ERRATA - November 1961

The following corrections are applicable to WADD Technical Report 61-96, entitled "Properties of Inorganic Energy-Conversion and Heat-Transfer Fluids for Space Applications," and dated November 1961:

Page $AlBr_3$-Syn-1

In the column headed "Property," sixth entry under Physical: Density of Solid, add: lb/ft^3

Page LiH-Ref-1

Code No. 8-8-61 should be corrected to read: Hoffman, H. W., ...

Aeronautical Systems Division
Air Force Systems Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

WADD TECHNICAL REPORT 61-96

PROPERTIES OF INORGANIC ENERGY-CONVERSION AND HEAT-TRANSFER FLUIDS FOR SPACE APPLICATIONS

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AERONAUTICAL SYSTEMS DIVISION
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FOREWORD

This report was prepared at Southwest Research Institute under USAF Contract No. AF 33(616)7206. The contract was initiated under Project No. 7381, "Materials Application," Task No. 73812, "Data Collection and Correlation." The work was administered under the direction of the Directorate of Materials and Processes, Deputy for Technology, Aeronautical Systems Division, Air Force Systems Command, with Mr. J. J. Sullivan acting as project engineer.

This report covers work conducted from March 1960 to November 1961.

The authors wish to acknowledge the aid of J. K. Dean who assisted in the preparation of this report, and of Emil Gavlick, who supervised the typing and printing of the report.

ABSTRACT

This report is a complete revision of WADC TR 59-598. It is intended to serve as a properties handbook for various inorganic fluids which may have potential value as energy-conversion or heat-transfer fluids for space applications. The fluids are presented as three distinct classes - namely, liquid metals, nonmetals, and gases. The liquid metals include mercury, cesium, rubidium, potassium, NaK (78), sodium, lithium, bismuth, and lead. The nonmetals include aluminum bromide, sulfur, and lithium hydride. The gases include argon, helium, and hydrogen.

Data are presented, where available, up to temperatures ranging from 2300°F for mercury to 4500°F for lead, and for pressures ranging from less than one atmosphere to greater than twenty atmospheres. The enumerated properties include vapor pressure, density, viscosity, surface tension, electrical resistivity, thermal conductivity, specific heat, latent heats, enthalpy-entropy relationships, melting point, critical properties, dielectric constant, ionization potential, magnetic susceptibility, thermal neutron cross sections, and corrosion characteristics.

The characteristics of the various fluids are discussed, and the recommended values for the fluid properties are presented in either tabular or graphical form, or both, with detailed documentation as to basis and source. In addition, background material, including thermodynamic-cycle, heat-transfer, compatibility, and working fluid considerations is discussed. A summary of current research activities in this field is presented.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

W. P. Conrardy

W. P. CONRARDY
Materials Engineering Branch
Applications Laboratory
Directorate of Materials & Processes

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I. INTRODUCTION

As the era of sustained space flight draws nearer, the development of auxiliary propulsion systems and power sources for space vehicles is becoming increasingly important. Accordingly, more emphasis is being placed upon both the availability and the reliability of data on the properties of substances which may be employed in such applications. For most fluids of interest, experimental data are meager and are distributed throughout diverse literature or proprietary sources.

For over two years, SwRI has been engaged, under the sponsorship of WADD, in a program to collect, appraise, and disseminate thermophysical property data on inorganic fluids of potential interest as heat-transfer or energy-conversion fluids for space applications. A properties handbook, which was issued in December 1959 as WADC TR 59-598 (ASTIA Document AD 230-065), presented an organized collection of recommended data on selected liquid metals, nonmetals, and gases. Because of the urgency for an early dissemination of the results, the initial project was conducted on an accelerated basis, and the initial report was of a somewhat preliminary nature. Therefore, it is the purpose of this report to provide a more comprehensive, revised compilation of fluid-property data, and this is presented in Section III of the report. To facilitate use of these data, the fluids are grouped into classes as liquid metals, nonmetals, and gases, and the information for these classes is presented on blue, buff, and green pages, respectively.

Objectives and Scope

The over-all objectives of this continuing program include continuous surveillance of literature and research activities which may provide information on thermophysical properties and corrosion characteristics of the fluids of interest. In addition to gathering property information, the program involves critical appraisal of data, theoretical extension of information, estimation of properties, and conducting experimental corrosion studies.

The fluids of current interest are: mercury, cesium, rubidium, potassium, NaK(78), sodium, lithium, bismuth, lead, aluminum bromide, sulfur, lithium hydride, helium, hydrogen, and argon. The ranges of temperature and pressure of interest are different for the different fluids, and these are summarized in Table 1.

The properties of interest include vapor pressure, density, viscosity, surface tension, electrical resistivity, thermal conductivity, specific heat, latent heats, enthalpy-entropy relationships, melting point, critical properties, dielectric constant, ionization potential, magnetic susceptibility, thermal neutron cross sections, and corrosion characteristics.

Manuscript released by authors March 1961 for publication as a WADD Technical Report. Sections on $AlBr_3$ and LiH added November 1961.

TABLE 1. TEMPERATURE AND PRESSURE RANGES OF INTEREST

Fluid	Temperature Range, °F	Pressure Range, Atm
Hg	450-1600	<0.5 -32
Cs	500-2300	<0.05-20
Rb	500-2300	<0.05-20
K	900-2500	<0.05-20
NaK 78	900-2500	<0.05-20
Na	950-2500	<0.05-20
Li	2000-3500	<0.05-15
Bi	2000-4000	<0.05-10
Pb	2000-4500	<0.05-10
S	350-1600	<0.01-32
He	0-3500	---
H_2	0-3500	---
A	0-3500	---

As design temperatures increase in the future, it may be necessary to consider less volatile fluids than those included in this report in order to avoid excessive pressures. With this thought in mind, Figure 1 presents a summary of selected metals with boiling points ranging from that of mercury at less than 700°F to that of tin at nearly 5000°F. Two criteria were used for selecting the specified metals. One is that the melting point is less than 640°F so that start-up does not present unnecessary problems. The other criterion is that the temperature range in which metal is liquid at atmospheric pressure is greater than 60% of the absolute boiling temperature in order that cycle temperatures and hence cycle efficiencies will not be unnecessarily restricted by the avoidance of solid-phase formation or excessive vapor pressures. It should be noted that the described selection criteria have ruled out consideration of aluminum, cadmium, zinc, magnesium, and antimony which have been considered previously as potential liquid-metal coolants.

Background Information

The thermodynamic-cycle, heat-transfer, compatibility, and working-fluid considerations which follow are presented as background information in order to place the text material in proper perspective.

Thermodynamic Cycles

Thermodynamic cycle considerations must be based on the nature of the energy source, the desired power level, environmental requirements, and anticipated design or operational problems. In the following discussion, the highlights of single-loop heat-transfer cycles and work cycles are pointed out. Complications introduced by multiple-loop cycles do not alter the fundamental thermodynamic concepts, and "hardware" considerations can be defined for specific applications only.

a. Heat-Transfer Cycle. As illustrated in Figure 2, a heat-transfer cycle consists of a heat-transfer loop which transports heat by mass flow from a heat source to a heat sink, accompanied by a consumption of work. In space applications the heat source would be a chemical converter, a nuclear reactor, a solar energy collector, or simply a heat exchanger of another cycle.

The heat sink could be a heat exchanger of another cycle or a radiating surface rejecting heat into space. The heat-transfer fluid could be a gas or liquid, or it could comprise a two-phase, boiling liquid and condensing vapor system. The specific type of fluid selected would depend upon cycle requirements and "hardware" considerations.

b. Carnot Cycle. The Carnot cycle, illustrated in Figure 3a, represents an idealized thermodynamic cycle. It yields the maximum

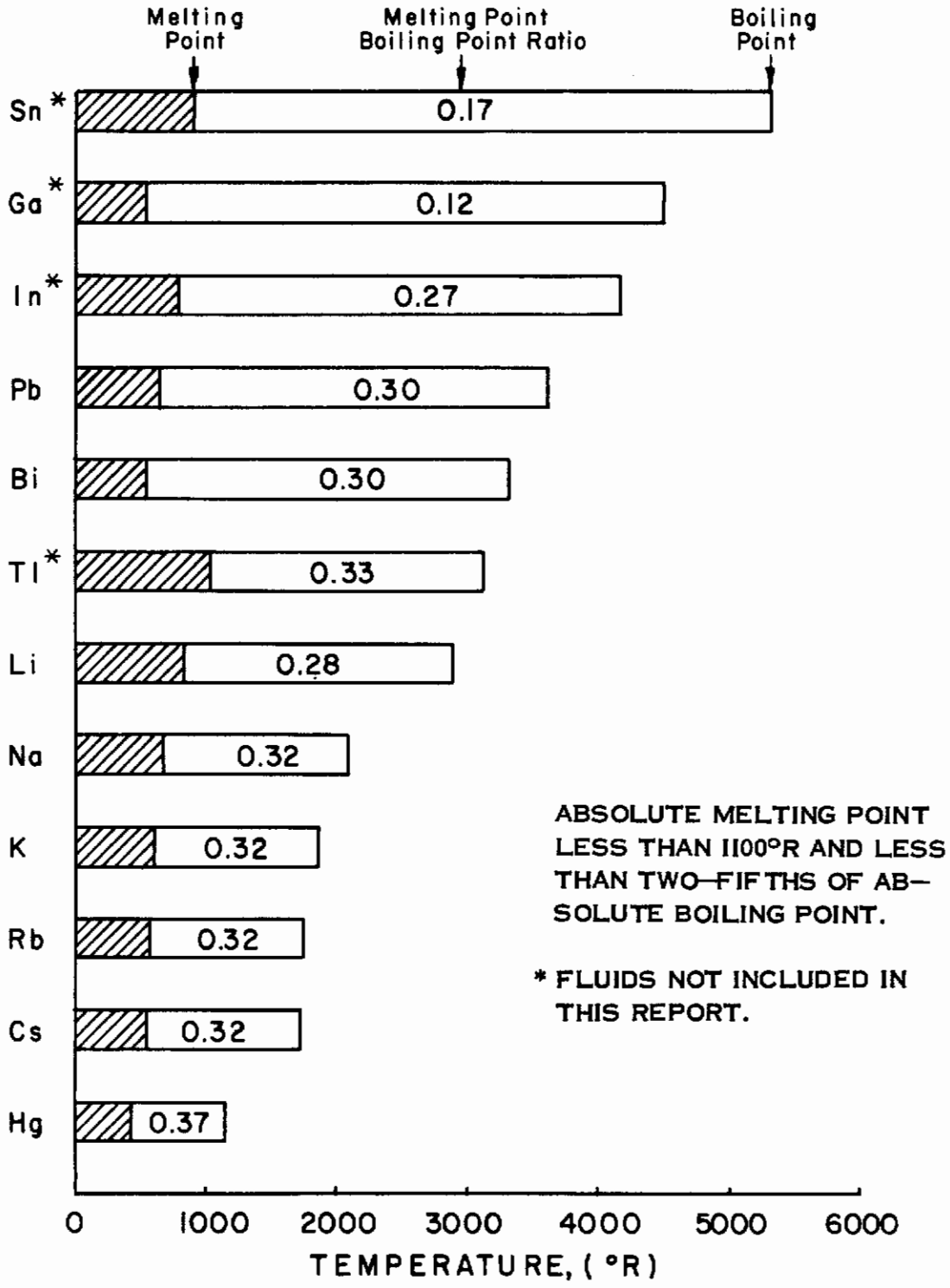


FIGURE I. METALS SUITABLE AS ENERGY-CONVERSION AND HEAT-TRANSFER FLUIDS FOR SPACE APPLICATIONS

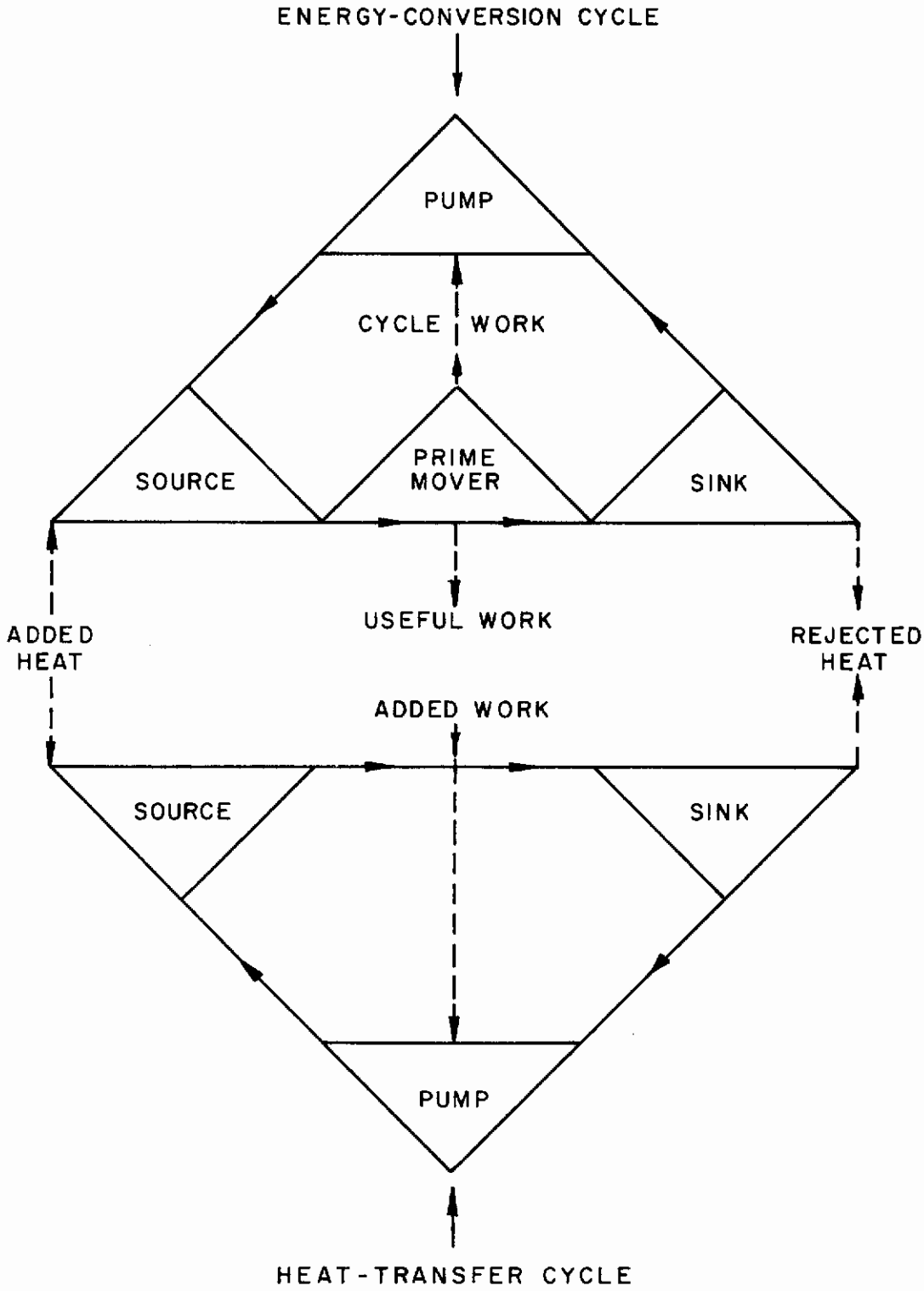
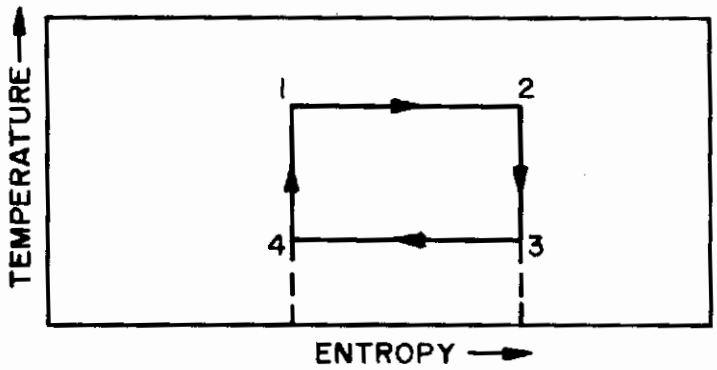
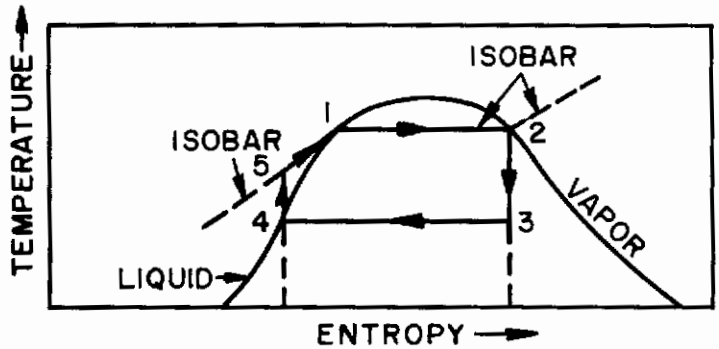


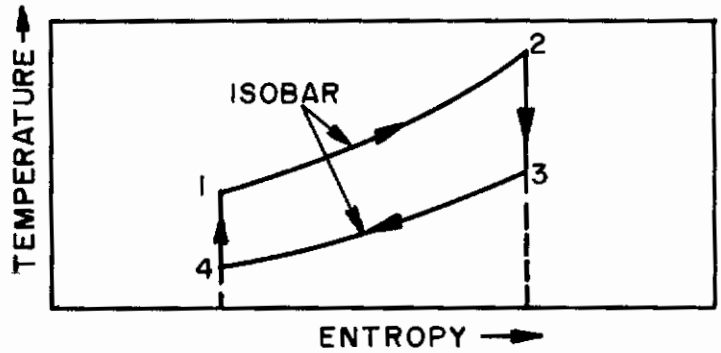
FIGURE 2. SCHEMATIC REPRESENTATION OF ENERGY–CONVERSION AND HEAT–TRANSFER CYCLES



A. CARNOT CYCLE



B. RANKINE SATURATED VAPOR-LIQUID CYCLE



C. BRAYTON GAS CYCLE

FIGURE 3. BASIC THERMODYNAMIC WORK CYCLES

amount of work obtainable for a heat engine operating between two fixed temperature limits. In this idealized cycle, the fluid undergoes isentropic compression between points 4 and 1, heat is added to the fluid isothermally between points 1 and 2, the fluid experiences isentropic expansion between points 2 and 3, and heat is rejected from the fluid isothermally between points 3 and 4. It can be shown that the efficiency of this idealized cycle is independent of the properties of the working fluid and is specified by the ratio of the temperature difference between the heat source and the heat sink to the temperature of the heat source.

c. Rankine Cycle. The Rankine cycle approaches the Carnot cycle in principle. Referring to Figure 3b, the liquid at point 4 is pumped to the pressure at point 5 which corresponds to the saturation pressure at points 1 and 2. It is then warmed to the saturation temperature at point 1 and is vaporized isothermally while absorbing heat from the heat source. The resulting vapor at point 2 undergoes isentropic expansion in the prime mover to the lower temperature at point 3. This downgraded fluid is then condensed isothermally to point 4 while rejecting heat to the heat sink, and the cycle is repeated. The path between points 4 and 1 is not isentropic as in the Carnot cycle since heat must be absorbed by the liquid between points 5 and 1 in order to increase its temperature. The ideal cycle efficiency is specified by the ratio of the difference in the effective temperature at which heat is absorbed and the temperature at which heat is rejected to the effective temperature at which heat is absorbed. Therefore, it is apparent that the absorption of heat by the liquid at temperatures less than the maximum (between points 5 and 1) decreases the efficiency to less than that of the corresponding Carnot cycle.

(1) An actual vapor-liquid cycle such as that illustrated in Figure 4, differs from the Rankine cycle only to the extent that the various portions of the cycle do not correspond exactly to those assumed in the ideal cycle. The actual pumping and expansion process would be accompanied by entropy increases, and the flow processes would involve pressure losses caused by fluid friction and changes in fluid momentum during phase changes. In many cases, however, preliminary cycle analyses may be made by neglecting the effects of all of these deviations except that for the expansion process. For many fluids, the expansion process is complicated by partial condensation which could lead to additional inefficiencies and mechanical difficulties. However, this problem may be diminished by the use of superheated vapor in the expansion process.

d. Brayton Cycle. The Brayton cycle, illustrated in Figure 3c, employs superheated vapor throughout the process. Referring to the figure,

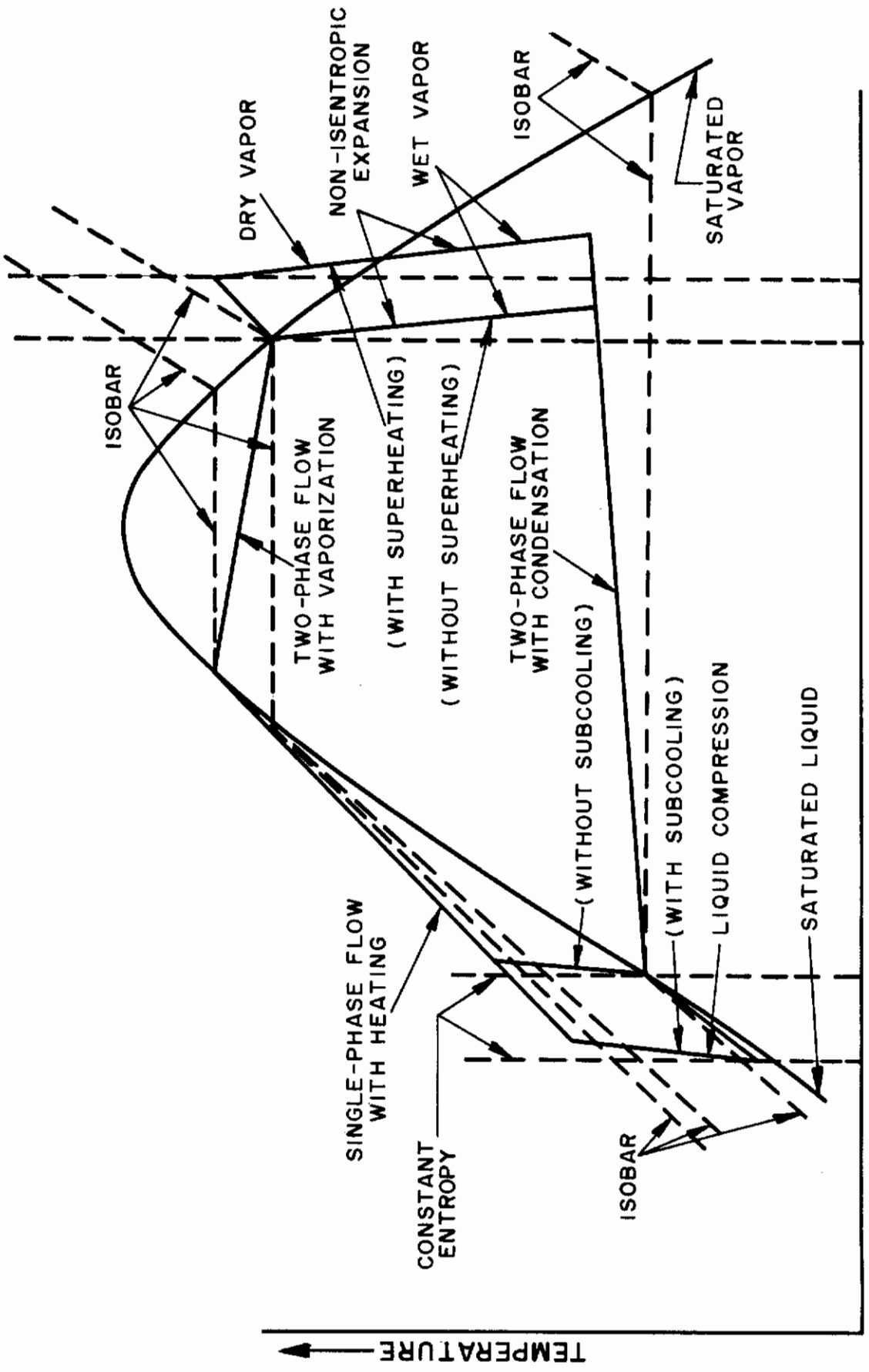


FIGURE 4. ACTUAL VAPOR–LIQUID CYCLE WITH EXAGGERATED NONIDEALITIES

gas at point 4 is subjected to isentropic compression to point 1 and is upgraded at constant pressure to the higher temperature at point 2 by the absorption of heat from the heat source. The fluid then experiences isentropic expansion in the prime mover to the lower temperature at point 3, and this fluid is further downgraded at constant pressure to point 4 by the rejection of heat to the heat sink, and the cycle is repeated. It can be shown that the ideal Brayton cycle efficiency is determined at any fixed entropy level by the ratio of the temperature difference between the heat source and heat sink to the temperature of the heat source at the specified constant entropy level. However, when the maximum and minimum cycle temperatures are considered, it becomes evident that the Brayton cycle efficiency is less than that of a Carnot cycle operating between the same over-all temperature limits.

(1) An actual gas cycle, such as that illustrated in Figure 5, differs from the Brayton cycle only to the extent that the various portions of the cycle do not correspond exactly to those assumed in the ideal cycle. The actual compression and expansion processes would be accompanied by entropy increases, and the flow processes would involve pressure losses caused by fluid friction. In many cases, however, preliminary cycle analyses may be made by neglecting fluid-flow pressure gradients while attempting to account for the nonideality of the compression and expansion processes. The major disadvantage of an actual gas cycle (modified Brayton cycle) lies in its use of a gas phase heat-transfer fluid as contrasted to the boiling and condensing phases employed in the vapor-liquid cycle. This necessitates much larger heat-transfer surface areas or significantly higher operating temperatures, or both, in order to achieve similar power levels. On the other hand, the lack of a liquid phase simplifies compatibility problems considerably.

Heat-Transfer

For space applications, the heat-transfer processes are complicated by the effects of variable gravitational forces which may range from many times normal gravity during periods of acceleration or deceleration to essentially zero in free flight. For this reason, conventional correlations for heat-transfer processes which could be influenced by variable gravity are of little or no value for space applications. Such processes include free convection, nonboiling and boiling viscous forced convection, pool boiling, and dropwise, or film condensation with gravitational condensate run-off. In fact several of these processes would be unworkable under zero-gravity conditions.

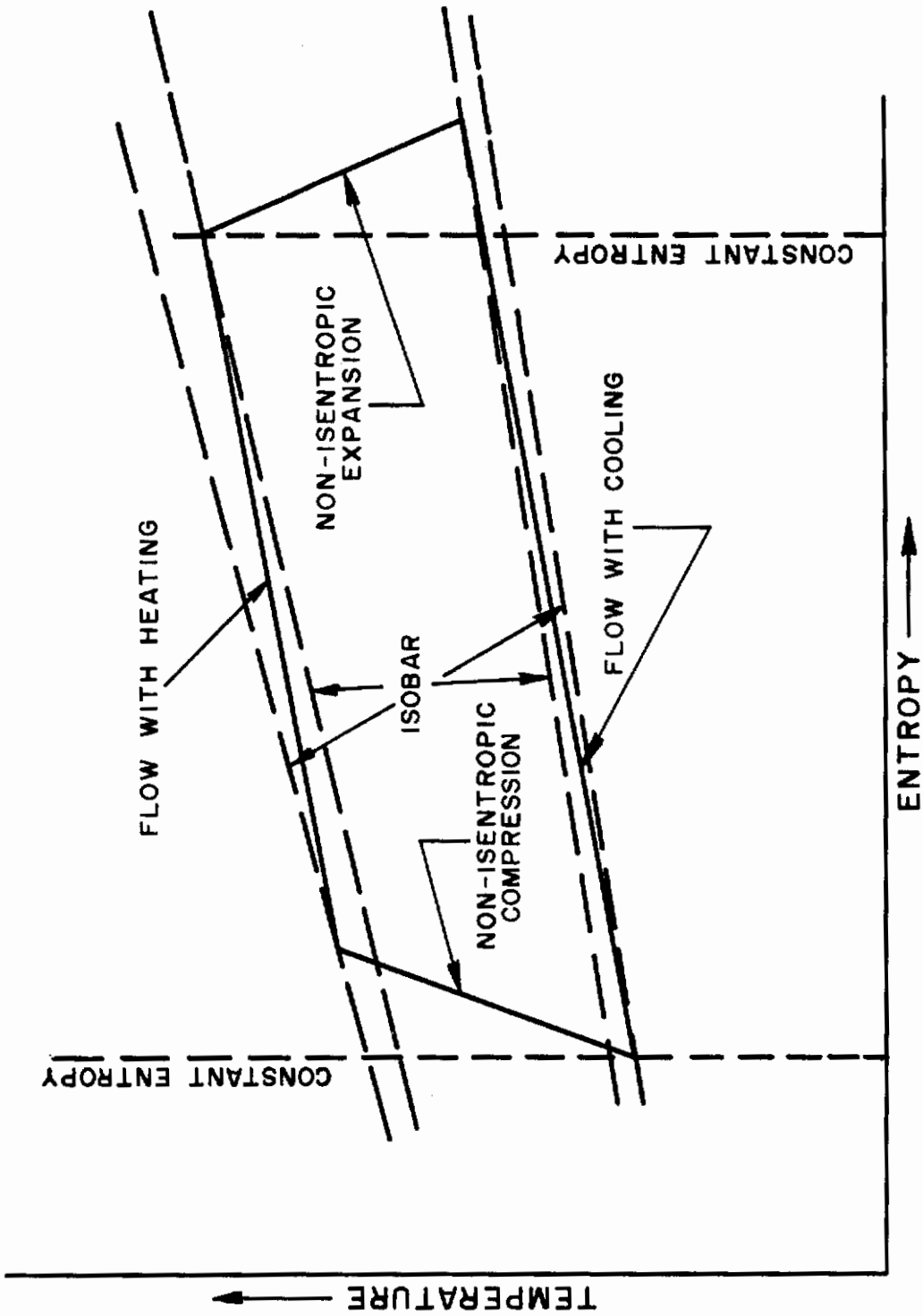


FIGURE 5. ACTUAL GAS CYCLE WITH EXAGGERATED NONIDEALITIES

The graphical classification of heat transfer processes presented in Figure 6 demonstrates the multiplicity of process-variable combinations which could be realized. It is apparent that the stagnant-fluid processes designated as pool convection, boiling, and condensation would be of doubtful value for space applications. Such processes possess inherent inefficiencies and are sensitive to gravitational forces. For the array shown in the figure, the influence of gravity diminishes toward the apexes of the diagram; however, for a particular heat transfer process, the effect of gravity would be modified by other variables such as system geometry and relative motions of the fluids within the system.

Some of the potential heat-transfer applications for space vehicle power systems may require the development of new correlations for variable gravity. However, in certain heat-transfer processes which are not appreciably affected by gravitational forces, existing correlations should prove adequate. Such gravity-insensitive processes could include nonboiling turbulent forced convection, turbulent forced-convection nucleate boiling, turbulent forced-convection film boiling with drag-induced total entrainment or dispersion of generated vapor, and turbulent forced-convection condensation with drag-induced total entrainment or dispersion of condensate.

Empirical correlations exist for some of the latter processes, and several generally useful ones are presented as follows.

a. Nonboiling Turbulent Forced Convection

(1) Ordinary Liquids in Circular Conduits (Ref. 11-15-7)

$$Nu = 0.023\, Re^{0.8} Pr^{0.4}$$

with fluid properties evaluated at the bulk fluid temperature.

(2) Gases in Circular Conduits (Ref. 11-15-7)

$$Nu = 0.023\, Re^{0.8} Pr^{0.4}$$

with fluid properties evaluated at the average of the bulk fluid and wall temperatures, and the fluid velocity evaluated at the bulk fluid temperature.

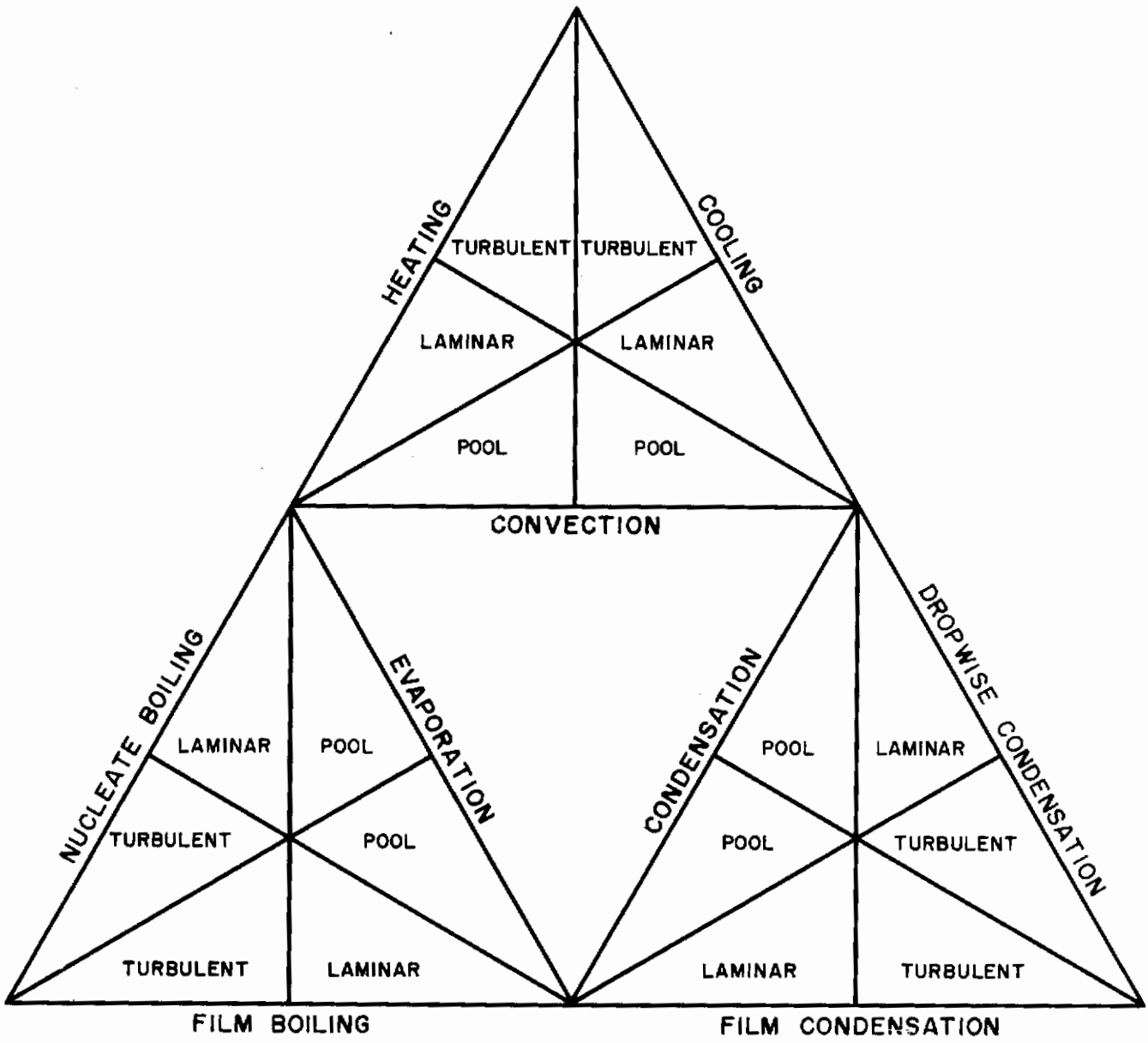


FIGURE 6. CLASSIFICATION OF FLUID HEAT TRANSFER PROCESSES ACCORDING TO MECHANISM AND FLOW CONDITION

(3) Ordinary Fluids in Annular Conduits (Ref. 19-2-8)

$$Nu = 0.0200\,(D_2/D_1)^{0.5} Pr^{1/3} Re^{0.8}$$

with fluid properties evaluated at the average of the bulk fluid and wall temperatures.

(4) Liquid Metals (Ref. 12-11-6)

$$Nu = 0.625\,Re^{0.4} Pr^{0.4} = 0.625\,Pe^{0.4}$$

where Nu = Nusselt No. = hD/k
Re = Reynolds No. = DG/μ
Pr = Prandtl No. = $C_p\mu/k$
h = film heat-transfer coefficient
D = conduit diameter
k = fluid thermal conductivity
G = fluid mass velocity (per unit conduit area)
μ = fluid viscosity (absolute)
C_p = fluid specific heat

b. Turbulent Forced-Convection Nucleate Boiling (ordinary liquids and liquid metals) (Ref. 6-7-9)

$$q = 4.3 \times 10^{-5} \left(\frac{a_\ell C_{p\ell} \rho_\ell T_s}{\sigma^{1/2} (\Delta H \rho_v)^{3/2}} \right) \left(C_{p\ell} T_s a_\ell^{1/2} \right)^{1/4}$$

$$(\rho_\ell / \mu_\ell)^{5/8} (Pr_\ell)^{1/3} \Delta P^2$$

where q = heat flux, BTU/hr ft^2
a = thermal diffusivity, ft^2/hr = $(k/C_p\rho)$
ρ = density, lb/ft^3
T_s = saturation temp, °R
T_w = surface temp, °R
ΔP = saturation pressure difference for $T_w - T_s$, lb/ft^2
ΔH = latent heat of vaporization, BTU/lb
μ = viscosity, lb/ft hr
σ = surface tension, lb/ft
C_p = specific heat at constant pressure, BTU/lb °F
k = thermal conductivity, BTU/hr ft °F

with liquid properties evaluated at T_w and vapor properties evaluated at T_s.

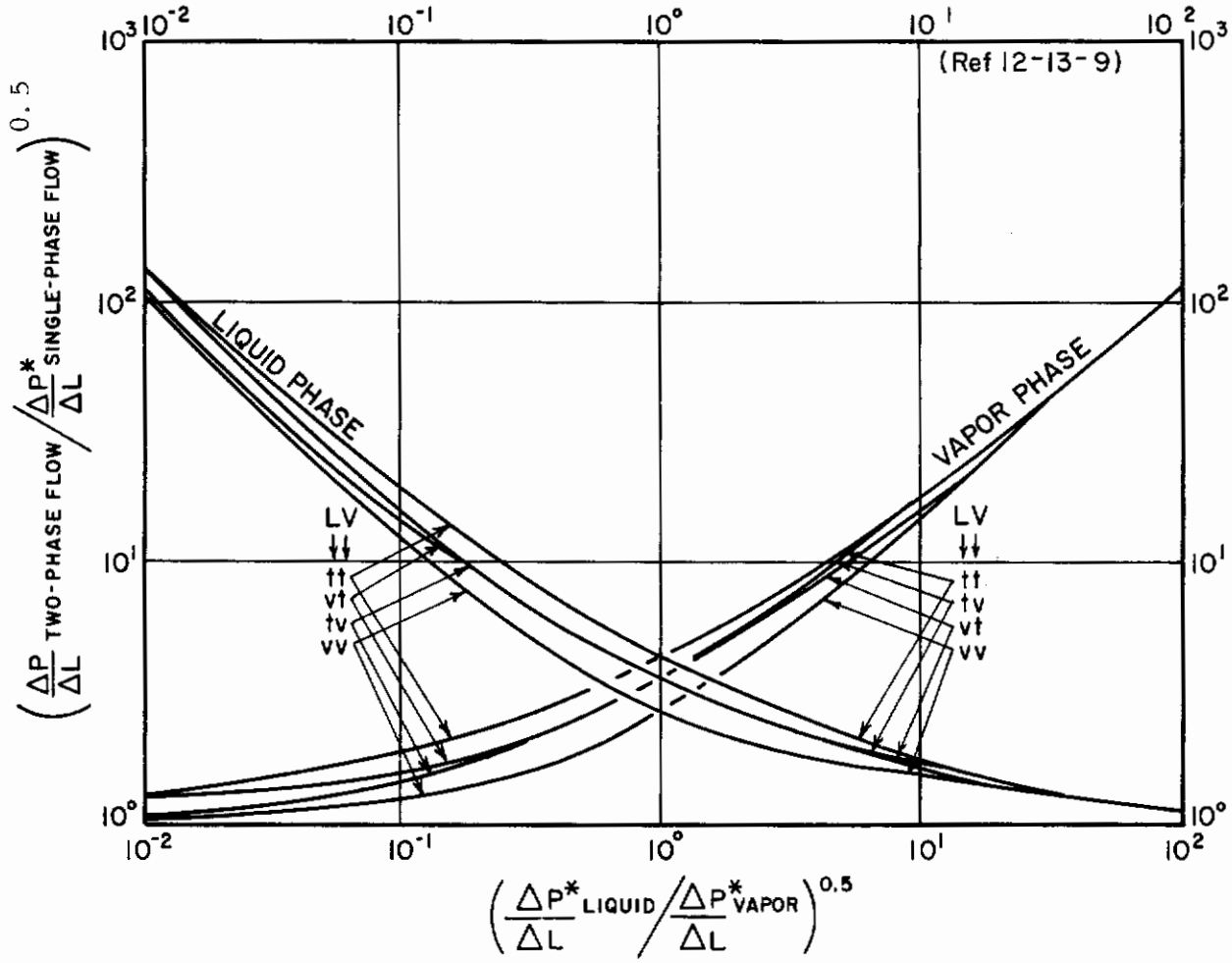
For boiling or condensing heat-transfer processes, the pressure drop experienced by the flowing fluid may be significantly greater than in single-phase-flow heat-transfer applications. The influence of the two-phase flow condition on the frictional pressure drop and on enlargement and contraction losses may be predicted approximately with the aid of the correlation presented in Figure 7. However, the flow velocities continually change because of continual phase change as the fluid proceeds through the heat-transfer conduit; hence, an acceleration or deceleration pressure-drop term must be determined by momentum balance and added to the frictional pressure drop. A detailed analysis of such processes could involve repetitive calculations for successive increments of conduit length; however, in some cases, satisfactory methods using average phase proportions throughout the length of the conduit may be developed.

Because of the increased pressure drop accompanying forced-convection boiling, it may not be practical in all cases to design equipment for total vaporization. In such cases, vapor generation may be achieved by partial vaporization or by flashing superheated liquid to a lower pressure; however, the latter procedures would require additional equipment for phase separation in the absence of gravity and for the recycle of residual liquid.

The influence of liquid-solid wetting characteristics on heat- and momentum-transfer processes has not been fully established. However, based on current literature, it can be presumed that single-phase systems are rather insensitive to surface wetting effects. Likewise, vapor-liquid-flow pressure drop is not appreciably altered by differences in wetting properties. For ordinary fluids, condensation heat-transfer rates are enhanced by poor wetting which leads to dropwise condensation. However, with metal fluids, this effect is not significant because the condensed-phase thermal conductivity is extremely high. Also, boiling heat-transfer rates may be altered significantly by wetting effects. This sensitivity stems partly from the tendency of nonwetting fluids to exhibit premature film boiling, and it also reflects the influence of liquid-solid contact angle on bubble growth rate. In general, boiling heat transfer is enhanced by improved wetting properties.

Compatibility

Space applications require long-term, maintenance-free operation of system components. Hence, the compatibility of working fluids with other system materials is of prime importance. The corrosion problem areas for liquid-metal working fluids may be brought into better focus by considering five arbitrary, but rather distinct, operating-temperature ranges. These temperature ranges, the most suitable type of alloy for each, and the appropriate fluids for each, are summarized in Table 2.



SYMBOL	SIGNIFICANCE
$\frac{\Delta P^*}{\Delta L}$	HYPOTHETICAL PRESSURE GRADIENT FOR ONE PHASE FLOWING THROUGH THE ENTIRE CROSS-SECTION OF THE CONDUIT AT THE MASS FLOW RATE OF THAT PHASE IN THE TWO-PHASE CASE
tt vt tv vv	LIQUID-VAPOR FLOW CONDITIONS (VISCOUS OR TURBULENT) CORRESPONDING TO REYNOLDS NUMBERS OF THE HYPOTHETICAL, SINGLE-PHASE FLOWS (v: Re < 1000, t: Re > 2000)

FIGURE 7. FRICTIONAL PRESSURE GRADIENT CORRELATION FOR VAPOR—LIQUID, TWO—PHASE FLOW

TABLE 2. CORROSION PROBLEM AREAS

Temperature Range, °F	Appropriate Fluids	Type of Alloy Required
<600	Hg	Mild steel alloys
600-1200	Hg, Cs, Rb, NaK, K, Na	Iron-base superalloys
1200-1800	Cs, Rb, NaK, K, Na, Li	Iron-, cobalt-, nickel-, and chromium-base superalloys
1800-2400	Cs, Rb, Nak, K, Na, Li, Bi, Pb	Refractory metal alloys
>2400	Li, Bi, Pb	Refractory metal alloys, ceramics or cermets

These ranges are based on considerations such as fluid properties, alloy properties, and known or estimated fluid-vs-alloy compatibilities.

Corrosion by liquid metals and their vapors may stem from several causes, and it may in turn, lead to various effects. Several representative causes and effects are briefly summarized in Table 3.

The rate of corrosive attack on metal surfaces by nonaqueous inorganic liquids may vary significantly with flow rate if the slowest step in the corrosion process is the rate at which solute diffuses through the liquid boundary film. On the other hand, the corrosion rate may be independent of flow rate if the slow step is the rate of dissolution of the solid or the rate of diffusion in the solid phase. Iron-mercury systems typify the first of these cases, and iron-sodium systems are representative of the latter.

In certain cases, the net thermal-gradient mass transfer of a pure metal phase from a hot zone to a cold zone may proceed by way of the formation of an intermediate chemical compound in the dissolution step. For example, it is believed that sodium oxide, dissolved in liquid sodium, may react with iron in a hot zone to form a compound containing iron, sodium, and oxygen, and that this compound may revert to sodium oxide and free iron in a cold zone and thereby cause a net transport of metallic iron.

TABLE 3 CORROSION CAUSES AND EFFECTS

Cause	Typical Mechanism	Effect on		
		Corroded Part	System	Fluid
Thermal gradient	(Dissolution) (Chemical reaction)	Weight loss	Mass transfer	Contaminated
Dissimilar metals	(Dissolution) (Chemical reaction)	Weight loss	Mass transfer	Contaminated
Reactive fluid	Chemical reaction	(Weight loss) ((or gain),) (scaling, sub-) (surface voids,) (penetration)	Sludge	Contaminated
Contaminated fluid	(Chemical reaction) (Abrasion)	(Weight loss) ((or gain),) (scaling, sub-) (surface voids,) (penetration)	Sludge	Contaminated
Fluid flow	(Fluid boundary-) (layer effects)	(Accelerated) ((or altered)) (corrosion) (mechanisms)		

In the case of the liquid alkali metals, the presence of dissolved oxygen or oxides (and dissolved nitrogen or nitrides in the case of lithium) renders the fluid more corrosive. This enhancement of the corrosivity may result from dissolved compound formation as discussed previously, or it may reflect the surface-fluxing ability of dissolved oxides, i.e., the tendency of dissolved oxides to remove protective oxide films from the metal surface. This problem may be minimized in practice by removing oxide contaminants as solids in a trap which allows the molten metal to cool to near its freezing point in the presence of suitable precipitation sites. In addition, certain metals, such as the alkaline earths, when used as additives, may reduce the corrosivity of the alkali metals by selectively consuming oxygen. Alternately, the liquid metal may be continuously stripped of oxygen content by exposing it to more easily oxidized metals such as titanium or zirconium, in hot-gettering traps.

Conventional experimental techniques employed in corrosion research may be categorized into several groups on the basis of the type of test, the source of fluid motion, and the state of the fluid. These groups are shown in Table 4

TABLE 4. CORROSION EXPERIMENTAL TECHNIQUES

Type of Test	Source of Fluid Motion	Fluid State	Typical Techniques
Static	Stagnant	Liquid	Stationary capsule
Nonflow	Mechanical	Liquid	Moving capsule
Nonflow	Natural	Vapor-Liquid	Reflux capsule
Dynamic	Natural	Liquid	Liquid loop
Dynamic	Forced	Liquid	Liquid loop
Dynamic	Natural	Vapor-Liquid	Boiling-condensing loop
Dynamic	Forced	Vapor-Liquid	Boiling-condensing loop
Dynamic Dynamic	Natural Forced	Liquid) Liquid)	Subcooled portion of boiling-condensing loop
Dynamic Dynamic	Natural Forced	Vapor) Vapor)	Superheated portion of boiling-condensing loop

The foregoing tables point up some of the complexities of liquid-metal corrosion research planning and interpretation. Moreover, compounding of these complications results when factors such as entrained vapor-liquid mists or froths, and flow-channels of irregular geometry must be considered.

Working Fluid Considerations

The selection of the working fluid for a particular application depends upon the temperature range and the type of thermodynamic cycle of the anticipated application. For example, inert fluids for gas-cycle applications are selected primarily on the basis of vapor-phase thermodynamic properties. On the other hand, metal fluids for vapor-liquid cycles are chosen on the basis of vapor pressure, liquid physical properties, and corrosion characteristics in addition to thermodynamic properties. The vapor-pressure data shown in Figure 8 illustrate the range of operating pressures which can be encountered at various temperatures with the alkali metals and mercury in vapor-liquid cycles.

a. Equilibrium Properties

It is well established that the vapors of many metals do not approach the normal behavior of gases because the molecular weight of such vapors changes as conditions are altered. It is generally believed that this phenomenon stems from variations in the quantities of discrete monomer, dimer, trimer, etc., species in the vapor. On the other hand, it has also been suggested that the variable molecular weight may reflect a variable, continuous distribution of different degrees of proximity (association) among the vapor molecules.(Ref. 105) This polymeric behavior, irrespective of mechanism, affects significantly the magnitude of physical and thermal properties such as viscosity, density, thermal conductivity, and specific heat (disproportionately in some cases). In fact, it has been observed that the specific heat of superheated sodium and other alkali-metal vapors may be approximately doubled by these polymerization effects.

In the calculation of the performance characteristics of thermodynamic cycles involving metal vapors, it is important that the vapor species composition effects be taken into account as fully and as accurately as possible. If such effects are not adequately considered, significant errors in the performance estimates will result. In order to visualize the importance of species equilibrium in metal vapors, consider the better-known case of the combustion of hydrocarbon-air mixtures. For example, it is known that when carbon and oxygen react, the reaction products are not constituted of CO_2 alone even if a stoichiometric mixture is used. On the other hand, depending upon the prevalent conditions, small quantities of CO and O_2 are also present at equilibrium. This means that a certain amount of energy is "locked up" by the so-called dissociated products, and is thus not available for the production of

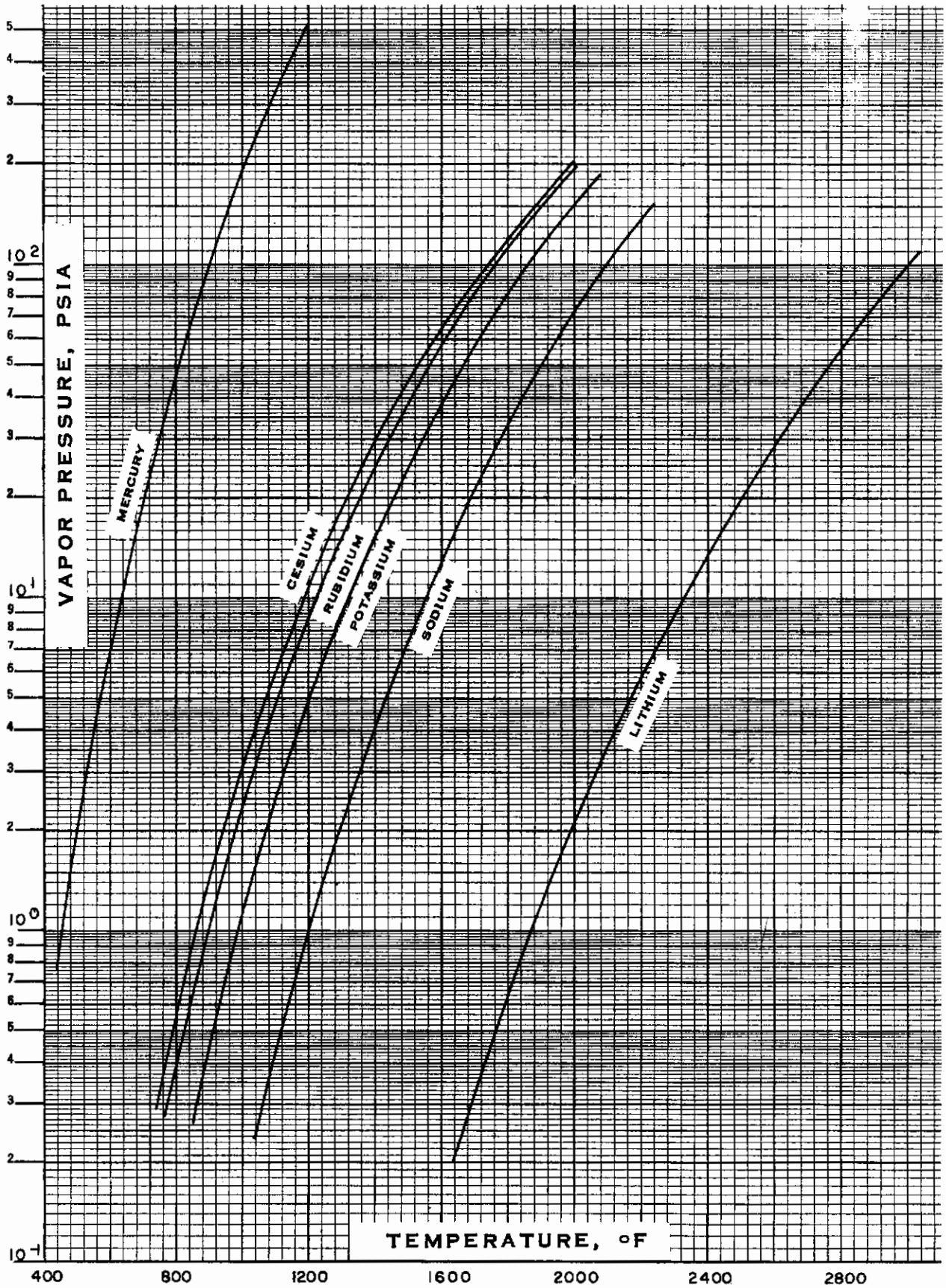


FIGURE 8. COMPARISON OF VAPOR PRESSURES OF ALKALI METALS AND MERCURY

heat or useful work. Conversely, in the present case, the presence of dimer, trimer, etc., at equilibrium represents a certain amount of energy made available which would not be available if these species were not present. However, changes in the fluid state which lead to decreases in dimer content require the consumption of energy for dissociation, and, hence, cause corresponding decreases in the amount of energy available as heat or useful work. Consequently, neglecting the effect of changing species equilibrium will result in errors in the thermodynamic calculations.

b. Nonequilibrium Properties

Quite apart from considerations of equilibrium, it should be recognized that very rapid processes may introduce additional uncertainties. At present, all calculations that have been made toward predicting the performance of space-vehicle power plants and heat-transfer systems are based upon theoretically computed equilibrium vapor compositions. Even if these computed values should be found to agree with future experimental equilibrium values, there is a possibility that thermodynamic cycle analyses and other heat-balance calculations based upon equilibrium properties could be in error if the rate of change of process conditions is fast relative to the rate of change of vapor composition. In combustion calculations, such as in the prediction of rocket thrust, the effects of changing composition are generally bracketed by considering that the nozzle expansion occurs with frozen composition and with shifting equilibrium, respectively. A similar bracketing procedure could be used in the case of changing metal-vapor species distribution.

Tables of Symbols and Conversion Factors

The following tables are presented in order to supplement and facilitate the use of information contained in this report.

a. Definition of Symbols

Symbol	Quantity	Dimensions
C_p	Specific heat at constant pressure	BTU/lb °R
D	Conduit diameter	ft
D_d	Diffusivity	ft^2/hr
F	Free energy	BTU/lb
G	Fluid mass velocity	$lb/hr\ ft^2$
g_c	Force-mass conversion factor	ft/hr^2
g	Local acceleration of gravity	ft/hr^2
H	Enthalpy	BTU/lb
ΔH	Latent heat of vaporization	BTU/lb
h	Film heat transfer coefficient	$BTU/hr\ ft^2\ °R$

Symbol	Quantity	Dimensions
k	Thermal conductivity	BTU/hr ft^2 (°R/ft)
L	Conduit length	ft
$\Delta P/\Delta L$	Pressure gradient	psi/ft
S	Entropy	BTU/lb °R
T	Temperature	°R, °F
t	Time	hr, sec
V	Fluid linear velocity	ft/hr
w	Fluid mass flow rate	lb/hr
β	Coefficient of cubical expansion	Volume increase per unit volume/°R
γ	Ratio of specific heat at constant pressure to that at constant volume	dimensionless
μ	Absolute viscosity	lb/ft hr
ρ	Fluid density	lb/ft^3
σ	Surface tension	lb/ft
Ω	Electrical resistance	microhms/in.

Subscripts	Significance
L, ℓ	Liquid phase
V, v	Vapor phase
o	Absolute zero temperature

b. Common Dimensionless Parameters

Parameter	Symbol	Quantities
Fanning friction factor	f	$g_c D(\Delta P/\Delta L)/2\rho V^2$
Graetz	Gz	wC/kL
Grashof	Gr	$D^3\rho^2 g\beta\Delta T/\mu^2$
Nusselt	Nu	hD/k
Peclet	Pe	$DV\rho C/k = RePr$
Prandtl	Pr	$C\mu/k$
Reynolds	Re	$DV\rho/\mu$
Schmidt	Sc	$\mu/\rho D_d$
Stanton	St	$h/CV\rho$

c. Useful Conversion Factors

To Convert From	To	Multiply By
°R	°K	1/1.8
BTU/lb mole °R	cal/gm mole °K	1.000
BTU/lb mole	cal/gm mole	1/1.8
BTU/ft hr °R	cal/cm sec °F	1/241.9
BTU/hr	watts	1/3.413
in.	cm	2.54
ft	cm	30.48
in^2	cm^2	6.45
ft^2	cm^2	929
in^3	cm^3	16.39
ft^3	cm^3	28,317
lb	grams	453.6
lb	dynes	4.45×10^5
lb/ft hr	centipoise	1/2.42
lb/ft^3	gm/cm^3	1/62.43
fps electromagnetic units per unit mass	cgs electromagnetic units, per unit mass	1/(929.4)(453.6)

II. DATA PROCESSING

Information Survey

Throughout this program, current and past literature sources have been scrutinized for information. In addition, several government agencies and numerous industrial organizations have been consulted, and the cooperation received has aided materially in the gathering of data for use in this report. These agencies and organizations are enumerated in the following table.

TABLE 5. ORGANIZATIONS CONSULTED

Organization	Individuals
Aerojet-General Nucleonics San Ramon, California	D. E. Deutsch P. F. Young F. Standifer David Sawle J. Payne K. Johnson
AiResearch Manufacturing Co. Phoenix, Arizona	W. L. Bowler R. Caldwell E. Kovacevich L. D. Six
Battelle Memorial Institute Columbus, Ohio	E. M. Simons A. W. Lemmon, Jr.
Babcock and Wilcox Co. Lynchburg, Virginia	A. L. Lowe
Brookhaven National Laboratory Upton, L. I., New York	John Weeks
General Electric Co. Flight Propulsion Laboratory Dept. Cincinnati, Ohio	Erwin Schnetzer R. J. Rossbach A. Shapiro
General Motors Corporation Allison Division Indianapolis, Indiana	J. R. Simmons
M. S. A. Research Corporation Callery, Pennsylvania	C. H. Staub J. W. Mansteller R. E. Lee J. Madaus
NASA, Lewis Research Center Cleveland, Ohio	B. Lubarsky L. Rosenblum H. Slone C. Barrett A. Glassman

TABLE 5. ORGANIZATIONS CONSULTED (Cont'd)

Organization	Individuals
National Bureau of Standards Washington, D. C.	C. W. Beckett J. Hilsenrath D. C. Ginnings W. E. Evans T. B. Douglas
National Academy of Sciences National Research Council Office of Critical Tables Washington, D. C.	G. Waddington R. Wiebe M. J. Callanan
Oak Ridge National Laboratory Oak Ridge, Tennessee	A. P. Fraas L. G. Epel E. E. Hoffman W. H. Cook D. H. Jansen
Pratt and Whitney Aircraft CANEL Middletown, Connecticut	K. J. Kelly G. Austin M. Freed S. Kapelner
Rocketdyne Division North American Aviation Canoga Park, California	H. Wolf T. A. Coultas R. J. Thompson R. J. Teitel J. R. McCarthy H. Burge
Sundstrand Aviation Denver, Colorado	John May J. Rosengard
Texas Gulf Sulphur Co. New York, N. Y.	J. R. West
U.S. Naval Research Laboratory Washington, D. C.	R. R. Miller C. T. Ewing
University of California Berkley and Livermore, California	A. W. Searcy B. Alder

Analysis and Selection of Data

The analysis of data has involved careful appraisal of information from various sources. Comments by authors of experimental papers and by review authors regarding the nature and reliability of the data have been considered in the selection of recommended values. When undocumented-source data disagreed with data from known sources, the former have been disregarded. However, in a few cases, no other information source was discovered, so these data are presented as recommended values. When more than one source of information was available, the data from all available sources were considered in the selection of recommended values.

The major criteria which have guided in the selection of recommended values have been consistency in selection and smoothing methods, mutual consistency among related properties (or properties which implicitly or explicitly involve other properties which are presented individually). For example, temperature-enthalpy data must be consistent with specific-heat data.

In the final selection of data, a major effort has been made to maintain consistent bases among the various fluids. It is anticipated that many potential users of the results of this program will employ the data to compare the relative merits of different fluids. Hence, consistency among the data of the various fluids is nearly as important as the absolute degree of accuracy. On the other hand, it is apparent that the deciding factor in the final selection of data has had to be based upon the estimated precision of the data for the individual fluids.

Prediction of Properties

In many instances, property data may not be available for the range of temperatures or pressures of interest in a particular design calculation. For such cases, reasonable estimates of certain properties can be made with the use of semitheoretical relationships or empirical generalized correlations. Because of the widespread literature references on this subject, it is beyond the scope of the report to attempt to classify and discuss such estimation procedures. However, several potentially useful methods have been reviewed in literature articles. For example, methods for estimating the viscosity, thermal conductivity, and specific heat of liquid metals, fused salts, and gases are described in Reference 7-0-9. This source also describes procedures for estimating surface tension and diffusivity. Several generalized correlations for predicting the influence of pressure and temperature on fluid properties such as density, viscosity, thermal conductivity, and specific heat are presented in References 5-0-8, 7-0-9, 11-11-8, and 13-12-3.

The vapor pressure data presented in this report for the alkali metals represent values which were theoretically adjusted by Reference 19-13-60 to maintain internally consistent thermodynamic properties. These adjusted data have been selected for use in this compilation for several reasons, some of which are summarized as follows: Relative to the data originally presented in WADC TR 59-598, the revised latent heats for cesium, rubidium, and sodium are in closer agreement with those of Reference 19-19-6; the adjusted vapor pressure curve for lithium agrees with that originally presented in WADC TR 59-598; the adjusted vapor pressure data for sodium agrees with that of Reference 10-0-5 up to about one atmosphere, and it is supported by experimental data of Reference 3-2-60 at higher pressures.

No data have been uncovered for the viscosity of alkali-metal vapors. Therefore, saturated-vapor viscosities have been estimated with the aid of the following theoretical relationship developed at SwRI (Ref. 23-4-61).

$$\mu = \frac{0.001667[M^2PV]^{1/2}}{[\sigma_o + 283/(M^2PV)^{1/2}]^2} \text{ lb/ft hr}$$

where M = equilibrium molecular weight
P = pressure, psia
V = vapor volume, ft^3/lb
σ_o = hard-core collision diameter, Å (computed from M and freezing-point densities for this work)

The thermal conductivity of saturated vapors of the alkali metals and mercury have been estimated from the presented viscosity and specific heat data, assuming a constant Prandtl number.

III. PROPERTY DATA

Method of Presentation

It is anticipated that this report will serve as a source-book for the properties of inorganic fluids for space applications. Therefore, the physical structure of the report has been devised for maximum flexibility so that individual data pages or entire fluid sections may be added, deleted, or replaced as new data become available, or as fluid emphasis changes.

The fluids have been divided into three logical groups - namely, liquid metals, nonmetals, and gases, each represented in the order of decreasing volatility. Each fluid is discussed individually with regard to its general description, general physical and chemical properties, material compatibility, and availability and cost. A tabular synopsis of properties is presented for each fluid in order to provide means for rapid preliminary appraisal of a fluid, or to expedite making preliminary comparisons of properties among various fluids. Detailed property tables are presented where tabular source material is available. It is considered of no real value to compose tables of data which are presented graphically.

Data-source references are tabulated at the end of the section on each fluid. The reference numbers were devised for use during the information survey in order that data sources could be cataloged upon receipt. These code numbers have been retained in the report to facilitate future revisions, but their significance is not important.

To facilitate rapid reference to the data presented in this report, each data section is identified by being printed on paper of a distinctive color. The liquid metals, nonmetals, and gases are printed on blue, buff, and green paper, respectively. The individual page numbers are coded to identify either the class of fluid, the particular fluid, or the type of information which is presented. For example, in the data section for mercury, the following page numbers are typical:

Content of Page	Page No.
Liquid Metals: fly sheet	Metals
Mercury: fly sheet	Metal-Hg
Mercury: general information	Hg-Gen-1
Mercury: synopsis of property data	Hg-Syn-1
Mercury: data tables fly sheet	Hg-Tab-1
Mercury: physical property tables	Hg-P-1
Mercury: viscosity table	Hg-μ-1

If there is more than one page of physical property tables, successive pages are designated by successive numerals: Hg-μ-2, Hg-μ-3, etc. However, in order to distinguish charts from tables, successive charts involving the same property are identified by successive letters: Hg-μ-a, Hg-μ-b, Hg-μ-c, etc.

The graphically portrayed data are identified as to basis and source by means of tables printed either directly on the charts or on the back of the pages. The sources of tabular data are identified at the beginning of each table, and, in some cases, the data basis is described on the first page of the table section. In many cases, the bases of data from published comprehensive compilations and handbooks would have been difficult to establish without exceeding the scope of this program. Hence, the reader is referred to the source references in such cases.

LIQUID METALS

MERCURY

a. General Discussion of Mercury. Mercury is a silver-white metal which is liquid at ordinary temperatures. It is the most volatile and most dense liquid metal, and it exhibits the highest gaseous ionization potential of all elements, excluding the inert gases. It does not react with oxygen at ordinary temperatures and is inert toward water. An oxide film may form on mercury surfaces after prolonged exposure to moist air; however, this film usually represents oxidized trace impurities. In fact, an effective purification technique commonly employed for reclaiming used mercury involves intimate contacting of the impure mercury with air at room temperature (to oxidize impurities) followed by filtration or distillation.

Mercury readily forms amalgams (mercury alloys) with most metals including the alkali metals and aluminum, bismuth, cadmium, cesium, gold, lead, magnesium, silver, tin, and zinc. Mercury is relatively noncorrosive toward ferrous alloys in static systems; however, serious thermal-gradient-induced mass transfer effects may be encountered in dynamic systems.

The well-known toxicity of mercury vapor should not present difficulties if reasonable precautions are exercised. Such precautions include adequate ventilation, separate clothes for use only when exposed to mercury and to be stored away from other clothes, refraining from smoking or eating while in the presence of mercury, thorough washing of hands and rinsing of mouth after exposure, and frequent medical examinations if repeated exposure is suspected. Potential contamination areas can be protected by coating walls and floors with special paints containing additives which convert mercury into relatively harmless salts.

Nominal 99.7 percent pure mercury is commercially available in 76-pound flasks at a cost of $208-$210 per flask.

b. Synopsis of Properties of Mercury.

Property	Value	Temp (°F)	Data Basis	Reference
Physical:				
Atomic Weight	200.61	---	Handbook	8-0-8
Melting Point, °F	-37.97	---	Handbook	8-0-8
Boiling Point, °F	674	---	Experimental	Page Hg-VP-a
Critical Point, psia	15,350*	2,659	Experimental T_c	8-0-8* 13-19-60
Density of Solid, lb/ft^3	845.67	68	Handbook	8-0-8
Density of Liquid, lb/ft^3	794.4	B.P.	Extrapolated	Page Hg-ρ-a
Density of Vapor, lb/ft^3	0.244	B.P.	Experimental and Theoretical	Page Hg-ρ-b
Viscosity of Liquid, lb/ft hr	2.15	B.P.	Reconciliation Plots	Page Hg-μ-a
Viscosity of Vapor, lb/ft hr	0.1475	B.P.	Experimental and Theoretical	Page Hg-μ-b
Surface Tension, lb/ft	0.02697	B.P.	Unknown	Page Hg-σ-a
Thermal:				
Thermal Conductivity of Liquid, BTU/hr ft °F	7.11	B.P.	Experimental	Page Hg-k-a
Thermal Conductivity of Vapor, BTU/hr ft °F	0.00501	B.P.	Estimated	Page Hg-k-b
Specific Heat of Liquid, BTU/hr °F	0.3233	B.P.	Experimental	Page Hg-C-a
Specific Heat of Vapor, BTU/lb °F	0.0248	B.P.	Experimental	19-19-6
Latent Heat of Fusion, BTU/lb	5.07	M.P.	Handbook	8-0-8
Latent Heat of Vaporization, BTU/lb	125.72	B.P.	Estimated and Experimental	Page Hg-ΔH-a

*Estimated from Van der Waal's constants given in reference.

Property	Value	Temp (°F)	Data Basis	Reference
Electrical and Magnetic:				
Resistivity, μ ohm-inch	53.62	B.P.	Extrapolated	Page Hg-Ω-a
Ionization Potential, volts	10.43	---	Experimental	11-0-60
Magnetic Susceptibility, fps electromagnetic units/unit mass	-0.0813	590 liq	Handbook	8-0-8
Thermal Neutron Cross Section (2200 m/s):				
Absorption, barns	380 ± 20	---	Handbook	8-0-8
Scattering, barns	20 ± 5	---	Handbook	8-0-8
Isotopic for Hg^{204}, barns	0.43 ± 0.10	---	Handbook	8-0-8

c. Property Tables for Mercury.

PHYSICAL PROPERTIES OF MERCURY
Saturated Phases

(Ref: 19-13-60)

Temperature (°R)	Equilibrium Vapor Molecular Weight	Vapor Pressure (psia)	Liquid Specific Volume (ft^3/lb)	Vapor Specific Volume (ft^3/lb)
900	200.610	7.6637×10^{-1}	1.228×10^{-3}	6.287×10^{1}
1000	200.610	3.2319×10^{0}	1.241×10^{-3}	1.657×10^{1}
1100	200.610	1.0415×10^{1}	1.254×10^{-3}	5.654×10^{0}
1200	200.610	2.7450×10^{1}	1.267×10^{-3}	2.340×10^{0}
1300	200.610	6.2007×10^{1}	1.281×10^{-3}	1.122×10^{0}
1400	200.610	1.2413×10^{2}	1.294×10^{-3}	6.038×10^{-1}
1500	200.610	2.2566×10^{2}	1.307×10^{-3}	3.559×10^{-1}
1600	200.610	3.7943×10^{2}	1.320×10^{-3}	2.258×10^{-1}
1700	200.610	5.9840×10^{2}	1.333×10^{-3}	1.521×10^{-1}
1800	200.610	8.9481×10^{2}	1.347×10^{-3}	1.077×10^{-1}
1900	200.610	1.2795×10^{3}	1.360×10^{-3}	7.950×10^{-2}
2000	200.610	1.7617×10^{3}	1.373×10^{-3}	6.078×10^{-2}
2100	200.610	2.3483×10^{3}	1.386×10^{-3}	4.788×10^{-2}
2200	200.610	3.0443×10^{3}	1.399×10^{-3}	3.869×10^{-2}
2300	200.610	3.8523×10^{3}	1.413×10^{-3}	3.196×10^{-2}
2400	200.610	4.7732×10^{3}	1.426×10^{-3}	2.692×10^{-2}
2500	200.610	5.8059×10^{3}	1.439×10^{-3}	2.305×10^{-2}
2600	200.610	6.9479×10^{3}	1.452×10^{-3}	2.003×10^{-2}
2700	200.610	8.1953×10^{3}	1.465×10^{-3}	1.764×10^{-2}

THERMAL PROPERTIES OF MERCURY
Saturated Phases

(Ref: 19-13-60)

Temperature (°R)	Frozen Specific Heat of Vapor (BTU/lb °R)	Ratio of Frozen Specific Heats of Vapor	Specific Heat of Liquid (BTU/lb °R)
900	0.02476	1.6667	0.0323
1000	0.02476	1.6667	0.0323
1100	0.02476	1.6667	0.0323
1200	0.02476	1.6667	0.0324
1300	0.02476	1.6667	0.0326
1400	0.02476	1.6667	0.0329
1500	0.02476	1.6667	0.0332
1600	0.02476	1.6667	0.0336
1700	0.02476	1.6667	0.0341
1800	0.02476	1.6667	0.0347
1900	0.02476	1.6667	0.0353
2000	0.02476	1.6667	0.0361
2100	0.02476	1.6667	0.0369
2200	0.02476	1.6667	0.0378
2300	0.02476	1.6667	0.0387
2400	0.02476	1.6667	0.0398
2500	0.02476	1.6667	0.0409
2600	0.02476	1.6667	0.0421
2700	0.02476	1.6667	0.0434

THERMODYNAMIC PROPERTIES OF MERCURY
Saturated Phases

(Ref: 19-13-60)

Temperature T (°R)	Enthalpy of Liquid $(H-H_o)_L$ (BTU/lb)	Enthalpy of Vapor $(H-H_o)_V$ (BTU/lb)	Entropy of Liquid S_L (BTU/lb °R)	Entropy of Vapor S_V (BTU/lb °R)
900	3.5753×10^{1}	1.62539×10^{2}	1.081×10^{-1}	2.490×10^{-1}
1000	3.8983×10^{1}	1.65319×10^{2}	1.115×10^{-1}	2.379×10^{-1}
1100	4.2212×10^{1}	1.68098×10^{2}	1.146×10^{-1}	2.291×10^{-1}
1200	4.5447×10^{1}	1.70884×10^{2}	1.174×10^{-1}	2.220×10^{-1}
1300	4.8697×10^{1}	1.73685×10^{2}	1.200×10^{-1}	2.162×10^{-1}
1400	5.1969×10^{1}	1.76507×10^{2}	1.225×10^{-1}	2.114×10^{-1}
1500	5.5272×10^{1}	1.79360×10^{2}	1.247×10^{-1}	2.075×10^{-1}
1600	5.8612×10^{1}	1.82251×10^{2}	1.269×10^{-1}	2.042×10^{-1}
1700	6.1998×10^{1}	1.85187×10^{2}	1.289×10^{-1}	2.014×10^{-1}
1800	6.5438×10^{1}	1.88178×10^{2}	1.309×10^{-1}	1.991×10^{-1}
1900	6.8939×10^{1}	1.91229×10^{2}	1.328×10^{-1}	1.972×10^{-1}
2000	7.2509×10^{1}	1.94350×10^{2}	1.346×10^{-1}	1.956×10^{-1}
2100	7.6157×10^{1}	1.97548×10^{2}	1.364×10^{-1}	1.942×10^{-1}
2200	7.9889×10^{1}	2.00831×10^{2}	1.382×10^{-1}	1.931×10^{-1}
2300	8.3714×10^{1}	2.04206×10^{2}	1.399×10^{-1}	1.922×10^{-1}
2400	8.7640×10^{1}	2.07683×10^{2}	1.415×10^{-1}	1.915×10^{-1}
2500	9.1674×10^{1}	2.11267×10^{2}	1.432×10^{-1}	1.910×10^{-1}
2600	9.5824×10^{1}	2.14968×10^{2}	1.448×10^{-1}	1.906×10^{-1}
2700	1.0010×10^{2}	2.18793×10^{2}	1.464×10^{-1}	1.904×10^{-1}

THERMODYNAMIC PROPERTIES OF MERCURY

Liquid Phase: $H^\circ_{536.67} - H^\circ_0 = 4,018$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^\circ - H^\circ_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^\circ - H^\circ_{536.67})/T$ (BTU/lb mole °R)
536	0	18.19	18.19
540	22	18.23	18.19
720	1210	20.13	18.45
900	2381	21.58	18.94
1080	3546	22.77	19.49

THERMODYNAMIC PROPERTIES OF MERCURY

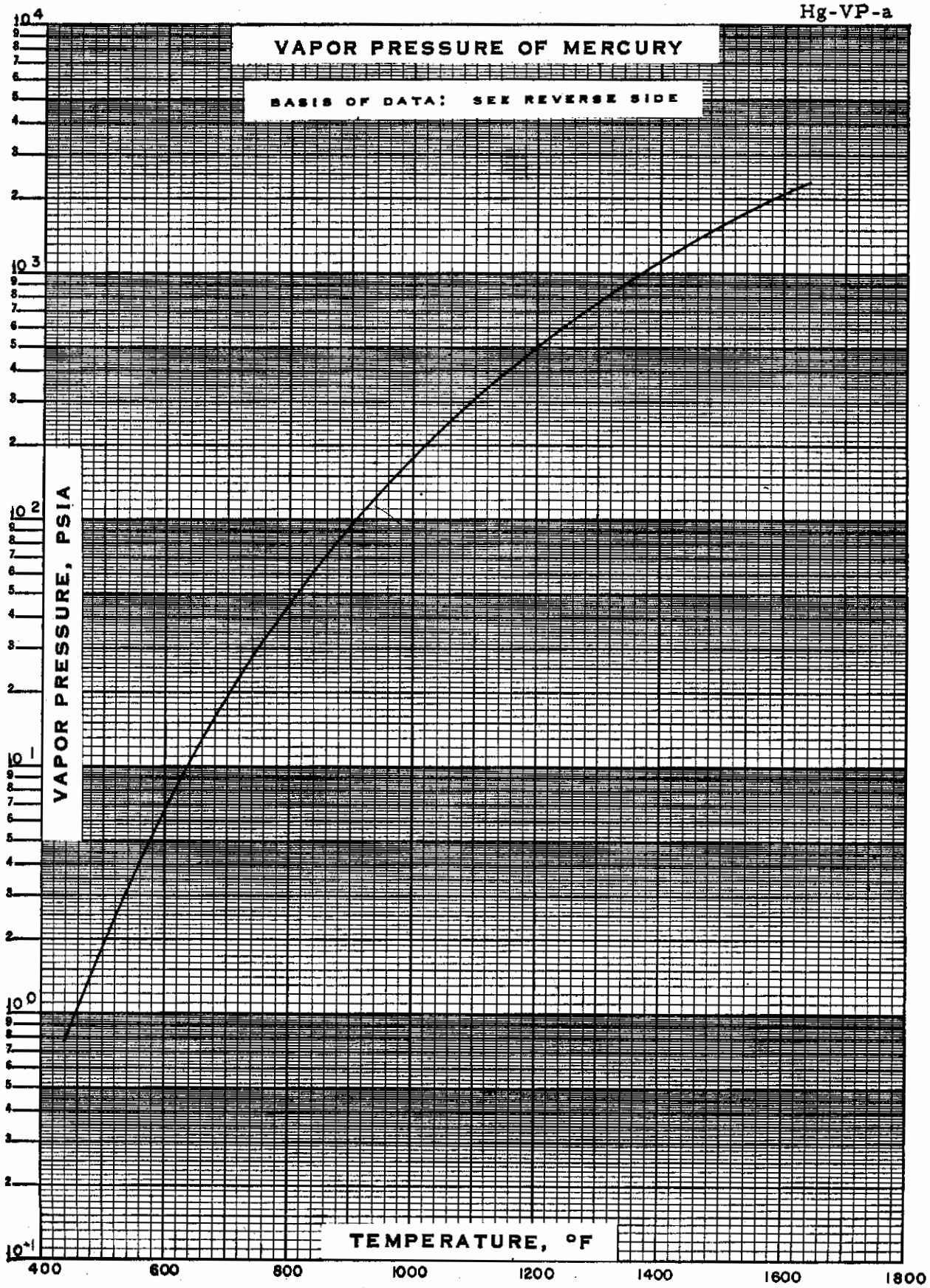
Ideal Monatomic Gas: $H^{\circ}_{536.67} - H^{\circ}_{o} = 2,666$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^{\circ} - H^{\circ}_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^{\circ} - H^{\circ}_{536.67})/T$ (BTU/lb mole °R)
900	1805	44.36	42.36
1080	2700	45.27	42.77
1260	3593	46.03	43.18
1440	4487	46.70	43.59
1620	5382	47.28	43.96
1800	6277	47.81	44.33
1980	7171	48.28	44.66
2160	8064	48.71	44.98
2340	8959	49.11	45.29
2520	9853	49.48	45.57
2700	10748	49.82	45.84
2880	11642	50.14	46.10
3060	12535	50.44	46.35
3240	13430	50.73	46.59
3420	14324	50.99	46.81
3600	15219	51.25	47.03

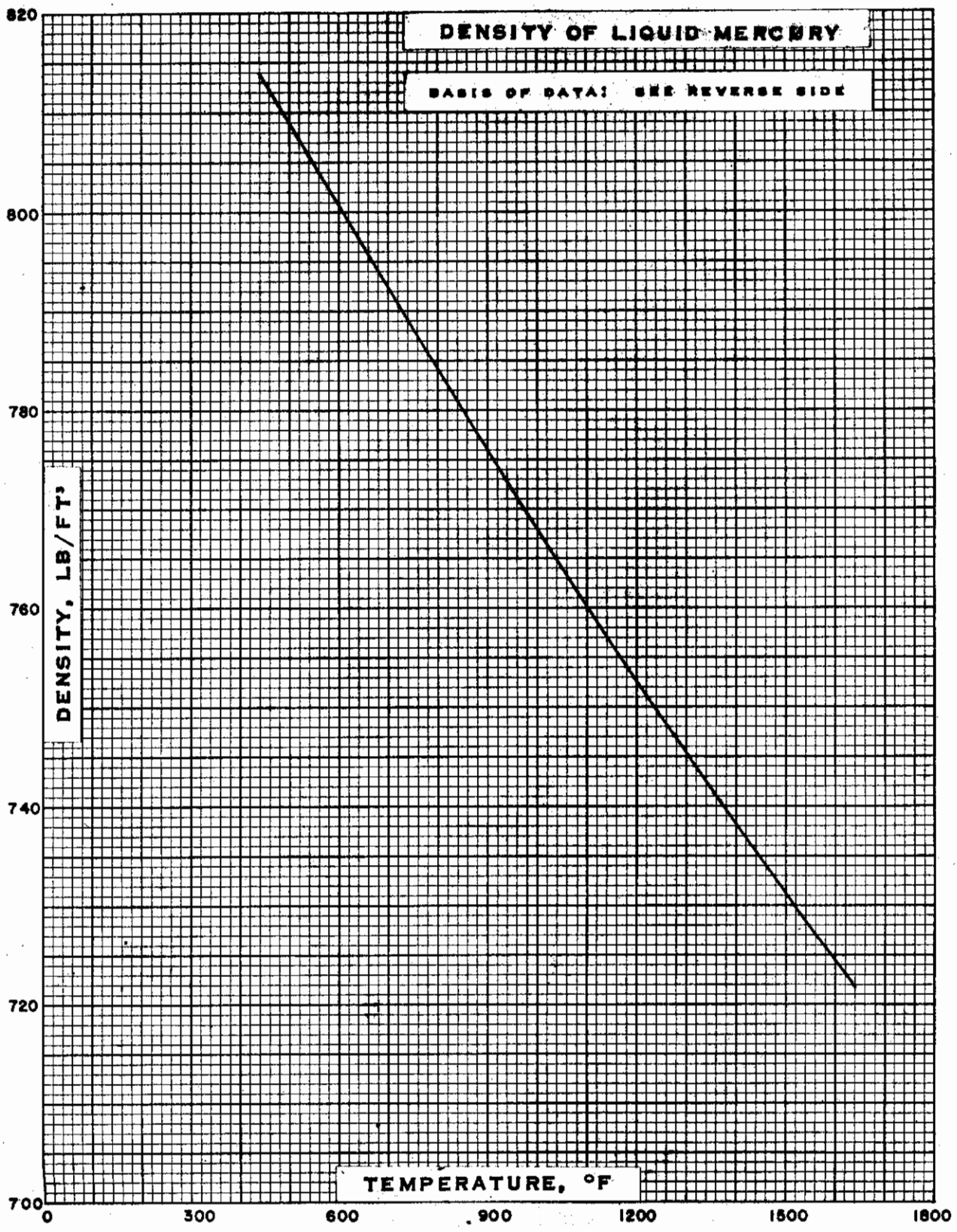
d. Working Charts for Mercury.

Hg-VP-a



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	4-7-1, 12-0-2, 19-13-60	440-700	The results of different investigators were correlated and the best results were employed to derive an equation representing the vapor pressure of mercury.
Theoretical	4-2-1, 721	440-932	A vapor pressure equation was obtained by theoretical methods. Values calculated from this equation were found to agree with certain published experimental values when independently derived gas-imperfection and published temperature-scale corrections were applied.
Theoretical	19-13-60	700-1640	A vapor pressure equation was derived by integration of the Clapeyron equation. The constants of the equation were taken from (12-0-2).
Reconciliation Plots	8-0-8, 19-0-7	440-675	Graphic methods were used to evaluate the collected data.

