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SUMMARY OF THERMOPHYSICAL PROPERTIES OF POTASSIUM

by Harold H. Coe

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Cleveland, Ohio

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Page 21: The ordinate scale for Density, g/cc, should be 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2} instead of 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}.

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SUMMARY

Recently reported thermodynamic and physical property data on the alkali metal potassium are compiled and the results of the various sources are compared with previously existing data. Data for the liquid properties of specific heat, thermal conductivity, enthalpy, entropy, viscosity, electrical resistivity, density, and surface tension are presented over the temperature range from 200° to 2200° F when possible. Data for the saturated vapor properties of specific heat, thermal conductivity, vapor pressure, heat of vaporization, entropy of vaporization, viscosity, and density are presented over the temperature range from 800° to 2200° F.

The results from the several sources agree very well for most of the properties in the lower temperature range up to about 1400° F. However, significant differences are apparent for some of the properties at temperatures above 1400° F.

INTRODUCTION

The alkali metals, such as sodium, potassium, rubidium, cesium, and lithium, have physical, thermodynamic, and transport properties that make them attractive fluids for elevated temperature applications. For this reason, alkali metals are being considered for use as reactor coolants and as working fluids in space power generation systems. Although the values of some of these properties had been established earlier, it became evident in recent years that more experimental data were required, not only to extend the temperature range, but also to resolve discrepancies that existed at the lower temperatures.

Beginning in 1960, several programs were initiated by NASA and the USAF (WADD) to determine and compile the properties of the alkali metals. The results of a USAF contract with Southwest Research Institute for collection of property data on a number of materials including the alkali metals were published in 1961 as reference 1. This report was considered one of the best sources of property data prior to the recent publication of the results of many of the other investigations (refs. 2 to 24).

The majority of the published reports were concerned with potassium, one of the more widely used alkali metals. There are many design and experimental studies of Rankine cycle space power generation systems with principal interest at present on potassium as the working fluid. These studies include the SPUR-SNAP 50 program (ref. 25), the General Electric boiling and condensing investigations (ref. 26), and several inhouse programs at the NASA Lewis Research Center. In all of these programs, accurate property data are required for design procedures and studies and for analysis of experimental and theoretical results.

The object of this report is to compile the recently reported property data on potassium, to compare the results of the various sources with previously existing data, and to identify any areas of discrepancy so that the designer can establish best judgement in the use of the available properties. Data on the saturated liquid properties of density, viscosity, surface tension, electrical resistivity, thermal conductivity, enthalpy, specific heat, and entropy are presented over the temperature range from 200° to 2200° F when possible. Data on the saturated vapor properties of vapor pressure, density, viscosity, thermal conductivity, heat of vaporization, entropy of vaporization, and specific heat are presented over the temperature range from 800° to 2200° F. The saturation lines on an enthalpy-entropy diagram are also presented. In format, the values determined in the recent experimental programs (refs. 2 to 16) are compared with the values reported in reference 1 and other previous data sources.

PRESENTATION OF RESULTS

The data are presented graphically with property values plotted against temperature, and comments are presented concerning the method each source employed in obtaining its data. The curves are numbered to facilitate reference in the text.

In order to make comparisons of the data, all property values were converted to the English system of units, with the metric system of units shown on the graphs for convenience. The percent differences between the data sources for each property were calculated and are noted in the comments on the individual properties.

The presentation of the comparisons has been separated into saturated liquid properties (figs. 1 to 8) and saturated vapor properties (figs. 9 to 16).

It should be noted that some work on potassium properties is still in progress by Aerojet-General Nucleonics (AGN) and MSA Research Corporation (MSAR) (refs. 16 and 20) and that the data presented from the U. S. Naval Research Laboratory (NRL) (refs. 3 and 11) and MSAR (refs. 4 and 8) are from interim progress reports and are not from a final technical report. As the present report was being published, potassium property data were made available by the NRL final technical report (ref. 27) and were added to the appropriate graphs. However, the NRL preliminary values were left in the present work for comparison because the two progress reports (refs. 3 and 11) show the results of two different methods of determining property data. In the final report (ref. 27),

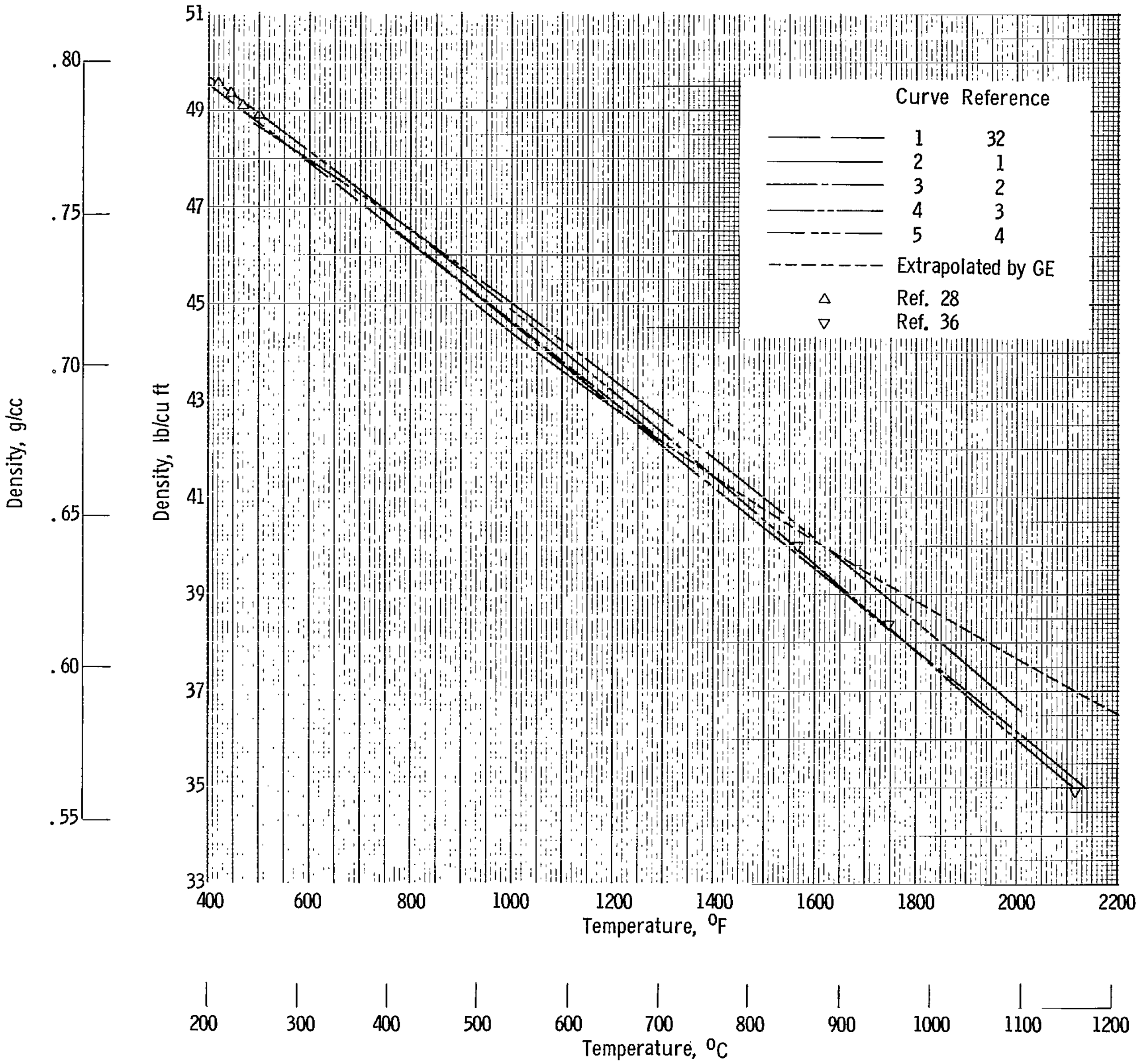

Figure 1. - Density of potassium liquid.

NRL determined the properties by the same method outlined in reference 11, and, although an error was found in the coefficient of expansion of niobium-1 zirconium, the final saturation values were only slightly changed from the preliminary data, with the exception of the specific heat of the saturated vapor.

SATURATED LIQUID PROPERTIES

Density (Fig. 1)

In 1948, NRL (ref. 28) presented a best line through the experimental density data of Ewing, et al. (ref. 28), MSAR, Rinck (ref. 29), and Hagen (ref. 30). Values of density from this best line were then given in table 2.2 of reference 31 and in table I-14 of reference 32 and are shown as curve 1 in figure 1. General Electric (GE) (ref. 33) extrapolated the data from reference 31 to temperatures above 1300° F, and WADD reported the GE values in reference 1; these values are shown as curve 2.

Battelle presented an equation in reference 5 derived by them to fit the data from reference 32 and a private communication from Ewing of NRL. Values of density calculated from this equation were tabulated in table C-2 of reference 2 and are shown as curve 3.

The values for the NRL curve (curve 4) were calculated from an equation presented in reference 3, derived by NRL as the best curve fit to the experimental density data of Hagen (ref. 30) and Ewing, et al. (ref. 28) at lower temperatures, Novikov, et al. (ref. 34), Jackson, et al. (ref. 35), and Rinck (ref. 29) at moderate temperatures, and Ewing, et al. (ref. 36) at higher temperatures. The data points from a quartz dilatometer in reference 28 and from a pynchnometer in reference 36 are also shown for comparison. The NRL final values from appendix A of reference 27 lie on curve 4.

MSAR presented an equation in reference 4 as the best representation of the MSAR experimental data obtained from a dilatometer over the temperature range of 470° to 2000° F. The standard deviation of the 39 data points was 0.0014 gram per cubic centimeter. Density values calculated from this equation are shown as curve 5.

It is stated by Cooke in reference 6 that the preliminary results obtained up to about 1300° F by the maximum bubble pressure method show good agreement with the composite data of reference 31 and average approximately 0.4 percent higher. These data then would be very close to the NRL curve (curve 4).

It can be seen that the recent experimental determination of MSAR agrees very well with the previous work, with a maximum difference of less than 2 percent at 2000° F. It should be noted that curve 2 has the wrong curvature and thus differs from the other determinations; this difference at 2000° F is a maximum of about 4 percent.

