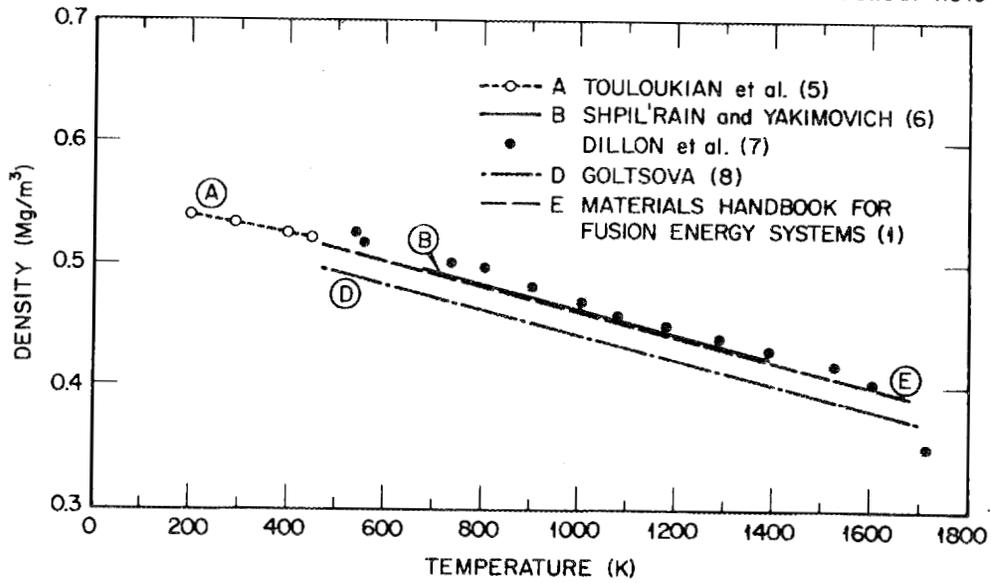


Fig. 1. Comparison of several experimental studies of the effect of temperature on the density of lithium.

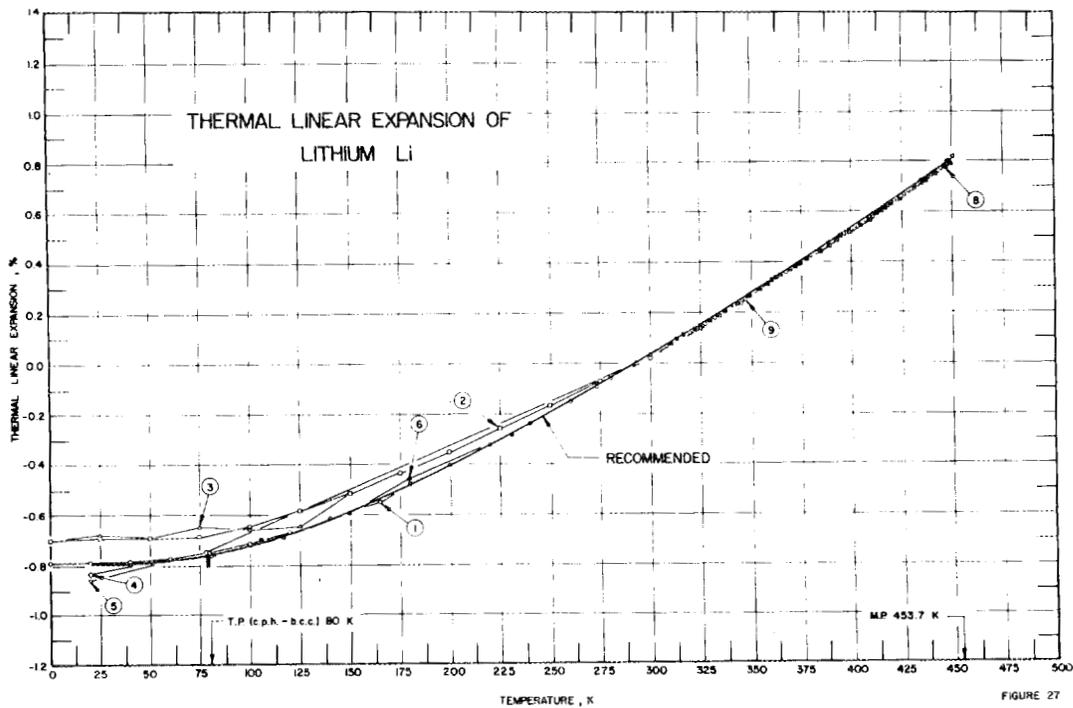


Fig. 2. Experimental data on the thermal expansion of solid lithium. Source: Y. S. Touloukian et al., "Thermal Expansion Metallic Elements and Alloys," pp. 186-189 in *Thermophysical Properties of Matter*, Vol. 12, IFI/Plenum, New York, 1975.

the expansion coefficient is given by

$$\alpha_{vL} = \frac{1.01 \times 10^{-4}}{0.5584 - 1.01 \times 10^{-4} T} = (5529 - T)^{-1} \quad \text{K}^{-1}, \quad (6)$$

for $453.7 \leq T \leq 1700 \text{ K}$.

This analysis shows that the expansion coefficient of Li increases about 20% on melting.

ENTHALPY, SPECIFIC HEAT, AND LATENT HEAT OF FUSION

Enthalpy can be obtained either from a direct measurement of heat content or by integration of the specific heat, C_p , curve. Specific heat data for the solid are shown in Fig. 3,¹⁰ and a more extensive set is shown in Fig. 4.¹¹⁻¹³ Figure 4 also shows the values recommended by Hultgren et al.¹⁴ Except for a 0.4% discrepancy at 298.15 K, the latter values appear to be the best available. From 200 to 453.7 K these C_p results fit the equation

$$\frac{S}{C_p} = \frac{-6.999 \times 10^8}{T^4} + \frac{1.087 \times 10^4}{T^2} + 3.039 + 5.605 \times 10^{-6} T^2 \quad \text{kJ/kg}\cdot\text{K}, \quad (7)$$

with an average difference of 0.07%. Enthalpy values for the solid can be obtained by integrating this equation, which is based on the high temperature series approximation to the Debye model.⁹

The heat of fusion, 0.4339 MJ/kg, is an average value, based on the work of Douglas et al.¹³ and Novikov et al.¹⁵ The two experimental results differ by 0.7%.

The thermal properties of liquid Li have been determined both by heat content and specific heat measurements. Figure 5 shows the results of two compilations.^{1,14} It is clear that the values given in the *Materials Handbook for Fusion Energy* should be corrected. Hultgren et al.¹⁴ have described the original data sources adequately; their enthalpy curve can be generated from the equation