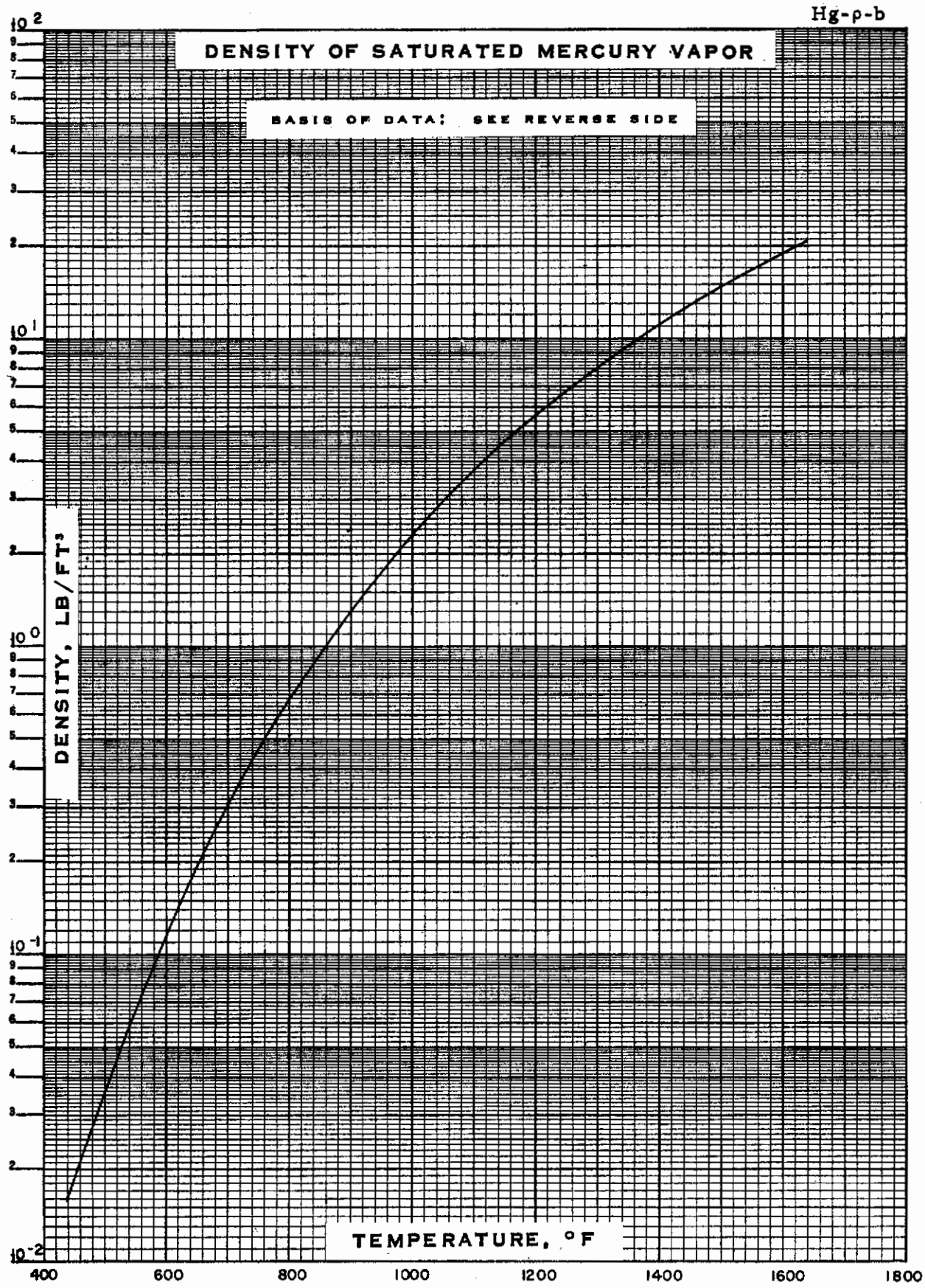
Hg-p-a



Hg-ρ-a (basis)

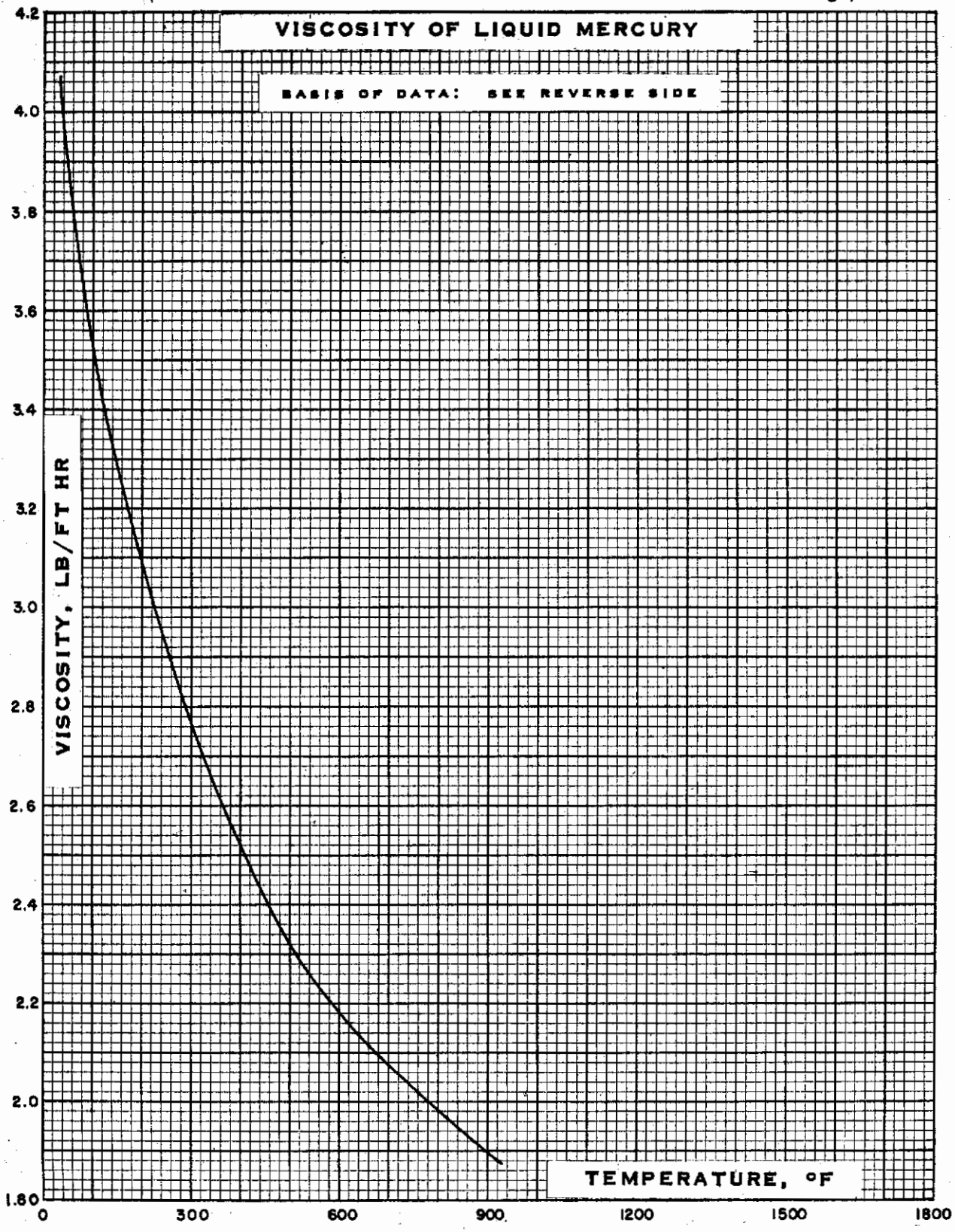
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Unknown	12-0-2; 19-13-60	440-572	Values were chosen from a compilation.
Extrapolated	19-13-60	572-1740	Extended (12-0-2) data.

Hg-ρ-b



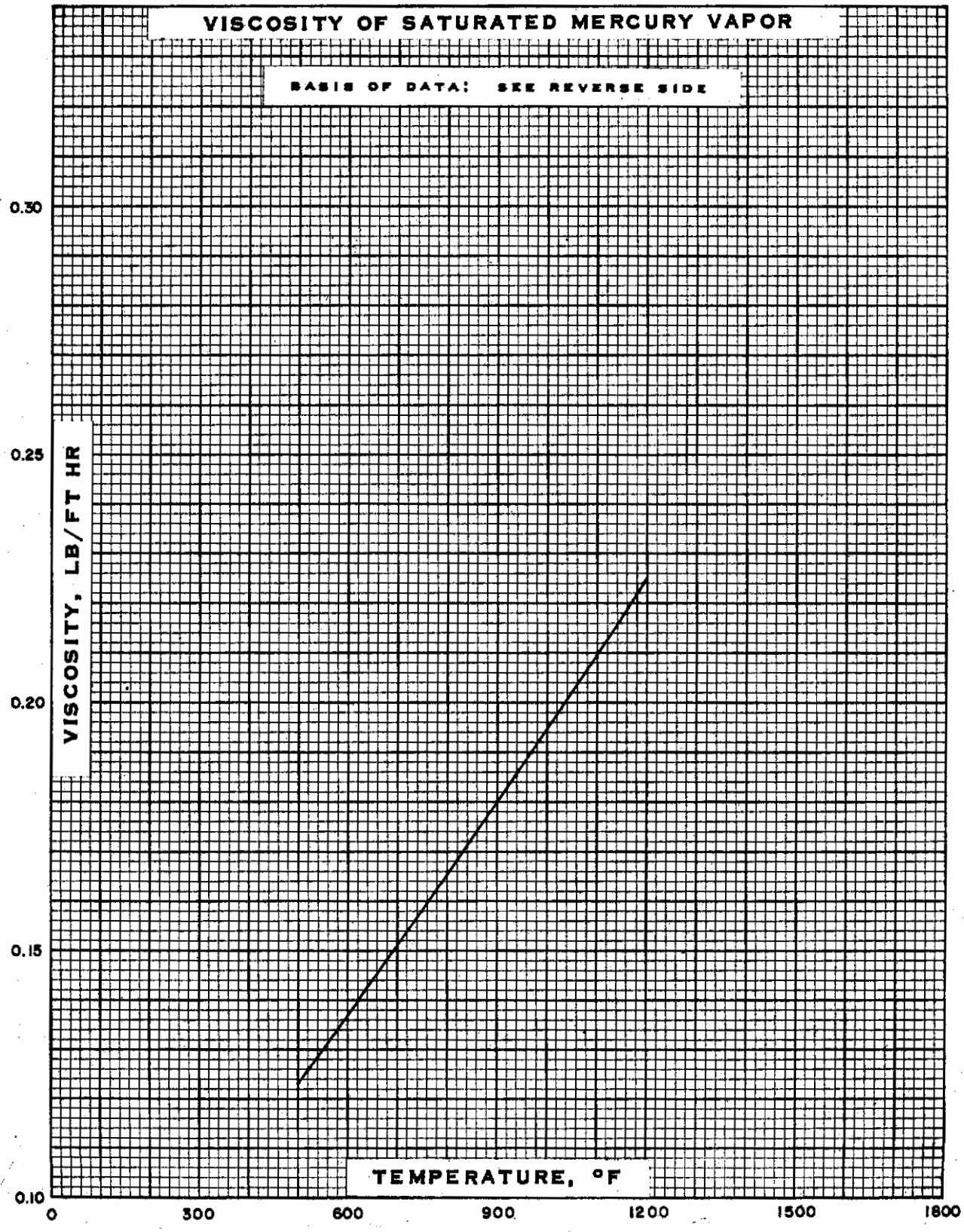
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental and Theoretical	4-2-1, 721	440-1640	Saturated mercury vapor at pressures not exceeding two atmospheres has been found experimentally to have densities that differ from those calculated for an ideal gas of less than 2%. From statistical mechanics an equation of state was derived and the viral coefficient in the equation was evaluated by use of spectroscopic evidence of Hg_2 in the mercury vapor.
Theoretical	19-13-60	440-1640	The specific volume of the vapor mixture was calculated from the perfect gas law.

Hg-μ-a



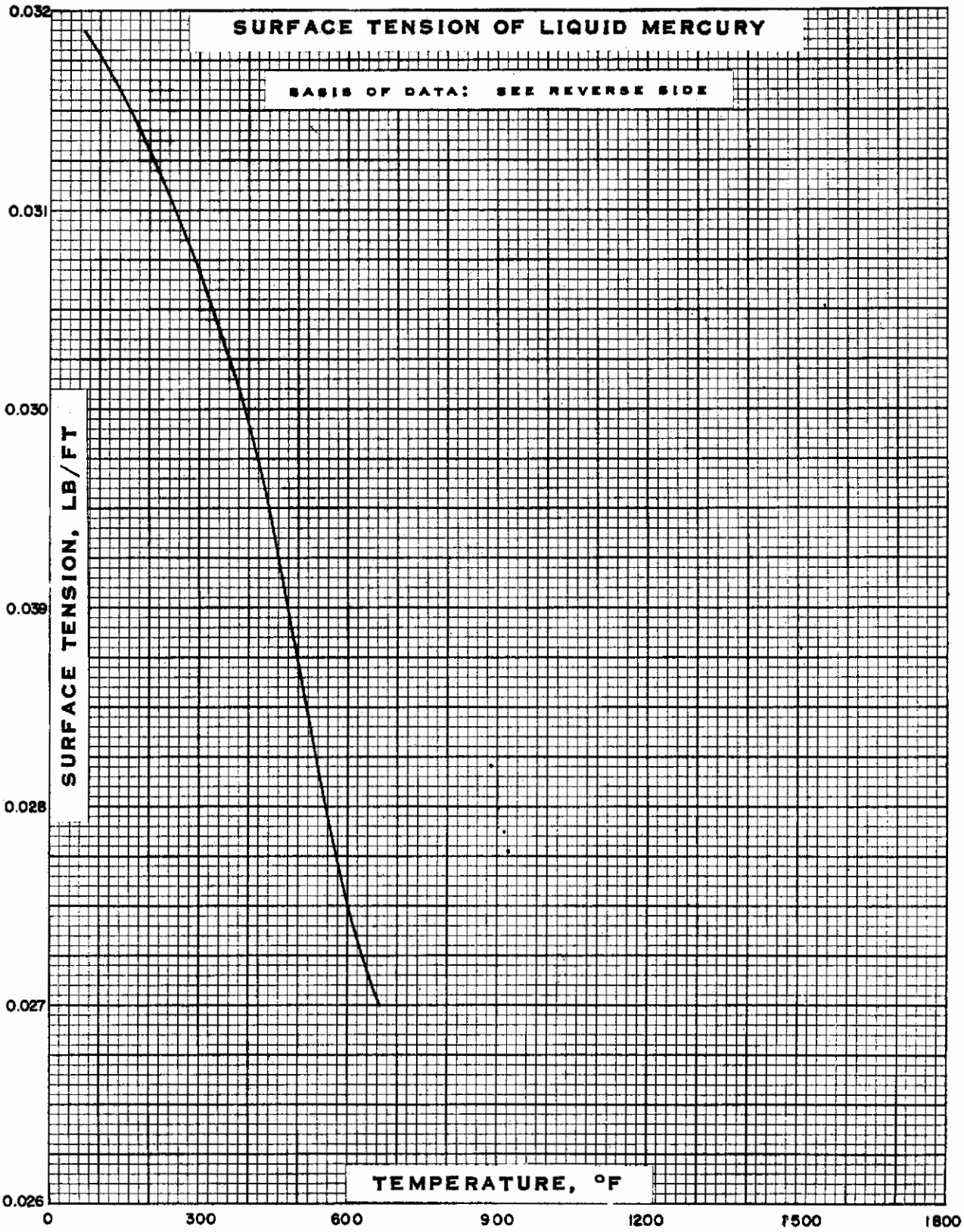
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Reconciliation Plots	11-2-9	32-932	Values of viscosity for liquid mercury were taken from several different references.
Unknown	8-0-8	32-400	Survey

Hg-μ-b

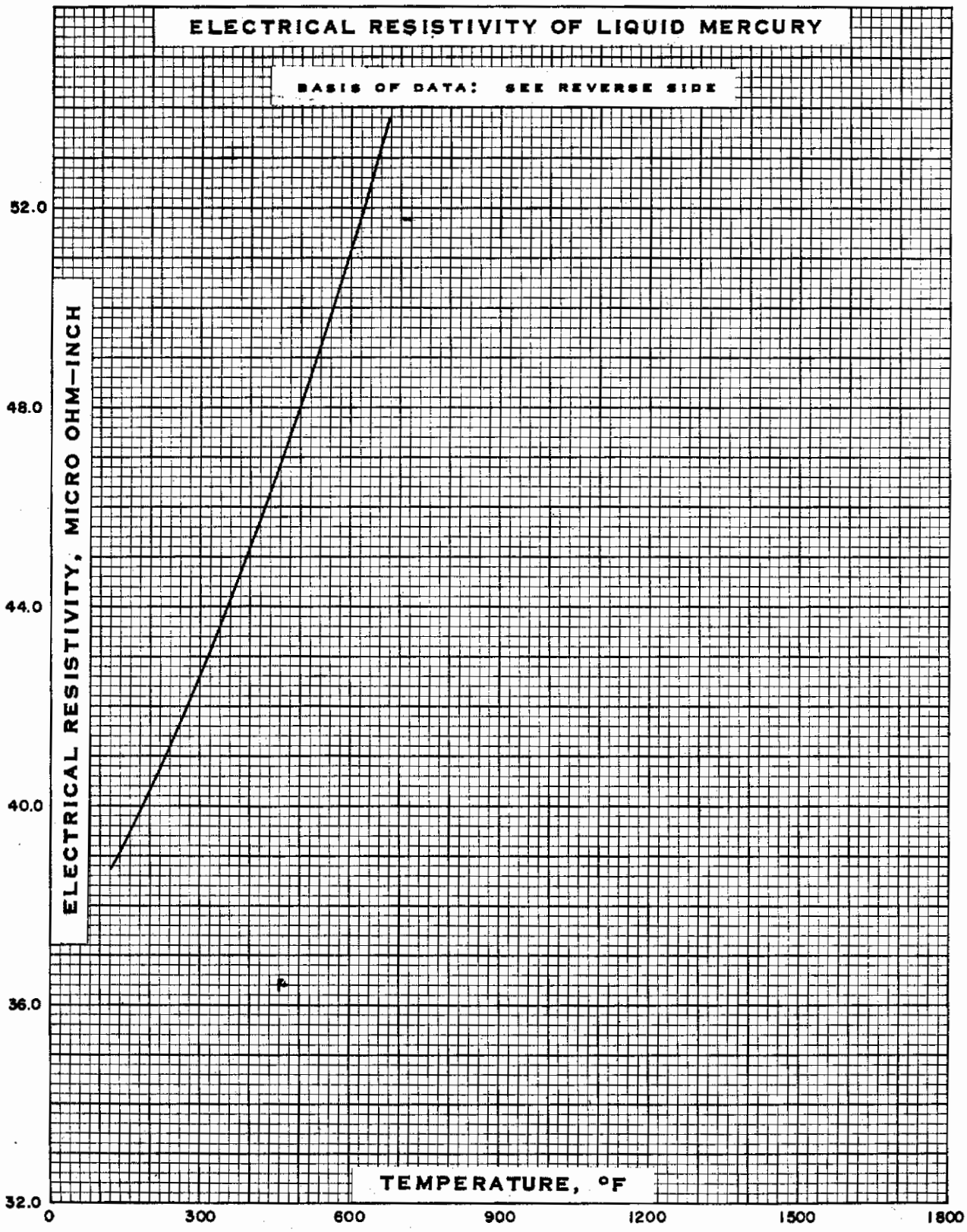


WADD TR 61-96

Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical and Experimental	5-16-00	500-1200	Saturated mercury viscosity data were obtained with Lennard Jones 6-12 potential. These data agree with existing experimental data.

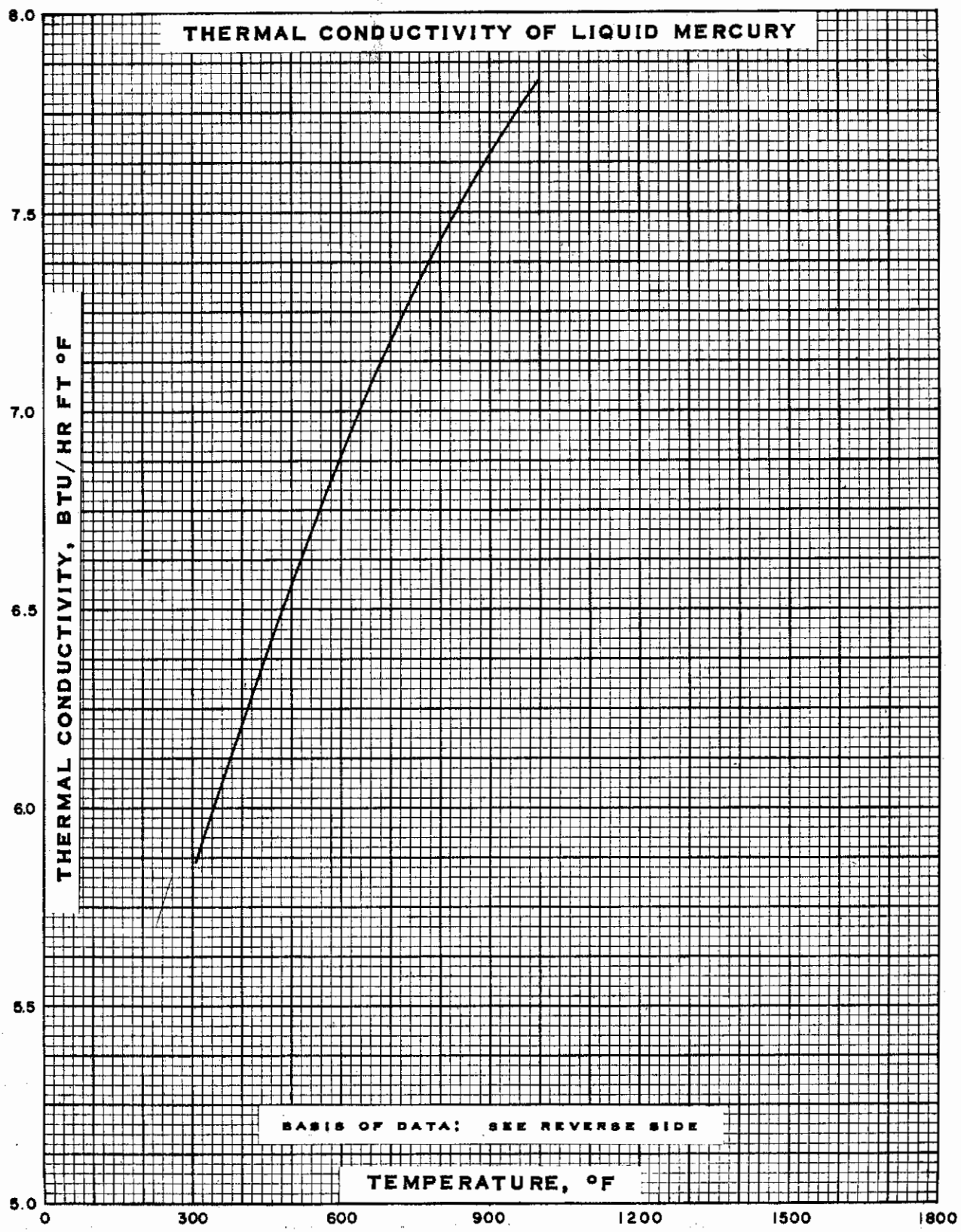


Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Unknown	12-0-2	65-680	Survey



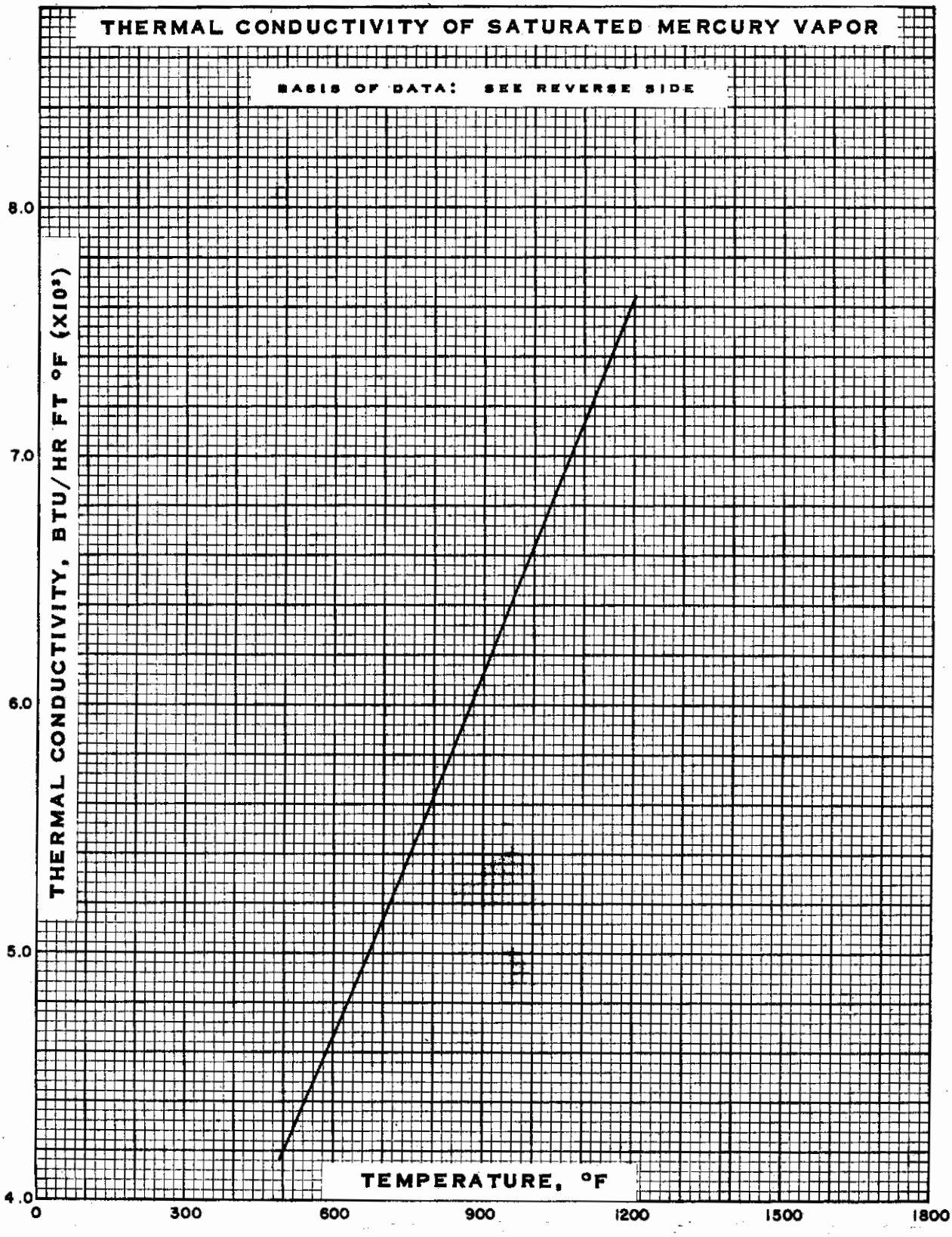
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Unknown	12-0-2	120-680	Survey

Hg-k-a



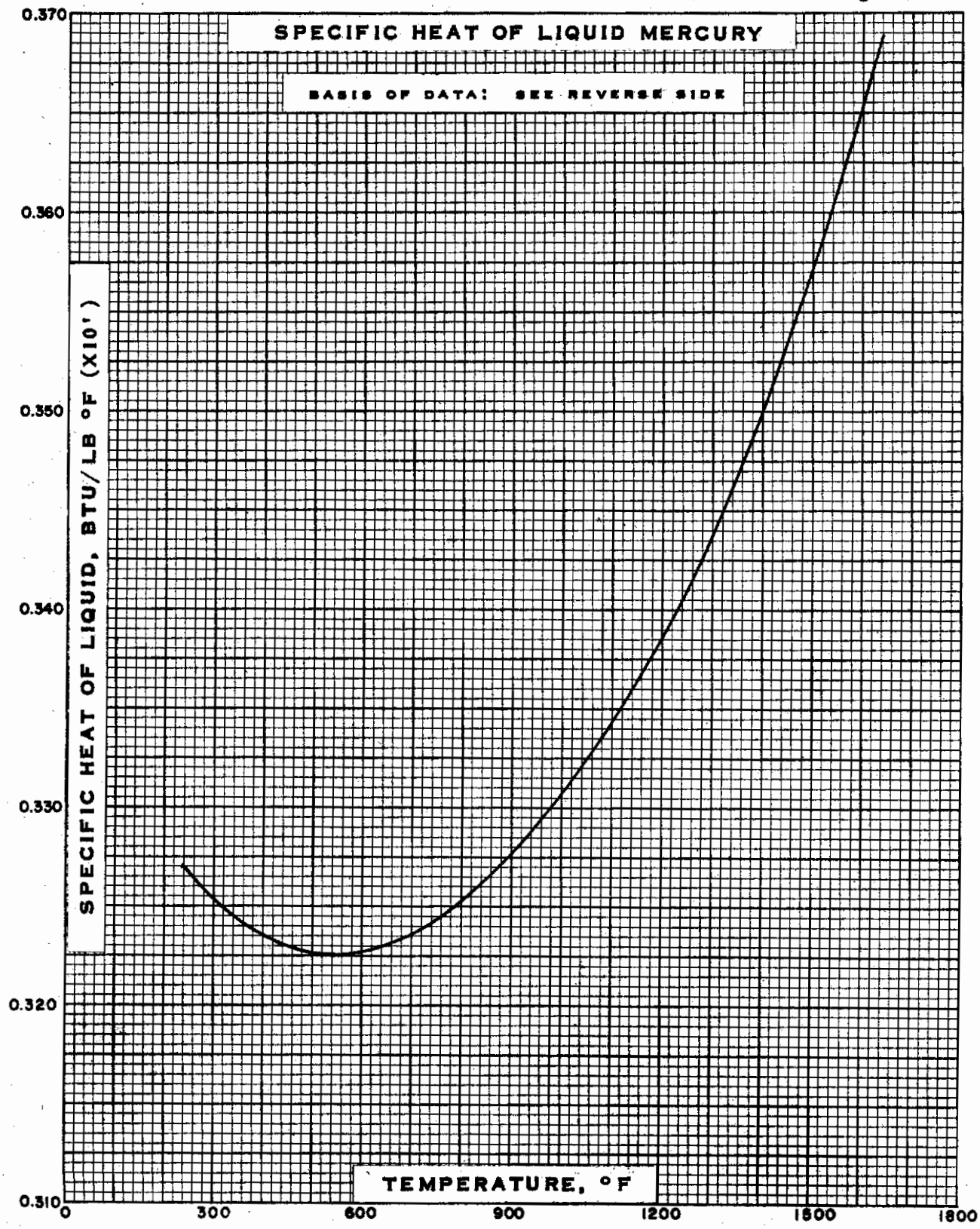
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	5-19-5	300-1000	A uni-axial measuring unit and integral control system was used for the thermal conductivity measurements on liquid mercury. Chemical analysis of mercury removed from the conductivity tube was: Fe-0.0004 wt %, Cr-0.0002 wt %, Ni-0.0001 wt %.
Experimental	11-2-9	300-932	Measured with a column having compensation for lateral heat losses with height.

Hg-k-b

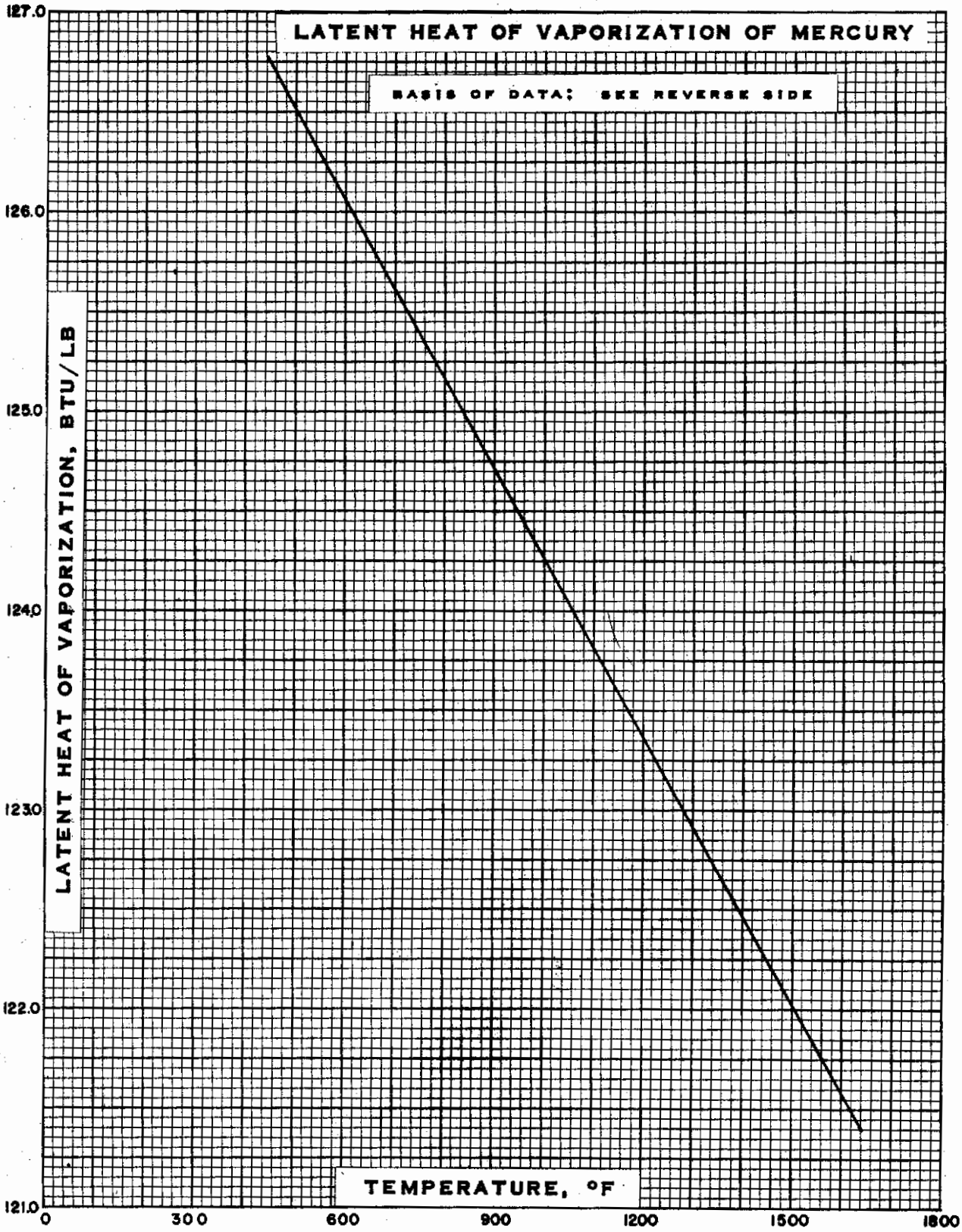


WADD TR 61-96

Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Estimated		500-1200	Calculated from the specific heat and viscosity (page Hg-μ-b) of saturated vapor assuming a constant Prandtl number of 0.73.



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	4-2-1, 12-0-2, 19-13-60	240-842	A total of 111 measurements of enthalpy were made from 32° to 842°F. These experimental data were represented by an equation which was employed to derive a specific heat equation.
Extrapolated	19-13-60	842-1640	Parabolic equation was derived that joined smoothly to the low temperature data.



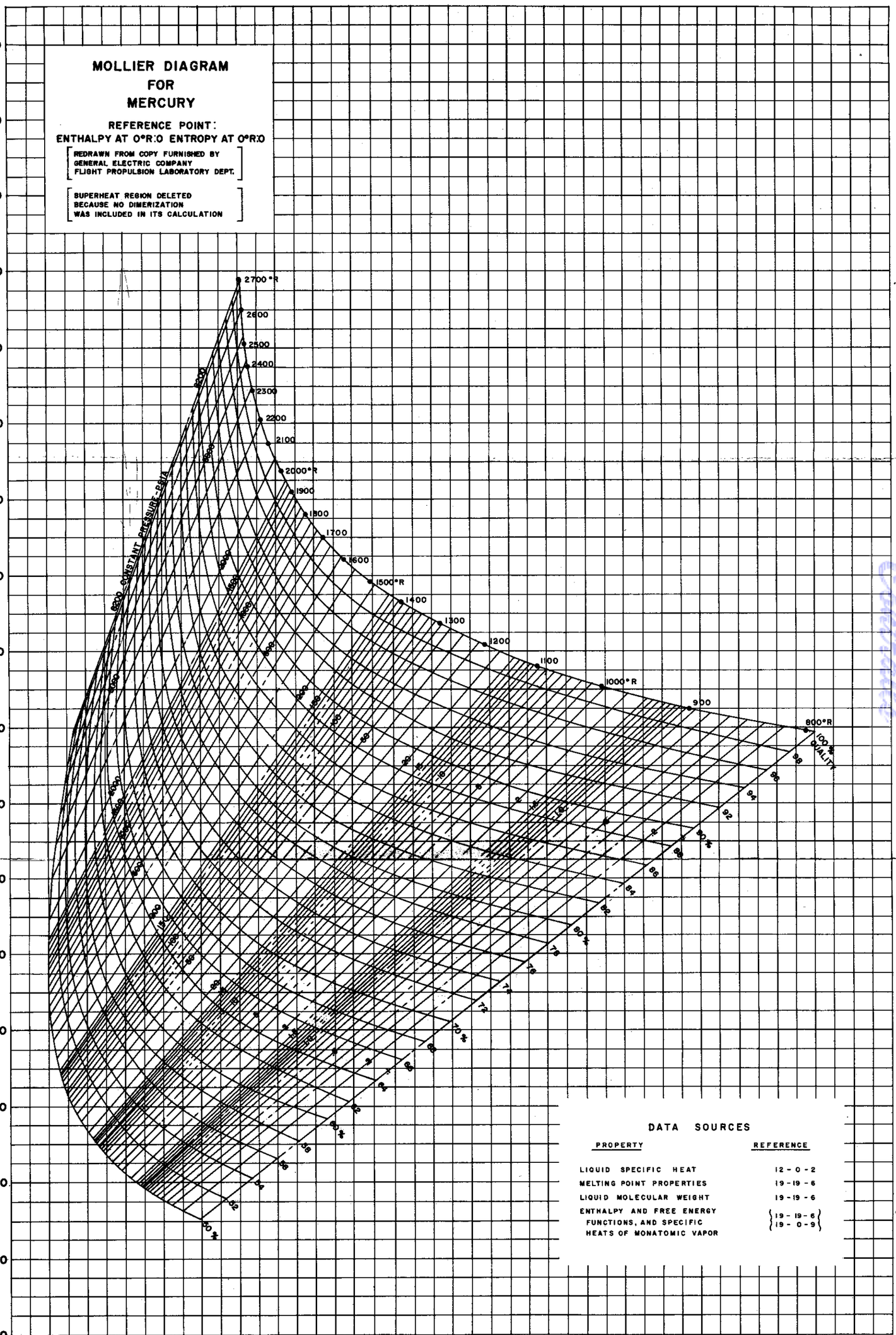
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Estimated and Experimental	19-13-60	440-1640	The heat of vaporization was assumed to vary linearly with temperature and satisfied an experimental value.

MOLLIER DIAGRAM FOR MERCURY

REFERENCE POINT:
ENTHALPY AT 0°R:0 ENTROPY AT 0°R:0

[REDRAWN FROM COPY FURNISHED BY GENERAL ELECTRIC COMPANY FLIGHT PROPULSION LABORATORY DEPT.]

[SUPERHEAT REGION DELETED BECAUSE NO DIMERIZATION WAS INCLUDED IN ITS CALCULATION]

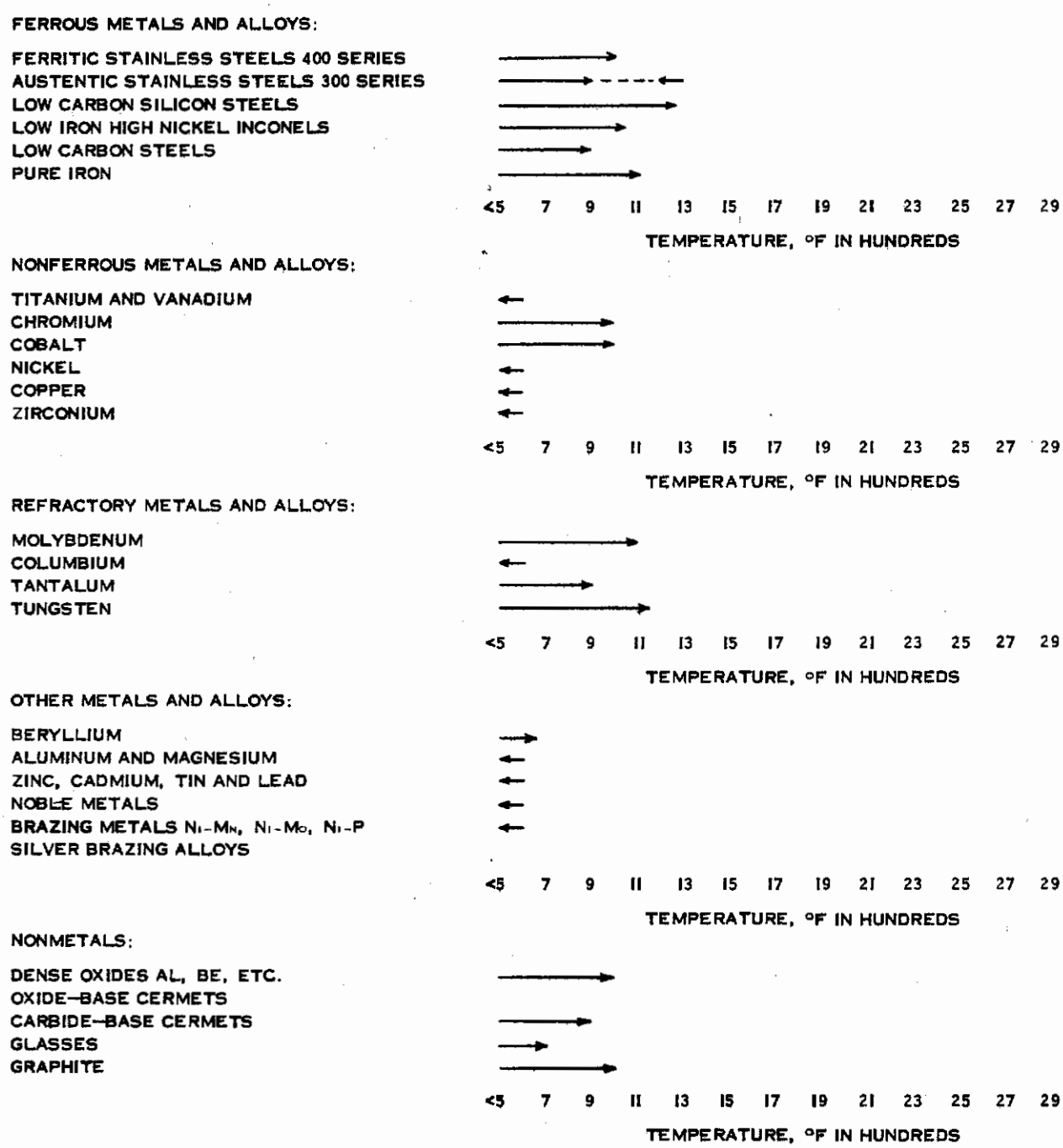


DATA SOURCES

PROPERTY	REFERENCE
LIQUID SPECIFIC HEAT	12 - 0 - 2
MELTING POINT PROPERTIES	19 - 19 - 6
LIQUID MOLECULAR WEIGHT	19 - 19 - 6
ENTHALPY AND FREE ENERGY FUNCTIONS, AND SPECIFIC HEATS OF MONATOMIC VAPOR	19 - 19 - 6 19 - 0 - 9

RESISTANCE OF MATERIALS TO LIQUID MERCURY

(SEE REVERSE SIDE OF SHEET FOR DATA BASIS)



NOTE: RIGHT-HAND ARROW-POINT INDICATES HIGHEST REPORTED TEST TEMPERATURE BELOW RESISTANCE LIMIT OF MATERIAL

LEFT-HAND ARROW-POINT INDICATES LOWEST REPORTED TEST TEMPERATURE ABOVE RESISTANCE LIMIT OF MATERIAL

(SEE FRONT SIDE OF SHEET FOR DATA)

	DATA SOURCE	REMARKS AND BASIS OF DATA
FERROUS METALS AND ALLOYS:		
FERRITIC STAINLESS STEELS 400 SERIES	(616)14-1-60	Reflux capsules (uninhibited)
AUSTENTIC STAINLESS STEELS 300 SERIES	(616)14-1-60, 12-0-2	Reflux capsules (uninhibited) and dynamic
LOW CARBON SILICON STEELS	12-0-2	Survey: dynamic
LOW IRON HIGH NICKEL INCONELS	12-0-2	Survey: static
LOW CARBON STEELS	(616)14-1-60	Reflux capsules (uninhibited)
PURE IRON	12-0-2	Survey
NONFERROUS METALS AND ALLOYS:		
TITANIUM AND VANADIUM	12-0-2	Survey
CHROMIUM	(127)14-1-60	1-1/4 - 2-1/4 Cr - 1/2 Mo: convection and boiling loops: 1500-4000 hrs
COBALT	(616)14-1-60	Reflux capsules (uninhibited)
NICKEL	12-0-2	Survey
COPPER	12-0-2	Survey
ZIRCONIUM	11-0-53	Soluble (16 ppm at 1022°F)
REFRACTORY METALS AND ALLOYS:		
MOLYBDENUM	12-0-2	Survey: dynamic
COLUMBIUM	721	Unknown
TANTALUM	(616)14-1-60	Reflux capsules (uninhibited)
TUNGSTEN	12-0-2	Survey: dynamic
OTHER METALS AND ALLOYS:		
BERYLLIUM	12-0-2	Survey: static
ALUMINUM AND MAGNESIUM	12-0-2	Survey
ZINC, CADMIUM, TIN AND LEAD	12-0-2	Survey
NOBLE METALS	12-0-2	Survey
BRAZING METALS $Ni\text{-}Mn$, $Ni\text{-}Mo$, $Ni\ P$	12-0-2	Survey
SILVER BRAZING ALLOYS		
NONMETALS:		
DENSE OXIDES AL, BE, ETC.	721	Unknown
OXIDE–BASE CERMETS		
CARBIDE–BASE CERMETS	(616)14-1-60	TiC, WC pure carbides: reflux capsules (uninhibited)
GLASSES	12-0-2	Survey
GRAPHITE	721	Unknown

e. Data Sources for Mercury.

Code No.	Source
3-12-60	Chem. Eng. News, pp 53-65 (December 26, 1960).
4-2-1	Douglas, T. B., Ball, A. F., and Ginnings, D. C., Jour. Res. N. B. S., 46, 334 (1951).
4-7-1	Ditchburn, R. W. and Gilmour, J. C., Reviews of Modern Physics, 13, 310 (1941).
5-0-7	Epstein, L. F., Chem. Eng. Prog. Symp. Series - Liquid Metals Technology, 53, No. 20, 67-81 (1957).
5-16-100	Epstein, L. F., and Powers, M. D., AECU-1893.
5-19-5	Ewing, C. T., Seebold, R. E., Grand, J. A. and Miller, R. R., J. Phys. Chem., 59, 524 (1955)
8-0-8	Hodgman, C. D., Editor, "Handbook of Chemistry and Physics," Cleveland, Chemical Rubber Publishing Co., 1958.
11-0-53	Koenig, R. F., KAPL-982, October 1, 1953.
11-0-60	Kiser, R. W., Dept. of Chemistry, Kansas State Univ., TID-6142, June 20, 1960.
11-2-9	Kutateladze, S. S., Borishanskii, V. M., Novikov, I. I., and Fedynskii, O. S., "Liquid-Metal Transfer Media," Atomnaia Energiia, Supp. No. 2, 1958, Translated by Consultants Bureau, Inc., New York, 1959.
12-0-2	Lyon, R. N., Editor, "Liquid-Metals Handbook," Second Ed., Washington, Atomic Energy Commission, Dept. of the Navy, 1952.
13-19-60	Makansi, M., Selke, W. A., and Bonilla, C. F., Chem. and Eng. Data, 5, No. 4, 441-52, (1960).

Code No.	Source
14-1-60	Notes of "NASA-AEC Liquid Metals Corrosion Meeting, December 7-8, 1960, Washington, D. C. (Proceedings published as NASA TN D-769, February 1961).
19-0-7	Stull, D. R., Ind. Eng. Chem., 39, No. 4, 517 (1947).
19-13-60	Shapiro, A., and Meisl, C. J., General Electric Co., Flight Propulsion Laboratory Dept., Report No. R 60 FPD358-A, November 9, 1960.
19-19-6	Stull, D. R., and Sinke, G. C., "Thermodynamic Properties of the Elements," Washington, American Chemical Society, 1956.
127	Brookhaven National Laboratory
616	Thompson-Ramo-Wooldridge
721	AiResearch Manufacturing Co. of Arizona

CESIUM

a. General Discussion of Cesium. Cesium is a soft, silver-white alkali metal with properties nearly the same as those of rubidium. It is the most volatile and dense of the alkali metals, and its vapor exhibits the lowest ionization potential of the liquid metals. Among the alkali metals, cesium is the most reactive with oxygen and water and the least reactive with nitrogen and hydrogen. It ignites spontaneously in dry air, and reacts violently with water, igniting the liberated hydrogen. Because of its chemical reactivity, it is usually immersed in a dry saturated hydrocarbon liquid or an inert gas atmosphere during storage and handling.

Cesium is known to form alloys with rubidium, bismuth and gold. It forms an alloy compound with sodium (Na_2Cs). Its compatibility with construction materials should be similar to that of rubidium.

Cesium is available only in small quantities, and 99+% cesium can be purchased for $100 to $585 per pound in one-pound to 25-pound quantities.

b. Synopsis of Properties of Cesium

Property	Value	Temp (°F)	Data Basis	Reference
Physical:				
Atomic Weight	132.91	---	Survey	19-19-6
Melting Point, °F	83	---	Survey	12-0-2
Boiling Point, °F	1260	---	Experimental	Page Cs-VP-a
Density of Solid, lb/ft^3	116.931	68	Handbook	8-0-8
Density of Liquid, lb/ft^3	104.8	B. P.	Extrapolated	Page Cs-ρ-a
Density of Vapor, lb/ft^3	0.114	B. P.	Theoretical	Page Cs-ρ-a
Viscosity of Liquid, lb/ft hr	1.66	M. P.	Extrapolated	Page Cs-μ-a
Viscosity of Vapor, lb/ft hr	0.0649	B. P.	Theoretical	Page Cs-μ-b
Surface Tension, lb/ft	0.0027	M. P.	Experimental	20-0-4
Thermal:				
Thermal Conductivity of Liquid, BTU/hr ft °F	10.65	M. P.	Calculated	12-0-2
Thermal Conductivity of Vapor, BTU/hr ft °F	0.0033	B. P.	Estimated	Page Cs-k-a
Specific Heat of Liquid, BTU/lb °F	0.0572	B. P.	Extrapolated	19-13-60
Specific Heat of Vapor BTU/lb °F	0.0372	B. P.	Theoretical	Page Cs-C-a
Latent Heat of Fusion,	6.907	M. P.	Survey	19-19-6
Latent Heat of Vaporization, BTU/lb	211.2	B. P.	Theoretical	Page Cs-ΔH-a
Electrical and Magnetic:				
Resistivity, μ ohm-inch	14.36	M. P.	Extrapolated	12-0-2
Ionization Potential, volts	3.893	---	Experimental	11-0-60
Magnetic Susceptibility, fps electromagnetic units/unitmass	-0.0421	64.4 sol	Handbook	8-0-8
Thermal Neutron Cross Section (2200 m/s):				
Absorption, barns	29.0 ± 1.5		Handbook	8-0-8
Scattering, barns	20.0 ± 10		Handbook	8-0-8

c. Property Tables for Cesium

Basis of data from Reference 19-13-60: Thermodynamic properties of equilibrium vapor mixtures were derived by machine computation with conventional relations, assuming the individual monomer and dimer species to be ideal gases. The equilibrium specific heat was then determined by differentiation. The frozen specific heat was computed by adding the contributions of the individual species. Free energies of the monatomic and diatomic forms of the vapor were used to calculate the dimerization equilibrium constant, hence, no added assumptions were required concerning heat of dissociation. Iterations on vapor pressure were made until the ratio of the heat of vaporization to temperature became identical to the entropy of vaporization. Therefore, all data from this reference are internally consistent.

PHYSICAL PROPERTIES OF CESIUM
Saturated Phases

(Ref: 19-13-60)

Temp (°R)	Equilibrium Vapor Molecular Weight	Vapor Pressure (psia)	Liquid Specific Volume (ft^3/lb)	Vapor Specific Volume (ft^3/lb)	Equilibrium Sonic Velocity (ft/sec)	Frozen Sonic Velocity (ft/sec)
1300	137.422	8.0137×10^{-1}	9.2232×10^{-3}	1.2669×10^{2}	675.4	876.7
1400	138.745	1.8925×10^{0}	9.2996×10^{-3}	5.7220×10^{1}	695.0	902.9
1500	140.169	3.9520×10^{0}	9.3760×10^{-3}	2.9060×10^{1}	713.0	927.1
1600	141.668	7.4718×10^{0}	9.4524×10^{-3}	1.6222×10^{1}	729.7	949.5
1700	143.110	1.3125×10^{1}	9.5288×10^{-3}	9.7128×10^{0}	746.0	971.0
1800	144.480	2.1648×10^{1}	9.6052×10^{-3}	6.1762×10^{0}	761.7	991.7
1900	145.884	3.3585×10^{1}	9.6816×10^{-3}	4.1618×10^{0}	776.7	1011.1
2000	147.220	4.9722×10^{1}	9.7580×10^{-3}	2.9322×10^{0}	791.3	1029.9
2100	148.446	7.0821×10^{1}	9.8344×10^{-3}	2.1437×10^{0}	805.9	1048.5
2200	149.560	9.7574×10^{1}	9.9108×10^{-3}	1.6179×10^{0}	820.3	1066.8
2300	150.564	1.3059×10^{2}	9.9872×10^{-3}	1.2554×10^{0}	834.7	1085.0
2400	151.564	1.6985×10^{2}	1.0064×10^{-2}	1.0005×10^{0}	848.7	1102.5
2500	152.544	2.1545×10^{2}	1.0140×10^{-2}	8.1633×10^{-1}	862.3	1119.5
2600	153.435	2.6768×10^{2}	1.0216×10^{-2}	6.7936×10^{-1}	875.9	1136.3
2700	154.092	3.2739×10^{2}	1.0293×10^{-2}	5.7438×10^{-1}	890.0	1153.9

THERMAL PROPERTIES OF CESIUM

Saturated Phases

(Ref: 19-13-60)

Temperature (°R)	Specific Heat of Equilibrium Vapor (BTU/lb °R)	Frozen Specific Heat of Vapor (BTU/lb °R)	Ratio of Frozen Specific Heats of Vapor	Specific Heat of Liquid (BTU/lb °R)
1300	0.0633	0.0372	1.634	0.0572
1400	0.0653	0.0372	1.625	0.0572
1500	0.0666	0.0372	1.616	0.0572
1600	0.0671	0.0372	1.606	0.0572
1700	0.0669	0.0371	1.597	0.0572
1800	0.0662	0.0371	1.588	0.0572
1900	0.0653	0.0371	1.579	0.0572
2000	0.0642	0.0371	1.571	0.0572
2100	0.0630	0.0371	1.563	0.0572
2200	0.0616	0.0371	1.557	0.0572
2300	0.0603	0.0372	1.550	0.0572
2400	0.0590	0.0372	1.544	0.0572
2500	0.0578	0.0372	1.538	0.0572
2600	0.0567	0.0372	1.533	0.0572
2700	0.0556	0.0373	1.529	0.0572

THERMODYNAMIC PROPERTIES OF CESIUM
Saturated Phases

(Ref: 19-13-60)

Temperature (°R)	Enthalpy of Liquid $(H - H_o)_L$ (BTU/lb)	Enthalpy of Vapor $(H - H_o)_V$ (BTU/lb)	Entropy of Liquid S_L (BTU/lb °R)	Entropy of Vapor S_V (BTU/lb °R)
1300	75.8	301.5	0.2150	0.3886
1400	81.5	303.8	0.2193	0.3781
1500	87.2	306.1	0.2232	0.3691
1600	92.9	308.3	0.2269	0.3615
1700	98.7	310.6	0.2304	0.3550
1800	104.4	313.0	0.2337	0.3495
1900	110.1	315.3	0.2367	0.3448
2000	115.8	317.8	0.2397	0.3407
2100	121.5	320.4	0.2425	0.3371
2200	127.3	323.1	0.2451	0.3341
2300	133.0	325.9	0.2477	0.3315
2400	138.7	328.7	0.2501	0.3293
2500	144.4	331.6	0.2524	0.3273
2600	150.1	334.5	0.2547	0.3256
2700	155.9	337.7	0.2568	0.3242

THERMODYNAMIC PROPERTIES OF CESIUM

Liquid Phase: $H^{\circ}_{536.67} - H^{\circ}_{o} = 3,274$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^{\circ} - H^{\circ}_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^{\circ} - H^{\circ}_{536.67})/T$ (BTU/lb mole °R)
900	3679	25.78	21.70
1080	5047	27.17	22.50
1260	6415	28.34	23.25
1440	7783	29.36	23.96
1620	9151	30.26	24.62

THERMODYNAMIC PROPERTIES OF CESIUM

Ideal Monatomic Gas: $H^{\circ}_{536.67} - H^{\circ}_{0} = 2,666$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^{\circ} - H^{\circ}_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^{\circ} - H^{\circ}_{536.67})/T$ (BTU/lb mole °R)
900	1805	44.51	42.51
1080	2700	45.42	42.92
1260	3593	46.18	43.33
1440	4487	46.85	43.74
1620	5382	47.43	44.11
1800	6277	47.96	44.48
1980	7171	48.43	44.81
2160	8064	48.86	45.13
2340	8959	49.26	45.44
2520	9855	49.63	45.72
2700	10751	49.97	45.99
2880	11648	50.29	46.25
3060	12548	50.60	46.50
3240	13451	50.88	46.73
3420	14360	51.16	46.97
3600	15275	51.42	47.18

THERMODYNAMIC PROPERTIES OF CESIUM

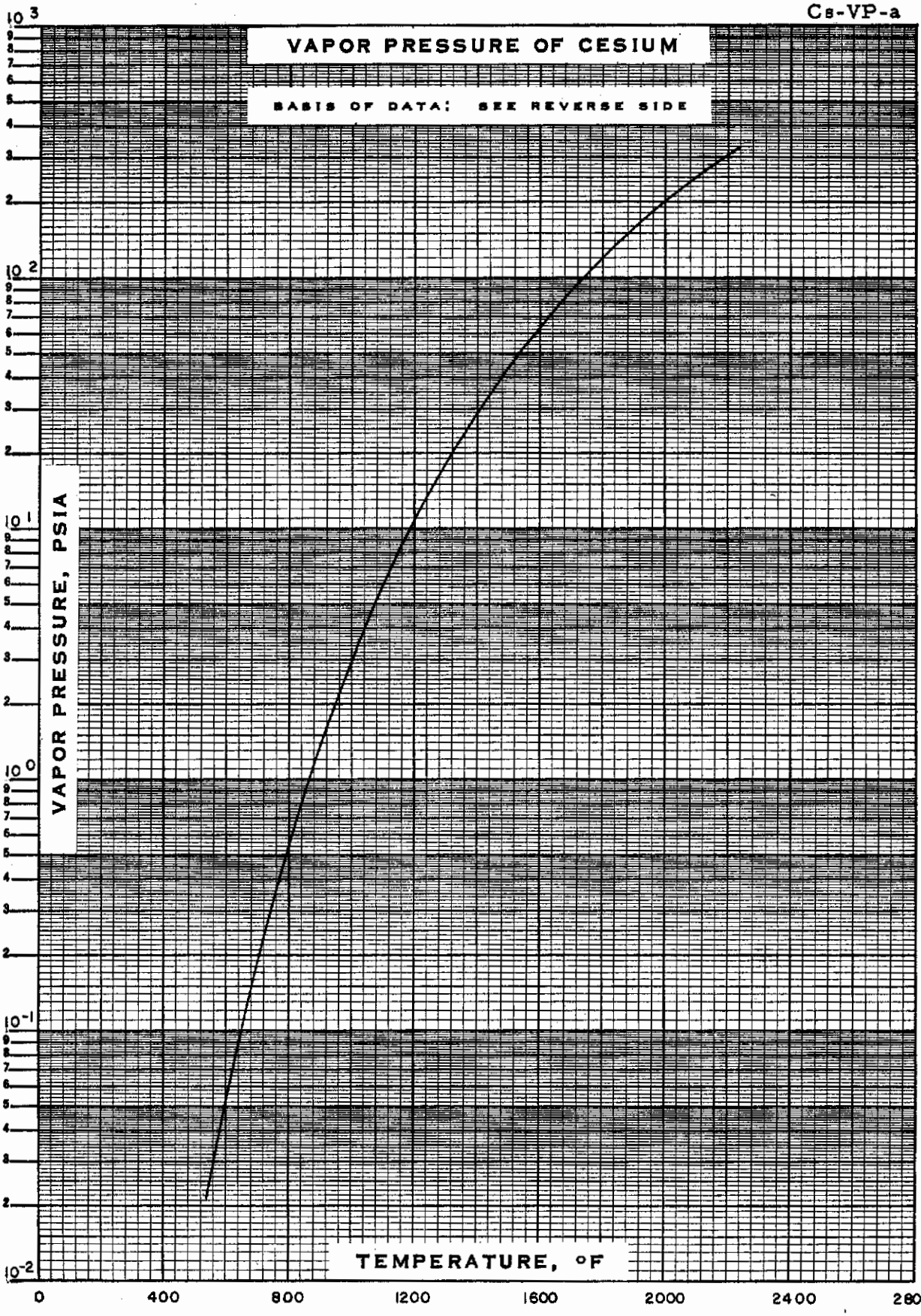
Ideal Diatomic Gas: $H^\circ_{536.67} - H^\circ_0 = 4,743$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^\circ - H^\circ_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^\circ - H^\circ_{536.67})/T$ (BTU/lb mole °R)
900	3334	72.60	68.90
1080	5000	74.28	69.65
1260	6674	75.72	70.43
1440	8361	76.97	71.17
1680	10066	78.09	71.88
1800	11783	79.09	72.55
1980	13495	80.00	73.19
2160	15239	80.84	73.79
2340	16997	81.62	74.36
2520	18745	82.34	74.91
2700	20504	83.01	75.42

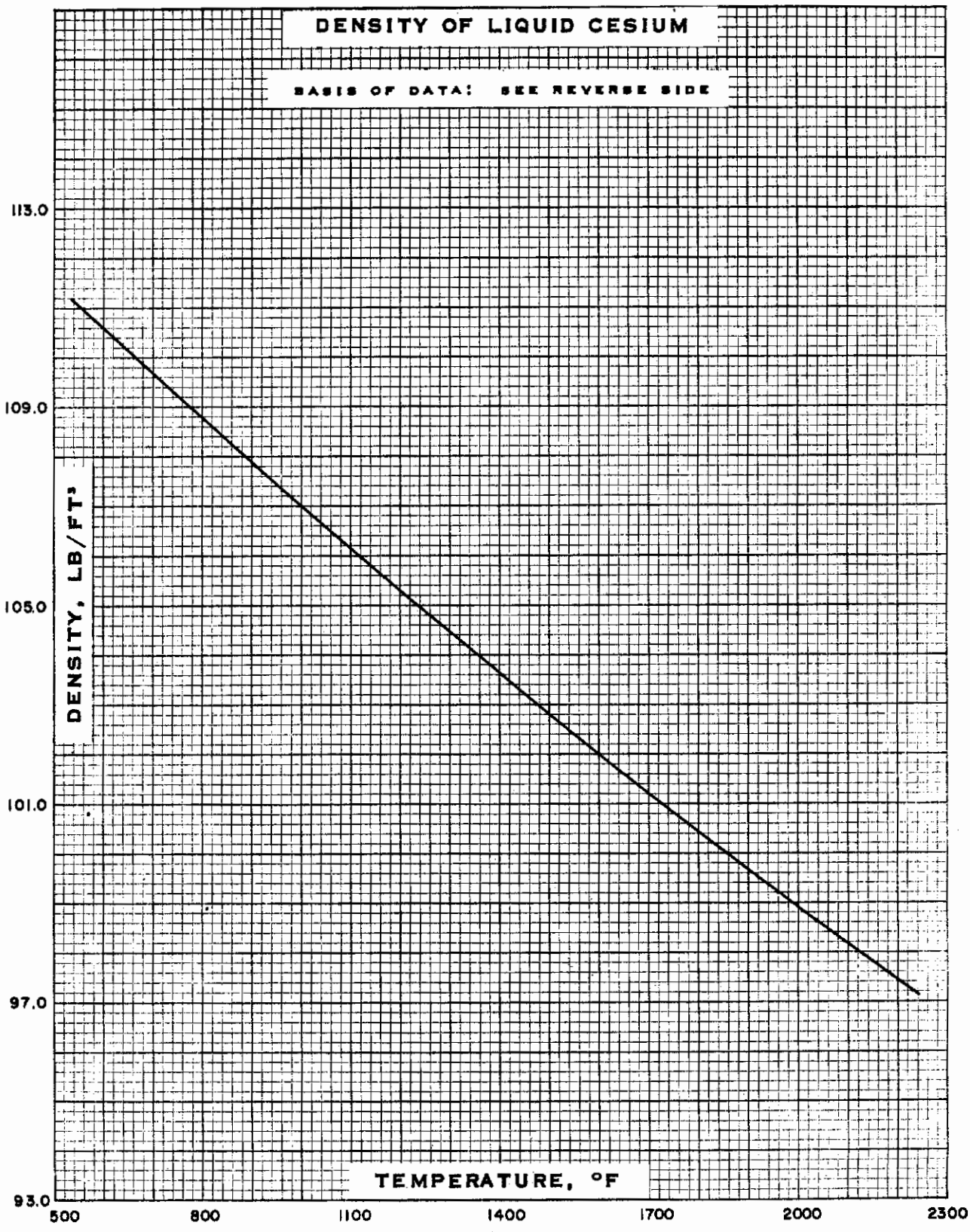
d. Working Charts for Cesium

Cs-VP-a



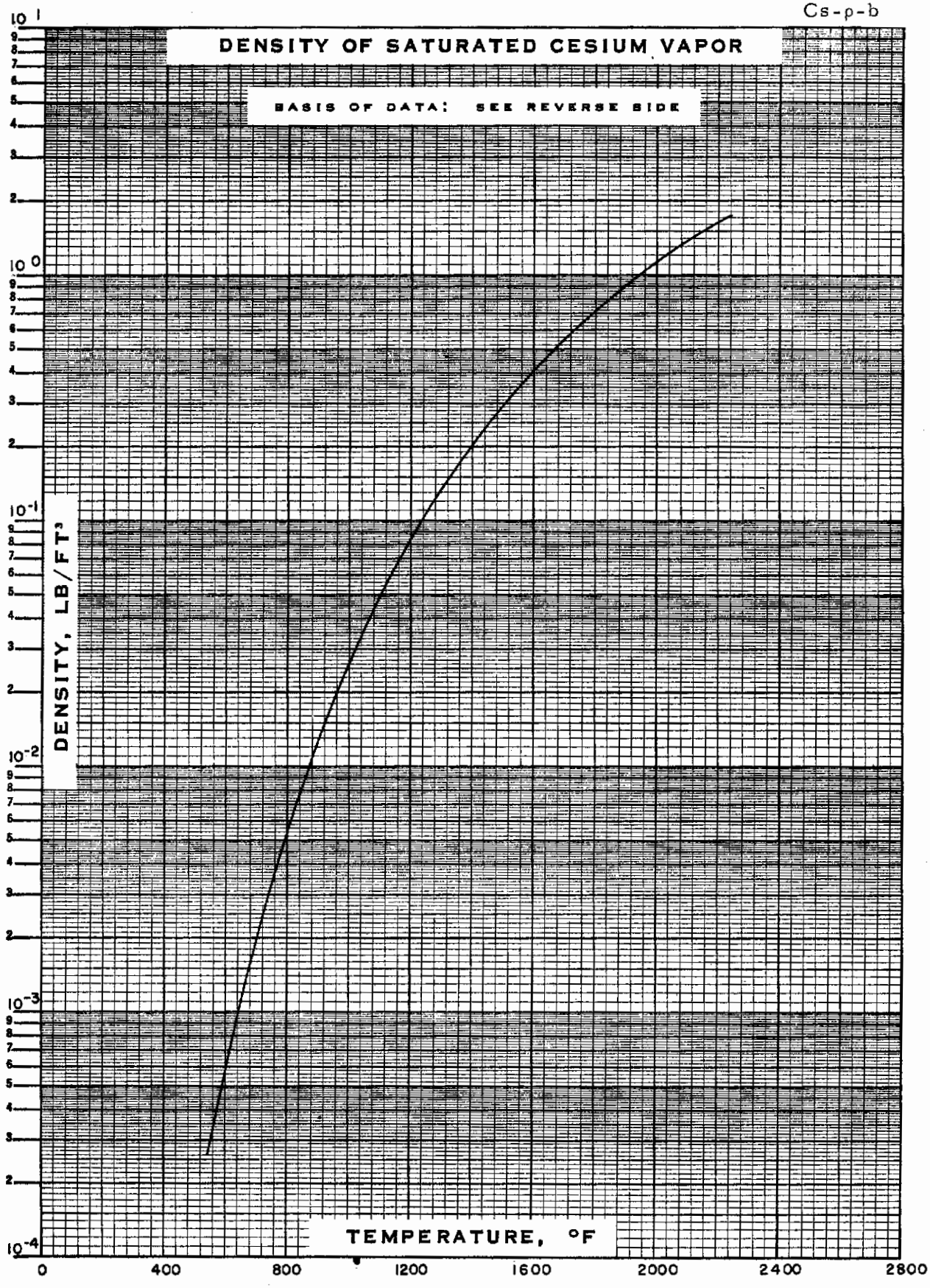
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	19-19-6	Boiling point	Survey
Semi-theoretical	19-13-60	540-2240	Experimental values were theoretically adjusted to yield consistent thermodynamic data.

Cs-ρ-a



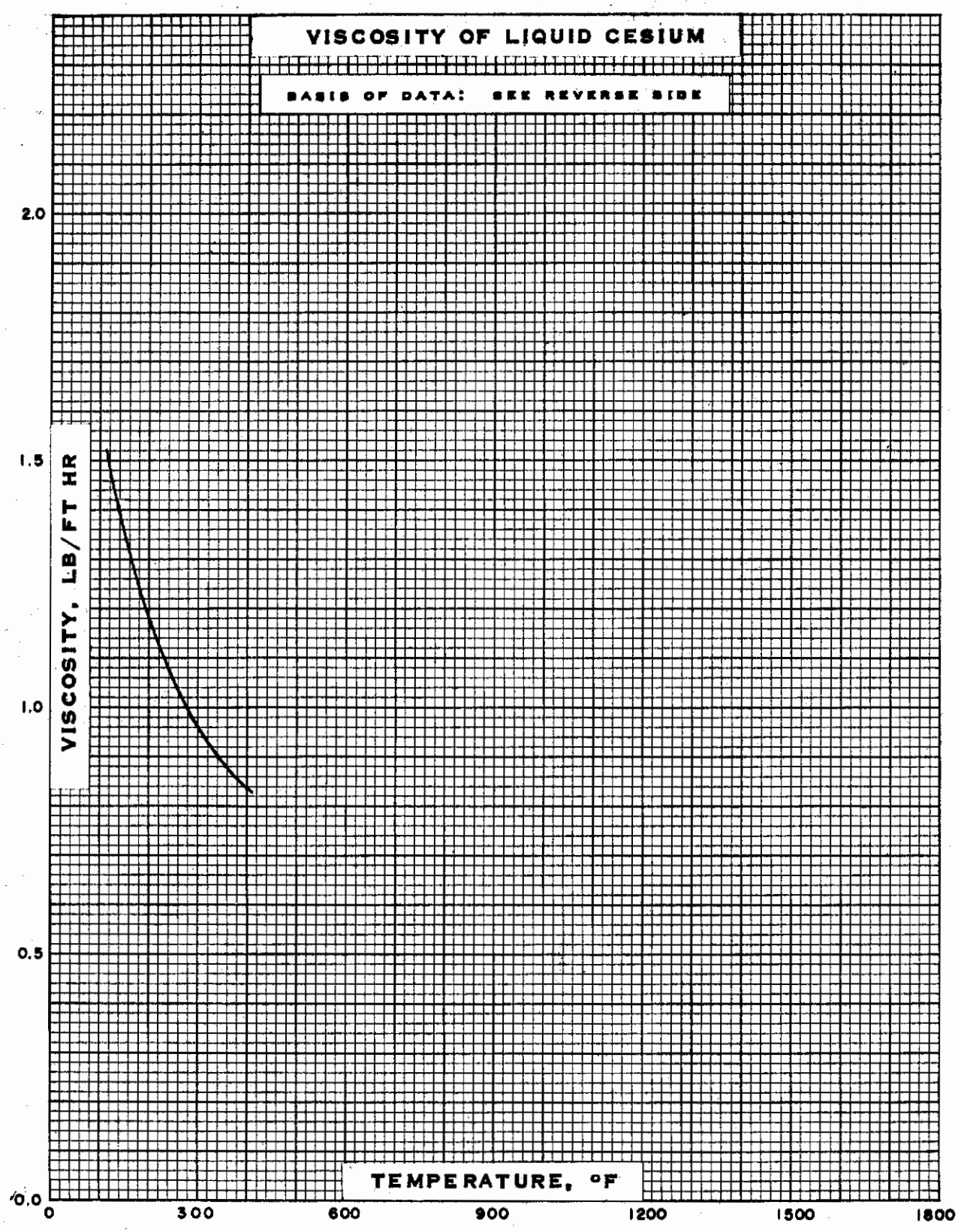
WADD TR 61-96

Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Extrapolated	19-13-60	540-2240	The density of cesium was given in (12-0-2) at 82°F and it was assumed that the density change with temperature was the same as that of sodium and potassium.



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	19-13-60	540-2240	The specific volume of the vapor mixture was calculated from the perfect gas law.

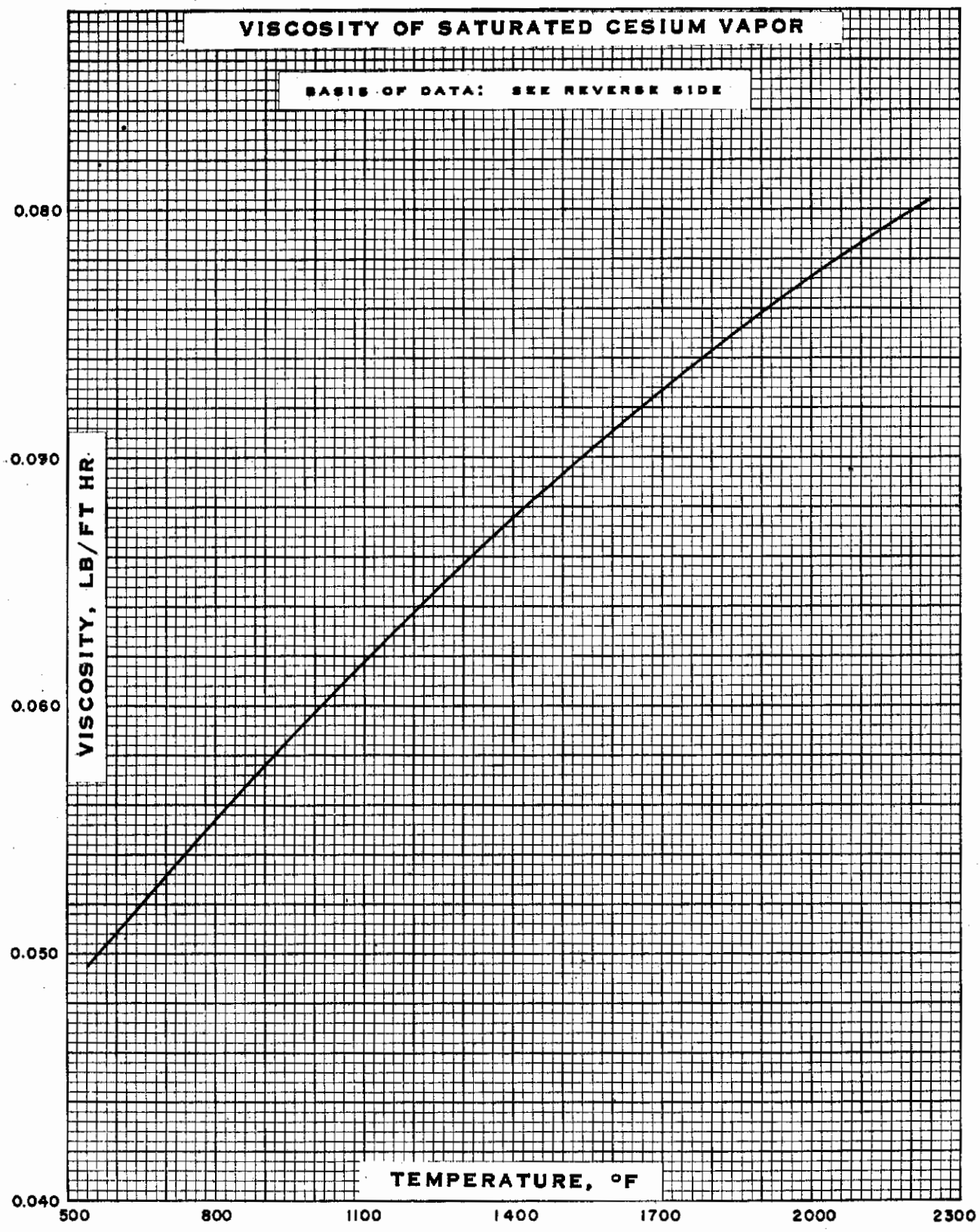
Cs-μ-a



WADD TR 61-96

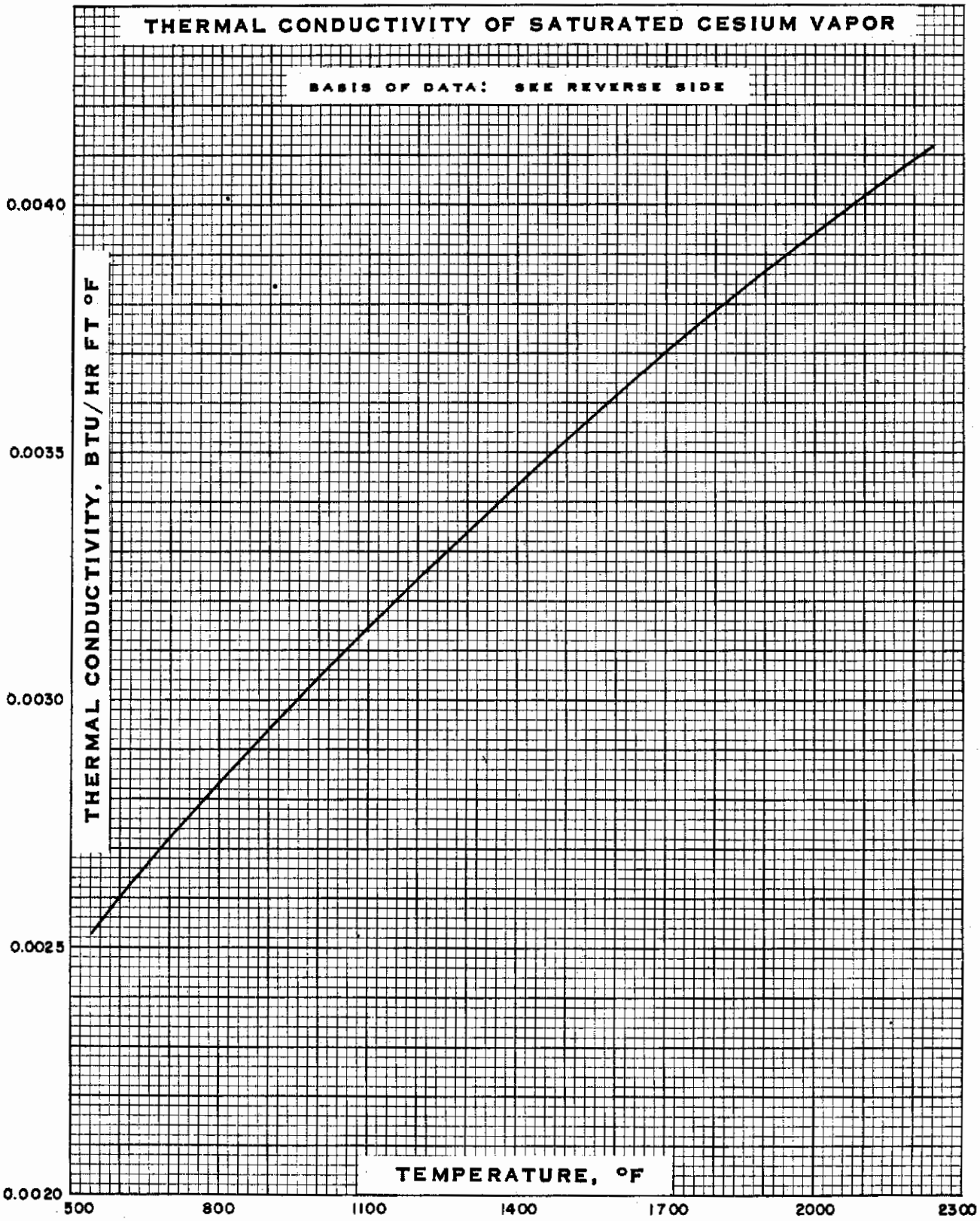
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	1-4-52, 12-0-2	110-410	The oscillating-sphere method was applied to observe the viscosity of cesium. The purity of the cesium was approximately 99.8%. The absolute accuracy is estimated as not worse than 1 part in 200. The error due to impurity is probably less than 1%.

Cs-μ-b



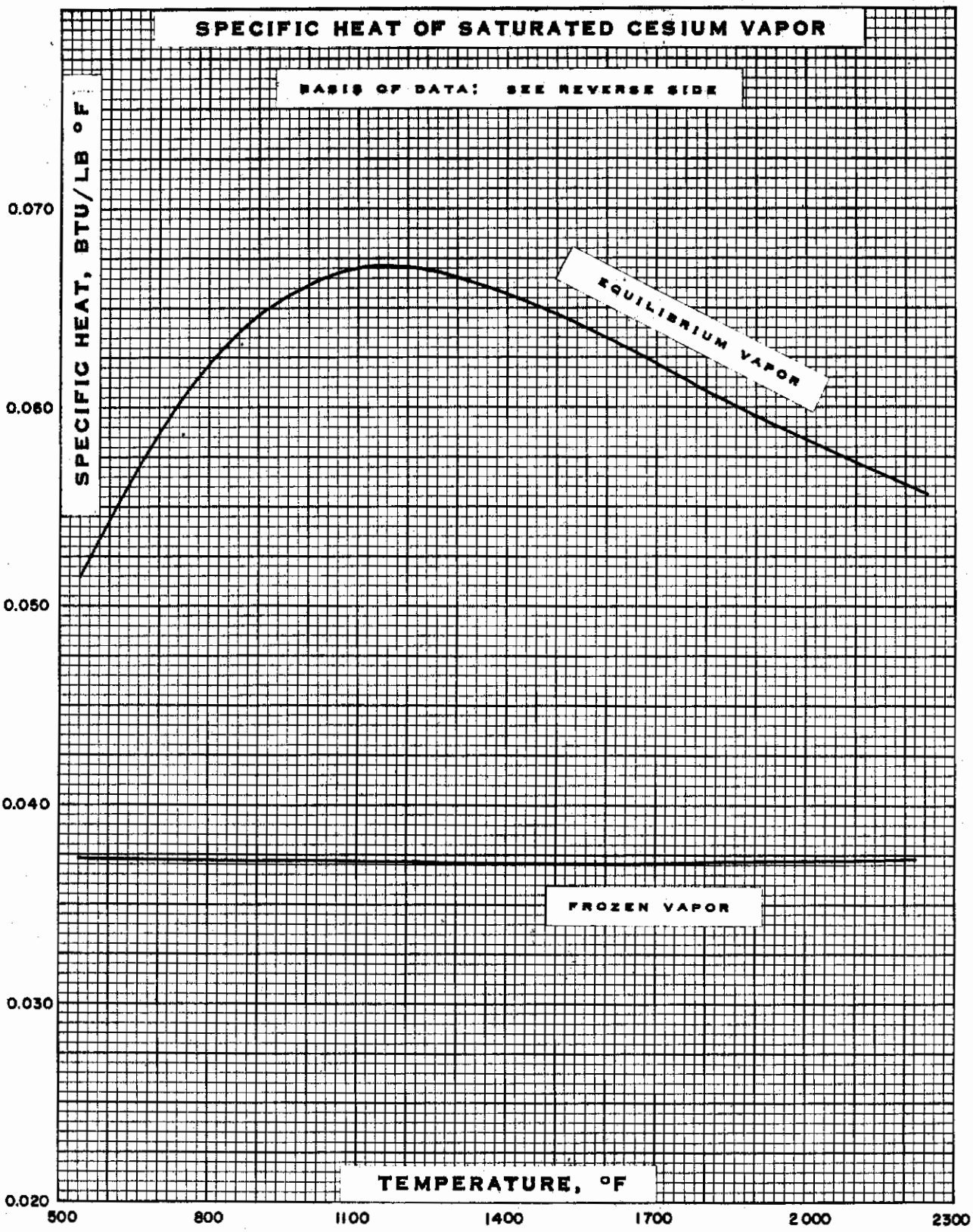
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	23-4-61	540-2240	Computed for variable molecular weight saturated vapor (page Cs-P-1) using new equation for gas viscosity.

Cs-k-a



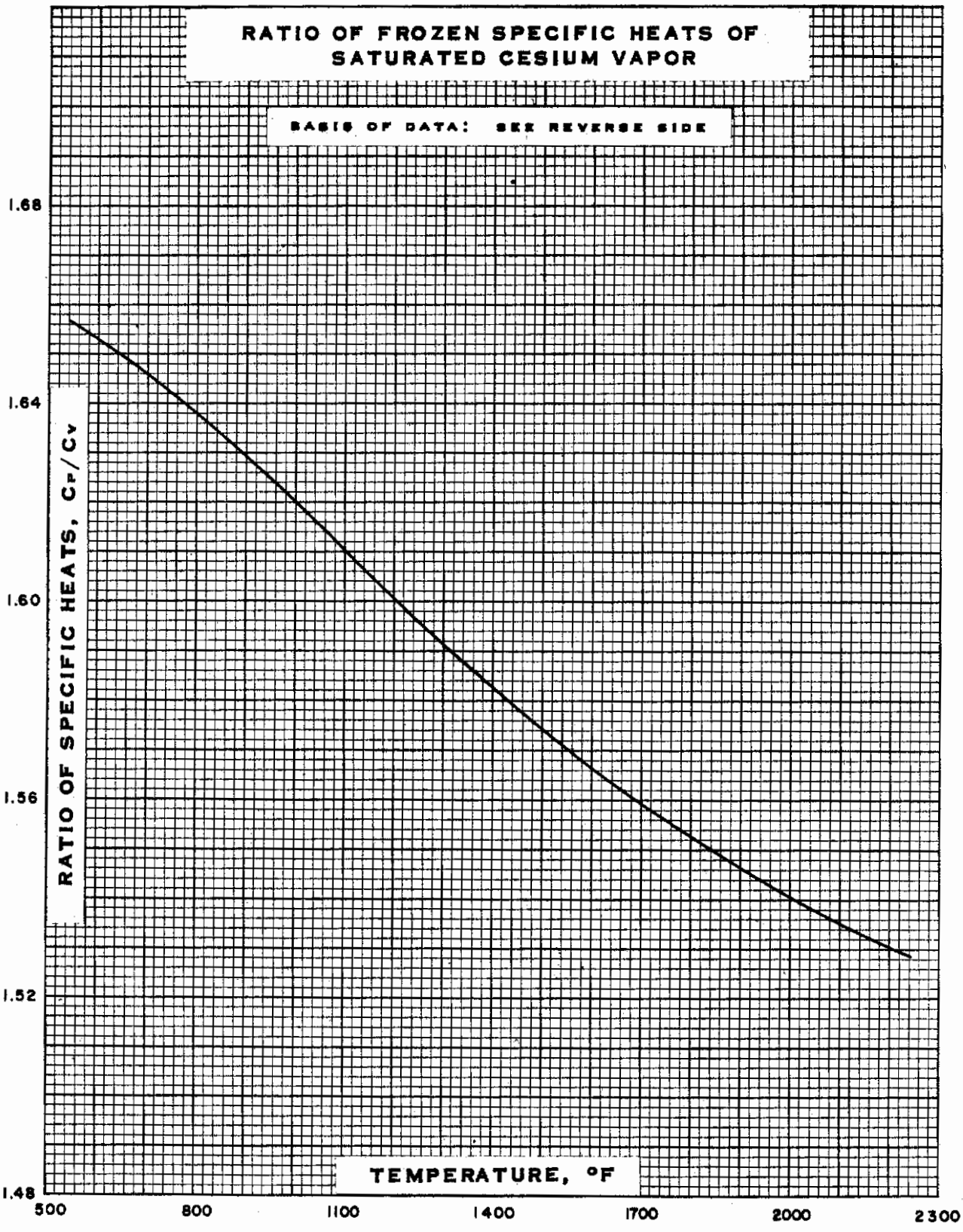
WADD TR 61-96

Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Estimated		540-2240	Calculated from the frozen specific heat (page Cs-C-a) and viscosity (page Cs-μ-b) of saturated vapor assuming a constant Prandtl No. of 0.73.



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	19-13-60	540-2240	Two specific heats were calculated for rubidium vapor: (1) The frozen specific heat is a state point property calculated by adding the separate contributions of the monatomic and diatomic vapors for a given equilibrium composition. (2) The equilibrium specific heat applies to the rigorous definition of specific heat, and includes the energy required to alter the degree of equilibrium dissociation.