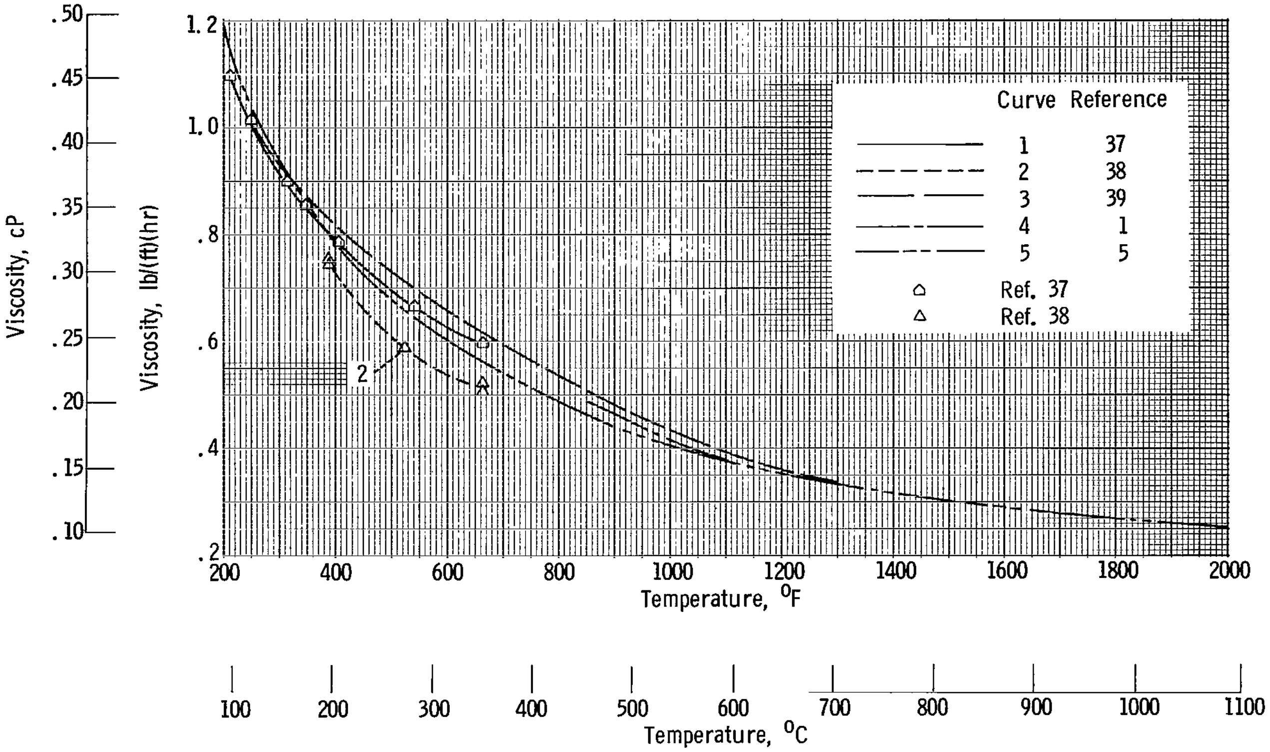

Figure 2. - Viscosity of potassium liquid.

Viscosity (Fig. 2)

The viscosity data obtained by Chiong (ref. 37), using a glass oscillating sphere, are shown in figure 2. A curve (curve 1) was drawn through the points for comparison. Chiong determined these values using the density data of Hagen (ref. 30).

Ewing, et al. (ref. 38) obtained some viscosity data up to 660° F using a nickel viscometer of the Ostwald type. These data points are shown in figure 2, with a curve (curve 2) drawn through the points for comparison.

Novikov, et al. (ref. 39) obtained viscosity data using the torsional oscillation method and the theory of Shvidkovsky (ref. 40). Values of kinematic viscosity were taken from the line through the data presented in reference 39. The absolute viscosity, calculated with the same density values used for curves 2 and 5 in order to make a better comparison, is shown as curve 3. Experimental data of Kutateladze, et al. (ref. 41), obtained by the damped torsional oscillations method, were reported by WADD (ref. 1) and are shown as curve 4.

Battelle (ref. 5) determined this property using the oscillating cylinder method and the Shvidkovsky (ref. 40) equation. Values of absolute viscosity calculated from the two Andrade (ref. 42) type equations presented in reference 5 as a least-squares fitting of the experimental data are shown as curve 5. The standard deviation of the points from the low temperature (154° to 698° F) equation was 0.005 and from the high temperature (698° to 2100° F) equation was 0.012. It should be noted that Battelle also fitted the data over the entire temperature range with a single equation of the Andrade type that resulted in a standard deviation of 0.018; it was obvious that the data were better fitted with the two equations.

It can be seen that the Battelle results (curve 5) lie generally midway between the other values presented. Chiong's values are about 4 percent lower than curve 5 at 211° F and about 5 percent higher at 666° F. Novikov's results (curve 3) are about 5 percent higher than Battelle's in the range from 400° to 1000° F but show good agreement at the higher and lower temperatures. Ewing's data are about 10 percent lower than Battelle's over the range shown.

Surface Tension (Fig. 3)

Using the capillary rise method, Ewing, et al. (ref. 28) determined an average value of about 0.00546 pound per foot (80 dynes/cm) for the surface tension of potassium over the temperature range from the melting point to 379° F (193° C), assuming a contact angle of zero degrees. The purity of the potassium was 99.6 percent.

Quarterman and Primak (ref. 43) also used the capillary rise method and reported an average value of 0.00587 pound per foot (86 dynes/cm) from the melting point to 308° F (153.4° C), assuming a contact angle of zero degrees. The contact angle was measured one year later and determined to be 24° to 26°. It

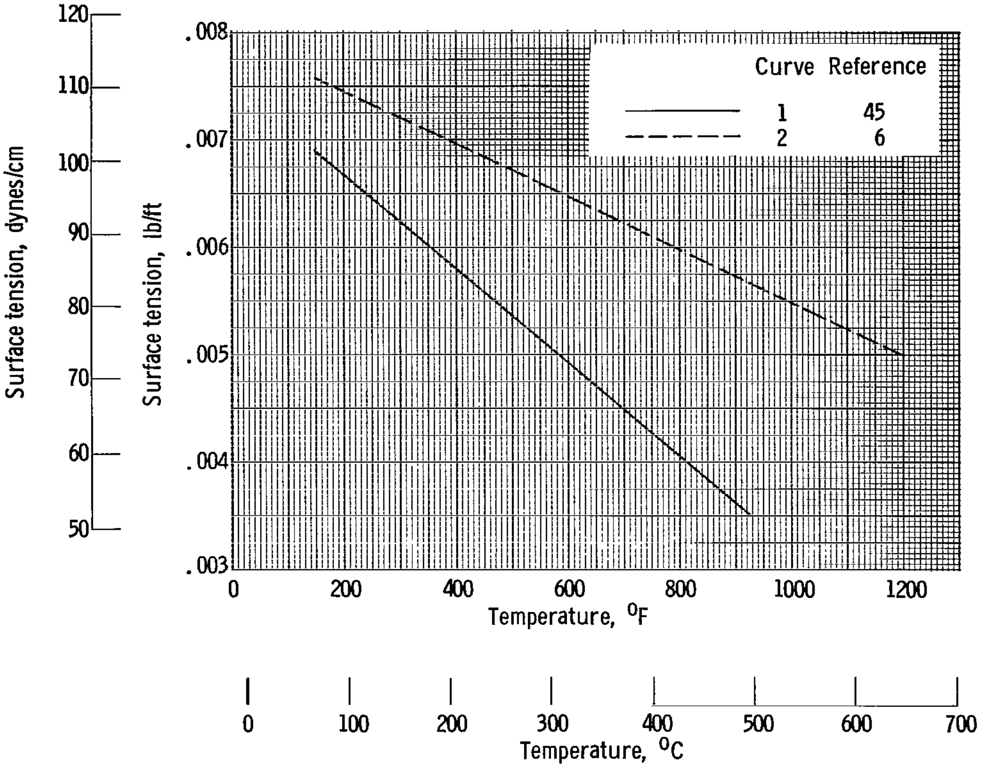

Figure 3. - Surface tension of potassium liquid.

was concluded that the actual contact angle during the surface tension measurements was less than 26°, which would result in a maximum correction of less than 11 percent. The value of surface tension at the melting point reported by WADD (ref. 1) was based on reference 44.

The data for curve 1 were calculated with the value of surface tension at the melting point and the recommended temperature coefficient (-0.11 erg/cm^2/°C) as determined experimentally by Taylor (ref. 45) using the maximum bubble pressure method with argon as a cover gas. The correct radius was determined by the method of Porter (ref. 46) and the correction for the distortion of the bubble from a spherical shape by the method of Sugden (ref. 47). The purity of the potassium used was 99.895 percent. The data scatter was approximately ±2 percent.

Preliminary surface tension data has been reported by Cooke (ref. 6). The data were obtained by the maximum bubble pressure method with helium gas and employing the Schrödinger equation (ref. 48). The values for curve 2 were calculated from a least-squares equation presented in reference 6. The mean-square deviation of the points was ±0.64 dyne per centimeter. A total of 202 determinations were made; however, several values around 400° F (200° C) were not included in the least-squares treatment, since they were up to 5 percent low. All of these low values were recorded shortly after the installation of a new capillary tube, and it was felt that these low values were the result of poor wetting of the capillary by the potassium.

It can be seen that the preliminary data of Cooke (curve 2) are considerably higher than Taylor's values (curve 1), ranging from almost 12 percent at 200° F to about 59 percent at 900° F. The data of Ewing, et al. (ref. 28) and Quarterman and Primak (ref. 43) are about 15 to 20 percent lower than those of Taylor, with the actual contact angle in considerable doubt. A larger contact angle would, of course, raise the values given. It should be noted that the purity of the potassium is important in the surface tension determination and may contribute to these discrepancies.

Electrical Resistivity (Fig. 4)

The values of electrical resistivity reported in reference 31 were taken from the data of Bornemann and Rauschenplat (ref. 49); these values are shown in figure 4 for comparison. The data for the Battelle curve (curve 1) were taken from table A-2 of reference 7; these data are interpolated values taken from a smooth curve visually fitted to the experimental data. Battelle measured the electrical resistivity during the thermal conductivity determination by passing a direct current through the specimen and measuring the voltage drop. The error was estimated to be less than ±2 percent.

The values for the MSAR curve (curve 2) were calculated from an equation given in reference 8 as a least-squares fit of the experimental data. The standard deviation of the 52 points was 0.102 micro-ohm-inch (0.259 $\mu\Omega$-cm) or 1.0 percent. The values for the Pratt and Whitney Aircraft (PWAC) curve (curve 3) were calculated from an equation in reference 9 given as a least-