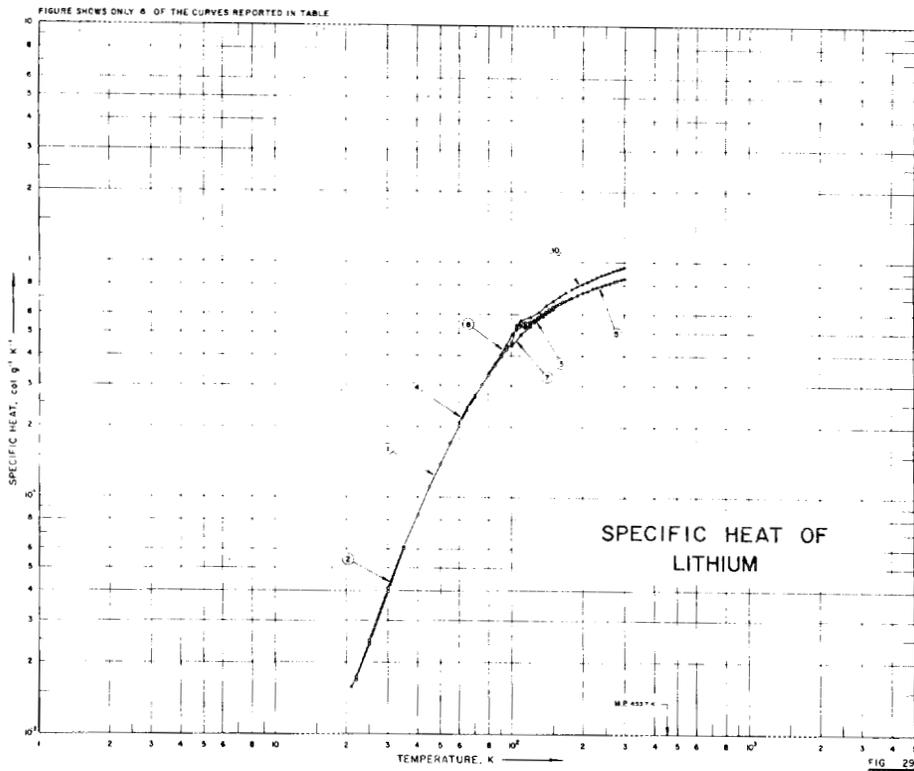


Fig. 3. Effect of temperature on the specific heat of solid lithium. *Source:* Y. S. Touloukian and E. H. Buyco, "Specific Heat, Metallic Elements and Alloys," pp. 117-20 in *Thermophysical Properties of Matter*, Vol. 4, IFI/Plenum, New York, 1970.

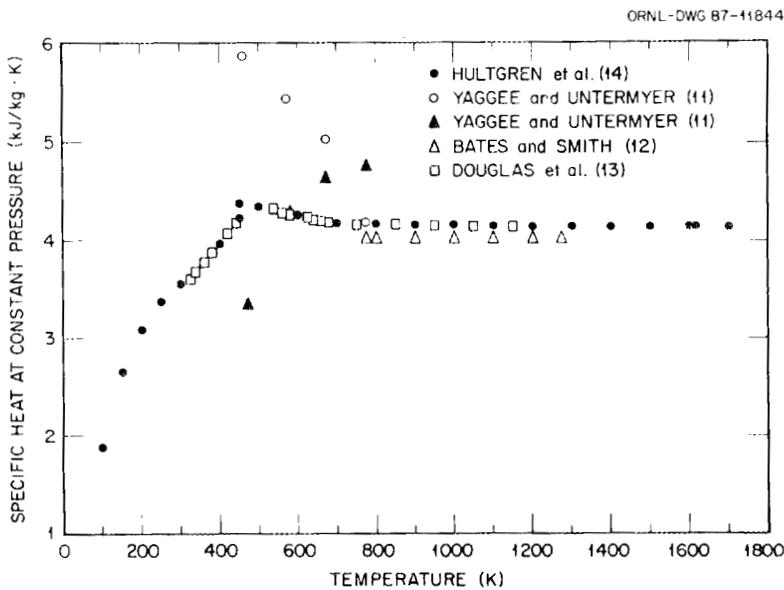


Fig. 4. Effect of temperature on the specific heat of solid and liquid lithium.

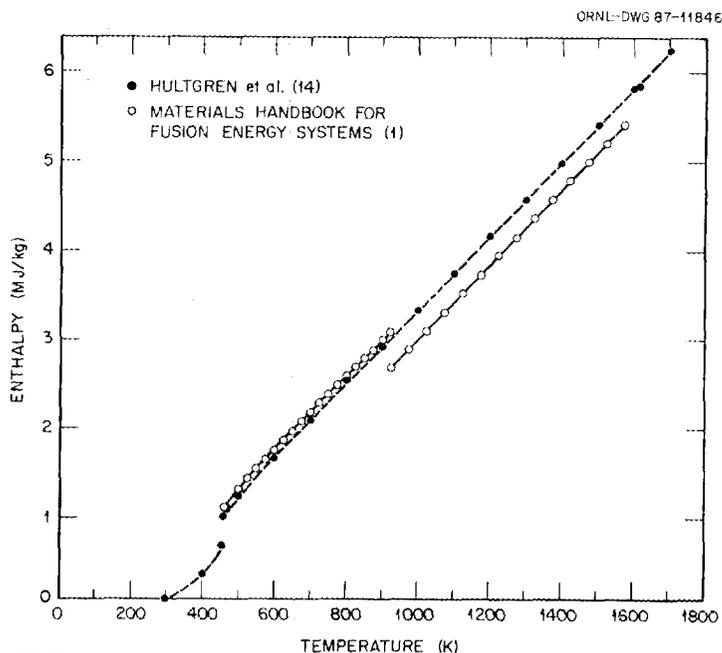


Fig. 5. Comparison of two enthalpy-temperature curves for lithium.

$$C_p^L = \frac{1.044 \times 10^5}{T^2} - \frac{135.1}{T} + 4.180 \quad \text{kJ/kg} \cdot \text{K} , \quad (8)$$

for $453.7 \leq T \leq 1608$.

This equation reproduces the tabulated specific heat values¹⁴ with an average difference of 0.14%. It should be noted that the normal boiling point of Li is ~1608 K. Thus, applying Eq. (8) above that temperature requires additional corrections for the pressure changes required to maintain the liquid state.

VAPOR PRESSURE AND HEAT OF VAPORIZATION

The vapor pressure curve shown in the *Materials Handbook for Fusion Energy Systems* is evidently based on the work of Rigney et al.¹⁶ and Bohdansky and Schins.¹⁷ Hultgren et al.¹⁴ provide a much more thorough review of all of the data available in 1973, point out that Li vapor is non-ideal above 800 K, and provide a table of vapor pressure values. The

heat of sublimation derived in this analysis, $\Delta H_{V,298.15} = 22.97$ MJ/kg, is probably the best available estimate of this quantity. The temperature dependence can be estimated by assuming that the vapor is ideal at lower temperatures and by using Eq. (7) to evaluate the ΔC_p terms. At higher temperatures, the experimental specific heat data for the liquid probably do not justify including the temperature variation of the heat of vaporization, but calculations assuming ideal vapor indicate that the heat of vaporization falls about 7% between the melting point and 1700 K.

Since publication of the Hultgren compilation, additional valuable experimental work by Schins et al.¹⁸ and Rajagopalan and Bonilla¹⁹ has appeared, and Alcock et al.²⁰ have given vapor pressure equations for both the solid and liquid states. Averaging data from seven experimental studies^{16-19,21-23} yields a normal boiling point of 1607.9 K, and an empirical fit of the Hultgren values

$$\log_{10} P(\text{Pa}) = \frac{-7975.6}{T} + 9.9624, \quad (9)$$

$$\text{for } 453.7 \leq T \leq 1700 \text{ K},$$

gives a boiling point of 1609.0 K. This equation differs from the vapor pressure values tabulated by Hultgren et al.¹⁴ by a maximum of 10.2%; it yields an average heat of vaporization from the liquid of 21.98 MJ/kg. The temperature-dependent heats of vaporization from the liquid calculated from the ΔC_p corrections vary from 22.40 MJ/kg at the melting point to 20.93 MJ/kg at 1700 K.

The vapor pressure over solid Li can be calculated²⁰:

$$\log_{10} P = \frac{-8310}{T} + 10.673 \quad \text{Pa} . \quad (10)$$

The enthalpy of sublimation derived from this equation is 0.2% smaller than the Hultgren et al.¹⁴ value cited above.

COMPRESSIBILITY

One set of experimental data²⁴ was located by the computer search of chemical abstracts, and the isothermal compressibility data are shown in Fig. 6. The dashed curve was predicted by Pasternak,²⁵ who used a corresponding states model that cannot be extended to higher temperatures. The two results differ by about 15% at 600 K and tend to approach each other more closely at high temperatures. The Novikov et al.²⁴ experimental data can be described by

$$\chi = \frac{1}{V} \frac{\partial V}{\partial P} \frac{1}{T} = 8.366 \times 10^{-11} + 2.0706 \times 10^{-14} T + 4.665 \times 10^{-17} T^2 \text{ Pa}^{-1}, (11)$$

for $453.7 \leq T \leq 1700 \text{ K}$.