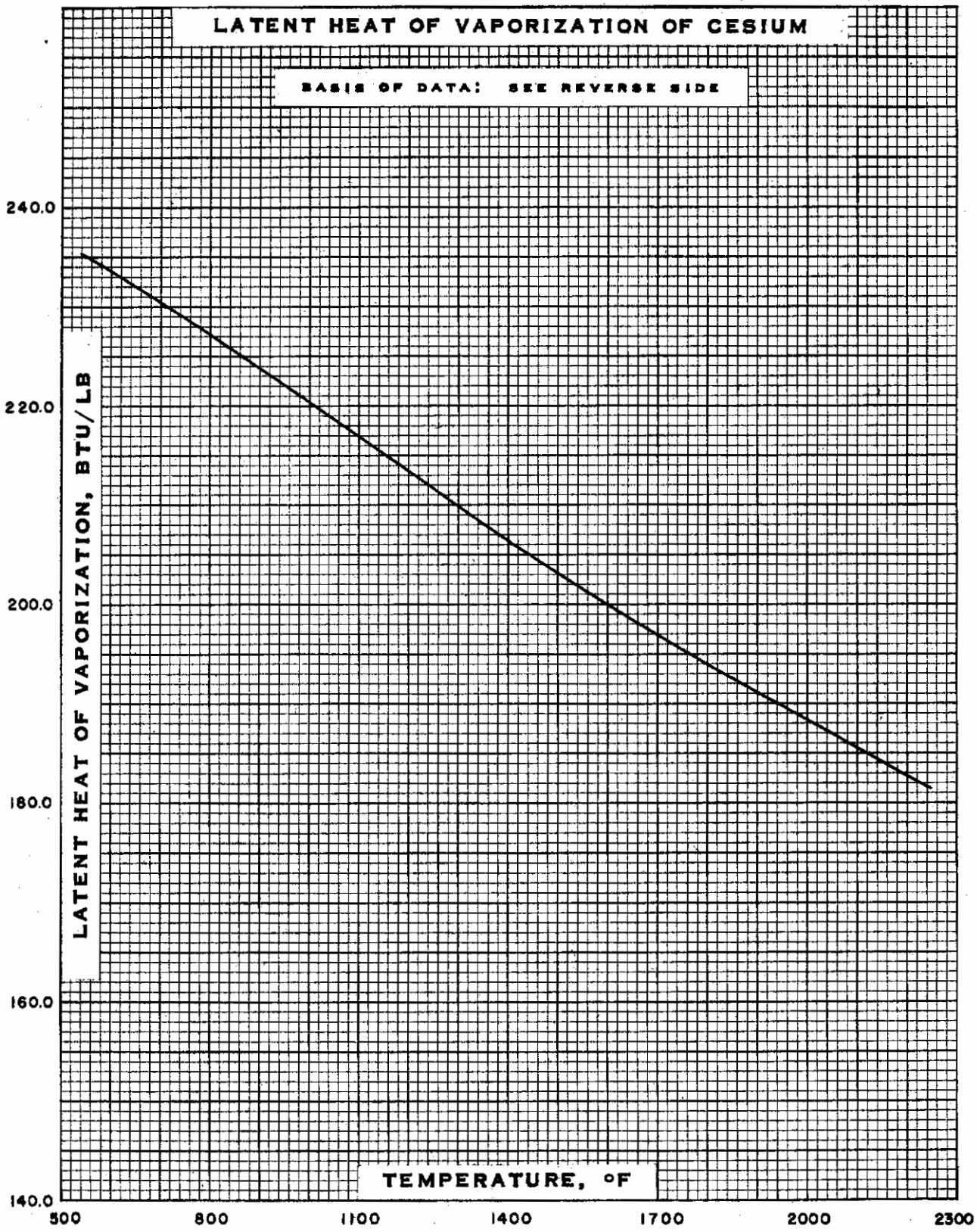
Cs-γ-a



WADD TR 61-96

Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	19-13-60	540-2240	Ratio of the frozen specific heat at constant pressure to the frozen specific heat at constant volume.

Cs-ΔH-a



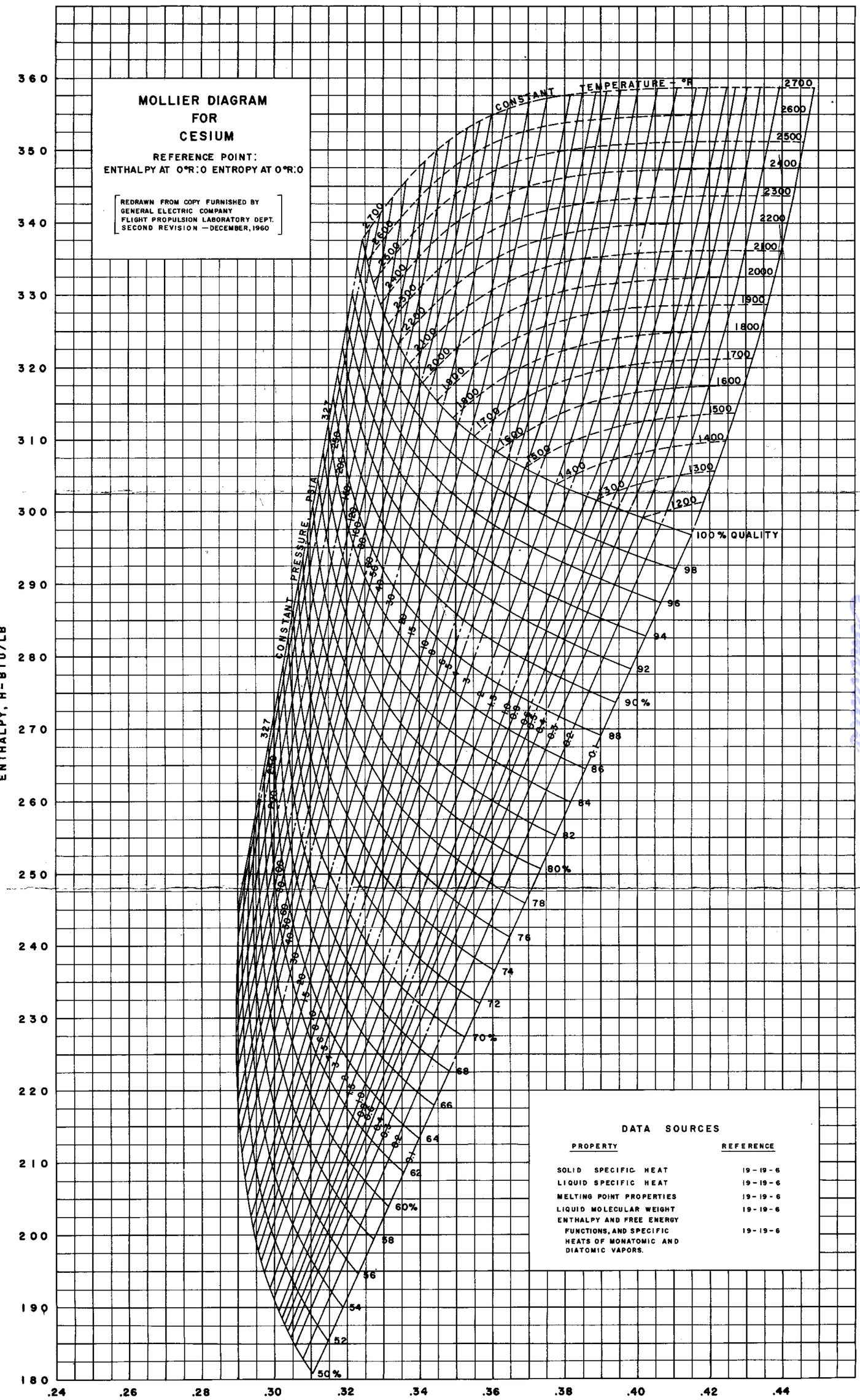
Cs-ΔH-a (basis)

Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	19-13-60	540-2240	

MOLLIER DIAGRAM FOR CESIUM

REFERENCE POINT:
ENTHALPY AT 0°R: 0 ENTROPY AT 0°R: 0

[REDRAWN FROM COPY FURNISHED BY GENERAL ELECTRIC COMPANY FLIGHT PROPULSION LABORATORY DEPT. SECOND REVISION — DECEMBER, 1960]



DATA SOURCES

PROPERTY	REFERENCE
SOLID SPECIFIC HEAT	19-19-6
LIQUID SPECIFIC HEAT	19-19-6
MELTING POINT PROPERTIES	19-19-6
LIQUID MOLECULAR WEIGHT	19-19-6
ENTHALPY AND FREE ENERGY FUNCTIONS, AND SPECIFIC HEATS OF MONATOMIC AND DIATOMIC VAPORS.	19-19-6

RESISTANCE OF MATERIALS TO LIQUID CESIUM

(SEE REVERSE SIDE OF SHEET FOR DATA BASIS)

FERROUS METALS AND ALLOYS:

FERRITIC STAINLESS STEELS 400 SERIES
AUSTENTIC STAINLESS STEELS 300 SERIES
LOW CARBON SILICON STEELS
LOW IRON HIGH NICKEL INCONELS
LOW CARBON STEELS
PURE IRON

<5 7 9 11 13 15 17 19 21 23 25 27 29

TEMPERATURE, °F IN HUNDREDS

NONFERROUS METALS AND ALLOYS:

TITANIUM AND VANADIUM
CHROMIUM
COBALT
NICKEL ←
COPPER
ZIRCONIUM

<5 7 9 11 13 15 17 19 21 23 25 27 29

TEMPERATURE, °F IN HUNDREDS

REFRACTORY METALS AND ALLOYS:

MOLYBDENUM
COLUMBIUM
TANTALUM
TUNGSTEN

<5 7 9 11 13 15 17 19 21 23 25 27 29

TEMPERATURE, °F IN HUNDREDS

OTHER METALS AND ALLOYS:

BERYLLIUM
ALUMINUM AND MAGNESIUM
ZINC, CADMIUM, TIN AND LEAD
NOBLE METALS
BRAZING METALS Ni-Mn, Ni-Mo, Ni-P
SILVER BRAZING ALLOYS

<5 7 9 11 13 15 17 19 21 23 25 27 29

TEMPERATURE, °F IN HUNDREDS

NONMETALS:

DENSE OXIDES AL, BE, ETC.
OXIDE–BASE CERMETS
CARBIDE–BASE CERMETS
GLASSES
GRAPHITE

<5 7 9 11 13 15 17 19 21 23 25 27 29

TEMPERATURE, °F IN HUNDREDS

NOTE: RIGHT-HAND ARROW-POINT INDICATES HIGHEST REPORTED TEST TEMPERATURE BELOW RESISTANCE LIMIT OF MATERIAL

LEFT-HAND ARROW-POINT INDICATES LOWEST REPORTED TEST TEMPERATURE ABOVE RESISTANCE LIMIT OF MATERIAL

(SEE FRONT SIDE OF SHEET FOR DATA)

	DATA SOURCE	REMARKS AND BASIS OF DATA
FERROUS METALS AND ALLOYS:		
FERRITIC STAINLESS STEELS 400 SERIES		
AUSTENTIC STAINLESS STEELS 300 SERIES		
LOW CARBON SILICON STEELS		
LOW IRON HIGH NICKEL INCONELS		
LOW CARBON STEELS		
PURE IRON		
NONFERROUS METALS AND ALLOYS:		
TITANIUM AND VANADIUM		
CHROMIUM		
COBALT		
NICKEL	(831)14-1-60	Capsules
COPPER		
ZIRCONIUM		
REFRACTORY METALS AND ALLOYS:		
MOLYBDENUM		
COLUMBIUM		
TANTALUM		
TUNGSTEN		
OTHER METALS AND ALLOYS:		
BERYLLIUM		
ALUMINUM AND MAGNESIUM		
ZINC, CADMIUM, TIN AND LEAD		
NOBLE METALS		
BRAZING METALS Ni-Mn, Ni-Mo. Ni-P		
SILVER BRAZING ALLOYS		
NONMETALS:		
DENSE OXIDES AL, BE, ETC.		
OXIDE–BASE CERMETS		
CARBIDE–BASE CERMETS		
GLASSES		
GRAPHITE		

e. Data Sources for Cesium

Code No.	Source
1-4-52	Andrade, E. N., and Dobbs, E. R., Proc. Roy. Soc. (London), 211, 12 (1952).
3-2-61	Chem. Eng. News, p 67 (Feb. 13, 1961).
3-12-60	Chem. Eng. News, pp 53-65 (Dec. 26, 1960).
8-0-8	Hodgman, C. D., Editor, "Handbook of Chemistry and Physics," Cleveland, Chemical Rubber Publishing Co., 1958.
11-0-60	Kiser, R. W., Dept. of Chemistry, Kansas State Univ., TID-6142, June 20, 1960.
12-0-2	Lyon, R. N., Editor, "Liquid-Metals Handbook," Second Ed., Washington, Atomic Energy Commission, Dept. of the Navy, 1952.
14-1-60	Notes of NASA-AEC Liquid Metals Corrosion Meeting, Dec. 7-8, 1960, Washington, D. C. (Proceedings published as NASA TN D-769, February 1961).
19-13-60	Shapiro, A., and Meisl, C. J., General Electric Co., Flight Propulsion Laboratory Dept., Report No. R 60 FPD358-A, November 9, 1960.
19-19-6	Stull, D. R., and Sinke, G. C., "Thermodynamic Properties of the Elements," Washington, American Chemical Society, 1956.
20-0-4	Taylor, J. W., AERE Tech. Note (ASTIA No. 139433), 1954.
23-4-61	Weatherford, W. D., Jr., "Momentum Dynamics of Gas-Phase Physical Processes," presented at American Physical Society 1961 Annual Meeting, New York, February 3, 1961.
721	AiResearch Manufacturing Co. of Arizona.
831	Rocketdyne Division, North American Aviation, Inc.

RUBIDIUM

a. General Discussion of Rubidium. Rubidium is a soft, silver-white, alkali metal intermediate between cesium and potassium in its chemical and physical properties. It ignites spontaneously in dry air, and also reacts violently with water, igniting the liberated hydrogen. Because of its chemical reactivity, it is usually immersed in a dry saturated hydrocarbon liquid or an inert gas atmosphere during storage and handling.

Rubidium forms alloys with gold, cesium, potassium, and sodium, and it readily amalgamates with mercury. Its corrosion characteristics are believed to be about the same as those of sodium and potassium.

Rubidium is available only in small quantities, and in January 1961, 99+% rubidium could be purchased for $440/lb and $350/lb in one pound, and 6 to 25 pound quantities, respectively.

b. Synopsis of Properties of Rubidium

Property	Value	Temp (°F)	Data Basis	Reference
Physical:				
Atomic Weight	85.48	---	Handbook	8-0-8
Melting Point, °F	102	---	Survey	12-0-2
Boiling Point, °F	1295	---	Semi-theoretical	Page Rb-VP-a
Critical Point, psia	2790	3032		616
Density of Solid, lb/ft^3	95.518	68	Handbook	8-0-8
Density of Liquid, lb/ft^3	81.91	B.P.	Extrapolated	Page Rb-ρ-a
Density of Vapor, lb/ft^3	0.0708	B.P.	Theoretical	Page Rb-ρ-b
Viscosity of Liquid, lb/ft hr	0.361	B.P.	Extrapolated	Page Rb-μ-a
Viscosity of Vapor, lb/ft hr	0.061	B.P.	Theoretical	Page Rb-μ-b
Surface Tension, lb/ft	0.0034	M.P.	Experimental	20-0-4
Thermal:				
Thermal Conductivity of Liquid, BTU/hr ft °F	11.65	B.P.	Unknown	Page Rb-k-a
Thermal Conductivity of Vapor, BTU/hr ft °F	0.00482	B.P.	Estimated	Page Rb-k-b
Specific Heat of Liquid, BTU/lb °F	0.0877	B.P.	Estimate	19-19-6
Specific Heat of Vapor, BTU/lb °F	0.0578	B.P.	Theoretical	Page Rb-C-a
Latent Heat of Fusion, BTU/lb	11.79	M.P.	Survey	19-19-6
Latent Heat of Vaporization, BTU/lb	347.8	B.P.	Theoretical	Page Rb-ΔH-a
Electrical and Magnetic:				
Resistivity, μ ohm-inch	8.81	M.P.	Survey	12-0-2
Ionization Potential, volts	4.126		Experimental	11-0-60
Magnetic Susceptibility, fps electromagnetic units/unit mass	0.0379	64.4 sol	Handbook	8-0-8

Property	Value	Temp (°F)	Data Basis	Reference
Thermal Neutron Cross Section (2200 m/s):				
Absorption, barns	0.70 ± 0.07	---	Handbook	8-0-8
Scattering, barns	12 ± 2	---	Handbook	8-0-8

c. Property Tables for Rubidium.

Basis of data for reference 19-13-60: Thermodynamic properties of equilibrium vapor mixtures were derived by machine computation with conventional relations assuming the individual monomer and dimer species to be ideal gases. The equilibrium specific heat was then determined with differentiation. The frozen specific heat was computed by adding the contributions of the individual species. Free energies of the monatomic and diatomic forms of the vapor were used to calculate the dimerization equilibrium constant, hence, no added assumtions were required concerning heat of dissociation. Iterations on vapor pressure were made until the ratio of the heat of vaporization to temperature became identical to the entropy of vaporization.

Therefore, all data from this reference are internally consistent.

PHYSICAL PROPERTIES OF RUBIDIUM
Saturated Phases

(Ref: 19-13-60)

Temperature (°R)	Equilibrium Vapor Molecular Weight	Vapor Pressure (psia)	Liquid Specific Volume (ft^3/lb)	Vapor Specific Volume (ft^3/lb)	Equilibrium Sonic Velocity (ft/sec)	Frozen Sonic Velocity (ft/sec)
1300	87.730	5.762×10^{-1}	1.166×10^{-2}	2.760×10^{2}	848.0	1099.7
1400	88.462	1.417×10^{0}	1.178×10^{-2}	1.199×10^{2}	873.3	1133.8
1500	89.262	3.076×10^{0}	1.190×10^{-2}	5.863×10^{1}	896.7	1165.4
1600	90.109	6.041×10^{0}	1.202×10^{-2}	3.154×10^{1}	918.5	1194.8
1700	90.952	1.093×10^{1}	1.214×10^{-2}	1.836×10^{1}	939.4	1222.6
1800	91.780	1.845×10^{1}	1.226×10^{-2}	1.141×10^{1}	959.3	1249.2
1900	92.647	2.931×10^{1}	1.238×10^{-2}	7.508×10^{0}	978.2	1274.0
2000	93.461	4.443×10^{1}	1.250×10^{-2}	5.169×10^{0}	996.7	1298.2
2100	94.177	6.480×10^{1}	1.262×10^{-2}	3.693×10^{0}	1015.3	1322.4
2200	94.873	9.100×10^{1}	1.274×10^{-2}	2.735×10^{0}	1033.4	1345.8
2300	95.567	1.236×10^{2}	1.286×10^{-2}	2.091×10^{0}	1050.9	1368.3
2400	96.228	1.630×10^{2}	1.298×10^{-2}	1.642×10^{0}	1068.1	1390.2
2500	96.837	2.099×10^{2}	1.310×10^{-2}	1.320×10^{0}	1085.1	1411.8
2600	97.366	2.650×10^{2}	1.322×10^{-2}	1.082×10^{0}	1102.4	1433.6
2700	97.774	3.291×10^{2}	1.334×10^{-2}	9.005×10^{-1}	1120.1	1456.1

THERMAL PROPERTIES OF RUBIDIUM
Saturated Phases

(Ref: 19-13-60)

Temperature (°R)	Specific Heat of Equilibrium Vapor (BTU/lb °R)	Frozen Specific Heat of Vapor (BTU/lb °R)	Ratio of Frozen Specific Heats of Vapor	Specific Heat of Liquid (BTU/lb °R)
1300	0.0963	0.05790	1.642	0.08770
1400	0.1005	0.05784	1.634	0.08770
1500	0.1035	0.05779	1.626	0.08770
1600	0.1053	0.05774	1.617	0.08770
1700	0.1059	0.05770	1.609	0.08770
1800	0.1056	0.05765	1.601	0.08770
1900	0.1049	0.05762	1.592	0.08770
2000	0.1036	0.05760	1.585	0.08770
2100	0.1018	0.05758	1.578	0.08770
2200	0.0999	0.05757	1.571	0.08770
2300	0.0980	0.05756	1.565	0.08770
2400	0.0962	0.05756	1.559	0.08770
2500	0.0943	0.05758	1.553	0.08770
2600	0.0925	0.05759	1.548	0.08770
2700	0.0905	0.05760	1.545	0.08770

THERMODYNAMICS OF RUBIDIUM
Saturated Phases

(Ref: 19-13-60)

Temperature T (°R)	Enthalpy of Liquid $(H-H_o)_L$ (BTU/lb)	Enthalpy of Vapor $(H-H_o)_V$ (BTU/lb)	Entropy of Liquid S_L (BTU/lb °R)	Entropy of Vapor S_V (BTU/lb °R)
1300	116.5	488.0	0.3115	0.5973
1400	125.3	491.7	0.3180	0.5798
1500	134.0	495.3	0.3241	0.5650
1600	142.8	498.8	0.3298	0.5523
1700	151.6	502.3	0.3351	0.5414
1800	160.3	506.0	0.3401	0.5321
1900	169.1	509.5	0.3448	0.5240
2000	177.9	513.2	0.3493	0.5170
2100	186.7	517.1	0.3536	0.5110
2200	195.4	521.2	0.3577	0.5058
2300	204.2	525.3	0.3616	0.5012
2400	213.0	529.4	0.3653	0.4972
2500	221.7	533.7	0.3689	0.4937
2600	230.5	538.2	0.3723	0.4907
2700	239.3	543.0	0.3756	0.4882

THERMODYNAMIC PROPERTIES OF RUBIDIUM

Liquid Phase: $H^{\circ}_{536.67} - H^{\circ}_{o} = 3.222$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^{\circ} - H^{\circ}_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^{\circ} - H^{\circ}_{536.67})/T$ (BTU/lb mole °R)
900	3733	23.90	19.76
1080	5083	25.26	20.56
1260	6433	26.42	21.32
1440	7783	27.42	22.02
1620	9133	28.30	22.67

THERMODYNAMIC PROPERTIES OF RUBIDIUM

Ideal Monatomic Gas: $H^{\circ}_{536.67} - H^{\circ}_{0} = 2,666$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^{\circ} - H^{\circ}_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^{\circ} - H^{\circ}_{536.67})/T$ (BTU/lb mole °R)
900	1805	43.20	41.20
1080	2700	44.10	41.60
1260	3593	44.87	42.02
1440	4487	45.53	42.42
1620	5382	46.12	42.80
1800	6277	46.64	43.16
1980	7171	47.11	43.49
2160	8064	47.55	43.82
2340	8959	47.94	44.12
2520	9853	48.31	44.40
2700	10748	48.66	44.68
2880	11644	48.98	44.94
3060	12541	49.28	45.19
3240	13437	49.56	45.42
3420	14337	49.83	45.64
3600	15241	50.09	45.86

THERMODYNAMIC PROPERTIES OF RUBIDIUM

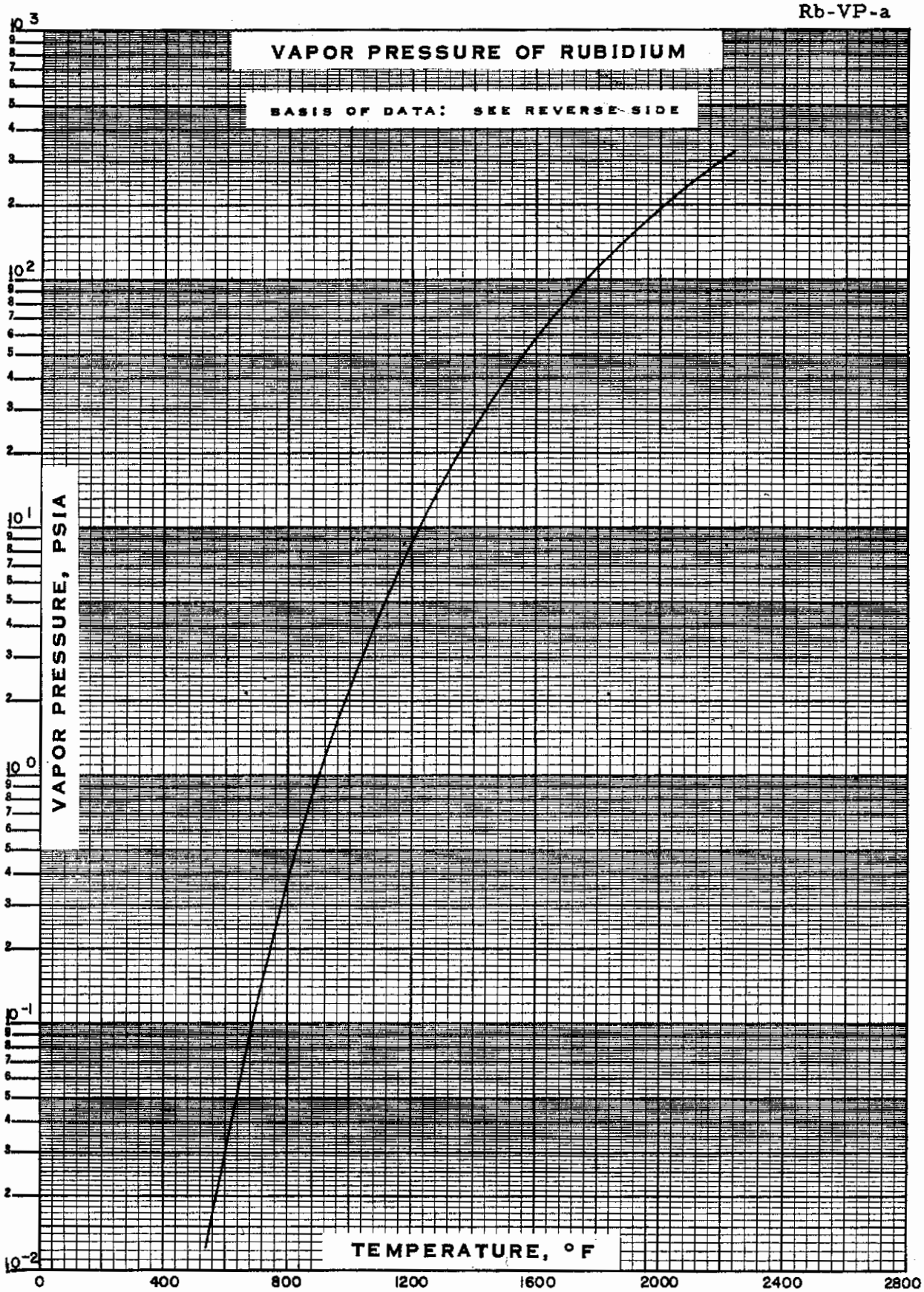
Ideal Diatomic Gas: $H^\circ_{536.67} - H^\circ_0 = 4,694$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^\circ - H^\circ_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^\circ - H^\circ_{536.67})/T$ (BTU/lb mole °R)
900	3310	69.40	65.73
1080	4961	71.07	66.48
1260	6620	72.49	67.24
1440	8294	73.73	67.97
1620	9967	74.83	68.68
1800	11650	75.81	69.34
1980	13343	76.71	69.98
2160	15048	77.53	70.57
2340	16763	78.30	71.14
2520	18464	79.00	71.68
2700	20200	79.66	72.18

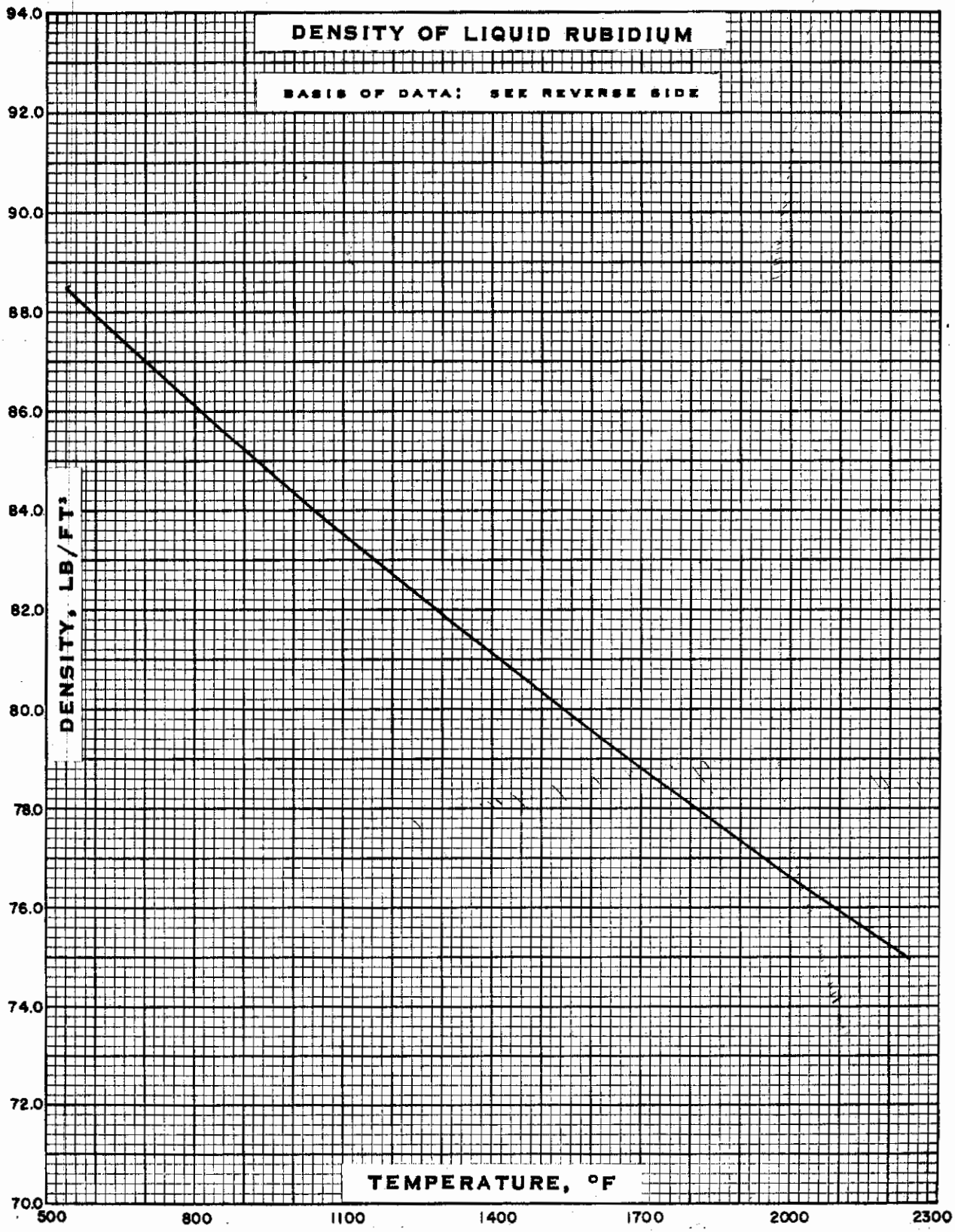
d. Working Charts for Rubidium.

Rb-VP-a



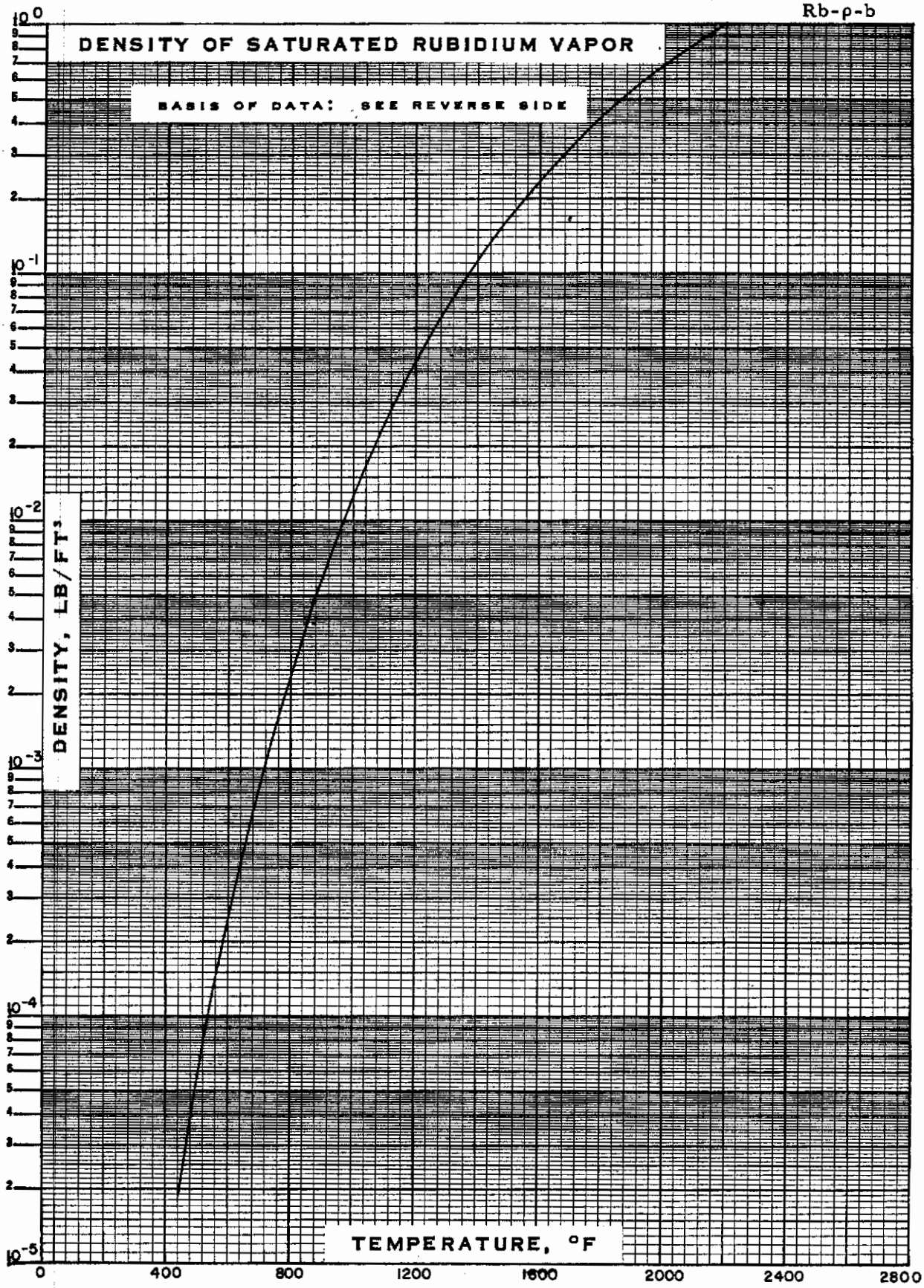
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Semi-Theoretical	19-13-60	540-2240	Experimental values were theoretically adjusted to yield consistent thermodynamic data.

Rb-ρ-a



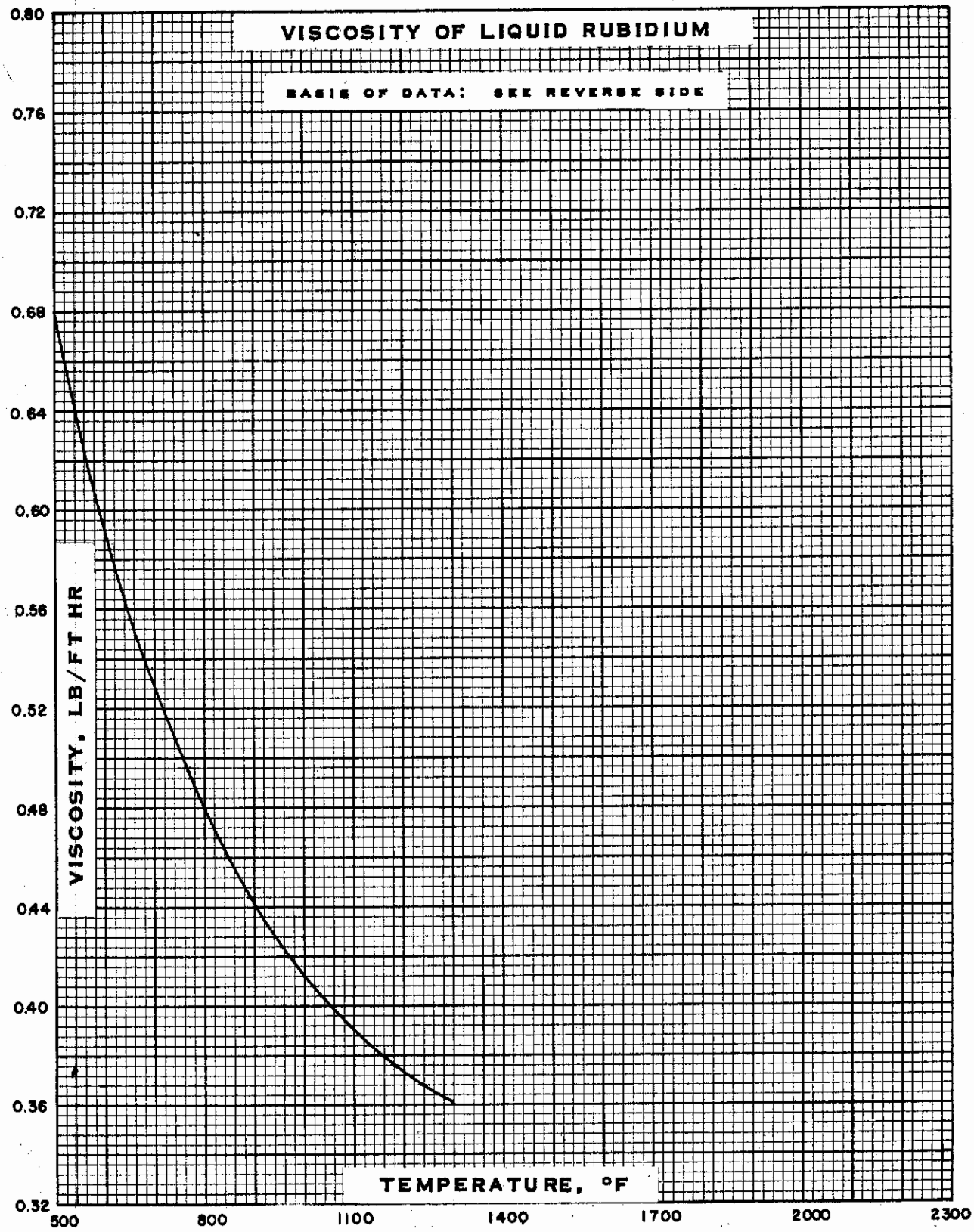
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Extrapolated	19-13-60	540-2240	The density of rubidium was given in (12-0-2) at 102°F and it was assumed that the density change with temperature was the same as that of potassium and sodium.

Rb-ρ-b



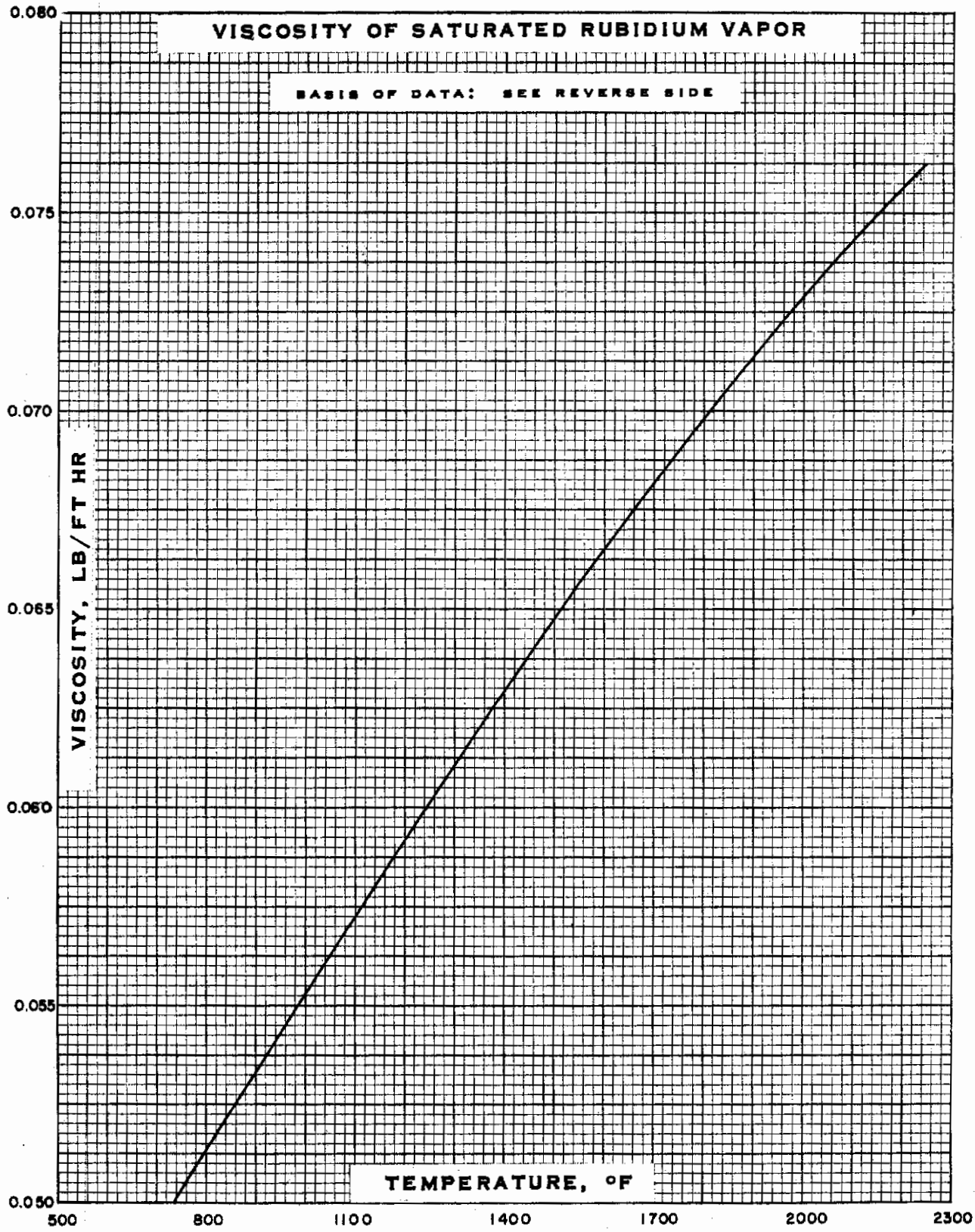
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	19-13-60	440-2200	The specific volume of the vapor mixture was calculated from the perfect gas law.

Rb-μ-a



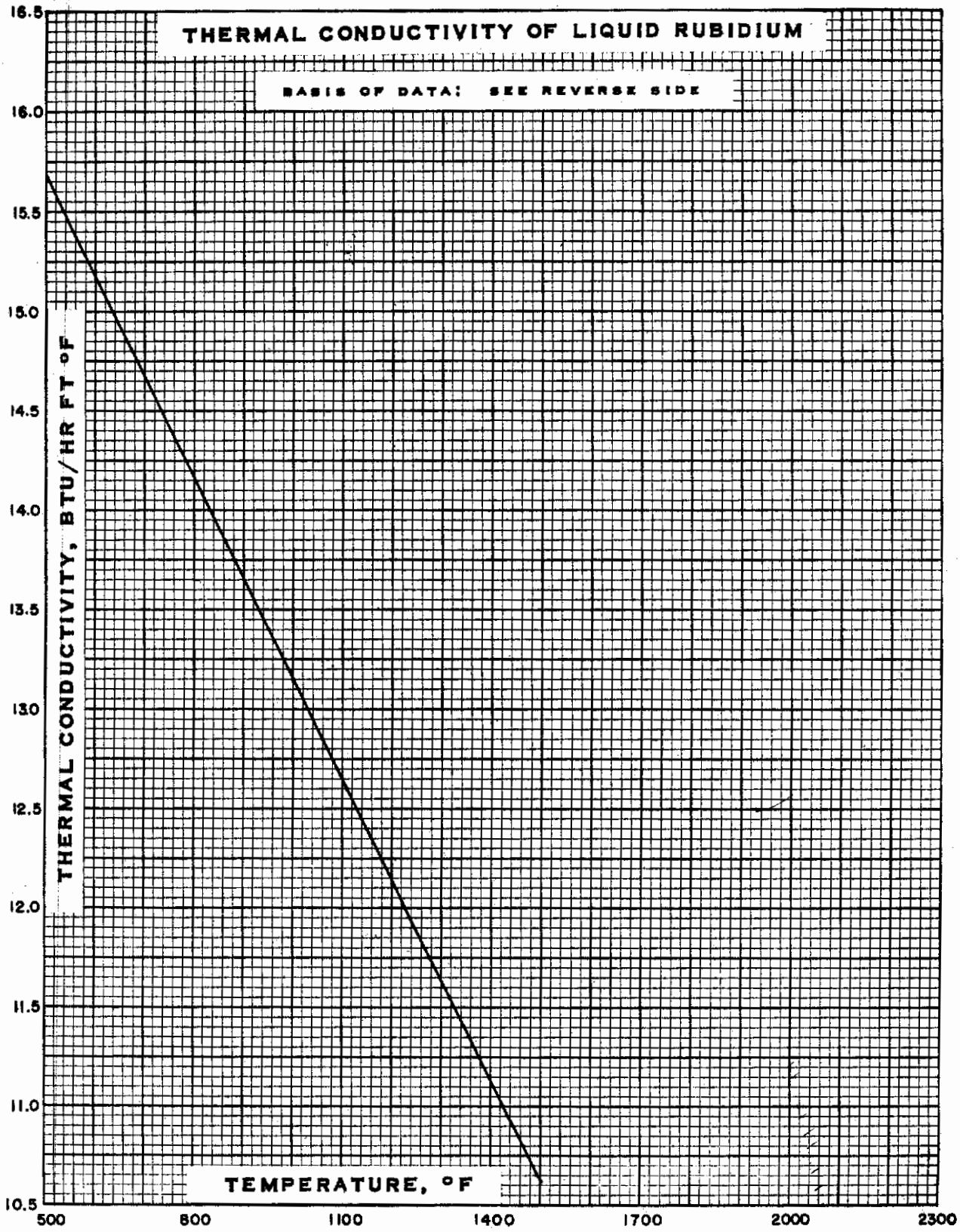
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Extrapolated	616	500-1300	This is an extension of the experimental data tabulated in (12-0-2). The method by which the data are extended is unknown.

Rb-μ-b



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	23-4-61	540-2240	Computed for variable molecular weight saturated vapor (page Rb-P-1) using new equation for gas viscosity.

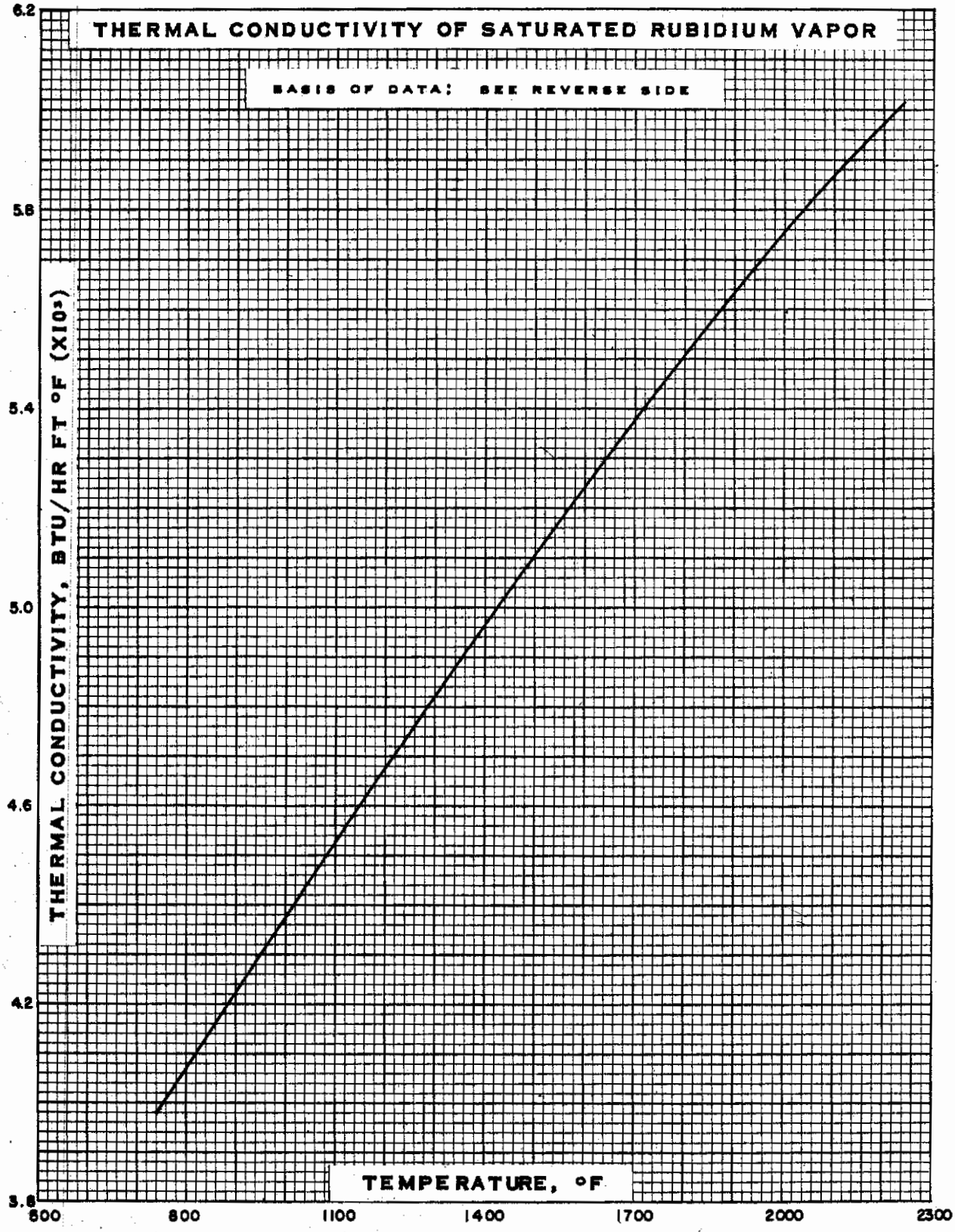
Rb-k-a



WADD TR 61-96

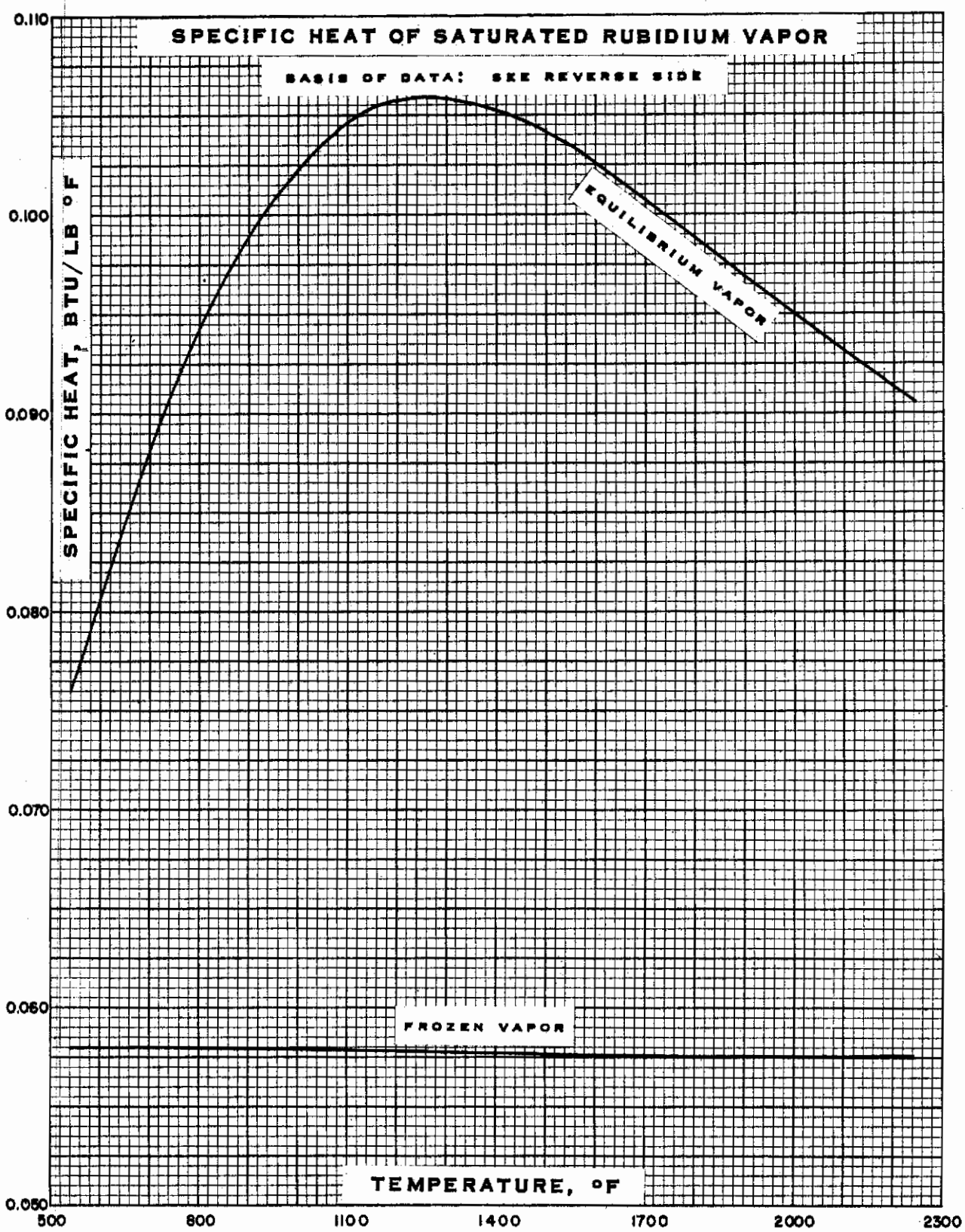
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Unknown	716, 721	500-1500	

Rb-k-b



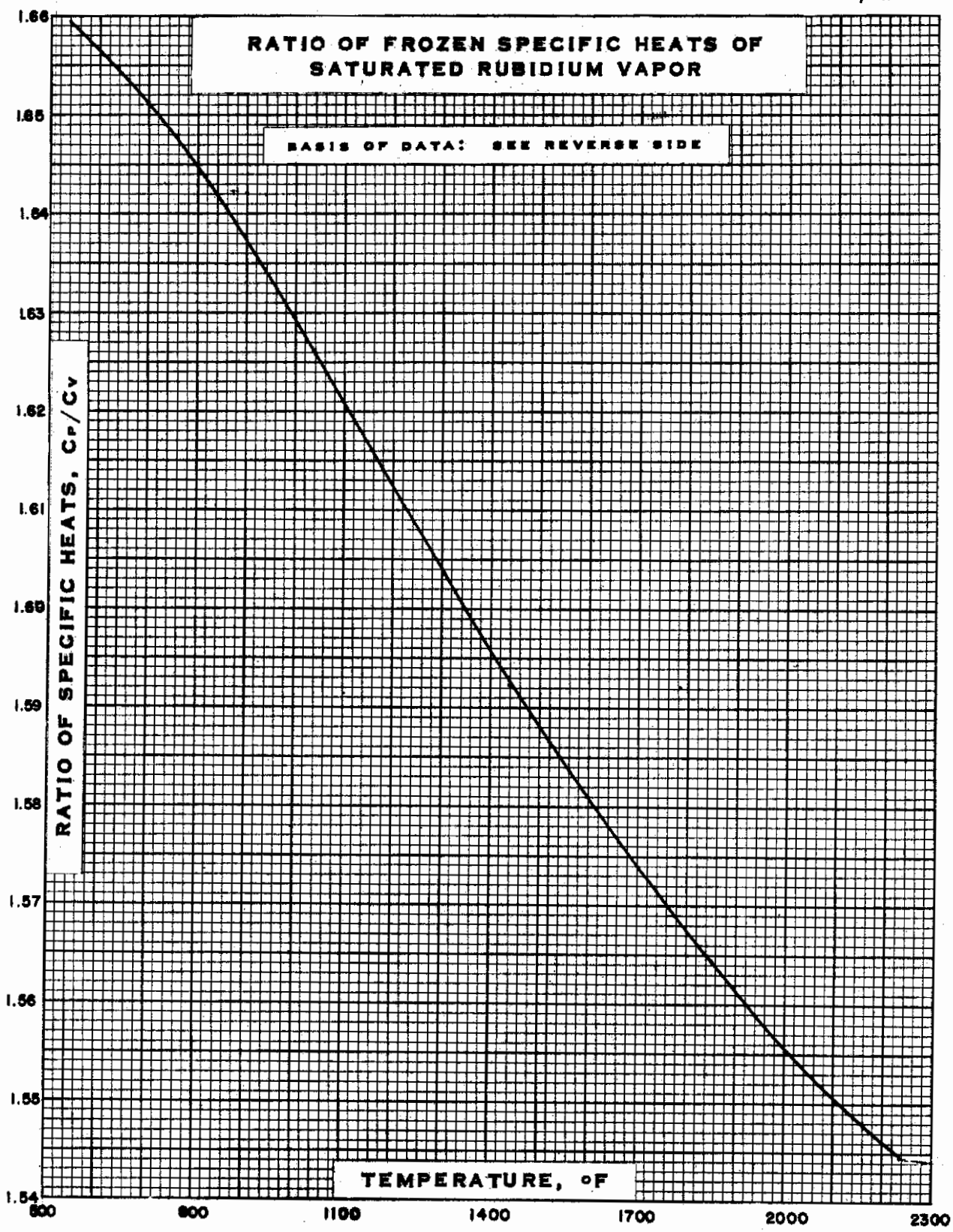
WADD TR 61-96

Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Estimated		540-2240	Calculated from the frozen specific heat (page Rb-C-a) and viscosity (page Rb-μ-b) of saturated vapor assuming a constant Prandtl No. of 0.73.



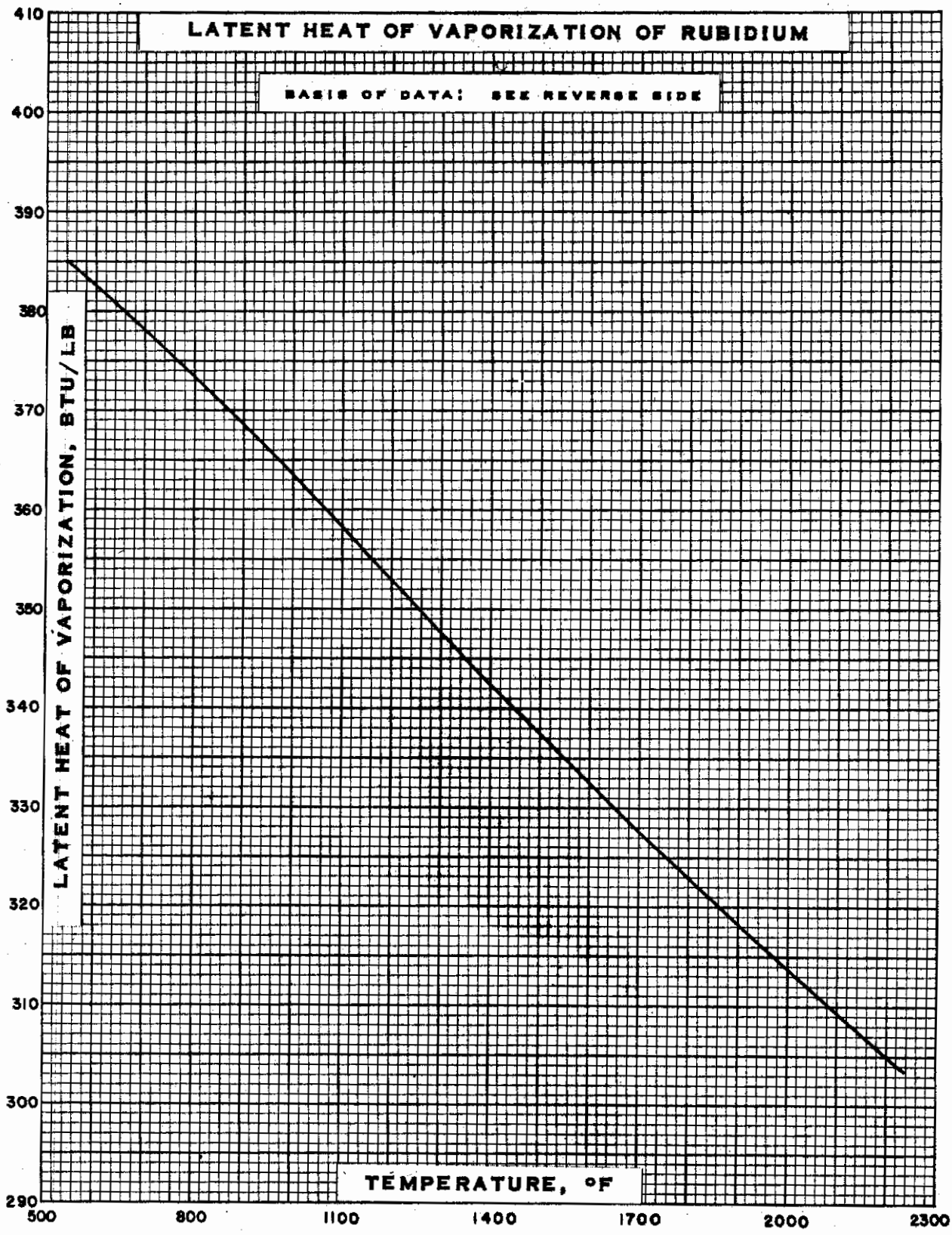
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	19-13-60	540-2240	Two specific heats were calculated for rubidium vapor. (1) The frozen specific heat is a state point property calculated by adding the separate contributions of the monatomic and diatomic vapors for a given equilibrium composition. (2) The equilibrium specific heat applies to the rigorous definition of specific heat, and includes the energy required to alter the degree of equilibrium dissociation.

Rb-γ-a



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	19-13-60	540-2240	Ratio of the frozen specific heat at constant pressure to the frozen specific heat at constant volume.

Rb-ΔH-a



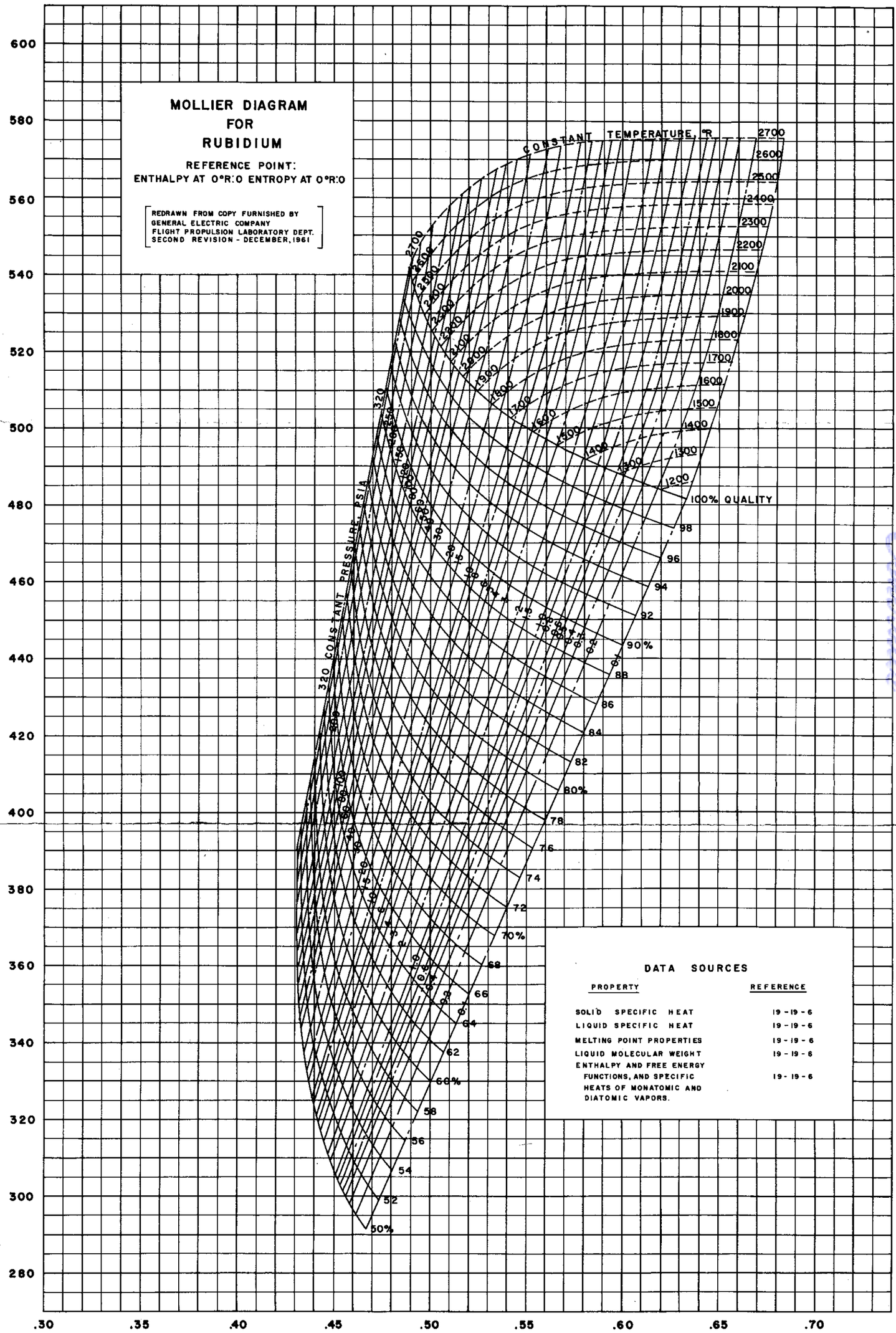
WADD TR 61-96

Basis of Data	Recommended Values	Temperature Range (°F)	Remarks
Theoretical	825	850	Based on experimental vapor pressure data in the temperature range 710° to 1070°F.
Theoretical	19-13-60	540-2240	
Theoretical	19-19-6	Boiling Point	

MOLLIER DIAGRAM FOR RUBIDIUM

REFERENCE POINT:
ENTHALPY AT 0°R: 0 ENTROPY AT 0°R: 0

[REDRAWN FROM COPY FURNISHED BY
GENERAL ELECTRIC COMPANY
FLIGHT PROPULSION LABORATORY DEPT.
SECOND REVISION - DECEMBER, 1961]



DATA SOURCES

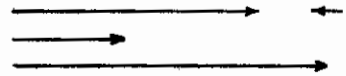
PROPERTY	REFERENCE
SOLID SPECIFIC HEAT	19-19-6
LIQUID SPECIFIC HEAT	19-19-6
MELTING POINT PROPERTIES	19-19-6
LIQUID MOLECULAR WEIGHT	19-19-6
ENTHALPY AND FREE ENERGY FUNCTIONS, AND SPECIFIC HEATS OF MONATOMIC AND DIATOMIC VAPORS.	19-19-6

RESISTANCE OF MATERIALS TO LIQUID RUBIDIUM

(SEE REVERSE SIDE OF SHEET FOR DATA BASIS)

FERROUS METALS AND ALLOYS:

FERRITIC STAINLESS STEELS 400 SERIES
AUSTENTIC STAINLESS STEELS 300 SERIES
LOW CARBON SILICON STEELS
LOW IRON HIGH NICKEL INCONELS
LOW CARBON STEELS
PURE IRON



<5 7 9 11 13 15 17 19 21 23 25 27 29

TEMPERATURE, °F IN HUNDREDS

NONFERROUS METALS AND ALLOYS:

TITANIUM AND VANADIUM
CHROMIUM
COBALT
NICKEL
COPPER
ZIRCONIUM

<5 7 9 11 13 15 17 19 21 23 25 27 29

TEMPERATURE, °F IN HUNDREDS

REFRACTORY METALS AND ALLOYS:

MOLYBDENUM
COLUMBIUM
TANTALUM
TUNGSTEN

<5 7 9 11 13 15 17 19 21 23 25 27 29

TEMPERATURE, °F IN HUNDREDS

OTHER METALS AND ALLOYS:

BERYLLIUM
ALUMINUM AND MAGNESIUM
ZINC, CADMIUM, TIN AND LEAD
NOBLE METALS
BRAZING METALS Ni-Mn, Ni-Mo, Ni-P
SILVER BRAZING ALLOYS

<5 7 9 11 13 15 17 19 21 23 25 27 29

TEMPERATURE, °F IN HUNDREDS

NONMETALS:

DENSE OXIDES AL, BE, ETC.
OXIDE–BASE CERMETS
CARBIDE–BASE CERMETS
GLASSES
GRAPHITE

<5 7 9 11 13 15 17 19 21 23 25 27 29

TEMPERATURE, °F IN HUNDREDS

NOTE: RIGHT–HAND ARROW–POINT INDICATES HIGHEST REPORTED TEST TEMPERATURE BELOW RESISTANCE LIMIT OF MATERIAL

LEFT–HAND ARROW–POINT INDICATES LOWEST REPORTED TEST TEMPERATURE ABOVE RESISTANCE LIMIT OF MATERIAL

(SEE FRONT SIDE OF SHEET FOR DATA)

	DATA SOURCE	REMARKS AND BASIS OF DATA
FERROUS METALS AND ALLOYS:		
FERRITIC STAINLESS STEELS 400 SERIES		
AUSTENTIC STAINLESS STEELS 300 SERIES	(825)(716)14-1-60	Static (1400°F): boiling loop (1600°F) showed intergranular penetration
LOW CARBON SILICON STEELS	825	Static
LOW IRON HIGH NICKEL INCONELS	(716)14-1-60	Boiling loop
LOW CARBON STEELS		
PURE IRON		
NONFERROUS METALS AND ALLOYS:		
TITANIUM AND VANADIUM		
CHROMIUM		
COBALT		
NICKEL	(716)14-1-60	Boiling loop
COPPER		
ZIRCONIUM		
REFRACTORY METALS AND ALLOYS:		
MOLYBDENUM		
COLUMBIUM		
TANTALUM		
TUNGSTEN		
OTHER METALS AND ALLOYS:		
BERYLLIUM	(825)14-1-60	Static
ALUMINUM AND MAGNESIUM		
ZINC, CADMIUM, TIN AND LEAD		
NOBLE METALS		
BRAZING METALS $Ni-Mn$, $Ni-Mo$, $Ni-P$		
SILVER BRAZING ALLOYS		
NONMETALS:		
DENSE OXIDES AL, BE, ETC.		
OXIDE–BASE CERMETS		
CARBIDE–BASE CERMETS	(825)14-1-60	Static
GLASSES		
GRAPHITE		

e. Data Sources for Rubidium.

Code No.	Source
8-0-8	Hodgman, C. D., Editor, "Handbook of Chemistry and Physics," Cleveland, Chemical Rubber Publishing Co., 1958.
11-0-60	Kiser, R. W., Dept. of Chemistry, Kansas State Univ., TID-6142, June 20, 1960.
12-0-2	Lyon, R. N., Editor, "Liquid-Metals Handbook," Second Ed., Washington, Atomic Energy Commission, Dept. of the Navy, 1952.
14-1-60	Notes of NASA-AEC Liquid Metals Corrosion Meeting, December 7-8, 1960, Washington, D. C. (Proceedings published as NASA TN D-769, February, 1961).
19-13-60	Shapiro, A., and Meisl, C. J., General Electric Co., Flight Propulsion Laboratory Dept., Report No. R 60 FPD358-A, November 9, 1960.
19-19-6	Stull, D. R., and Sinke, G. C., "Thermodynamic Properties of the Elements," Washington, American Chemical Society, 1956.
20-0-4	Taylor, J. W., AERE Tech. Note (ASTIA No. 139433), 1954.
23-4-61	Weatherford, W. D., Jr., "Momentum Dynamics of Gas-Phase Physical Processes," presented at American Physical Society 1961 Annual Meeting, New York, February 3, 1961.
509	MSA Research Corp.
616	Thompson-Ramo-Wooldridge
716	Oak Ridge National Laboratory
721	AiResearch Manufacturing Co. of Arizona
723	American Potash and Chemical Corp.
825	Battelle Memorial Institute

POTASSIUM

a. General Discussion of Potassium. Potassium is a soft, silver-white alkali metal intermediate between rubidium and sodium in chemical and physical properties. At ordinary temperatures, it does not burn in dry air, but it rapidly becomes encrusted when exposed to moist air and reacts violently with liquid water, igniting the liberated hydrogen. Because of its chemical reactivity, it is usually packed in sealed containers or immersed in a dry saturated hydrocarbon liquid or inert gas atmosphere during storage and handling.

Potassium forms an alloy compound (Na_2K) with sodium, and it alloys with cesium, rubidium, magnesium, aluminum, gold, antimony, zinc, and cadmium. Its corrosion properties are almost identical to those of sodium.

Potassium is commercially available in large or small quantities. The price ranges from less than $1.00/lb for 150-ton quantities to $4.75/lb for 1-5 pound quantities.

b. Synopsis of Properties of Potassium.

Property	Value	Temp (°F)	Data Basis	Reference
Physical:				
Atomic Weight	39.10	---	Handbook	8-0-8
Melting Point, °F	145.8	---	Survey	19-19-6
Boiling Point, °F	1395	---	Experimental	Page K-VP-a
Critical Point, psia	2500 ± 735	3095 ± 540	Survey	11-15-7
Density of Solid, lb/ft^3	53.690	68	Handbook	8-0-8
Density of Liquid, lb/ft^3	41.45	B.P.	Extrapolated	Page K-ρ-a
Density of Vapor, lb/ft^3	0.0314	B.P.	Theoretical	Page K-ρ-b
Viscosity of Liquid, lb/ft hr	0.324	B.P.	Extrapolated	Page K-μ-a
Viscosity of Vapor, lb/ft hr	0.0469	B.P.	Extrapolated	Page K-μ-b
Surface Tension, lb/ft	0.0059	M.P.	Experimental	20-0-4
Thermal:				
Thermal Conductivity of Liquid, BTU/hr ft °F	17.98	B.P.	Extrapolated	Page K-k-a
Thermal Conductivity of Vapor, BTU/hr ft °F	0.00814	B.P.	Estimated	Page K-k-b
Specific Heat of Liquid, BTU/lb °F	0.1867	B.P.	Experimental	Page K-C-a
Specific Heat of Vapor, BTU/lb °F	0.1264	B.P.	Theoretical	Page K-C-b
Latent Heat of Fusion BTU/lb	25.5	M.P.	Survey	19-19-6
Latent Heat of Vaporization BTU/lb	850.1	B.P.	Theoretical	Page K-ΔH-a

Property	Value	Temp (°F)	Data Basis	Reference
Electrical and Magnetic:				
Resistivity, μ ohm-inch	5.30	M.P.	Extrapolated	12-0-2
Ionization Potential, volts	4.339	---	Experimental	11-0-60
Magnetic Susceptibility, fps electromagnetic units/unit mass	0.2191	64.4 sol	Handbook	8-0-8
Thermal Neutron Cross Section (2200 m/s):				
Absorption, barns	1.97 ± 0.06.	---	Handbook	8-0-8
Scattering, barns	1.5 ± 0.3	---	Handbook	8-0-8

c. Property Tables for Potassium.

Basis of data from Reference 19-13-60: Thermodynamic properties of equilibrium vapor mixtures were derived by machine computation with conventional relations assuming the individual monomer and dimer species to be ideal gases. The equilibrium specific heat was then determined by differentiation. The frozen specific heat was computed by adding the contributions of the individual species. Free energies of the monatomic and diatomic forms of the vapor were used to calculate the dimerization equilibrium constant, hence, no added assumptions were required concerning heat of dissociation. Iterations on vapor pressure were made until the ratio of the heat of vaporization to temperature became identical to the entropy of vaporization. Therefore, all data from this reference are internally consistent.

PHYSICAL PROPERTIES OF POTASSIUM

Saturated Phases

(Ref: 19-13-60)

Temperature (°R)	Equilibrium Vapor Molecular Weight	Vapor Pressure (psia)	Liquid Specific Volume (ft^3/lb)	Vapor Specific Volume (ft^3/lb)	Equilibrium Sonic Velocity (ft/sec)	Frozen Sonic Velocity (ft/sec)
1300	39.650	2.364×10^{-1}	2.189×10^{-2}	1.489×10^{3}	1268.1	1641.3
1400	39.883	6.374×10^{-1}	2.229×10^{-2}	5.910×10^{2}	1308.4	1695.4
1500	40.156	1.501×10^{0}	2.269×10^{-2}	2.672×10^{2}	1346.0	1745.5
1600	40.467	3.166×10^{0}	2.309×10^{-2}	1.340×10^{2}	1380.3	1791.7
1700	40.797	6.105×10^{0}	2.349×10^{-2}	7.325×10^{1}	1412.5	1835.1
1800	41.135	1.092×10^{1}	2.389×10^{-2}	4.301×10^{1}	1443.0	1876.0
1900	41.494	1.828×10^{1}	2.429×10^{-2}	2.688×10^{1}	1471.6	1914.3
2000	41.858	2.902×10^{1}	2.469×10^{-2}	1.767×10^{1}	1498.8	1950.0
2100	42.219	4.407×10^{1}	2.509×10^{-2}	1.211×10^{1}	1525.1	1985.2
2200	42.569	6.439×10^{1}	2.549×10^{-2}	8.614×10^{0}	1550.8	2018.8
2300	42.902	9.097×10^{1}	2.589×10^{-2}	6.325×10^{0}	1576.0	2051.5
2400	43.231	1.243×10^{2}	2.629×10^{-2}	4.793×10^{0}	1600.5	2083.0
2500	43.553	1.649×10^{2}	2.669×10^{-2}	3.735×10^{0}	1624.4	2113.6
2600	43.858	2.136×10^{2}	2.709×10^{-2}	2.979×10^{0}	1648.0	2143.6
2700	44.123	2.716×10^{2}	2.749×10^{-2}	2.418×10^{0}	1672.1	2174.0

THERMAL PROPERTIES OF POTASSIUM
Saturated Phases

(Ref: 19-13-60)

Temperature (°R)	Specific Heat of Equilibrium Vapor (BTU/lb °R)	Frozen Specific Heat of Vapor (BTU/lb °R)	Ratio of Frozen Specific Heats of Vapor	Specific Heat of Liquid (BTU/lb °R)
1300	0.1787	0.1268	1.653	0.1823
1400	0.1893	0.1267	1.647	0.1820
1500	0.1985	0.1266	1.641	0.1823
1600	0.2062	0.1265	1.634	0.1829
1700	0.2116	0.1265	1.626	0.1841
1800	0.2149	0.1264	1.618	0.1857
1900	0.2168	0.1263	1.610	0.1878
2000	0.2173	0.1263	1.602	0.1903
2100	0.2167	0.1262	1.594	0.1933
2200	0.2151	0.1262	1.586	0.1967
2300	0.2128	0.1262	1.579	0.2007
2400	0.2102	0.1262	1.572	0.2050
2500	0.2073	0.1262	1.566	0.2099
2600	0.2041	0.1262	1.559	0.2151
2700	0.2007	0.1263	1.554	0.2209

THERMODYNAMIC PROPERTIES OF POTASSIUM
Saturated Phases

(Ref: 19-13-60)

Temperature T (°R)	Enthalpy of Liquid $(H-H_o)_L$ (BTU/lb)	Enthalpy of Vapor $(H-H_o)_V$ (BTU/lb)	Entropy of Liquid S_L (BTU/lb °R)	Entropy of Vapor S_V (BTU/lb °R)
1300	246.5	1152.3	0.5988	1.2956
1400	264.7	1161.6	0.6123	1.2530
1500	283.0	1170.4	0.6249	1.2166
1600	301.2	1178.7	0.6367	1.1851
1700	319.6	1186.8	0.6478	1.1580
1800	338.0	1194.8	0.6584	1.1344
1900	356.7	1202.7	0.6685	1.1137
2000	375.6	1210.5	0.6782	1.0956
2100	394.8	1218.4	0.6875	1.0797
2200	414.3	1226.5	0.6966	1.0658
2300	434.2	1234.9	0.7054	1.0536
2400	454.4	1243.4	0.7141	1.0428
2500	475.2	1252.0	0.7225	1.0333
2600	496.4	1260.9	0.7308	1.0249
2700	518.2	1270.4	0.7391	1.0177

THERMODYNAMIC PROPERTIES OF POTASSIUM

Liquid Phase: $H^{\circ}_{536.67} - H^{\circ}_{0} = 3,051$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^{\circ} - H^{\circ}_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^{\circ} - H^{\circ}_{536.67})/T$ (BTU/lb mole °R)
1260	6316	23.35	18.34
1440	7596	24.30	19.03
1620	8881	25.14	19.66
1800	10177	25.90	20.25

THERMODYNAMIC PROPERTIES OF POTASSIUM

Ideal Monatomic Gas: $H^\circ_{536.67} - H^\circ_0 = 2,666$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^\circ - H^\circ_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^\circ - H^\circ_{536.67})T$ (BTU/lb mole °R)
1260	3593	42.54	39.69
1440	4487	43.20	40.09
1620	5832	43.79	40.47
1800	6277	44.31	40.83
1980	7171	44.78	41.16
2160	8064	45.21	41.48
2340	8959	45.61	41.79
2520	9853	45.98	42.07
2700	10748	46.32	42.34
2880	11644	46.65	42.61
3060	12539	46.95	42.86
3240	13437	47.23	43.09
3420	14335	47.50	43.31
3600	15235	47.76	43.53

THERMODYNAMIC PROPERTIES OF POTASSIUM

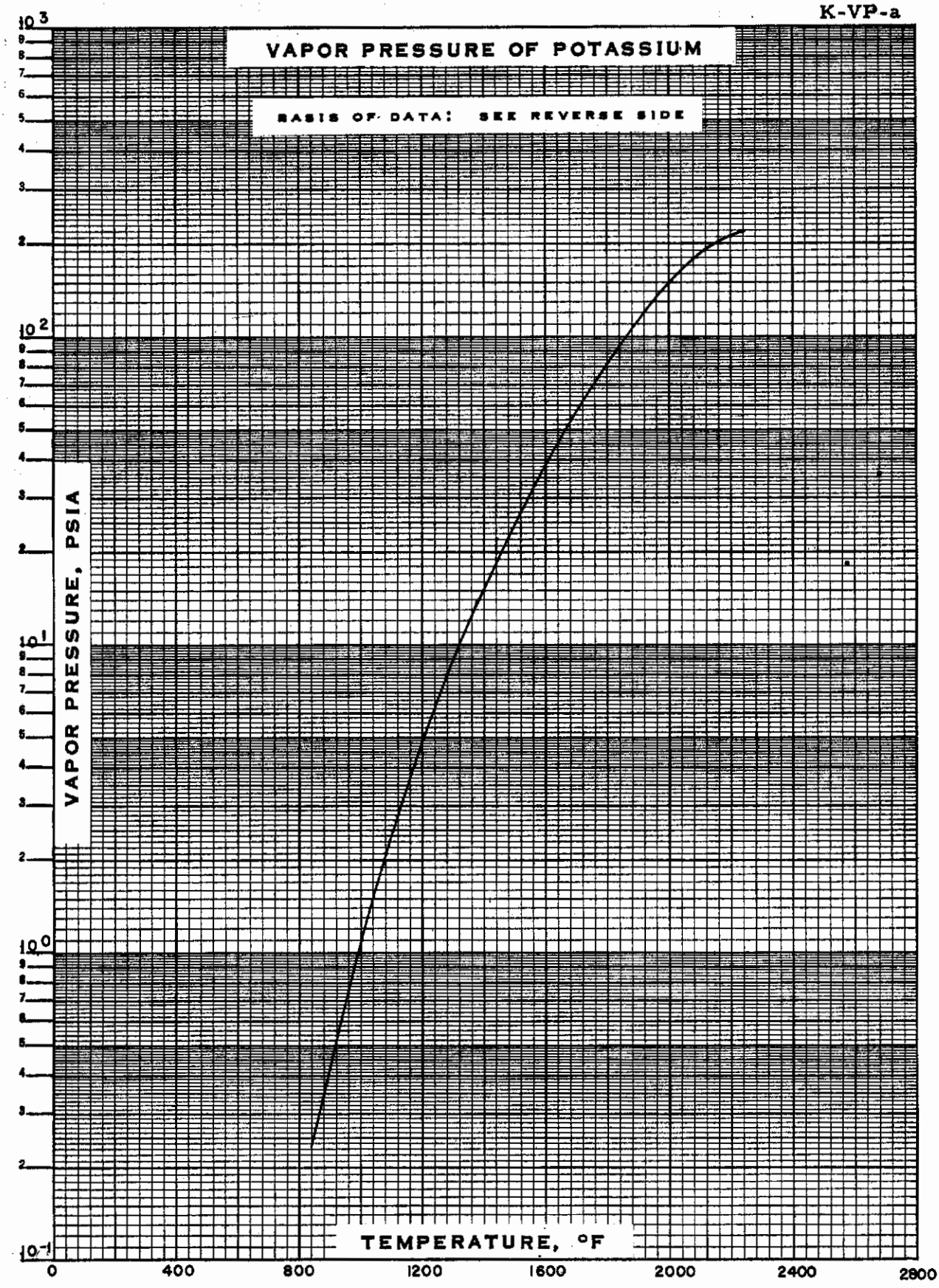
Ideal Diatomic Gas: $H^\circ_{536.67} - H^\circ_0 = 4,619$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^\circ - H^\circ_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^\circ - H^\circ_{536.67})/T$ (BTU/lb mole °R)
1260	6633	67.48	62.22
1440	8312	68.72	62.95
1620	9994	69.83	63.67
1800	11689	70.82	64.33
1980	13399	71.72	64.96
2160	15102	72.55	65.56
2340	16816	73.31	66.13
2520	18540	74.02	66.67
2700	20302	74.69	67.18

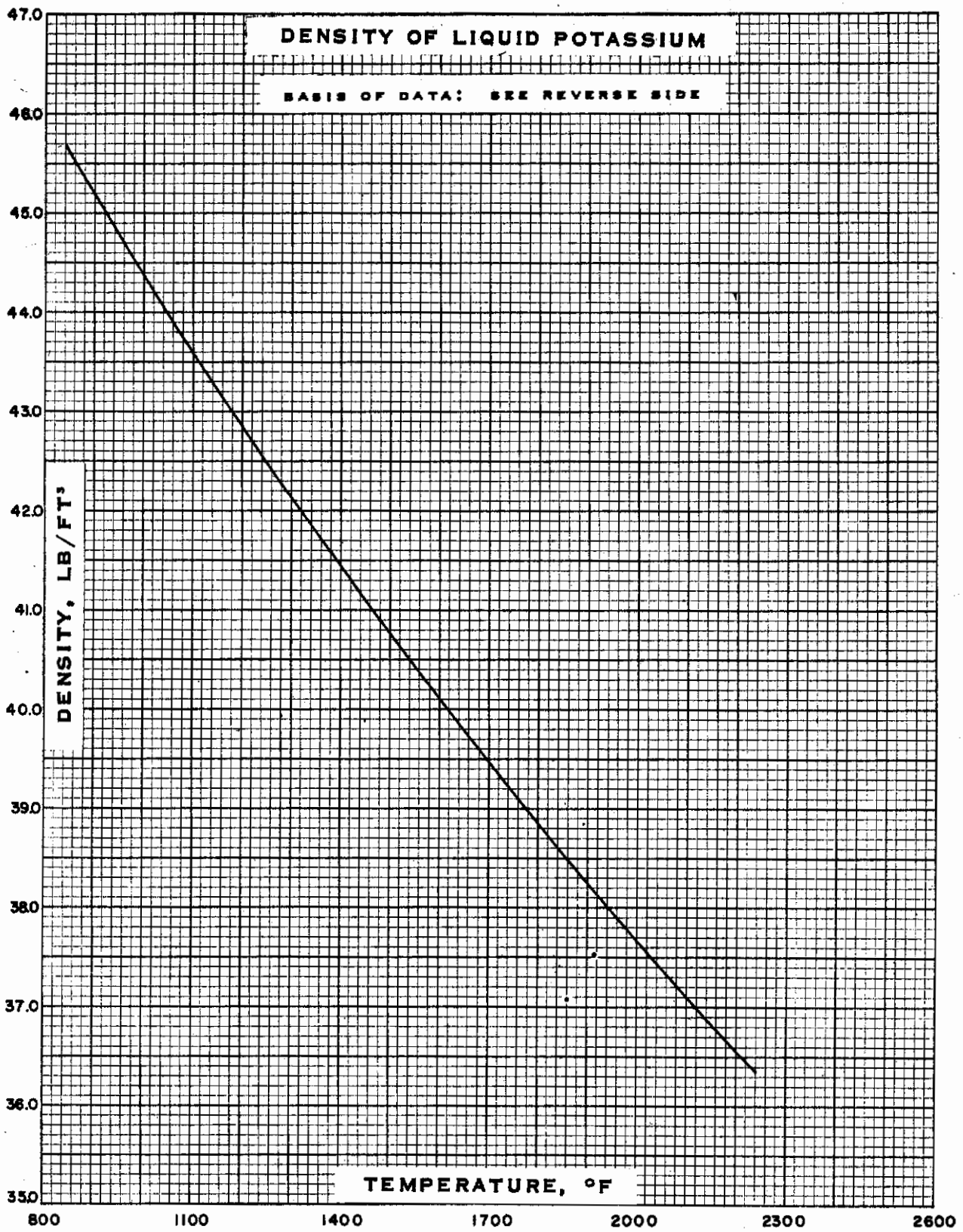
d. Working Charts for Potassium.