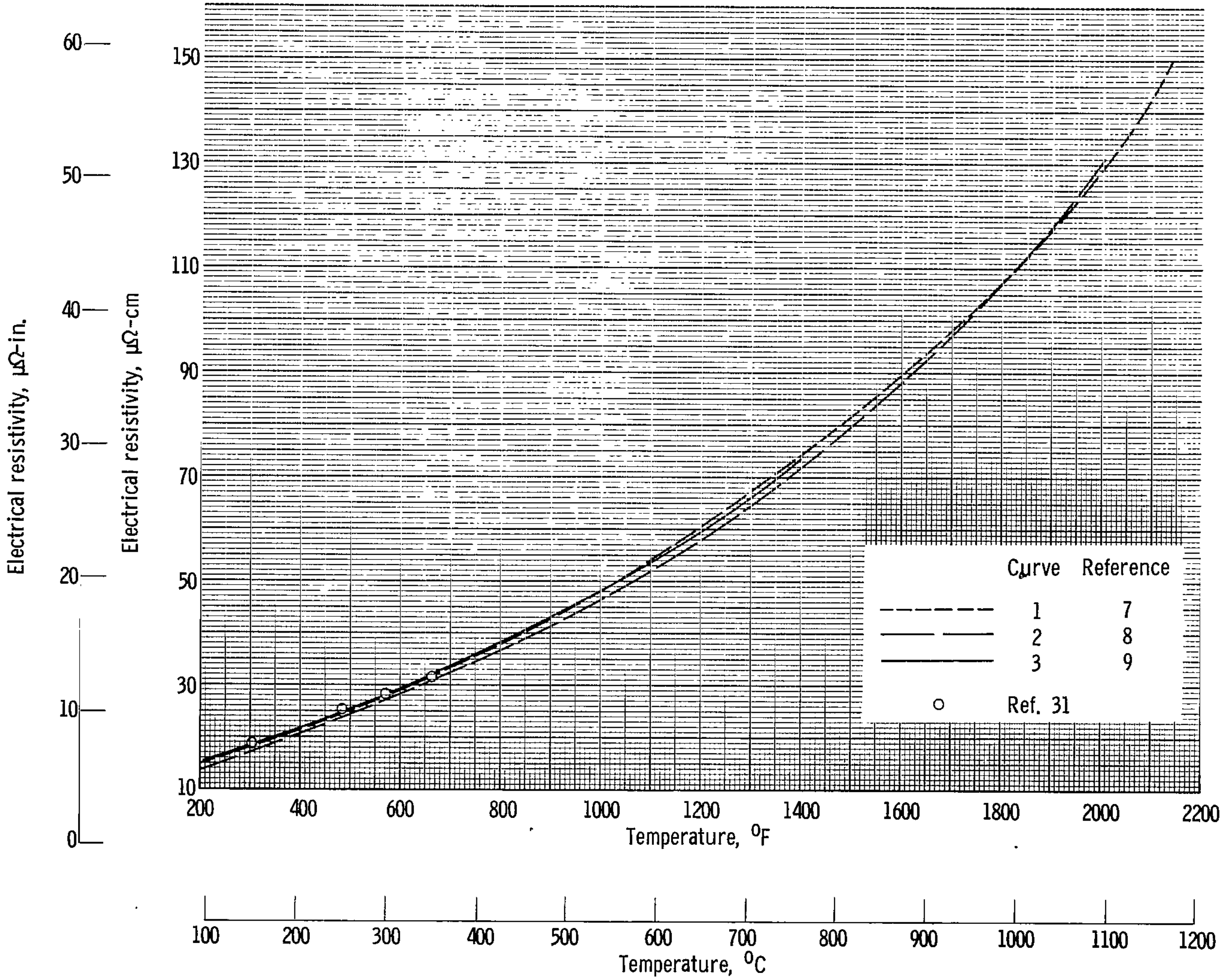

Figure 4. - Electrical resistivity of potassium liquid.

squares fit of the experimental data. The electrical resistivity was measured by passing a known current through a calibrated stainless-steel tube containing the liquid potassium at a uniform temperature and measuring the potential drop across a well-defined length of the tube. The mean deviation of the 15 experimental points was ±0.71 percent, with a maximum deviation of 2.3 percent at 494° F (256.4° C).

It can be seen that all the experimental data agree very closely over the entire temperature range, with a maximum difference of only about 3 percent.

Thermal Conductivity (Fig. 5)

The experimental thermal conductivity data of Ewing, et al. (ref. 50), obtained from a longitudinal heat-flow apparatus, is shown in figure 5 as curve 1. These data were also reported in reference 31. An extrapolation of Ewing's data by AiResearch Company was reported in reference 1 and is shown as curve 2.

Novikov, et al. (ref. 39) concluded that the direct measurement of the thermal conductivity of the liquid alkali metals was not suitable and, therefore, chose to measure the thermal diffusivity and to calculate the thermal conductivity as the product of the thermal diffusivity, the specific heat, and the density. The specific heat values were taken from Douglas, et al. (ref. 51) and the density from reference 31. The deviation of the readings from the mean was reported not to exceed 0.5 percent. The values for curve 3 were read from a smooth curve in reference 39.

Nikol'skii (ref. 10) developed a method of measuring thermal conductivity called the method of successive stationary states. The results of experiments using this method are shown as curve 4. The values for this curve were taken from table 12 of reference 10; these values were obtained from the smoothed curve through the experimental data. Although no values were given for data scatter, most of the data points appeared to be within about ±2 Btu per hour per foot per °F of the smoothed curve.

Battelle (ref. 7) measured the thermal conductivity up to 1472° F (800° C), using a longitudinal-heat-flow, steady-state, comparative method, with an estimated experimental error of 8 percent. Two equations were derived for the data by the method of least squares. The first, a straight line equation (that was valid only from 100° to 800° C) had a standard deviation of 0.8 Btu per hour per foot per °F (0.014 W/(cm)(°C)) for the 50 data points, while the second, a second-degree equation (that could be extrapolated) had a standard deviation of 0.6 Btu per hour per foot per °F (0.011 W/(cm)(°C)). Values calculated from this second equation (extrapolated to 2100° F) were reported in table A-6 of reference 7 and are shown as curve 5.

The Wiedemann-Franz-Lorenz equation states that the product of the thermal conductivity and the electrical resistivity divided by the absolute temperature is equal to a constant called the Lorenz number. The average value of the Lorenz number derived from the Battelle experimental data was 2.14×10^{-8} watt-ohm per degree squared. It should be noted that the average value of the

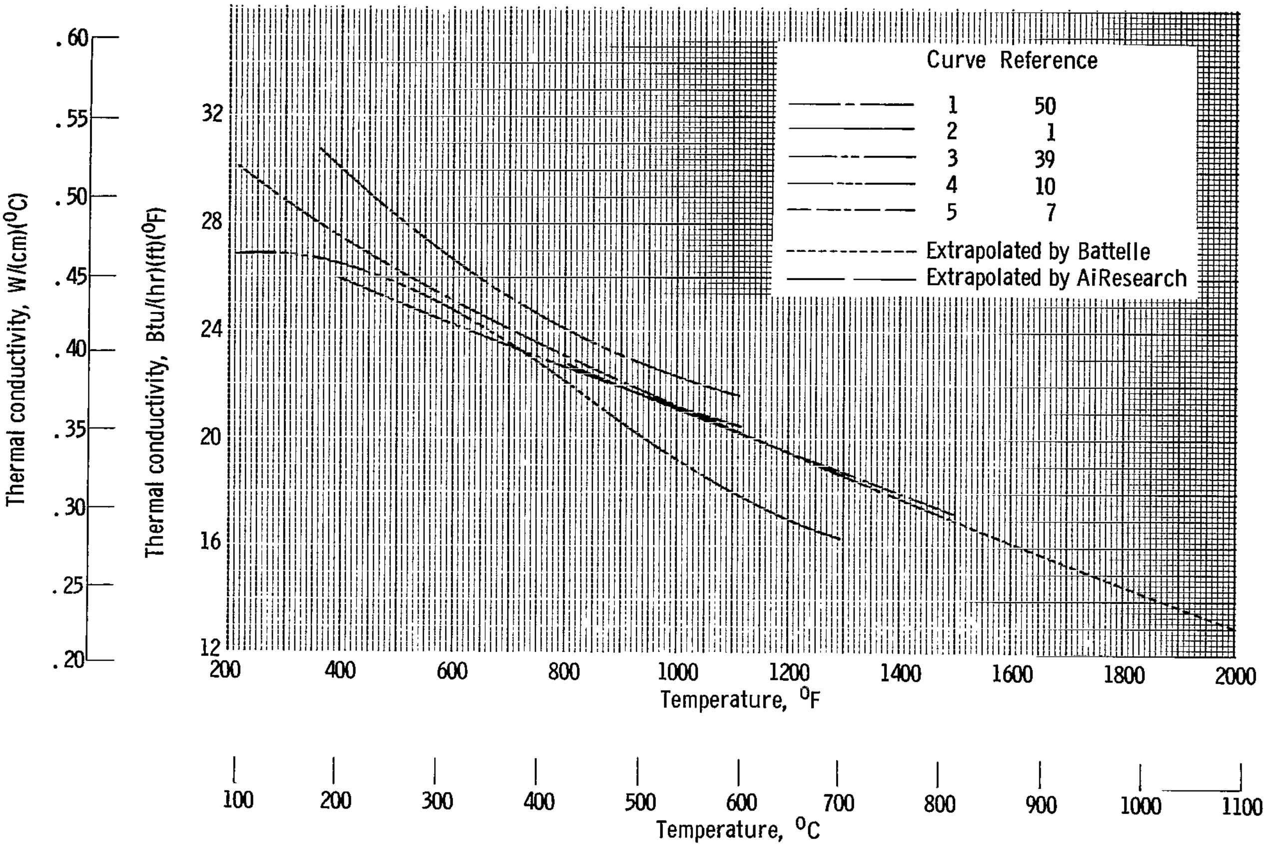

Figure 5. - Thermal conductivity of potassium liquid.

Lorenz number obtained using the thermal conductivity data of Ewing, et al. (ref. 50) and the electrical resistivity data of reference 9 was also 2.14×10^{-8} watt-ohm per degree squared. Values of thermal conductivity calculated by Battelle up to 2100° F with this average value of the Lorenz number were also reported in table A-6 of reference 7 and showed very good agreement with curve 5.

MSAR (ref. 8) reported values of thermal conductivity calculated directly from MSAR experimental electrical resistivity data, using the Wiedemann-Franz-Lorenz equation with the theoretical value of the Lorenz number of 2.45×10^{-8} watt-ohm per degree squared. Since this theoretical value is about 14 percent higher than the Battelle experimental Lorenz number and the electrical resistivity values of these two sources differ only slightly, it can be seen that the MSAR thermal conductivity values reported are also about 14 percent higher than Battelle's over the entire temperature range.

The data of Battelle (curve 5) are approximately in the middle of the values presented. Novikov's values (curve 3) are from about 9 percent at 400° F to 7 percent at 1100° F higher than curve 5. The data of Ewing, et al. (curve 1) are about 6 percent lower than Battelle's at 400° F and cross curve 5 at about 1000° F. The data of Nikol'skii (curve 4) diverge at both the higher and lower temperatures, differing from that of Battelle by about 14 percent at 200° F and 12 percent at 1300° F.

Enthalpy (Fig. 6)

Douglas, et al. (ref. 51) determined the enthalpy of potassium liquid up to 1472° F (800° C) using an ice calorimeter. Errors in the enthalpy values as given by the equation presented were believed to be less than 0.3 percent for temperatures above 400° F (200° C). Several values calculated with this enthalpy equation and a constant from the work of Evans, et al. (ref. 52) (in order to refer the enthalpy to 0° R) are shown in figure 6 for comparison.

The liquid enthalpy in reference 33 was determined by integrating the liquid specific heat relation, as given in reference 31, and adding the enthalpy of the solid and the enthalpy of melting as determined from reference 53. It should be noted that the specific heat relation reported in reference 31 was actually from the data of Douglas, et al. (ref. 51). The values of enthalpy calculated in reference 33 (extrapolated to 2100° F) were reported in reference 1 and are shown as curve 1 in figure 6.