This equation reproduces the only set of experimental results with an average error of 0.1%; the T^2 term is included because data for the other alkali metals²⁵ show similar positive curvature.

SURFACE TENSION

Figure 7 shows that the experimental results of Taylor,²⁶ Achener,²⁷ and Bohdansky and Schins²⁸ are in good agreement, while the data reported by Hoffman and Keyes²⁹ are 5-10% higher. The experiments all show that the surface tension, σ , decreases linearly with increasing temperature, and the various parameters derived from the data are shown in Table 1. The values given in the *Materials Handbook for Fusion Energy Systems*¹ rely completely on the work of Bohdansky and Schins;²⁸ but as shown in Fig. 7, the agreement is good enough that this is acceptable.

VISCOSITY

Six sets of experimental data^{21,30-34} are available, and the results are shown in Fig. 8. The values given in the *Materials Handbook for Fusion Energy Systems*¹ follow the low edge of the data envelope as defined by the results of Andrade and Dobbs³² and Rigney et al.²⁹ Because the

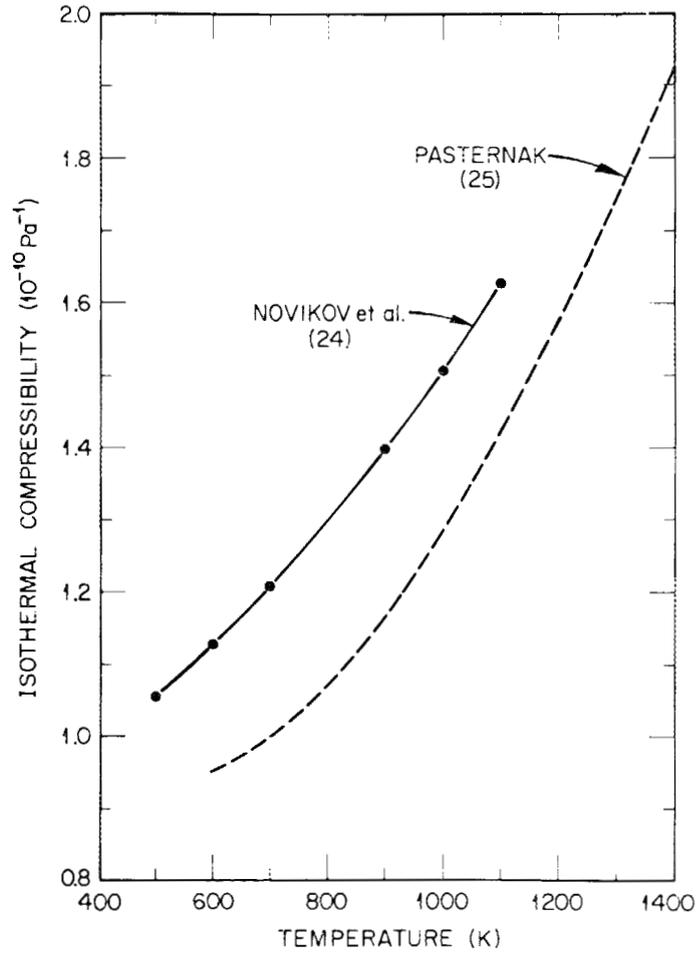


Fig. 6. Effect of temperature on the isothermal compressibility of lithium.

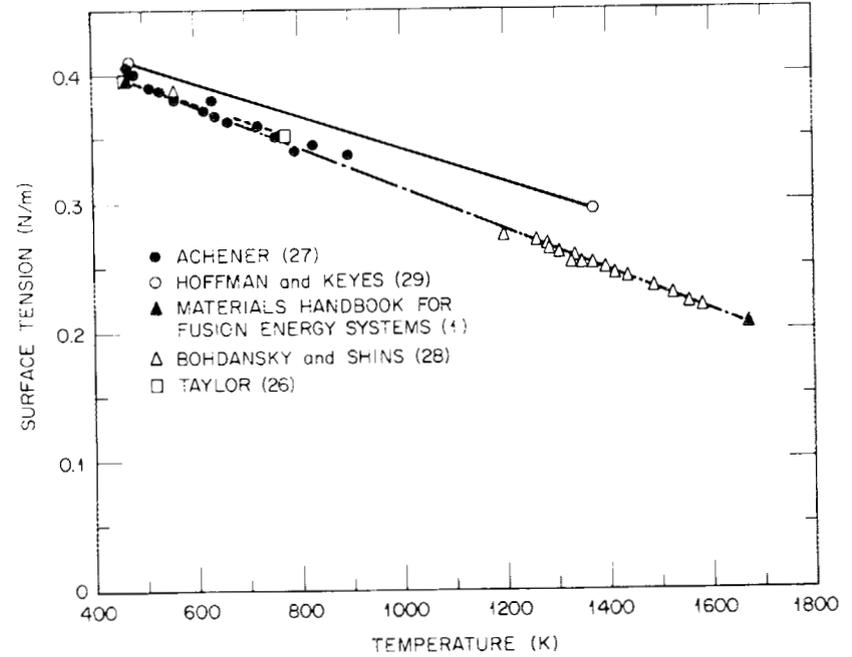


Fig. 7. Comparison of four experimental determinations of the surface tension of lithium.

Table 1. Parameters derived from experimental data

$$(\sigma = A + BT)$$

Investigator	Slope (B) [N/m·K ($\times 10^4$)]	Intercept (A) (N/m)
Taylor ²⁶	-1.477	0.4652
Achener ²⁷	-1.539	0.4709
Bohdansky and Schins ²⁸	-1.627	0.4738
Hoffman and Keyes ²⁹	-1.280	0.4695

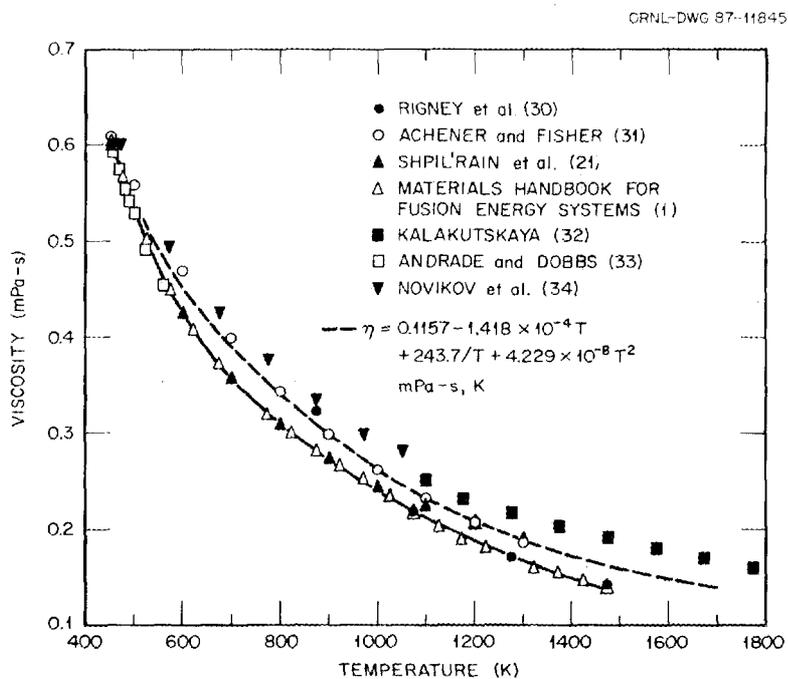


Fig. 8. The effect of temperature on the viscosity of lithium as found by six investigators.

high temperature data of Kalakutskaya³¹ were apparently not considered in earlier evaluations, these experimental values are shown in Fig. 9. The scatter is $\sim \pm 10\%$. This considerable body of data, falling at the upper edge of the envelope of experimental points, is consistent with the results of Novikov.³³ At present, there is no way to decide which experimental result is most nearly correct, and therefore it seems that some weight should be given to all of the results and that the best estimate curve should fall in approximately the middle of the experimental results. The empirical equation

$$\mu = 0.1157 - 1.418 \times 10^{-4} T + 4.229 \times 10^{-8} T^2 + \frac{243.7}{T} \text{ (mPa - s, K) , } \quad (12)$$

for $453.7 \leq T \leq 1700 \text{ K}$,

shown in Fig. 8 and falls in about the required position. At 1300 K the range of experimental values is $\sim \pm 15\%$.