K-VP-a



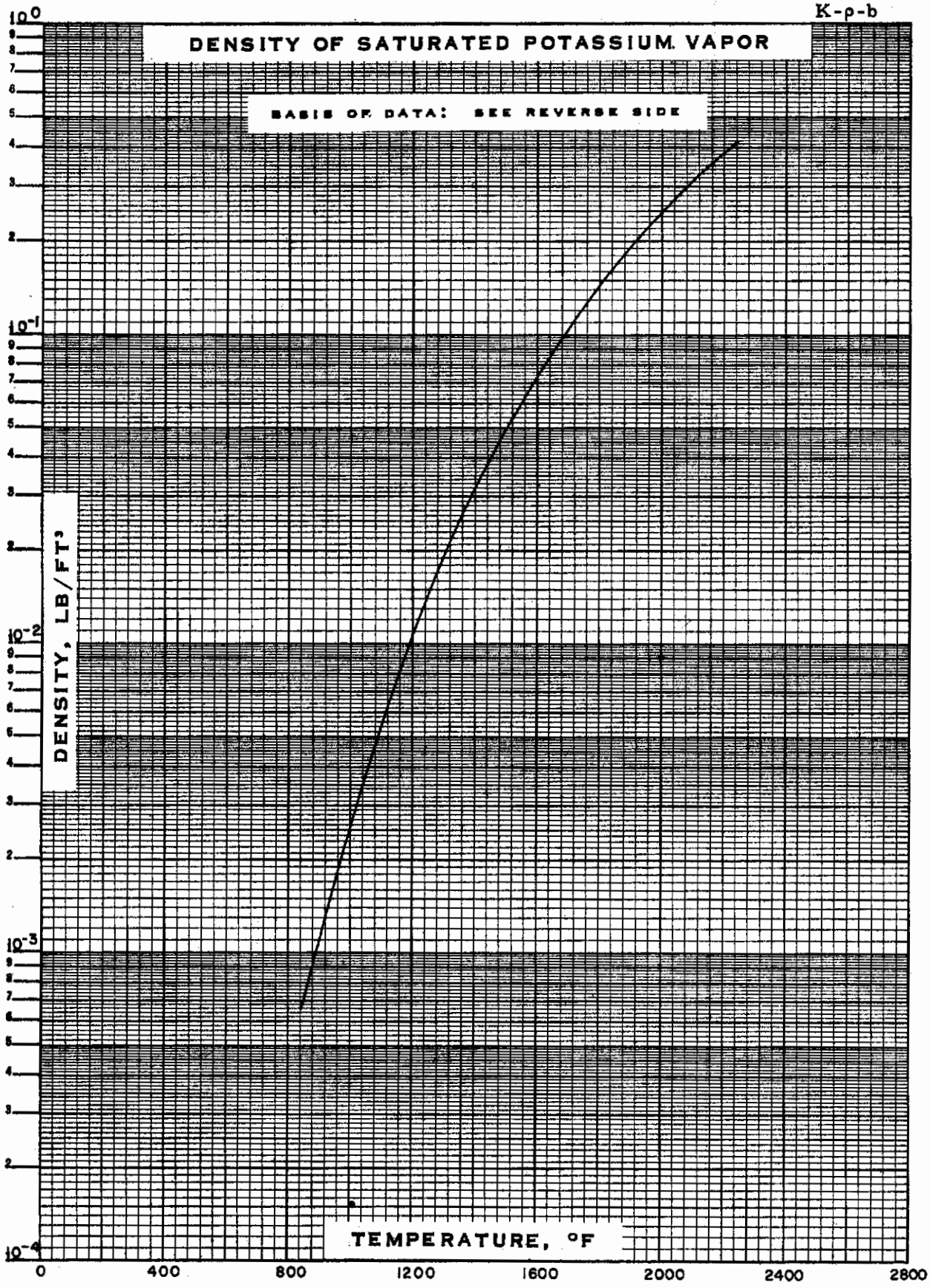
WADD TR 61-96

Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	4-7-1, 12-0-2	1190-1400	The results of different investigators were correlated and the best results were employed to derive an equation representing the vapor pressure of potassium.
Semi-theoretical	19-13-60	840-2240	Experimental values were theoretically adjusted to yield consistent thermodynamic data.



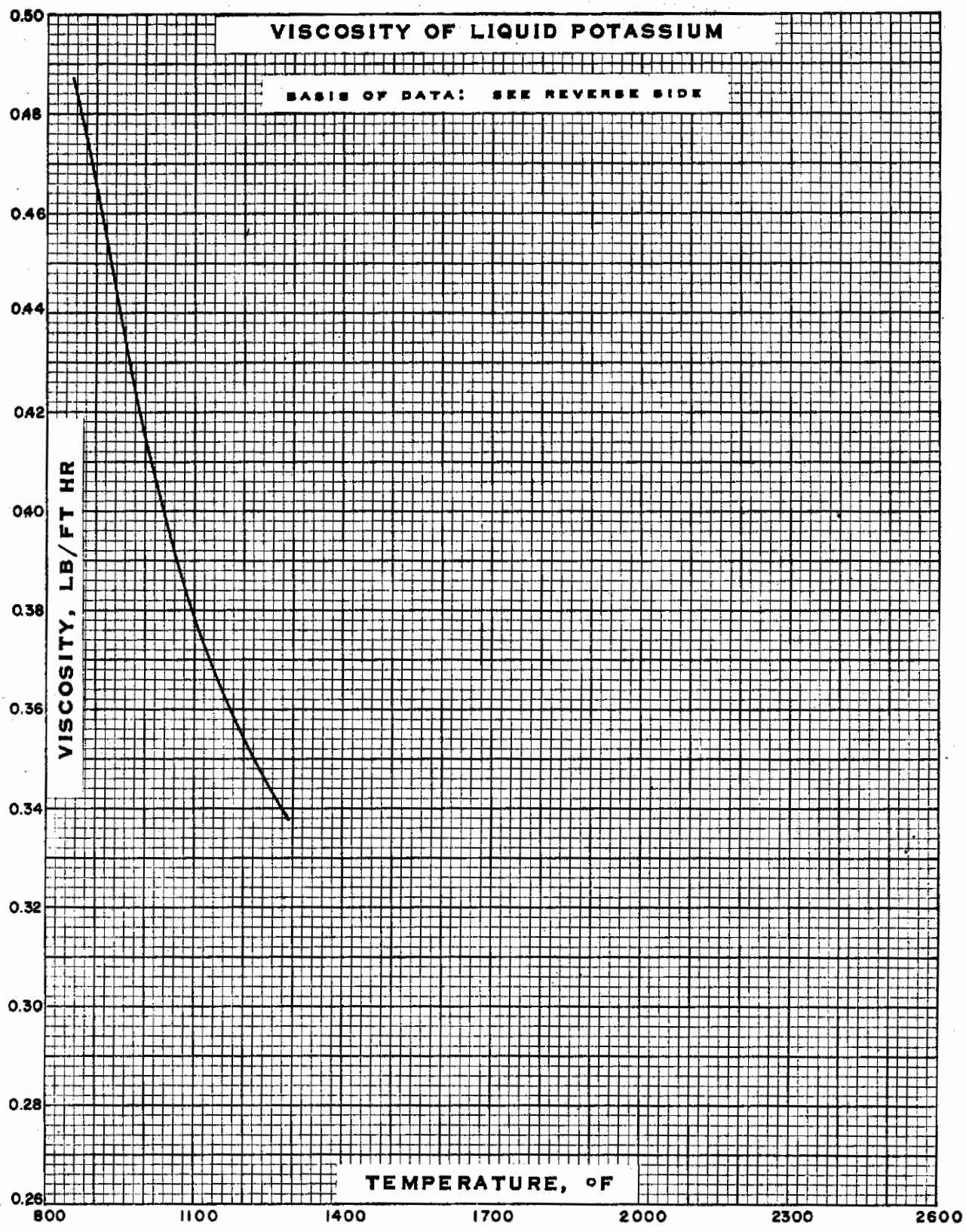
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	12-0-2, 19-13-60	840-1292	The accuracy of the density values to 1292 °F is better than 1%.
Extrapolated	19-13-60	1292-2240	Extended (12-0-2) data.

K-ρ-b



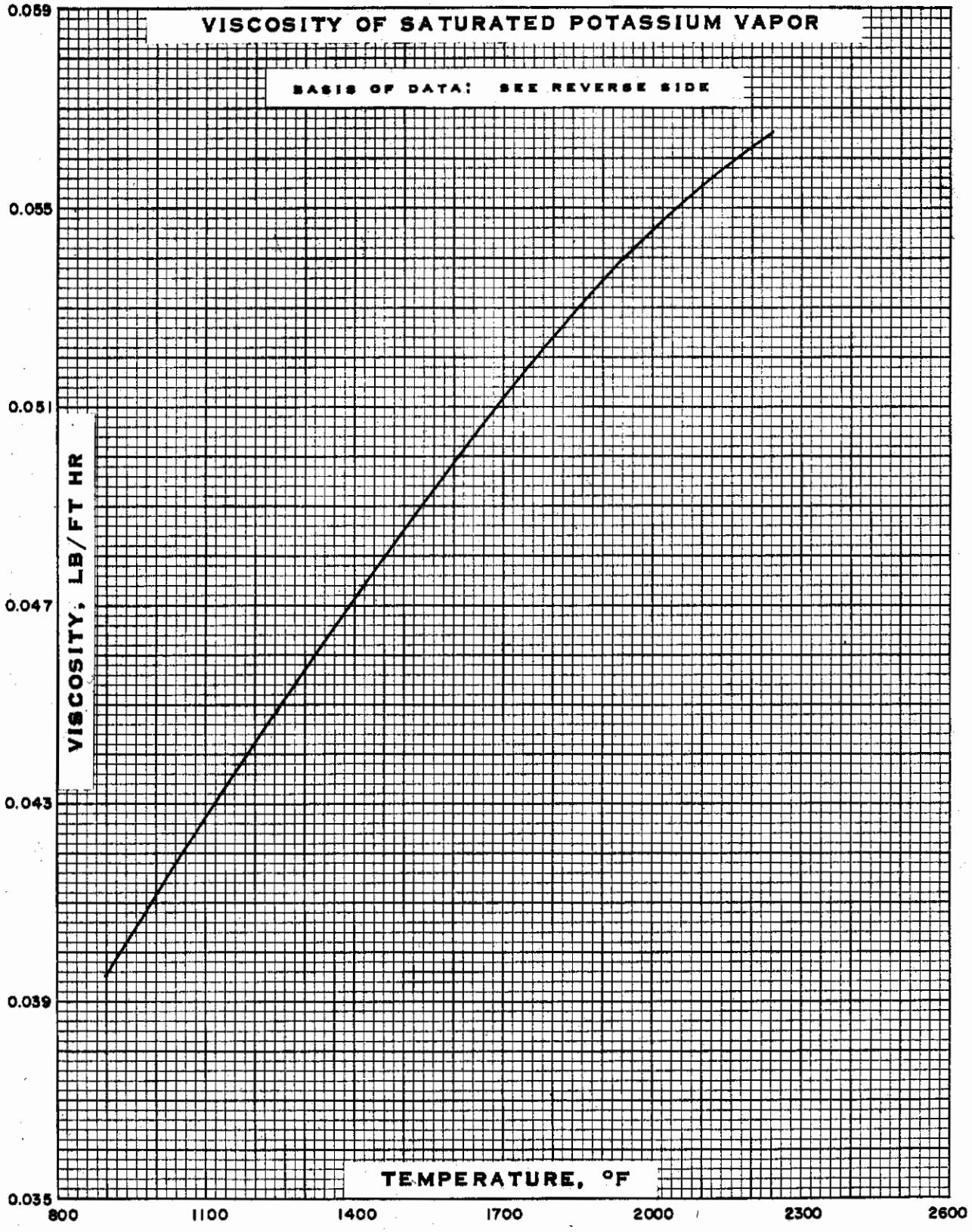
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	19-13-60	840-2240	The specific volume of the vapor mixture was calculated from the perfect gas law.

K-μ-a

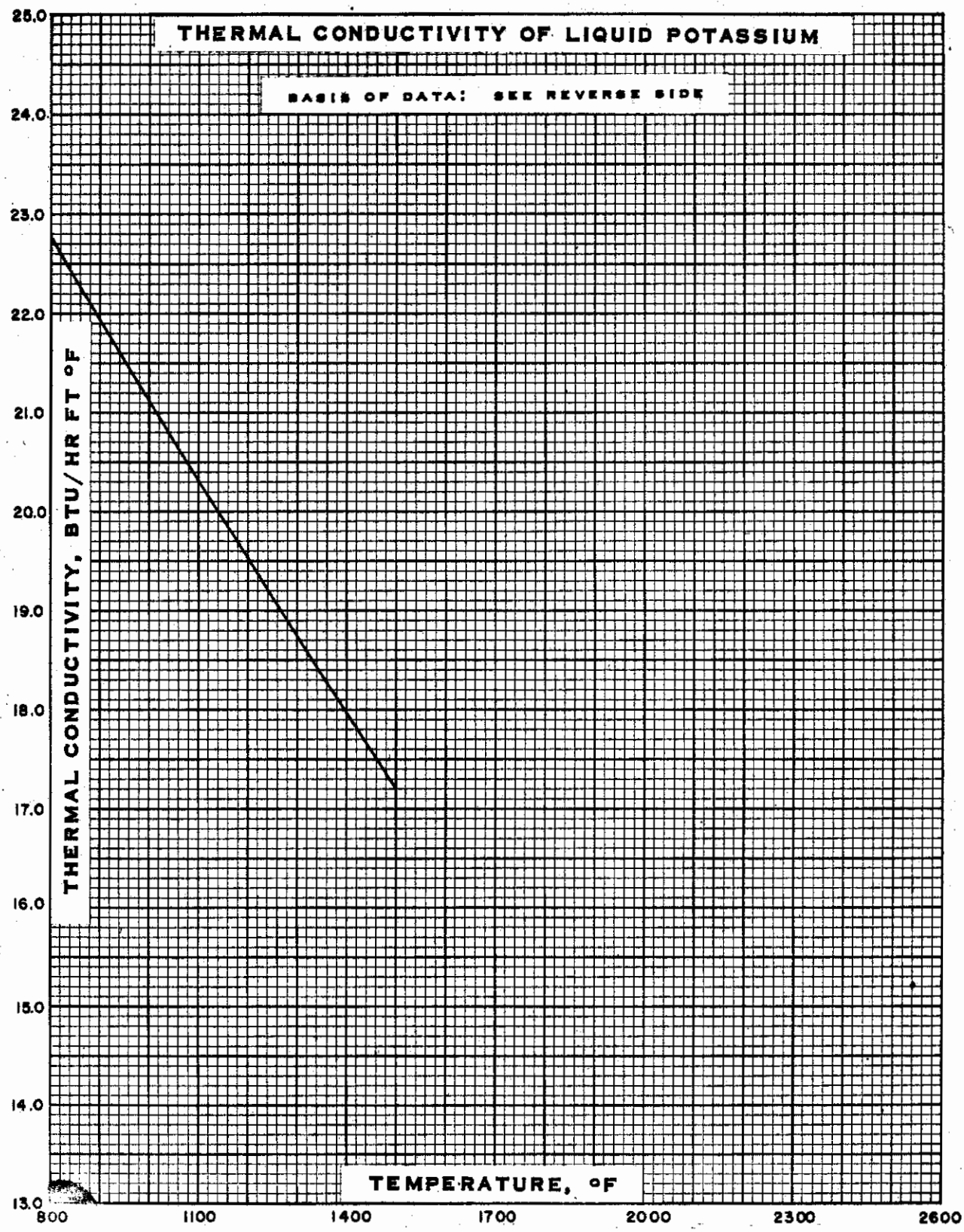


Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	11-2-9	850-1292	Measured by the method of damped torsional oscillations.

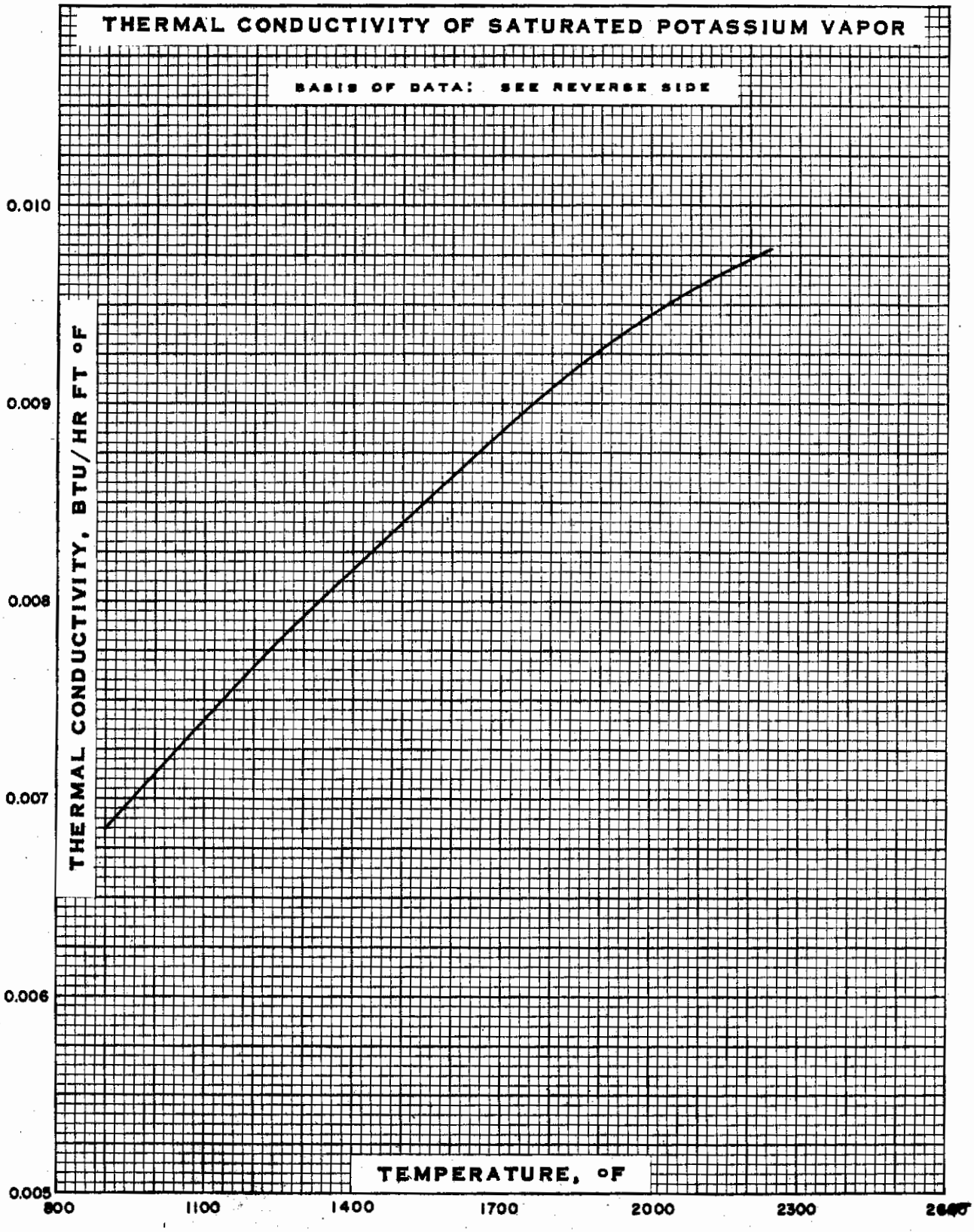
K-μ-b



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	23-4-61	840-2240	Computed for variable molecular weight saturated vapor (page K-P-1) using new equation for gas viscosity.

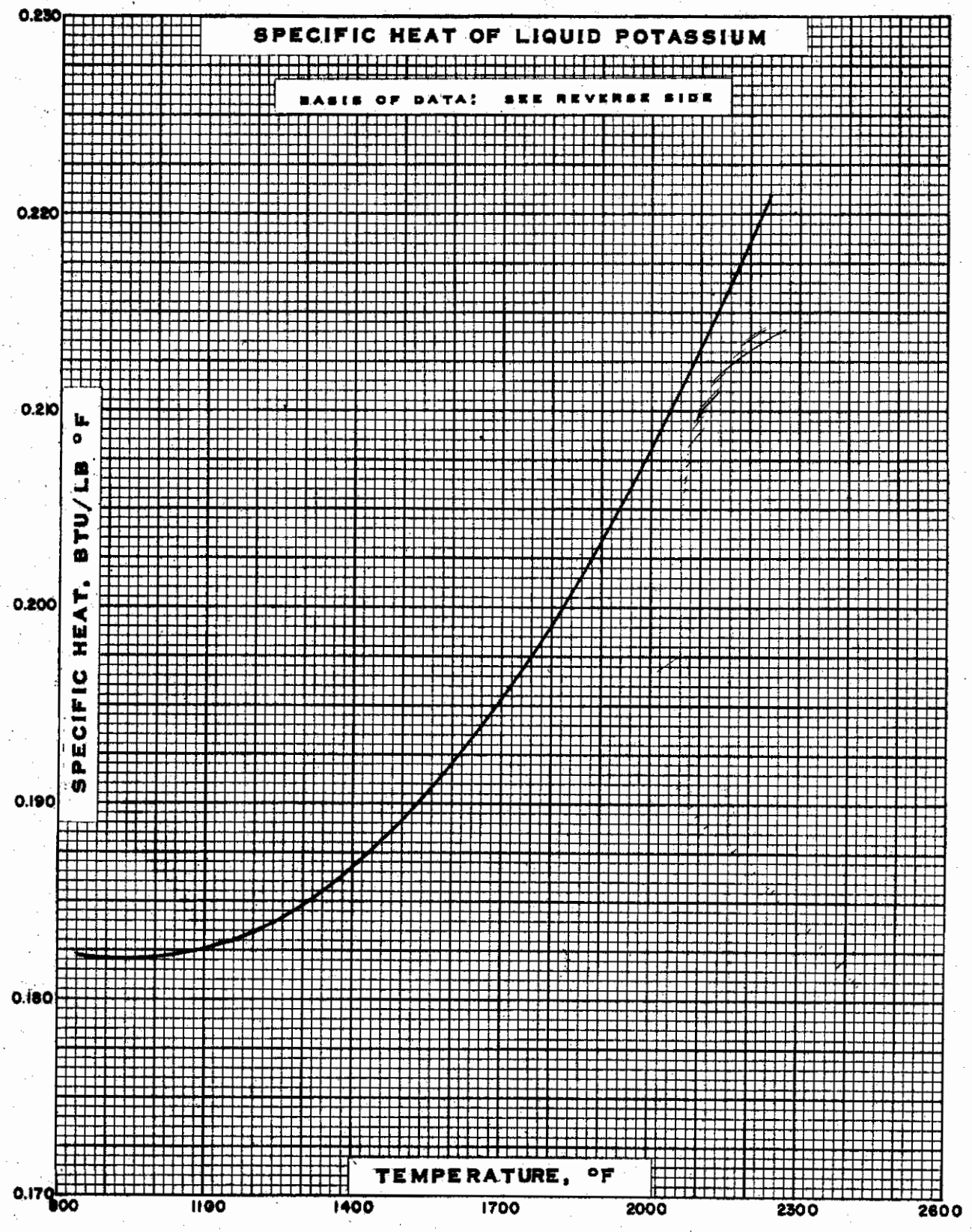


Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	5-7-2, 12-0-2, 721	800-1140	Thermal conductivity values were measured with a longitudinal heat flow apparatus. The oxide content of the potassium, based on the analysis of the distilled material was less than 0.001% oxygen. Spectrochemical analysis of distilled K: Na, Ca, Al, Rb, Li - less than 0.00001% Ag, Si, Mg, Cs, Ba, Fe, Cr, Ni, Sn, Pb - nil
Extrapolated	721	1140-1500	Method of extrapolation is unknown.

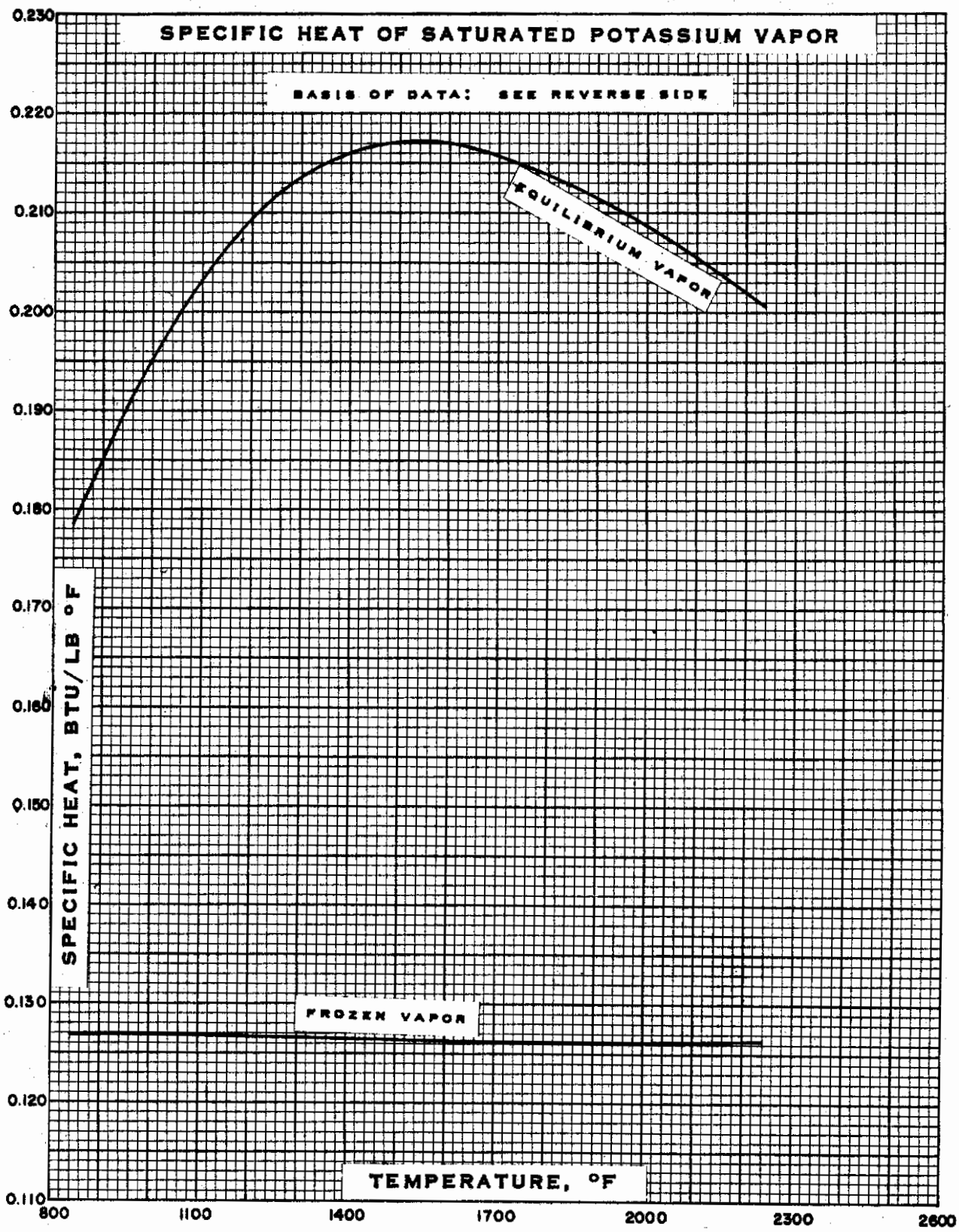


Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Estimated		840-2240	Calculated from the frozen specific heat (page K-C-b) and viscosity (page K-μ-b) of saturated vapor, assuming a constant Prandtl No. of 0.73

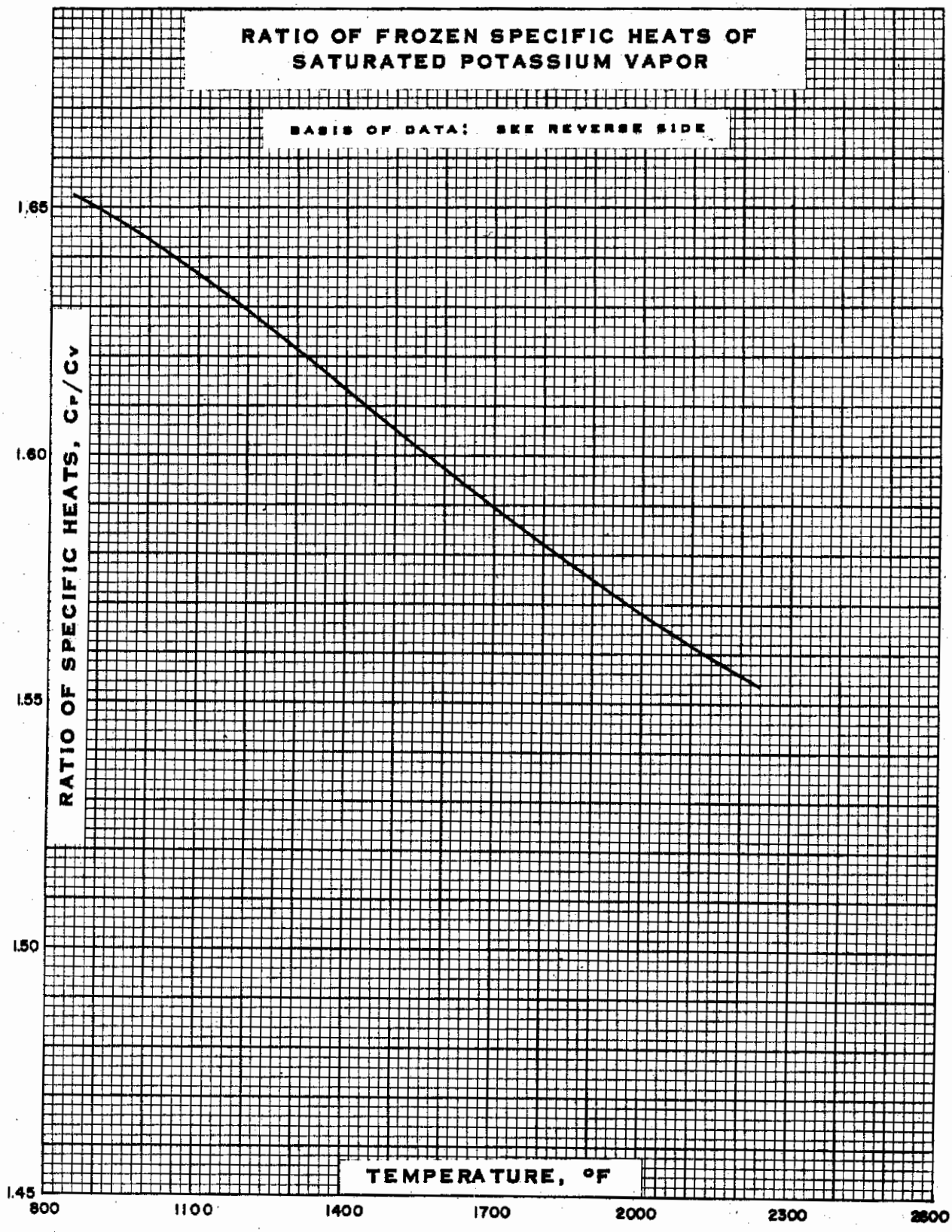
K-C-8



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	4-2-2, 5-10-5, 12-0-2, 19-13-60, 19-19-6	840-1472	Measurements were made of the changes in enthalpy, using an ice calorimeter. From the enthalpy values, the specific heats were calculated. The nominally pure potassium was triple distilled and a used sample analyzed spectrochemically gave these results: Na - 0.01-0.1%, Ca - 0.001-0.01%, Al, Cr, Fe, Mg, Rb, Mn, Si - less than 0.001% each. The uncertainty assigned to the calculated values up to 1292°F was 0.4%.
Extrapolated	19-13-60	1472-2240	Parabolic equation was derived that joined smoothly to the low temperature data.

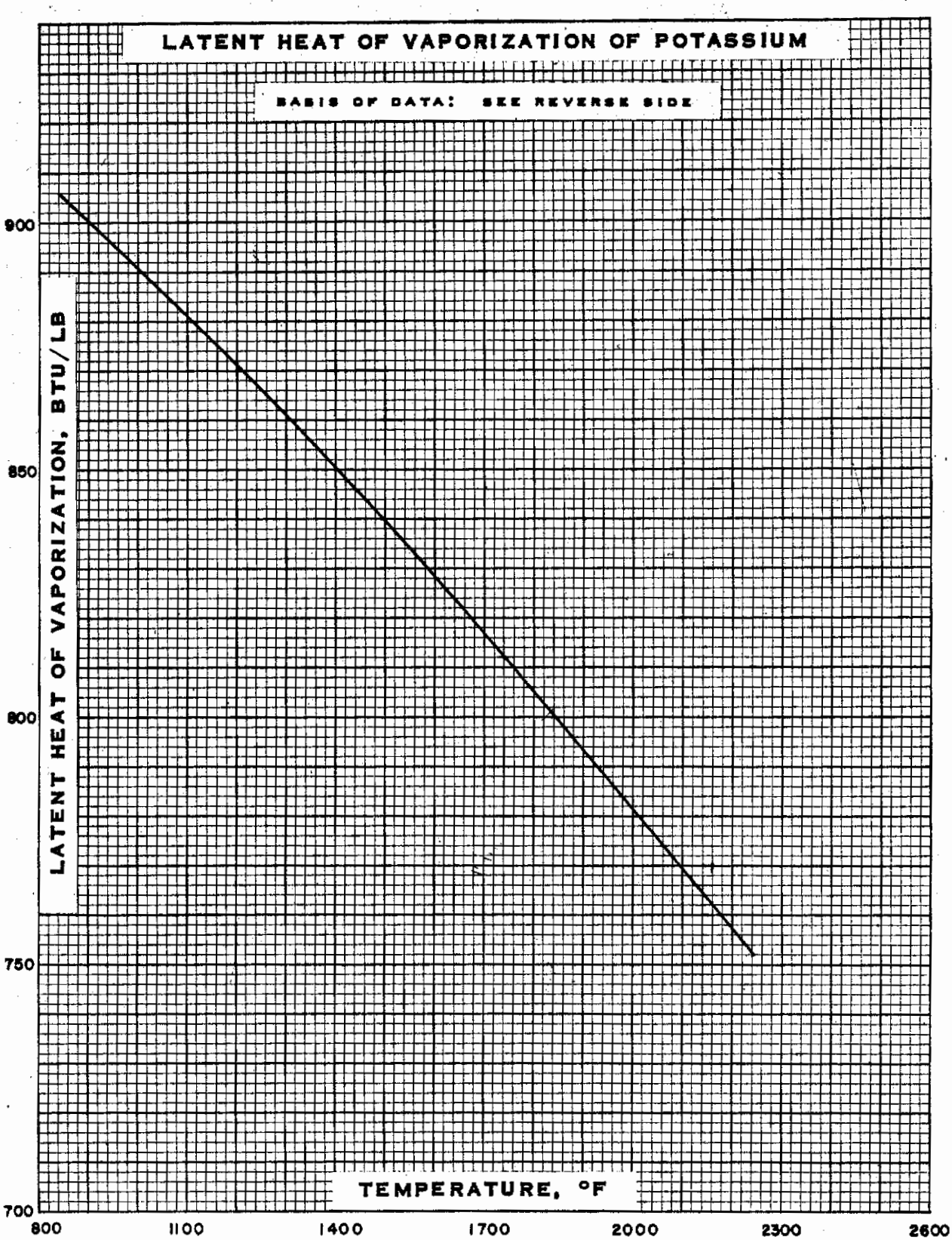


Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	19-13-60	840-2240	Two specific heats were calculated for potassium vapor. (1) The frozen specific heat is a state point property calculated by adding the separate contributions of the monatomic and diatomic vapors for a given equilibrium composition. (2) The equilibrium specific heat applies to the rigorous definition of specific heat, and includes the energy required to alter the degree of equilibrium dissociation.



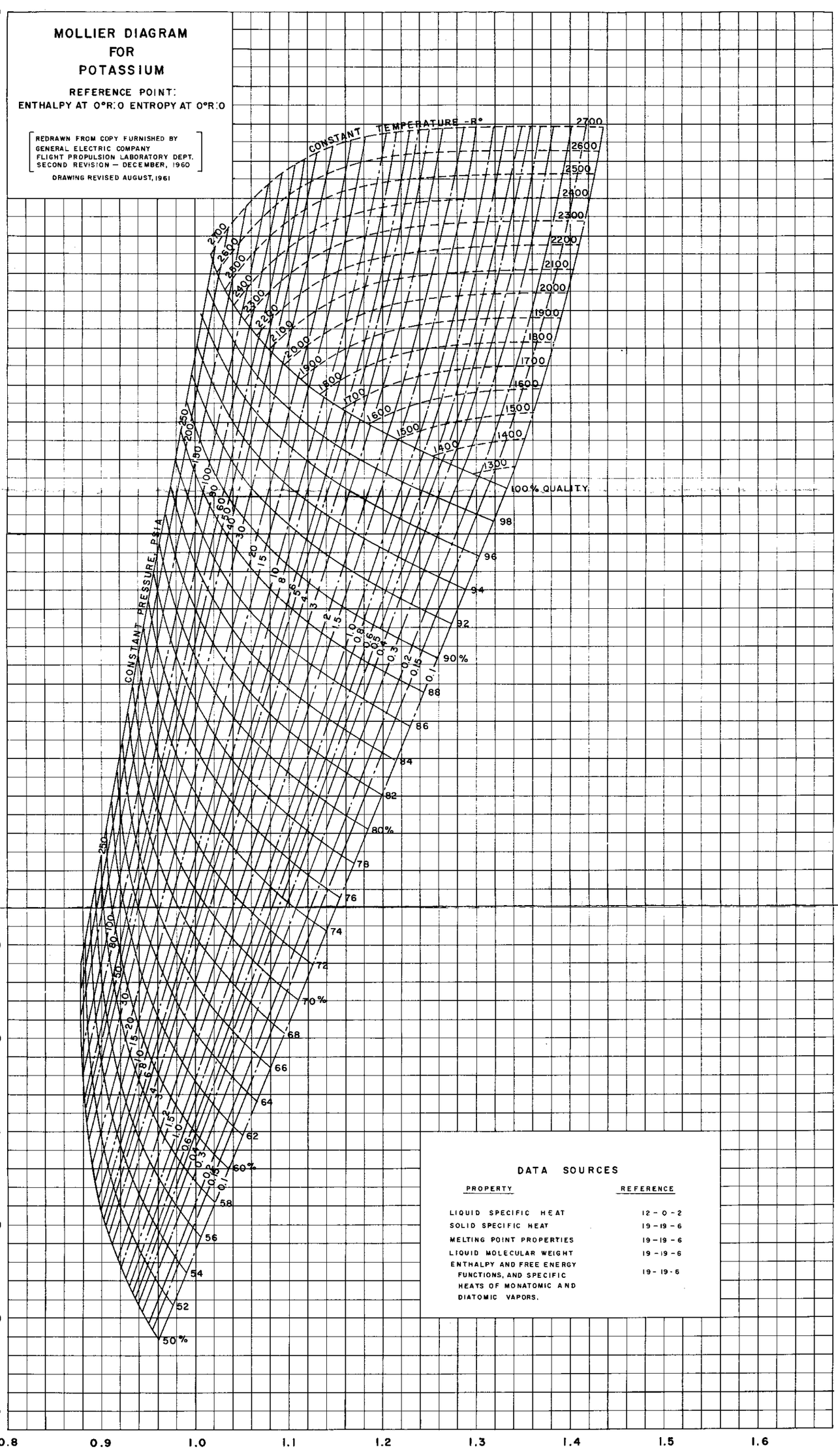
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	19-13-60	840-2240	Ratio of the frozen specific heat at constant pressure to the frozen specific heat at constant volume.

K-ΔH-a



WADD TR 61-96

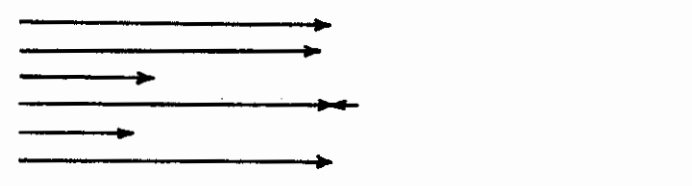
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	19-13-60	840-2240	
Theoretical	19-19-6	Boiling point	
Semi-theoretical	716	840-1740	Based on NBS tables.



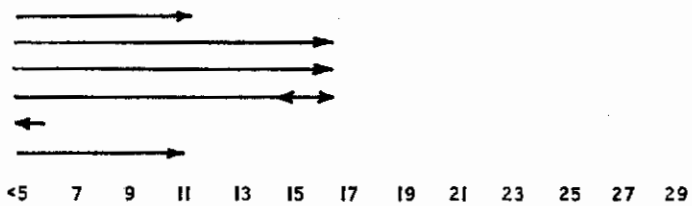
RESISTANCE OF MATERIALS TO LIQUID POTASSIUM

(SEE REVERSE SIDE OF SHEET FOR DATA BASIS)

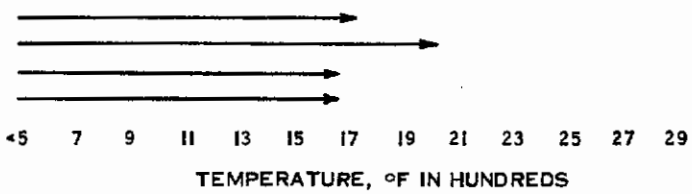
FERROUS METALS AND ALLOYS:



NONFERROUS METALS AND ALLOYS:

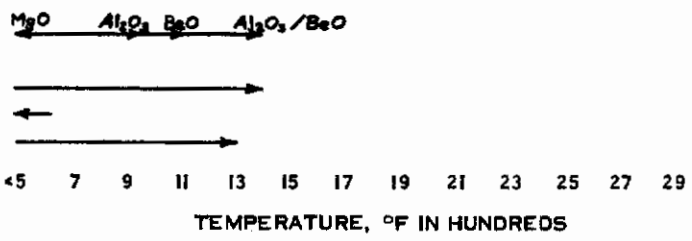


REFRACTORY METALS AND ALLOYS:



OTHER METALS AND ALLOYS:

NONMETALS:



NOTE: RIGHT-HAND ARROW-POINT INDICATES HIGHEST REPORTED TEST TEMPERATURE BELOW RESISTANCE LIMIT OF MATERIAL

LEFT-HAND ARROW-POINT INDICATES LOWEST REPORTED TEST TEMPERATURE ABOVE RESISTANCE LIMIT OF MATERIAL

(SEE FRONT SIDE OF SHEET FOR DATA)

	DATA SOURCE	REMARKS AND BASIS OF DATA
FERROUS METALS AND ALLOYS:		
FERRITIC STAINLESS STEELS 400 SERIES	12-0-2	Survey
AUSTENTIC STAINLESS STEELS 300 SERIES	(716)14-1-60	Boiling loop: some mass transfer and intergranular penetration
LOW CARBON SILICON STEELS	12-0-2	Survey
LOW IRON HIGH NICKEL INCONELS	(615)14-1-60	Boiling loop: severe intergranular penetration at vapor-liquid interface only
LOW CARBON STEELS	12-0-2	Survey
PURE IRON	12-0-2	Survey
NONFERROUS METALS AND ALLOYS:		
TITANIUM AND VANADIUM	12-0-2	Survey
CHROMIUM	12-0-2	Survey
COBALT	12-0-2	Survey
NICKEL	12-0-2, (831)14-1-60	Survey (Ni transfers to Cb above 1450°F)
COPPER	12-0-2	Survey
ZIRCONIUM	12-0-2	Survey
REFRACTORY METALS AND ALLOYS:		
MOLYBDENUM	(618)14-1-60	Mo - 1/2 Zr: SS capsules: 300 hrs
COLUMBIUM	(831)14-1-60	Cb - 1 Zr: capsules: (intergranular penetration at welds)
TANTALUM	12-0-2	Survey
TUNGSTEN	12-0-2	Survey
OTHER METALS AND ALLOYS:		
BERYLLIUM	12-0-2	Survey
ALUMINUM AND MAGNESIUM	12-0-2	Survey
ZINC, CADMIUM, TIN AND LEAD	721	Unknown
NOBLE METALS	12-0-2	Survey
BRAZING METALS Ni-Mn, Ni-Mo. Ni-P	12-0-2	Survey
SILVER BRAZING ALLOYS	721	Unknown
NONMETALS:		
DENSE OXIDES AL, BE, ETC.	12-0-2	Survey: static
OXIDE-BASE CERMETS		
CARBIDE-BASE CERMETS	12-0-2	Survey (less than 100 ppm O_2)
GLASSES	12-0-2	Survey
GRAPHITE	12-0-2	Survey

e. Data Sources for Potassium

Code No.	Source
4-2-2	Douglas, T. B., Ball, A. F., and Ginnings and Davis, J. Am. Chem. Soc., 74, 2472 (1952).
4-7-1	Ditchburn, R. W., and Gilmour, J. C., Reviews of Modern Physics, 13, No. 4., 310 (1941).
5-7-2	Ewing, C. T., Grand, J. A., and Miller, R. R., J. Am. Chem. Soc., 74, No. 1, 11 (1952).
5-10-5	Evans, W. H., Jacobson, E., Munson, T. R., and Wagman, D. D., Journal of Research of the NBS, Vol. 55, No. 2, 1955.
8-0-8	Hodgman, C. D., Editor, "Handbook of Chemistry and Physics," Cleveland, Chemical Rubber Publishing Co., 1958.
11-0-60	Kiser, R. W., Dept. of Chemistry, Kansas State Univ., TID-6142, June 20, 1960.
11-2-9	Kutateladze, S. S., Borishanskii, V. M., Novikov, I. I., and Fedynskii, O. S., "Liquid-Metal Heat Transfer Media," Atomnaia Energiia, Supp. No. 2, 1958, Translated by Consultants Bureau, Inc., New York, 1959.
11-15-7	Kirk, R. E., Othmer, D. F., Editors, "Encyclopedia of Chemical Technology," Vol. 1, 10, 13, First Sup. Vol., New York, The Interscience Encyclopedia, Inc., 1947.
12-0-2	Lyon, R. N., Editor, "Liquid-Metals Handbook," Second Ed., Washington, Atomic Energy Commission, Dept. of the Navy, 1952.
14-1-60	Notes of NASA-AEC Liquid Metals Corrosion Meeting, Dec. 7-8, 1960, Washington, D. C. (Proceedings published as NASA TN D-769, February, 1961).

Code No.	Source
19-13-60	Shapiro, A., and Meisl, C. J., General Electric Co., Flight Propulsion Laboratory Dept., Report No. R 60 FPD358-A, Nov. 9, 1960.
19-19-6	Stull, D. R., and Sinke, G. C., "Thermodynamic Properties of the Elements," Washington, American Chemical Society, 1956.
20-0-4	Taylor, J. W., AERE Tech. Note (ASTIA No. 139433), 1954.
23-4-61	Weatherford, W. D., Jr., "Momentum Dynamics of Gas-Phase Physical Processes," presented at American Physical Society 1961 Annual Meeting, New York, February 3, 1961.
509	MSA Research Corp.
615	National Aeronautics and Space Administration, Lewis Research Center.
618	General Electric, Flight Propulsion Laboratory Dept.
716	Oak Ridge National Laboratory
721	AiResearch Manufacturing Co. of Arizona
831	Rocketdyne Division, North American Aviation, Inc.

NaK (78)

a. General Discussion of NaK. Sodium-potassium alloys generally exhibit properties between those of sodium and potassium. However, the melting points lie at or below room temperature for a wide range of compositions. The eutectic composition of 77.7 wt % K exhibits higher electrical resistance, and correspondingly lower thermal conductivity than either sodium or potassium. The chemical properties of these alloys are intermediate to those of sodium and potassium; however, being liquid at room temperature, NaK presents somewhat greater hazards than does solid sodium or potassium.

b. Synopsis of Properties of NaK (78 wt % K)

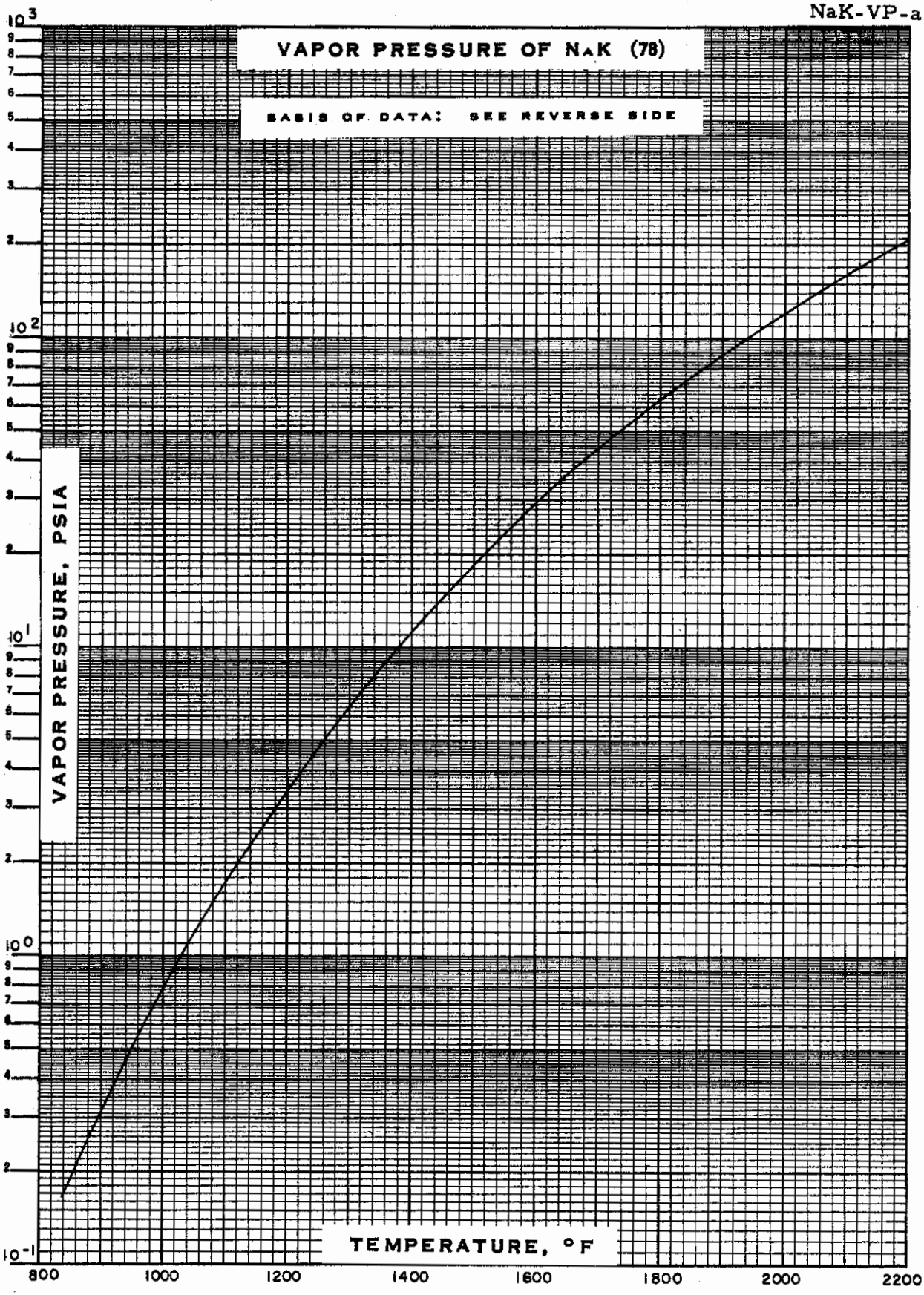
Property	Value	Temp (°F)	Data Basis	Reference
Physical:				
Eutectic Composition, wt % K	77.7	---	Experimental	5-19-5
Melting Point, °F	12.0	---		509
Boiling Point, °F	1456	---	Calculated	Page NaK-VP-a
Density of Liquid, lb/ft^3	32.878	212		509
	49.78	600	Experimental	Page NaK-ρ-a
	44.72	1200	Experimental	Page NaK-ρ-a
Viscosity, lb/ft hr	0.686	600	Experimental	Page NaK-μ-a
	0.388	1200	Experimental	Page NaK-μ-a
Surface Tension, lb/ft	7.375×10^{-8}	212		509
Thermal:				
Thermal Conductivity of Liquid, BTU/hr ft °F	15.01	600	Experimental	Page NaK-k-a
	14.87	1200	Experimental	Page NaK-k-a
Specific Heat of Liquid, BTU/lb °F	0.2117	600	Experimental	Page NaK-C-a
	0.2099	1200	Experimental	Page NaK-C-a
Electrical and Magnetic:				
Resistivity, μ ohm-inch	20.55	600	Experimental	Page NaK-Ω-a
	32.50	1200	Experimental	Page NaK-Ω-a

c. Property Tables for NaK

None presented.

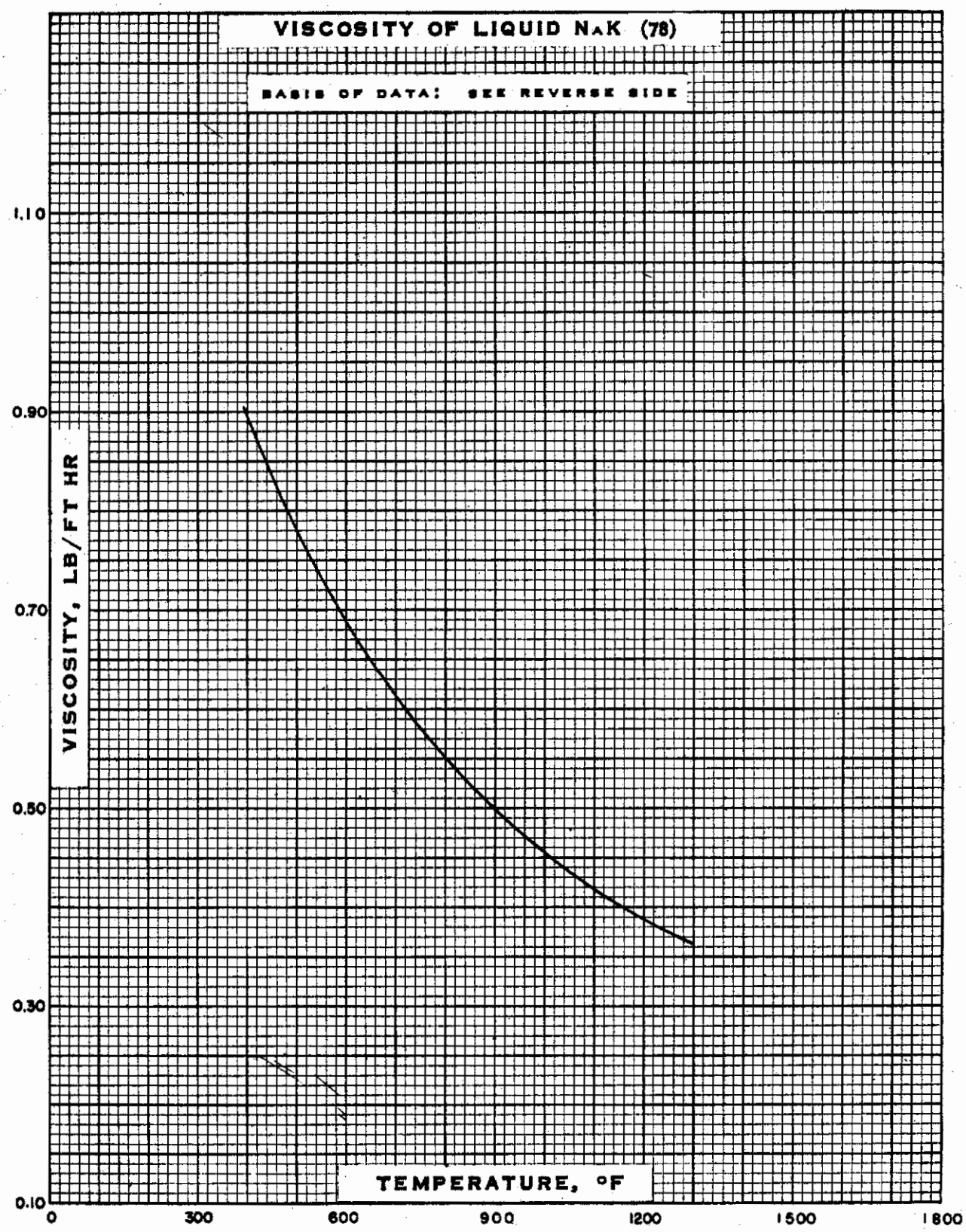
d. Working Charts for NaK

NaK-VP-a



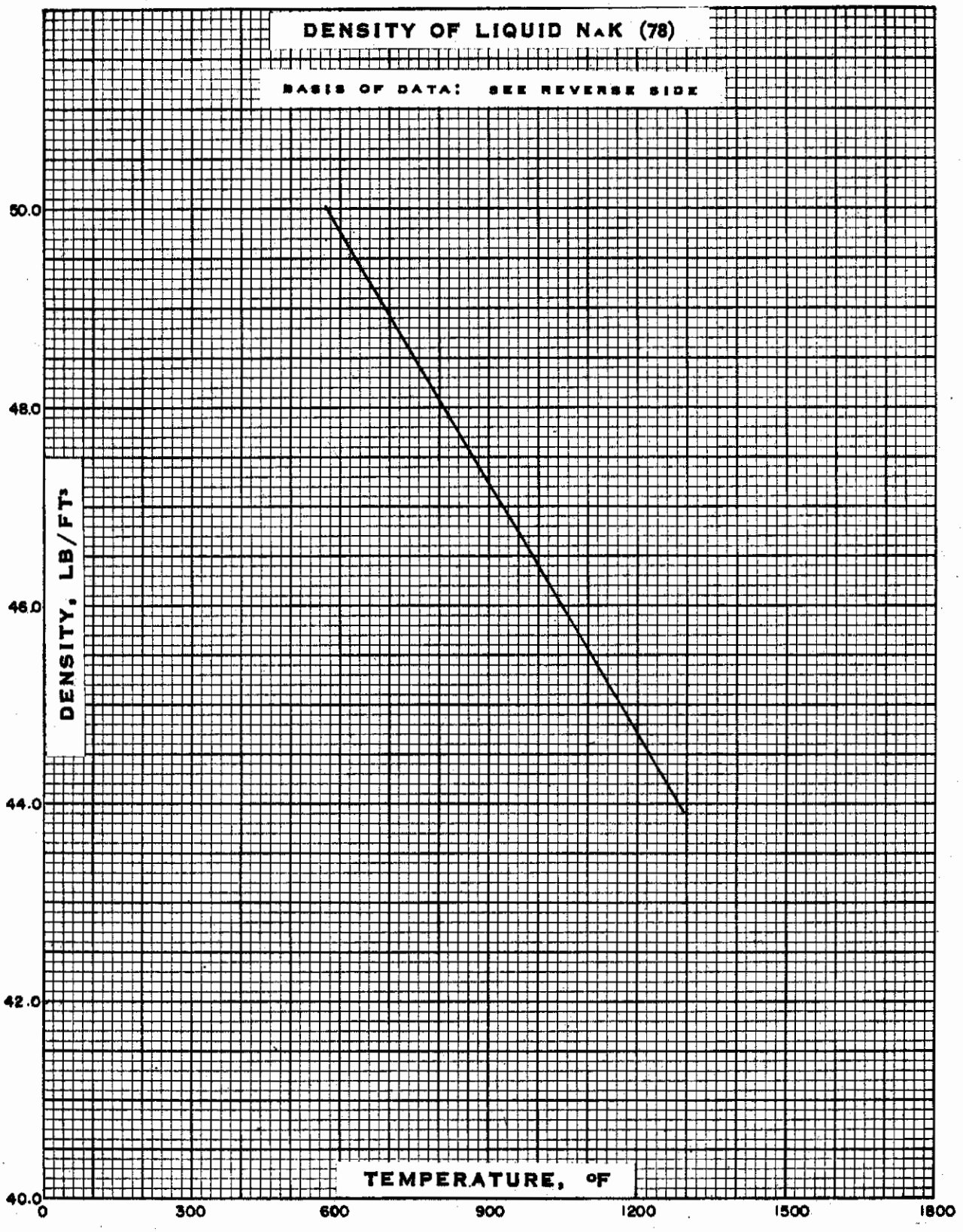
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Calculated		840-2200	Raoult's law was used to calculate the vapor pressure of NaK. The data for this computation were obtained from the sodium and potassium sections of this report.

NaK-μ-a



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	11-2-9	392-1292	The viscosity of NaK (75 wt % K) was measured by the method of damped torsional oscillations.

NaK-ρ-a



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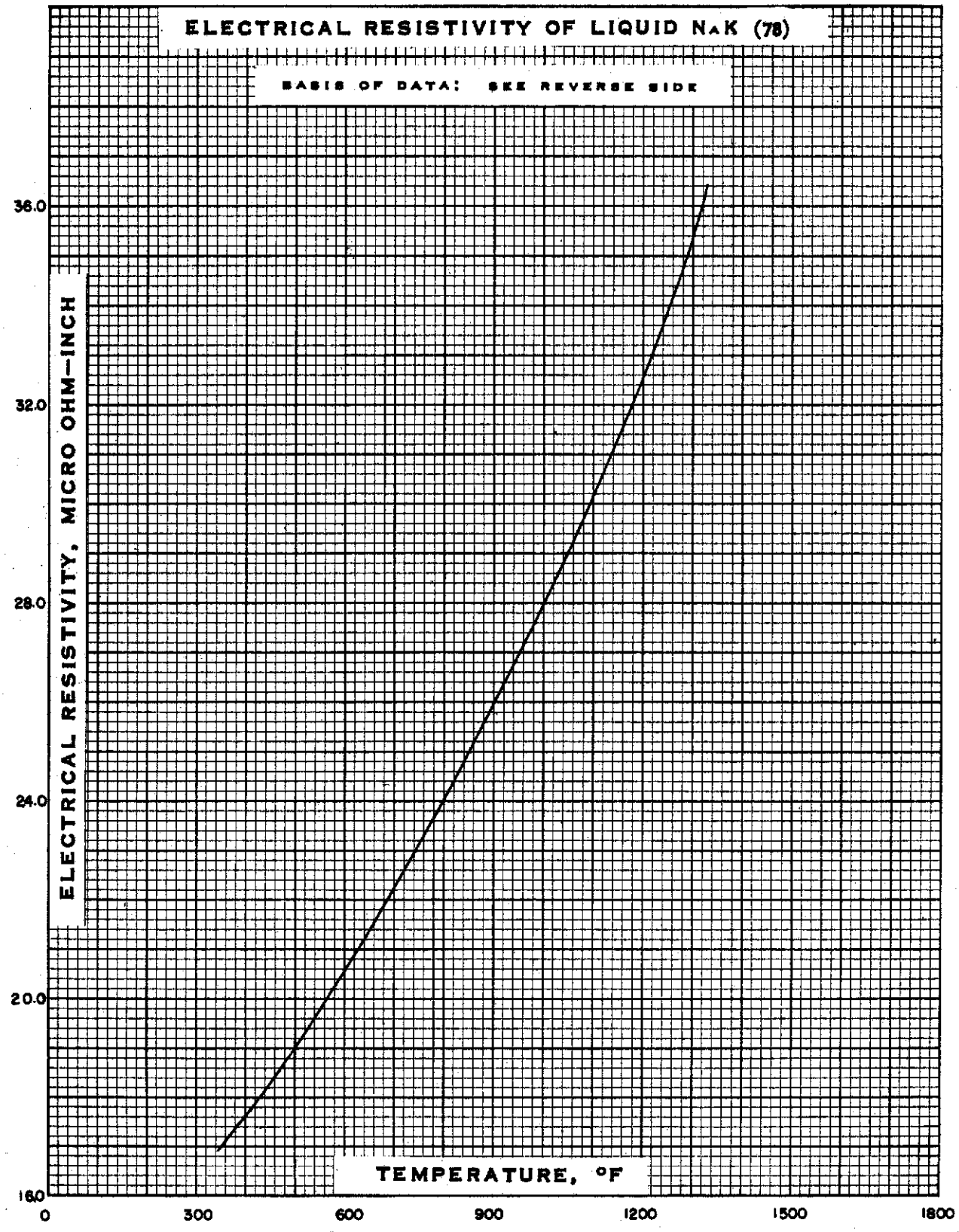
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	10-0-5, 11-2-9	572-1292	The NaK data tabulated in (10-0-5) are for 78.6 wt % K and those in (11-2-9) are for 75 wt % K. The 75 wt % data were determined by the method of heavy suspension in the molten metal and by the pycnometer method. The data of the two different references are in close agreement and an intermediate curve has been chosen to represent the density of NaK (78).

NaK-Ω-a



WADD TR 61-96

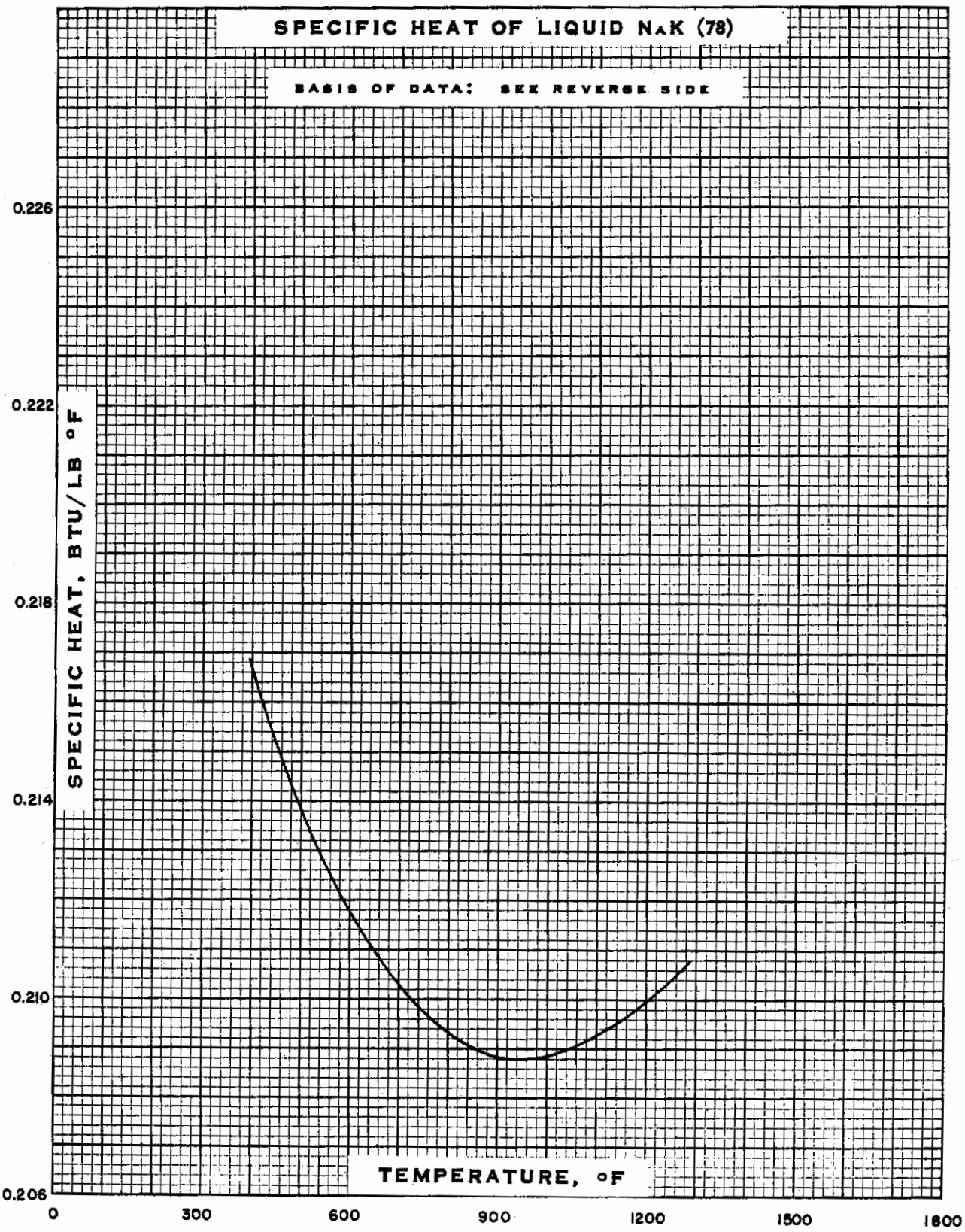
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	5-19-5, 10-0-5, 4-18-47	345-1328	The method of measuring the resistivity of NaK (80 wt % K) consisted of passing a measured current through a calibrated Inconel tube containing NaK, heating the central portion to a uniform temperature and measuring the potential drop across the heated length. The resistance was then calculated from the formula for parallel resistors.

NaK-k-a

WADD TR 61-96

Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	5-19-5, 10-0-5	392-1292	The thermal conductivity of NaK (77.7 wt % K) was measured in a uniaxial heat flow system. The calculated probable error for these results is 1.0%. The values at a particular temperature were duplicable to better than 0.3%.

NaK-C-a

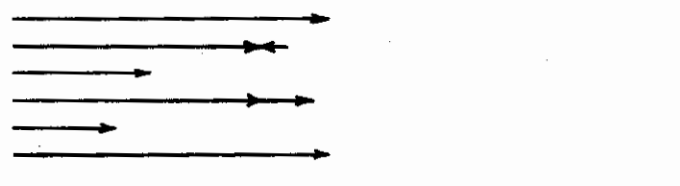


Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	4-2-2, 10-0-5	392-1472	Enthalpy measurements were made by the drop method using an ice calorimeter and a well designed constant-temperature furnace. Specific heat values were determined from these measurements. A sample was analyzed spectrochemically after the experiment, and showed only calcium, magnesium, rubidium, iron, and silicon in trace amounts.

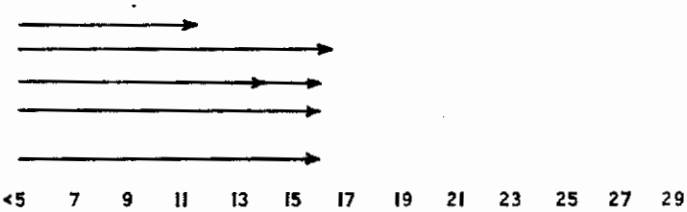
RESISTANCE OF MATERIALS TO LIQUID NaK

(SEE REVERSE SIDE OF SHEET FOR DATA BASIS)

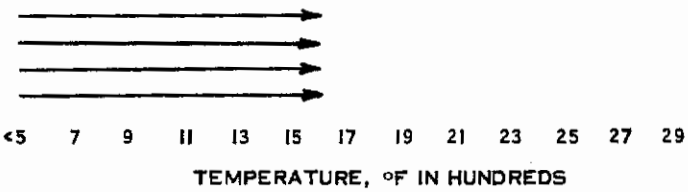
FERROUS METALS AND ALLOYS:



NONFERROUS METALS AND ALLOYS:

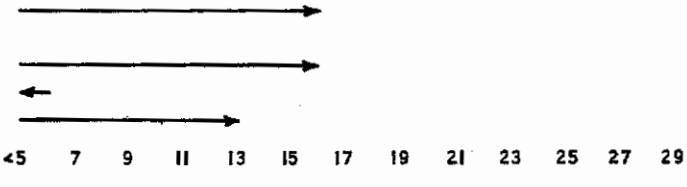


REFRACTORY METALS AND ALLOYS:



OTHER METALS AND ALLOYS:

NONMETALS:



NOTE: RIGHT-HAND ARROW-POINT INDICATES HIGHEST REPORTED TEST TEMPERATURE BELOW RESISTANCE LIMIT OF MATERIAL

LEFT-HAND ARROW-POINT INDICATES LOWEST REPORTED TEST TEMPERATURE ABOVE RESISTANCE LIMIT OF MATERIAL

(SEE FRONT SIDE OF SHEET FOR DATA)

	DATA SOURCE	REMARKS AND BASIS OF DATA
FERROUS METALS AND ALLOYS:		
FERRITIC STAINLESS STEELS 400 SERIES	12-0-2	Survey
AUSTENTIC STAINLESS STEELS 300 SERIES	(727)14-1-60	Loop: 3500 hrs: mass transfer and intergranular penetration
LOW CARBON SILICON STEELS	12-0-2	Survey
LOW IRON HIGH NICKEL INCONELS	(727)(825)12-1-60	Tilting furnace (slight mass transfer in loop 2000 hrs at 1400°F)
LOW CARBON STEELS	12-0-2	Survey
PURE IRON	12-0-2	Survey
NONFERROUS METALS AND ALLOYS:		
TITANIUM AND VANADIUM	12-0-2	Survey
CHROMIUM	12-0-2	Survey
COBALT	(727)(825)14-1-60	Tilting furnace (slight mass transfer and intergranular penetration in loop 2000 hrs at 1400°F)
NICKEL	(825)14-1-60	Tilting furnace
COPPER	12-0-2	Survey
ZIRCONIUM	(825)14-1-60	Tilting furnace
REFRACTORY METALS AND ALLOYS:		
MOLYBDENUM	(727)(825)14-1-60	Tilting furnace (also loop 2000 hrs at 1400°F)
COLUMBIUM	(825)14-1-60	Tilting furnace
TANTALUM	(825)14-1-60	Tilting furnace
TUNGSTEN	(825)14-1-60	Tilting furnace
OTHER METALS AND ALLOYS:		
BERYLLIUM	12-0-2	Survey
ALUMINUM AND MAGNESIUM	12-0-2	Survey
ZINC, CADMIUM, TIN AND LEAD	721	Unknown
NOBLE METALS	12-0-2	Survey
BRAZING METALS Ni Mn, Ni Mo, Ni P	12-0-2	Survey
SILVER BRAZING ALLOYS	721	Unknown
NONMETALS:		
DENSE OXIDES AL, BE, ETC.	(825)14-1-60	Tilting furnace
OXIDE-BASE CERMETS		
CARBIDE-BASE CERMETS	(825)14-1-60	Tilting furnace
GLASSES	12-0-2	Survey
GRAPHITE	12-0-2	Survey

e. Data Sources for NaK (78)

Code No.	Source
4-2-2	Douglas, T. B., Ball, A. F., Ginnings and Davis, J. Am. Chem. Soc., 74, 2472 (1952).
4-18-47	Drugas, P. G., Rehn, I. R., Wilkinson, W. D., ANL-5115, 1947.
5-19-5	Ewing, C. T., Seebold, R. E., Grand, J. A., and Miller, R. R., J. Phys. Chem., 59, 524 (1955).
10-0-5	Jackson, C. B., Editor, "Liquid Metals Handbook, Third Ed., Sodium (NaK) Supplement," Washington, Atomic Energy Commission, Department of the Navy, 1955.
11-2-9	Kutateladze, S. S., Borishanskii, V. M., Novikov, I. I., and Fedynskii, O. S., "Liquid-Metal Heat Transfer Media," Atomnaia Energiia, Supp. No. 2, 1958, Translated by Consultants Bureau, Inc., New York, 1959.
12-0-2	Lyon, R. N., Editor, "Liquid-Metals Handbook," Second Ed., Washington, Atomic Energy Commission, Dept. of the Navy, 1952.
14-1-60	Notes of "NASA-AEC Liquid Metals Corrosion Meeting, Dec. 7-8, 1960, Washington, D. C. (Proceedings published as NASA TN D-769, February, 1961).
509	MSA Research Corp.
721	AiResearch Manufacturing Co. of Arizona
727	Atomics International
825	Battelle Memorial Institute

SODIUM

a. General Discussion of Sodium. Sodium is a soft, silver-white alkali metal intermediate between potassium and lithium in its chemical and physical properties. It does not burn in dry air at ordinary temperatures, but it tarnishes rapidly in moist air and reacts violently with liquid water, igniting the liberated hydrogen. Because of its chemical reactivity, sodium is usually packed in sealed containers or immersed in a dry, saturated hydrocarbon liquid or inert gas atmosphere during storage and handling.

Sodium forms alloy compounds with antimony, arsenic, bismuth, cadmium, gold, lead, mercury, potassium, and tin. It also alloys to some extent with silver, calcium, lithium, magnesium, zinc, cerium, gallium, germanium, indium, palladium, and platinum. The corrosion properties of sodium which are nearly identical with those of potassium and sodium-potassium alloys, have been studied extensively. Hence, a significant amount of quantitative compatibility information is available.

Sodium is available in large quantities as bricks in cans or pails, or as cast-solid in drums or tank cars. The current price ranges from $0.17/lb in tank car lots to $0.50/lb for 1-2 pound bricks in 3-1/2 gallon pails.

b. Synopsis of Properties of Sodium

Property	Value	Temp (°F)	Date Basis	Reference
Physical:				
Atomic Weight	22.991	---	Survey	19-19-6
Melting Point, °F	208	---	Survey	19-19-6
Boiling Point, °F	1630	---	Semi-theoretical	Page Na-VP-a
Critical Point, psia	4409	4166 ± 740	Estimated	13-19-60
Density of Solid, lb/ft^3	60.619	68	Handbook	8-0-8
Density of Liquid, lb/ft^3	46.25	B.P.	Extrapolated	Page Na-ρ-a
Density of Vapor, lb/ft^3	0.0157	B.P.	Theoretical	Page Na-ρ-b
Viscosity of Liquid, lb/ft hr	0.366	B.P.	Extrapolated	Page Na-μ-a
Viscosity of Vapor, lb/ft hr	0.0551	B.P.	Extrapolated	Page Na-μ-b
Surface Tension, lb/ft	0.01308	M.P.	Experimental	10-0-5
Thermal:				
Thermal Conductivity of Liquid, BTU/hr ft °F	32.05	B.P.	Extrapolated	Page Na-k-a
Thermal Conductivity of Vapor, BTU/hr ft °F	0.0161	B.P.	Estimated	Page Na-k-b
Specific Heat of Liquid, BTU/ft °F	0.3073	B.P.	Experimental	Page Na-C-a
Specific Heat of Vapor, BTU/ft °F	0.213	B.P.	Theoretical	Page Na-C-b
Latent Heat of Fusion, BTU/lb	48.68	M.P.	Survey	19-19-6
Latent Heat of Vaporization, BTU/lb	1662	B.P.	Theoretical	Page Na-ΔH-a
Electrical and Magnetic:				
Resistivity, μ ohm-inch	3.80	M.P.	Extrapolated	19-0-6
Ionization Potential, volts	5.14	---	Experimental	11-0-60
Magnetic Susceptibility, fps electromagnetic units/unit mass	0.2149	64.4 sol	Handbook	8-0-8
Thermal Neutron Cross Sections (2200 m/s):				
Absorption, barns	505 ± 10	---	Handbook	8-0-8
Scattering, barns	4.0 ± 0.5	---	Handbook	8-0-8

c. Property Tables for Sodium

Basis of data from Reference 19-13-60: Thermodynamic properties of equilibrium vapor mixtures were derived by machine computation with conventional relations assuming the individual monomer and dimer species to be ideal gases. The equilibrium specific heat was then determined by differentiation. The frozen specific heat was computed by adding the contributions of the individual species. Free energies of the monatomic and diatomic forms of the vapor were used to calculate the dimerization equilibrium constant, hence, no added assumptions were required concerning heat of dissociation. Iterations on vapor pressure were made until the ratio of the heat of vaporization to temperature became identical to the entropy of vaporization. Therefore, all data from this reference are internally consistent.

PHYSICAL PROPERTIES OF SODIUM
Saturated Phases

(Ref: 19-13-60)

Temperature (°R)	Equilibrium Vapor Molecular Weight	Vapor Pressure (psia)	Liquid Specific Volume (ft^3/lb)	Vapor Specific Volume (ft^3/lb)	Equilibrium Sonic Velocity (ft/sec)	Frozen Sonic Velocity (ft/sec)
1300	23.791	3.392×10^{-2}	1.913×10^{-2}	2.452×10^{4}	1622.8	2107.2
1400	24.050	8.135×10^{-2}	1.944×10^{-2}	7.680×10^{3}	1667.9	2168.5
1500	24.330	2.335×10^{-1}	1.976×10^{-2}	2.833×10^{3}	1709.2	2224.5
1600	24.625	5.842×10^{-1}	2.008×10^{-2}	1.194×10^{3}	1747.5	2276.2
1700	24.922	1.317×10^{0}	2.039×10^{-2}	5.559×10^{2}	1783.9	2324.7
1800	25.217	2.716×10^{0}	2.071×10^{-2}	2.820×10^{2}	1818.7	2370.5
1900	25.510	5.153×10^{0}	2.102×10^{-2}	1.551×10^{2}	1852.1	2414.0
2000	25.793	9.153×10^{0}	2.134×10^{-2}	9.091×10^{1}	1884.7	2455.9
2100	26.060	1.539×10^{1}	2.166×10^{-2}	5.619×10^{1}	1917.0	2496.7
2200	26.314	2.469×10^{1}	2.197×10^{-2}	3.634×10^{1}	1948.7	2536.6
2300	26.554	3.801×10^{1}	2.229×10^{-2}	2.445×10^{1}	1980.0	2575.6
2400	26.781	5.621×10^{1}	2.260×10^{-2}	1.711×10^{1}	2011.0	2614.0
2500	26.994	8.024×10^{1}	2.292×10^{-2}	1.239×10^{1}	2041.7	2652.0
2600	27.186	1.112×10^{2}	2.324×10^{-2}	9.233×10^{0}	2072.5	2689.9
2700	27.352	1.505×10^{2}	2.355×10^{-2}	7.038×10^{0}	2103.8	2728.2

THERMAL PROPERTIES OF SODIUM
Saturated Phases

(Ref: 19-13-60)

Temperature (°R)	Specific Heat of Equilibrium Vapor (BTU/lb °R)	Frozen Specific Heat of Vapor (BTU/lb °R)	Ratio of Frozen Specific Heats of Vapor	Specific Heat of Liquid (BTU/lb °R)
1300	0.6431	0.2150	1.635	0.3035
1400	0.6841	0.2147	1.625	0.3016
1500	0.7097	0.2144	1.615	0.3004
1600	0.7217	0.2141	1.604	0.2999
1700	0.7213	0.2139	1.594	0.3001
1800	0.7119	0.2137	1.584	0.3010
1900	0.6974	0.2135	1.574	0.3026
2000	0.6786	0.2133	1.565	0.3048
2100	0.6567	0.2132	1.556	0.3077
2200	0.6339	0.2131	1.548	0.3113
2300	0.6113	0.2131	1.541	0.3156
2400	0.5890	0.2130	1.534	0.3206
2500	0.5674	0.2130	1.528	0.3262
2600	0.5467	0.2130	1.522	0.3326
2700	0.5269	0.2131	1.517	0.3396

THERMODYNAMIC PROPERTIES OF SODIUM
Saturated Phases

(Ref: 19-13-60)

Temperature T (°R)	Enthalpy of Liquid $(H-H_o)_L$ (BTU/lb)	Enthalpy of Vapor $(H-H_o)_V$ (BTU/lb)	Entropy of Liquid S_L (BTU/lb °R)	Entropy of Vapor S_V (BTU/lb °R)
1300	408.2	2262.8	0.8807	2.3073
1400	438.4	2269.3	0.9031	2.2109
1500	468.5	2274.9	0.9239	2.1282
1600	498.5	2280.0	0.9433	2.0567
1700	528.5	2285.3	0.9615	1.9948
1800	558.6	2291.1	0.9786	1.9411
1900	588.8	2297.2	0.9949	1.8941
2000	619.1	2304.1	1.0105	1.8530
2100	649.7	2312.1	1.0255	1.8171
2200	680.7	2321.0	1.0399	1.7855
2300	712.0	2330.7	1.0538	1.7576
2400	743.8	2341.2	1.0673	1.7329
2500	776.2	2352.6	1.0805	1.7111
2600	809.1	2365.1	1.0934	1.6919
2700	842.7	2378.8	1.1061	1.6751

THERMODYNAMIC PROPERTIES OF SODIUM

Liquid Phase: $H^{\circ}_{536.67} - H^{\circ}_{0} = 2,758$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^{\circ} - H^{\circ}_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^{\circ} - H^{\circ}_{536.67})/T$ (BTU/lb mole °R)
1260	6338	20.05	15.02
1440	7592	20.98	15.71
1620	8836	21.80	16.35
1800	10075	22.52	16.93
1980	11327	23.19	17.47

THERMODYNAMIC PROPERTIES OF SODIUM

Ideal Monatomic Gas: $H^\circ_{536.67} - H^\circ_o = 2,666$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^\circ - H^\circ_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^\circ - H^\circ_{536.67})/T$ (BTU/lb mole °R)
1260	3593	40.95	38.10
1440	4487	41.62	38.51
1620	5382	42.20	38.88
1800	6277	42.73	39.25
1980	7171	43.20	39.58
2160	8064	43.63	39.90
2340	8959	44.03	40.21
2520	9853	44.40	40.49
2700	10748	44.74	40.76
2880	11642	45.06	41.02
3060	12535	45.36	41.27
3240	13430	45.65	41.51
3420	14324	45.92	41.74
3600	15219	46.17	41.95

THERMODYNAMIC PROPERTIES OF SODIUM

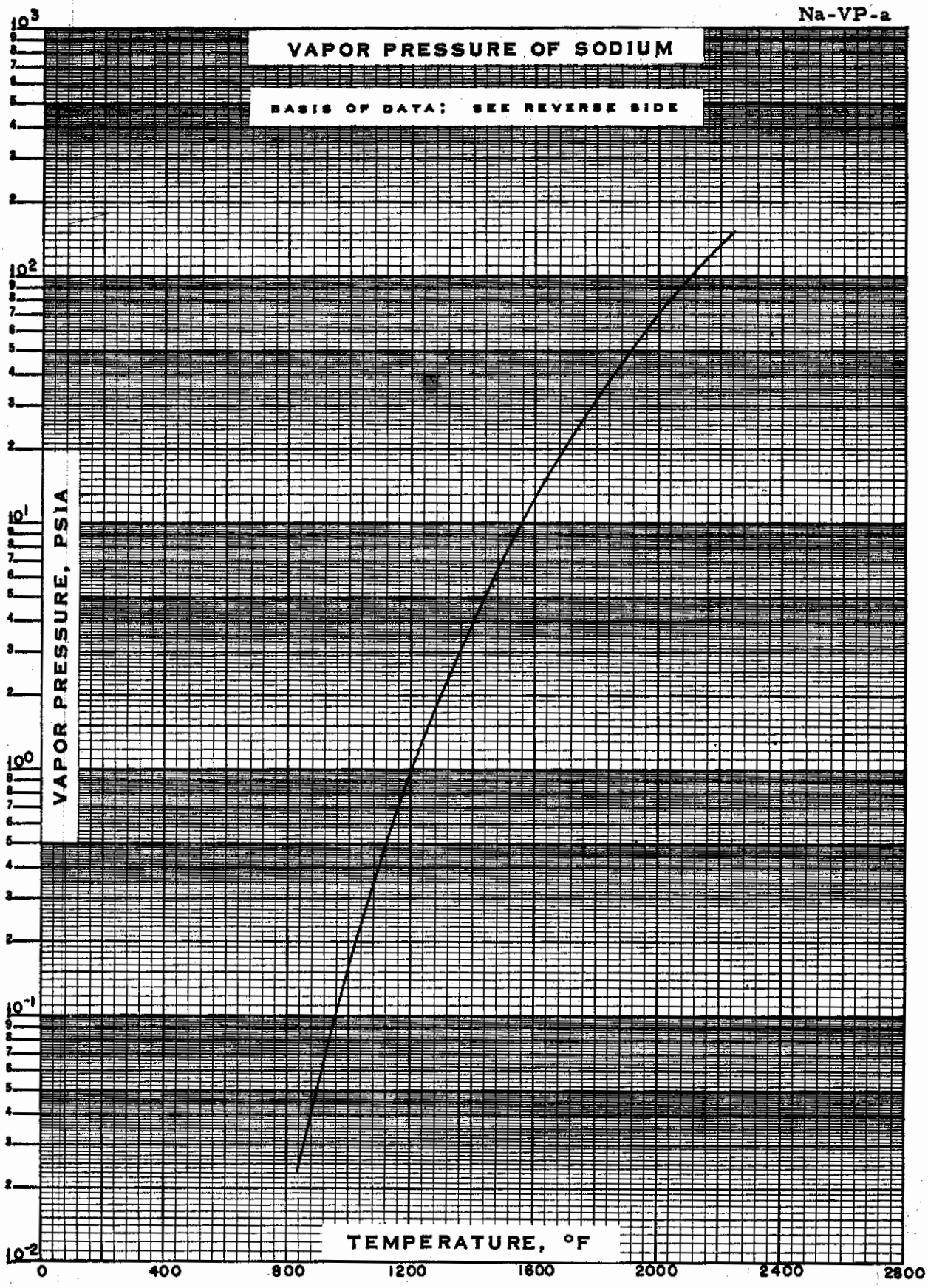
Ideal Diatomic Gas: $H^\circ_{536.67} - H^\circ_0 = 4,471$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^\circ - H^\circ_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^\circ - H^\circ_{536.67})/T$ (BTU/lb mole °R)
1440	8244	63.98	58.26
1620	9898	65.06	58.95
1800	11585	66.05	59.62
1980	13250	66.93	60.24
2160	14947	67.75	60.83
2340	16636	68.50	61.40
2520	18335	69.20	61.93
2700	20045	69.85	62.43

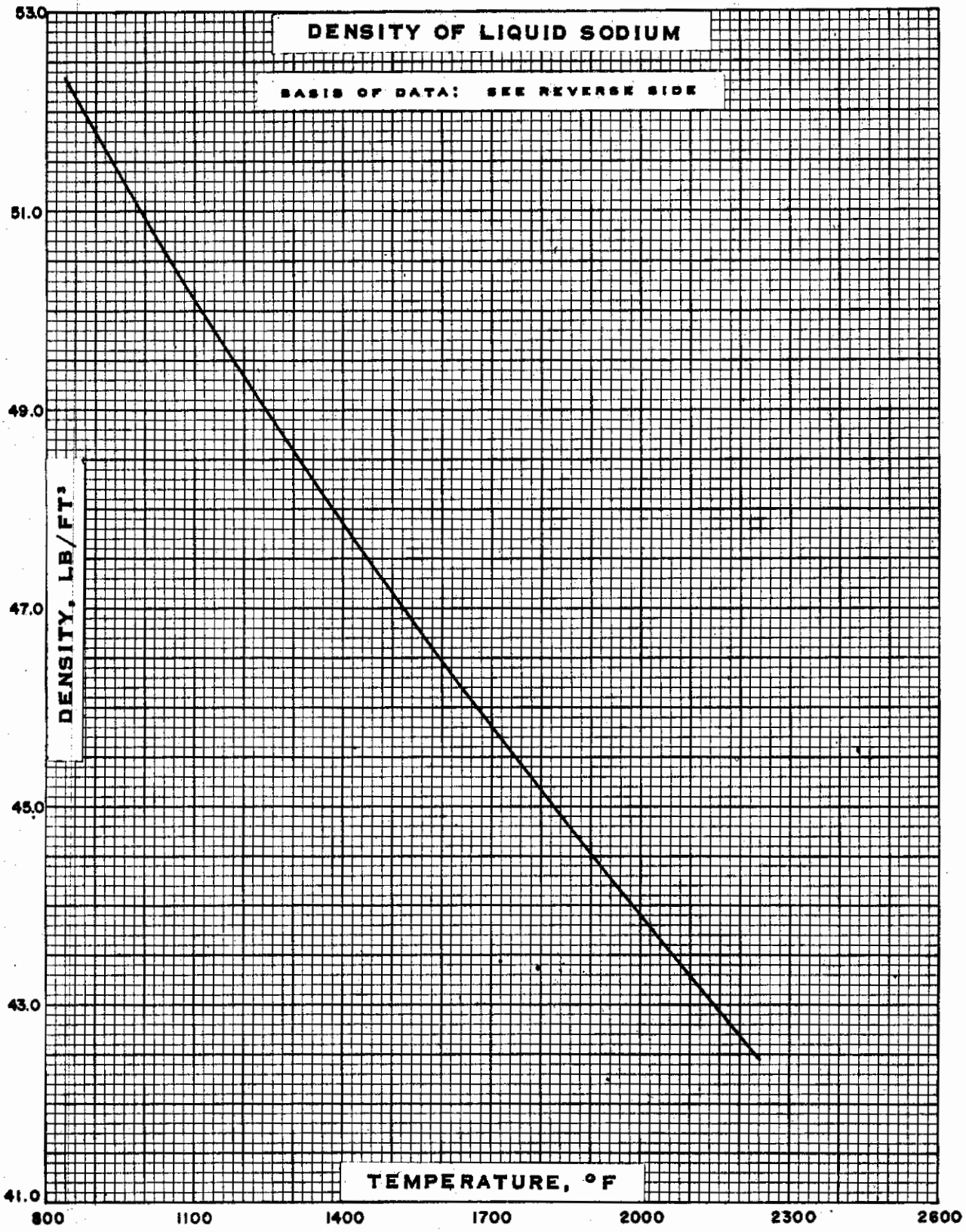
d. Working Charts for Sodium

Na-VP-a



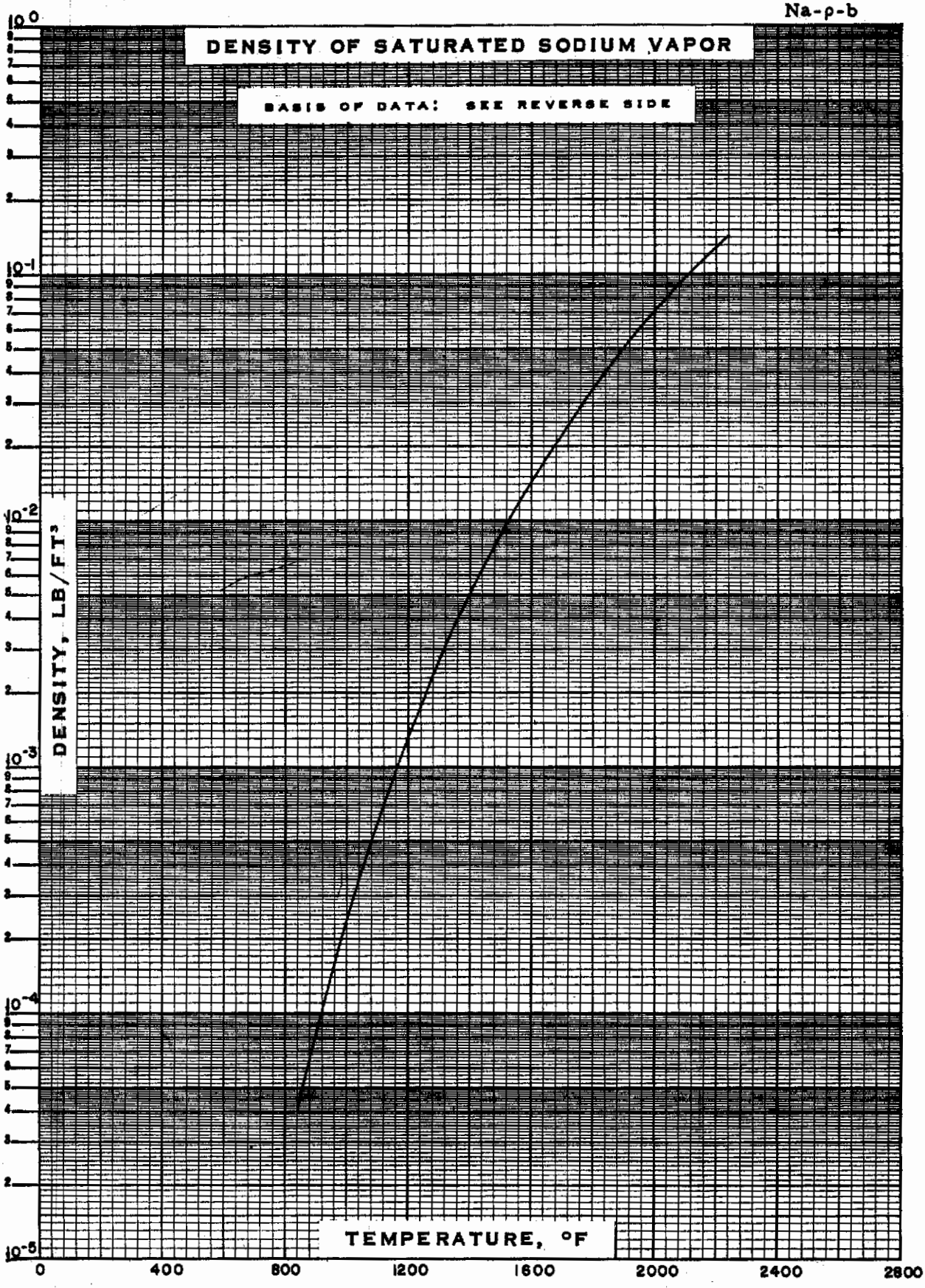
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	3-2-60	1640-2000	Experimental bomb.
	10-0-5	1150-1600	Triple-distilled sodium was employed. The method used consisted of boiling the sodium and then refluxing it with a condenser in which the pressure was maintained with purified argon. The argon pressure was measured by a mercury manometer which provided an indirect indication of the vapor pressure of sodium.
Semi-theoretical	19-13-60	840-2240	Experimental values were theoretically adjusted to yield consistent thermodynamic data.
Reconciliation plots	8-0-8, 19-0-7	1020-1520	Graphic methods were used to evaluate the collected data.