Battelle (ref. 12) measured the liquid enthalpy up to 2100° F (1150° C) using a Bunsen Ice Calorimeter. It was apparent that greater confidence existed for the data up to about 1470° F (800° C) than for the data at the higher temperatures, since the data scatter was more pronounced at temperatures above 1470° F (800° C). The data scatter at the higher temperatures was due, in part, to the effect of oxidation of the capsule. This oxidation not only was not uniform, but also was not the same for both the empty and the specimen capsules. In the least-squares solution, therefore, Battelle gave the data below 1470° F a weighting of three, compared to a weighting of one for the higher temperature

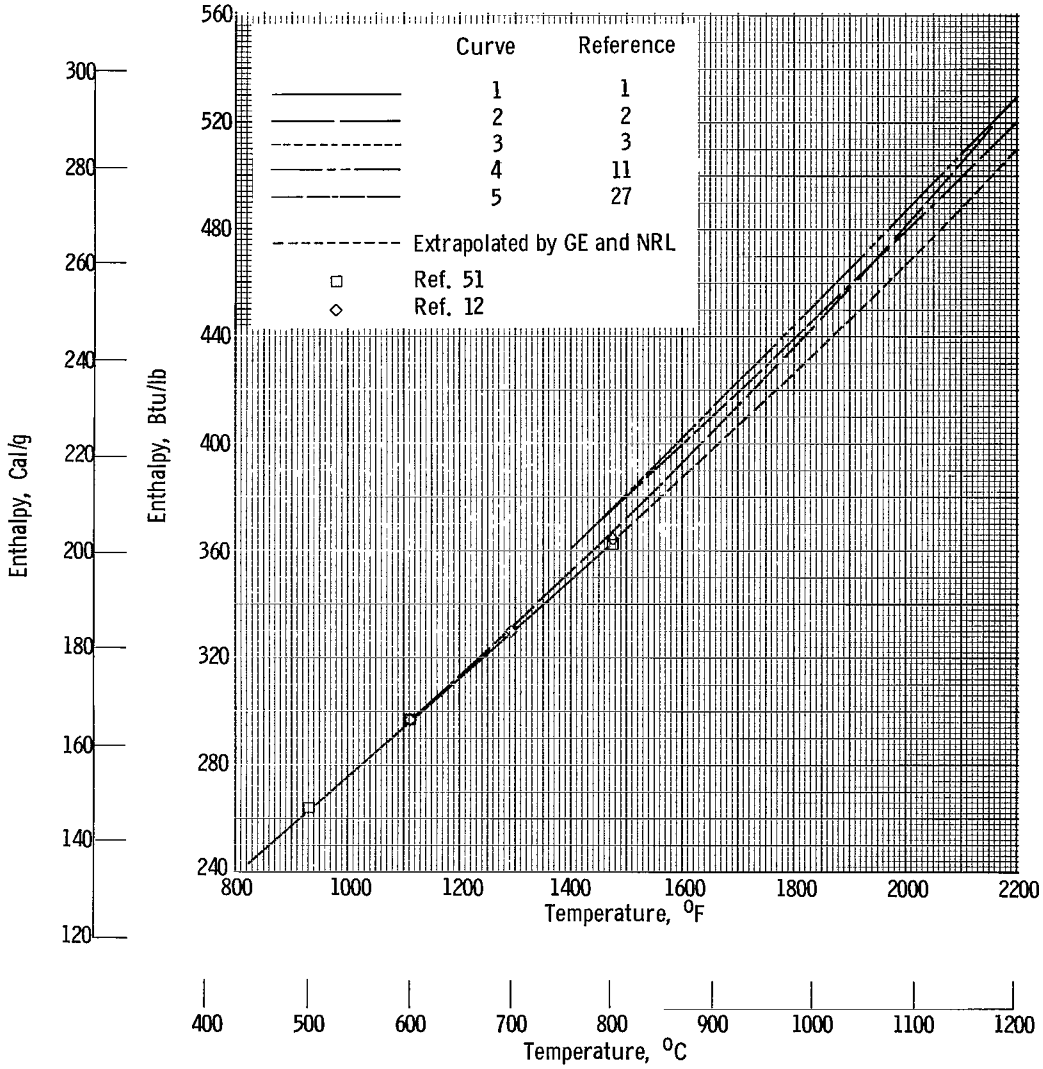

Figure 6. - Enthalpy of potassium liquid (saturated) referenced to 0° R.

data. The standard deviation from the resulting equation was 3.04 Btu per pound (1.69 Cal/g) for the 23 values from the melting point to 2100° F. The standard deviation was 1.20 Btu per pound (0.67 Cal/g) for the 13 values below 1470° F and 4.55 Btu per pound (2.53 Cal/g) for the 10 values above 1470° F. By changing the units of the previous equation and adding a constant from the work of Evans, et al. (ref. 52), Battelle obtained an equation (presented in ref. 2) for liquid enthalpy referenced to 0° R (0° K). Values calculated from this equation were presented in table C-2 of reference 2 and are shown as curve 2.

Battelle also determined a least-squares fit of only the data from the melting point to 1470° F; the standard deviation of the 13 points from this equation (presented in table 6 of ref. 12) was 0.77 Btu per pound (0.43 Cal/g). Several values calculated by means of this enthalpy equation and a constant from the work of Evans, et al. (ref. 52) (in order to refer the enthalpy to 0° R) are shown in figure 6.

The data for one NRL curve (curve 3) were taken from table 5 of reference 3; these enthalpy values were calculated from an equation derived by NRL directly from the work of Douglas, et al. (ref. 51), with a constant from the work of Evans, et al. (ref. 52), and extrapolated by NRL to 2500° F. Preliminary specific heat results at NRL (ref. 13) in the temperature range from 1300° to 2100° F show an average deviation of ±1.4 percent from values calculated from the equation of reference 51 and tend to justify the enthalpy extrapolation.

The data for the other NRL curve (curve 4) were taken from table 11 of reference 11; NRL obtained these enthalpy values by subtracting the enthalpy of vaporization from the enthalpy of the saturated vapor, using the values presented in table 11 (ref. 11). The enthalpy of the saturated vapor presented in reference 11 was computed with virial coefficients, by using the properties of the monomeric gas at one atmosphere as given by Evans, et al. (ref. 52) as a base, or starting point. The NRL final values from appendix A of reference 27 are shown as curve 5.

It can be seen from figure 6 that the values calculated from the Battelle (ref. 12) equation, which considered only the data at temperatures less than 1470° F (800° C), agree very well with the values calculated from Douglas, et al. (ref. 51). The extrapolated curves of NRL (curve 3) and WADD (curve 1) (both based on the data of ref. 51) agree very well with each other. The NRL curve (curve 4) is from 3 to 4 percent higher, while the final NRL curve (curve 5) is 2 to 3 percent higher than curve 1 over the range shown. The Battelle data (curve 2) agree very closely with curve 1 at the lower temperatures and lie between the values given by NRL at the higher temperatures, differing from curve 3 by 3 percent at 2000° F. While this difference is small, the difference in the slope of curve 2 affects the change in enthalpy with temperature (therefore, the specific heat) to a greater degree.

Specific Heat (Fig. 7)

Douglas, et al. (ref. 51), derived the specific heat relation from a corrected first derivative of the equation representing their experimental liquid

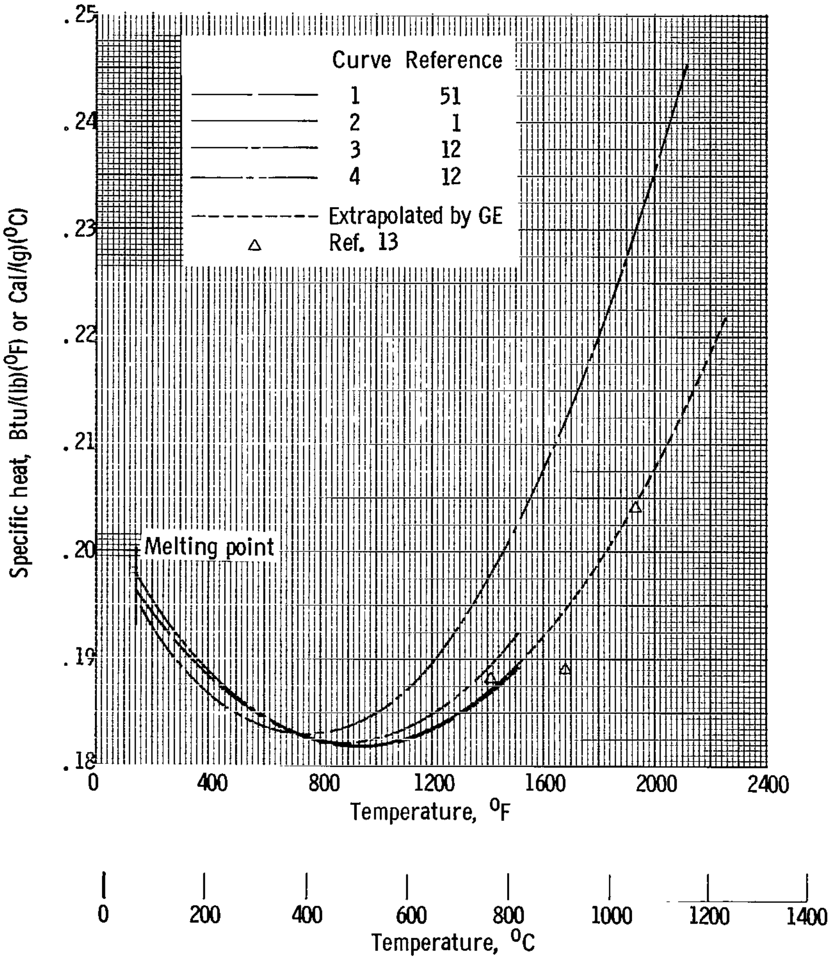

Figure 7. - Specific heat of potassium liquid.

enthalpy data. The uncertainty assigned to the heat capacity values calculated from the derived equation was 0.4 percent for the range from 200° to 1300° F (100° to 700° C). The values from reference 51 were also reported in reference 31 and are shown as curve 1 in figure 7. The data reported in reference 31 were extrapolated to 2200° F in reference 33; these values were also reported by WADD (ref. 1) and are shown as curve 2.

Values of specific heat determined by Nikol'skii (ref. 10) using the direct heating method are identical to the values of reference 51 for the range of 200° to 750° F (100° to 400° C).

Battelle (ref. 12) determined the specific heat from a corrected first derivative of the equation derived by a least-squares fit of the experimental liquid enthalpy data. As noted in the discussion of liquid enthalpy, Battelle presented two equations to represent the experimental enthalpy data, because of the increased data scatter at temperatures above 1470° F (800° C); therefore, two equations were also derived for the specific heat. When the enthalpy data over the entire temperature range (melting point to 2100° F) were considered in the least-squares fit, the specific heat results (tabulated in table 4 of ref. 12) were as shown in curve 3. However, when only the enthalpy data over the temperature range of the melting point to 1472° F (800° C) were used for the least-squares fit, the results (tabulated in table 6 of ref. 12) were as shown in curve 4. Preliminary values of specific heat reported by NRL in reference 13 are also shown for comparison.

It can be seen that the Battelle specific heat values (curve 4) that were based on the more reliable of their enthalpy data agree very well with the work of Douglas, et al. (curve 1). It can also be seen that the preliminary values reported by NRL tend to justify the extrapolated values of curve 2. The other Battelle curve (curve 3) shows good agreement at the lower temperatures but differs significantly at the higher temperatures; this difference at 2000° F is 13 percent.

Entropy (Fig. 8)

Douglas, et al. (ref. 51) derived an equation for liquid entropy from their specific heat relation. Several values calculated with this entropy equation and a constant from the work of Evans, et al. (ref. 52) (in order to refer the entropy to 0° F) are shown in figure 8 for comparison.

GE (ref. 33) determined the entropy of the liquid using the GE extrapolated specific heat relation, which was actually based on reference 51, and a constant from reference 53. The GE values were also reported by WADD (ref. 1) and are shown in figure 8 as curve 1.