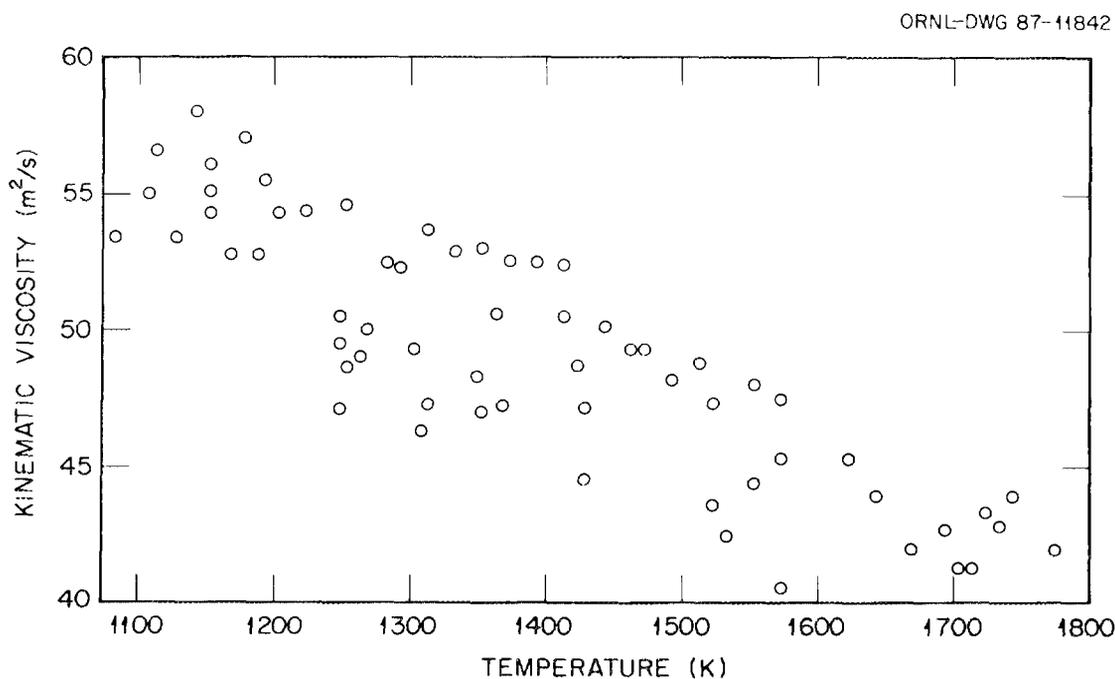


Fig. 9. High temperature kinematic viscosity data for lithium.
 Source: N. A. Kalakutskaya, "Viscosity of Liquid Alkali Metals Potassium, Sodium, and Lithium, at High Temperature," *Teplofiz. Vys. Temp.* 6(3), 455-60 (1968).

The isotope effect has been studied by Ban et al.,³⁵ who found that at the melting point the viscosity of ⁷Li is 1.44 times larger than the viscosity of ⁶Li. Their results also show that this difference diminishes as the temperature is increased.

ELECTRICAL RESISTIVITY

The transport properties of the alkali metals have been extensively studied by the scientific community because they are thought to be the simplest metals, offer the most direct tests of the theory of the conductivity of metals. Chi³⁶ reviewed the literature existing in 1974 and concluded that there were 21 sets of data for solid Li in the temperature range 30–453.7 K and that the range of values is ~5%. The experimental data are shown in Fig. 10. The recommended values derived by Chi differ slightly from those of Meaden,³⁷ but the maximum difference is only 0.5%. It should be noted that impurities may have a large influence on the resistivity of Li at low temperatures. Typically, 1 at. % of impurities might increase the resistivity at 200 K by as much as 20%. The isotope effect has also been studied,^{37,38} and the resistivity of ⁶Li was found to be about 3% lower than that of natural Li at 200 K. The resistivity values recommended for solid Li³⁶ can be calculated from the equation

$$\rho_S = \frac{-2.508 \times 10^3}{T^4} + \frac{1.225 \times 10^5}{T^2} - 4.330 + .04271T \quad (10^{-8}\Omega\text{m}, \text{K}), \quad (13)$$

for $200 \leq T \leq 453.7$.

The average difference between the calculated and Chi recommended value is 0.09%. This approximates the Bloch-Grüneisen Equation.⁹

Melting increases the resistivity of Li by about 60%.³⁶ The data for liquid Li are also shown in Fig. 10. Calaway³⁹ has also reviewed the data for liquid Li, including his own results and data from several studies⁴⁰⁻⁴³ that have been published since 1974. These results do little to change the experimental picture because values calculated from Calaway's recommended equation differ from those of Chi by a maximum of only 1.1%, and