Note: the recommended vapor pressure curve does not agree with any of the available boiling points, but tends to fall between those listed in the literature.



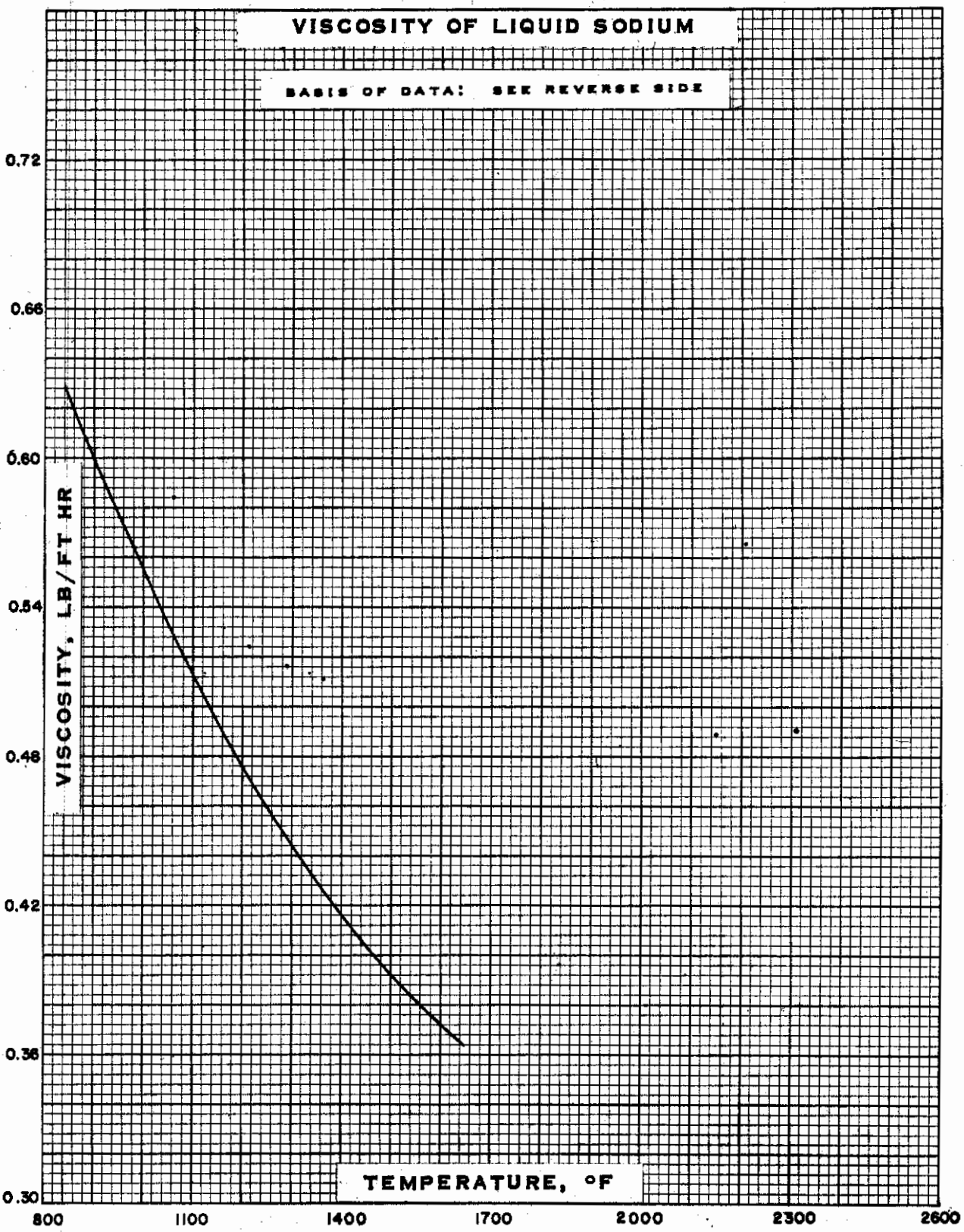
Basis of Data	Known Reference Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	5-19-60, 10-0-5	840-1500	Values were calculated from an equation based on experimental values.
Experimental	11-2-9	840-1300	Determined by the method of heavy suspension in the metal and by the pycnometer method.
Experimental	12-0-2, 19-13-60	840-1292	The accuracy of the density values to 1292°F is better than 1%.
Extrapolated	19-13-60	1292-2240	Extended (12-0-2) data.

Na-ρ-b



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	19-13-60	840-2240	The specific volume of the vapor mixture was calculated from the perfect gas law.

Na-μ-a



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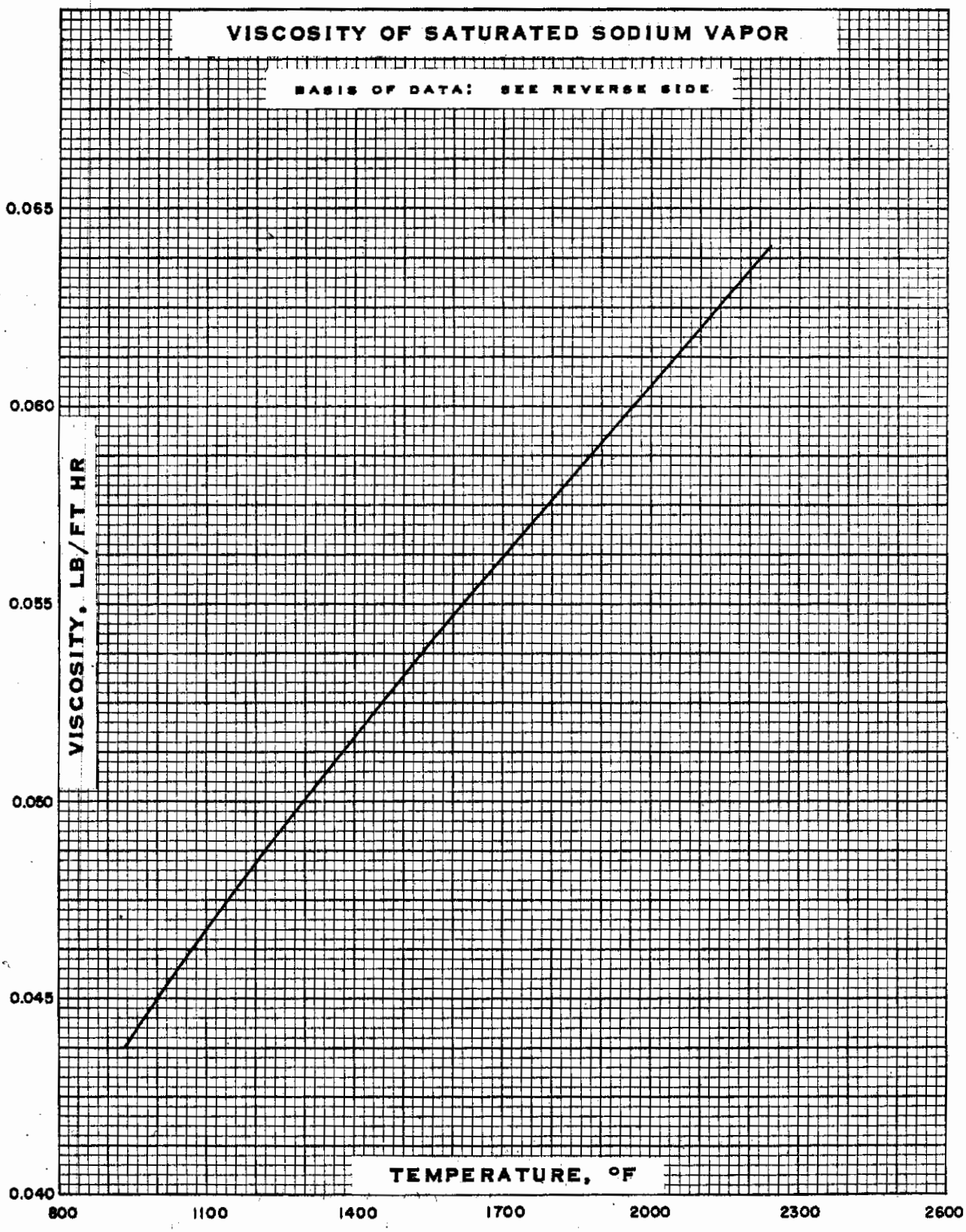
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	5-7-4	840-1062	A nickel viscometer of the Ostwald type was employed to measure the viscosity coefficients of sodium. Within the limits of the experimental analysis the sodium was 100.0% pure.
Experimental	11-2-9	840-1292	Measured by the method of damped torsional oscillations.
Extrapolated	10-0-5	1112-1652	Extrapolated by the equation of Andrade.

Na-μ-b



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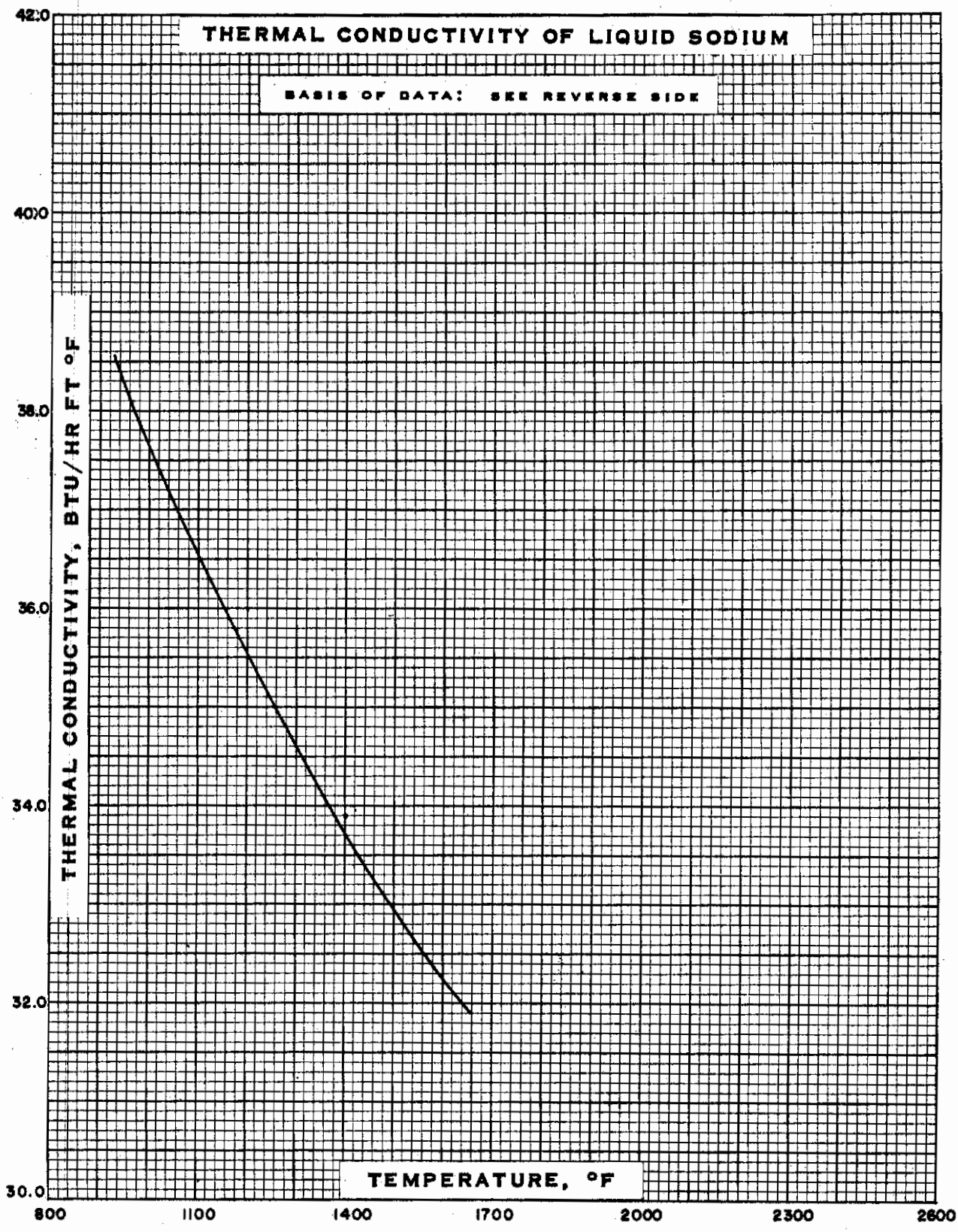
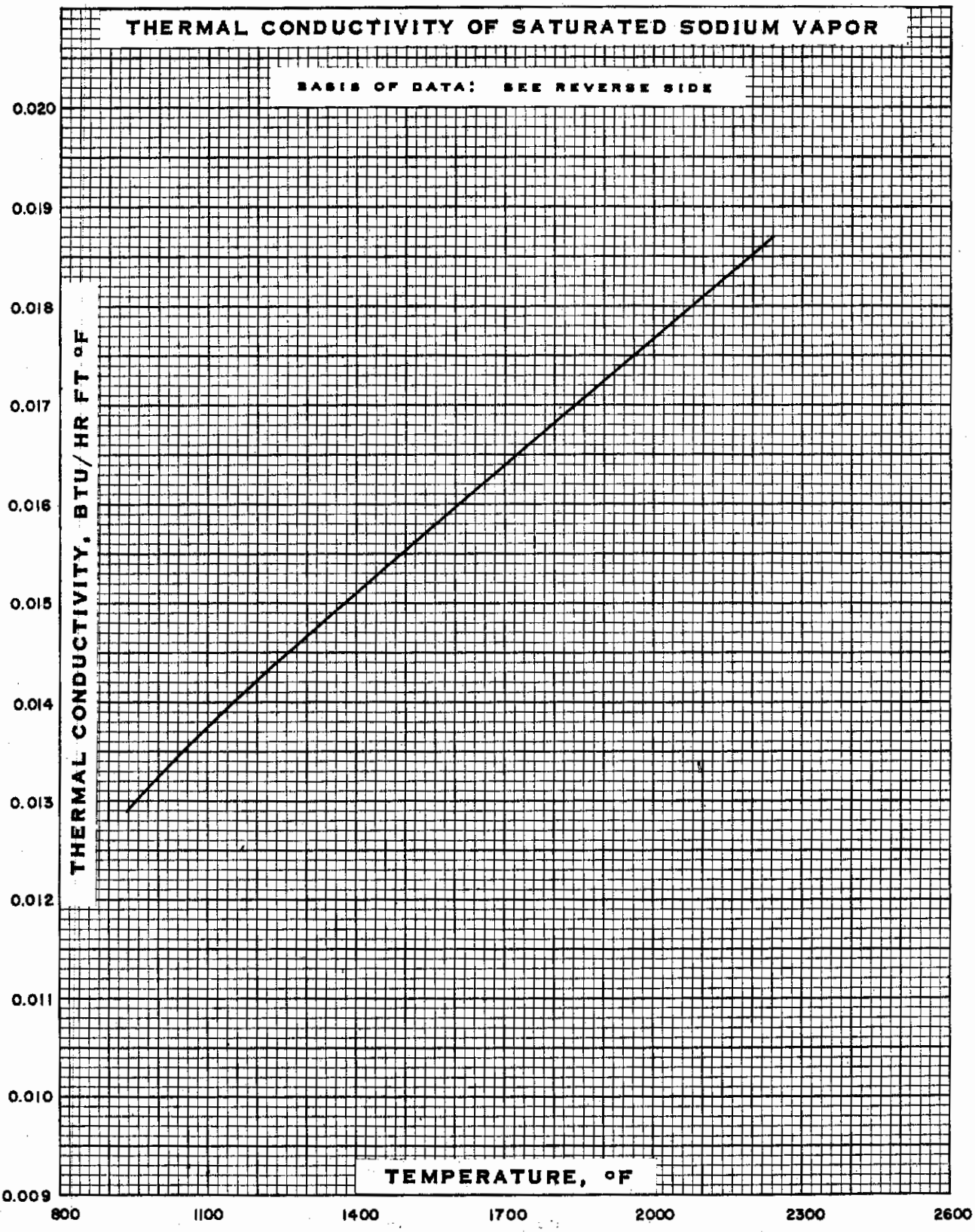
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	23-4-61	840-2240	Computed for variable molecular weight saturated vapor using new equation for gas viscosity.

Na-k-a

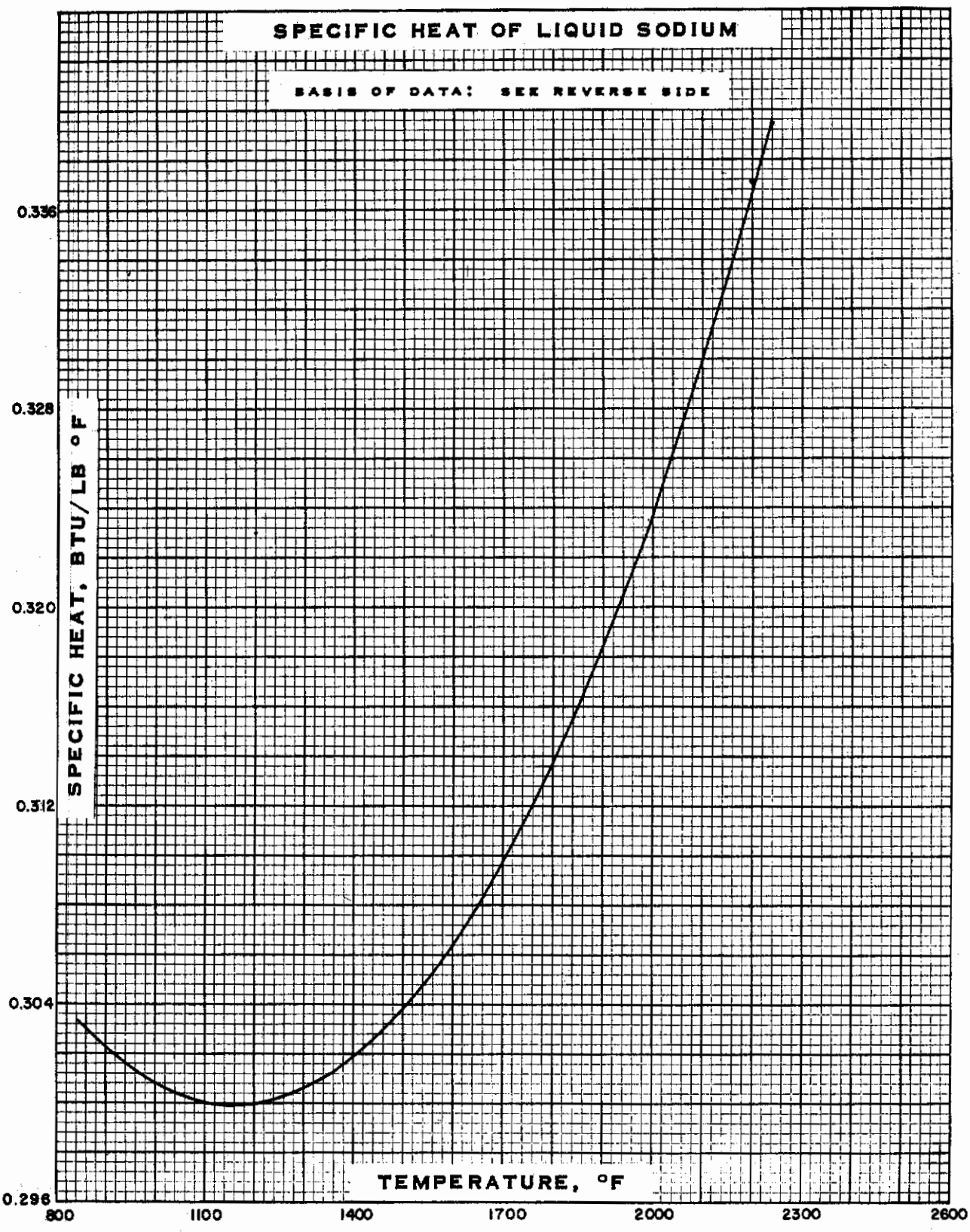


Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Extrapolated	10-0-5	932-1472	The thermal conductivity of sodium was measured in a uniaxial heat flow system up to 950°F. The calculated probable error in the measurements was 1%. A value of the Lorentz function (2.35) determined over the measured range along with values of the electrical resistivity was used to calculate an extension of the thermal conductivity values up to a temperature of 1500°F.

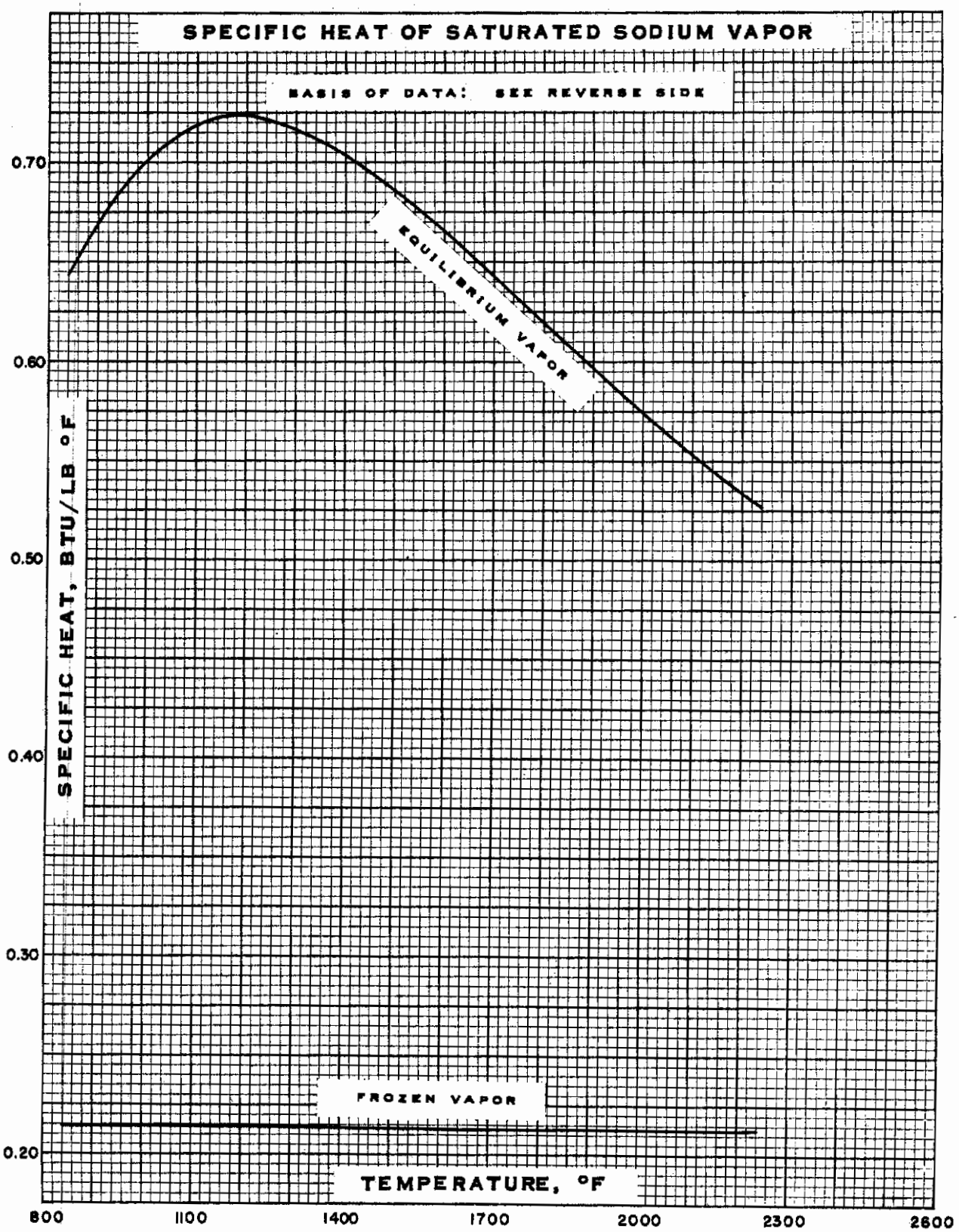


Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Estimated		840-2240	Calculated from the frozen specific heat (page Na-C-b) and viscosity (page Na-μ-b) of saturated vapor assuming a constant Prandtl No. of 0.73.

Na-C-a

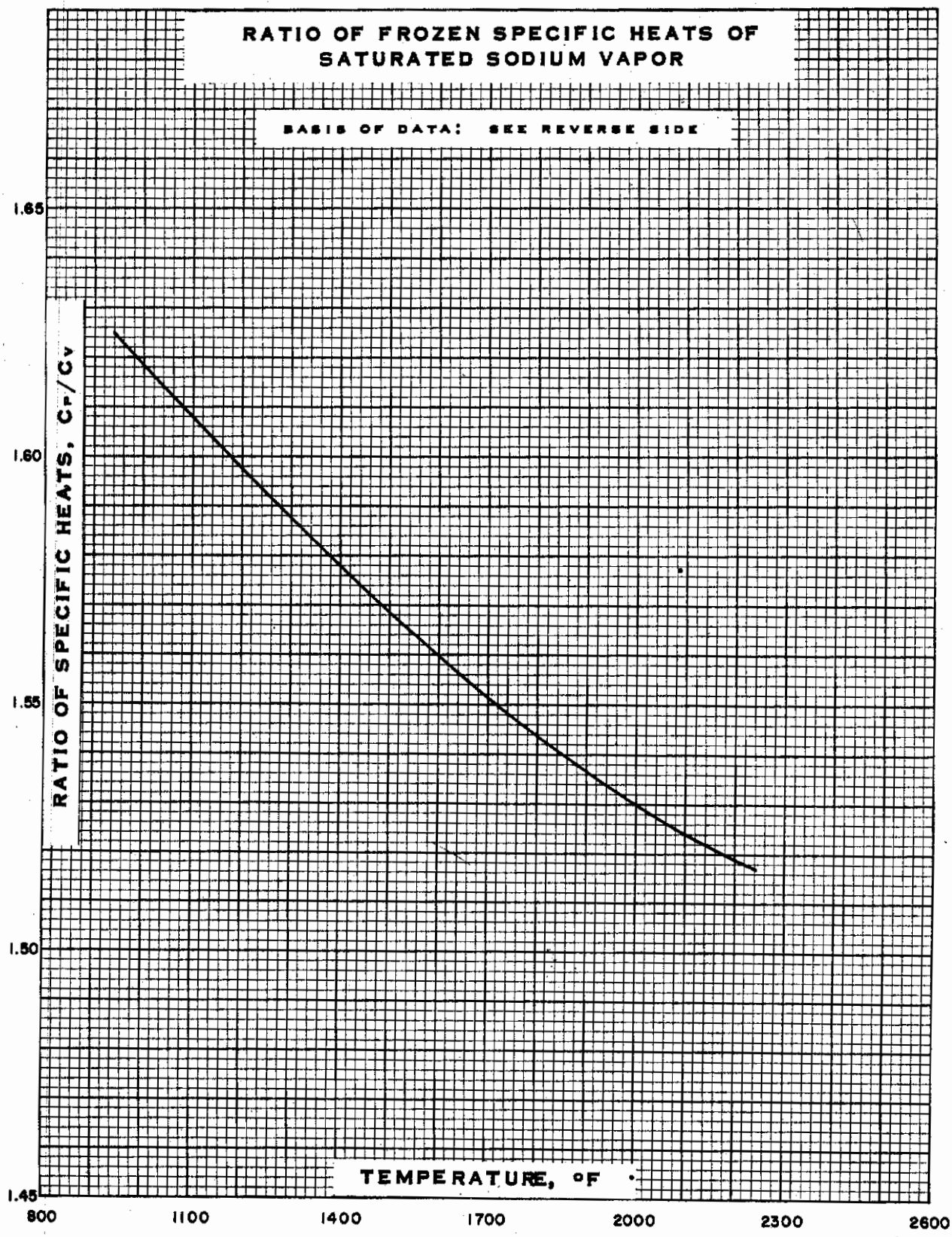


Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	7-4-0, 19-13-60	840-1652	Enthalpy measurements were made by the drop method using an ice calorimeter and a well designed constant temperature furnace. Specific heat values of liquid sodium were determined from these measurements. The sample was analyzed spectrochemically after the experiments. Of the 47 elements tested for, calcium and lithium were estimated as occupying between 0.0001 and 0.001 wt % and potassium between 0.001 and 0.01 wt %. Other samples from the same original source distilled by the same procedure contained as much as 0.01 wt % oxygen. All the results lead to a probable error of as much as 0.3 % for the derived specific heat values. There is an increased uncertainty between 1472° and 1652°F due to the difficulty of determining the derivative of an empirical function accurately near its end points.
Extrapolated	19-13-60	1652-2240	Extended by a parabolic equation.



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	19-13-60	840-2240	Two specific heats were calculated for sodium vapor. (1) The frozen specific heat is a state point property calculated by adding the separate contributions of the monatomic and diatomic vapors for a given equilibrium composition. (2) The equilibrium specific heat applies to the rigorous definition of specific heat, and includes the energy required to alter the degree of equilibrium dissociation.

Na-γ-a



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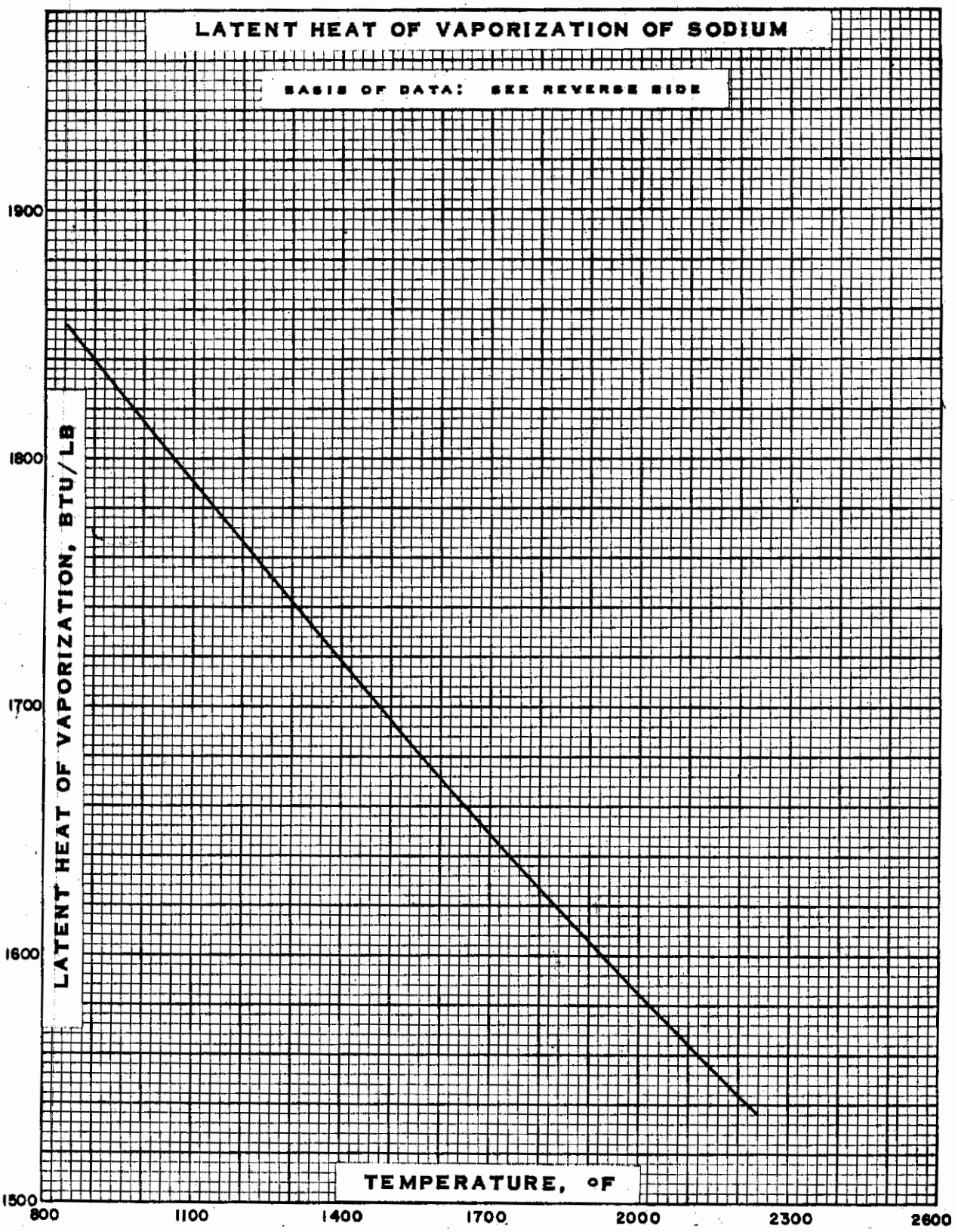
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	19-13-60	940-2240	Ratio of the frozen specific heat at constant pressure to the frozen specific heat at constant volume.

Na-ΔH-a



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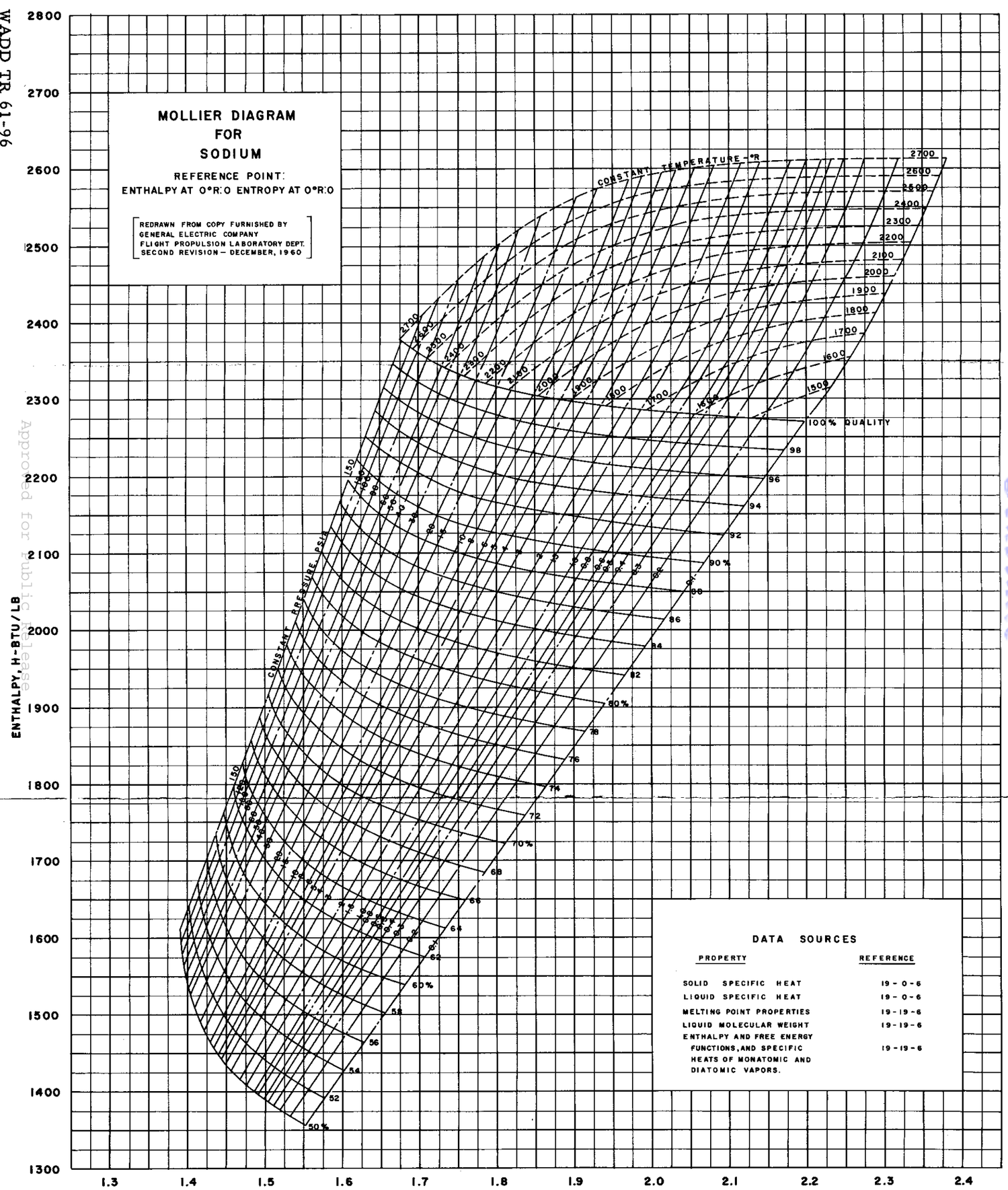
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	5-19-60	840-2000	Calculated from the Clapeyron equation.
Theoretical	19-13-60	840-2240	
Theoretical	19-19-6	Boiling Point	

MOLLIER DIAGRAM FOR SODIUM

REFERENCE POINT:
ENTHALPY AT 0°R: 0 ENTROPY AT 0°R: 0

[REDRAWN FROM COPY FURNISHED BY GENERAL ELECTRIC COMPANY FLIGHT PROPULSION LABORATORY DEPT. SECOND REVISION – DECEMBER, 1960]



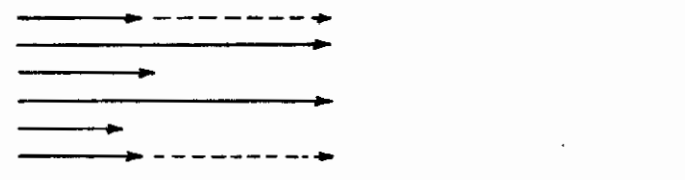
DATA SOURCES

PROPERTY	REFERENCE
SOLID SPECIFIC HEAT	19-0-6
LIQUID SPECIFIC HEAT	19-0-6
MELTING POINT PROPERTIES	19-19-6
LIQUID MOLECULAR WEIGHT	19-19-6
ENTHALPY AND FREE ENERGY FUNCTIONS, AND SPECIFIC HEATS OF MONATOMIC AND DIATOMIC VAPORS.	19-19-6

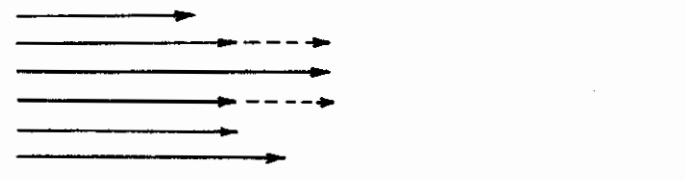
RESISTANCE OF MATERIALS TO SOLUTION AND MASS TRANSFER IN LIQUID SODIUM

(SEE REVERSE SIDE OF SHEET FOR DATA BASIS)

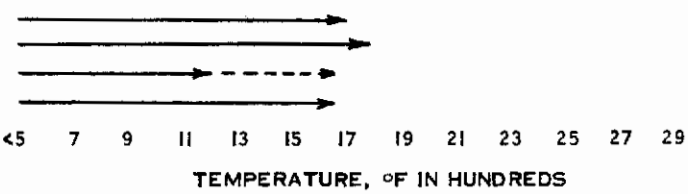
FERROUS METALS AND ALLOYS:



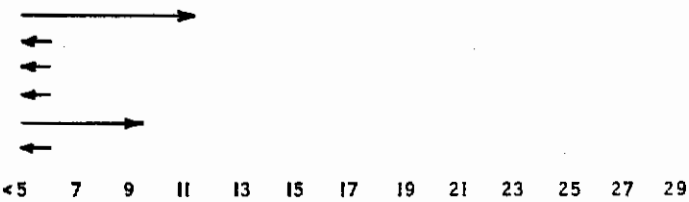
NONFERROUS METALS AND ALLOYS:



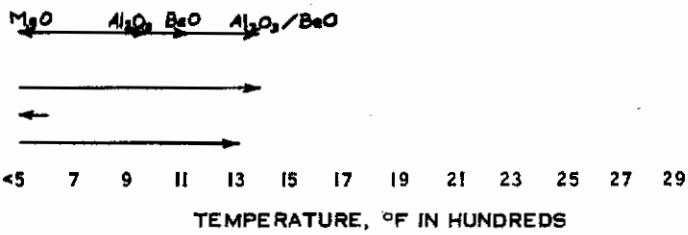
REFRACTORY METALS AND ALLOYS:



OTHER METALS AND ALLOYS:



NONMETALS:



NOTE: RIGHT-HAND ARROW-POINT INDICATES HIGHEST REPORTED TEST TEMPERATURE BELOW RESISTANCE LIMIT OF MATERIAL

LEFT-HAND ARROW-POINT INDICATES LOWEST REPORTED TEST TEMPERATURE ABOVE RESISTANCE LIMIT OF MATERIAL

(SEE FRONT SIDE OF SHEET FOR DATA)

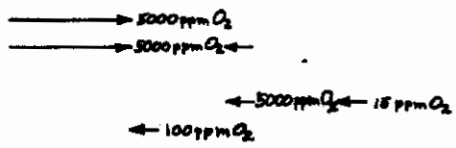
	DATA SOURCE	REMARKS AND BASIS OF DATA
FERROUS METALS AND ALLOYS:		
FERRITIC STAINLESS STEELS 400 SERIES	2-11-54, 12-0-2	Static and dynamic: (less than 200 ppm O_2): extended by 12-0-2
AUSTENTIC STAINLESS STEELS 300 SERIES	2-0-58, 10-0-5, (831)14-1-60, 2-11-54	Dynamic
LOW CARBON SILICON STEELS	10-0-5, 12-0-2	Survey
LOW IRON HIGH NICKEL INCONELS	(831)14-1-60	Boiling loop component
LOW CARBON STEELS	10-0-5, 12-0-2	Survey
PURE IRON	10-0-5, 12-0-2	Dynamic (100 ppm O_2): extended by 12-0-2
NONFERROUS METALS AND ALLOYS:		
TITANIUM AND VANADIUM	10-0-5, 12-0-2	Survey
CHROMIUM	10-0-5, 12-0-2	Static: (100 ppm O_2): extended by 12-0-2
COBALT	(831)14-1-60	Boiling loop component
NICKEL	10-0-5, 12-0-2	Static: (100 ppm O_2): extended by 12-0-2
COPPER	10-0-5	17-14, Cu Mo: static (1200°F dynamic) (100 ppm O_2)
ZIRCONIUM	11-0-53	Static, isothermal
REFRACTORY METALS AND ALLOYS:		
MOLYBDENUM	(618)14-1-60	Mo - 1/2 Zr: 300 hrs: SS capsule
COLUMBIUM	(716)14-1-60	Cb - W
TANTALUM	18-23-58, 12-0-2	316 SS forced circulation loop: (less than 10 ppm O_2) extended by 12-0-2
TUNGSTEN	10-0-5, 12-0-2	Survey
OTHER METALS AND ALLOYS:		
BERYLLIUM	10-0-5, 12-0-2	Survey
ALUMINUM AND MAGNESIUM	12-0-2	Survey
ZINC, CADMIUM, TIN AND LEAD	721	Unknown
NOBLE METALS	10-0-5, 12-0-2	Survey
BRAZING METALS $Ni-Mn$, $Ni-Mo$. $Ni-P$	10-0-5, 12-0-2	Survey
SILVER BRAZING ALLOYS	721	Unknown
NONMETALS:		
DENSE OXIDES AL, BE, ETC.	10-0-5, 12-0-2	Survey: static
OXIDE–BASE CERMETS		
CARBIDE–BASE CERMETS	12-0-2	Survey (less than 100 ppm O_2)
GLASSES	10-0-5, 12-0-2	Survey
GRAPHITE	7-0-57	Experimental C - solubility to 1300°F: (260 ppm O_2): ln (ppm) = 5.61-209/(°R)

RESISTANCE OF MATERIALS TO CHEMICAL REACTION OR INTERGRANULAR PENETRATION BY SODIUM OR ITS CONTAMINANTS

(SEE REVERSE SIDE OF SHEET FOR DATA BASIS)

FERROUS METALS AND ALLOYS:

FERRITIC STAINLESS STEELS 400 SERIES
AUSTENTIC STAINLESS STEELS 300 SERIES
LOW CARBON SILICON STEELS
LOW IRON HIGH NICKEL INCONELS
LOW CARBON STEELS
PURE IRON

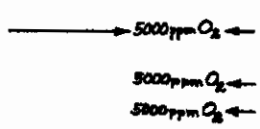


5 7 9 11 13 15 17 19 21 23 25 27 29

TEMPERATURE, °F IN HUNDREDS

NONFERROUS METALS AND ALLOYS:

TITANIUM AND VANADIUM
CHROMIUM
COBALT
NICKEL
COPPER
ZIRCONIUM

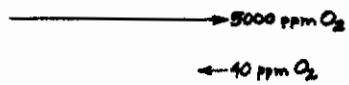


5 7 9 11 13 15 17 19 21 23 25 27 29

TEMPERATURE, °F IN HUNDREDS

REFRACTORY METALS AND ALLOYS:

MOLYBDENUM
COLUMBIUM
TANTALUM
TUNGSTEN



5 7 9 11 13 15 17 19 21 23 25 27 29

TEMPERATURE, °F IN HUNDREDS

OTHER METALS AND ALLOYS:

BERYLLIUM
ALUMINUM AND MAGNESIUM
ZINC, CADMIUM, TIN AND LEAD
NOBLE METALS
BRAZING METALS Ni-Mn, Ni-Mo, Ni-P
SILVER BRAZING ALLOYS

5 7 9 11 13 15 17 19 21 23 25 27 29

TEMPERATURE, °F IN HUNDREDS

NONMETALS:

DENSE OXIDES AL, BE, ETC.
OXIDE–BASE CERMETS
CARBIDE–BASE CERMETS
GLASSES
GRAPHITE

5 7 9 11 13 15 17 19 21 23 25 27 29

TEMPERATURE, °F IN HUNDREDS

NOTE: RIGHT-HAND ARROW-POINT INDICATES HIGHEST REPORTED TEST TEMPERATURE BELOW RESISTANCE LIMIT OF MATERIAL

LEFT-HAND ARROW-POINT INDICATES LOWEST REPORTED TEST TEMPERATURE ABOVE RESISTANCE LIMIT OF MATERIAL

(SEE FRONT SIDE OF SHEET FOR DATA)

	DATA SOURCE	REMARKS AND BASIS OF DATA
FERROUS METALS AND ALLOYS:		
FERRITIC STAINLESS STEELS 400 SERIES	2-11-54	Intergranular penetration: static and dynamic
AUSTENTIC STAINLESS STEELS 300 SERIES	2-11-54, 10-0-5	Intergranular penetration: static and dynamic
LOW CARBON SILICON STEELS		
LOW IRON HIGH NICKEL INCONELS	(716)14-1-60	Intergranular penetration: static and dynamic
LOW CARBON STEELS	10-0-5	Decarburization: static
PURE IRON		
NONFERROUS METALS AND ALLOYS:		
TITANIUM AND VANADIUM		
CHROMIUM	10-0-5	Intergranular penetration: static
COBALT		
NICKEL	10-0-5	Intergranular penetration: static
COPPER	10-0-5	Intergranular penetration: static
ZIRCONIUM		
REFRACTORY METALS AND ALLOYS:		
MOLYBDENUM	10-0-5	Surface roughing: static
COLUMBIUM		
TANTALUM	18-23-58	Intergranular penetration
TUNGSTEN		
OTHER METALS AND ALLOYS:		
BERYLLIUM	11-7-60	50 micron nitride layer in 500 hrs: SS forced circulation loop
ALUMINUM AND MAGNESIUM		
ZINC, CADMIUM, TIN AND LEAD		
NOBLE METALS		
BRAZING METALS Ni-Mn, Ni-Mo. Ni-P		
SILVER BRAZING ALLOYS		
NONMETALS:		
DENSE OXIDES AL, BE, ETC.		
OXIDE-BASE CERMETS		
CARBIDE-BASE CERMETS		
GLASSES		
GRAPHITE	10-0-5	Carbon transfer to 347 SS

e. Data Sources for Sodium

Code No.	Source
2-0-58	Bischel, N. A., Babcock & Wilcox Co., BAW-1105, UC-81, September 1958.
2-11-54	Brush, E. G., and Koenig, R. F., KAPL-1103, April 22, 1954.
3-2-60	Coultas, T. A., and Burge, H. L., Rocketdyne Research Report No. 59-44, February 3, 1960.
3-12-60	Chem. Eng. News, pp 53-65 (Dec. 26, 1960).
5-7-4	Ewing, C. T., Grand, J. A., and Miller, R. R., J. Phys. Chem., 58, 1086 (1954).
5-19-60	Ewing, C. T., Stone, J. P. and Miller, R. R., NRL Memorandum Report 1069, U. S. Naval Research Laboratory, Washington, D. C., 29 July 1960.
7-0-57	Gratton, J. G., KAPL-1807, June 30, 1957.
7-4-0	Ginnings, D. C., Douglas, T. B. and Ball, A. F., NBS Research Paper RP2110, Vol. 45, July 1950.
8-0-8	Hodgman, C. D., Editor, "Handbook of Chemistry and Physics," Cleveland, Chemical Rubber Publishing Co., 1958.
10-0-5	Jackson, C. B., Editor, "Liquid Metals Handbook, Third Ed., Sodium (NaK) Supplement," Washington, Atomic Energy Commission, Department of the Navy, 1955.
11-0-53	Koenig, R. F., KAPL-982, October 1, 1953.
11-0-60	Kiser, R. W., Dept. of Chemistry, Kansas State Univ., TID-6142, June 20, 1960.
11-2-9	Kutateladze, S. S., Borishanskii, V. M., Novikov, I. I., and Fedynskii, O. S., "Liquid-Metal Heat Transfer Media," Atomnaia Energiia, Supp. No. 2, 1958, Translated by Consultants Bureau, Inc., New York, 1959.

Code No.	Source
11-7-60	Kendall, W. W., GEAP-3333, January 15, 1960.
12-0-2	Lyon, R. N., Editor, "Liquid-Metals Handbook," Second Ed., Washington, Atomic Energy Commission, Dept. of the Navy, 1952.
13-19-60	Makansi, M., Selke, W. A., and Bonilla, C. F., Chem. and Eng. Data, 5, No. 4, 441-52, (1960).
14-1-60	Notes of NASA-AEC Liquid Metals Corrosion Meeting, December 7-8, 1960, Washington, D. C. (Proceedings published as NASA TN D-769, February 1961).
18-23-58	Raines, G. E., and Weaver, C. V., BMI-1284, August 21, 1958.
19-0-6	Sittig, M., "Sodium, Its Manufacture, Properties, and Uses," New York, Reinhold Publishing Corp., 1956.
19-0-7	Stull, D. R., Ind. Eng. Chem., 39, No. 4, 517, (1947).
19-13-60	Shapiro, A., and Meisl, C. J., General Electric Co., Flight Propulsion Laboratory Dept., Report No. R 60 FPD358-A, November 9, 1960.
19-19-6	Stull, D. R., and Sinke, G. C., "Thermodynamic Properties of the Elements," Washington, American Chemical Society, 1956.
23-4-61	Weatherford, W. D., Jr., "Momentum Dynamics of Gas-Phase Physical Processes," presented at American Physical Society 1961 Annual Meeting, New York, February 3, 1961.
716	Oak Ridge National Laboratory.
721	AiResearch Manufacturing Co. of Arizona.
831	Rocketdyne Division, North American Aviation, Inc.

LITHIUM

a. General Discussion of Lithium. Lithium is a silver-white alkali metal. It is the hardest, least volatile, and least dense alkali metal. Among the alkali metals, it is the least reactive with oxygen and water, but the most reactive with nitrogen and hydrogen and in some of its properties lithium resembles the alkaline earth metals, calcium, barium, and strontium. It is not tarnished by dry air below 100°C, but it reacts with moist nitrogen at ordinary temperatures to form a black nitride. It reacts slowly with cold water and does not ignite the liberated hydrogen. As in the case of other alkali metals, lithium is immersed in a dry saturated hydrocarbon liquid or inert gas atmosphere during storage and handling.

Lithium forms alloy compounds with magnesium, zinc, cadmium, bismuth, silicon, aluminum, tin, lead, mercury, silver, and thallium. It also alloys with sodium, beryllium, barium, and calcium. The corrosion properties of lithium are significantly different from those of the other alkali metals, being more similar to bismuth and lead in many respects. The presence of nitrogen is believed to render corrosivity to molten lithium as the presence of oxygen does to liquid sodium and other alkali metals.

Lithium is commercially available in 99.5 percent purity at $9.00-$11.00/lb. It is furnished as granular particles, wire, or 8" x 1-1/2" diameter castings.

b. Synopsis of Properties of Lithium

Property	Value	Temp (°F)	Data Basis	Reference
Physical:				
Atomic Weight	6.94	---	Experimental	13-0-8 (716)
Melting Point, °F	357	---	Experimental	4-5-5
Boiling Point, °F	2,430	---	Theoretical	Page Li-VP-a
Critical Point, psia	11,850	4,135		5-0-8
Density of Solid, lb/ft^3	33.338	68	Handbook	8-0-8
Density of Liquid, lb/ft^3	26.180	B.P.	Extrapolated	Page Li-ρ-a
Density of Vapor, lb/ft^3	0.00375	B.P.	Theoretical	Page Li-ρ-b
Viscosity of Liquid, lb/ft hr	1.044	M.P.	Experimental	Page Li-μ-a
Viscosity of Vapor, lb/ft hr	0.0473	B.P.	Theoretical	Page Li-μ-b
Surface Tension, lb/ft	0.027	M.P.	Experimental	20-0-4
Thermal:				
Thermal Conductivity of Liquid, BTU/hr ft °F	26.54	M.P.	Extrapolated	Page Li-k-a
Thermal Conductivity of Vapor, BTU/hr ft °F	0.0459	B.P.	Estimated	Page Li-k-b
Specific Heat of Liquid, BTU/lb °F	0.979	B.P.	Extrapolated	Page Li-C-a
Specific Heat of Vapor BTU/lb °F	0.708	B.P.	Theoretical	Page Li-C-b
Latent Heat of Fusion, BTU/lb	186	M.P.	Calculated	4-5-5
Latent Heat of Vaporization, BTU/lb	8,338	B.P.	Theoretical	Page Li-ΔH-a

Property	Value	Temp (°F)	Data Basis	Reference
Electrical and Magnetic:				
Resistivity, μ ohm-inch	17.81	446 liq	Survey	13-0-8 (716)
Ionization Potential, volts	5.39	---	Experimental	11-0-60
Magnetic Susceptibility fps electromagnetic units/unit mass	1.0198	367 liq	Survey	13-0-8 (716)
Thermal Neutron Cross Section (2200 m/s):				
Absorption, barns	71.0 ± 1.0	---	Handbook	8-0-8
Scattering, barns	1.4 ± 0.3	---	Handbook	8-0-8

c. Property Tables for Lithium.

Basis of data from Reference 19-13-60: Thermodynamic properties of equilibrium vapor mixtures were derived by machine computation with conventional relations assuming the individual monomer and dimer species to be ideal gases. The equilibrium specific heat was then determined by differentiation. The frozen specific heat was computed by adding the contributions of the individual species. Free energies of the monatomic and diatomic forms of the vapor were used to calculate the dimerization equilibrium constant, hence, no added assumptions were required concerning heat of dissociation. Iterations on vapor pressure were made until the ratio of the heat of vaporization to temperature became identical to the entropy of vaporization. Therefore, all data from this reference are internally consistent.

PHYSICAL PROPERTIES OF LITHIUM
Saturated Phases

(Ref: 19-13-60)

Temperature (°R)	Equilibrium Vapor Molecular Weight	Vapor Pressure (psia)	Liquid Specific Volume (ft^3/lb)	Vapor Specific Volume (ft^3/lb)	Equilibrium Sonic Velocity (ft/sec)	Frozen Sonic Velocity (ft/sec)
2400	7.482	1.453×10^{0}	3.658×10^{-2}	2.369×10^{3}	3874.7	5046.9
2500	7.555	2.519×10^{0}	3.691×10^{-2}	1.410×10^{3}	3924.0	5112.6
2600	7.624	4.170×10^{0}	3.723×10^{-2}	8.776×10^{2}	3973.5	5177.5
2700	7.688	6.640×10^{0}	3.755×10^{-2}	5.676×10^{2}	4023.3	5241.8
2800	7.755	1.028×10^{1}	3.787×10^{-2}	3.768×10^{2}	4070.7	5302.6
2900	7.821	1.544×10^{1}	3.819×10^{-2}	2.578×10^{2}	4117.4	5361.8
3000	7.884	2.250×10^{1}	3.852×10^{-2}	1.815×10^{2}	4163.8	5419.7
3100	7.945	3.199×10^{1}	3.884×10^{-2}	1.309×10^{2}	4209.5	5476.4
3200	8.006	4.450×10^{1}	3.916×10^{-2}	9.640×10^{1}	4254.5	5532.1
3300	8.063	6.084×10^{1}	3.948×10^{-2}	7.219×10^{1}	4299.4	5586.1
3400	8.119	8.176×10^{1}	3.981×10^{-2}	5.497×10^{1}	4344.1	5638.8
3500	8.173	1.077×10^{2}	4.013×10^{-2}	4.267×10^{1}	4388.5	5691.2
3600	8.226	1.384×10^{2}	4.045×10^{-2}	3.393×10^{1}	4432.2	5744.4

THERMAL PROPERTIES OF LITHIUM
Saturated Phases

(Ref: 19-13-60)

Temperature (°R)	Specific Heat of Equilibrium Vapor (BTU/lb °R)	Frozen Specific Heat of Vapor (BTU/lb °R)	Ratio of Frozen Specific Heats of Vapor (BTU/lb °R)	Specific Heat of Liquid (BTU/lb °R)
2400	2.452	0.7095	1.598	0.9870
2500	2.463	0.7089	1.589	0.9853
2600	2.448	0.7085	1.581	0.9836
2700	2.416	0.7082	1.574	0.9821
2800	2.379	0.7079	1.567	0.9805
2900	2.334	0.7076	1.560	0.9789
3000	2.284	0.7076	1.553	0.9773
3100	2.231	0.7074	1.546	0.9757
3200	2.176	0.7072	1.540	0.9741
3300	2.121	0.7076	1.534	0.9725
3400	2.066	0.7083	1.527	0.9709
3500	2.012	0.7089	1.522	0.9693
3600	1.960	0.7086	1.517	0.9677

THERMODYNAMIC PROPERTIES OF LITHIUM
Saturated Phases

(Ref:: 19-13-60)

Temperature T (°R)	Enthalpy of Liquid $(H-H_o)_L$ (BTU/lb)	Enthalpy of Vapor $(H-H_o)_V$ (BTU/lb)	Entropy of Liquid S_L (BTU/lb °R)	Entropy of Vapor S_V (BTU/lb °R)
2400	2311.8	11066.8	2.6694	6.3173
2500	2410.4	11074.4	2.7089	6.1745
2600	2508.9	11086.6	2.7480	6.0471
2700	2607.2	11103.1	2.7861	5.9327
2800	2705.6	11118.8	2.8211	5.8258
2900	2803.5	11136.5	2.8550	5.7284
3000	2900.9	11156.8	2.8884	5.6403
3100	2998.2	11178.9	2.9207	5.5596
3200	3095.8	11202.7	2.9518	5.4852
3300	3193.2	11229.1	2.9812	5.4163
3400	3290.5	11257.9	3.0092	5.3526
3500	3387.6	11288.6	3.0367	5.2942
3600	3484.6	11320.4	3.0651	5.2417

THERMODYNAMIC PROPERTIES OF LITHIUM

Liquid Phase: $H^{\circ}_{536.67} - H^{\circ}_{0} = 1,966$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^{\circ} - H^{\circ}_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^{\circ} - H^{\circ}_{536.67})/T$ (BTU/lb mole °R)
900	3688	11.71	7.62
1080	4973	13.01	8.41
1260	6232	14.09	9.15
1440	7479	15.01	9.82
1620	8723	15.83	10.45
1800	9965	16.55	11.02
1980	11203	17.21	11.56
2160	12442	17.81	12.05
2340	13676	18.36	12.52
2520	14911	18.86	12.95
2700	16141	19.34	13.37
2880	17366	19.78	13.75

THERMODYNAMIC PROPERTIES OF LITHIUM

Ideal Monatomic Gas: $H^\circ_{536.67} - H^\circ_0 = 2,666$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^\circ - H^\circ_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^\circ - H^\circ_{536.67})/T$ (BTU/lb mole °R)
900	1805	35.71	33.71
1080	2700	36.62	34.12
1260	3593	37.38	34.53
1440	4487	38.05	34.94
1620	5382	38.63	35.31
1500	6277	39.16	35.68
1980	7171	39.63	36.01
2160	8064	40.06	36.33
2340	8959	40.46	36.64
2520	9853	40.83	36.92
2700	10748	41.17	37.19
2880	11642	41.49	37.45
3060	12537	41.79	37.70
3240	13432	42.08	37.94
3420	14326	42.35	38.17
3600	15224	42.60	38.38
3780	16121	42.84	38.58
3960	17021	43.08	38.79

THERMODYNAMIC PROPERTIES OF LITHIUM

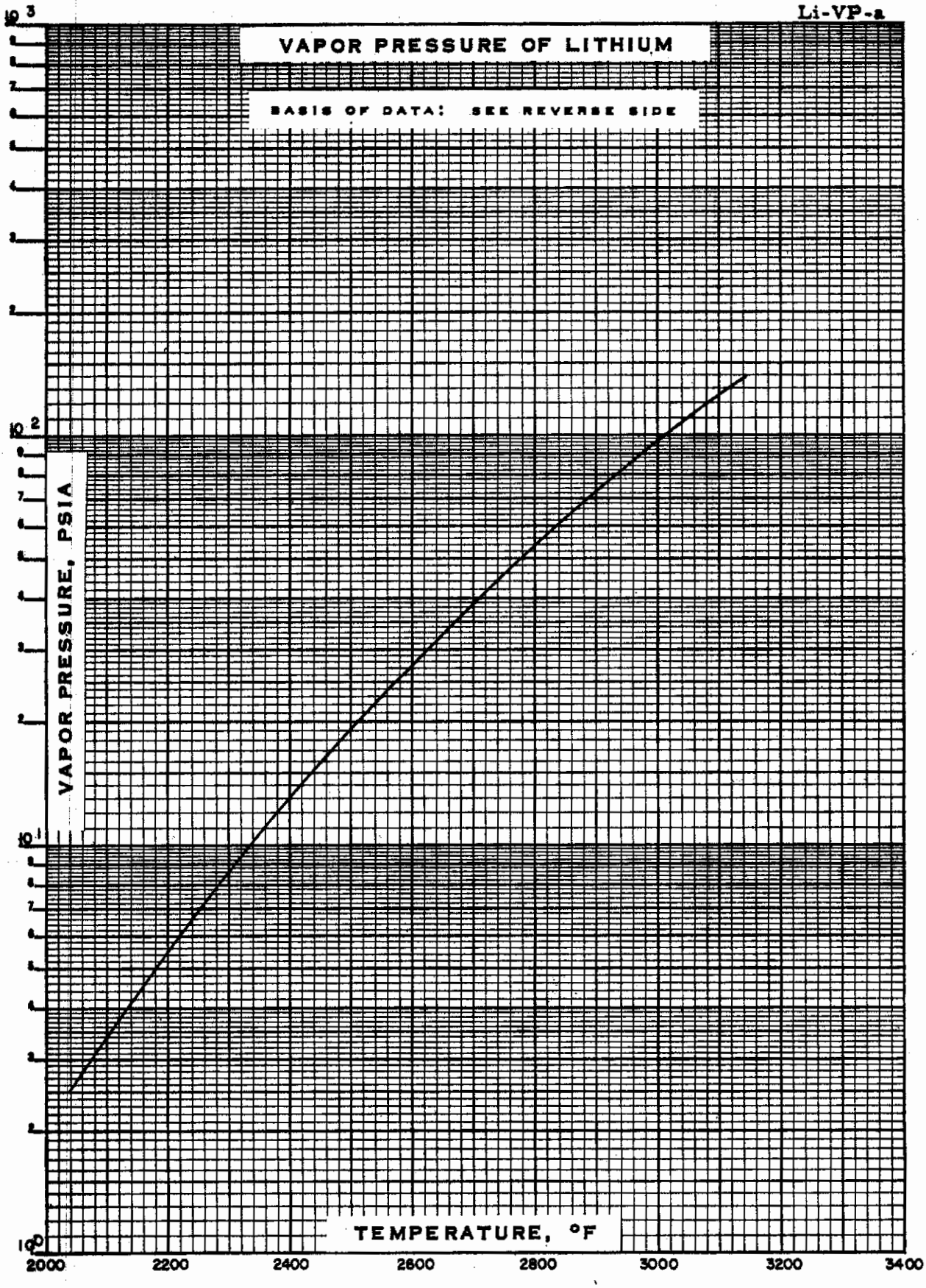
Ideal Diatomic Gas: $H^\circ_{536.67} - H^\circ_0 = 4,162$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^\circ - H^\circ_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^\circ - H^\circ_{536.67})/T$ (BTU/lb mole °R)
900	3200	51.62	48.07
1080	4813	53.25	48.80
1260	6448	54.66	49.55
1440	8078	55.86	50.25
1620	9738	56.95	50.94
1800	11390	57.92	51.60
1980	13045	58.79	52.21
2160	14717	59.60	52.79
2340	16407	60.35	53.34
2520	18090	61.05	53.88
2700	19760	61.69	54.38
2880	21458	62.30	54.85
3060	23161	62.87	55.31
3240	24871	63.42	55.75
3420	26586	63.93	56.16
3600	28307	64.42	56.56

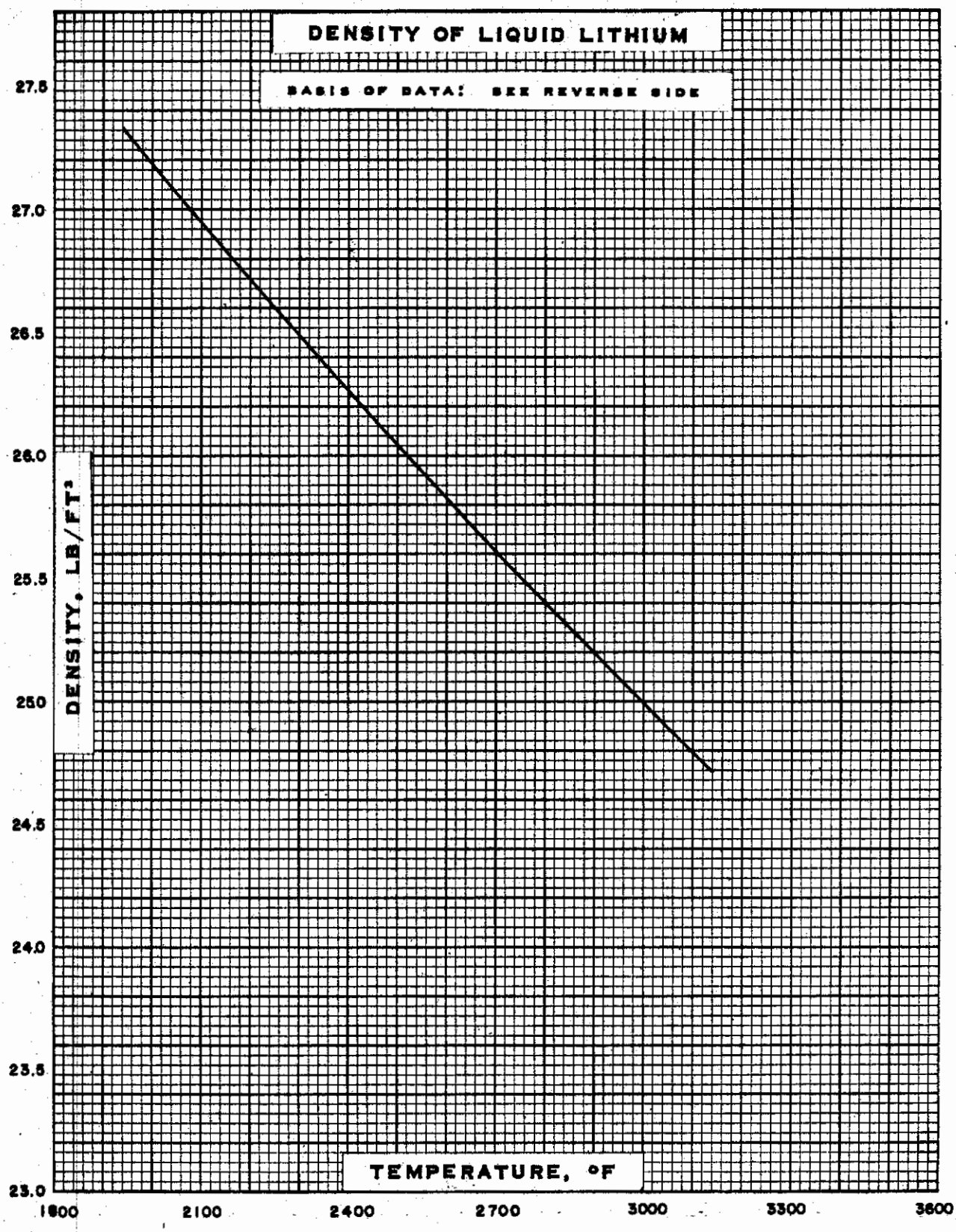
d. Working Charts for Lithium.

Li-VP-a



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	19-19-6	Boiling point	Vapor pressure was calculated from monatomic and diatomic data.
Semi-Theoretical	19-13-60	2040-3140	Experimental values were theoretically adjusted to yield consistent thermodynamic data.

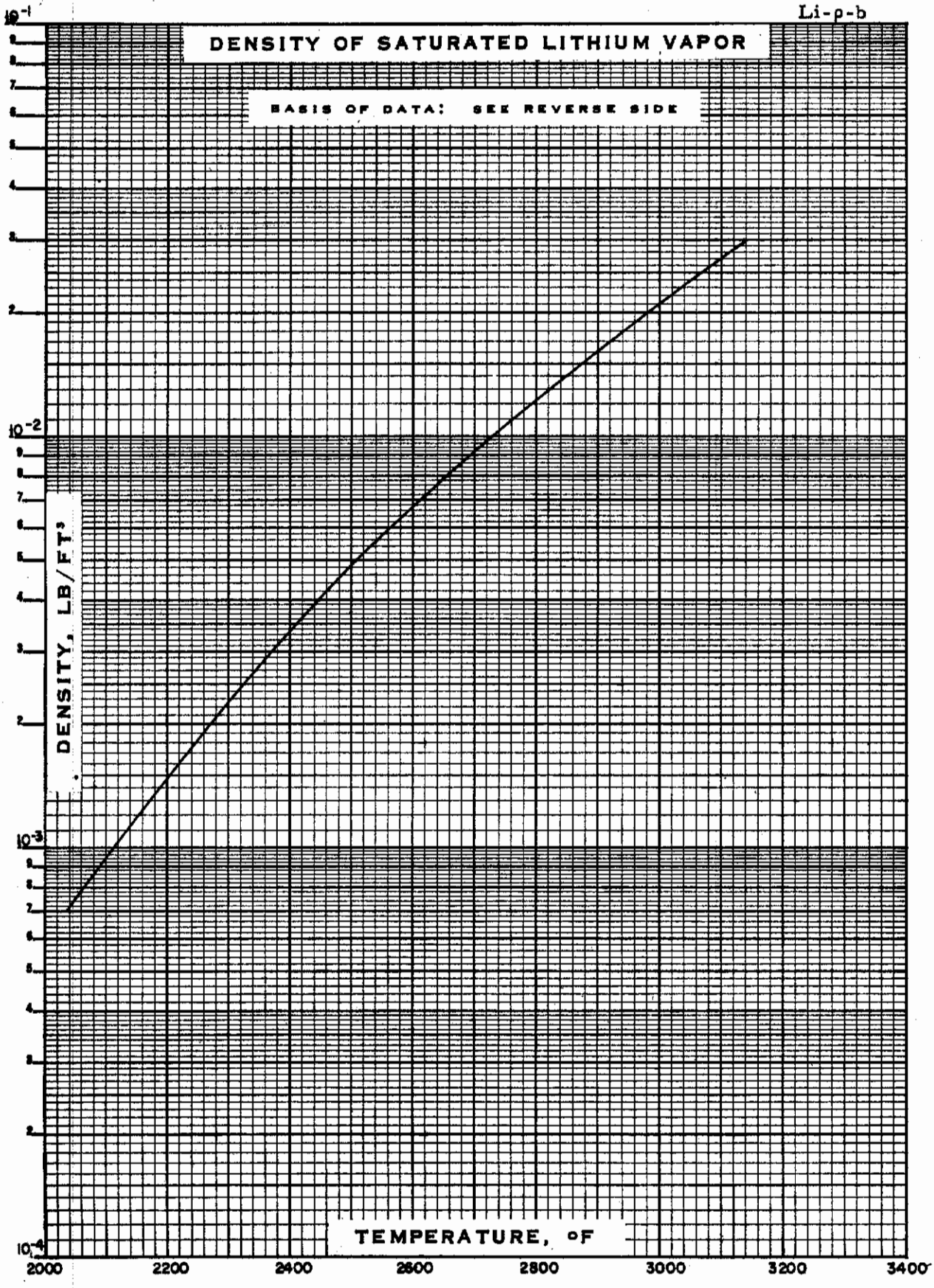
Li-ρ-a



WADD TR 61-96

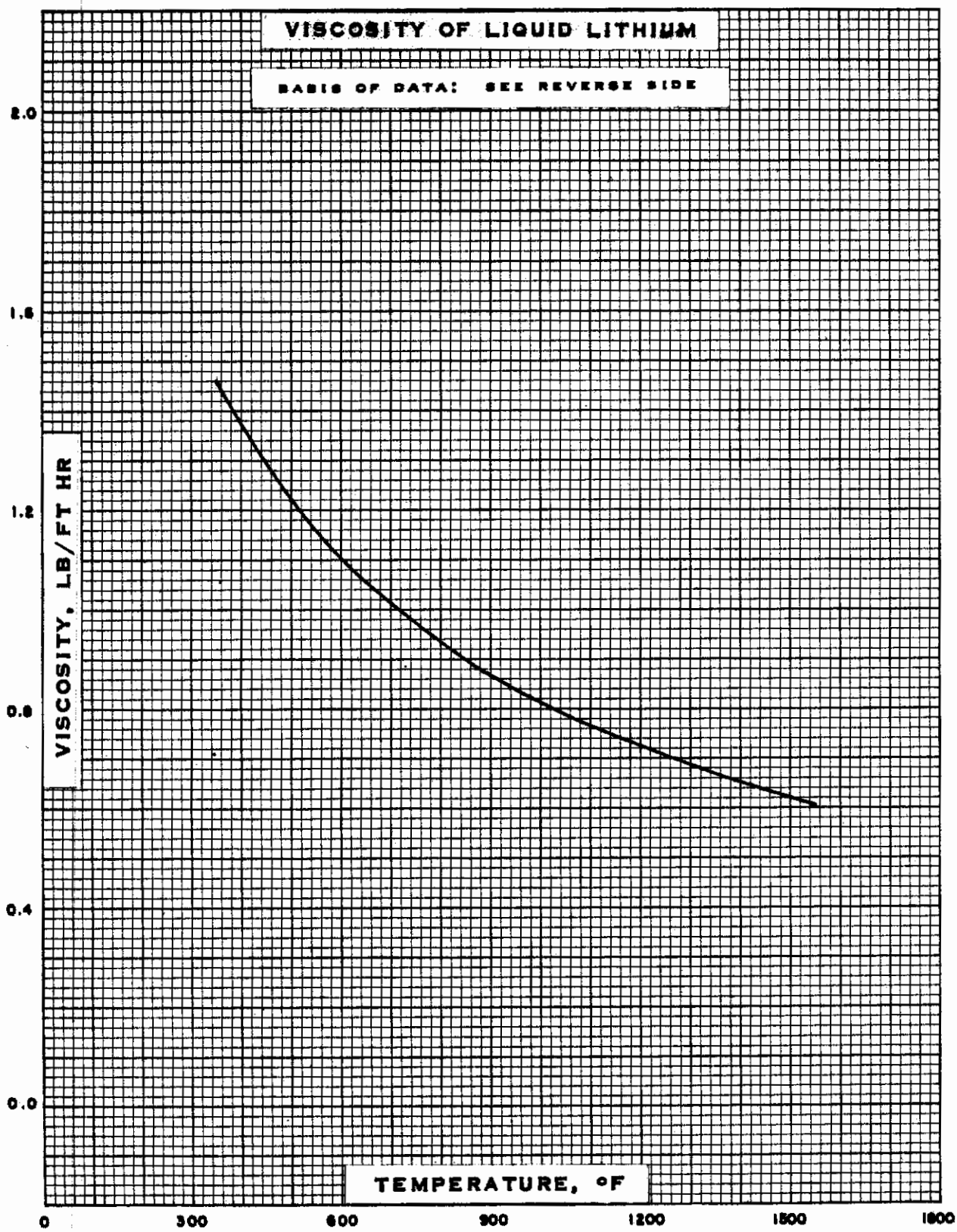
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Extrapolated	19-13-60	1940-3140	Extended (12-0-2) data.

Li-ρ-b



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	19-13-60	2040-3140	The specific volume of the vapor mixture was calculated from the perfect gas law.