The entropy values presented by Battelle in table C-2 of reference 2 were calculated by means of the Battelle full temperature range liquid heat capacity relation (ref. 12) and a constant from the work of Evans, et al. (ref. 52). These values are presented in figure 8 as curve 2.

The values for curve 3 were taken from table 5 of reference 3; these values

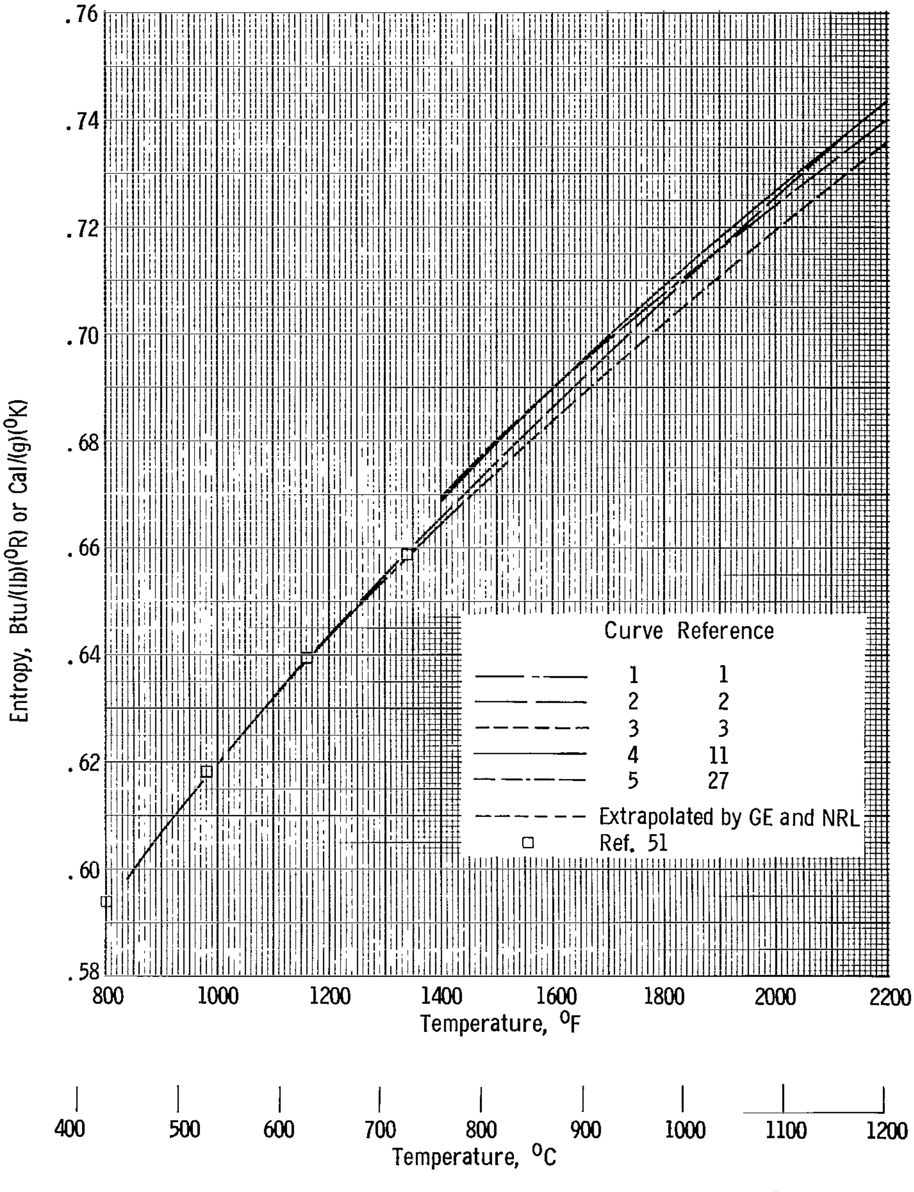

Figure 8. - Entropy of potassium liquid (saturated) referenced to 0° R.

were calculated by means of an equation derived by NRL from the work of Douglas, et al. (ref. 51) using a constant from the work of Evans, et al. (ref. 52) and extrapolated by NRL to 2500° F. Preliminary specific heat results at NRL (ref. 13) in the temperature range from 1300° to 2100° F show an average deviation of ±1.4 percent from the values calculated from the equation of reference 51 and tend to justify the entropy extrapolation.

The values for curve 4 were obtained by NRL by subtracting the entropy of vaporization from the entropy of the saturated vapor as presented in table 11 of reference 11. The entropy of saturated vapor as presented in reference 11 was computed with virial coefficients, using the properties of the monomeric gas at one atmosphere as given by Evans, et al. (ref. 52), as a base, or starting point. The NRL final values from appendix A of reference 27 are shown as curve 5.

It can be seen that the extrapolated curves of WADD (curve 1) and NRL (curve 3) (both based on ref. 51) agree very well with each other. The NRL curve (curve 4) is about 1 percent higher than curve 3, and curve 5 is within 0.5 percent of curve 4. The Battelle curve (curve 2) agrees very well with the values calculated from Douglas, et al. (ref. 51) at the lower temperatures and lies between the two values given by NRL at the higher temperatures, differing from curve 3 by only 1 percent at 2000° F.

SATURATED VAPOR PROPERTIES

Vapor Pressure (Fig. 9)

In 1941, Ditchburn and Gilmour (ref. 54) correlated the vapor pressure data of several investigators (refs. 55 to 61) and derived an equation with an estimated accuracy of 5 percent for the range from 620° to 1520° F or 20 percent for the range from 170° to 1700° F. Values of vapor pressure calculated from this equation were also reported in reference 31, and several of these values are shown in figure 9 for comparison.

The values given by the equation of reference 54 (as presented in ref. 31) were modified by GE (ref. 33) in order to yield consistent results in the calculation of thermodynamic properties. The results of this modification were also reported by WADD (ref. 1) and are shown in figure 9 as curve 1.

Makansi, et al., (ref. 62) measured the vapor pressure in the range from 0.162 to 6.529 atmospheres absolute (2.4 to 96 psia). The data were fitted with a least-squares equation with a reported standard error of 1.1 percent of the value of the pressure. Values calculated from this equation are shown as curve 2.

Battelle (ref. 14) measured the vapor pressure by determining the temperature at which the pressure of the potassium vapor became equal to a fixed helium pressure. This temperature was obtained by observing the slope of the time-temperature curve as the specimen capsule was heated at a set rate. With the stainless-steel capsule used at the lower temperatures, the slope of this

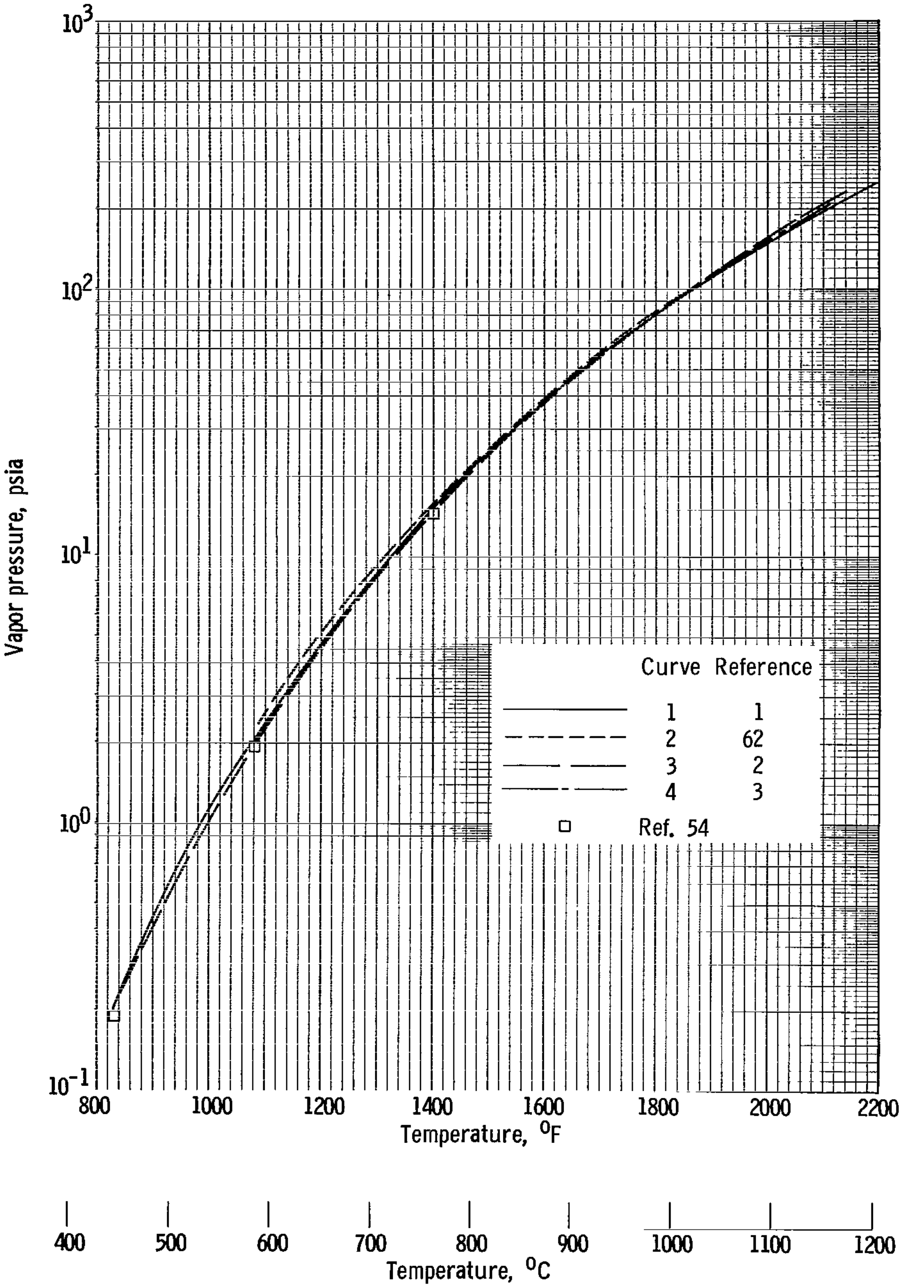

Figure 9. - Vapor pressure of potassium.

curve changed abruptly as the boiling point was reached; however, with the niobium-1 zirconium capsule used at higher temperatures, no abrupt change was noted. Instead, the change of slope was very gradual near the boiling point. Therefore, the nearly constant slope regions of preboiling and postboiling were extrapolated to their intersection to determine the boiling point. An equation to represent the experimental data was derived, based on the relation of Thorn and Winslow (ref. 63). The standard deviation for the Battelle equation was ±0.0097 in the logarithm of the pressure in atmospheres. This standard deviation corresponds to an uncertainty in the vapor pressure of 2.26 percent. Values calculated from the Battelle equation were tabulated in table C-1 of reference 2 and are shown in figure 9 as curve 3.

The values for the NRL curve (curve 4) were taken from table 5 of reference 3; these values were calculated from an equation obtained by a least-squares treatment of the NRL experimental vapor pressure data, measured during the pressure-volume-temperature (PVT) experiments. The average deviation of the observed values from the corresponding calculated values was ±0.31 percent. The NRL final values from appendix A in reference 27 are the same as curve 4.