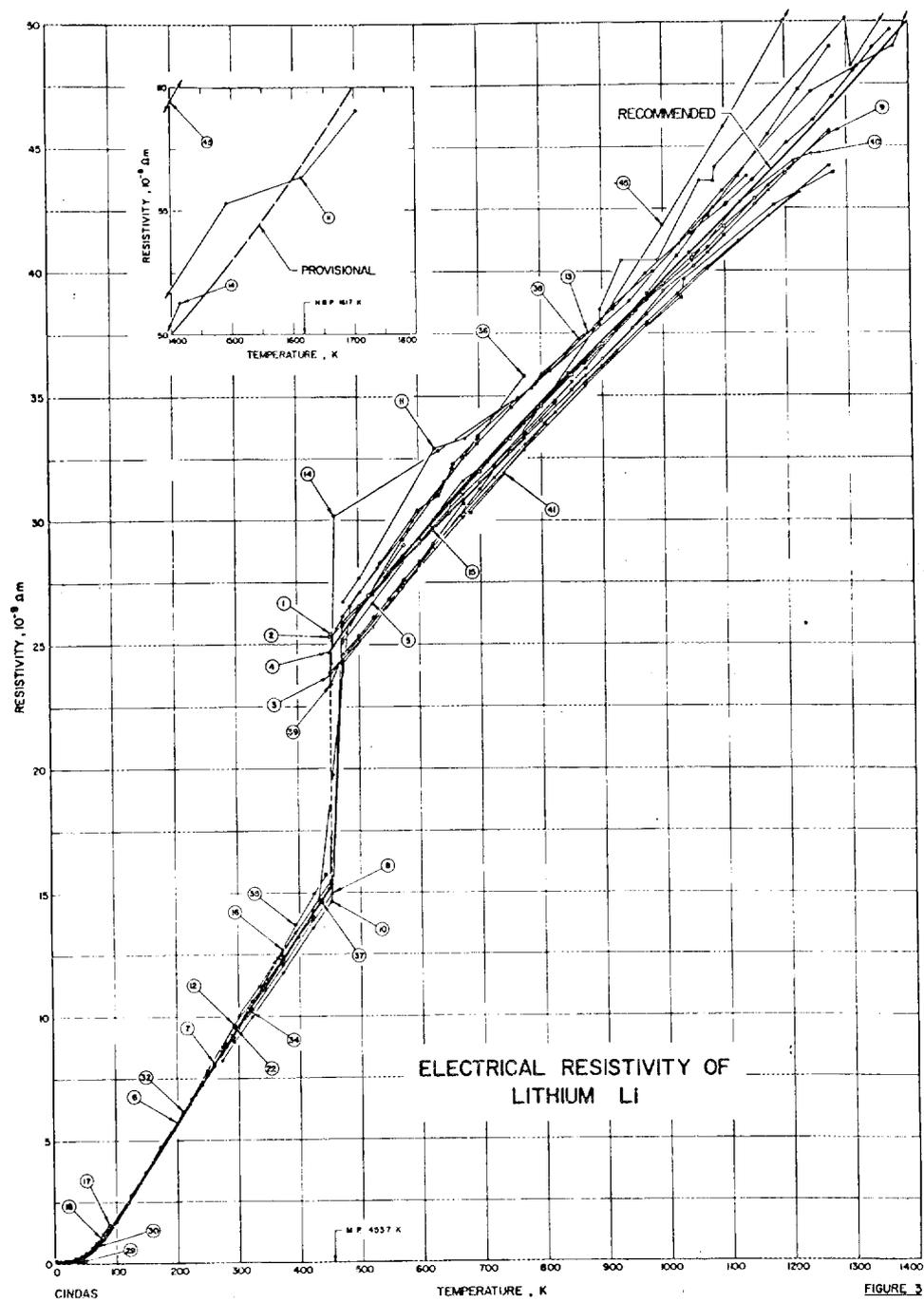


Fig. 10. Experimental data for the electrical resistivity of lithium as compiled by Chi. Source: T. C. Chi, "Electrical Resistivity of Alkali Elements," *J. Phys. Chem. Ref. Data* 8(2), 339-438 (1979).

this difference occurs at the melting point. As seen from Fig. 10, the main experimental uncertainty is at very high temperatures. At 1700 K the Chi³⁶ and Calaway³⁹ values differ by only 0.3%. The Chi values for the liquid fit the equation

$$\rho_L = 5.819 + 0.05282T - 2.843 \times 10^{-5} T^2 + 9.474 \times 10^{-9} T^3 \quad (10^{-8}\Omega\text{m},\text{K}), \quad (14)$$

$$\text{for } 453.7 \leq T \leq 1700 \text{ K},$$

with an average error of 0.08% (the experimental uncertainty is demonstrated in Fig. 10). This is the function chosen by Calaway. It should be noted that the resistivity values for liquid Li were not corrected for the thermal expansion of the container. At 1300 K this correction is about 2%.

THERMAL CONDUCTIVITY

The experimental situation is shown in Fig. 11.⁴⁴ For the temperature range of interest there is apparently only one set of data for solid Li, and the results for the liquid scatter by $\sim \pm 10\%$. For the solid, the thermal conductivity, λ , values given by Touloukian et al.,⁴⁴ should be used. These values disregard the experimental data in the 300-450 K range (Fig. 11), which is probably justified because the electrical resistivity results do not show any unusual behavior in this region.³⁶ Klemens and Williams⁴⁵ have analyzed the electrical and thermal conductivity data for solid Li and have concluded that the data can be satisfactorily accounted for by the standard theory. The equation

$$\lambda_S = 44.00 + 0.02019 T + \frac{8037}{T} \quad \text{W/m}\cdot\text{K}, \text{ K}, \quad (15)$$

$$\text{for } 200 \leq T \leq 453.7,$$

reproduces the thermal conductivity values tabulated by Touloukian et al.⁴⁴ with an average difference of only 0.3%. Figure 11 demonstrates that this

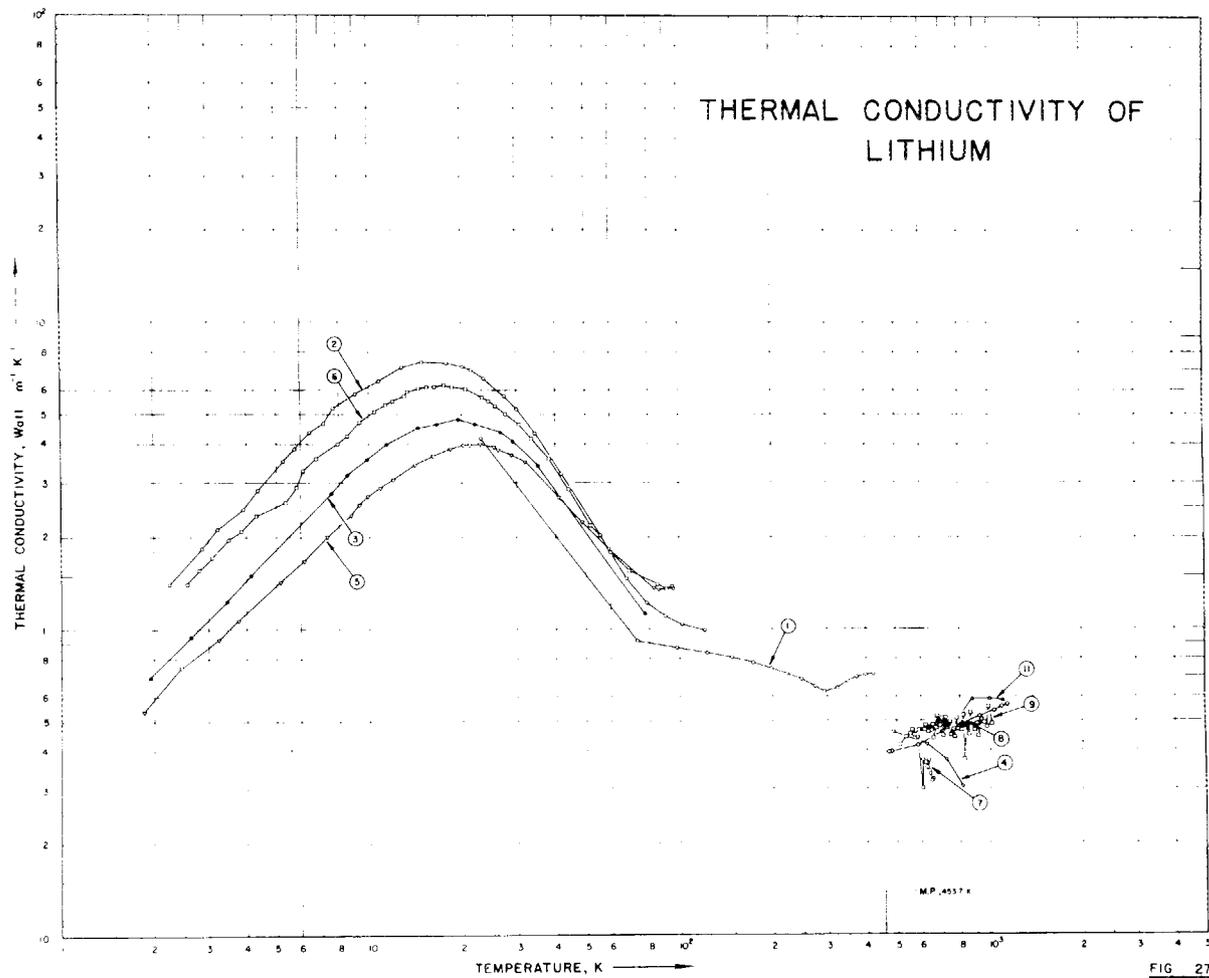


Fig. 11. Experimental values for the thermal conductivity of lithium. Note that the thermal conductivity units are W/cm·K, not W/m·K. Source: Y. S. Touloukian et al., "Thermal Conductivity Metallic Elements and Alloys," pp. 192-7 in *Thermophysical Properties of Matter*, Vol. 1, IFI/Plenum, New York, 1970.

average difference is far less than the experimental uncertainty. It should also be noted that at lower temperatures the thermal conductivity, like the electrical resistivity, becomes increasingly sensitive to impurity content.