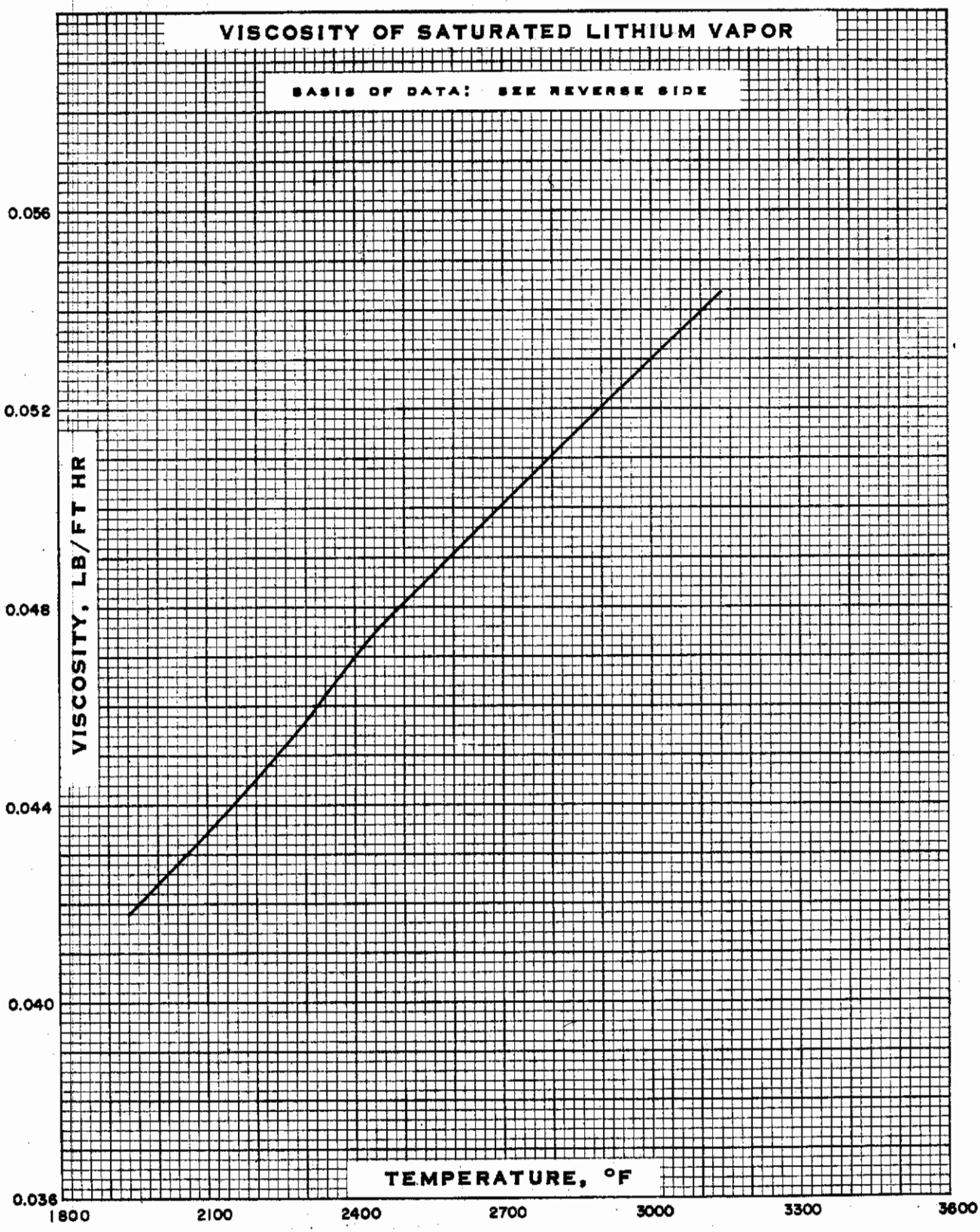
Li-μ-a



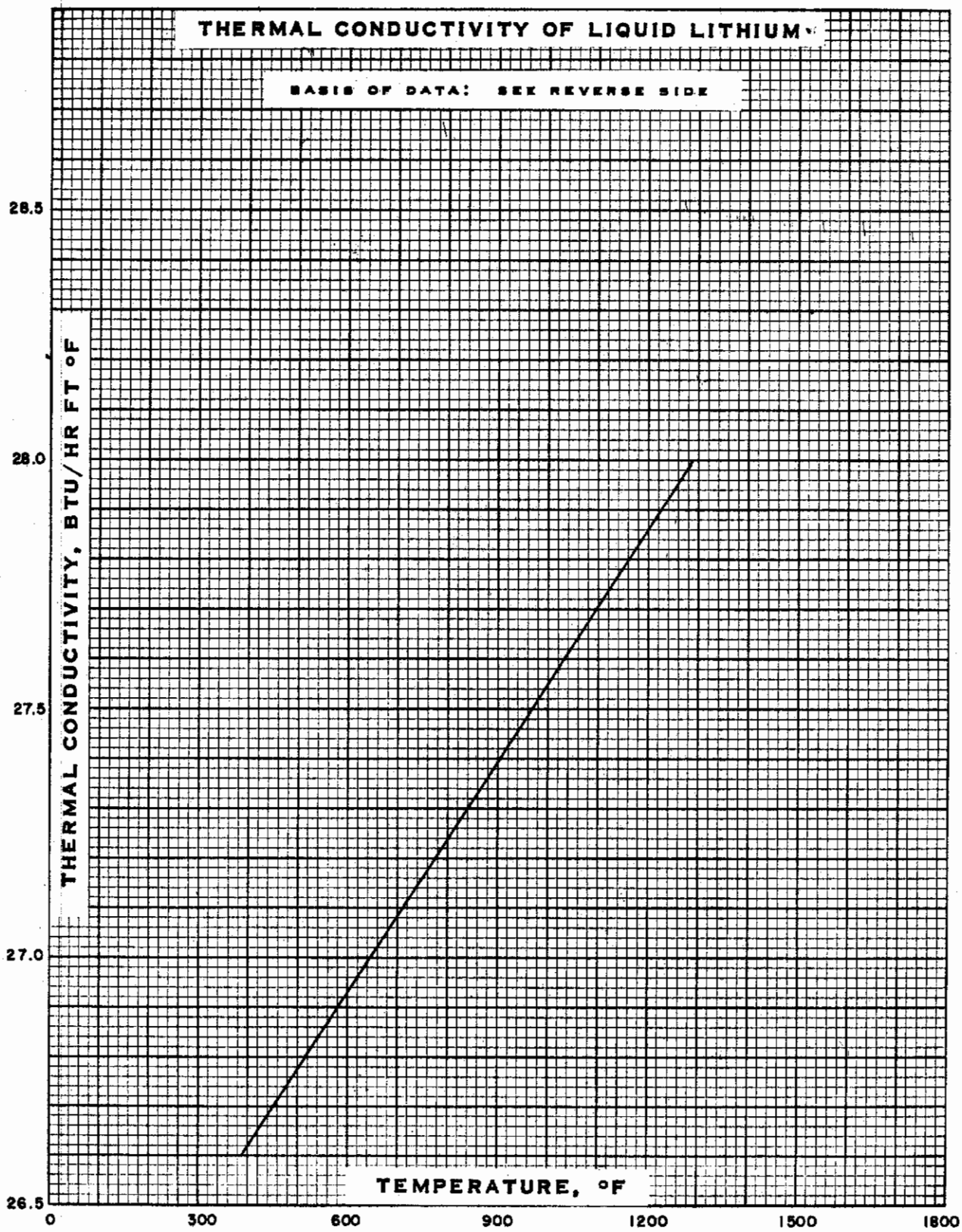
WADD TR 61-96

Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	11-2-9	392-1292	Measured by the method of damped torsional oscillations.
	5-0-8, 12-0-2	362-545	
	13-0-8	500-1500	Extrapolation

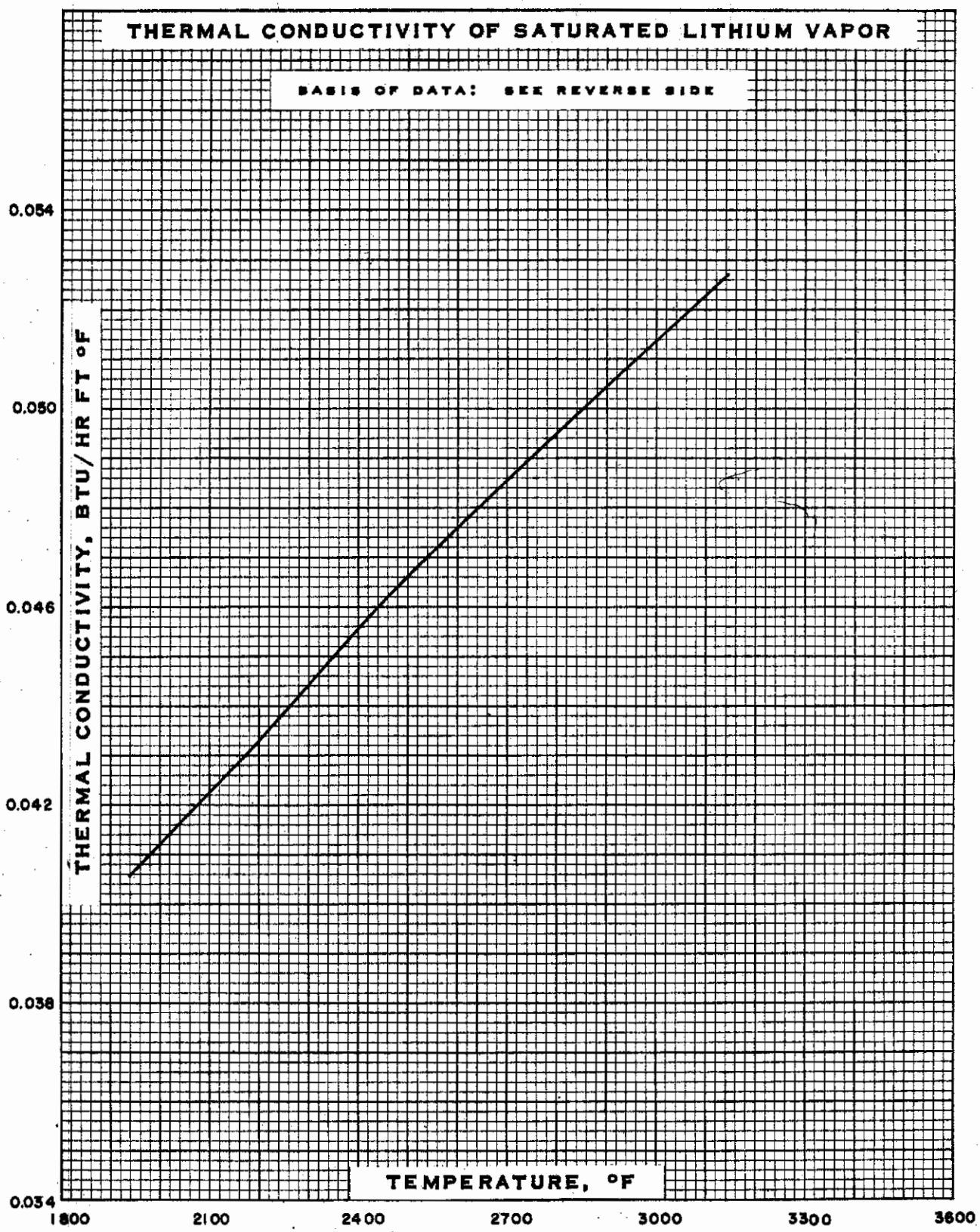
Li-μ-b



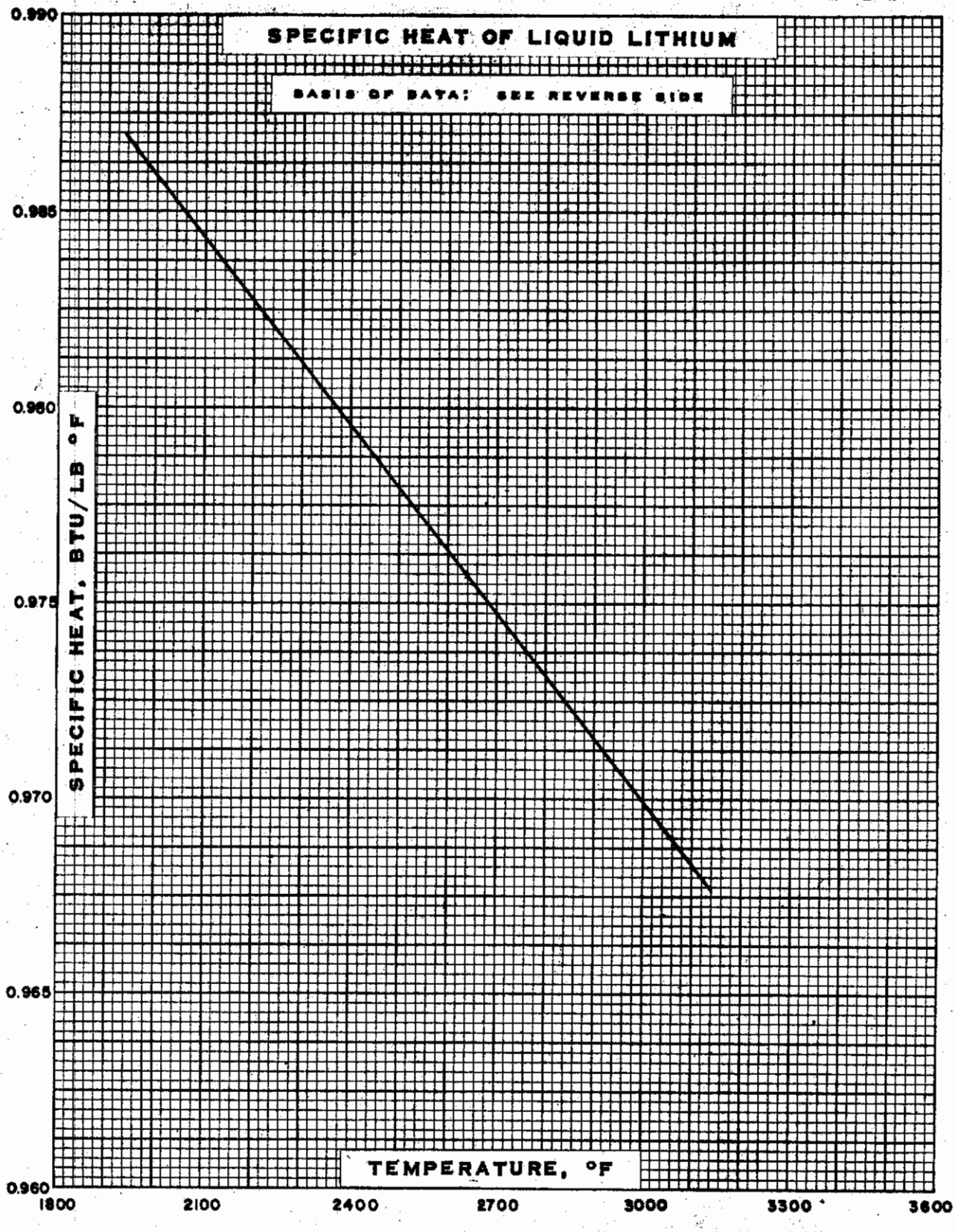
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	23-4-61	1940-3140	Computed for variable molecular weight saturated vapor (page Li-P-1) using new equation for gas viscosity.



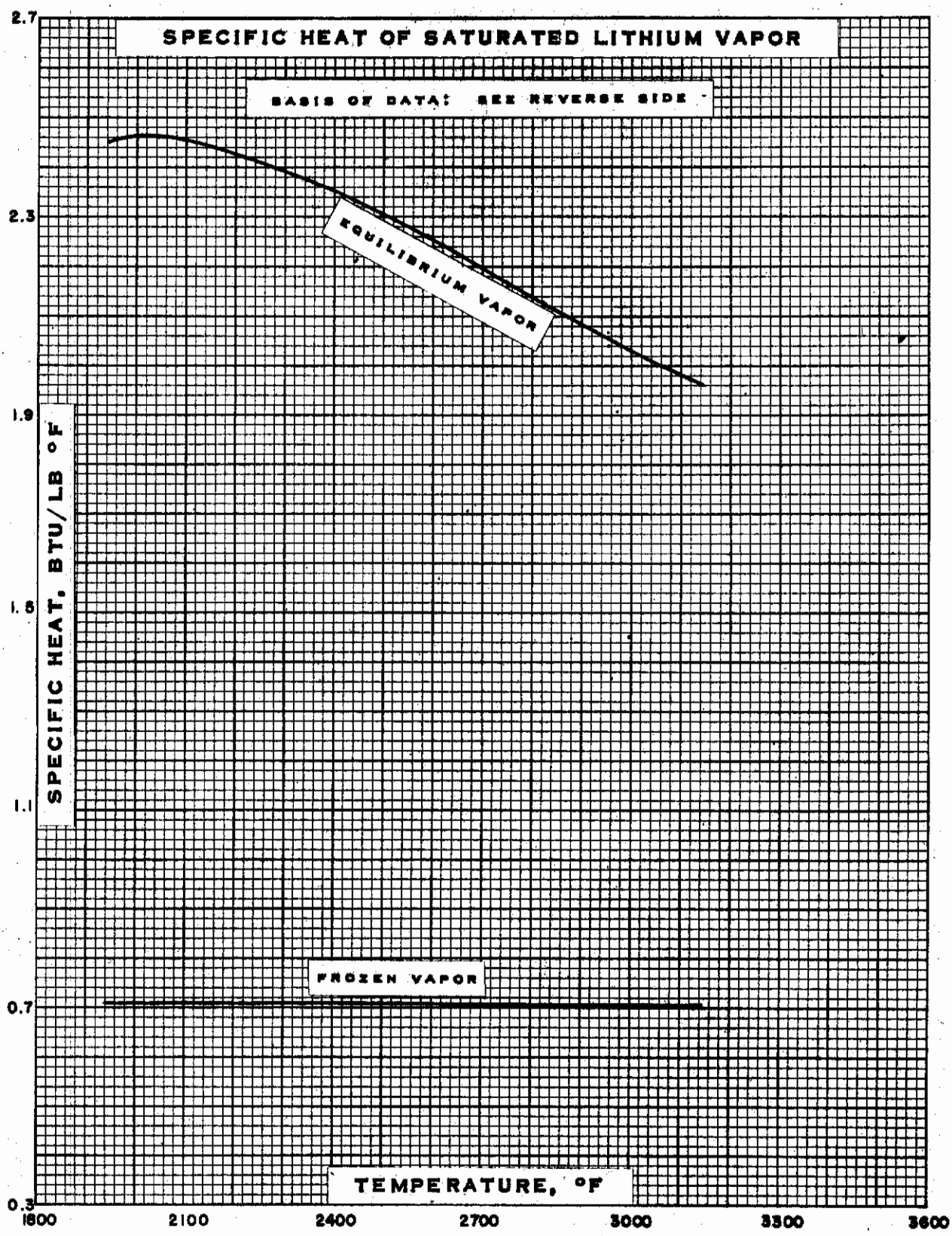
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	11-2-9	392-1292	Experimental values calculated by successive steady-state approximations.
Experimental	716	650-1450	Experimental values measured directly with heat flowing downward in vertical column of fluid.



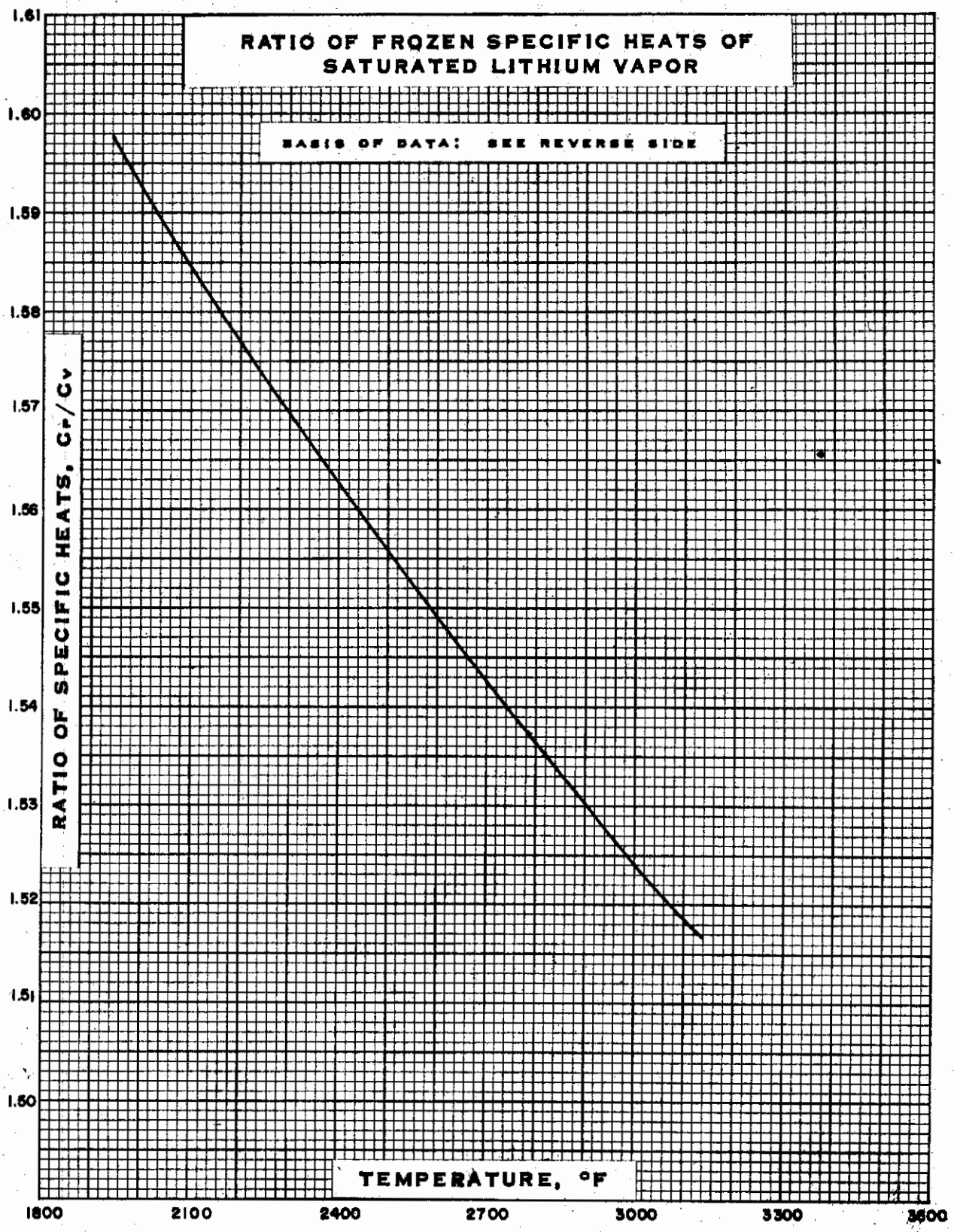
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Estimated		1940-3140	Calculated from the frozen specific heat (page Li-C- b) and viscosity (page Li-μ-b) of saturated vapor assuming a constant Prandtl No. of 0.73.



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical Extrapolation	5-10-5, 19-13-60, 19-19-6	1940-2420	High-temperature specific heat values were obtained by extending the low-temperature, experimental, heat content data.
Extrapolated	19-13-60	2420-3140	Above data were extrapolated to higher temperatures.

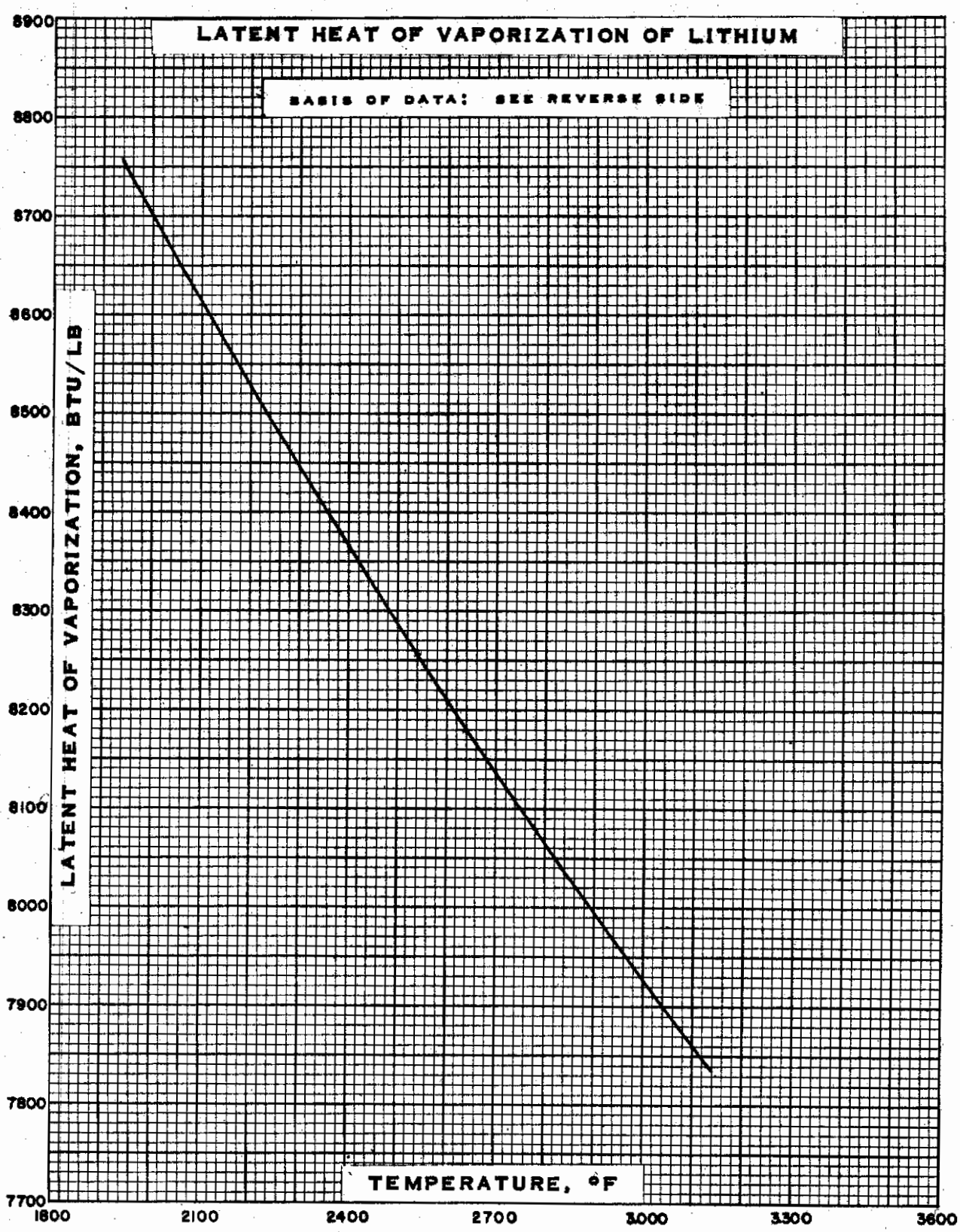


Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	19-13-60	1940-3140	Two specific heats were calculated for lithium vapor. (1) The frozen specific heat is a state point property calculated by adding the separate contributions of the monatomic and diatomic vapors for a given equilibrium composition. (2) The equilibrium specific heat applies to the rigorous definition of specific heat, and includes the energy required to alter the degree of equilibrium dissociation.



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	19-13-60	1940-3140	Ratio of the frozen specific heat at constant pressure to the frozen specific heat of constant volume

Li-ΔH-a

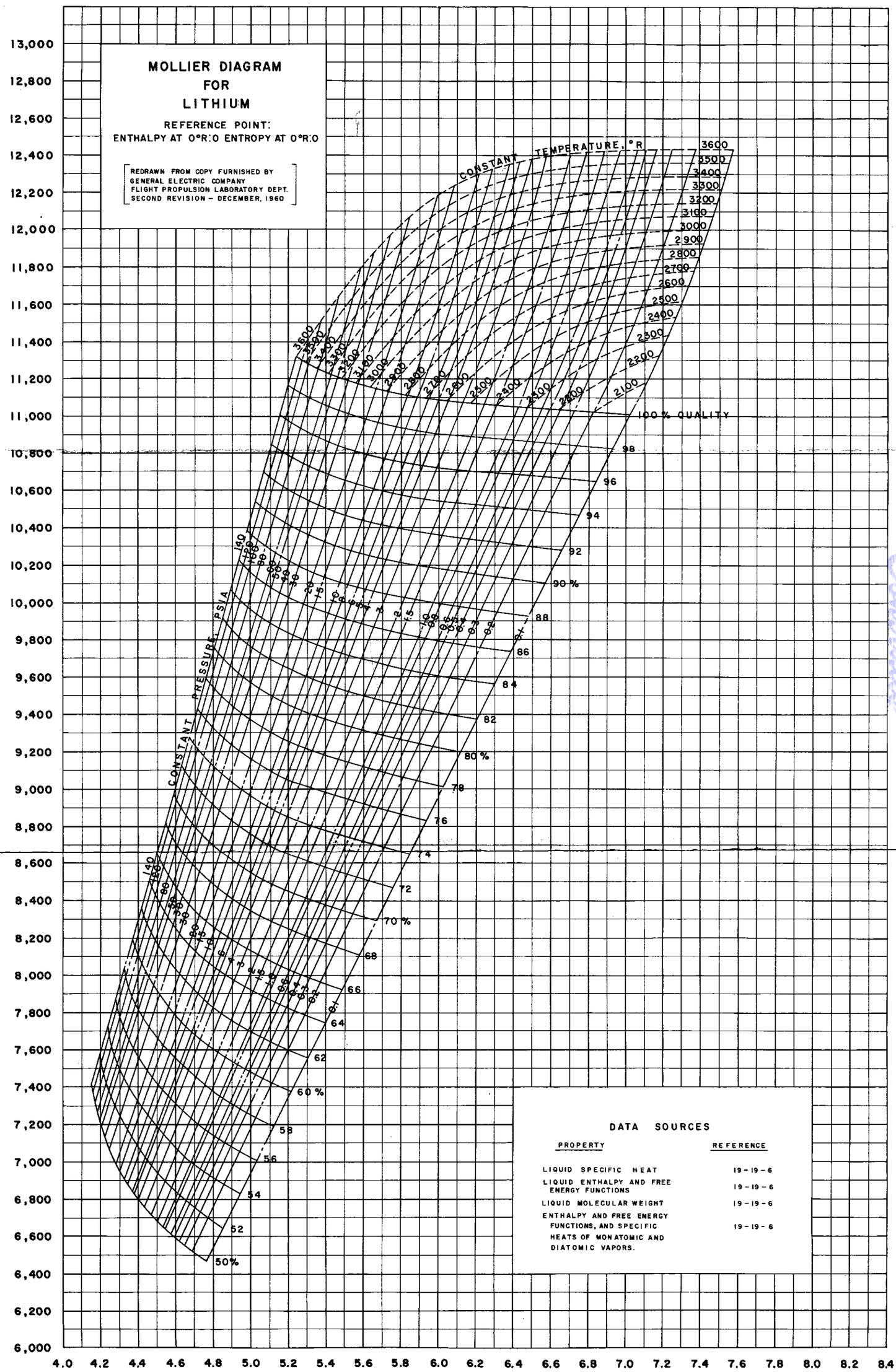


Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	19-13-60	1940-3140	
Theoretical	19-19-6	Boiling point	

MOLLIER DIAGRAM FOR LITHIUM

REFERENCE POINT:
ENTHALPY AT 0°R:0 ENTROPY AT 0°R:0

[REDRAWN FROM COPY FURNISHED BY GENERAL ELECTRIC COMPANY FLIGHT PROPULSION LABORATORY DEPT. SECOND REVISION – DECEMBER, 1960]

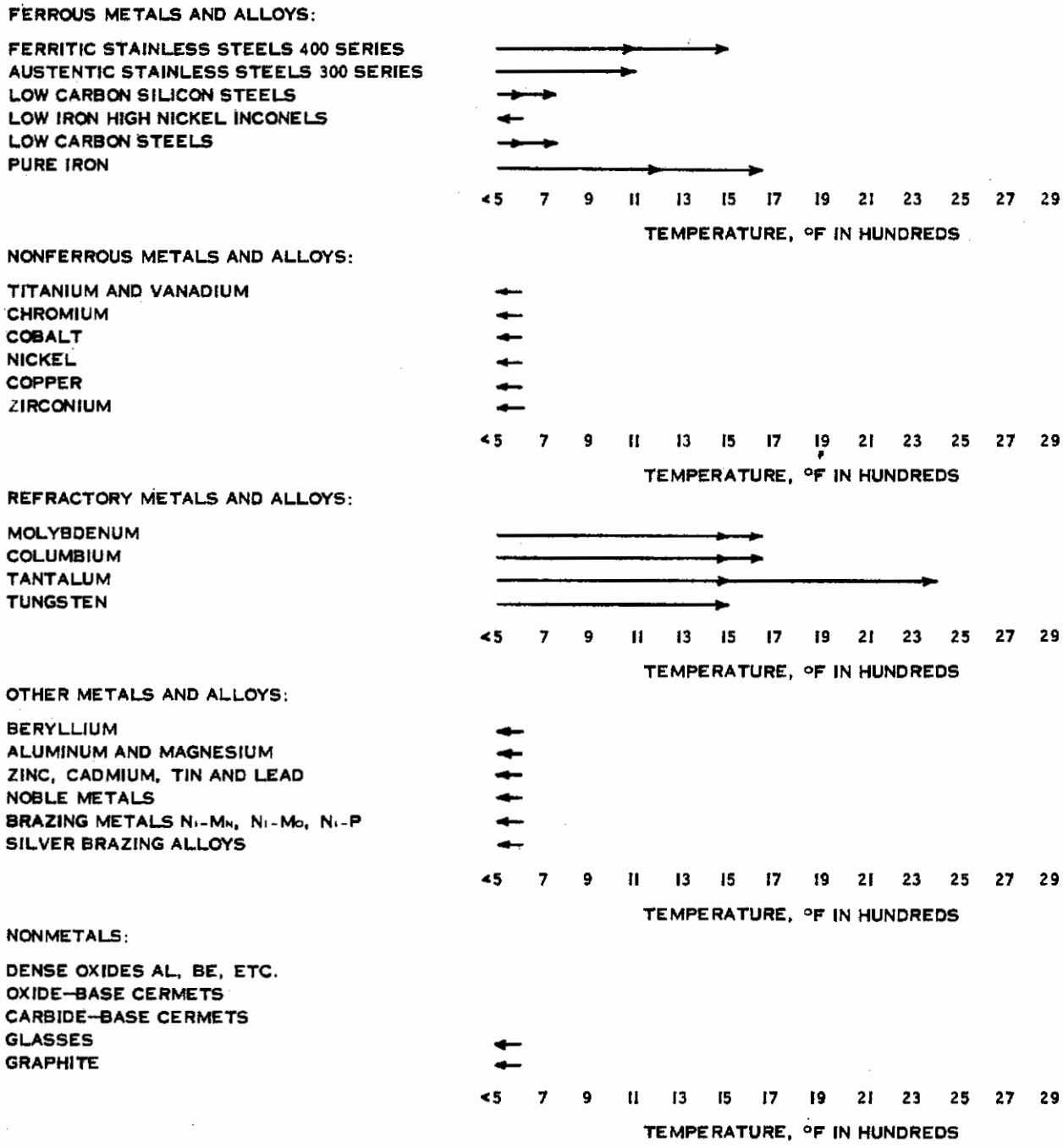


DATA SOURCES

PROPERTY	REFERENCE
LIQUID SPECIFIC HEAT	19-19-6
LIQUID ENTHALPY AND FREE ENERGY FUNCTIONS	19-19-6
LIQUID MOLECULAR WEIGHT	19-19-6
ENTHALPY AND FREE ENERGY FUNCTIONS, AND SPECIFIC HEATS OF MONATOMIC AND DIATOMIC VAPORS.	19-19-6

RESISTANCE OF MATERIALS TO LIQUID LITHIUM

(SEE REVERSE SIDE OF SHEET FOR DATA BASIS)



NOTE: RIGHT-HAND ARROW-POINT INDICATES HIGHEST REPORTED TEST TEMPERATURE BELOW RESISTANCE LIMIT OF MATERIAL

LEFT-HAND ARROW-POINT INDICATES LOWEST REPORTED TEST TEMPERATURE ABOVE RESISTANCE LIMIT OF MATERIAL

(SEE FRONT SIDE OF SHEET FOR DATA)

	DATA SOURCE	REMARKS AND BASIS OF DATA
FERROUS METALS AND ALLOYS:		
FERRITIC STAINLESS STEELS 400 SERIES	12-0-2, 13-9-57	Survey (lower point - dynamic data for less than 0.005" attack in 1000 hrs)
AUSTENTIC STAINLESS STEELS 300 SERIES	13-9-57	Dynamic data for less than 0.005" attack in 1000 hrs
LOW CARBON SILICON STEELS	12-0-2, 13-9-57	Survey (lower point - dynamic data for less than 0.005" attack in 1000 hrs)
LOW IRON HIGH NICKEL INCONELS	12-0-2	Survey
LOW CARBON STEELS	12-0-2, 13-9-57	Survey (lower point - dynamic data for less than 0.005" attack in 1000 hrs)
PURE IRON	12-0-2, 13-9-57	Survey (lower point - dynamic data for less than 0.005" attack in 1000 hrs)
NONFERROUS METALS AND ALLOYS:		
TITANIUM AND VANADIUM	12-0-2	Survey
CHROMIUM	12-0-2	Survey
COBALT	12-0-2	Survey
NICKEL	12-0-2	Survey
COPPER	12-0-2	Survey
ZIRCONIUM	12-0-2	Survey
REFRACTORY METALS AND ALLOYS:		
MOLYBDENUM	12-0-2	Survey
COLUMBIUM	12-0-2	Survey
TANTALUM	(128)14-1-60	Boiling
TUNGSTEN	13-9-57	Dynamic data for less than 0.005" attack in 1000 hrs
OTHER METALS AND ALLOYS:		
BERYLLIUM	12-0-2	Survey
ALUMINUM AND MAGNESIUM	12-0-2	Survey
ZINC, CADMIUM, TIN AND LEAD	12-0-2	Survey
NOBLE METALS	12-0-2	Survey
BRAZING METALS Ni-Mn, Ni-Mo. Ni-P	12-0-2	Survey
SILVER BRAZING ALLOYS	12-0-2	Survey
NONMETALS:		
DENSE OXIDES AL, BE, ETC.		
OXIDE-BASE CERMETS		
CARBIDE-BASE CERMETS		
GLASSES	12-0-2	Survey
GRAPHITE	12-0-2	Survey

e. Data Sources for Lithium

Code No.	Source
3-12-60	Chem. Eng. News, pp 53-65 (Dec. 26, 1960).
4-5-5	Douglas, T. B., Epstein, L. F., Dever, J. L., and Howland, W. H., Jour. Am. Chem. Soc., 77, 2144 (1955).
5-0-8	Ellis, J. F., UKAEA Industrial Group, R & DB(CA)TN-154, 1958.
5-10-5	Evans, W. H., Jacobson, E., Munson, T. R. and Wagman, D. D., Journal of Research of the NBS, Vol 55, No. 2, 1955.
8-0-8	Hodgman, C. D., Editor, "Handbook of Chemistry and Physics," Cleveland, Chemical Rubber Publishing Co., 1958.
11-0-60	Kiser, R. W., Dept. of Chemistry, Kansas State Univ., TID-6142, June 20, 1960.
11-2-9	Kutateladze, S. S., Borishanskii, V. M., Novikov, I. I., and Fedynskii, O. S., "Liquid-Metal Heat Transfer Media," Atomnaia Energiia, Supp. No. 2, 1958, Translated by Consultants Bureau, Inc., New York, 1959.
12-0-2	Lyon, R. N., Editor, "Liquid-Metals Handbook," Second Ed., Washington, Atomic Energy Commission, Dept. of the Navy, 1952.
13-0-8	McGlothlan, C. K., Oak Ridge National Laboratory, USAEC, 1958.
13-9-57	"Metallurgy Information Meeting, Ames Laboratory, Iowa State College, May 2-4, 1956," Ames Laboratory, Iowa State College, TID-7526 (Pt-1), February 1957.
14-1-60	Notes of NASA-AEC Liquid Metals Corrosion Meeting, Dec. 7-8, 1960, Washington, D. C. (Proceedings published as NASA TN D-769, February 1961).

Code No.	Source
19-13-60	Shapiro, A., and Meisl, C. J., General Electric Co., Flight Propulsion Laboratory Dept., Report No. R 60 FPD358-A, November 9, 1960.
19-19-6	Stull, D. R., and Sinke, G. C., "Thermodynamic Properties of the Elements," Washington, American Chemical Society, 1956.
20-0-4	Taylor, J. W., AERE Tech. Note (ASTIA No. 139433), 1954.
23-4-61	Weatherford, W. D., Jr., "Momentum Dynamics of Gas-Phase Physical Processes," presented at American Physical Society 1961 Annual Meeting, New York, February 3, 1961.
128	Nuclear Development Corp. of America
716	Oak Ridge National Laboratory

BISMUTH

a. General Discussion of Bismuth. Bismuth is a lustrous, pinkish-white metal which is very brittle. It is a relatively poor electrical conductor. Moist air causes bismuth surfaces to oxidize at room temperature, and, at high temperatures, molten bismuth is easily ignited.

Bismuth is available commercially in ton lots at $2.25 per pound.

b. Synopsis of Properties of Bismuth.

Property	Value	Temp (°F)	Data Basis	Reference
Physical:				
Atomic Weight	209.00	---	Handbook	8-0-8
Melting Point, °F	520.34	---	Handbook	8-0-8
Boiling Point, °F	2875	---	Theoretical	Page Bi-VP-a
Density of Solid, lb/ft^3	608.5	68	Handbook	8-0-8
Density of Liquid, lb/ft^3	628.3	M.P.	Extrapolated	Page Bi-ρ-a
Viscosity of Liquid, lb/ft hr	4.48	M.P.	Extrapolated	Page Bi-μ-a
Surface Tension	0.0258	572	Survey	11-15-7
	0.0236	1436	Survey	11-15-7
Thermal:				
Thermal Conductivity of Liquid, BTU/hr ft °F	8.34	M.P.	Extrapolated	Page Bi-k-a
Specific Heat of Liquid, BTU/lb °F	0.035	M.P.	Extrapolated	Page Bi-C-a
Latent Heat of Fusion, BTU/lb	23.40	B.P.	Survey	11-15-7
Latent Heat of Vaporization, BTU/lb	367.76	B.P.	Survey	11-15-7

Property	Value	Temp (°F)	Data Basis	Reference
Electrical and Magnetic:				
Resistivity, μ ohm-inch	50.748	572.0 liq	Handbook	8-0-8
Ionization Potential, volts	8.0	---	Handbook	8-0-8
Magnetic Susceptibility, fps electromagnetic units/unit mass	-0.4298	500	Handbook	8-0-8
Thermal Neutron Cross Section (2200 m/s):				
Absorption, barns	32 ± 2 mb	---	Handbook	
Scattering, barns	9 ± 1	---	Handbook	8-0-8

c. Property Tables for Bismuth.

EQUILIBRIUM COMPOSITION OF SATURATED BISMUTH VAPOR

(Ref: 105)

Temperature (°F)	Mole Percent Dimer
980	61.9
1160	59.5
1340	57.2
1520	55.0
1700	52.6
1880	50.3
2060	48.2
2240	46.0
2420	44.1
2600	42.1
2780	40.3
2960	38.7
3140	36.9

THERMODYNAMIC PROPERTIES OF BISMUTH

Liquid Phase: $H^\circ_{536.67} - H^\circ_o = 2,765$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^\circ - H^\circ_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^\circ - H^\circ_{536.67})/T$ (BTU/lb mole °R)
1080	8424	23.12	15.32
1260	9774	24.28	16.53
1440	11124	25.28	17.56
1620	12474	26.16	18.46
1800	13824	26.95	19.27
1980	15174	27.67	20.01
2160	16524	28.32	20.67
2340	17874	28.92	21.29
2520	19224	29.47	21.85
2700	20574	29.99	22.37
2880	21924	30.48	22.87
3060	23274	30.93	23.33
3240	24624	31.36	23.76

THERMODYNAMIC PROPERTIES OF BISMUTH

Ideal Monatomic Gas: $H^\circ_{536.67} - H^\circ_0 = 2,666$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^\circ - H^\circ_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole°R)	Free Energy Function $-(F^\circ - H^\circ_{536.67})/T$ (BTU/lb mole °R)
1080	2700	48.14	45.64
1260	3593	48.91	46.06
1440	4487	49.57	46.46
1620	5382	50.16	46.84
1800	6277	50.68	47.20
1980	7171	51.16	47.54
2160	8064	51.59	47.86
2340	8959	51.99	48.17
2520	9853	52.35	48.44
2700	10748	52.70	48.72
2880	11644	53.02	48.98
3060	12541	53.32	49.23
3240	13437	53.60	49.46
3420	14335	53.87	49.68
3600	15237	54.13	49.90
3780	16139	54.38	50.12
3960	17046	54.61	50.31
4140	17955	54.84	50.51
4320	18869	55.05	50.69
4500	19789	55.26	50.87

THERMODYNAMIC PROPERTIES OF BISMUTH

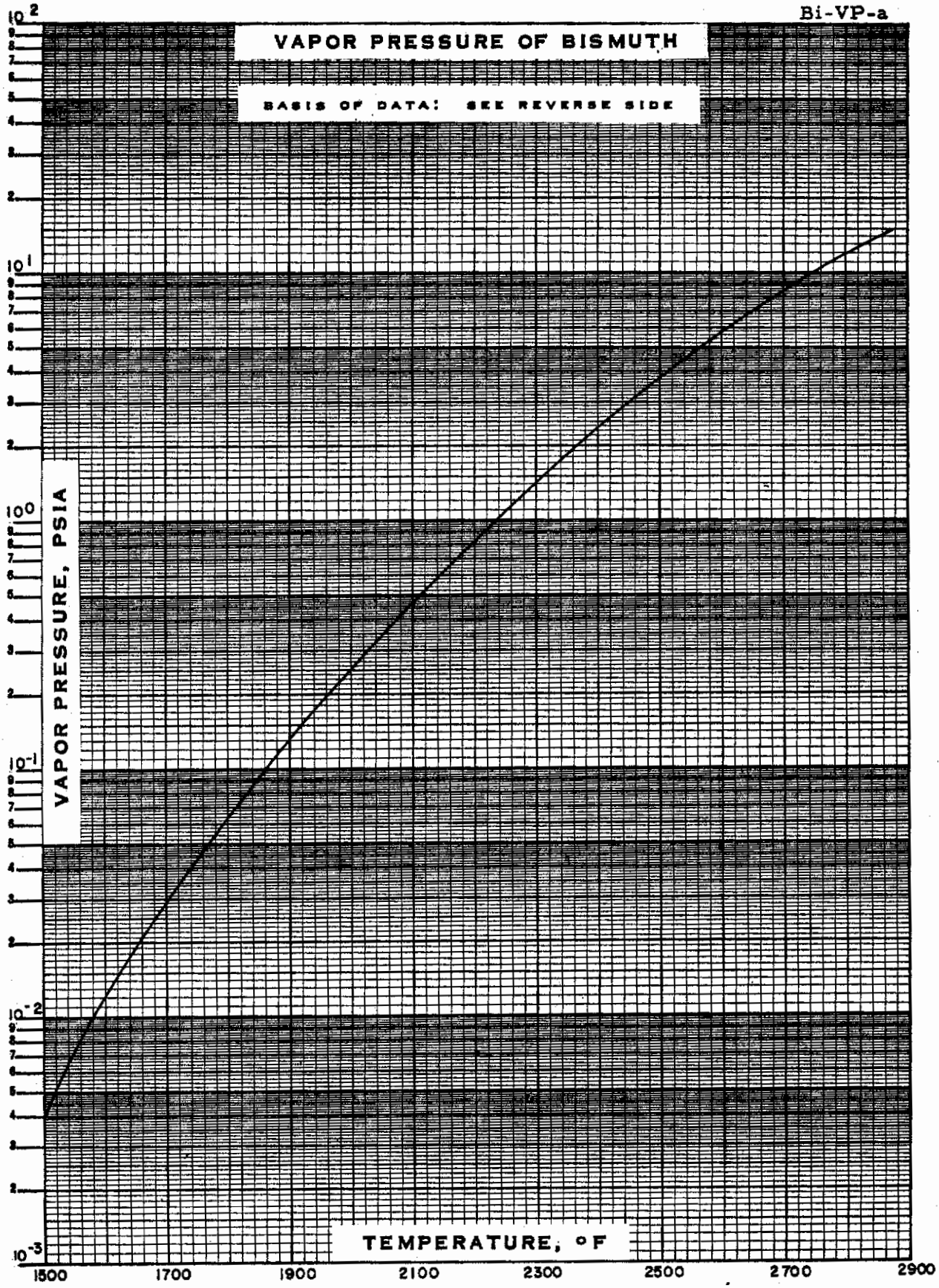
Ideal Diatomic Gas: $H^\circ_{536.67} - H^\circ_0 = 4,415$ BTU/lb mole

(Ref: 19-19-6)

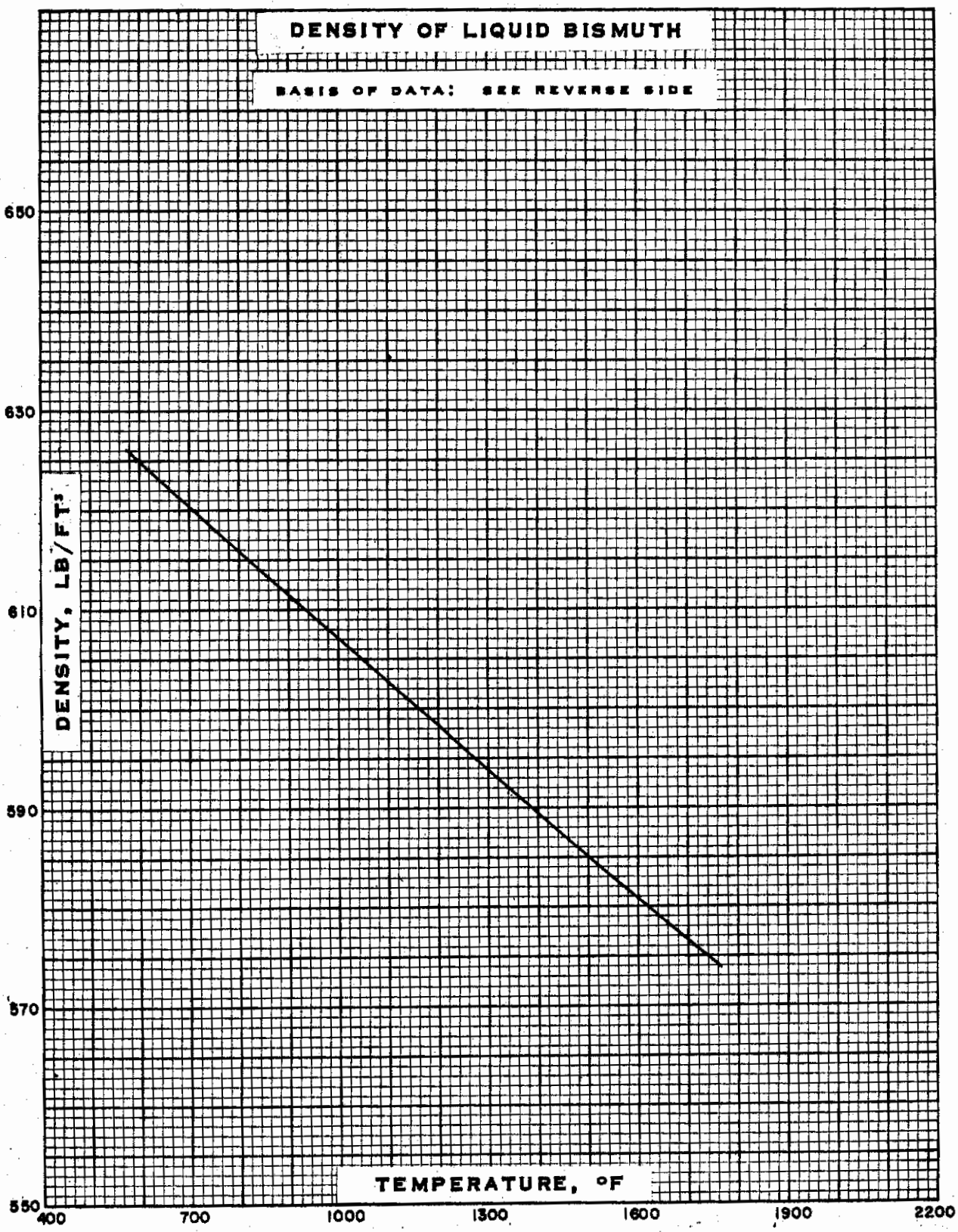
Temperature T (°R)	Enthalpy $H^\circ - H^\circ_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^\circ - H^\circ_{536.67})/T$ (BTU/lb mole °R)
1080	4833	71.62	67.15
1260	6435	72.99	67.89
1440	8037	74.18	68.60
1620	9648	75.23	69.28
1800	11250	76.17	69.92
1980	12852	77.02	70.53
2160	14472	77.80	71.10
2340	16074	78.51	71.65
2520	17694	79.18	72.16
2700	19296	79.79	72.65
2880	20907	80.37	73.12
3060	22518	80.91	73.56
3240	24120	81.42	73.98
3420	25731	81.91	74.39
3600	27342	82.36	74.77

d. Working Charts for Bismuth.

Bi-VP-a

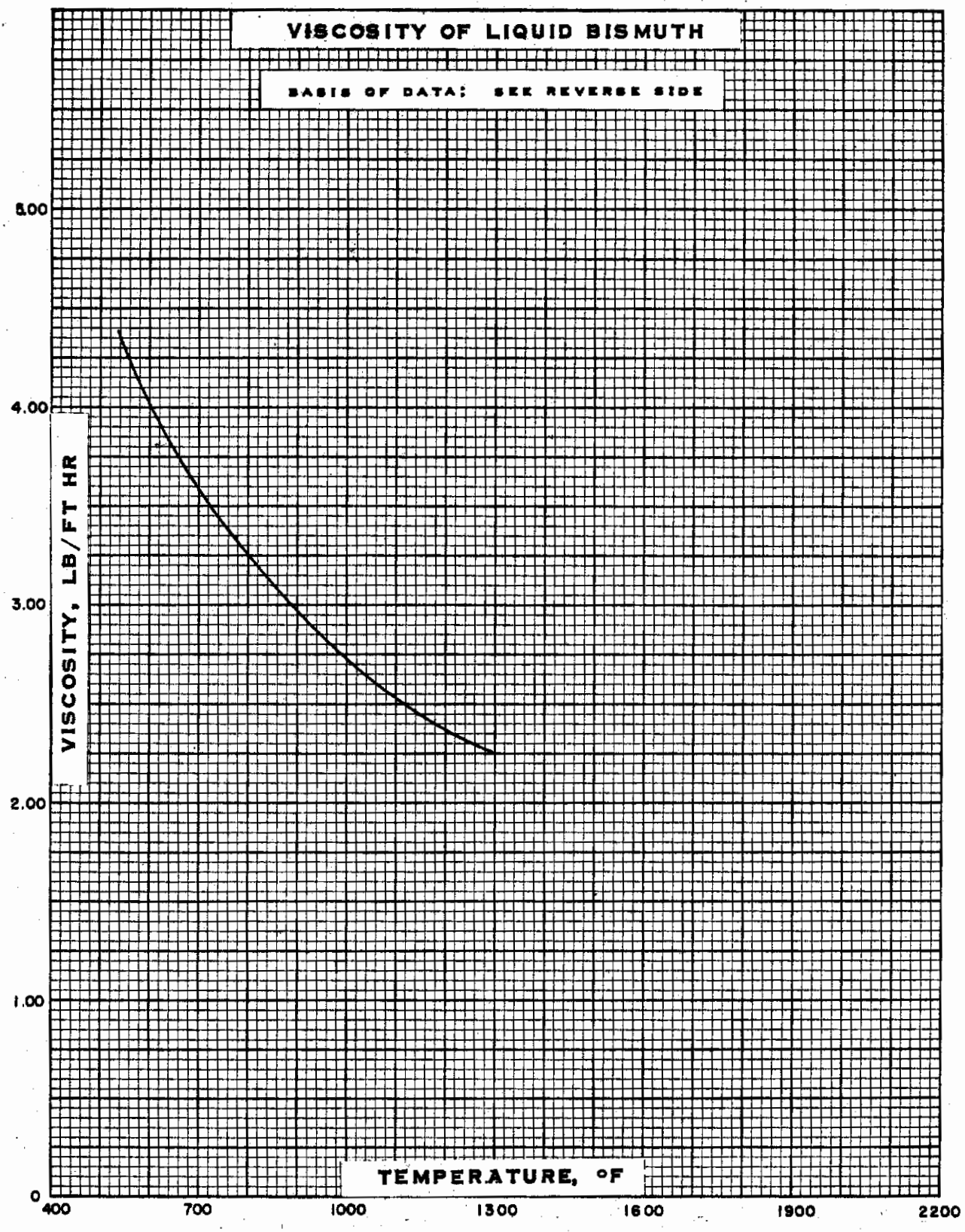


Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	105	1520-1736	Survey
Theoretical	105	1736-2874	The above experimental data were theoretically extended.



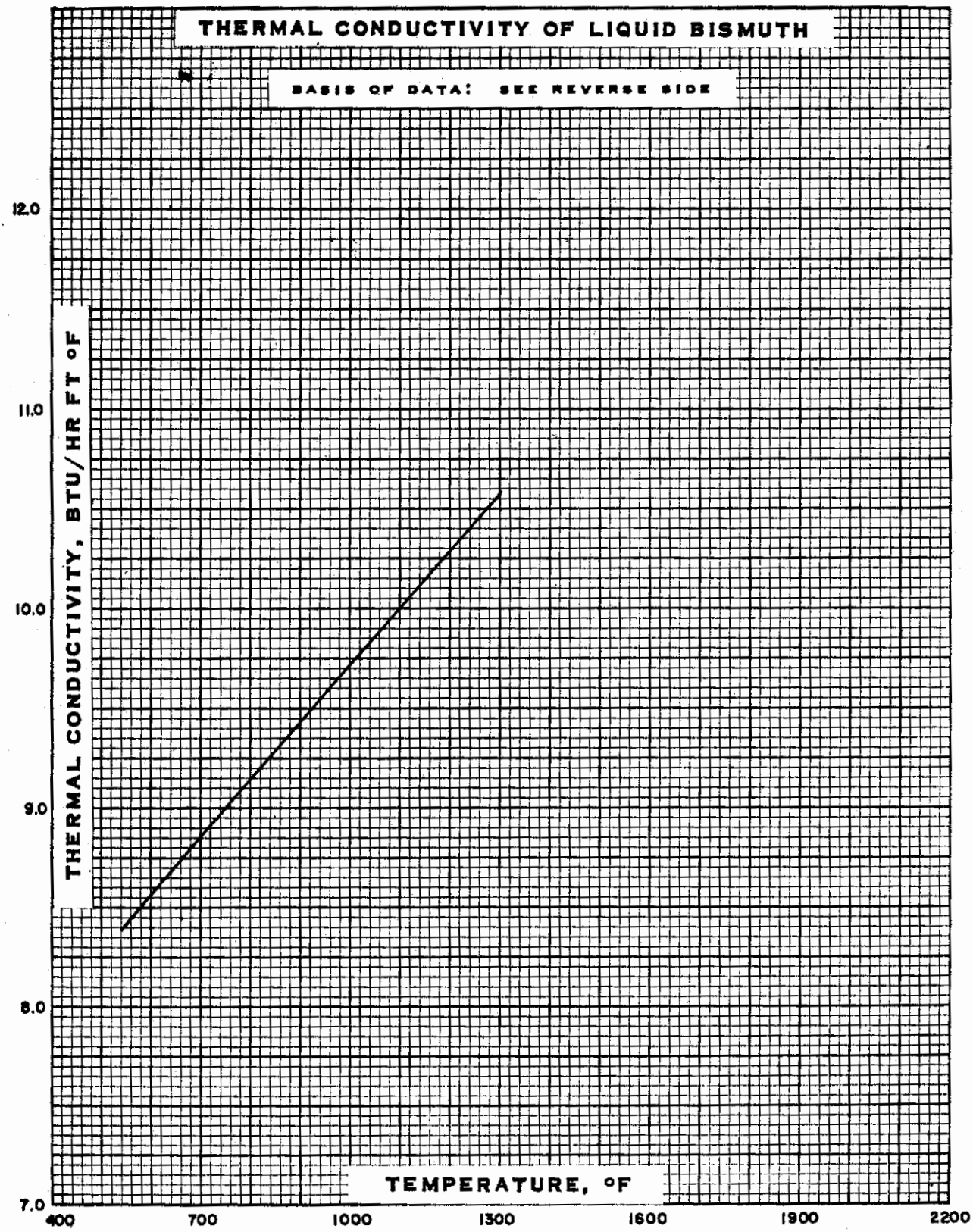
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Unknown	11-2-9, 12-02	572-1764	Values were plotted from several different published papers.

Bi-μ-a

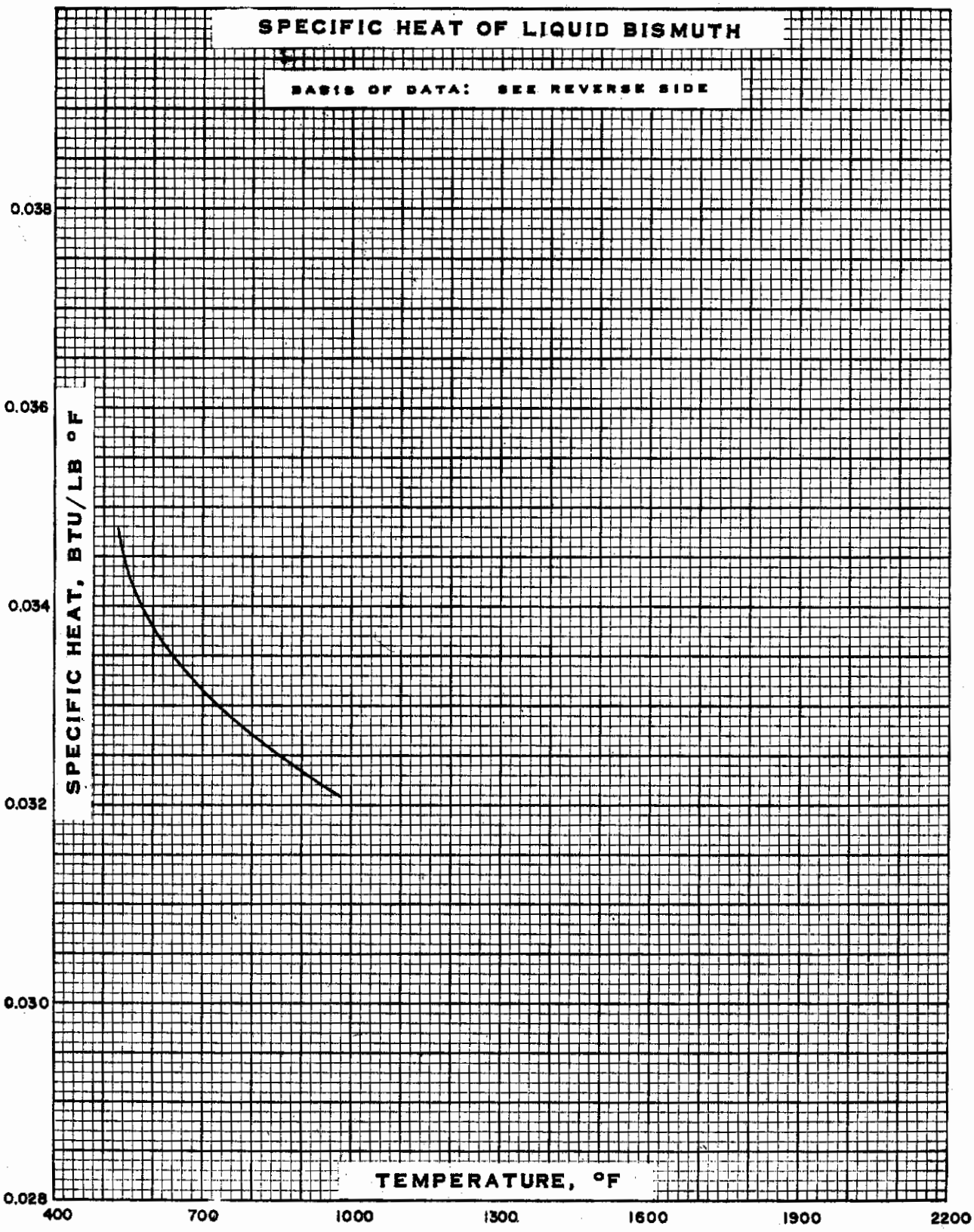


Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	11-2-9	536-1292	Measured by the method of damped torsional oscillations.

Bi-k-a



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	11-2-9	536-1292	Experimental values calculated by successive steady-state approximations.



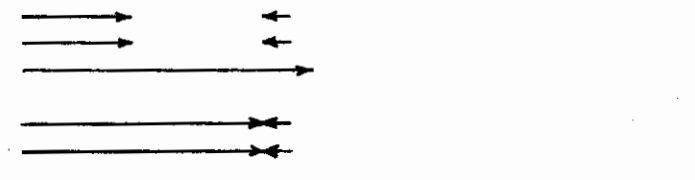
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	2-8-60	530-980	Specific heats of 99.9999% pure bismuth were measured by the method of mixtures, using a liquid bismuth calorimeter.

RESISTANCE OF MATERIALS TO LIQUID BISMUTH

(SEE REVERSE SIDE OF SHEET FOR DATA BASIS)

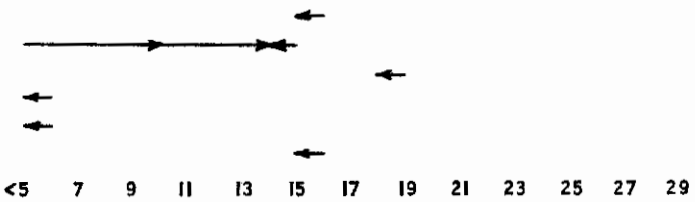
FERROUS METALS AND ALLOYS:

FERRITIC STAINLESS STEELS 400 SERIES
AUSTENTIC STAINLESS STEELS 300 SERIES
LOW CARBON SILICON STEELS
LOW IRON HIGH NICKEL INCONELS
LOW CARBON STEELS
PURE IRON



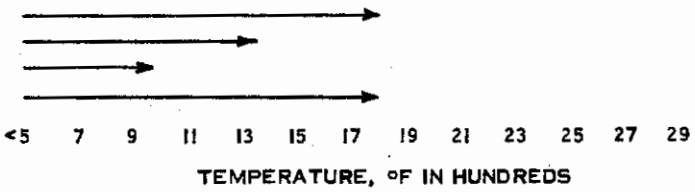
NONFERROUS METALS AND ALLOYS:

TITANIUM AND VANADIUM
CHROMIUM
COBALT
NICKEL
COPPER
ZIRCONIUM



REFRACTORY METALS AND ALLOYS:

MOLYBDENUM
COLUMBIUM
TANTALUM
TUNGSTEN

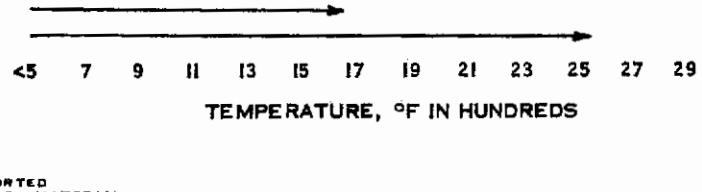


OTHER METALS AND ALLOYS:

BERYLLIUM
ALUMINUM AND MAGNESIUM
ZINC, CADMIUM, TIN AND LEAD
NOBLE METALS
BRAZING METALS Ni-Mn, Ni-Mo, Ni-P
SILVER BRAZING ALLOYS

NONMETALS:

DENSE OXIDES AL, BE, ETC.
OXIDE–BASE CERMETS
CARBIDE–BASE CERMETS
GLASSES
GRAPHITE



NOTE: RIGHT-HAND ARROW-POINT INDICATES HIGHEST REPORTED TEST TEMPERATURE BELOW RESISTANCE LIMIT OF MATERIAL

LEFT-HAND ARROW-POINT INDICATES LOWEST REPORTED TEST TEMPERATURE ABOVE RESISTANCE LIMIT OF MATERIAL

(SEE FRONT SIDE OF SHEET FOR DATA)

	DATA SOURCE	REMARKS AND BASIS OF DATA
FERROUS METALS AND ALLOYS:		
FERRITIC STAINLESS STEELS 400 SERIES	12-0-2, 16-16-58	Static
AUSTENTIC STAINLESS STEELS 300 SERIES	12-0-2, 16-16-58	Static
LOW CARBON SILICON STEELS	16-16-58	Static
LOW IRON HIGH NICKEL INCONELS		
LOW CARBON STEELS	12-0-2, 16-16-58	Static
PURE IRON	12-0-2, 16-16-58	Static
NONFERROUS METALS AND ALLOYS:		
TITANIUM AND VANADIUM	12-0-2	Survey
CHROMIUM	4-6-60, 12-0-2, 16-16-58	1-1/4 - 2-1/4 Cr - 1/2 Mo: dynamic: chrome plate failed (1380 °F)
COBALT	12-0-2	Survey
NICKEL	12-0-2	Survey
COPPER	12-0-2	Survey
ZIRCONIUM	12-0-2	Survey
REFRACTORY METALS AND ALLOYS:		
MOLYBDENUM	12-0-2, 22-18-58	Static
COLUMBIUM	12-0-2	Survey
TANTALUM	19-0-59	Capsule: 1000 hrs (U, Mg, Zr additives)
TUNGSTEN	22-18-58	Static
OTHER METALS AND ALLOYS:		
BERYLLIUM	12-0-2	Survey
ALUMINUM AND MAGNESIUM	12-0-2	Survey
ZINC, CADMIUM, TIN AND LEAD		
NOBLE METALS	12-0-2	Survey
BRAZING METALS Ni-Mn, Ni-Mo, Ni-P	12-0-2	Survey
SILVER BRAZING ALLOYS		
NONMETALS:		
DENSE OXIDES AL, BE, ETC.		
OXIDE-BASE CERMETS		
CARBIDE-BASE CERMETS		
GLASSES	12-0-2	Survey
GRAPHITE	8-0-52	Convection loop

e. Data Sources for Bismuth.

Code No.	Source
2-8-60	Bell, H. and Hultgren, R., Materials Research Laboratory, Series No. 155, Issue No. 1, July 1, 1960.
3-12-60	Chem. Eng. News, pp 53-65 (December 26, 1960).
4-6-60	Deville, R. E. and Foley, W. R., Babcock & Wilcox Co., BAW-1253, UC 81, TID-4500 (24th ed.), June 1960.
8-0-8	Hodgman, C. D., Editor, "Handbook of Chemistry and Physics," Cleveland, Chemical Rubber Publishing Co., 1958.
8-0-52	Hallett, W. J., et al., NAA-SR-188 (September 1952).
11-2-9	Kutateladze, S. S., Borishanskii, V. M., Novikov, I. I., and Fedynskii, O. S., "Liquid-Metal Heat Transfer Media," Atomnaia Energiia, Supp. No. 2, 1958, Translated by Consultants Bureau, Inc., New York, 1959.
11-15-7	Kirk, R. E., Othmer, D. F., Editors, "Encyclopedia of Chemical Technology," Vol. 1, 10, 13, First Sup. Vol., New York, The Interscience Encyclopedia, Inc., 1947.
12-0-2	Lyon, R. N., Editor, "Liquid-Metals Handbook", Second Ed., Washington, Atomic Energy Commission, Dept. of the Navy, 1952.
16-16-58	Pray, H. A., Peoples, R. S., and Boyd, W. K., BMI-773, October 15, 1952.
19-0-59	Seifert, J. W., Babcock & Wilcox Co., BAW-1067, May 14, 1959.
19-19-6	Stull, D. R., and Sinke, G. C., "Thermodynamic Properties of the Elements," Washington, American Chemical Society, 1956.

Code No.	Source
22-18-58	Vogel, R. C., and Rodger, W. A., ANL-5933, November 1958.
105	"Selected Values for the Thermodynamic Properties of Metals and Alloys," Minerals Research Laboratory, Berkeley, Calif., 1960.

LEAD

a. General Discussion of Lead. Lead is a lustrous, bluish-white metal which is very malleable. It is a relatively poor electrical conductor and is resistant to chemical attack at room temperature. Moist air causes lead surfaces to oxidize, and the resulting oxide film may become carbonated by atmospheric carbon dioxide. The toxicity of lead is significant because of its action as a cumulative poison.

Lead pigs may be purchased in carload lots at $0.12 per pound.

b. Synopsis of Properties of Lead.

Property	Value	Temp (°F)	Data Basis	Reference
Physical:				
Atomic Weight	207.21	---	Handbook	8-0-8
Melting Point, °F	621.32	---	Handbook	8-0-8
Boiling Point, °F	3169	---	Unknown	Page Pb-VP-a
Density of Solid, lb/ft^3	708.0	68	Handbook	8-0-8
Density of Liquid, lb/ft^3	661.7	M.P.	Extrapolated	Page Pb-ρ-a
Viscosity, lb/ft hr	5.121	625.8	Survey	11-15-7
	2.868	1551.2	Survey	11-15-7
Surface Tension, lb/ft	0.0303	662	Survey	11-15-7
	0.0295	932	Survey	11-15-7
Thermal:				
Thermal Conductivity of Liquid, BTU/hr ft °F	8.72	M.P.	Extrapolated	Page Pb-k-a
Specific Heat of Liquid, BTU/lb °F	0.03029	B.P.	Extrapolated	Page Pb-C-a
Specific Heat of Vapor, BTU/lb °F	0.0286	B.P.	Theoretical	Page Pb-C-b
Latent Heat of Fusion, BTU/lb	10.54	B.P.	Survey	11-15-7
Latent Heat of Vaporization, BTU/lb	365.4	B.P.	Survey	11-15-7

Property	Value	Temp (°F)	Data Basis	Reference
Electrical and Magnetic:				
Resistivity, μ ohm-inch	37.244	M.P.	Survey	11-15-7
Ionization Potential, volts	7.38	---	Handbook	8-0-8
Magnetic Susceptibility, fps electromagnetic units/unit mass	-0.0337	626 liq	Survey	11-15-7
Thermal Neutron Cross Section (2200 m/s):				
Absorption, barns	0.170 ± 0.010			
Scattering, barns	11 ± 1			

c. Property Tables for Lead.

THERMODYNAMIC PROPERTIES OF LEAD

Liquid Phase: $H^\circ_{536.67} - H^\circ_0 = 2,959$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^\circ - H^\circ_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^\circ - H^\circ_{536.67})/T$ (BTU/lb mole °R)
1260	6991	23.15	17.61
1440	8289	24.11	18.36
1620	9572	25.00	19.10
1800	10843	25.70	19.68
1980	12101	26.37	20.26
2160	13347	26.97	20.80
2340	14586	27.51	21.28
2520	15804	28.02	21.75
2700	17010	28.48	22.18
2880	18198	28.91	22.60
3060	19368	29.30	22.98
3240	20538	29.67	23.34
3420	21690	30.02	23.68
3600	22824	30.34	24.00

THERMODYNAMIC PROPERTIES OF LEAD

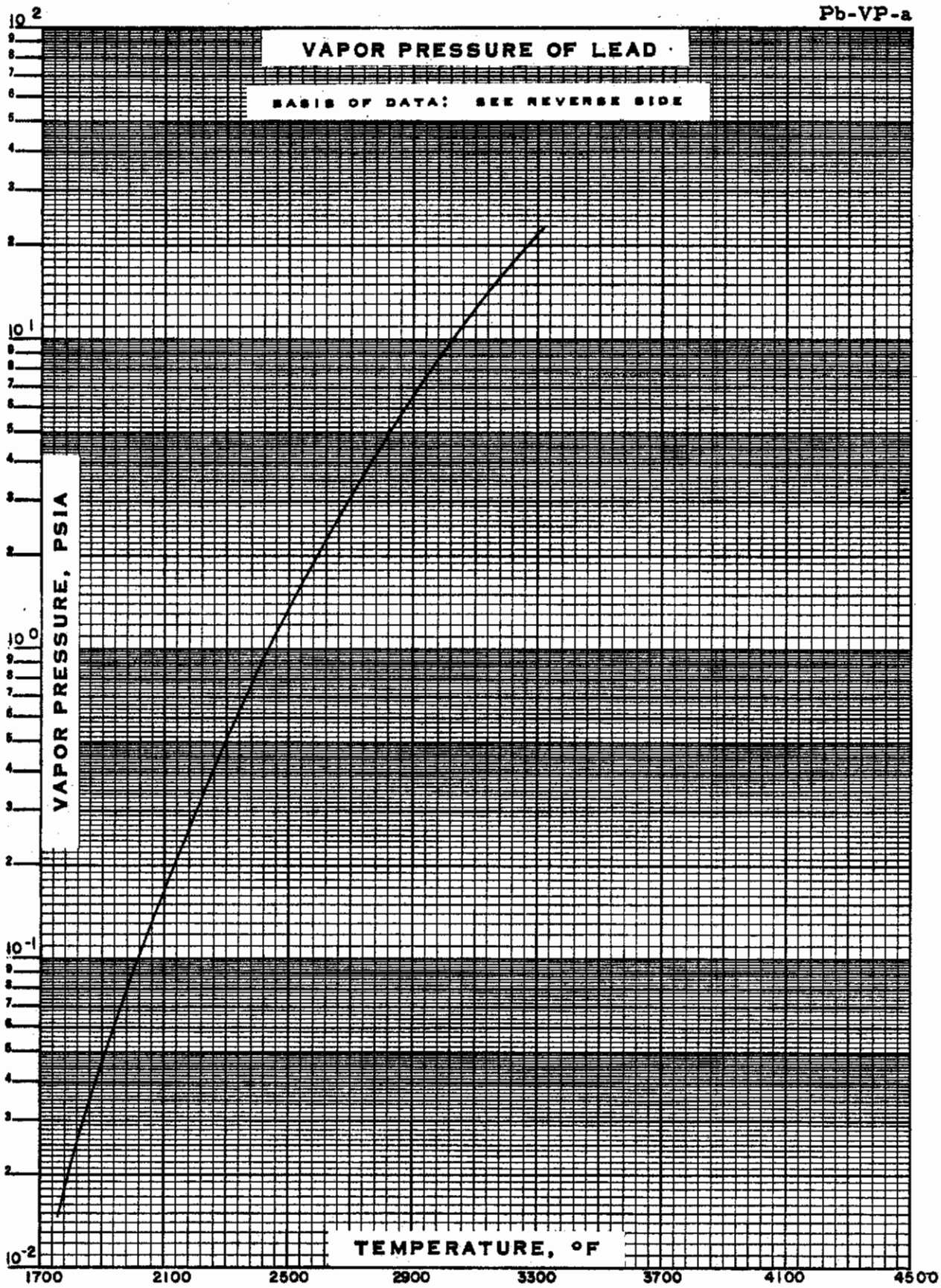
Ideal Monatomic Gas: $H^{\circ}_{536.67} - H^{\circ}_{o} = 2,666$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^{\circ} - H^{\circ}_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^{\circ} - H^{\circ}_{536.67})/T$ (BTU/lb mole °R)
1260	3593	46.13	43.28
1440	4487	46.79	43.68
1620	5382	47.38	44.06
1800	6278	47.90	44.42
1980	7175	48.38	44.76
2160	8077	48.81	45.08
2340	8982	49.22	45.39
2520	9896	49.59	45.67
2700	10825	49.95	45.95
2880	11765	50.29	46.21
3060	12730	50.61	46.45
3240	13718	50.92	46.69
3420	14731	51.23	46.93
3600	15777	51.53	47.15
3780	16857	51.82	47.37
3960	17973	52.11	47.58
4140	19727	52.39	47.77
4320	20318	52.67	47.97
4500	21551	52.95	48.17
4680	22822	53.23	48.36
4860	24131	53.51	48.55
5040	25475	53.78	48.73

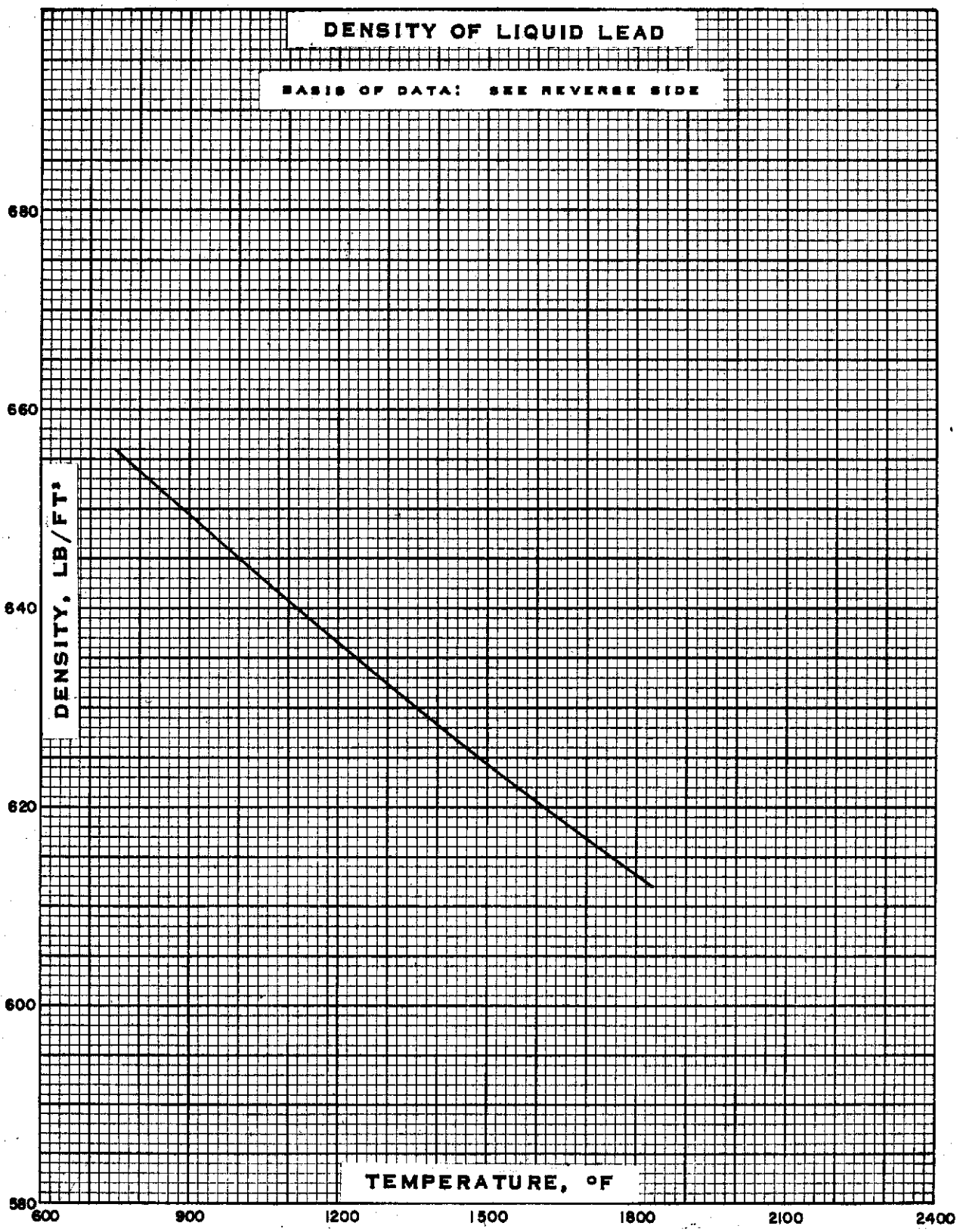
d. Working Charts for Lead.

Pb-VP-a



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	18-4-5, 18-4-25, 105	2044-2415	The lead was boiled under reduced pressure in an inert atmosphere and the temperatures read by thermocouple.
Unknown	105	1752-2044 and 2415-3320	Several different references were employed to obtain the vapor pressure data in these temperature ranges.

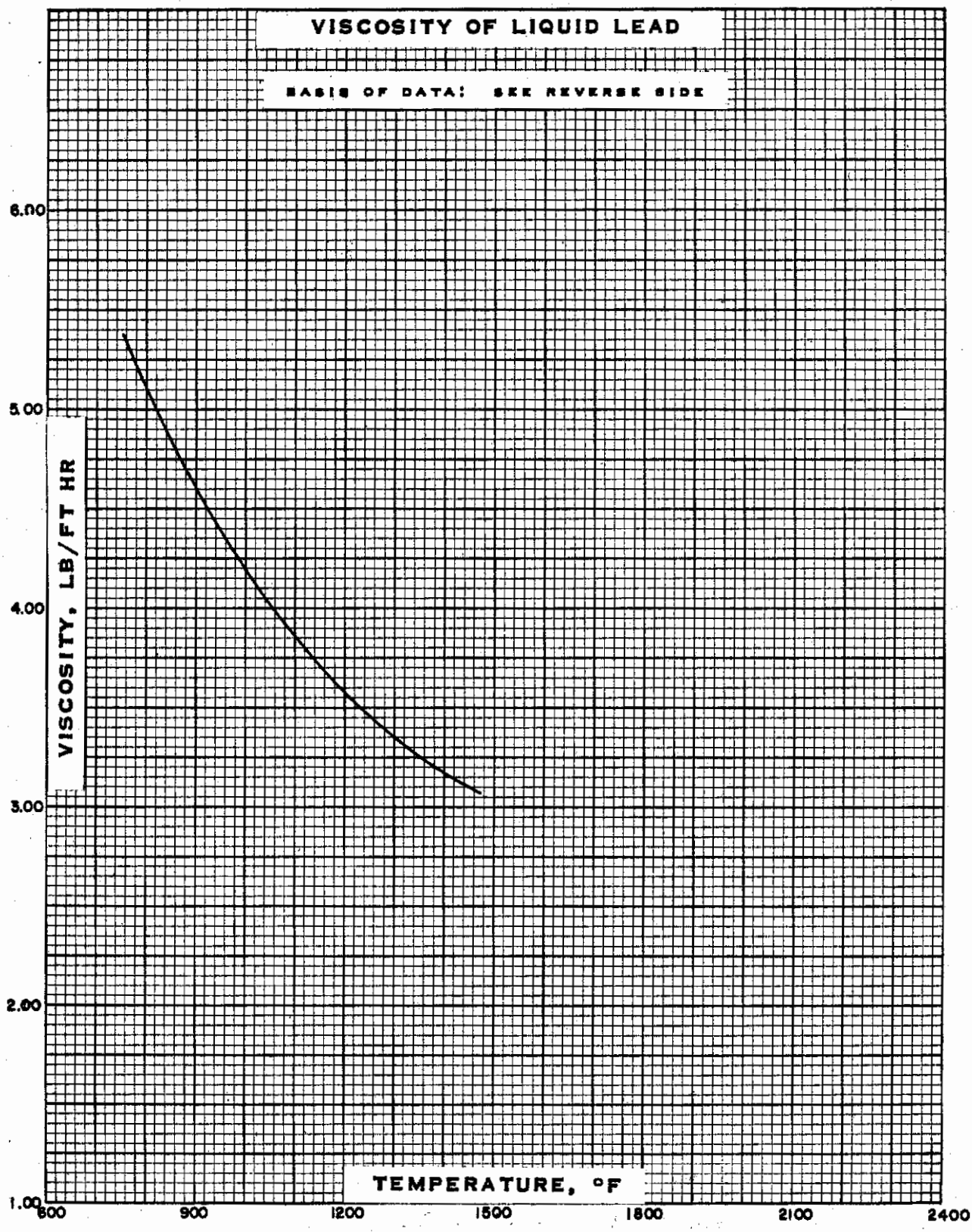
Pb-p-a



Pb-ρ-a (basis)

Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Unknown	12-0-2	752-1832	Survey

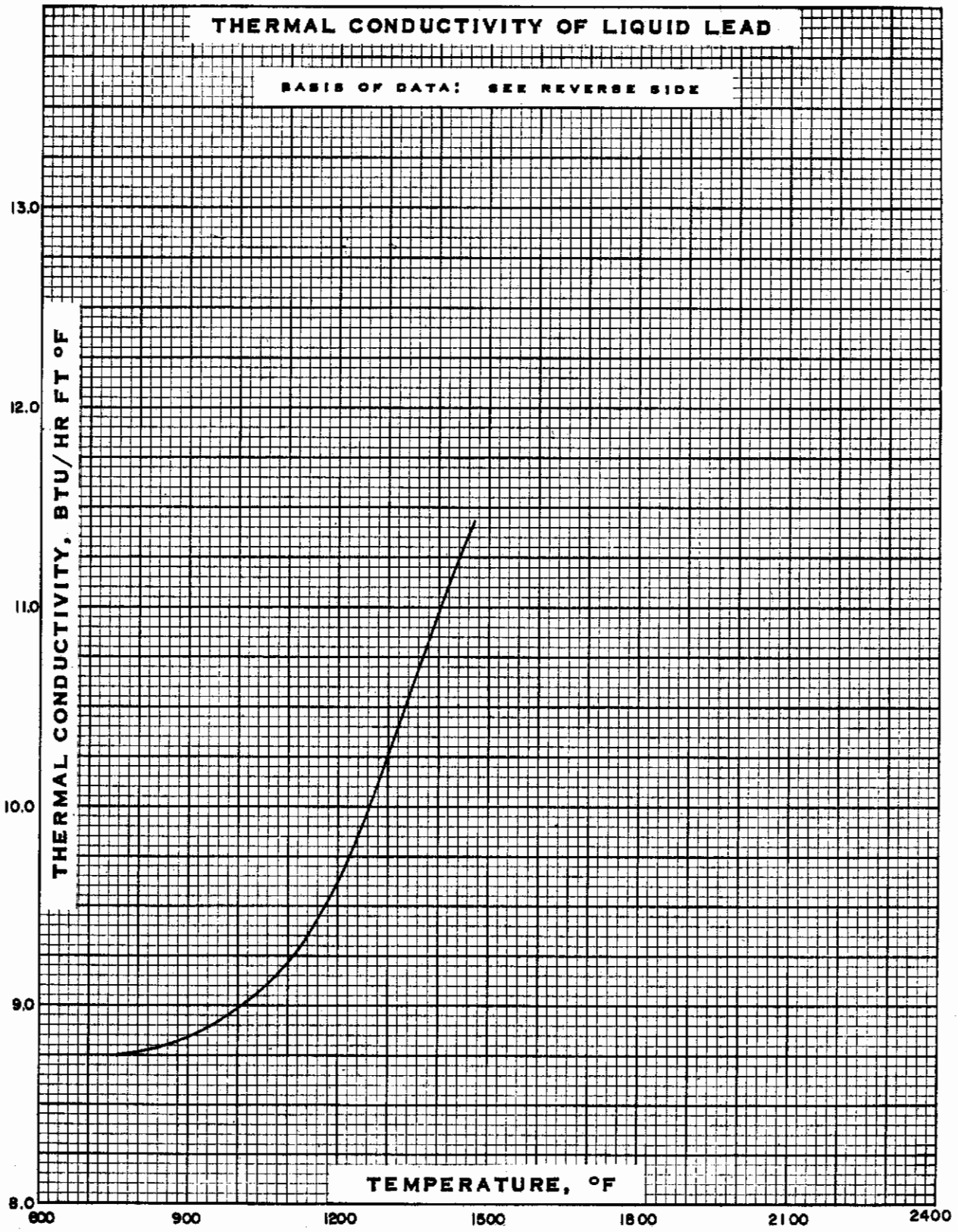
Pb-μ-a



WADD TR 61-96

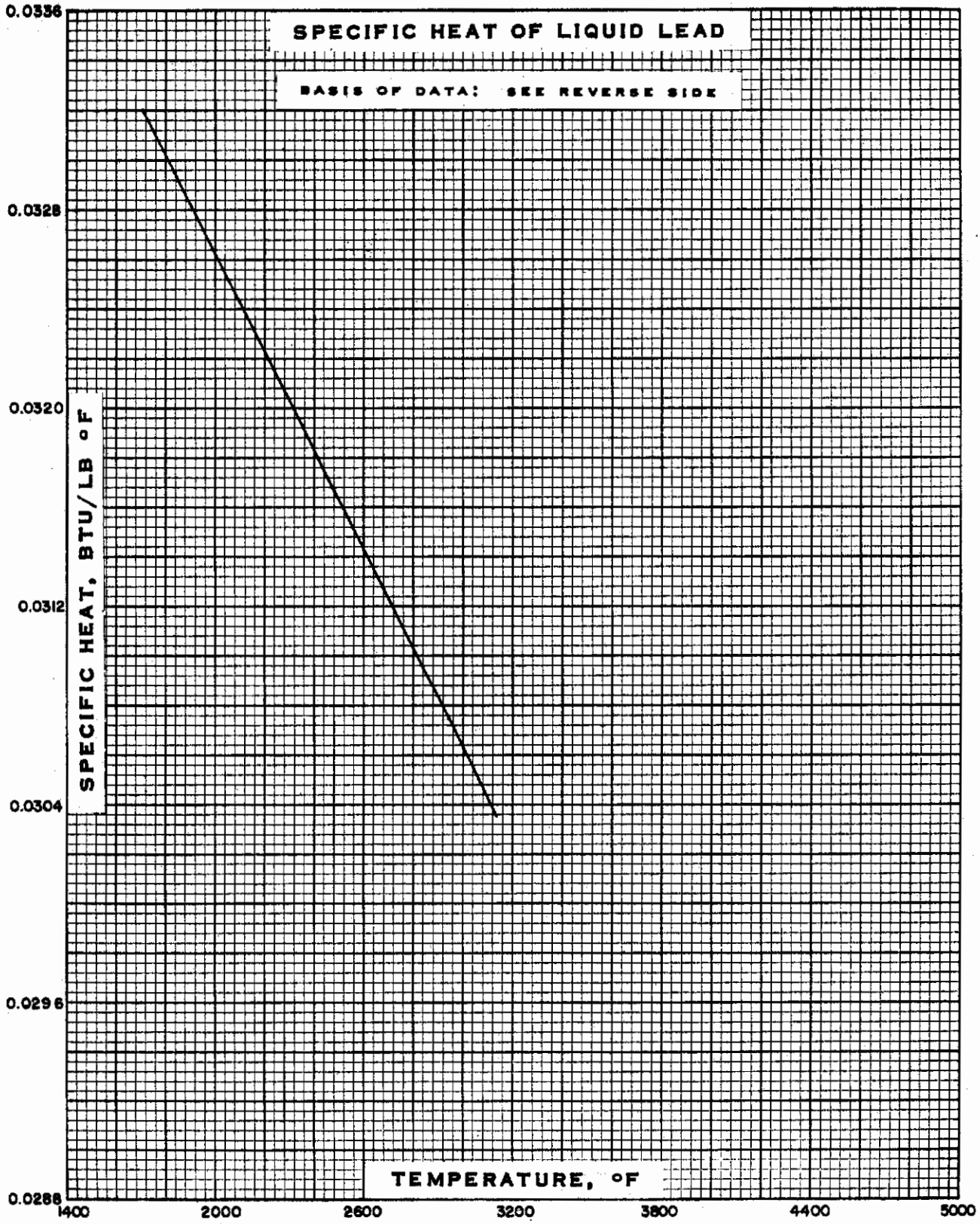
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	11-2-9	752-1472	Measured by the method of damped torsional oscillations.