It was noted in reference 14 that the data of Grachev and Kirillov (ref. 64) deviated widely at all temperatures and must be in error.

It can be seen in figure 9 that the Battelle curve (curve 3) shows good agreement with the correlated values of Ditchburn and Gilmour (ref. 54) in the lower temperature range and with the NRL experimental values (curve 4) at the higher temperatures. The maximum difference with NRL is about 5 percent at 1400° F. The modified values reported by WADD (curve 1) are from 6 to 8 percent higher than Battelle's at the lower temperatures and up to 3 percent lower at the higher temperatures, crossing at about 1650° F. The values of Makansi, et al. (curve 2) are higher than those of Battelle and NRL over the range shown and differ from Battelle's by 10 to 15 percent at the lower temperatures.

Density (Fig. 10)

The specific volumes of the saturated vapor presented by GE (ref. 33) were theoretical values calculated from the perfect gas law. Values taken from table 2 of reference 33 are shown as curve 1 in figure 10. Values of vapor density reported by WADD (ref. 1) were based on reference 33.

Values for the Battelle curve (curve 2) were taken from table C-1 of reference 2; these values were calculated using virial coefficients. It should be noted that the values of the second virial coefficient obtained by Battelle from the PVT experiments were slightly different from the values of Thorn and Winslow (ref. 63). Since problems with the PVT apparatus were encountered by Battelle, due in part to the complexity of the pressure measuring system, it was concluded by Battelle that the more reliable second virial coefficients could be obtained from an equation taken from the work of Thorn and Winslow (ref. 63) and presented in reference 2. The third virial coefficient, determined originally from the vapor pressure work (ref. 14), was modified from the PVT data as shown in appendix B of reference 2. This modified coefficient was

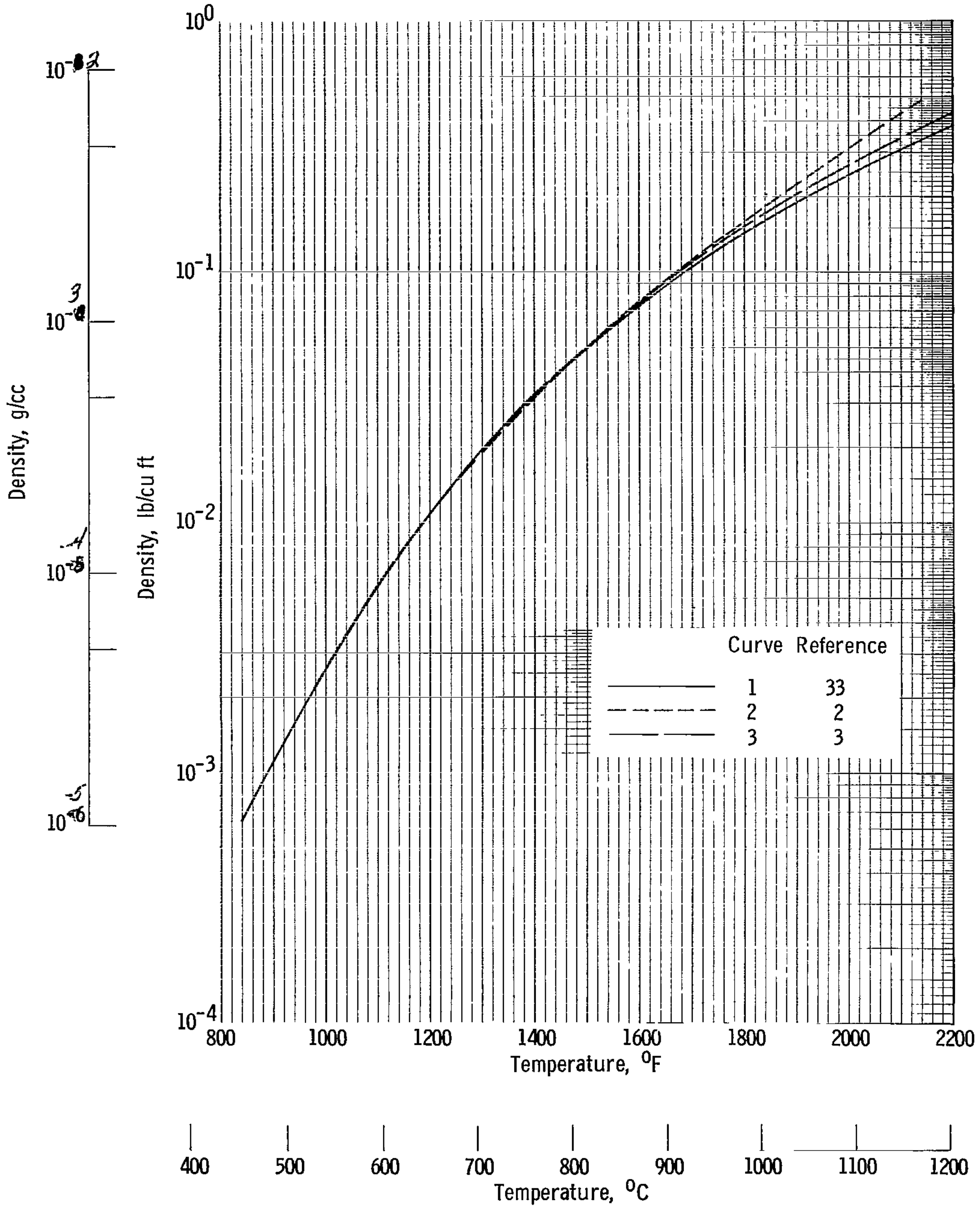

Figure 10. - Density of potassium vapor (saturated).

used in the calculation of the vapor specific volume.

The data for the NRL curve (curve 3) were taken from table 5 of reference 3; these data were computed from the virial equation of state. The virial coefficients were derived graphically from the PVT data of reference 3. Specific volumes at saturation for nine temperatures from 1570° to 2289° F were also directly observed by NRL and were presented in table 4 of reference 3. The observed values deviated from computed values by an average of ±0.33 percent. The NRL final values from appendix A of reference 27 lie on curve 3.

The Battelle curve (curve 2) agrees very well with the theoretical values of curve 1 at the lower temperatures, and both the Battelle and NRL curves deviate from the theoretical values at the higher temperatures. At 2000° F, the Battelle value of vapor density is 16 percent higher than the NRL value, and the NRL value is 10 percent higher than the theoretical value.

Viscosity (Fig. 11)

The values presented by WADD (ref. 1) are theoretical and were computed for variable molecular weight saturated vapor by means of an equation for gas viscosity presented in reference 65.

It should be noted that Battelle (ref. 15) attempted to determine this property, but experimental difficulties prevented completion of the program.

Thermal Conductivity (Fig. 12)

The values presented by WADD (ref. 1) were estimated by assuming a constant Prandtl number of 0.73. Values of frozen specific heat (curve 1, fig. 15) and absolute viscosity (fig. 11) were then used to compute the thermal conductivity of the saturated vapor. These WADD values are shown in figure 12. Battelle (ref. 15) attempted to determine this property, but experimental difficulties prevented completion of the program.

It can be seen that the value of the thermal conductivity calculated in this manner is directly affected by the values used for specific heat and viscosity as well as the value assumed for the Prandtl number.

Heat of Vaporization (Fig. 13)

GE calculated the theoretical values for the enthalpy of the saturated vapor using constants from reference 53. Values of the heat of vaporization obtained by subtracting the enthalpy of the saturated liquid from the enthalpy of the saturated vapor at the same temperature as given in table 2 of reference 33 were also reported by WADD (ref. 1) and are shown as curve 1 in figure 13.

Battelle calculated the heat of vaporization using the Battelle experimentally determined vapor pressure equation (ref. 14) and the Clapeyron equation

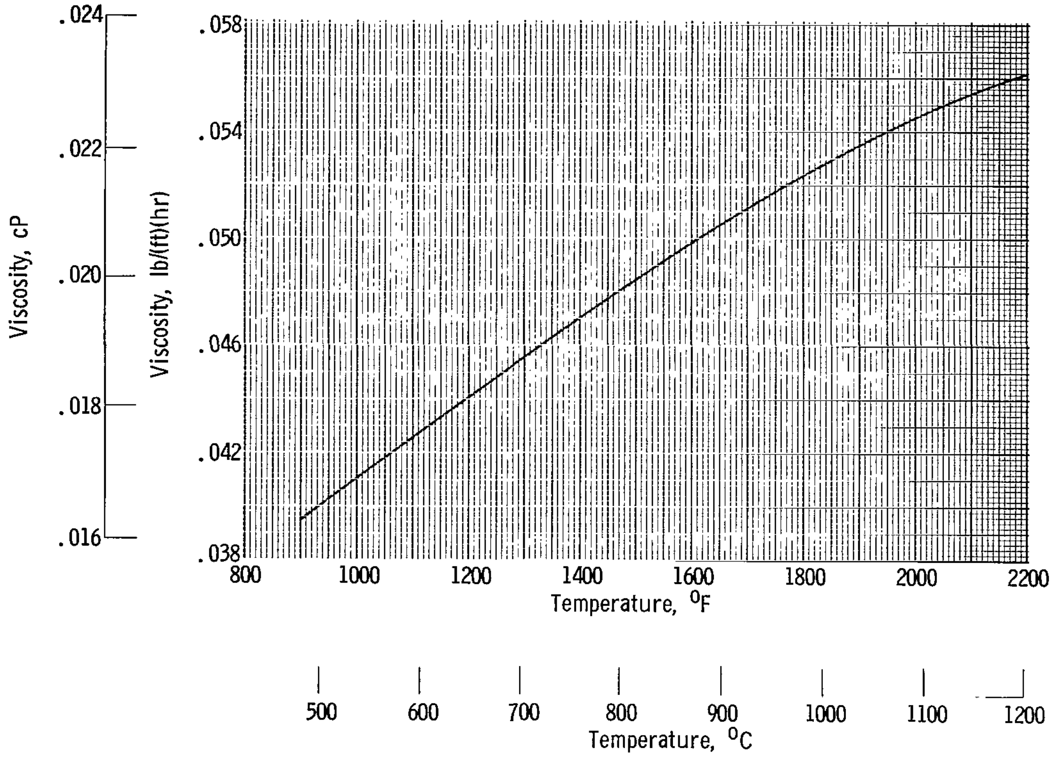

Figure 11. - Viscosity of potassium vapor (saturated). (Data taken from ref. 1.)