According to Touloukian et al.,⁴⁴ melting decreases the thermal conductivity of Li by ~50%. This decrease is 10% less than the corresponding change in electrical resistivity and cannot be explained by the lower vibrational contribution to the thermal conductivity of the liquid. This also applies to the values in the *Materials Handbook for Fusion Energy Systems*.¹ At higher temperatures, the Touloukian and *Materials Handbook* values generally agree. When combined with the electrical resistivity data, they yield a Lorenz ratio close to the Sommerfeld value, L_0 (ref. 46). This is gratifying, but at least two observations cast doubt on the thermal conductivity values. First, Shpil'rain and Krainova⁴⁷ have produced data that are less temperature dependent (lower Lorenz function). One set of data might be discounted because Cooke's data^{48,49} are closer to the Touloukian values (Fig. 12). However, the Russian observations are also consistent with the data of Cook et al.⁵⁰ and Cook,⁵¹ who showed that the Lorenz functions of Rb and Cs were affected by electron-electron scattering and were about 10% lower than the Sommerfeld value at 600 K. Because these concerns will probably remain unresolved for the foreseeable future, the best currently available values are calculated by fitting the Touloukian values⁴⁴ to an empirical equation,

$$\lambda_L = 21.42 + 0.05230T - 1.371 \times 10^{-5} T^2 \quad \text{W/m}\cdot\text{K}, \quad \text{K}, \quad (16)$$

for $453.7 \leq T \leq 1700 \text{ K}$.

The third term is included because Touloukian values shown in Fig. 12 are negatively curved, and extrapolation of the linear *Material Handbook*¹ equation would lead to values about 5% too large at 1700 K. If the Lorenz numbers are as indicated by Shpil'rain and Krainova,⁴⁷ the values calculated from Eq. (16) would be ~20% too large.

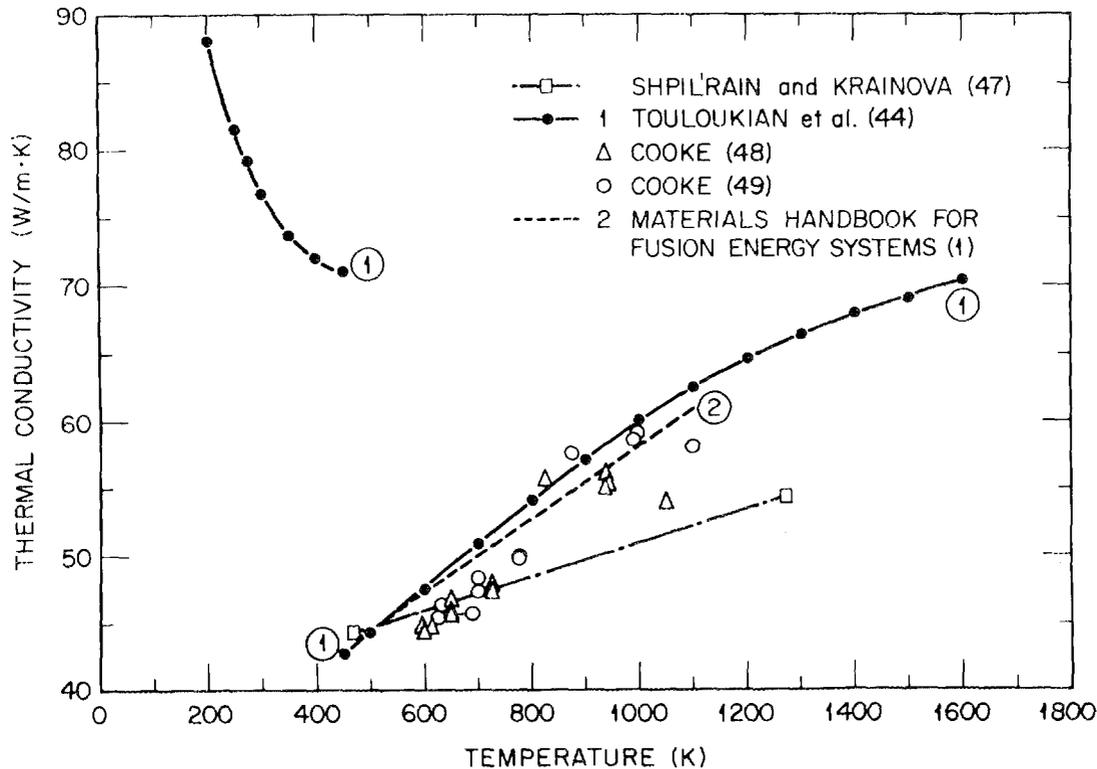


Fig. 12. Comparison of some compiled and experimental values for the thermal conductivity of lithium.

REFERENCES

1. *Materials Handbook for Fusion Energy Systems*, DOE/TIC-10122, U.S. Department of Energy, April 1981.
2. J. O. Cowles and A. D. Pasternak, *Lithium Properties Related to Use as a Nuclear Reactor Coolant*, UCRL-50647, Lawrence Radiation Laboratory, Livermore, Calif., April 1969.
3. D. W. Jeppson et al., *Lithium Literature Review: Lithium's Properties and Interactions*, HEDL-TME 78-15, Hanford Engineering Development Laboratory, Richland, Wash., April 1978.
4. *Metals Handbook. Properties and Selection of Metals*, Vol. 1, American Society for Metals, Metals Parks, Ohio, 1961.
5. Y. S. Touloukian et al., "Thermal Expansion Metallic Elements and Alloys," in pp. 186-9 in *Thermophysical Properties of Matter*, Vol. 12, IFI/Plenum, New York, 1975.

6. E. E. Shpil'rain and K. A. Yakimovich, "Density of Liquid Lithium, Rubidium, and Cesium at High Temperatures," *High Temp.* **5**, 211-6 (1967).
7. I. G. Dillon et al., *Determination of Densities of Alkali Metals by Gamma Radiation Attenuation Technique*, Final Report, ORO-3604-8, U.S. Department of Energy, Oak Ridge Operations Office, March 1972.
8. E. I. Goltsova, "Densities of Lithium, Sodium, and Potassium at Temperatures up to 1500-1600°C," *High Temp.* **4**, 348 (1966).
9. W. M. Rogers and Robert L. Powell, *Tables of Transport Integrals*, NBS Circular 595, National Bureau of Standards, Boulder, Colorado, July 1958.
10. Y. S. Touloukian and E. H. Buyco, "Specific Heat, Metallic Elements and Alloys," pp. 117-20 in *Thermophysical Properties of Matter*, Vol. 4, IFI/Plenum, New York, 1970.
11. F. L. Yaggee and S. Untermyer, *The Relative Thermal Conductivities of Liquid Lithium, Sodium, & Eutectic NaK, and the Specific Heat of Liquid Lithium*, ANL-4458, Argonne National Laboratory, Argonne, Ill., pp. 1-27 (1950).
12. A. G. Bates and D. J. Smith, *Specific Heat and Enthalpy of Liquid Lithium in the Range of 500°C to 1000°C*, AEC 3728-51 N-X-7, U.S. Atomic Energy Commission, pp. 1-31, 1951.
13. T. B. Douglas et al., "Lithium: Heat Content from 0 to 900°, Triple Point and Heat of Fusion, and Thermodynamic Properties of the Solid and Liquid," *J. Am. Chem. Soc.* **77**, 2144-50 (1955).
14. R. Hultgren et al., *Selected Values of the Thermodynamic Properties of the Elements*, American Society for Metals, Metals Park, Ohio, 1973, pp. 281-6.
15. I. I. Novikov, V. V. Roschupkin, and L. C. Fordeyeva, "Solid and Liquid Lithium Enthalpy: Experimental Investigation Near the Melting Point," *Int. J. Thermophy.* **4**(3), 227-33 (1983).
16. D. V. Rigney, S. M. Kapelner, and R. E. Cleary, *The Vapor Pressure of Lithium Between 1307 and 1806 K*, CANEL Report TIM-844, Hartford, Conn., September 1965.