Pb-k-a



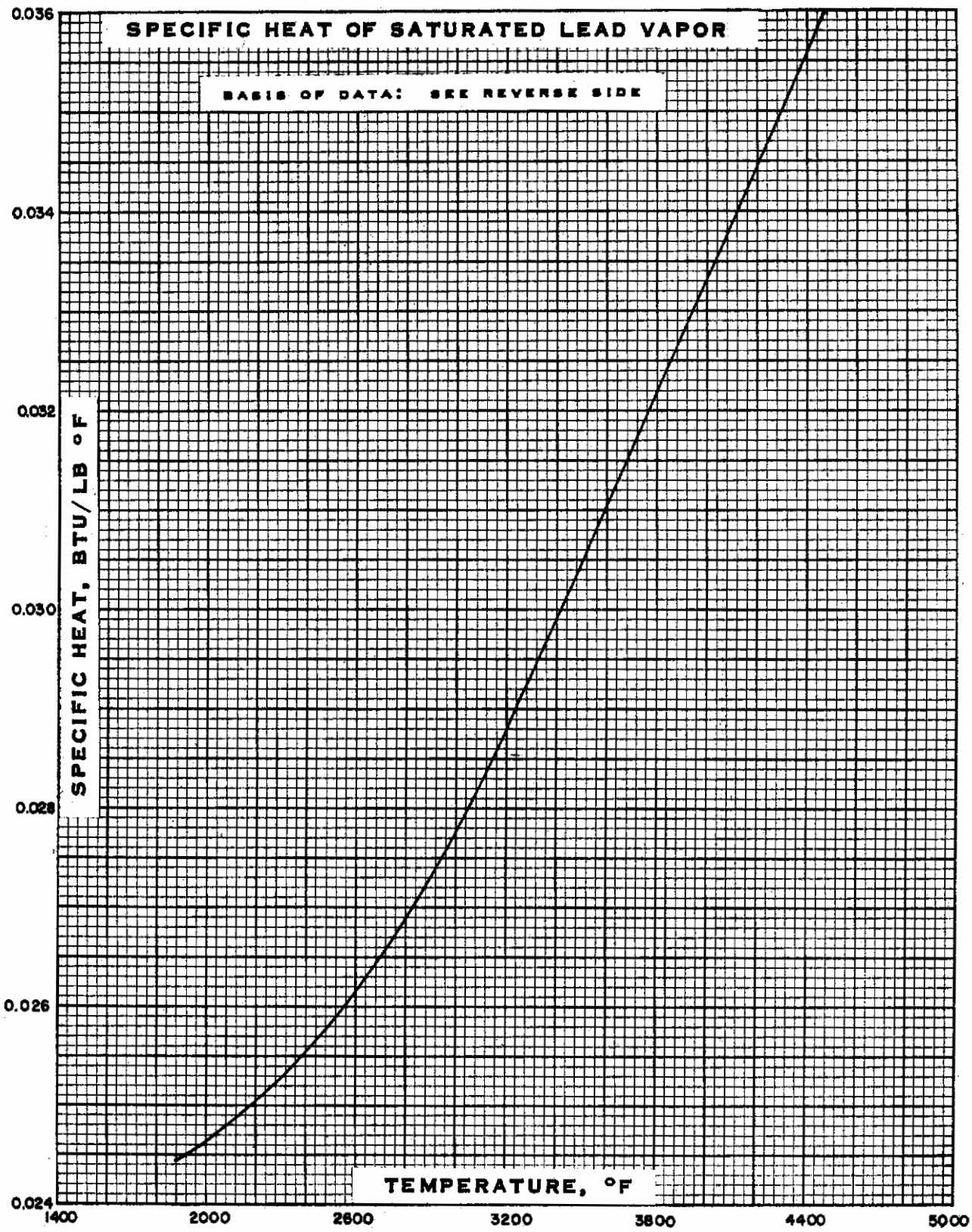
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	11-2-9	752-1472	Experimental values calculated by successive steady-state approximations.

Pb-C-a



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Extrapolated	19-19-6	1700-3140	The extended data are based on the experimental work of (4-4-3).

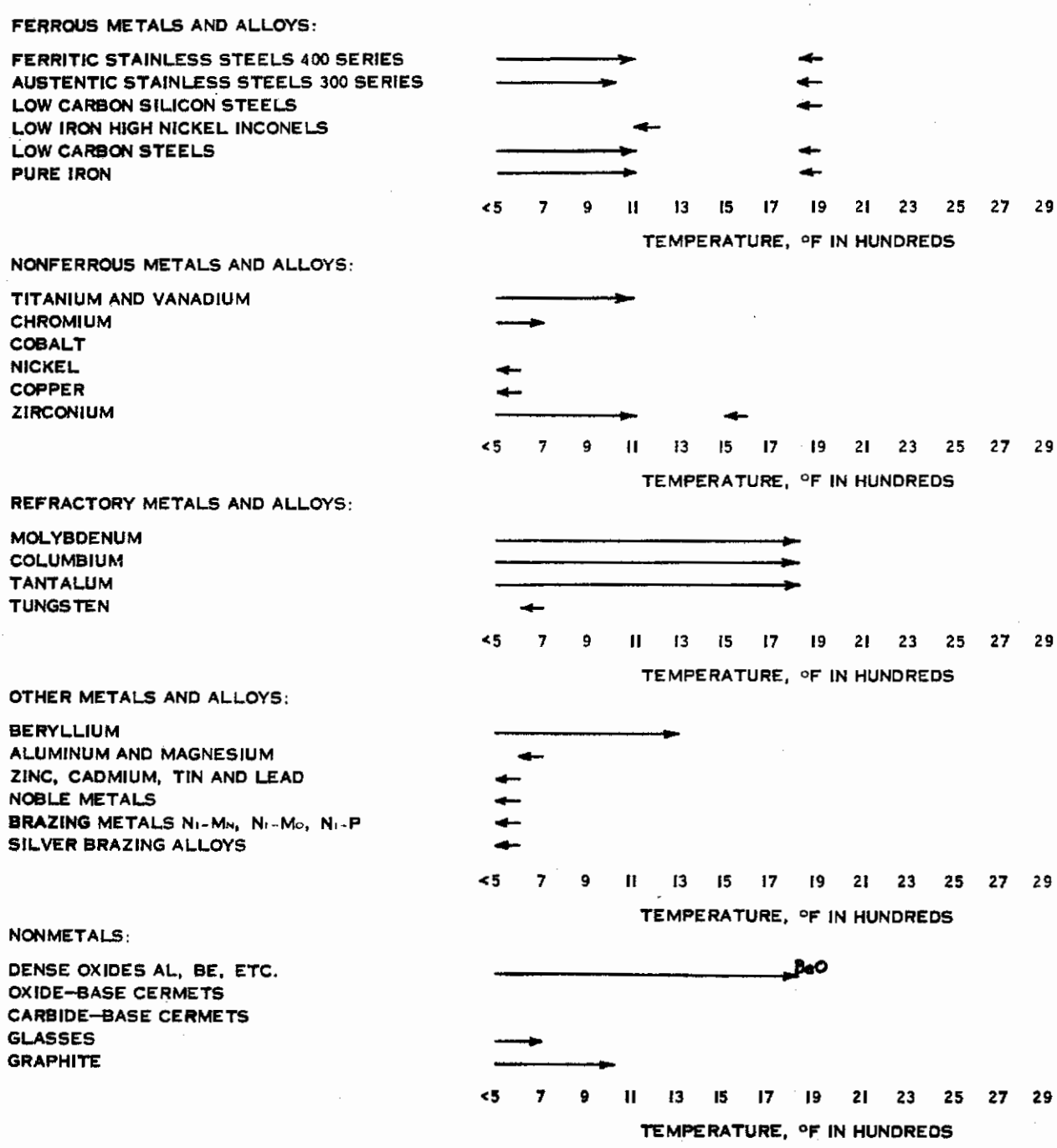
Pb-C-b



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	19-19-6	1880-4470	Specific heats of the ideal monatomic gas were calculated from the energy levels listed in (12-0-2).

RESISTANCE OF MATERIALS TO LIQUID LEAD

(SEE REVERSE SIDE OF SHEET FOR DATA BASIS)



NOTE: RIGHT-HAND ARROW-POINT INDICATES HIGHEST REPORTED TEST TEMPERATURE BELOW RESISTANCE LIMIT OF MATERIAL

LEFT-HAND ARROW-POINT INDICATES LOWEST REPORTED TEST TEMPERATURE ABOVE RESISTANCE LIMIT OF MATERIAL

(SEE FRONT SIDE OF SHEET FOR DATA)

	DATA SOURCE	REMARKS AND BASIS OF DATA
FERROUS METALS AND ALLOYS:		
FERRITIC STAINLESS STEELS 400 SERIES	12-0-2, 23-8-55	Static
AUSTENTIC STAINLESS STEELS 300 SERIES	12-0-2, 23-8-55	Static
LOW CARBON SILICON STEELS	23-8-55	Static
LOW IRON HIGH NICKEL INCONELS	12-0-2	Static
LOW CARBON STEELS	12-0-2, 23-8-55	Static
PURE IRON	12-0-2, 23-8-55	Static
NONFERROUS METALS AND ALLOYS:		
TITANIUM AND VANADIUM	12-0-2	Survey
CHROMIUM	12-0-2	Survey
COBALT		
NICKEL	12-0-2	Survey
COPPER	12-0-2	Survey
ZIRCONIUM	12-0-2, 11-0-53	Static
REFRACTORY METALS AND ALLOYS:		
MOLYBDENUM	12-0-2	Static
COLUMBIUM	23-8-55	Static
TANTALUM	23-8-55	Static
TUNGSTEN	12-0-2	Survey
OTHER METALS AND ALLOYS:		
BERYLLIUM		
ALUMINUM AND MAGNESIUM	12-0-2	Survey
ZINC, CADMIUM, TIN AND LEAD	12-0-2	Survey
NOBLE METALS	12-0-2	Survey
BRAZING METALS Ni-Mn, Ni-Mo, Ni-P	12-0-2	Survey
SILVER BRAZING ALLOYS	12-0-2	Survey
NONMETALS:		
DENSE OXIDES AL, BE, ETC.	23-8-55	Static
OXIDE–BASE CERMETS		
CARBIDE–BASE CERMETS		
GLASSES	12-0-2	Survey
GRAPHITE	12-0-2	Survey

e. Data Sources for Lead

Code No.	Source
3-12-60	Chem. Eng. News, pp 53-65 (Dec. 26, 1960).
4-4-3	Douglas, T. B. and Dever, J. L., NBS Report 2544, April 18, 1953.
8-0-8	Hodgman, C. D., Editor, "Handbook of Chemistry and Physics," Cleveland, Chemical Rubber Publishing Co., 1958.
11-0-53	Koenig, R. F., KAPL-982, October 1, 1953.
11-2-9	Kutateladze, S. S., Borishanskii, V. M., Novikov, I. I., and Fedynskii, O. S., "Liquid-Metal Heat Transfer Media," Atomnaia Energiia, Supp. No. 2, 1958, Translated by Consultants Bureau, Inc., New York, 1959.
11-15-7	Kirk, R. E., Othmer, D. F., Editors, "Encyclopedia of Chemical Technology," Vol. 1, 10, 13, First Sup. Vol., New York, The Interscience Encyclopedia, Inc., 1947.
12-0-2	Lyon, R. N., Editor, "Liquid-Metals Handbook,"Second Ed., Washington, Atomic Energy Commission, Dept. of the Navy, 1952.
18-4-5	Rodebush, W. H. and Dixon, A. L., Phys. Rev., 26, No. 6, 851 (1925).
18-4-25	Rodebush, W. H. and Dixon, A. L., J. Chem. Soc., 47, 1036 (1925).
19-19-6	Stull, D. R., and Sinke, G. C., "Thermodynamic Properties of the Elements," Washington, American Chemical Society, 1956.
23-8-55	Wilkinson, W. D., Hoyt, E. W., and Rhude, H. V., ANL-5449, October 1955.
105	"Selected Values for the Thermodynamic Properties of Metals and Alloys," Minerals Research Laboratory, Berkeley, Calif., 1960.

NONMETALS

ALUMINUM BROMIDE

a. General Description of Aluminum Bromide. Aluminum bromide solid exists as colorless, rhombic, deliquescent plates. It is soluble in acetone, water, carbon disulfide, and alcohol. Aluminum bromide reacts violently with water, and it liberates bromine and alumina when heated in air. At ordinary temperatures, the superheated vapor and the vapor in equilibrium with the liquid phase are composed primarily of the dimer, Al_2Br_6; however, the monomer $AlBr_3$, becomes a major constituent of the atmospheric-pressure vapor at temperatures in excess of about 1000°F.

The primary interest in aluminum bromide as a possible working fluid is related to the fact that the temperature-entropy diagram for this fluid is skewed so that an isentropic expansion of the saturated vapor should yield superheated vapor rather than wet vapor.

CP grade anhydrous aluminum bromide is available for approximately $24.00 per pound.

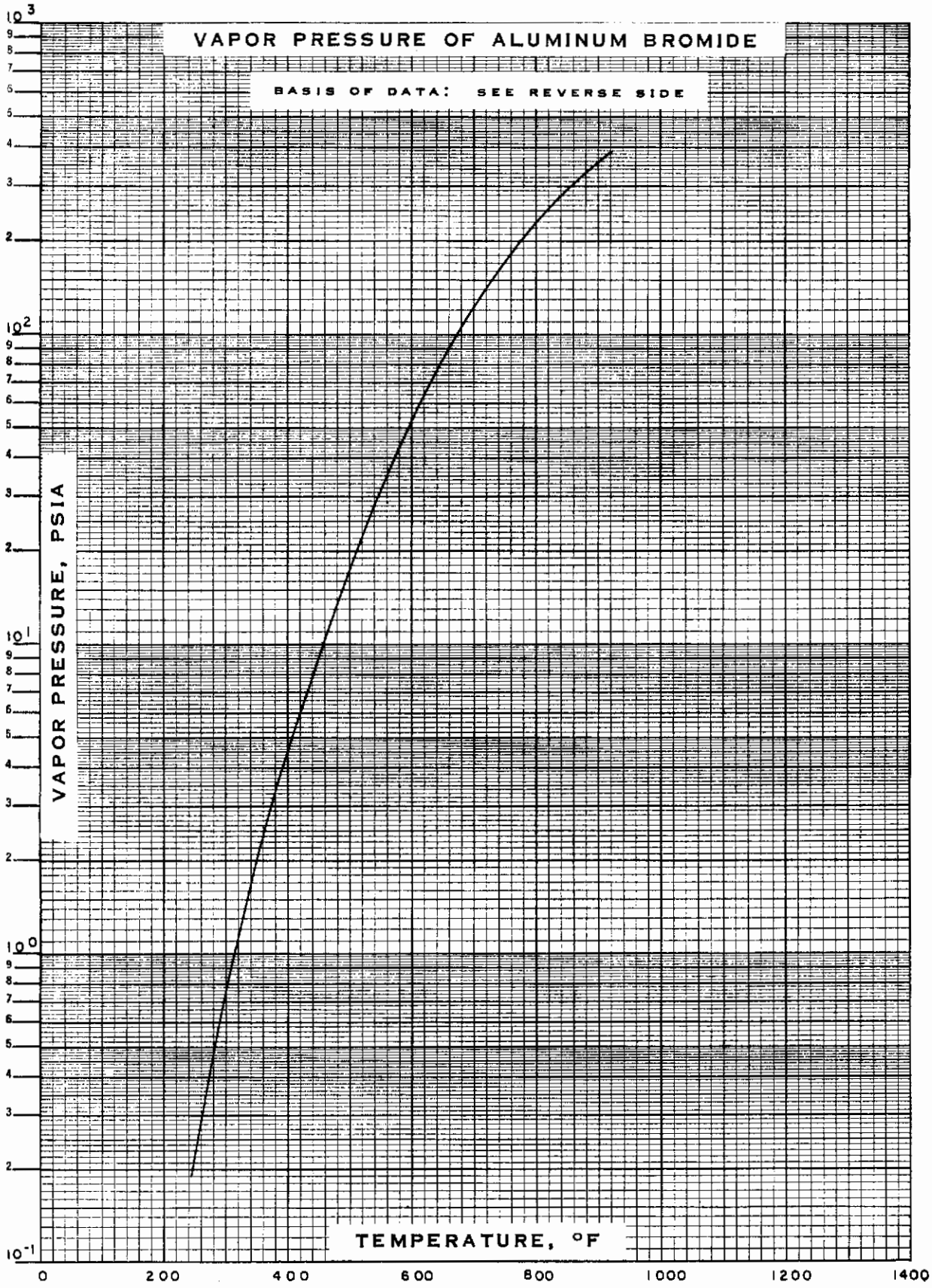
b. Synopsis of Properties of Aluminum Bromide

Property	Value	Temp (°F)	Data Basis	Reference
Physical:				
Molecular Weight	266.72 (monomer)	---	Handbook	8-0-8
Triple Point, °F	210.0	---		722
Melting Point, °F	207.6	---	Handbook	8-0-8
Boiling Point, °F	485	---	Experimental	$AlBr_3$-VP-a
Critical Point, psia	390	923	Experimental	721, 26-11-37
Density of Solid	187.8	77	Handbook	8-0-8
Density of Liquid, lb/ft^3	142	B.P.	Experimental	Page $AlBr_3$-ρ-a
Density of Vapor, lb/ft^3	0.70	B.P.	Experimental	Page $AlBr_3$-ρ-b
Viscosity of Liquid, lb/ft hr	1.07	B.P.	Calculated	Page $AlBr_3$-μ-a
Viscosity of Vapor, lb/ft hr	0.0435	B.P.	Calculated	Page $AlBr_3$-μ-b
Thermal:				
Thermal Conductivity of Liquid, BTU/lb ft °F	0.0397	B.P.	Calculated	Page $AlBr_3$-k-a
Thermal Conductivity of Vapor, BTU/lb ft °F	0.00304	B.P.	Calculated	Page $AlBr_3$-k-b
Specific Heat of Liquid, BTU/lb °F	0.095	B.P.	Experimental	Page $AlBr_3$-C-a
Specific Heat of Vapor, BTU/lb °F	0.0664	---	Experimental	26-11-37
Latent Heat of Vaporization, BTU/lb	40.8	B.P.	Experimental	Page $AlBr_3$-ΔH-a
Electrical and Magnetic:				
Magnetic Susceptibility fps electromagnetic units/unit mass	-0.1348	66.2 sol	Handbook	8-0-8

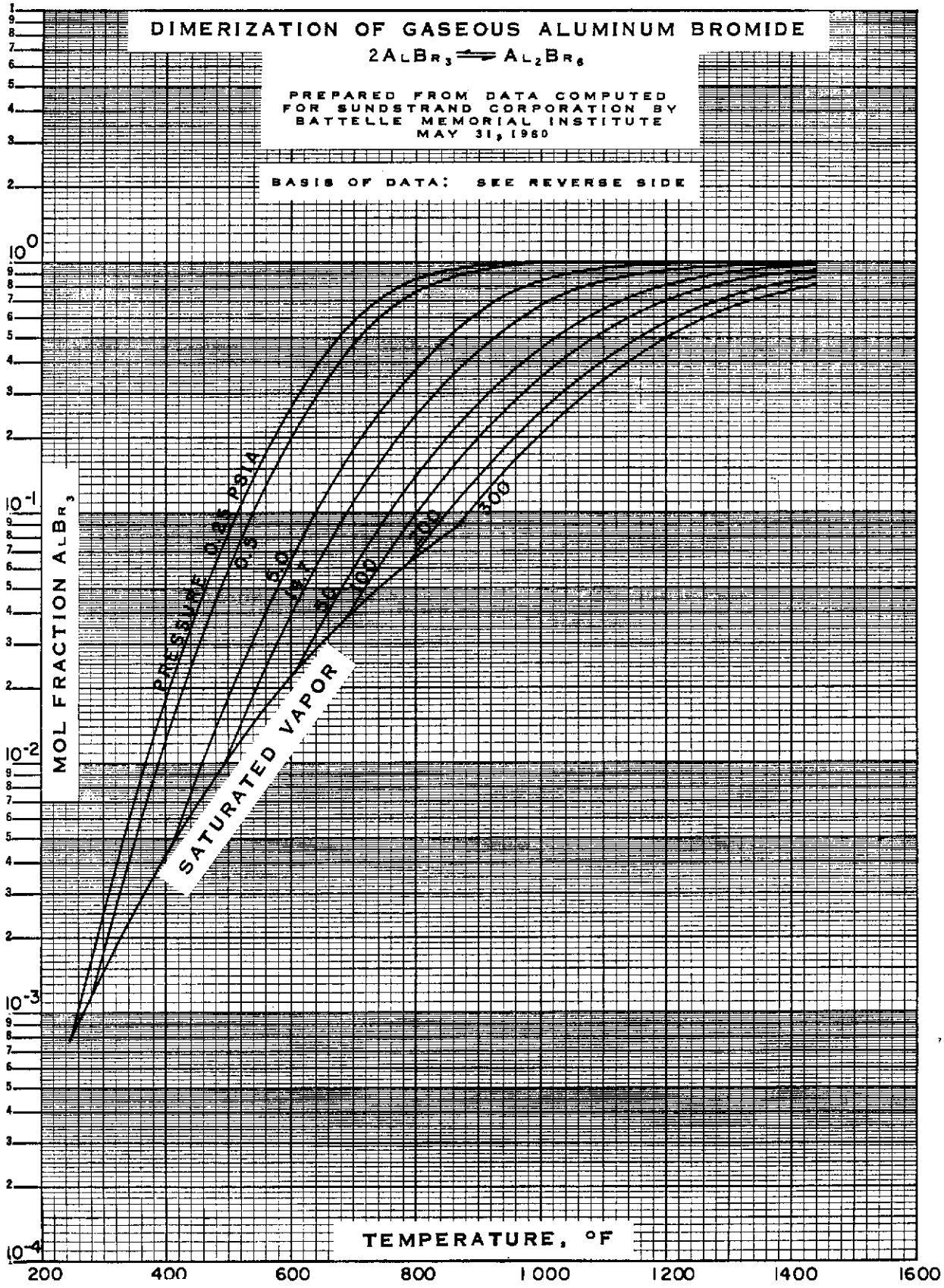
c. Property Tables for Aluminum Bromide

(None presented)

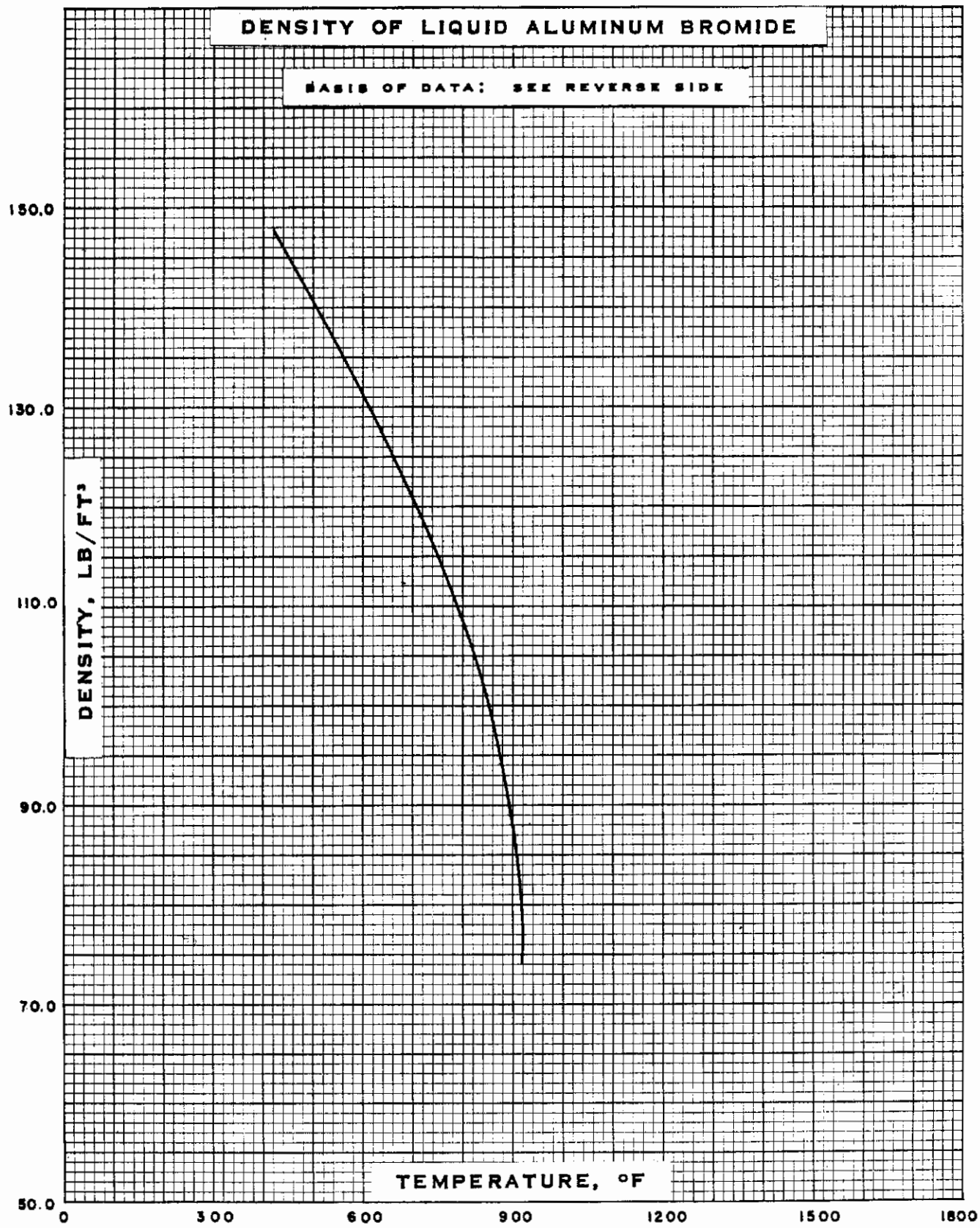
d. Working Charts for Aluminum Bromide



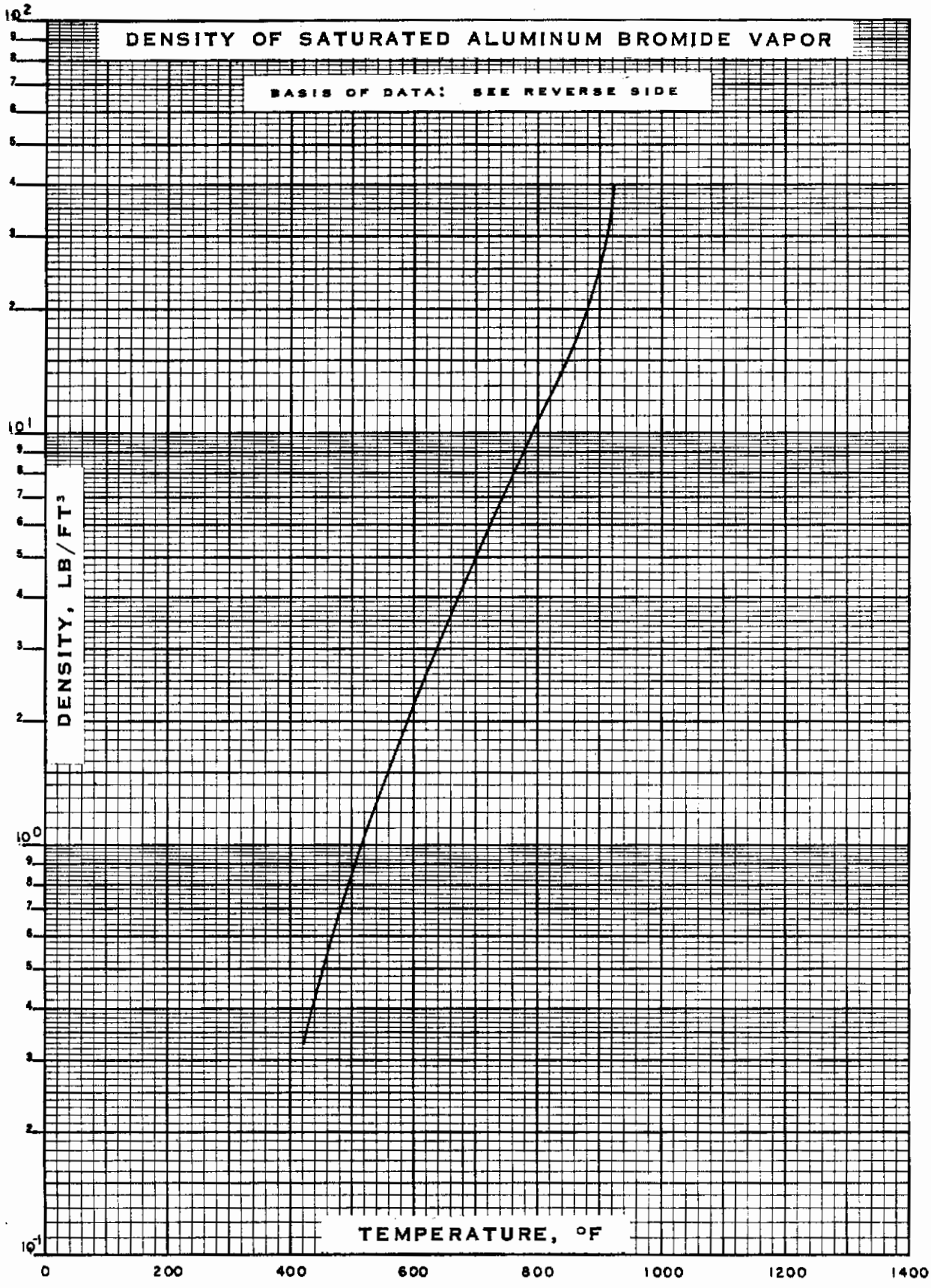
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Handbook	8-0-8	244-302	Vapor pressures of many pure substances were collected from the literature and private sources and presented in tables. Graphic methods were used to evaluate the data.
Experimental	26-11-37, 722, 8-0-8	340-923	These vapor pressure data have been experimentally verfied over this temperature range by 722.



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical and Experimental	722, 825	252-1472	Computed (by 825 for 722). Based on experimental data (26-11-37).

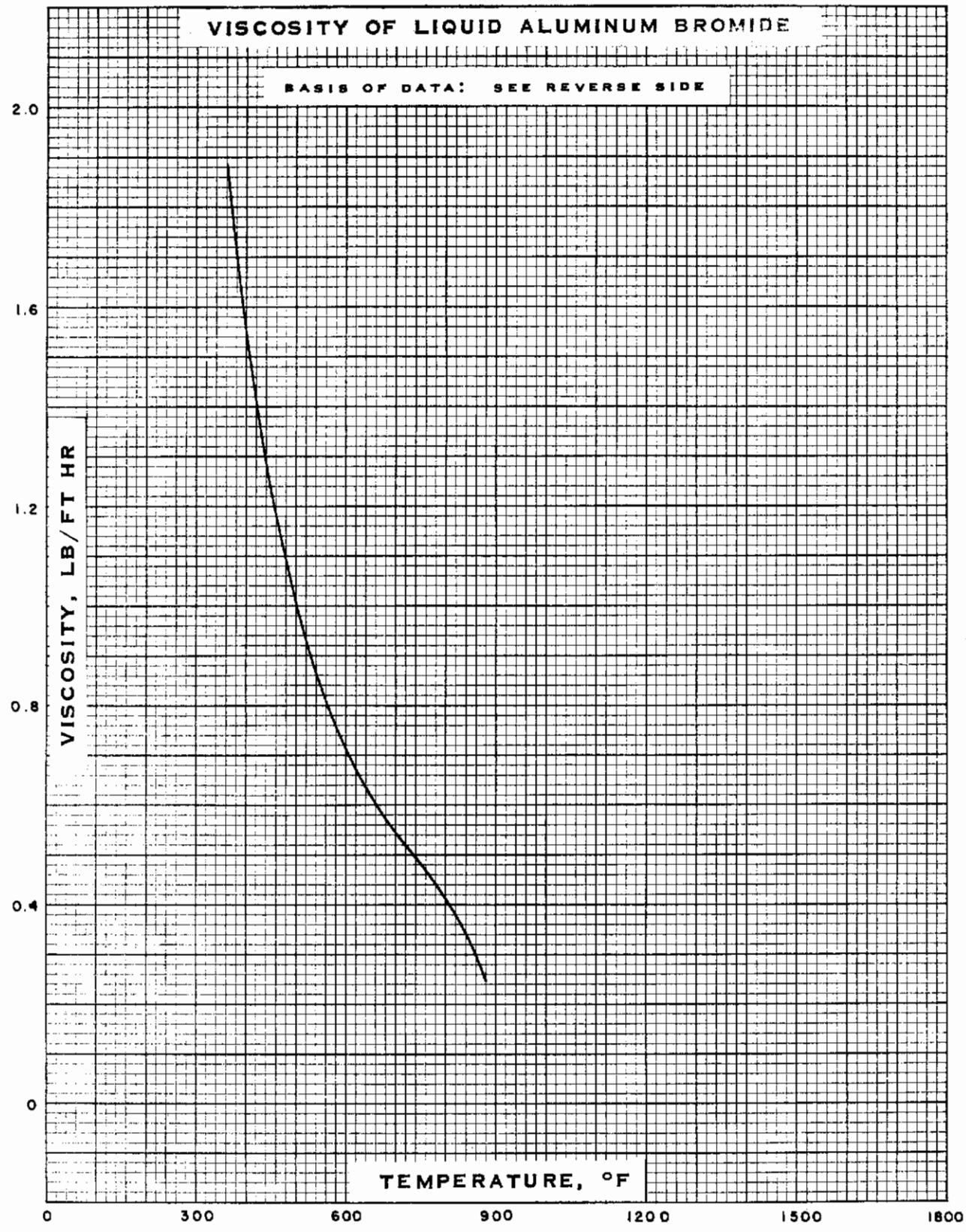


Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	26-11-37	420-920	Replotted from material furnished by 721

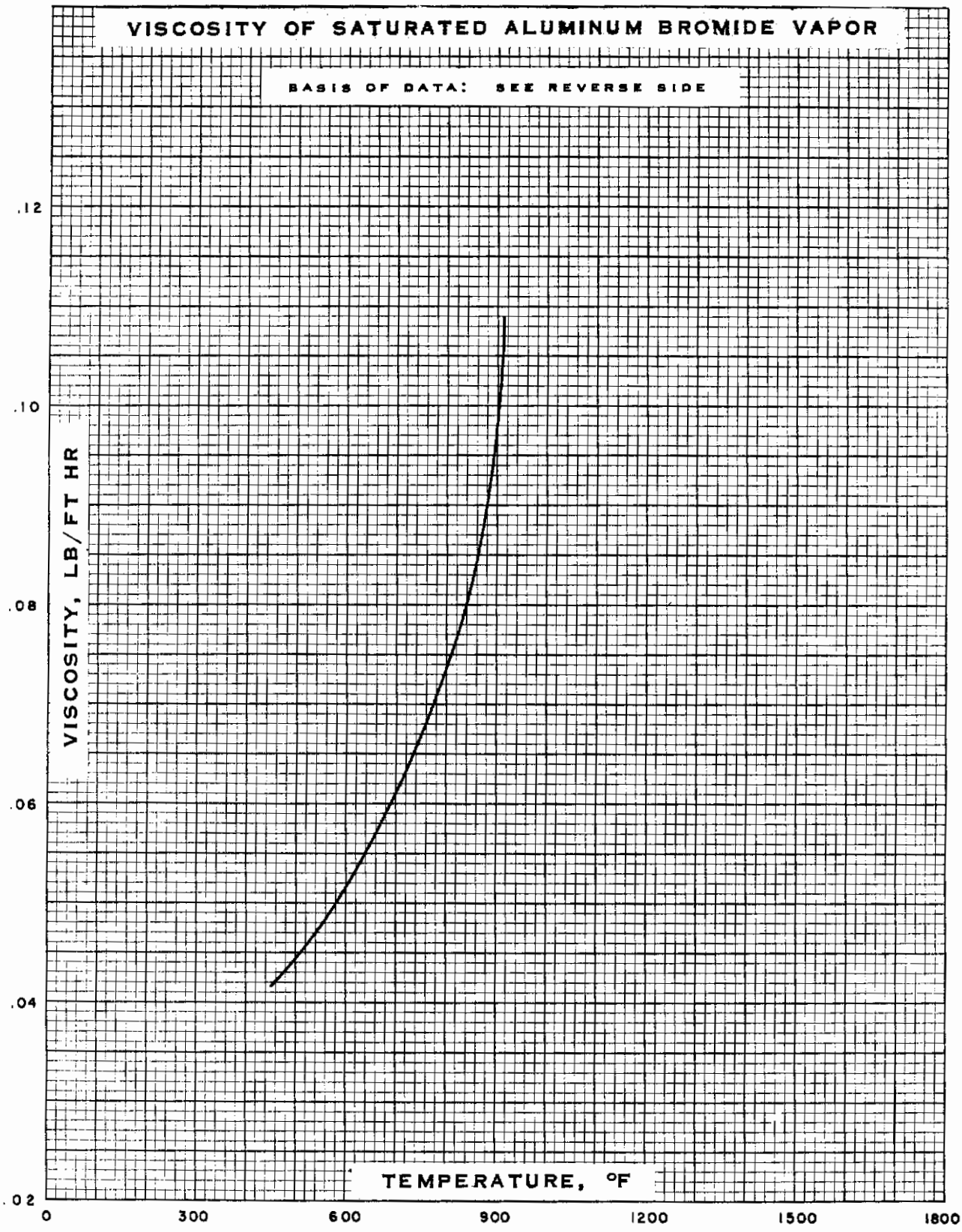


$AlBr_3$-ρ-b (basis)

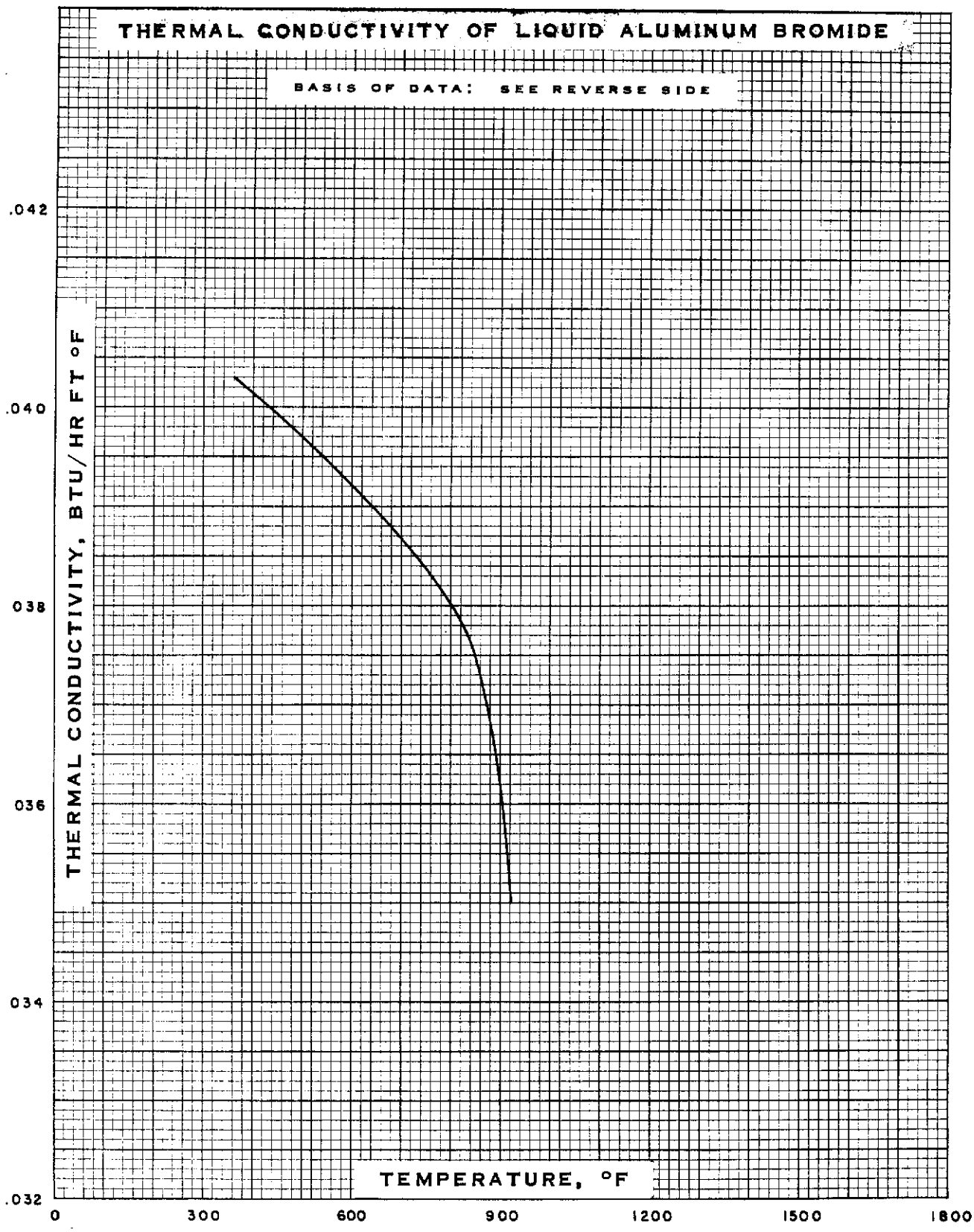
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	26-11-37	425-920	Replotted from material furnished by 721



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Calculated	721	360-880	Calculated from Uyehara-Watson Chart (21-23-44)

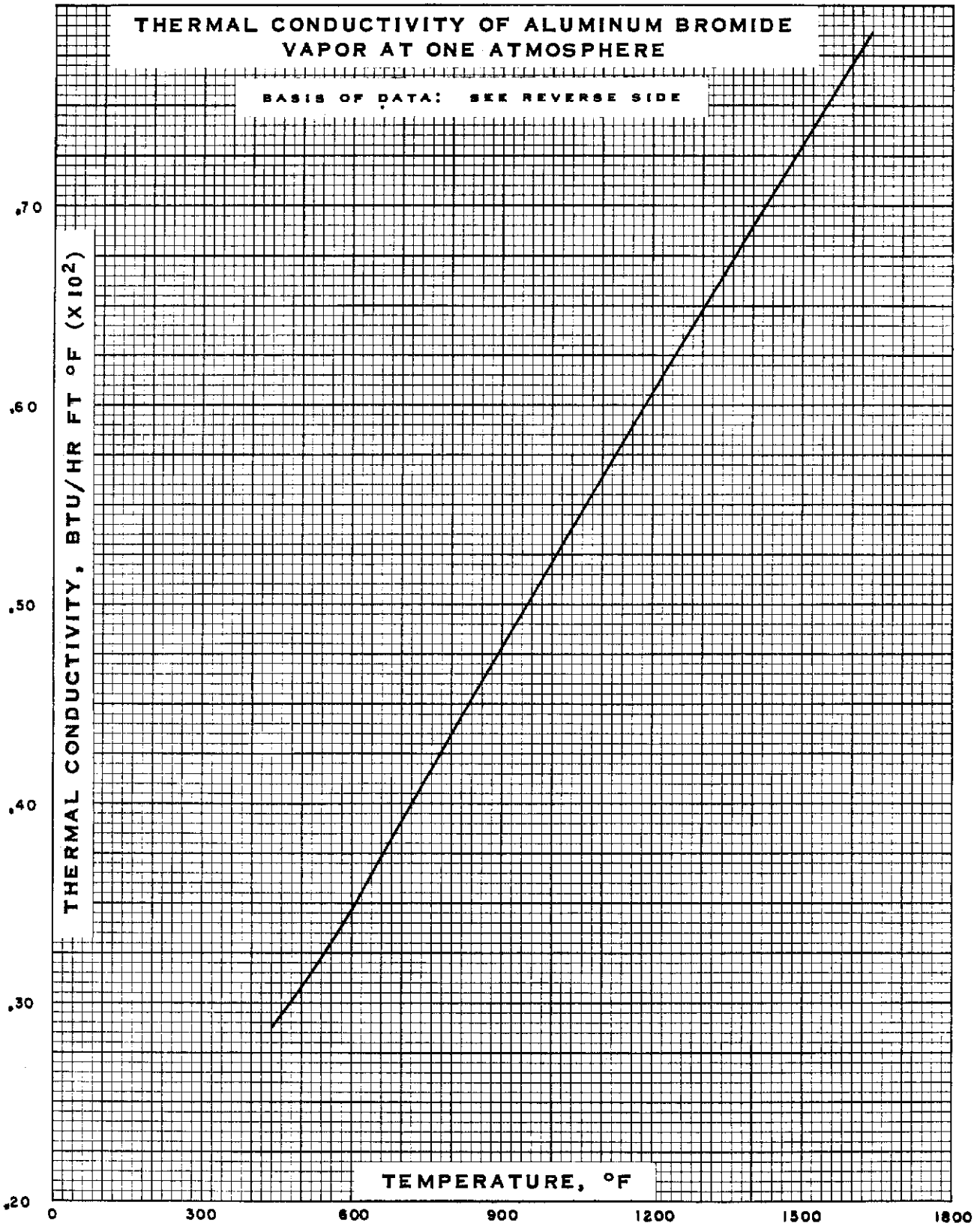


Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Calculated	721	450-910	Calculated from Uyehara-Watson Chart (21-23-44)

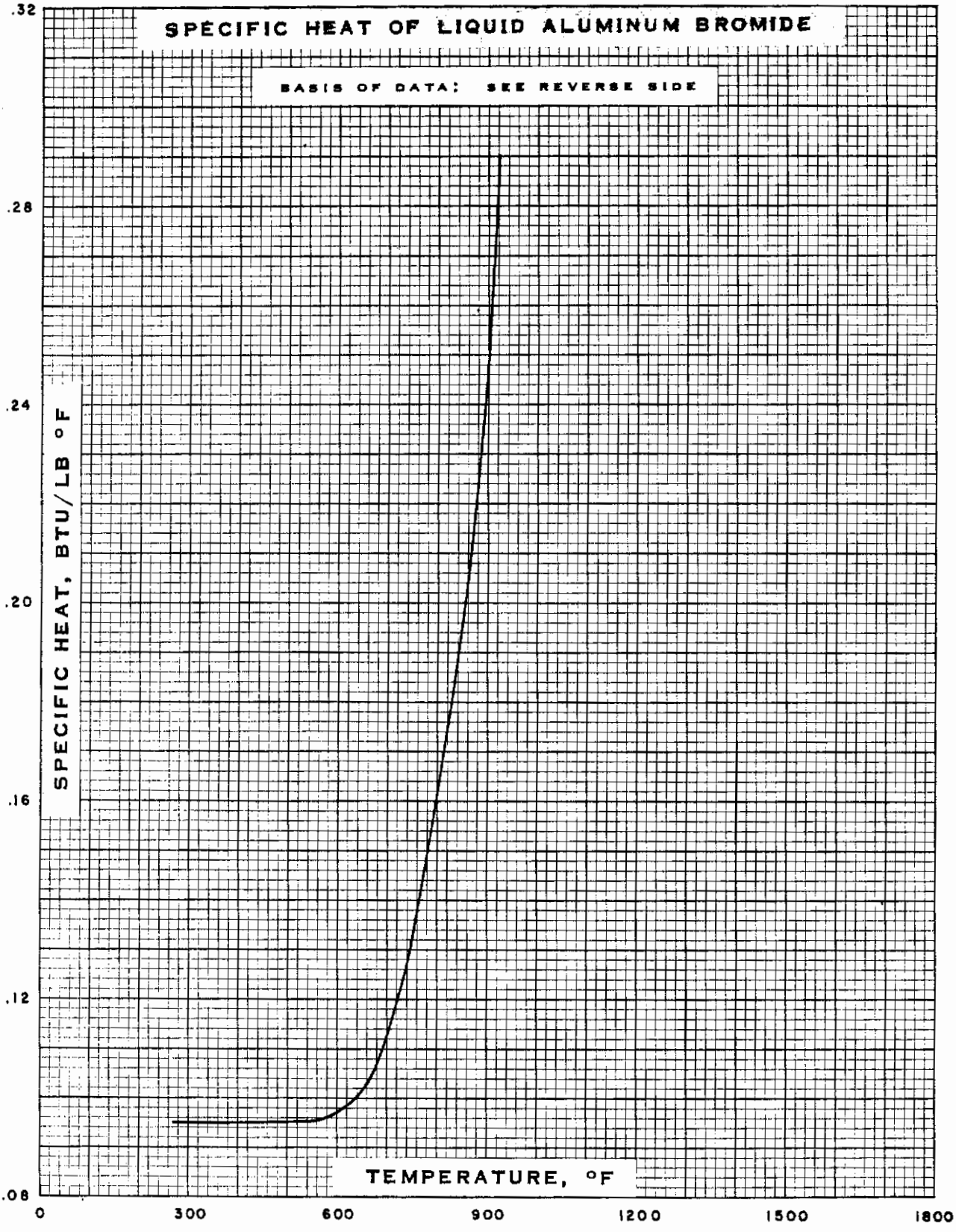


$AlBr_3$-k-a (basis)

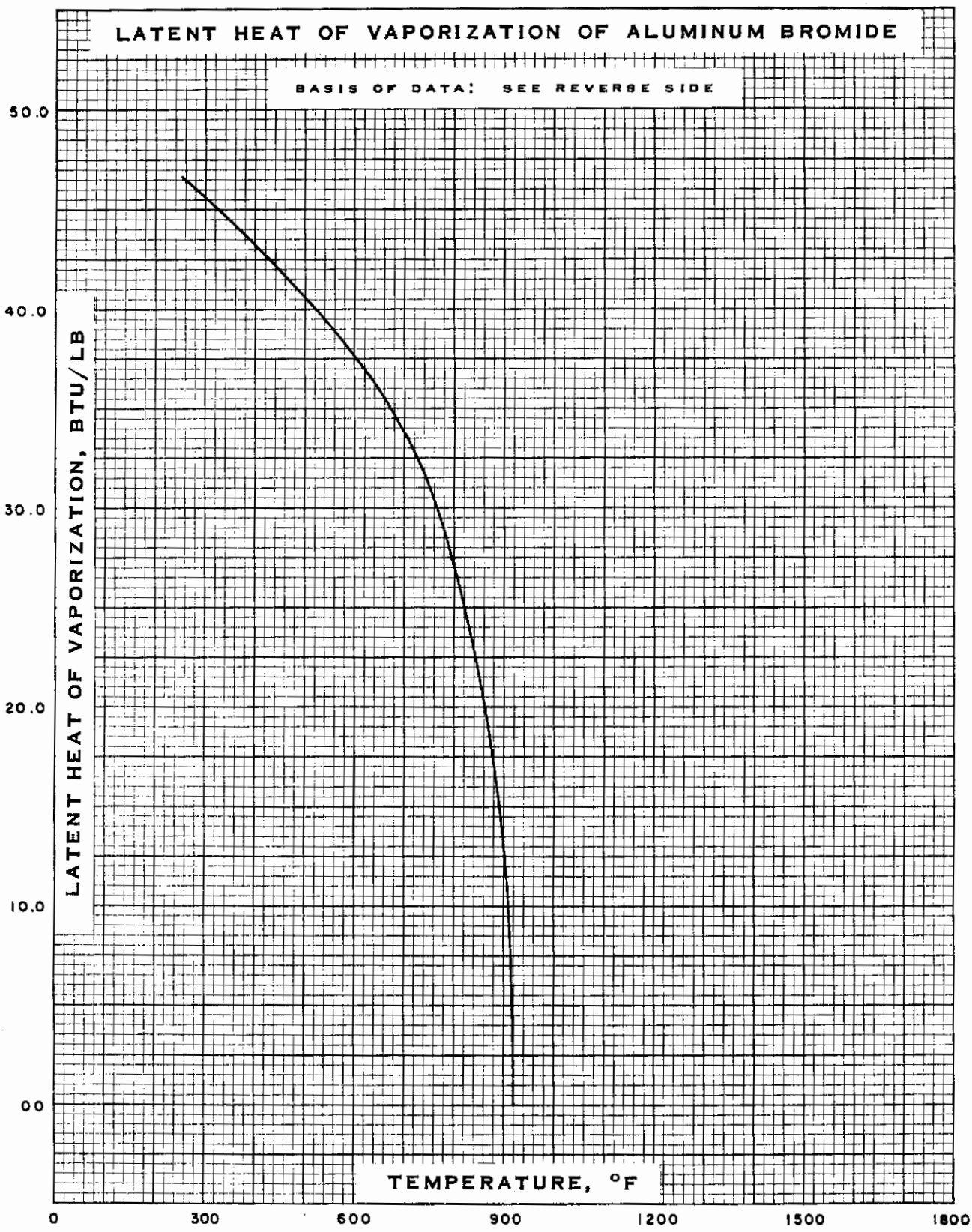
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Calculated	721	360-920	Calculated by method described in International Critical Tables, Vol. V.



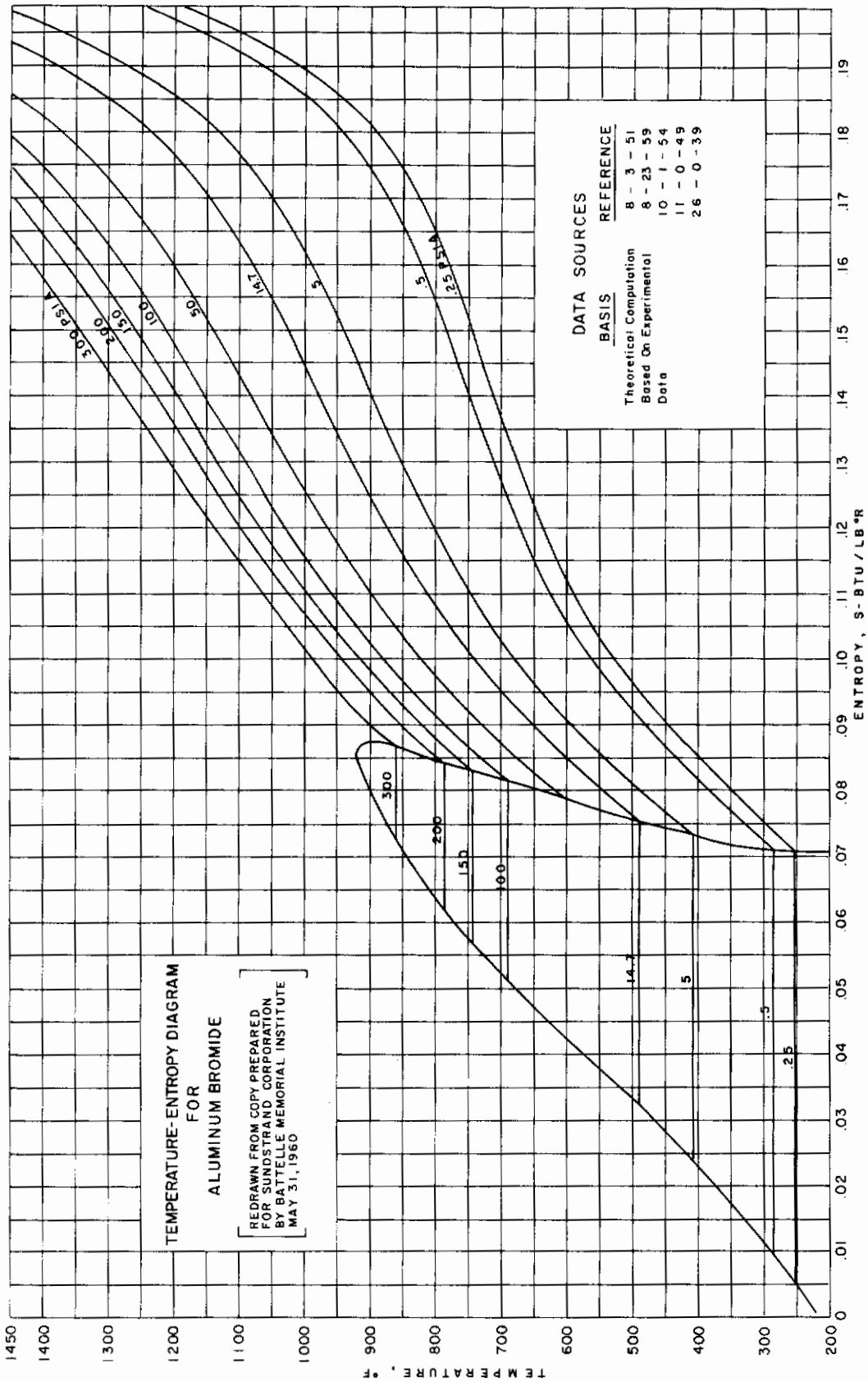
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Calculated	721	440-1640	Calculated from Bromley Equation (2-0-52) and Gamson Chart (7-0-49).



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	26-11-37	270-910	Replotted from material furnished by 721



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Extrapolated	722	250-356	Both 721 and 722 use data from 26-11-37.
Experimental	721, 722, 26-11-37	356-250	



e. Data Sources for Aluminum Bromide

Code No.	Source
2-0-52	Bromley, L. A., USAEC Report UCRL-1852 (1952).
7-0-49	Gamson, B. W., Chem. Eng. Prog. 45, 154 (1949).
8-0-8	Hodgman, C. D., Editor, "Handbook of Chemistry and Physics," Cleveland, Chemical Rubber Publishing Co., 1958.
11-15-7	Kirk, R. E., Othmer, D. F., Editors, "Encyclopedia of Chemical Technology," Vol. 1, New York, The Interscience Encyclopedia, Inc., 1947.
21-23-44	Uyehara, O.A., and Watson, K. M., Nat'l. Pet. News, Tech. Sect., 36, R 764 (Oct. 4, 1944).
26-11-37	Zhuravlev and Kostrova, J. Tech. Physics (USSR) 16 (1937).
721	AiResearch Manufacturing Company of Arizona
722	Sundstrand Corporation
825	Battelle Memorial Institute

SULFUR

a. General Discussion of Sulfur. Sulfur is a yellow solid at normal temperatures, but becomes progressively lighter in color as the temperature is lowered. At the temperature of liquid air it is almost white. Solid sulfur exists in two crystalline forms (rhombic and monoclinic) and also as an elastomer. Liquid sulfur, at the melting point, is a light yellow, transparent, mobile liquid. As the temperature of the liquid is raised it darkens, becoming deep orange in hue. Apparently the structure of the liquid undergoes an abrupt change at about 320°F, and this transformation is accompanied by a heat absorption of 4.951 BTU per lb. The marked rise in the viscosity-temperature curve is but one indication of a structural alteration at this temperature since other properties also show a marked discontinuity. The peak in the viscosity-temperature curve may be reduced or eliminated by the addition of hydrogen sulfide, chlorine, bromine, iodine, or organic matter. Beyond 370°F the viscosity decreases but the color remains dark up to the boiling point. If sulfur at the boiling point is cooled slowly, it passes through the changes described above in the reverse order.

Various investigators have found indications of S_8, S_7, S_6, S_5, S_4, S_2, and S_1 in sulfur vapor. However, there is very little agreement regarding the quantitative distribution of species.

Sulfur unites directly with almost all of the elements with the exception of gold, platinum, and the inert gases. When it is exposed to air at ordinary temperatures, it oxidizes at an extremely slow rate. At higher temperatures, it burns in air to form sulfur dioxide and often small amounts of sulfur trioxide. Prolonged exposure of the solid to moist air will cause the formation of minute amounts of sulfuric acid.

Sulfur and hydrogen can be made to unite directly to form hydrogen sulfide; however, hydrogen sulfide is usually prepared by the action of acids on metal sulfides. Sulfur reacts vigorously with lithium, sodium, potassium, rubidium, cesium, calcium, strontium, and barium at room temperature. Sulfur will also react with the alkali and alkaline earth hydroxides, in the presence of water, to form sulfides and thiosulfates. At ordinary temperatures, sulfur combines readily with copper, silver, and mercury. The application of heat causes a vigorous combination in mixtures of powdered sulfur with zinc, aluminum, tin, or iron. Chromium, tungsten, uranium, iron, cobalt, and nickel are comparatively resistant to sulfur.

Crude, bright, 99.5 percent bulk sulfur is available in carloads for $23.50-$25.00 per long ton. Commercial 99.5 percent sulfur flour is priced at $2.45 per 100-lb bag in carload lots. Refined sulfur, with purity not less than 99.8 percent, is available for $7.75 per 100-lb bag.

b. Synopsis of Properties of Sulfur.

Property	Value	Temp (°F)	Data Basis	Reference
Physical:				
Atomic Weight	32.066±0.003	---	Handbook	8-0-8
Melting Point, °F	246.1	---	Survey	20-19-4
Boiling Point, °F	832	---	Experimental	Page S-VP-a
Critical Point, psia	1706	1900	Survey	20-19-4
Density of Solid, lb/ft^3	124.9	68	Handbook	8-0-8
Density of Liquid, lb/ft^3	99.4	B.P.	Experimental	Page S-ρ-a
Density of Vapor, lb/ft^3	0.218	B.P.	Theoretical	Page S-ρ-b
Viscosity of Liquid, lb/ft hr	205	B.P.	Extrapolated	Page S-μ-a
Viscosity of Vapor, lb/ft hr	0.0476	B.P.	Experimental	Page S-μ-b
Surface Tension, lb/ft	0.00278	B.P.	Experimental	Page S-σ-a
Thermal:				
Thermal Conductivity of Liquid, BTU/hr ft °F	0.0964	B.P.	Estimated	Page S-k-a
Thermal Conductivity of Vapor, BTU/hr ft °F	0.00560	B.P.	Extrapolated	Page S-k-b
Specific Heat of Liquid, BTU/lb °F	0.2398	B.P.	Extrapolated	Page S-C-a
Specific Heat of Vapor, BTU/lb °F	0.382	B.P.	Theoretical	Page S-C-b
Latent Heat of Fusion, BTU/lb	18.9	M.P.	Survey	19-19-6
Latent Heat of Vaporization, BTU/lb	123.4	B.P.	Theoretical	Page S-ΔH-a

Property	Value	Temp (°F)	Data Basis	Reference
Electrical and Magnetic:				
Resistivity, ohm-inch	2.69×10^6	B. P.	Extrapolated	Page S-Ω-a
Ionization Potential, volts	10.3	---	Handbook	8-0-8
Magnetic Susceptibility, fps electromagnetic units/ unit mass	-0.20648	428 liq	Handbook	8-0-8
Dielectric Constant	3.52	244 liq	Handbook	8-0-8
	3.48	448	Handbook	8-0-8
Thermal Neutron Cross Section (2200 m/s):				
Absorption, barns	0.49±0.02	---	Handbook	8-0-8
Scattering, barns	1.1±0.2	---	Handbook	8-0-8

c. Property Tables for Sulfur.

SATURATED SULFUR VAPOR

(Ref: 722)

Partial Pressures of Each Component, psi

Temperature (°F)	P_{tot}	P_2	P_4	P_6	P_8
428	8.90×10^{-2}	7.73×10^{-5}	1.72×10^{-4}	2.38×10^{-2}	6.50×10^{-2}
464	0.178	2.32×10^{-4}	4.83×10^{-4}	4.89×10^{-2}	0.128
500	0.332	6.19×10^{-4}	1.06×10^{-3}	9.46×10^{-2}	0.236
536	0.584	1.57×10^{-3}	3.09×10^{-3}	0.172	0.407
572	0.975	3.67×10^{-3}	6.77×10^{-3}	0.296	0.669
608	1.560	8.12×10^{-3}	1.45×10^{-2}	0.487	1.050
662	2.943	2.44×10^{-2}	4.02×10^{-2}	0.944	1.934
716	5.192	6.57×10^{-2}	0.104	1.688	3.334
788	10.14	0.213	0.309	3.401	6.217
860	18.30	0.615	0.824	6.348	10.51
932	31.03	1.535	1.885	10.84	16.77
1004	49.94	3.554	4.076	17.56	24.75

THERMODYNAMIC PROPERTIES OF SULFUR

Liquid Phase: $H^\circ_{536.67} - H^\circ_o = 1,895$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^\circ - H^\circ_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^\circ - H^\circ_{536.67})/T$ (BTU/lb mole °R)
720	1859	10.45	7.87
900	3506	12.48	8.59
1080	5036	14.03	9.37
1260	6579	15.35	10.13

THERMODYNAMIC PROPERTIES OF SULFUR

Ideal Monatomic Gas: $H^{\circ}_{536.67} - H^{\circ}_{o} = 2,864$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^{\circ} - H^{\circ}_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^{\circ} - H^{\circ}_{536.67})/T$ (BTU/lb mole °R)
720	1028	41.74	40.32
900	2018	42.96	40.72
1080	2988	43.95	41.19
1260	3942	44.76	41.64
1440	4883	45.46	42.07
1620	5818	46.07	42.48
1800	6745	46.62	42.88
1980	7668	47.10	43.23
2160	8586	47.55	43.58
2340	9500	47.95	43.89
2520	10415	48.33	44.20
2700	11326	48.68	44.49
2880	12238	49.01	44.77
3060	13149	49.31	45.02
3240	14060	49.60	45.27
3420	14972	49.88	45.51
3600	15887	50.14	45.73

THERMODYNAMIC PROPERTIES OF SULFUR

Ideal Diatomic Gas: $H^\circ_{536.67} - H^\circ_0 = 3,854$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^\circ - H^\circ_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^\circ - H^\circ_{536.67})/T$ (BTU/lb mole °R)
720	1460	56.85	54.83
900	2950	58.69	55.42
1080	4473	60.23	56.09
1260	6025	61.56	56.78
1440	7594	62.73	57.46
1620	9171	63.76	58.10
1800	10744	64.68	58.72
1980	12343	65.52	59.29
2160	13945	66.30	59.85
2340	15545	67.01	60.37
2520	17163	67.68	60.87
2700	18772	68.30	61.35
2880	20387	68.88	61.81
3060	22003	69.42	62.23
3240	23623	69.94	62.65
3420	25243	70.43	63.05
3600	26867	70.89	63.43

THERMODYNAMIC PROPERTIES OF SULFUR

Ideal Octatomic Gas: $H^\circ_{536.67} - H^\circ_0 = 13,585$ BTU/lb mole

(Ref: 19-19-6)

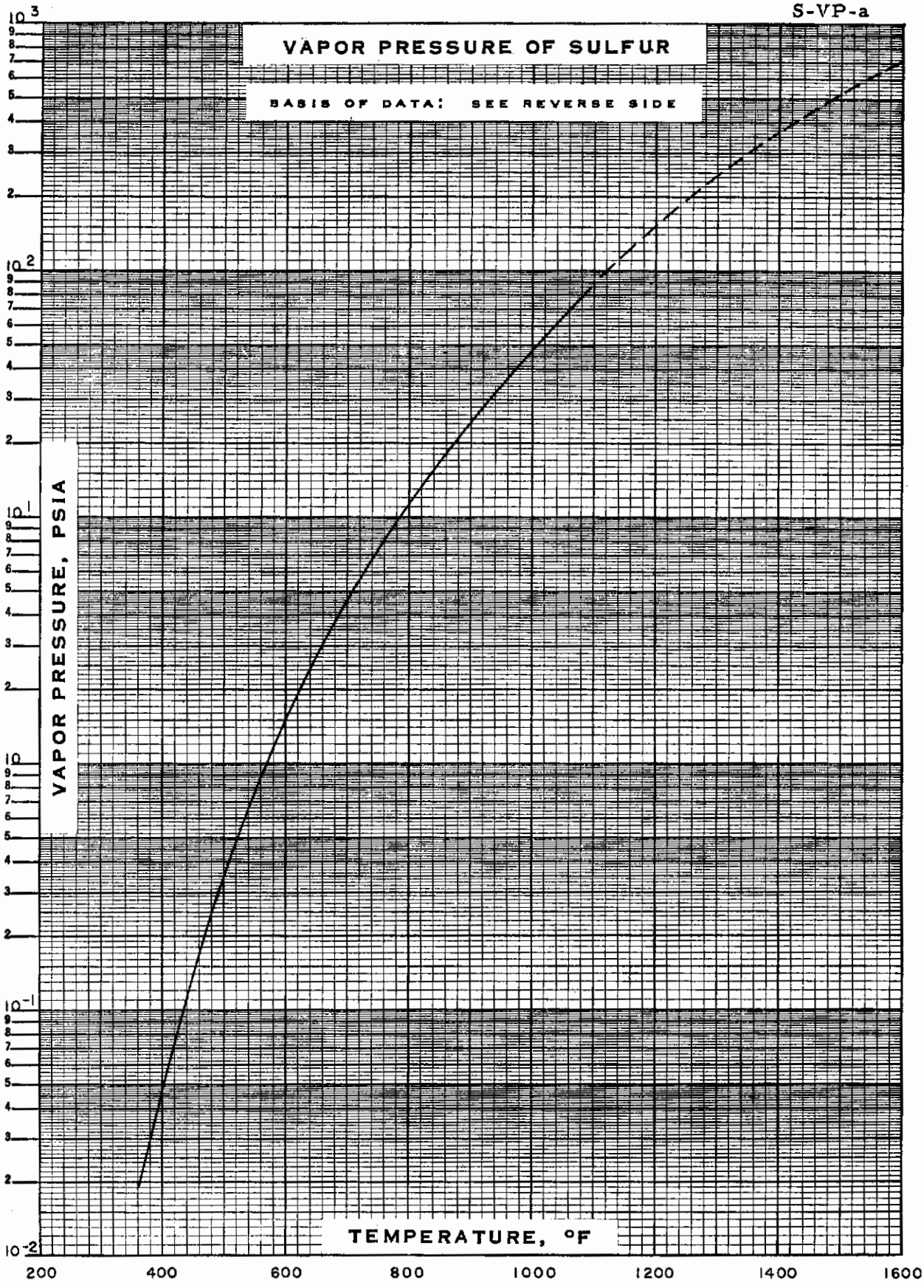
Temperature T (°R)	Enthalpy $H^\circ - H^\circ_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^\circ - H^\circ_{536.67})/T$ (BTU/lb mole °R)
720	7079	114.08	104.25
900	14369	123.13	107.17
1080	21821	130.66	110.46
1260	29394	137.15	113.83
1440	37044	142.82	117.10
1620	44730	147.85	120.24
1800	52452	152.38	123.24

d. Working Charts for Sulfur.

S-VP-a

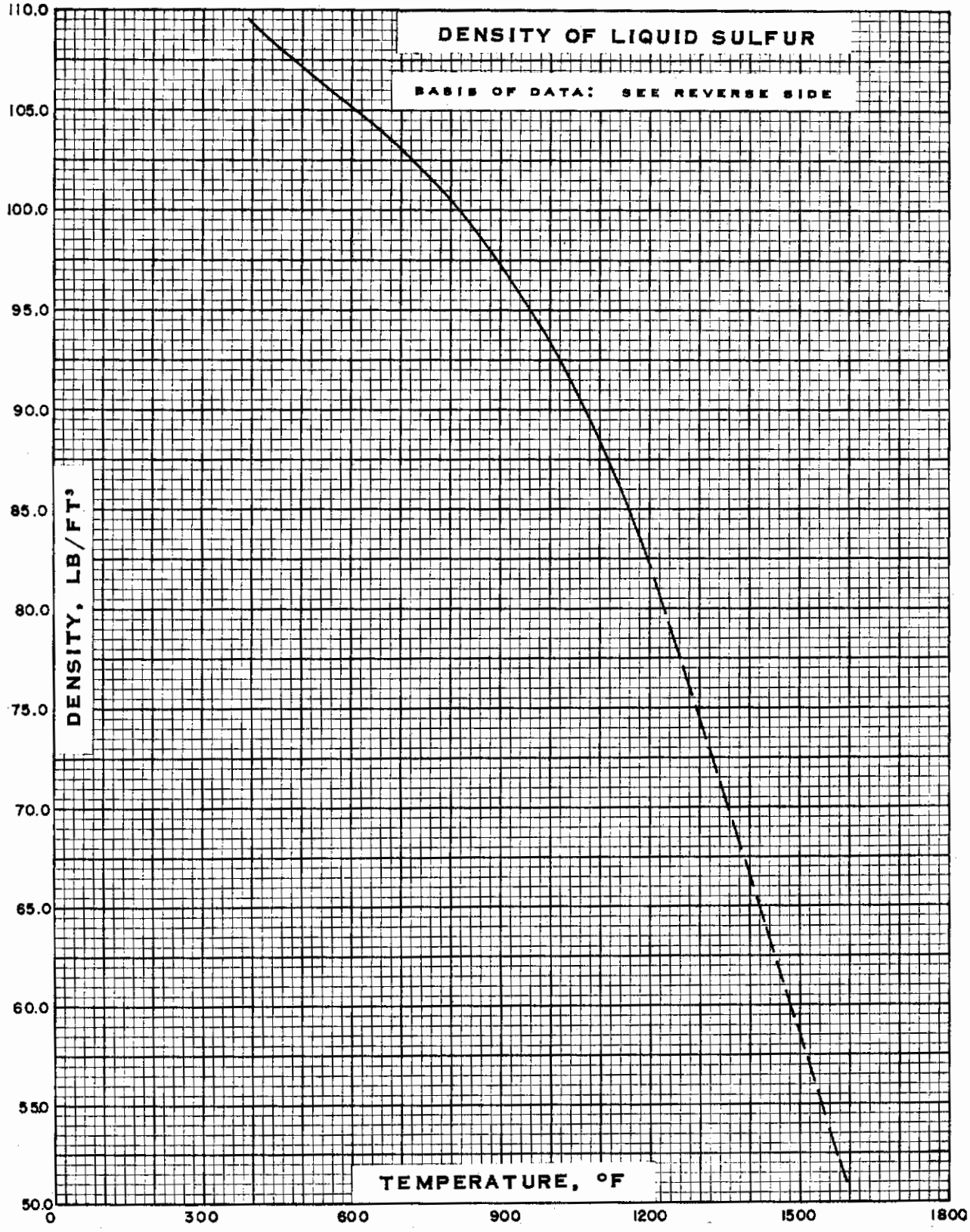
VAPOR PRESSURE OF SULFUR

BASIS OF DATA: SEE REVERSE SIDE



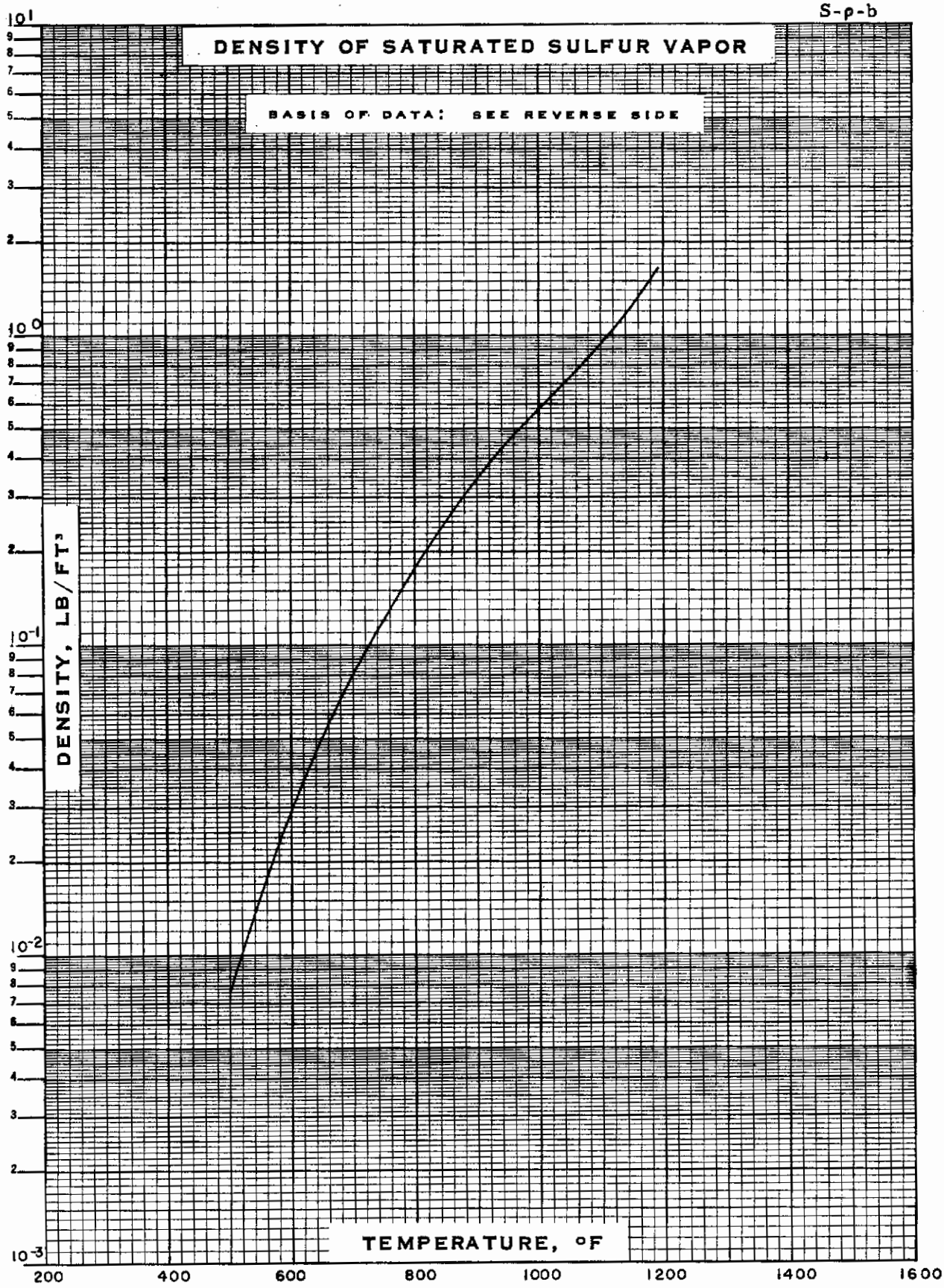
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	6-1-3	360-1022	West and Menzies have measured the vapor pressures of sulfur over this temperature range.
Extrapolated	23-0-0	1022-1600	The above data were extended by extrapolating the measured vapor pressures to an estimated critical point.

S-ρ-a



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	6-1-3, 20-19-4	390-833	The density of liquid sulfur was determined by three different experimental methods: (1) a large glass dilatometer, (2) a small quartz weight-thermometer, and (3) a large quartz dilamometer. The agreement of the different series seems satisfactory.
Extrapolated	23-0-0	833-1600	The above data were extended by extrapolating the measured densities to a calculated critical-point density.

S-ρ-b

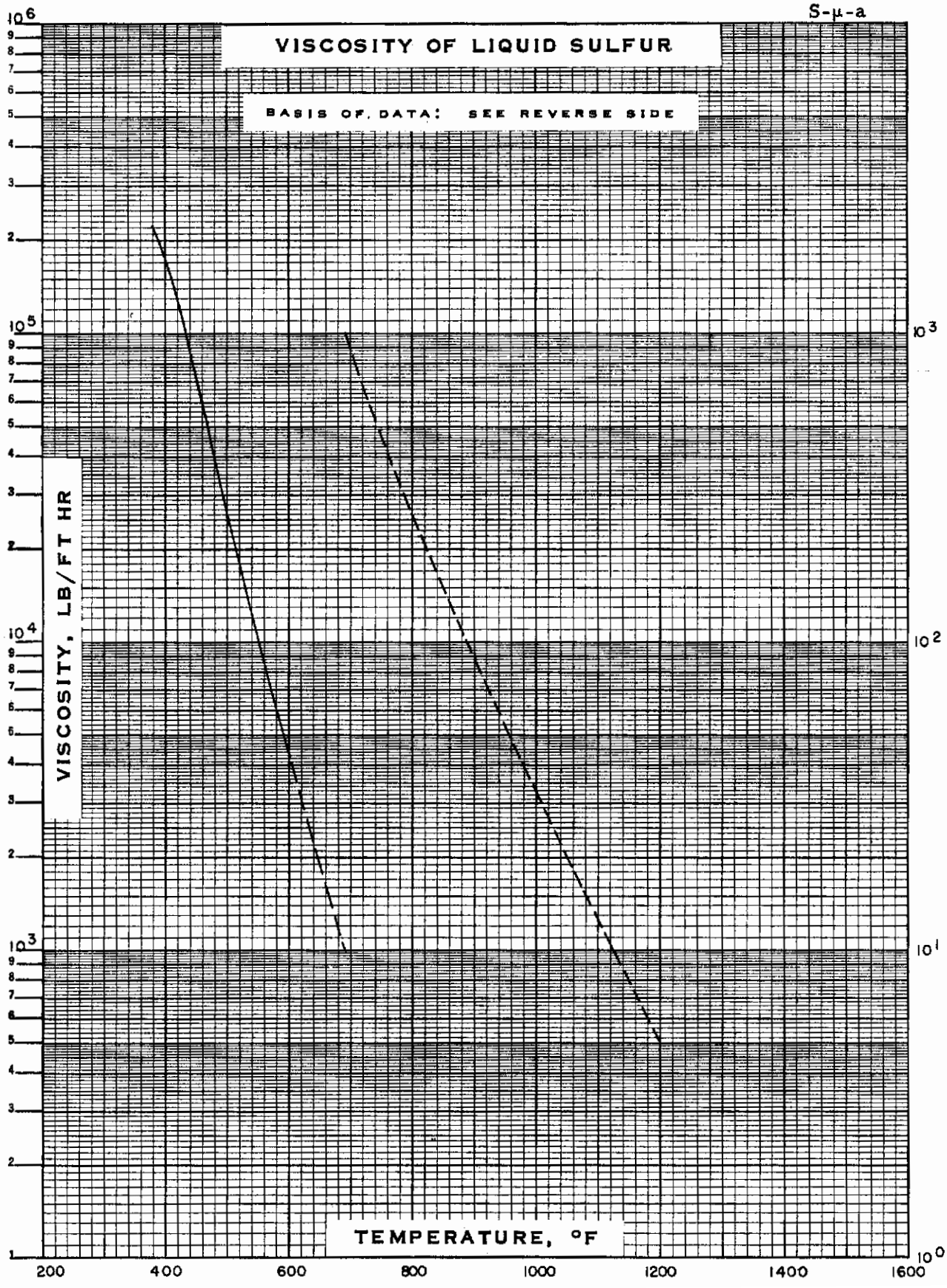


Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	20-19-4, 23-0-0	500-1200	The volume of each molecular species was estimated from the ideal gas law. Then the specific volumes of the equilibrium mixtures were calculated from these values.