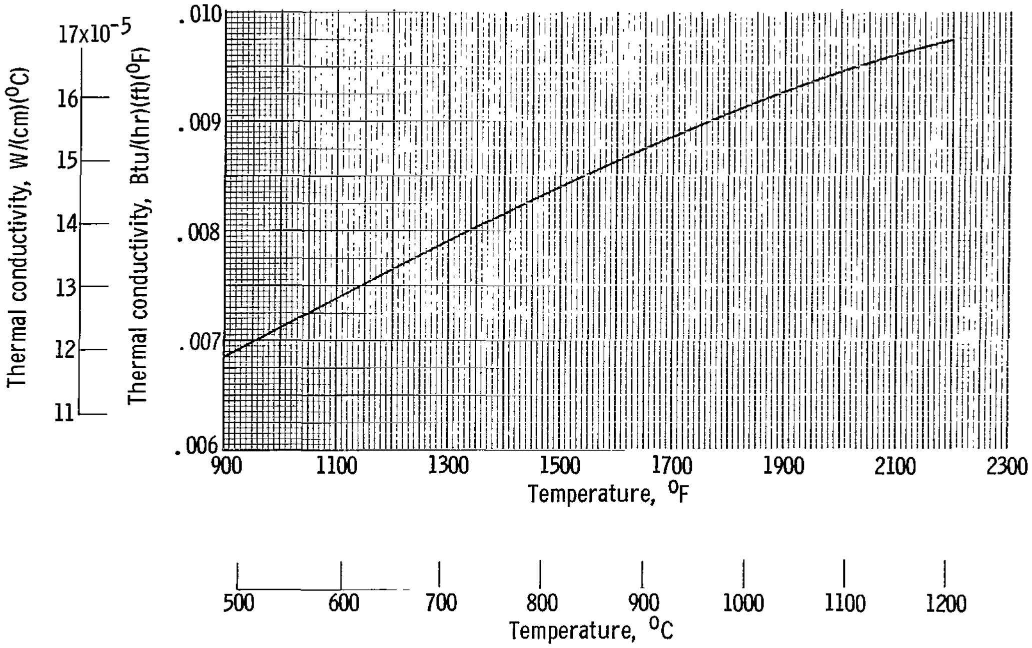

Figure 12. - Thermal conductivity of potassium vapor (saturated). (Data taken from ref. 1.)

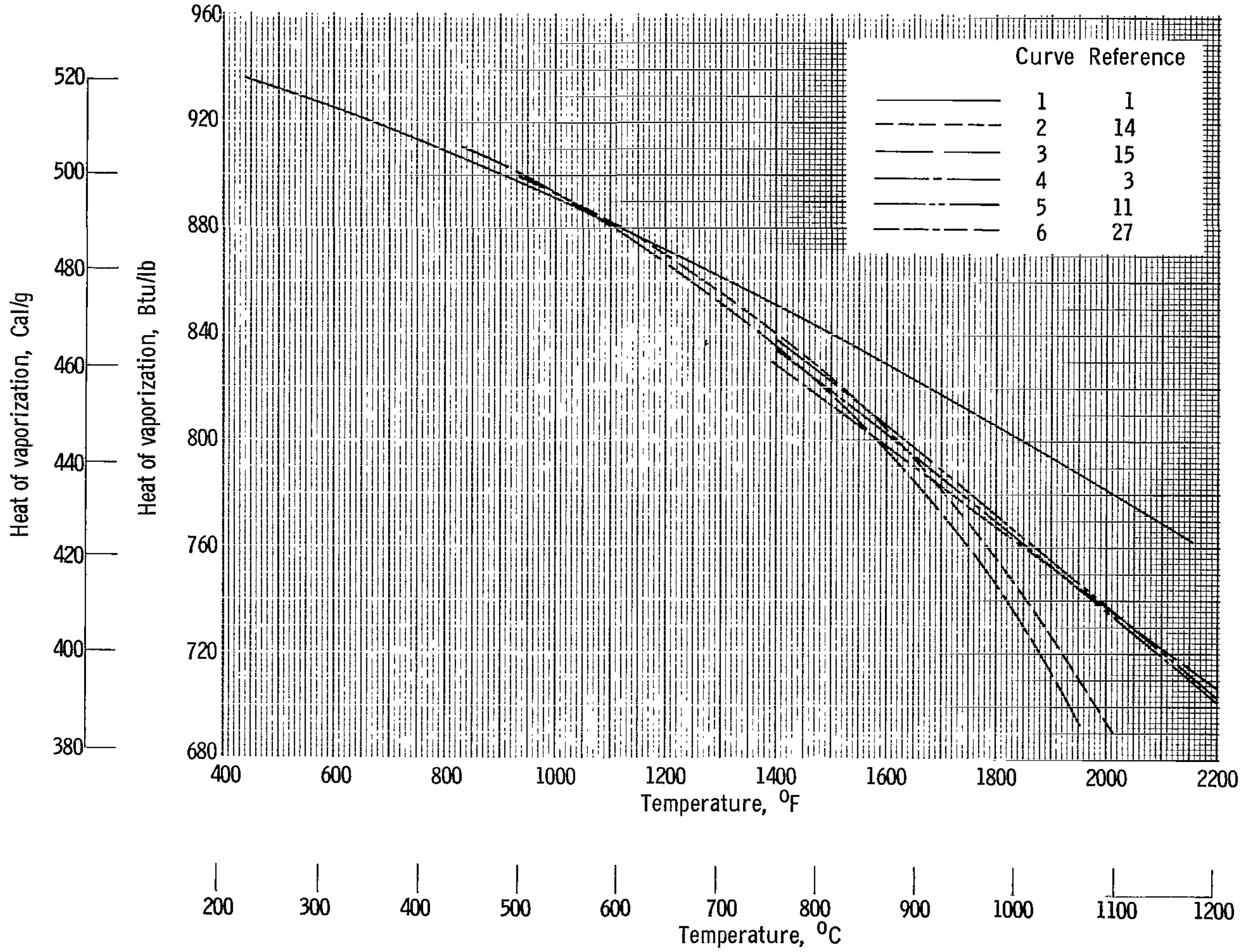

Figure 13. - Heat of vaporization of potassium.

with the nonideal gas theory and virial coefficients. These coefficients were discussed in the vapor density section of the present report, and both relations derived for the third virial coefficient were used to calculate values of the heat of vaporization. Battelle used the original relation for the third virial coefficient (as obtained from the vapor pressure work, ref. 14) to calculate the values presented in table 2 of reference 14, shown in figure 13 as curve 2. Battelle then used the final or modified relation for the coefficient to calculate the values presented in table 5 of reference 15, shown in figure 13 as curve 3.

The data for the NRL curve (curve 4) were taken from table 5 of reference 3; these data were calculated by using the NRL vapor pressure equation (ref. 3) with the Clapeyron equation. The values of specific volume used in that calculation were computed from an equation presented as a representation of NRL experimental data.

The values for the NRL curve (curve 5) were taken from table 11 of reference 11; these values also were calculated using the NRL vapor pressure equation with the Clapeyron equation. However, the two NRL curves (curves 3 and 4) differ very slightly; apparently the values of saturated vapor specific volume used in the calculation in reference 11 were computed from the virial equation of state. The NRL final values from appendix A of reference 27 are shown as curve 6.

The latent heat of vaporization is being determined by direct measurement (ref. 16), and very preliminary results indicate values approximately 5 percent lower than curve 1 over the range of measurement (up to 1700° F in ref. 16).

It can be seen that the values given by both NRL and Battelle deviate significantly from the theoretical values of WADD (curve 1) at the higher temperatures. At 2000° F, NRL is about 6 percent lower than WADD and Battelle is even lower at about 11 percent for curve 2 and 14 percent for curve 3. Curve 6 is within 1 percent of curve 4.

Entropy of Vaporization (Fig. 14)

Theoretical values of the entropy of saturated vapor were calculated by GE with constants from reference 53. These entropy values were also reported by WADD (ref. 1). Data for the entropy of vaporization, obtained by subtracting the entropy of the saturated liquid from the entropy of the saturated vapor at the same temperature using values presented in table 2 of reference 33, are shown as curve 1 in figure 14.

Battelle calculated this property by dividing the enthalpy of vaporization (as given by curve 3, fig. 13) by the absolute temperature. Values for the Battelle curve (curve 2) were obtained by subtracting the entropy of the saturated liquid from the entropy of the saturated vapor as presented in tables C-2 and C-1, respectively, of reference 2.

NRL also calculated this property by dividing the enthalpy of vaporization

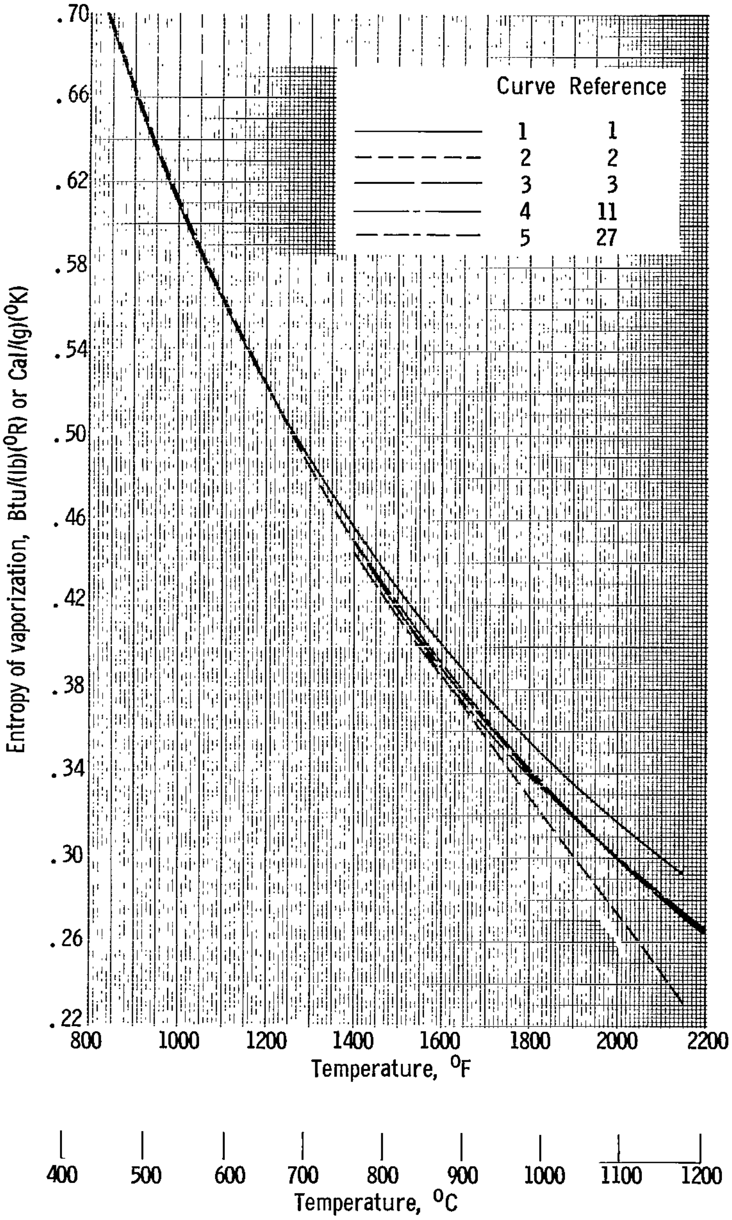

Figure 14. - Entropy of vaporization of potassium.

by the saturation temperature. The data for the NRL curves (curves 3 and 4) were taken from table 5 of reference 3 and table 11 of reference 11, respectively, and differ very little from the NRL final values from appendix A of reference 27 shown as curve 5.

It can be seen that both the NRL and Battelle values deviate significantly from the theoretical values of WADD (curve 1) at the higher temperatures. At 2000° F, the NRL values are 6 percent lower than those of WADD, and the Battelle values are 14 percent lower than those of WADD.