17. J. Bohdansky and H. E. J. Schins, "Vapor Pressure of Different Metals in the Pressure Range of 50 to 4000 Torr," *J. Phys. Chem.* **71**, 215-7 (1967).
18. H. E. J. Schins, R. W. M. van Wijk, and B. Dorpeman, "The Heat-Pipe Boiling-Point Method and the Vapor Pressure of Twelve Metallic Elements in the Range 10^{-10} Torr," *Z. Metallk.* **61**, 330-6 (1971).
19. A. S. Rajagopalan and C. F. Bonilla, "The Experimental High Temperature Vapor Pressure and the Estimated Critical Properties of Lithium," pp. 431-6 in *Proceedings of the Eighth Symposium on Thermophysical Properties*, American Society of Mechanical Engineers, New York, 1982.
20. C. B. Alcock, V. P. Itkin, and M. K. Horrigan, "Vapor Pressure Equations for the Metallic Elements: 298-2500 K," in *Can. Metall. Q.* **23**(3), 309-13 (1984).
21. E. E. Shpil'rain et al., "Experimental Investigation of Thermal and Electrical Properties of Liquid Alkali Metals at High Temperatures," *High Temp.* **3**, 870-74 (1965).
22. P. Y. Achener and D. L. Fisher, *The Vapor Pressure of Lithium*, AEC AGN-8191, Vol. 2, U.S. Atomic Energy Commission, 1967.
23. L. D. Volyak, "Heat of Vaporization and Critical Parameters of Alkali Metals," *Zh. Prikl. Mekh. Tekh. Fiz.* **6**, 137-9 (1968).
24. I. I. Novikov, Yu. S. Trelin, and T. A. Tsyganova, "Experimental Data on the Speed of Sound in Lithium up to 1100 K," *Teplofiz. Vys. Temp.* **7**(6), 1140-41 (1969).
25. A. D. Pasternak, "Isothermal Compressibility of the Liquid Alkali Metals," *Mater. Sci. Eng.* **3**(2), 65-70 (1968).
26. J. W. Taylor, "The Surface Energies of the Alkali Metals," *Philos. Mag.* **46**, 867-76 (1955).
27. P. Y. Achener, *Alkali Metals Evaluation Program Surface Tension and Contact Angle of Lithium and Sodium*, AGN-8191, Vol. 3, Aerojet General Nuclear, San Ramon, Calif., April 1969.
28. J. Bohdansky and H. E. J. Schins, "The Surface Tension of the Alkali Metals," *J. Inorg. Nucl. Chem.* **29**(9), 2172-9 (September 1967).

29. H. W. Hoffman and J. J. Keyes, Jr., *Studies in Heat Transfer and Fluid Mechanics Progress Report for Period Oct. 1-June 30, 1964*, ORNL/TM-1148, August 1965.
30. D. V. Rigney, S. M. Kapelner, and R. E. Cleary, *The Viscosity of Lithium*, CANEL Report TIM-849, Pratt & Whitney Aircraft, Hartford, Conn., 1965.
31. P. Y. Achener and D. L. Fisher, *Alkali Metals Evaluation Viscosity of Liquid Sodium and Lithium*, AGN-8191, Vol. 5, Aerojet General Nuclear, San Ramon, Calif., May 1967.
32. N. A. Kalakutskaya, "Viscosity of Liquid Alkali Metals Potassium, Sodium, and Lithium, at High Temperature," *Teplofiz. Vys. Temp.* 6(3), 455-60 (1968).
33. E. N. da C. Andrade and E. R. Dobbs, "The Viscosities of Liquid Lithium, Rubidium and Caesium, pp. 12-30 in *Proceedings of the Royal Society of London*, Vol. 211, 1951.
34. I. I. Novikov et al., "The Heat-Transfer and High-Temperature Properties of Liquid Alkali Metals," *J. Nucl. Energy* 4, 387-408 (1957).
35. N. T. Ban, C. M. Randall, and D. J. Montgomery, "Effect of Isotopic Mass on Viscosity of Molten Lithium," *Phys. Rev.* 128, 6-11 (1962)
36. T. C. Chi, "Electrical Resistivity of Alkali Elements," *J. Phys. Chem. Ref. Data* 8(2), 339-438 (1979).
37. G. T. Meaden, p. 15 in *Electrical Resistance of Metals*, Plenum, New York, 1965.
38. J. S. Dungdale and D. Gagan, "The Effect of the Martensitic Transformation on the Electrical Resistance of Lithium and Dilute Lithium-Magnesium Alloys," *Cryogenics* 2, 103 (1961).
39. W. F. Calaway, "The Electrical Resistivity of Liquid Lithium," *J. Less-Common Met.* 86(2), 305-19 (1982).
40. G. K. Creffield, M. G. Down, and R. J. Pulham, "Electrical Resistivity of Liquid and Solid Lithium," *J. Chem Soc. Dalton Trans.* 2325-9 (1974).
41. P. D. Feitsma et al., "Electrical Resistivities and Phase Separation of Liquid-Sodium Alloys," *Phys. G* 79B, 35-52 (1975).

42. H. U. Güntherodt, H. U. Künzi, and R. Müller, "Hall Coefficient and Electrical Resistivity of Liquid Lithium," *Phys. Lett. A* **54**(2), 155-6 (1975).
43. J. B. Van Zytveld, "Electronic Properties of Liquid Li-Mg," *J. Phys. F* **5**, 506-14 (1975).
44. Y. S. Touloukian et al., "Thermal Conductivity Metallic Elements and Alloys," pp. 192-7 in *Thermophysical Properties of Matter*, Vol. 1, IFI/Plenum, New York, 1970.
45. P. G. Klemens and R. K. Williams, "Thermal Conductivity of Metals and Alloys," *Int. Met. Rev.* **31**(5), 197-215 (1986).
46. J. M. Ziman, p. 385 in *Electrons and Phonons--The Theory of Transport Phenomena in Solids*, Oxford at the Clarendon Press, 1960.
47. E. E. Shpil'rain and I. F. Krainova, "Measurement of the Thermal Conductivity of Liquid Lithium," *Teplofiz. Vys. Temp.* **8**(5), 1036-8 (1969).
48. J. W. Cooke, *Proceedings of 1963 High-Temperature Liquid-Metal Heat Transfer Technology Meeting*. ORNL-3605. pp. 66-87. 1963.
49. J. W. Cooke, "Experimental Determination of the Thermal Conductivity of Molten Lithium from 320 to 830°C," *J. Chem. Phys.* **40**(7), 1902-09 (1964).
50. J. G. Cook, M. P. Van Der Meer, and D. J. Brown, "Measurement of the Transport Properties of Liquid Rb Using Automated Equipment," *Can. J. Phys.* **60**(9), 1311-6 (1982).
51. J. G. Cook, "Transport Properties of Solid and Liquid Cs," *Can. J. Phys.* **60**, 1759-69 (1982).

APPENDIX

SUMMARY OF SELECTED PROPERTIES OF LITHIUM

Heat of fusion: 0.4339 MJ/kg

Average heat of vaporization from the liquid - 21.98 MJ/kg

DENSITY

$$D_S = 0.5633 - 8.898 \times 10^{-5} T - \frac{1.16}{T},$$

for temperatures between 200 and 453.7 K; density expressed in Mg/m³.

$$D_L = 0.5584 - 1.01 \times 10^{-4} T,$$

for temperatures between 453.7 and 1700 K; density expressed in Mg/m³.

VOLUMETRIC THERMAL EXPANSION

$$\alpha_{vS} = \frac{d \ln V}{dT} = 1.968 \times 10^{-4} - \frac{6.724}{T^2} + \frac{1.413 \times 10^5}{T^4},$$

for temperatures between 200 and 453.7; volumetric thermal expansion expressed in 1/K.

$$\alpha_{vL} = \frac{1.01 \times 10^{-4}}{0.5584 - 1.01 \times 10^{-4} T} = (5529 - T)^{-1},$$

for temperatures between 453.7 and 1700 K; volumetric thermal expansion expressed in 1/K.