Specific Heat (Fig. 15)

Two theoretical curves for specific heat of saturated vapor were calculated by GE (ref. 33), using constants from reference 53. These theoretical values were also reported by WADD (ref. 1) and are shown in figure 15 as curves 1 and 2. In curve 1, the frozen specific heat was calculated as a state point property by adding the separate contributions of the monotomic and diatomic vapors for a given equilibrium composition. In curve 2, the equilibrium specific heat was calculated according to the rigorous definition of specific heat and includes the energy required to alter the degree of equilibrium as a result of dissociation.

The data for the Battelle curve (curve 3) were taken from table C-1 of reference 2; these data were calculated using the heat capacity of the ideal monomer, as given by Evans, et al. (ref. 52), and virial coefficients. These coefficients were discussed in the vapor density section of the present report, and the final or modified relation for the third virial coefficient (ref. 2) was used to calculate the specific heat.

The values for the NRL curve (curve 4) were taken from tabulated data in appendix C of reference 3; NRL obtained these values by numerical evaluation of the change of vapor enthalpy with respect to temperature. The enthalpy of the vapor was determined by adding the heat of vaporization to the enthalpy of the liquid, as given in reference 3.

The data for the NRL curve (curve 5) were taken from table 12 of reference 11; these data were calculated using the specific heat of the monomeric gas at one atmosphere as derived directly from the work of Evans, et al. (ref. 52), and the NRL experimental virial coefficients. These coefficients were also discussed in the vapor density section of the present report. The NRL final values from appendix B of reference 27 are shown as curve 6.

The values for the specific heat of the saturated vapor from the several sources differ widely. The theoretical values of frozen specific heat (curve 1) are around 40 percent lower than the theoretical values of equilibrium specific heat (curve 2). The Battelle curve (curve 3) is concave upward, while the other curves are concave downward. At 2000° F, the Battelle value is about 156 percent higher than the theoretical value reported by WADD (curve 2). The two preliminary NRL curves (curves 4 and 5), determined by two different methods, agree rather well with each other, differing by 6 percent at 1400° F

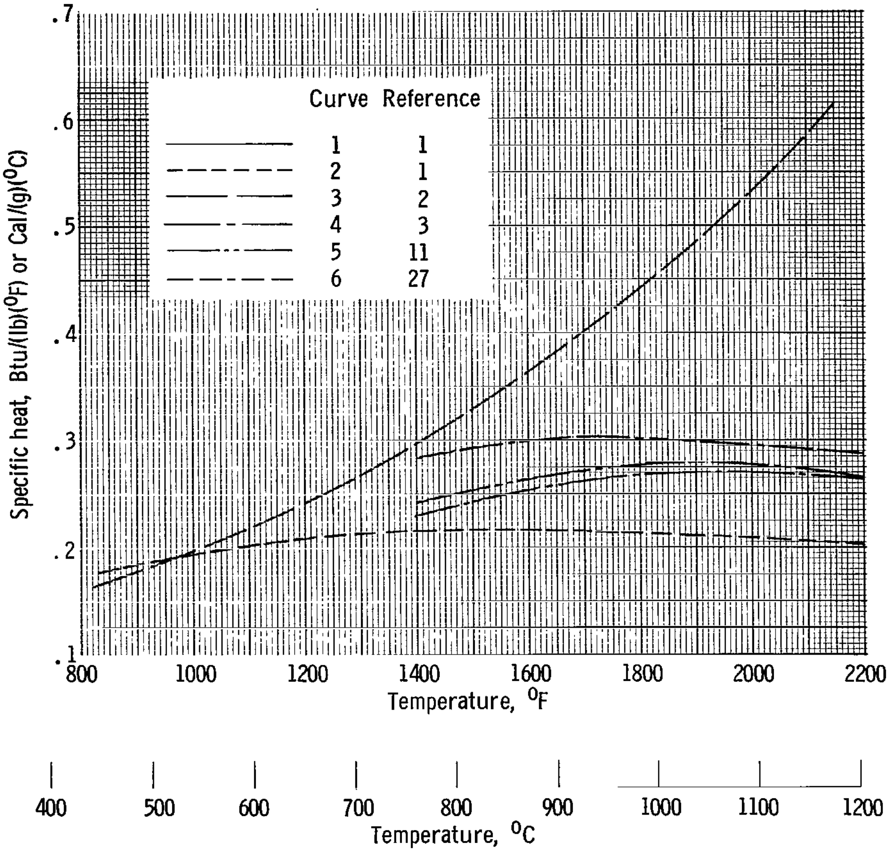

Figure 15. - Specific heat of potassium vapor (saturated).

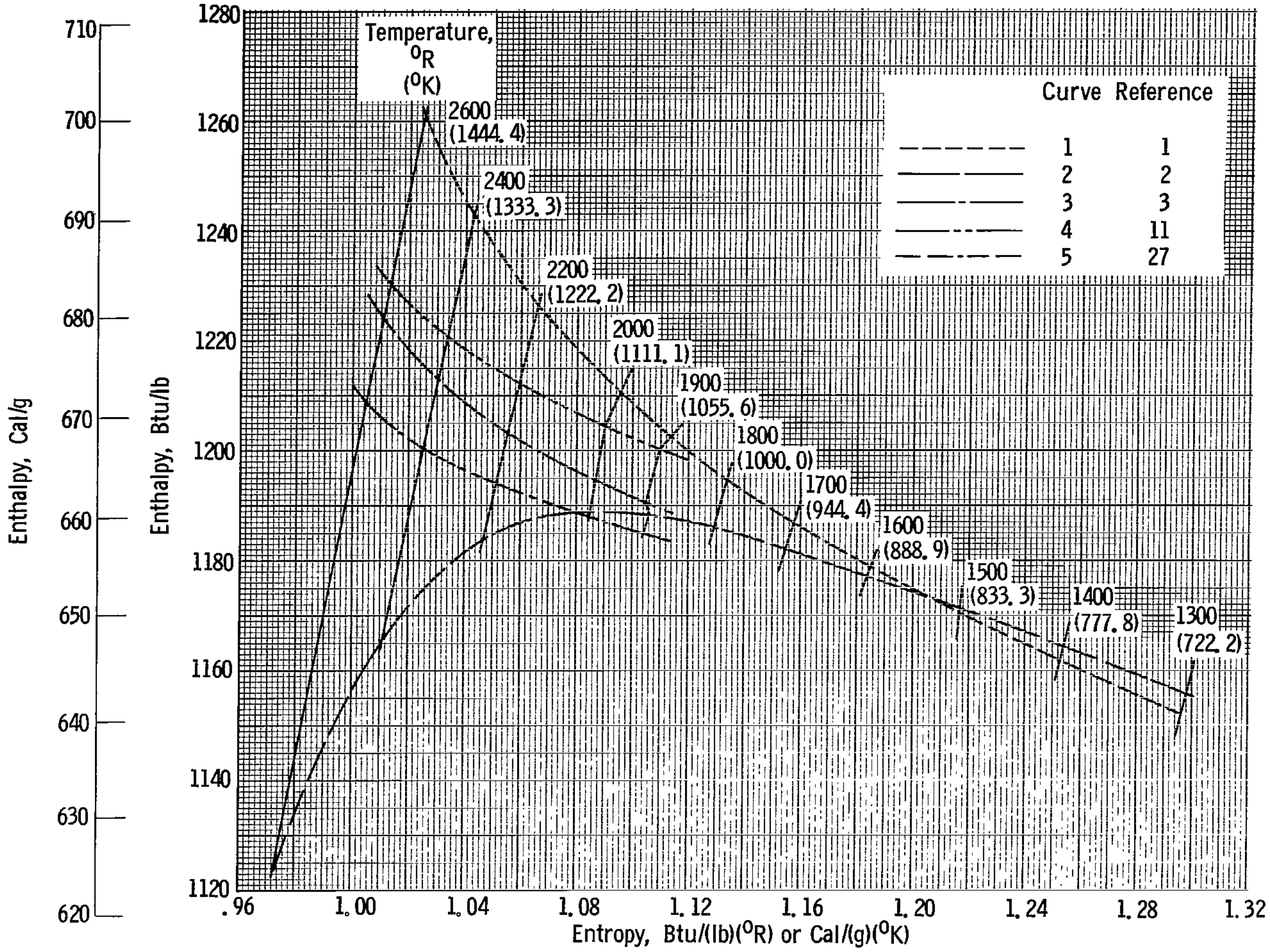

Figure 16. - Saturation lines on enthalpy-entropy diagram.

and 2.5 percent at 2000° F. The NRL final curve (curve 6) is about 6 to 16 percent higher than curve 5 over the range shown and at 2000° F is about 41 percent higher than the theoretical value of curve 2.

Enthalpy and Entropy (Fig. 16)

The saturation lines on an enthalpy-entropy diagram are shown for several sources in figure 16. The solid lines on the figure merely connect points of equal temperature on the curves. Theoretical values for the enthalpy and entropy of the saturated vapor were calculated by GE (ref. 33) with constants from reference 53. These values were also reported by WADD (ref. 1) and are shown as curve 1.

The data for the Battelle curve (curve 2) were taken from table C-1 of reference 2; Battelle calculated these data by adding the absolute values of enthalpy and entropy of saturated liquid to the values for the enthalpy and entropy of vaporization.

The data for the NRL curve (curve 3) were taken from table 5 of reference 3; NRL calculated these data by adding the change in enthalpy and entropy with vaporization to the values for the saturated liquid.

The values for the NRL curve (curve 4) were taken from table 11 of reference 11; NRL calculated these values with virial coefficients using the state of the monomeric gas at one atmosphere as derived directly from the work of Evans, et al. (ref. 52) as a base, or starting point. These coefficients were discussed in the vapor density section of the present report. The NRL final values from appendix A of reference 27 are shown as curve 5.

It can be seen that the Battelle values (curve 2) agree very closely with the theoretical values reported by WADD (curve 1) at the lower temperatures but deviate at the higher temperatures. At 2600° R, the Battelle values are 11 percent lower for enthalpy and 5 percent lower for entropy than the WADD curve. It can also be seen that the shape of the Battelle curve deviates significantly from the other curves shown.

The two preliminary NRL curves (curves 3 and 4) agree rather well with each other, differing by only 2 percent in enthalpy and 1 percent in entropy at 2600° R, and both curves are slightly lower than the theoretical values of curve 1. The NRL final curve (curve 5) is within 1 percent of curve 4.

CONCLUDING REMARKS

The results of the recent investigations have extended the temperature range of the previously existing potassium property data. The values from the several sources for most of these properties agree very well at the lower temperatures. However, significant differences are apparent for some of the properties at the higher temperatures (above about 1400° F).

The largest disagreements in the liquid properties were in the values of surface tension, thermal conductivity, and specific heat. For surface tension, the difference between the two sources at 900° F was about 60 percent. The difference between the highest and lowest values of thermal conductivity at 1300° F was about 20 percent, and the specific heat values differed by about 13 percent at 2000° F. Data for the liquid properties reported by WADD (ref. 1) in 1961 generally compared well with the recent experimental data.

The largest disagreement in the vapor properties was in the value of specific heat, where the difference between the several sources was over 100 percent at 2000° F. The theoretical vapor property values reported by WADD (ref. 1) showed good agreement with the values derived in the recent determinations at the lower temperatures, but differed significantly at the higher temperatures. In general, the differences between the reported sources increased as the temperature increased. At this time there has been no successful experimental determination of the viscosity or thermal conductivity of the saturated vapor.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 30, 1965.

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