SPECIFIC HEAT

$$C_p = \frac{-6.999 \times 10^8}{T^4} + \frac{1.087 \times 10^4}{T^2} + 3.039 + 5.605 \times 10^{-6} T^2,$$

for temperatures between 200 and 453.7; specific heat expressed in kJ/kg·K.

$$C_p = \frac{1.044 \times 10^5}{T^2} - \frac{135.1}{T} + 4.180 ,$$

for temperatures between 453.7 and 1700; specific heat expressed in kJ/kg·K.

VAPOR PRESSURE

$$\log_{10} P = \frac{-8310}{T} + 10.673 ,$$

for temperatures between 200 and 453.7 K; vapor pressure expressed in Pa.

$$\log_{10} P = \frac{-7975.6}{T} + 9.9624 ,$$

for temperatures between 453.7 and 1700 K; vapor pressure expressed in Pa.

COMPRESSIBILITY

$$\chi = - \frac{1}{V} \frac{\partial V}{\partial P} = 8.366 \times 10^{-11} + 2.0706 \times 10^{-14} T + 4.665 \times 10^{-17} T^2 ,$$

for temperatures between 453.7 and 1700 K; compressibility expressed in 1/Pa.

SURFACE TENSION

$$\sigma = 0.4738 - 1.627 \times 10^{-4} T ,$$

for temperatures between 453.7 and 1700 K; surface tension expressed in N/m.

VISCOSITY

$$\mu = 0.1157 - 1.418 \times 10^{-4} T + 4.229 \times 10^{-8} T^2 + \frac{243.7}{T} ,$$

for temperatures between 453.7 and 1700 K; viscosity expressed in mPa·s.

ELECTRICAL RESISTIVITY

$$\rho_S = \frac{-2.508 \times 10^3}{T^4} + \frac{1.225 \times 10^5}{T^2} - 4.330 + 0.04271 T ,$$

for temperatures between 200 and 453.7; electrical resistivity expressed in $10^{-8} \Omega\text{m}$.

$$\rho_L = 5.819 + 0.05282 T - 2.843 \times 10^{-5} T^2 + 9.474 \times 10^{-8} T^3 ,$$

for temperatures between 453.7 and 1700 K; electrical resistivity expressed in $10^{-8} \Omega\text{m}$.

THERMAL CONDUCTIVITY

$$\lambda_S = 44.00 + 0.02019 T + \frac{8037}{T} ,$$

for temperatures between 200 and 453.7; thermal conductivity expressed in $\text{W/m}\cdot\text{K}$.

$$\lambda_L = 21.42 + 0.05230T - 1.371 \times 10^{-5} T^2 ,$$

for temperatures between 453.7 and 1700 K; thermal conductivity expressed in $\text{W/m}\cdot\text{K}$.

INTERNAL DISTRIBUTION

1-2.	Central Research Library	27.	F. E. Kosinski
3.	Document Reference Section	28.	R. W. McClung
4-5.	Laboratory Records Department	29.	D. L. McElroy
6.	Laboratory Records, ORNL RC	30.	A. J. Moorhead
7.	ORNL Patent Section	31.	J. P. Nichols
8.	D. E. Bartine	32.	A. R. Olsen
9.	T. M. Besmann	33.	R. E. Pawel
10.	E. E. Bloom	34.	G. M. Slaughter
11.	K. W. Boling	35.	V. J. Tennery
12.	W. H. Butler	36-39.	P. T. Thornton
13-17.	G. L. Coleman	40.	P. F. Tortorelli
18.	R. H. Cooper, Jr.	41.	F. W. Wiffen
19.	D. F. Craig	42-46.	R. K. Williams
20.	J. H. DeVan	47-51.	D. W. Yarbrough
21.	J. R. DiStefano	52.	H. D. Brody (Consultant)
22.	W. S. Dritt	53.	G. Y. Chin (Consultant)
23.	M. L. Grossbeck	54.	F. F. Lange (Consultant)
24.	H. W. Hoffman	55.	W. D. Nix (Consultant)
25.	J. A. Horak	56.	D. P. Pope (Consultant)
26.	O. F. Kimball	57.	E. R. Thompson (Consultant)

EXTERNAL DISTRIBUTION

- 58-64. GENERAL ELECTRIC COMPANY, Space Nuclear Engineering and Technology
Operations, P.O. Box 530954, San Jose, CA 95153-5354
- H. S. Bailey
M. Kangilaski
A. W. Dalcher
P. J. Ring
E. D. Sayre
S. Vaidyanathan
J. C. Whipple
65. GENERAL ELECTRIC COMPANY, Advanced Reactor Systems Department,
175 Curtner Avenue, San Jose, CA 95125
- P. Roy

- 66-69. GENERAL ELECTRIC COMPANY, Astro-Space Systems Division,
P.O. Box 8555, Philadelphia, PA 19101
- D. N. Elliott
 - A. Josloff
 - R. J. Katucki
 - R. E. Morgan
- 70-72. IDAHO NATIONAL ENGINEERING LABORATORY, P.O. Box 1625, Idaho Falls,
ID 83415
- J. W. Henscheid
 - D. Hughes
 - J. S. Martinell
- 73-75. JET PROPULSION LABORATORY, 4800 Oak Grove Drive, Pasadena, CA 91109
- R. R. Ferber
 - J. F. Mondt
 - V. C. Truscello
- 76-82. LOS ALAMOS NATIONAL LABORATORY, P.O. Box 1663, Los Alamos, NM 87545
- R. E. Baars
 - D. R. Bennett
 - J. E. Hanson
 - R. E. Mason
 - R. B. Matthews
 - M. B. Parker
 - R. B. Rothrock
83. MCDONNELL DOUGLAS ASTRONAUTICS COMPANY EAST, P.O. Box 516,
St. Louis, MO 63166
- J. W. Davis
- 84-87. NASA LEWIS RESEARCH CENTER, 2100 Brookpark Road, Cleveland, OH 44135
- H. S. Bloomfield
 - C. M. Scheuermann
 - J. R. Stephens
 - R. H. Titran
88. NUS CORPORATION, 910 Clopper Road, Gaithersburg, MD 30878
- A. Weitzberg
- 89-90. ROCKWELL INTERNATIONAL, Energy Technology Engineering Center,
P.O. Box 1449, Canoga Park, CA 92304
- R. A. Johnson
 - B. B. Gillies
91. UNIVERSITY OF FLORIDA, Department of Nuclear Engineering Sciences,
202 Nuclear Sciences Center, Gainesville, FL 32611
- S. Anghaie

- 92-93. WESTINGHOUSE ELECTRIC CORPORATION, Advanced Energy Systems Division,
P.O. Box 10864, Pittsburgh, PA 15236
R. W. Buckman
V. K. Sazawal
- 94-95. WESTINGHOUSE HANFORD COMPANY, P.O. Box 1970, Richland, WA 99352
C. M. Cox
D. S. Dutt
J. J. Holmes
R. J. Puigh
- 96-99. DOE, DIVISION OF DEFENSE ENERGY PROJECTS, NE-521 (GTN), Washington,
DC 20545
W. P. Carroll
S. S. Voss
E. J. Wahlquist
J. W. Warren
100. DOE, OAK RIDGE OPERATIONS OFFICE, P.O. Box E, Oak Ridge, TN 37831
Office of Assistant Manager for Energy Research and
Development
- 101-103. DOE, SAN FRANCISCO OPERATIONS OFFICE, 1333 Broadway, Oakland,
CA 94612
W. E. Keheley
R. L. Saalborn
W. L. Von Flue
- 104-155. DOE, OFFICE OF SCIENTIFIC AND TECHNICAL INFORMATION, Office of
Information Services, P.O. Box 62, Oak Ridge, TN 37831
For distribution as shown in DOE/TIC-4500, Distribution
Category UC-404 (Materials)