S-μ-a

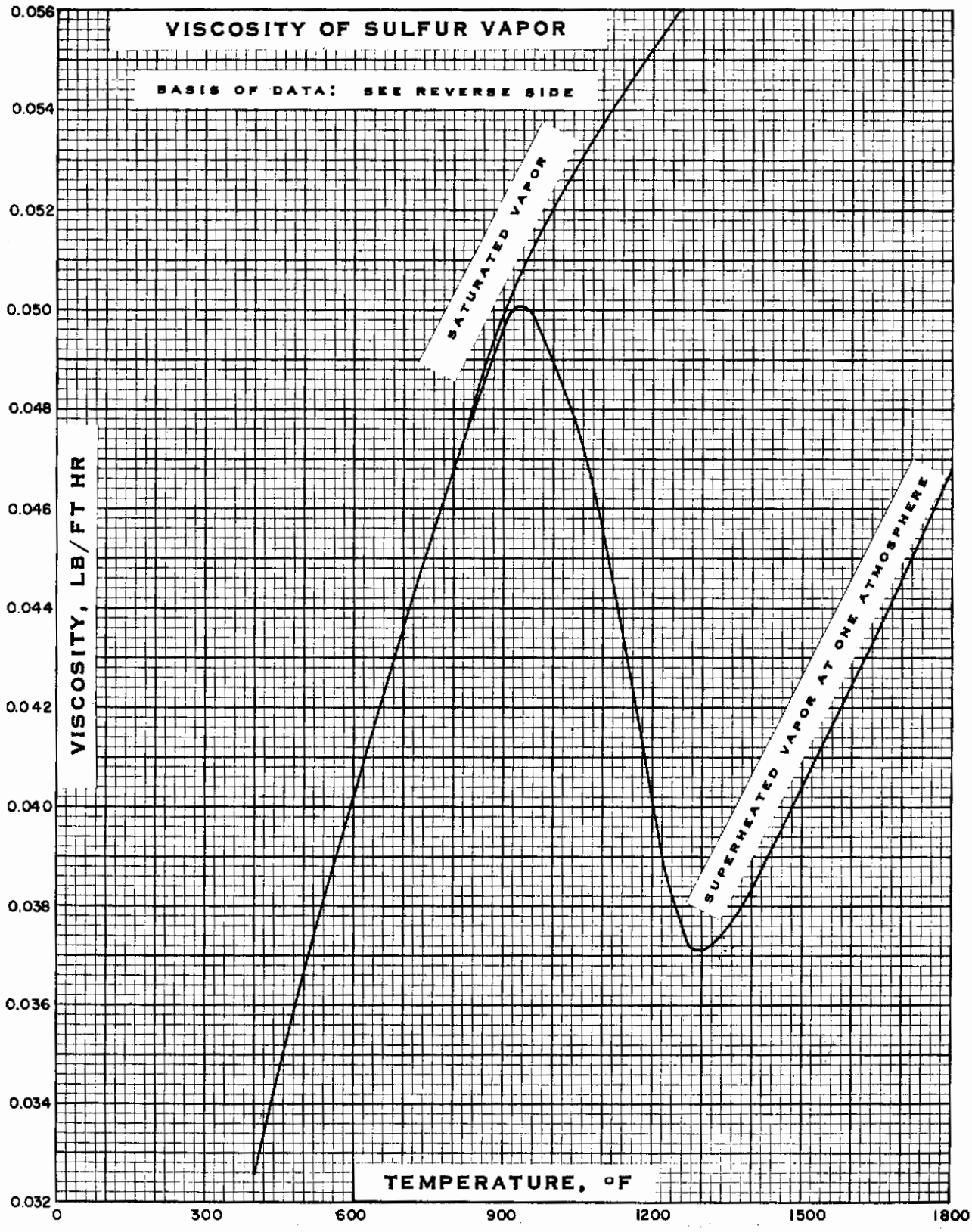
VISCOSITY OF LIQUID SULFUR

BASIS OF DATA: SEE REVERSE SIDE



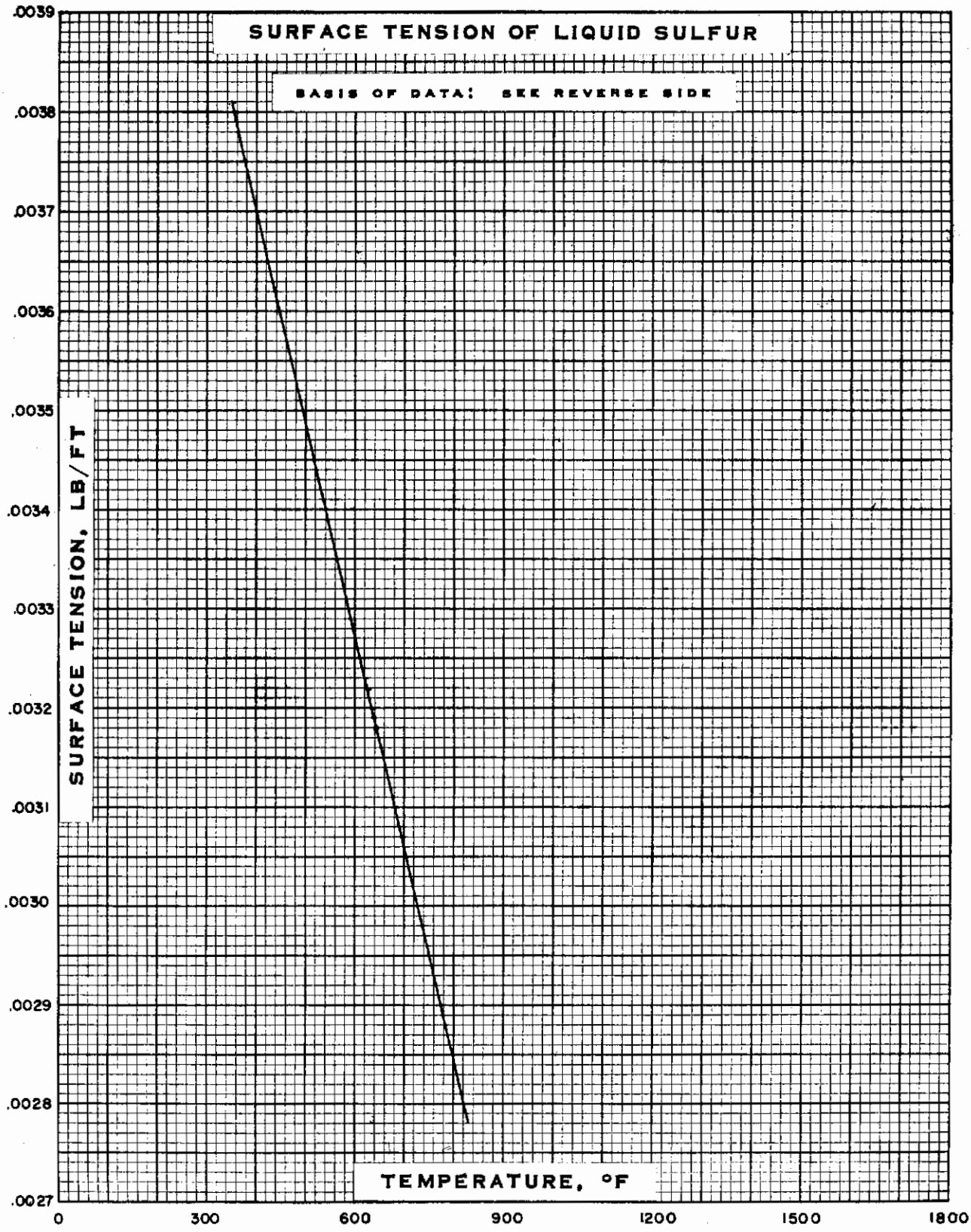
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	2-6-3, 20-19-4, 721	380-583	A definite vacuum was impressed on a capillary tube immersed in the pure sulfur and the time required for the sulfur column to rise to a measured height in the capillary was noted. Viscosity was then calculated using Poiseuille's equation.
Extrapolated	721	583-1200	Method of extrapolation is unknown.

S-μ-b



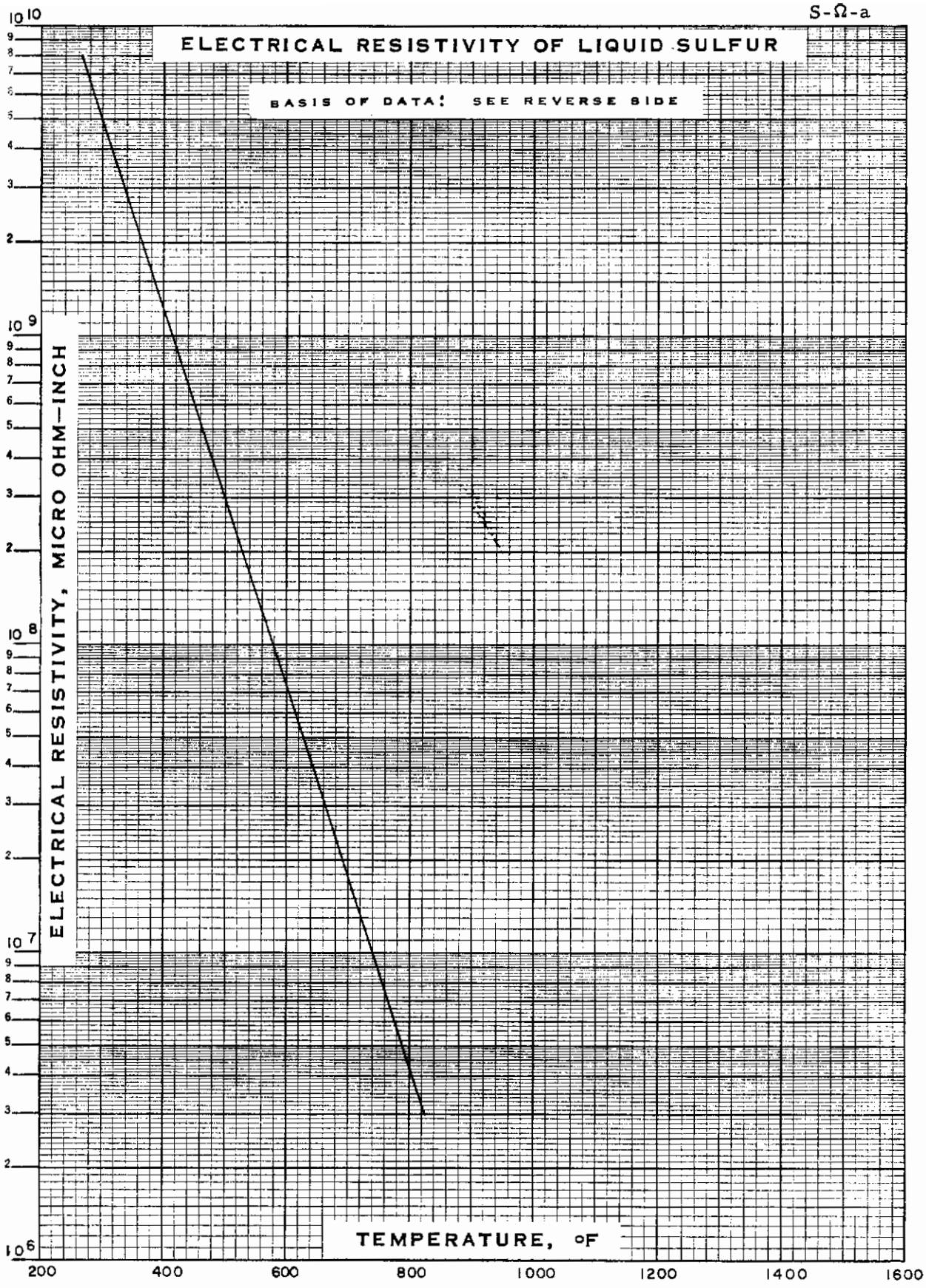
WADD TR 61-96

Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	4-23-0, 20-19-4, 721	Boiling point	The viscosity of sulfur vapor was measured by the capillary method and compares favorably with calculated values.
Estimated	4-23-0, 20-19-4 721	400-1800	Two empirical methods that are generally reliable within 10% were used to calculate the viscosity of sulfur vapor. The plotted values are the average of the values calculated from the two methods. The values above the boiling point were estimated at one atmosphere while those below this temperature were based on the vapor pressure of sulfur at the corresponding temperature.
Extrapolated	721	832-1250	Method of extrapolation is unknown.



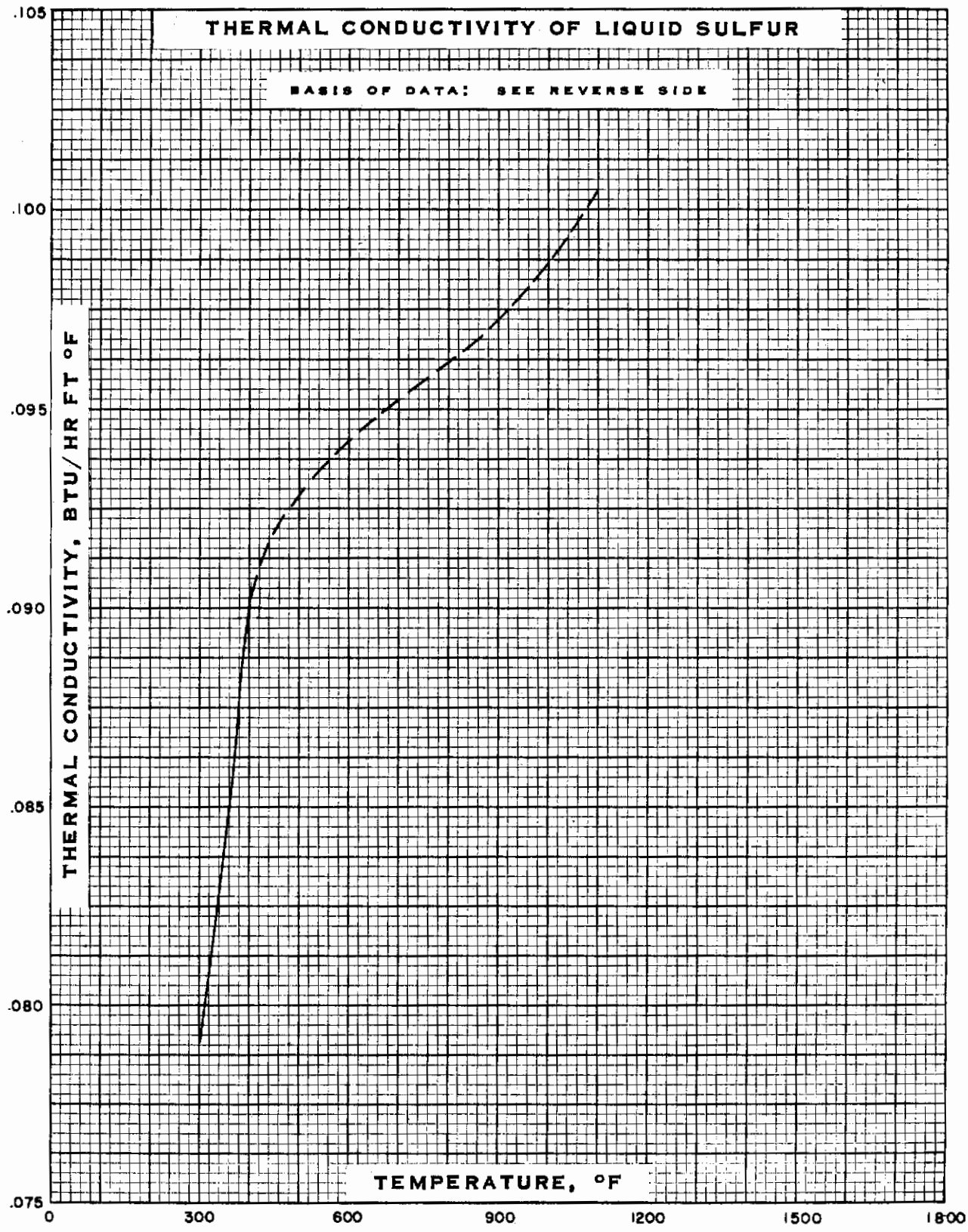
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	6-0-0, 20-19-4	350-830	A double capillary modification of the maximum bubble pressure method was employed. This method is independent of such factors as contact angle and the presence of minute impurities which give trouble in the capillary rise method.

S-Ω-a



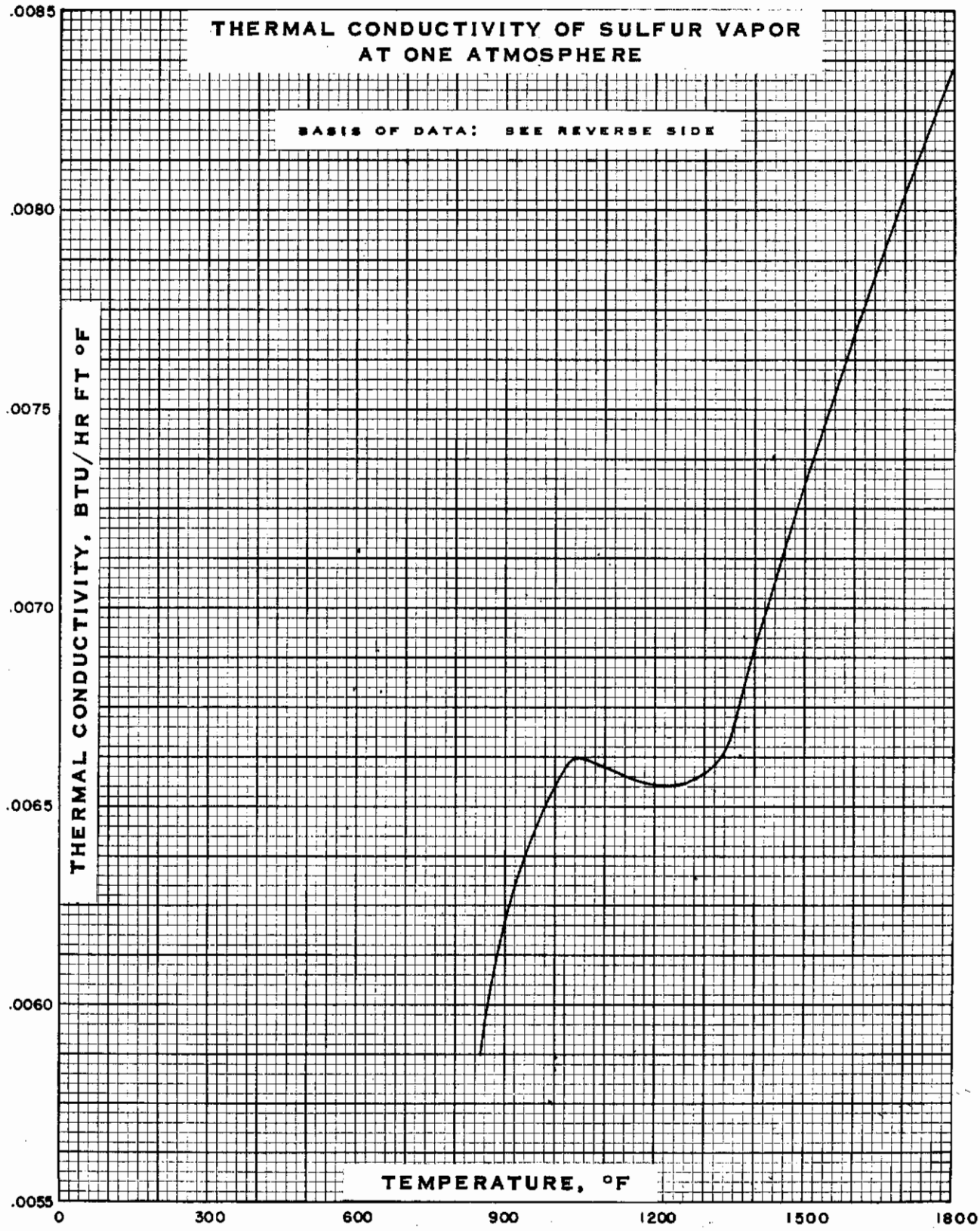
WADD TR 61-96

Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Unknown	20-19-4	266-824	Electrical resistivity of sulfur in the dark.



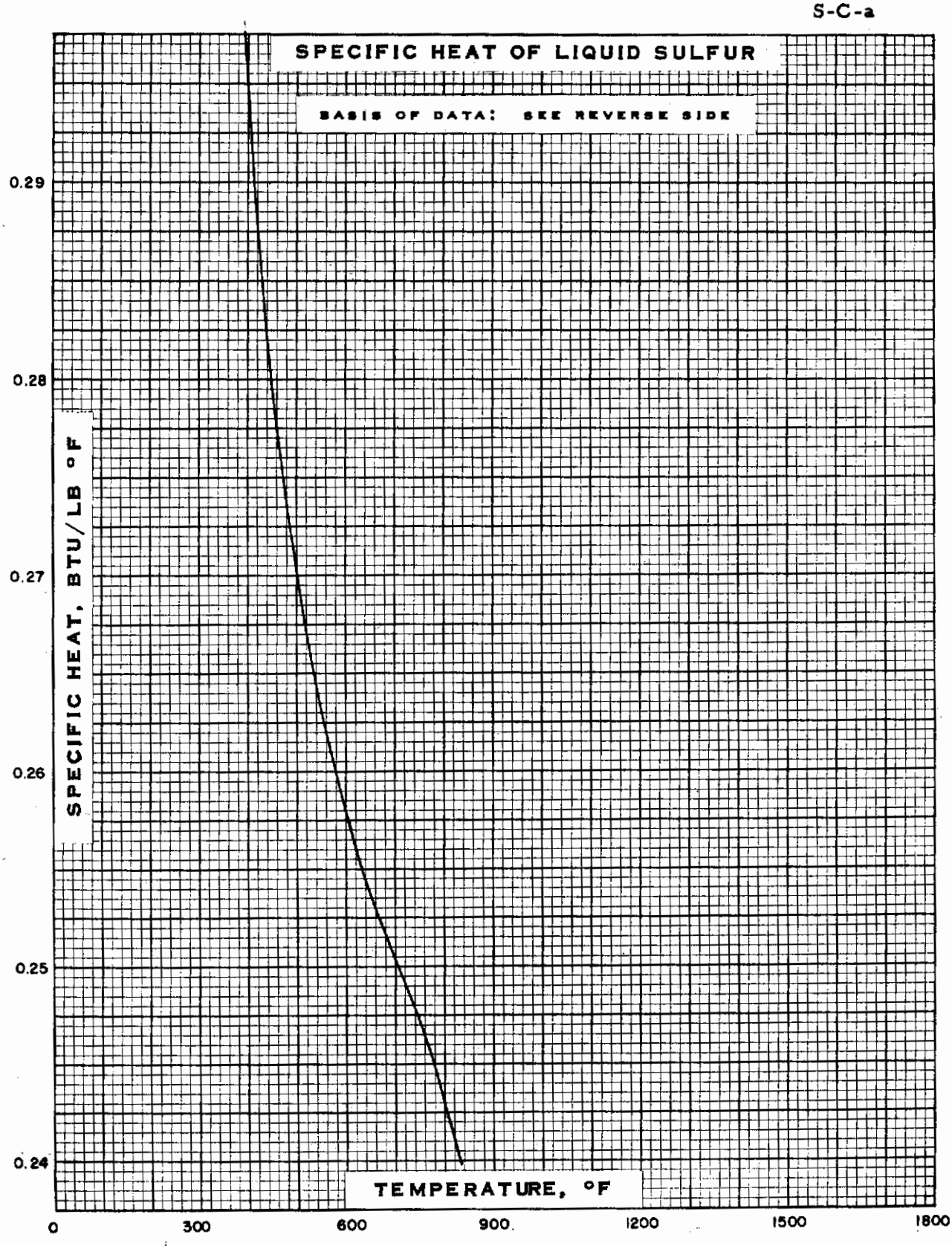
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	11-8-9, 20-19-4, 721	300-410	The thermal conductivities were obtained by a "plate" method using a small temperature drop across the specimen. An accuracy of 1% in the experimental values was aimed for. The sulfur used was the pure crystalline variety and was boiled in order to free it from dissolved gases as much as possible.
Estimated	721	410-1100	Calculated by the method described in International Critical Tables, Vol V.

S-k-b

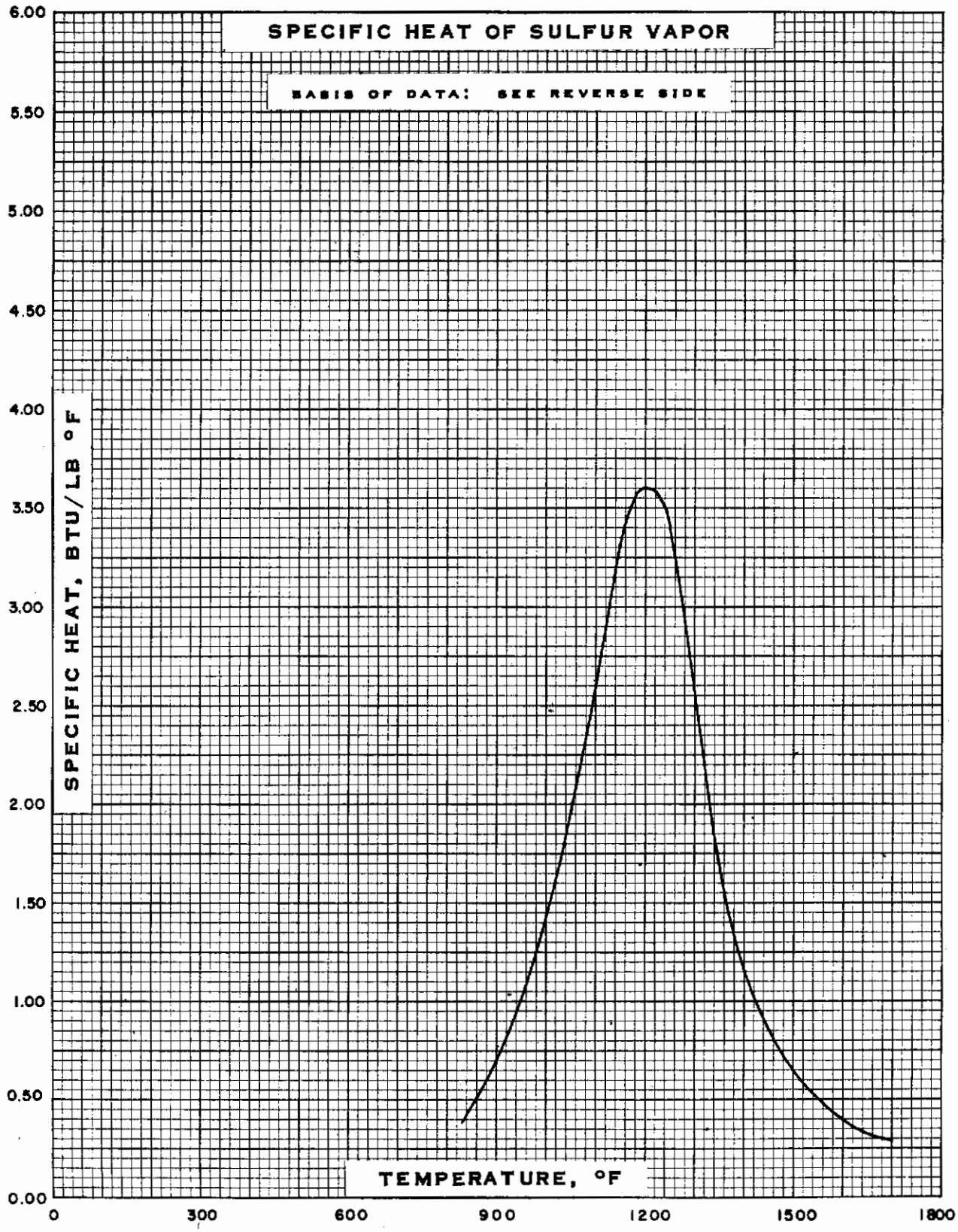


WADD TR 61-96

Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Estimated	20-19-4, 23-0-1	850-1800	Sulfur vapor was assumed to consist of octatomic, hexatomic, and diatomic molecules and the thermal conductivity values were calculated from estimated Prandtl numbers of the species. The exact molecular composition of sulfur vapor is not known and these results are offered for estimational purposes only.

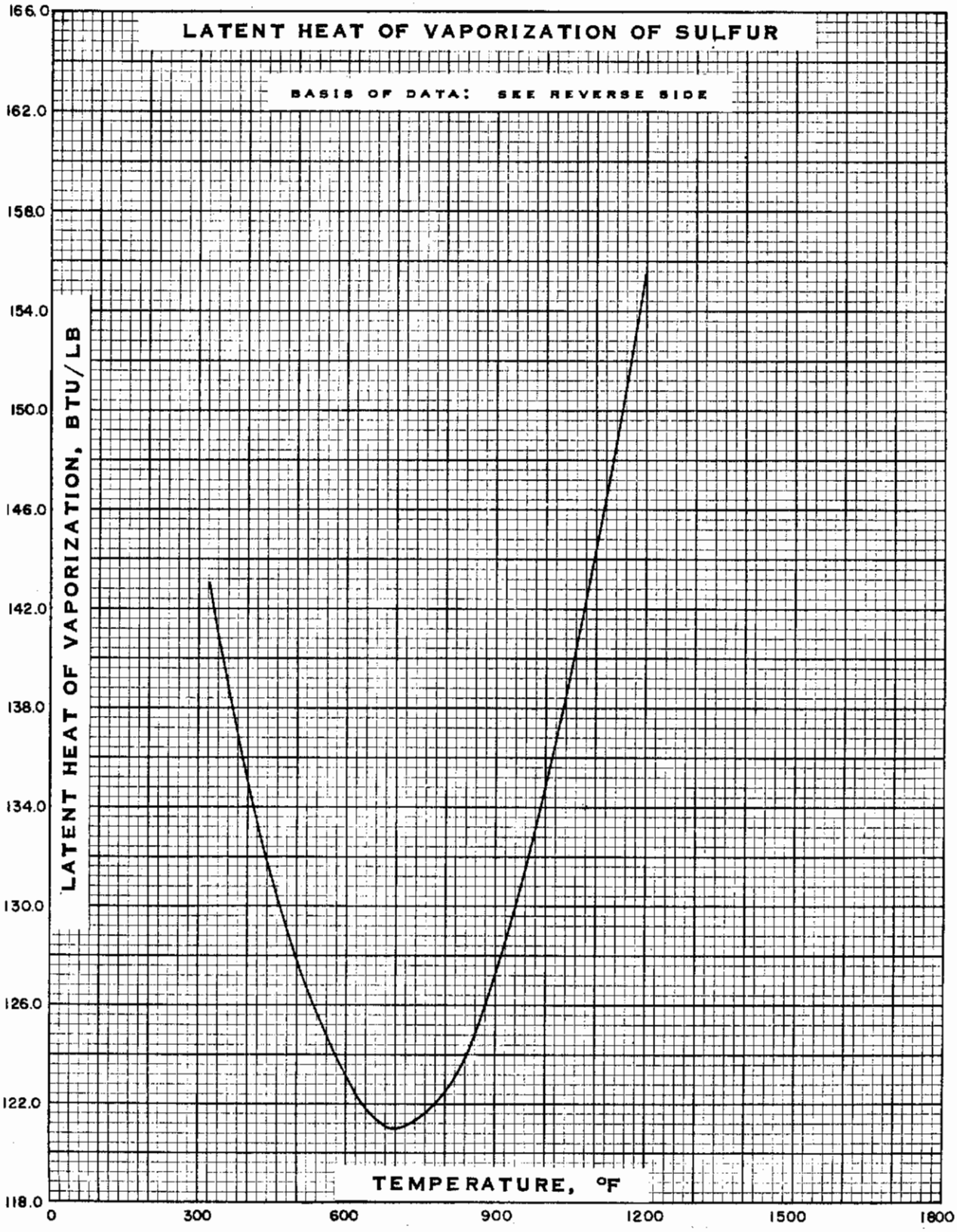


Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	23-0-9, 721	400-762	The specific heat of liquid sulfur (99.999% pure) was determined with an accuracy of 0.1 to 0.2% using an adiabatic calorimeter.
Extrapolated	721	762-830	Method of extrapolation is not known.



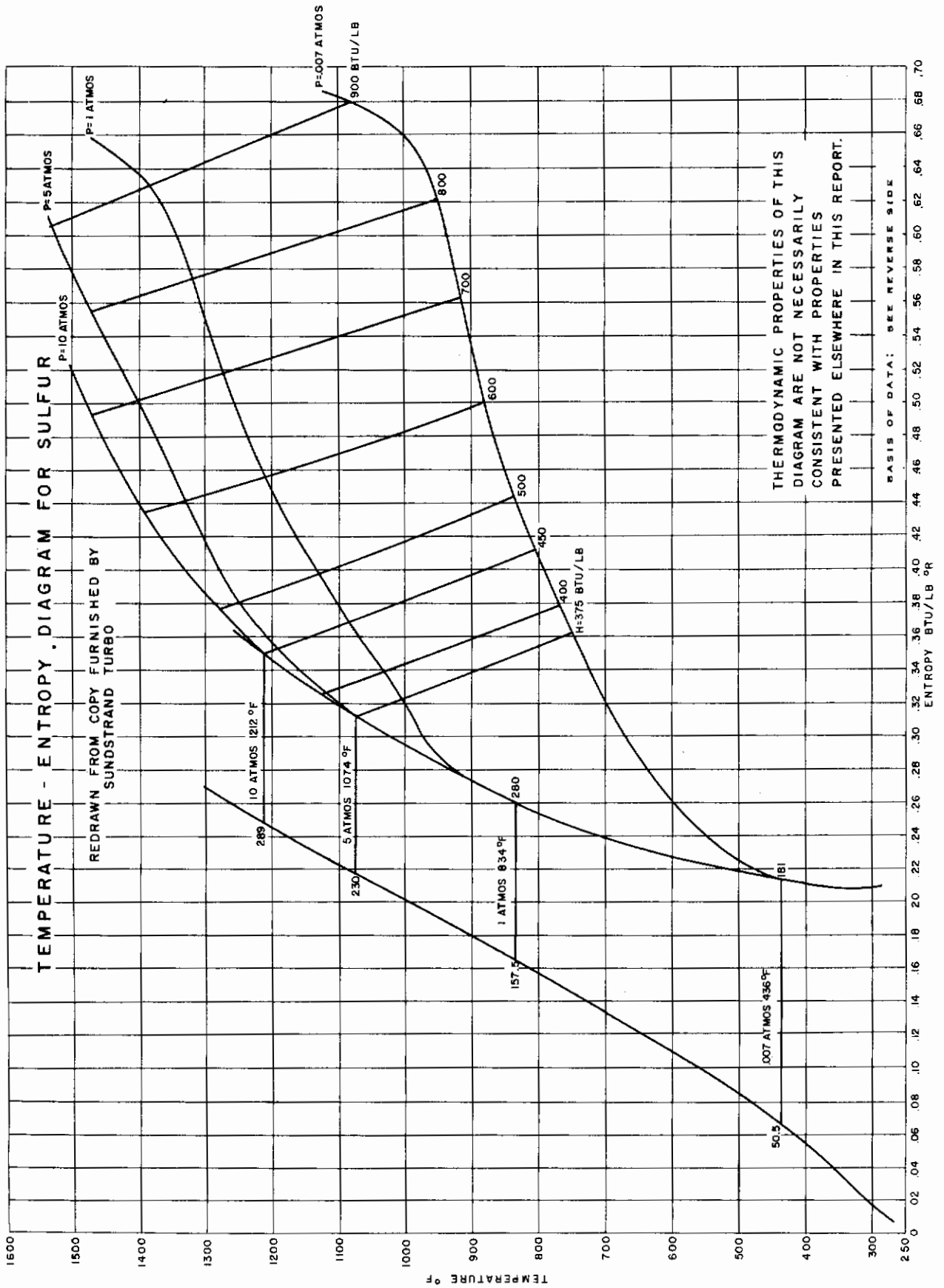
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	19-0-49, 20-19-4	832-1700	Specific heat of sulfur was calculated for the equilibrium vapor containing one gram atomic weight of sulfur at one atmosphere distributed among the octatomic hexatomic, and diatomic molecules.

S-ΔH-a



WADD TR 61-96

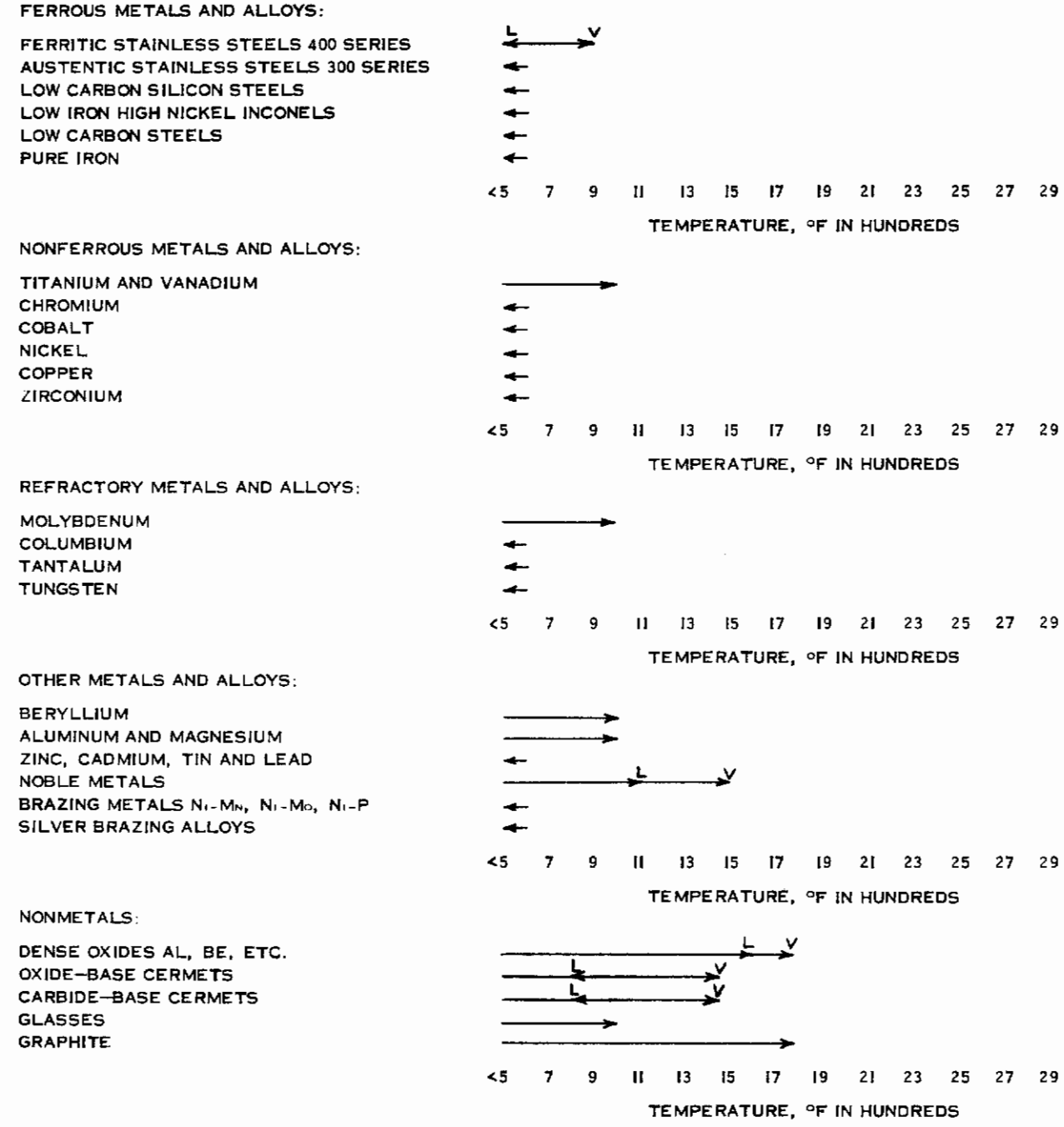
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	6-1-3, 20-19-4	320-1004	The latent heat of vaporization of sulfur vapor was calculated from the Clausius-Clapeyron relation.
Extrapolated	6-1-3, 20-19-4	1004-1195	The values were extended by use of the above data.



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	722	300-1500	Theoretical extension of data from literature survey.

RESISTANCE OF MATERIALS TO SULFUR

(SEE REVERSE SIDE OF SHEET FOR DATA BASIS)



NOTE: RIGHT-HAND ARROW-POINT INDICATES HIGHEST REPORTED TEST TEMPERATURE BELOW RESISTANCE LIMIT OF MATERIAL

LEFT-HAND ARROW-POINT INDICATES LOWEST REPORTED TEST TEMPERATURE ABOVE RESISTANCE LIMIT OF MATERIAL

(SEE FRONT SIDE OF SHEET FOR DATA)

	DATA SOURCE	REMARKS AND BASIS OF DATA
FERROUS METALS AND ALLOYS:		
FERRITIC STAINLESS STEELS 400 SERIES	721, 722	Static and dynamic
AUSTENTIC STAINLESS STEELS 300 SERIES	721	Static
LOW CARBON SILICON STEELS	721	Static
LOW IRON HIGH NICKEL INCONELS	721	Static
LOW CARBON STEELS	721	Static
PURE IRON	721, 722	Static and dynamic
NONFERROUS METALS AND ALLOYS:		
TITANIUM AND VANADIUM	722	Static and dynamic
CHROMIUM	721	Static
COBALT	721	Static
NICKEL	721	Static
COPPER	721	Static
ZIRCONIUM	721	Static
REFRACTORY METALS AND ALLOYS:		
MOLYBDENUM	722	Static and dynamic
COLUMBIUM	721	Static
TANTALUM	721	Static
TUNGSTEN	721	Static
OTHER METALS AND ALLOYS:		
BERYLLIUM	721	Static
ALUMINUM AND MAGNESIUM	722	Static and dynamic (no Cl or Br additives)
ZINC, CADMIUM, TIN AND LEAD	721	Static
NOBLE METALS	722	Static and dynamic
BRAZING METALS Ni Mn, Ni Mo, Ni P	721	Static
SILVER BRAZING ALLOYS	721	Static
NONMETALS:		
DENSE OXIDES AL, BE, ETC.	721, 722	Static and dynamic
OXIDE–BASE CERMETS	721, 722	Static and dynamic
CARBIDE–BASE CERMETS	721, 722	Static and dynamic
GLASSES	721	Static
GRAPHITE	722	Static and dynamic

e. Data Sources for Sulfur

Code No.	Source
2-6-3	Bacon, R. F., and Fanelli, R., J. Am. Chem. Soc., 65, 639 (1943).
3-12-60	Chem. Eng. News, pp 53-65 (December 26, 1960).
4-23-0	Dalin, G. A., and West, J. R., J. Phys. and Colloid. Chem., 54, 1215 (1950).
6-0-0	Fanelli, R., J. Am. Chem. Soc., 72, 4016 (1950).
6-1-3	"Facts About Sulphur," New York, Texas Gulf Sulphur Co., 1953.
8-0-8	Hodgman, C. D., Editor, "Handbook of Chemistry and Physics," Cleveland, Chemical Rubber Publishing Co., 1958.
11-8-9	Kaye, G. W. C. and Higgins, W. F., Proc. Roy. Soc. (London), A122, 633 (1929).
19-0-49	Stull, D. R., Ind. Eng. Chem., 41, 1968 (1949).
19-19-6	Stull, D. R., and Sinke, G. C., "Thermodynamic Properties of the Elements," Washington, American Chemical Society, 1956.
20-19-4	Tuller, W. N., Editor, "The Sulphur Data Book," New York, McGraw-Hill Book Co., Inc., 1954.
23-0-0	West, J. R., Ind. Eng. Chem. 42, 713 (1950).
23-0-1	West, J. R., J. Phys. and Colloid. Chem., 55, 402 (1951).
23-0-9	West, E. D., J. Am. Chem. Soc., 81, 29 (1959).
721	AiResearch Manufacturing Co. of Arizona
722	Sundstrand Corporation

LITHIUM HYDRIDE

a. General Description of Lithium Hydride. Lithium hydride is a white crystalline substance, considerably more dense than lithium metal. It contracts upon melting and forms cubic crystals upon freezing. It is extremely reactive with water. It may be exposed briefly to relatively dry air; however, hydroxide and carbonate films are formed immediately.

Lithium hydride is of particular interest for use as a thermal-storage medium. Because of its low molecular weight, it displays relatively high specific heat and latent heat per unit mass.

Commercially, 93-98% lithium hydride is available in steel containers (1/4, 1, 25, and 100 lb lots) at $9.50 to $11.00 per lb.

b. Synopsis of Properties of Lithium Hydride

Property	Value	Temp (°F)	Data Basis	Reference
Physical:				
Molecular Weight	7.948	---	Handbook	10-4-60
Melting Point, °F	1270.4 ± 1.8	---	Experimental	13-7-57
Temperature for 1 atm Dissociation Pressure, °F	1647	---	Extrapolated	13-7-57
Density of Solid, lb/ft^3	48.4	77	Experimental	13-7-57
Density of Liquid, lb/ft^3	36.2	M. P.	Estimated	13-7-57
Density of Equilibrium H_2 Vapor, lb/ft^3	0.0013	1647 (1 atm)	Theoretical	Ideal Gas
Viscosity of Liquid, lb/ft hr	0.93	M. P.	Experimental	14-13-61
Viscosity of Equilibrium H_2 Vapor, lb/ft hr	0.054	1647 (1 atm)	Extrapolated	Page H_2-μ-a
Thermal:				
Thermal Conductivity of Solid, BTU/hr ft °F	2.8	650	Experimental	6-8-58, 13-7-57
Thermal Conductivity of Equilibrium H_2 Vapor, BTU/hr ft °F	0.256	1647 (1 atm)	Experimental	Page H_2-k-a
Specific Heat of Liquid, BTU/lb °F	1.9	M. P.	Estimated	8-8-61, 13-7-57
Specific Heat of Equilibrium H_2 Vapor, BTU/lb °F	3.7	1647 (1 atm)	Extrapolated	Page H_2-C-a
Ratio of Specific Heats of Equilibrium H_2 Vapor	1.36	1647 (1 atm)	Handbook	8-0-8
Latent Heat of Fusion, BTU/lb	1250	M. P.	Experimental (Extrapolation of Enthalpy Equation)	8-8-61 (716)
Electrical and Magnetic:				
Magnetic Susceptibility, fps electromagnetic units/unit mass	-0.244	---	Experimental	6-20-35

c. Property Tables for Lithium Hydride

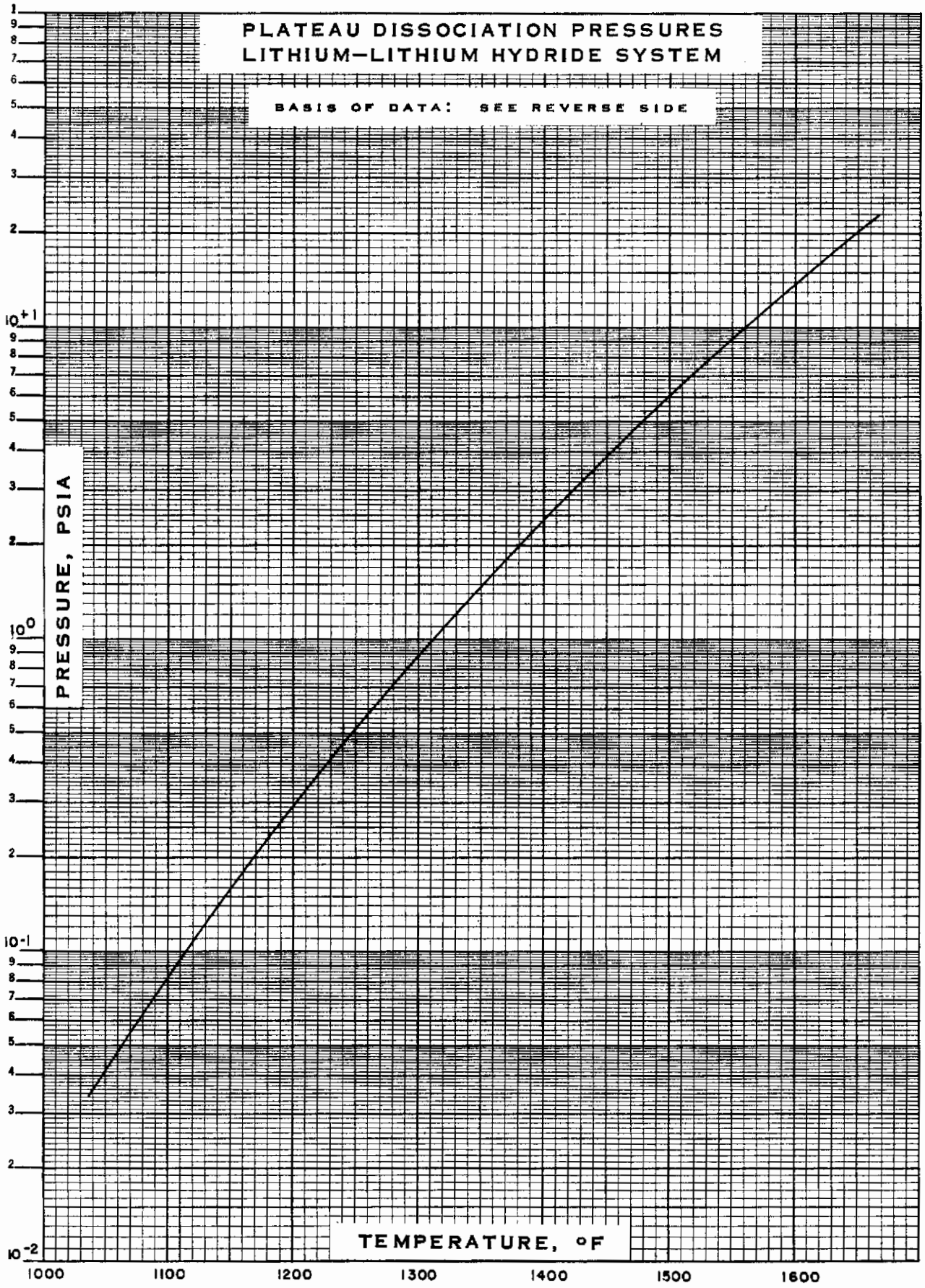
THERMODYNAMIC PROPERTIES OF LITHIUM HYDRIDE

Ideal Diatomic Gas: $H^{\circ}_{536.67} - H^{\circ}_{o} = 3,737$ BTU/lb mole

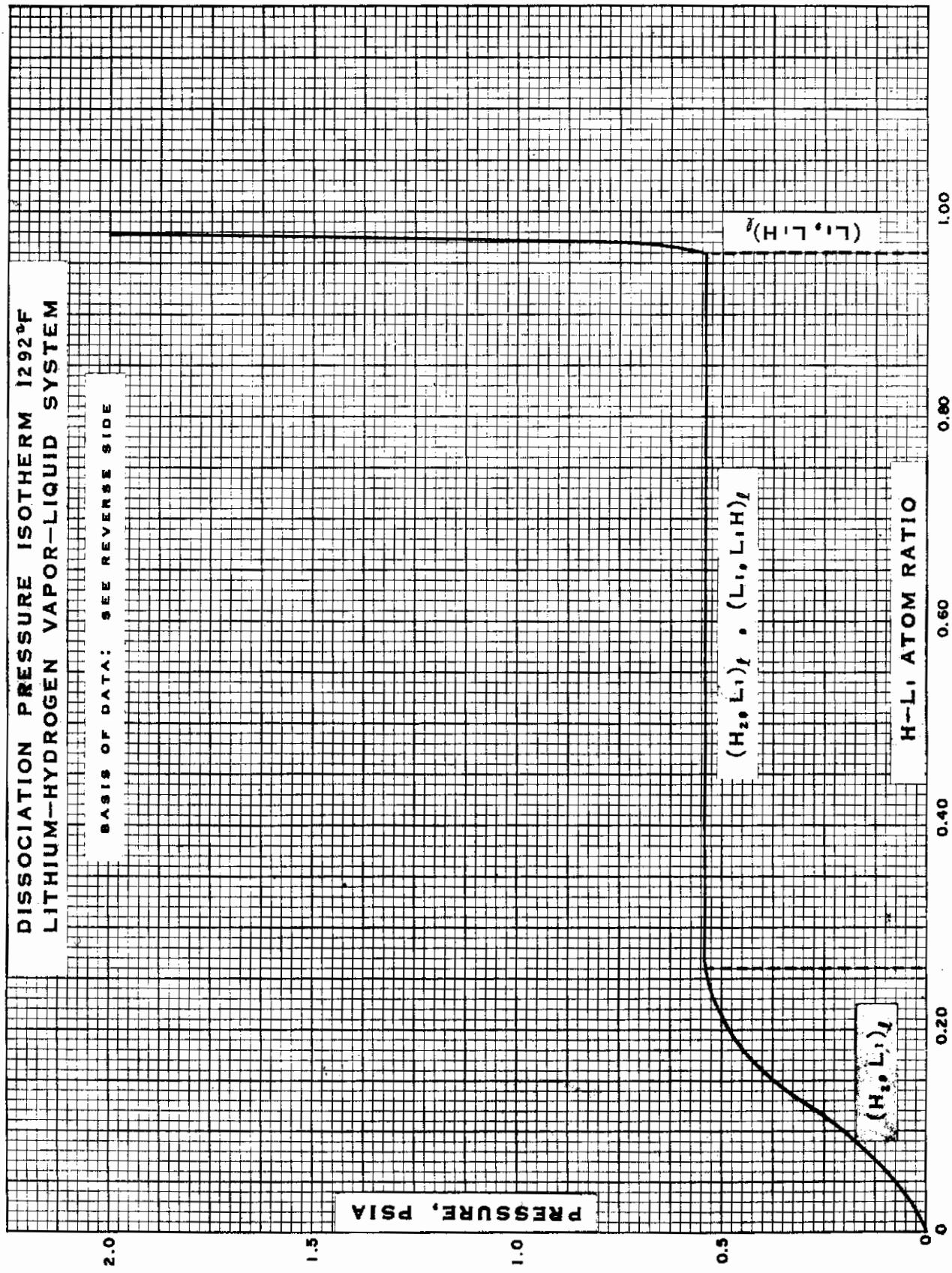
(Ref: 10-4-60)

Temperature T (°R)	Enthalpy $H^{\circ} - H^{\circ}_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R	Free Energy Function $-(F^{\circ} - H^{\circ}_{536.67})/T$ (BTU/lb mole °R)
540	23.4	40.869	40.826
720	1,324.8	42.948	41.107
900	2,676.6	44.623	41.648
1080	4,080.6	46.043	42.265
1260	5,526.0	47.281	42.895
1440	7,011.0	48.382	43.513
1620	8,523.0	49.372	44.110
1800	10,062.0	50.272	44.682
1980	11,619.0	51.096	45.228
2160	13,194.0	51.857	45.749
2340	14,783.4	52.564	46.247
2520	16,383.6	53.223	46.722
2700	17,996.4	53.842	47.176
2880	19,620.0	54.423	47.611
3060	21,250.8	54.973	48.028

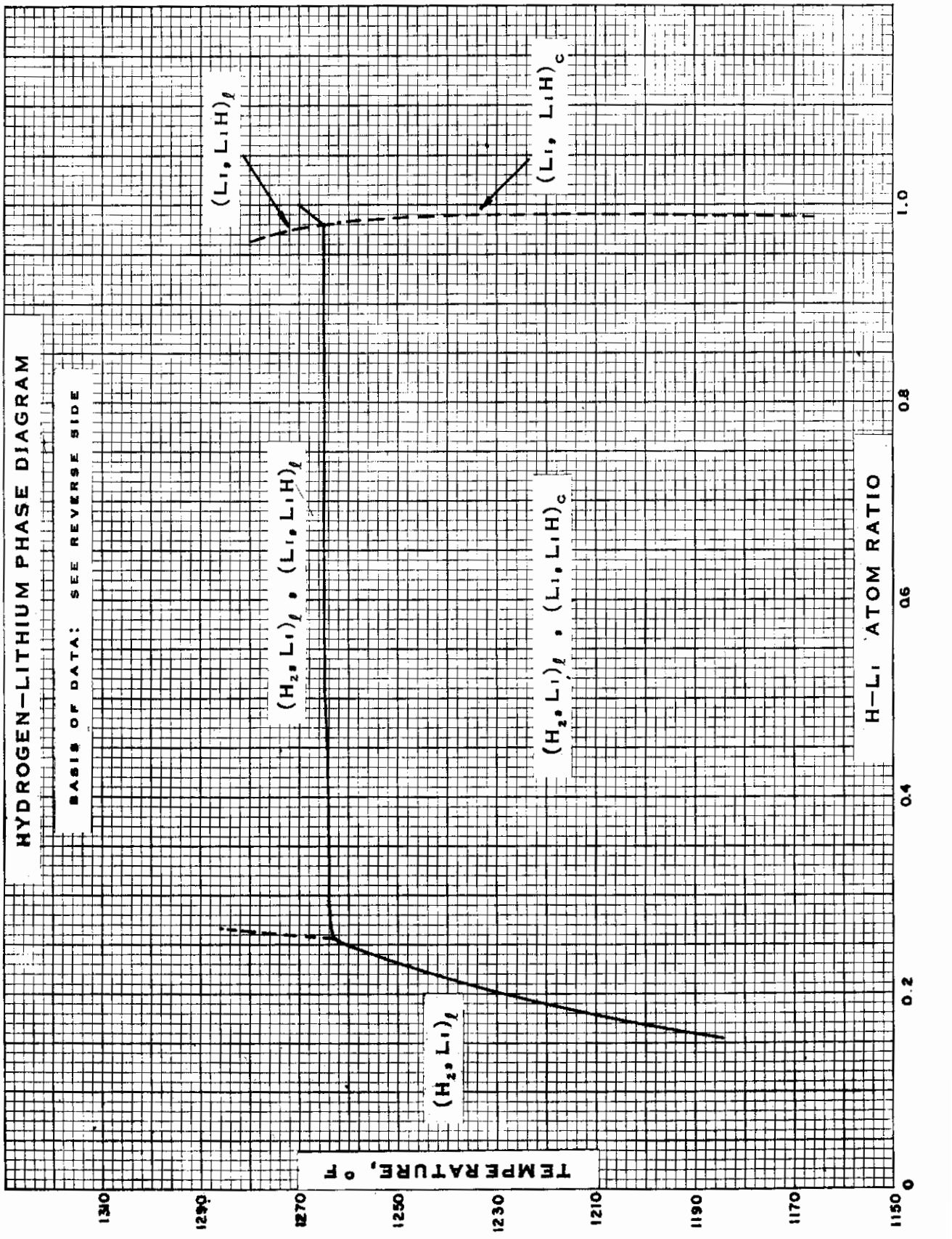
d. Working Charts for Lithium Hydride



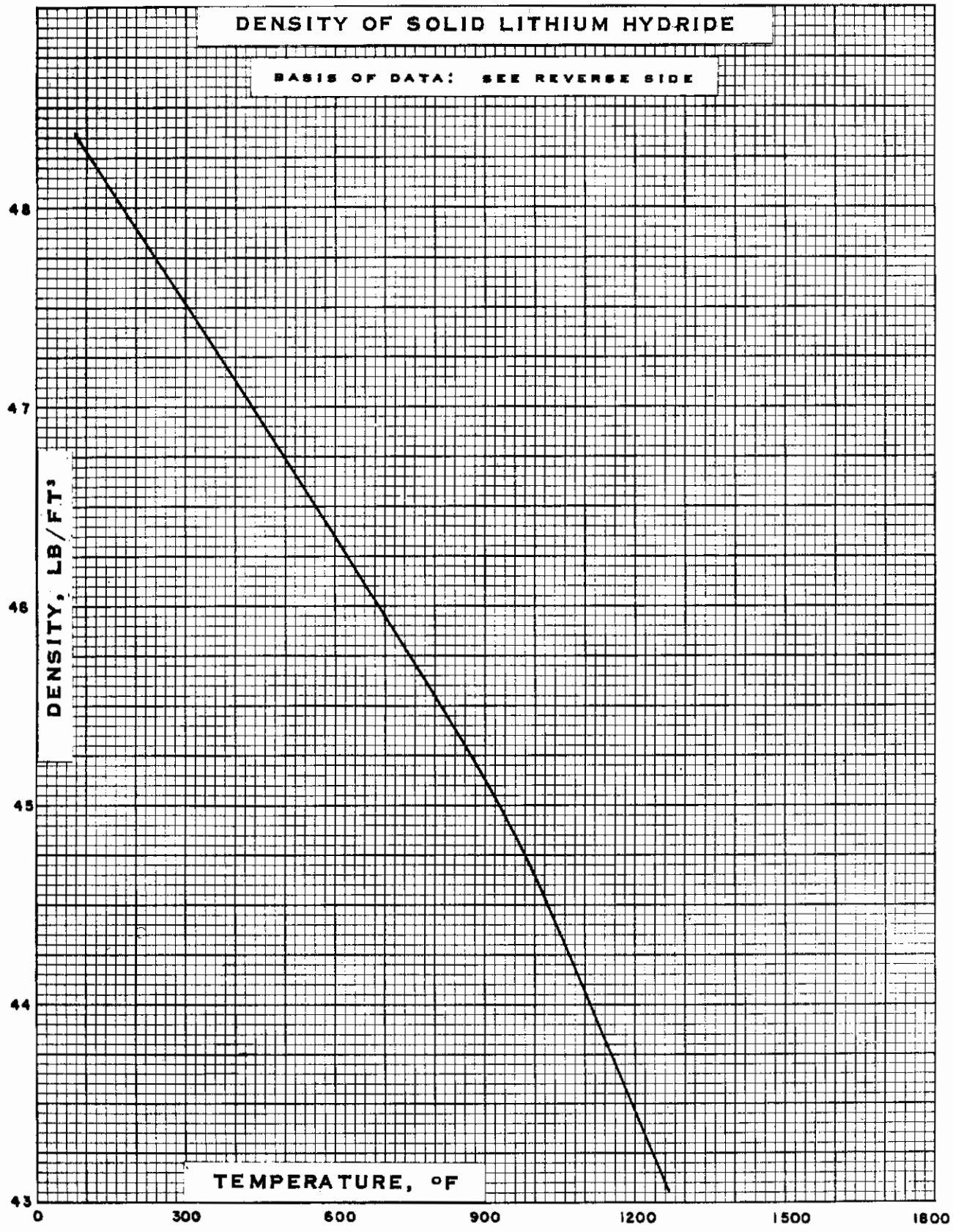
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	8-19-56, 13-7-57	1290-1480	Compositions within plateau region (30 - 90 at. % LiH).
Extrapolated		1040-1290, 1480-1670	Extrapolation of above data by least squares equation.



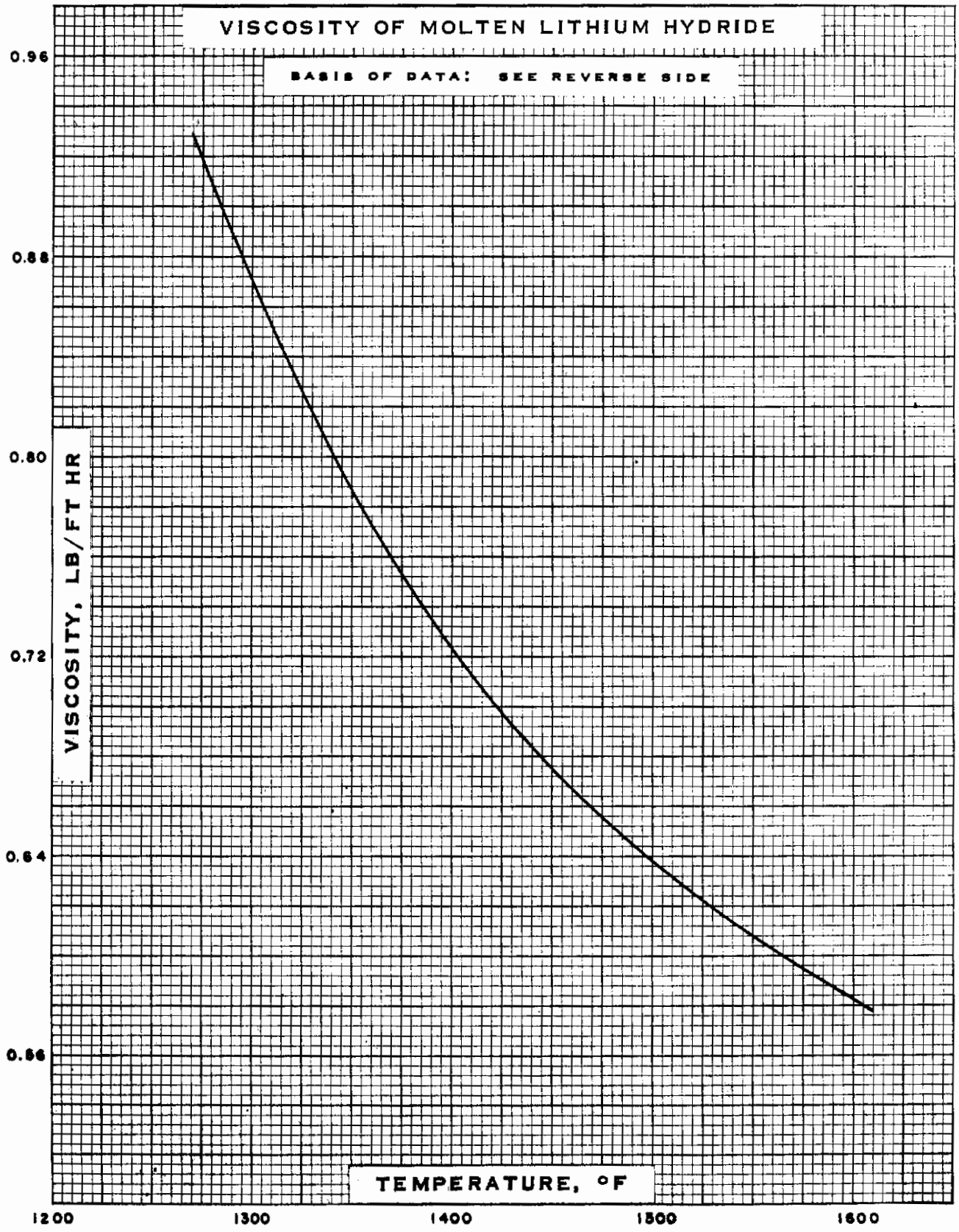
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	8-19-56, 13-7-57	1292	



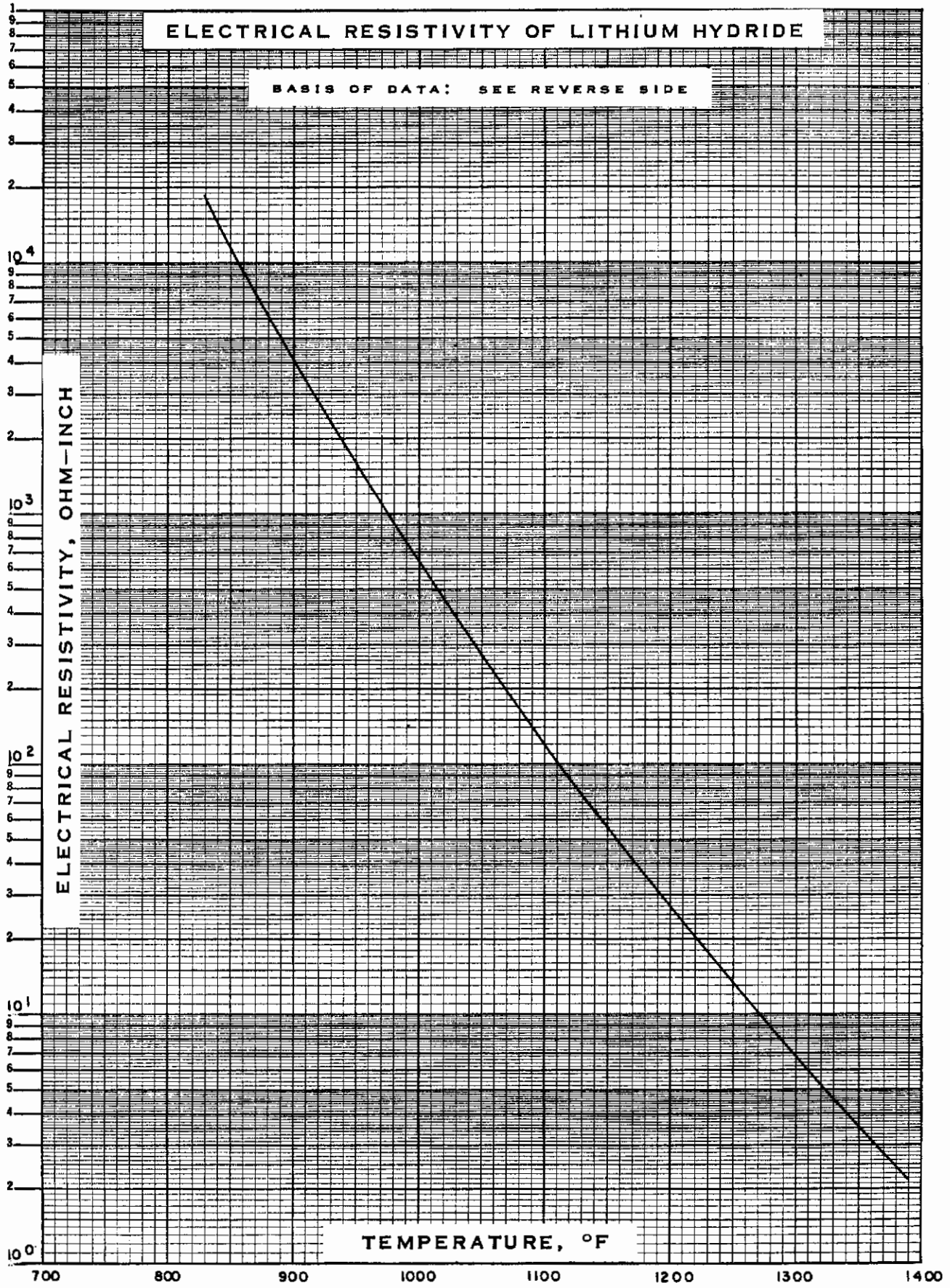
Basis of Data	Recommended Values	Temperature Range (°F)	Remarks
Experimental	13-7-57, 13-19-57	1184-1270	The solid lines represent portions of the equilibrium curves determined experimentally. The dashed curves represent hypothetical portions.



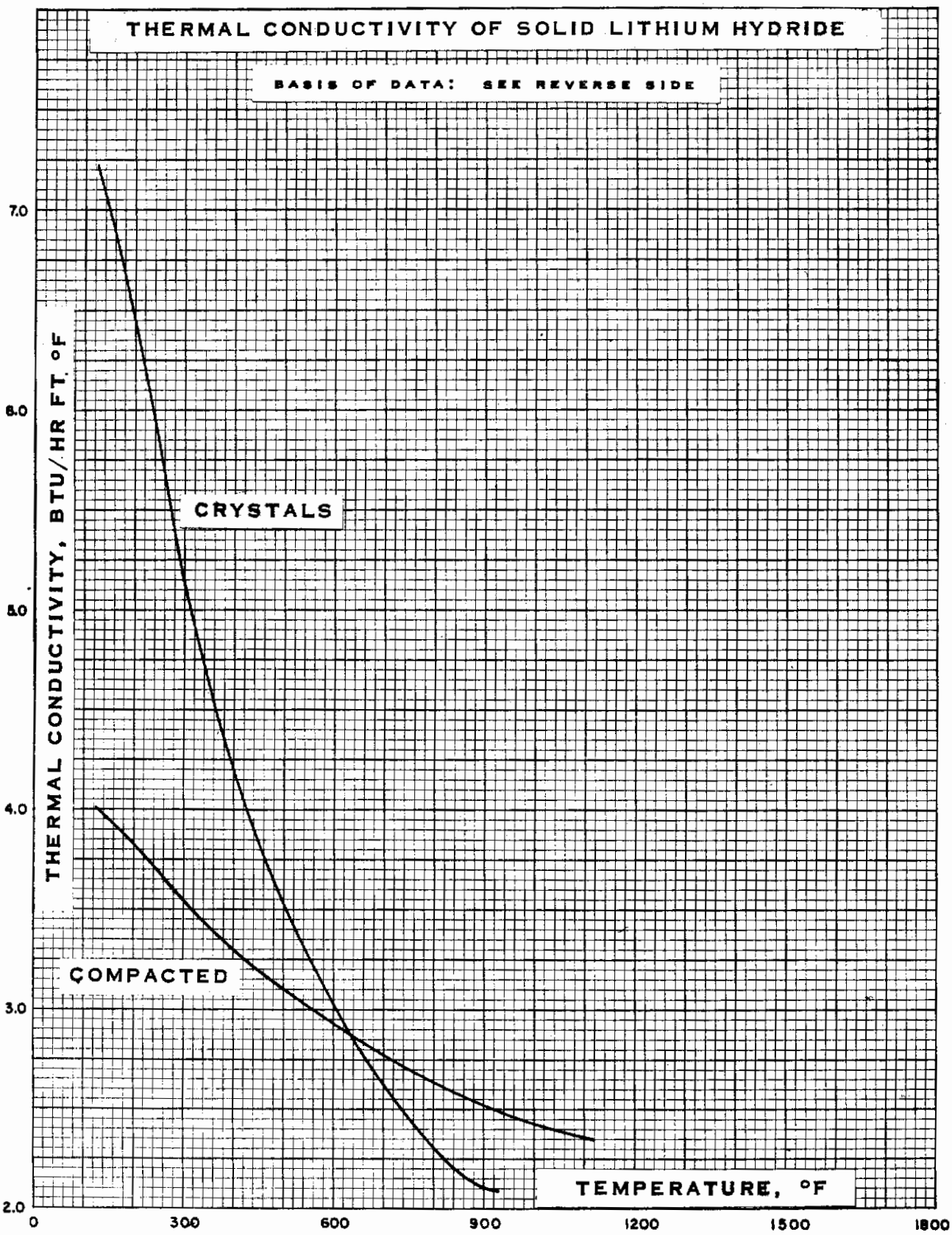
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Calculated and Estimated	13-7-57, 26-0-53	77-1270	The coefficient of expansion at high temperatures was determined by 26-0-53, who measured the lattice constant from 77-977°F by X-ray diffraction. These data enable calculations of the density up to 977°F and its estimation at higher temperature.



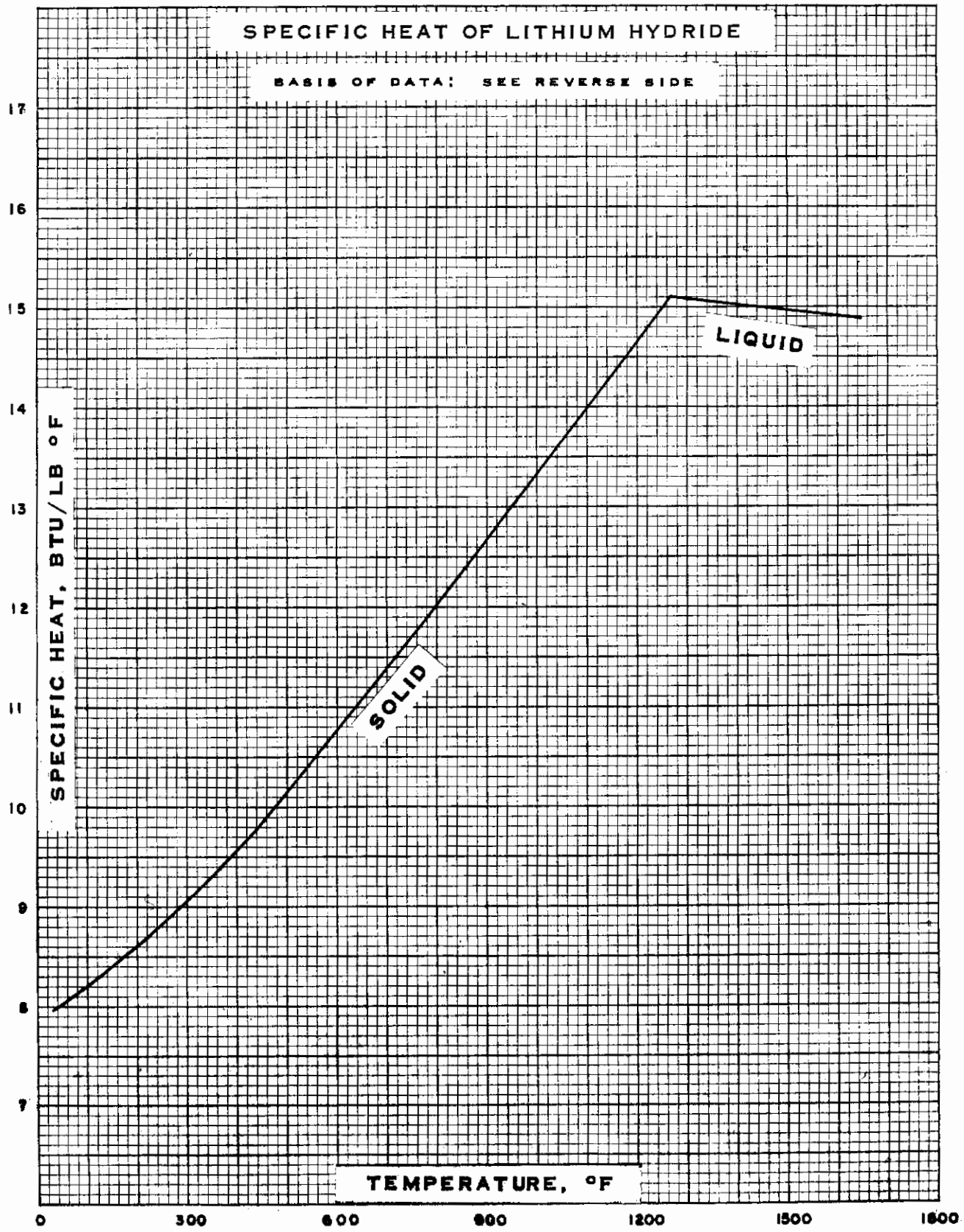
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	14-13-61	1250-1580	The lithium hydride used for this study melted at 1252°F. A rotating viscometer was used for the experimental measurements.



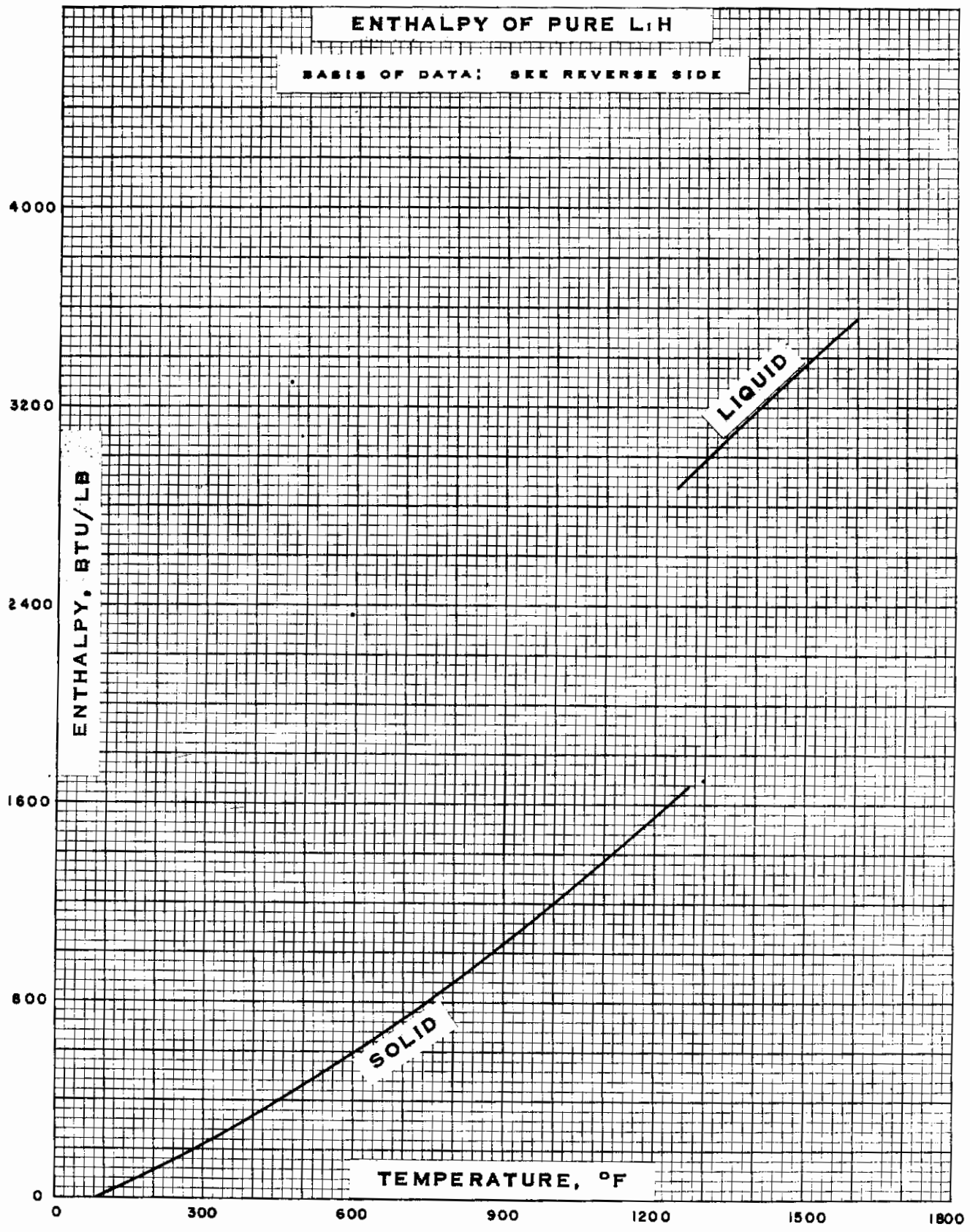
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	13-0-20	830-1390	Experimental AC measurements.



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	13-7-57	122-1112	Compacted 3" × 3/4" specimens and cast crystalline specimens.



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	8-0-8	32	Handbook
Calculated	8-8-61	212-1650	Calculated from least squares fit of experimental enthalpy data.



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	8-8-61	212-1650	Least squares fit of experimental data. Reference point: zero enthalpy at 86°F.

e. Data Sources for Lithium Hydride

Code No.	Source
6-8-58	Fieldhouse, I. B., Hedge, J. C., and Lang, J. I., WADC Tech. Report 58-274, Nov. 1958.
6-20-35	Freed, S., and Thode, H. G., J. Chem. Phys., 3, 212-15 (1935).
8-0-8	Hodgman, C. D., Editor, "Handbook of Chemistry and Physics," Cleveland, Chemical Rubber Publishing Co., 1958.
8-8-61	Haufman, H. W., Oak Ridge Nat. Lab., Private Communication, May 12, 1961.
8-19-56	Heumann, F. K, and Salmon, O. N., KAPL-1667, December 1, 1956.
10-4-60	JANAF Interim Thermochemical Tables, December 31, 1960.
13-0-20	Moers, K., Z. Anorg. Allgem. Chem., 113, 179-228 (1920).
13-7-57	Messer, C. E. and Gibb, T. R. P., Jr., USAEC, NYO-8022 Supplement, August 31, 1957.
13-19-57	Messer, C. E., Seales, R. A. and Mellor, J., USAEC, NYO-8021, July 26, 1957.
14-13-61	Welch, F. H., (Northup, H. W., Mink, W. H., and Lemmon, A. W., Battelle Mem. Inst., March 16, 1961), General Electric ANP Dept., XDC-61-4-59, April 1961.
26-0-53	Zalkin, A., Report UCRL-4239, Nov. 16, 1953.
53	Maywood Chemical Works.
511	Foote Mineral Co.
525	Lithium Corporation of America, Inc.

GASES

HELIUM

a. General Discussion of Helium. Helium is a colorless, tasteless, odorless gas referred to as a "rare gas," an "inert gas," or a "noble gas." It is a constituent of the atmosphere and is obtained by compression and fractionation of the gas from certain natural gas wells and from many radioactive minerals.

Helium is available in cylinders at $19.00 per 190 cu ft cylinder. It is also available in tank car quantities.

b. Synopsis of Properties of Helium.

Property	Value	Temp (°F)	Data Basis	Reference
Physical:*				
Atomic Weight	4.003	---	Handbook	8-0-8
Melting Point, °F	-458 (26 atm)	---	Handbook	8-0-8
Boiling Point, °F	-452	---	Handbook	8-0-8
Critical Point, psia	33.2	-450.2	Survey	11-12-3
Density, lb/ft^3	0.00517	600		5-4-9
	0.00330	1200		5-4-9
Viscosity, lb/ft hr	0.0753	600	Unknown	Page He-μ-a
	0.1000	1200	Unknown	Page He-μ-a
Thermal:*				
Thermal Conductivity, BTU/hr ft °F	0.133	600	Theoretically extrapolated	Page He-k-a
	0.1775	1200	Theoretically extrapolated	Page He-k-a
Specific Heat, BTU/lb °F	1.242	600	Experimental and theoretical	5-4-9
	1.242	1200	Experimental and theoretical	5-4-9
Ratio of Specific Heats	1.666	---	Survey	11-15-7
Electrical and Magnetic:				
Ionization Potential, volts	24.46	---	Handbook	8-0-8
Magnetic Susceptibility, fps electromagnetic units/unit mass	-0.19806	68	Handbook	8-0-8
Dielectric Constant	1.0001	32	Handbook	8-0-8

*All properties are at atmospheric pressure unless otherwise specified.

Property	Value	Temp(°F)	Data Basis	Reference
Thermal Neutron Cross Section (2200 m/s):				
Absorption, barns: He^3	5400 ± 300		Handbook	8-0-8
He^4	0		Handbook	8-0-8
Scattering, barns	0.8 ± 0.2		Handbook	8-0-8

c. Property Tables for Helium.

THERMODYNAMIC PROPERTIES OF HELIUM

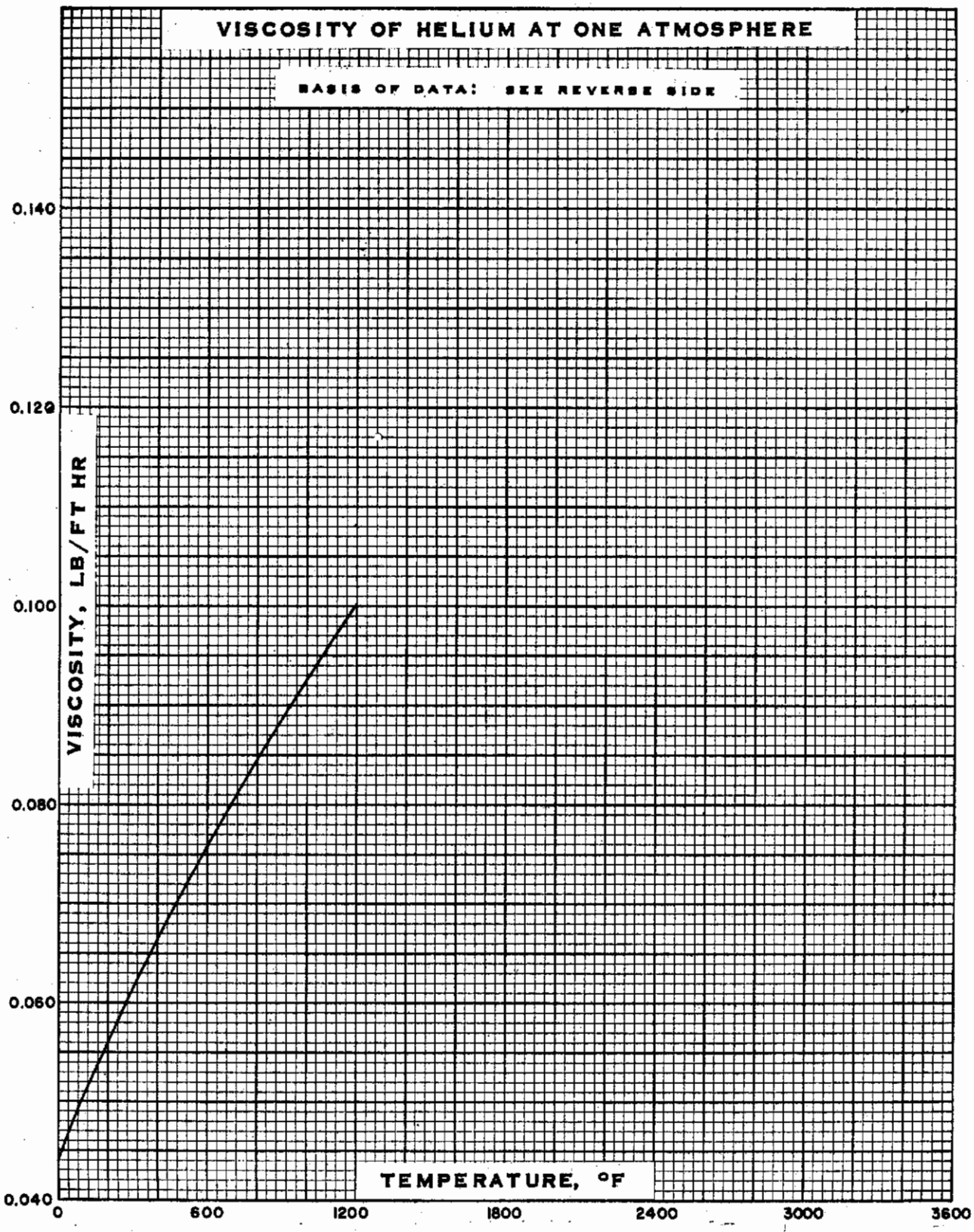
Ideal Monatomic Gas: $H^\circ_{536.67} - H^\circ_o = 2,666$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^\circ - H^\circ_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^\circ - H^\circ_{536.67})/T$ (BTU/lb mole °R)
537	0	30.13	30.13
540	16.2	30.16	30.13
720	910.8	31.59	30.33
900	1805	32.69	30.69
1080	2700	33.60	31.10
1260	3593	34.36	31.51
1440	4487	35.03	31.92
1620	5382	35.61	32.29
1800	6277	36.14	32.66
1980	7171	36.61	32.99
2160	8064	37.04	33.31
2340	8959	37.44	33.62
2520	9853	37.81	33.90
2700	10748	38.15	34.17
2880	11642	38.47	34.43
3060	12535	38.77	34.68
3240	13430	39.06	34.92
3420	14324	39.33	35.15
3600	15219	39.58	35.36
3780	16114	39.82	35.56
3960	17006	40.06	35.77

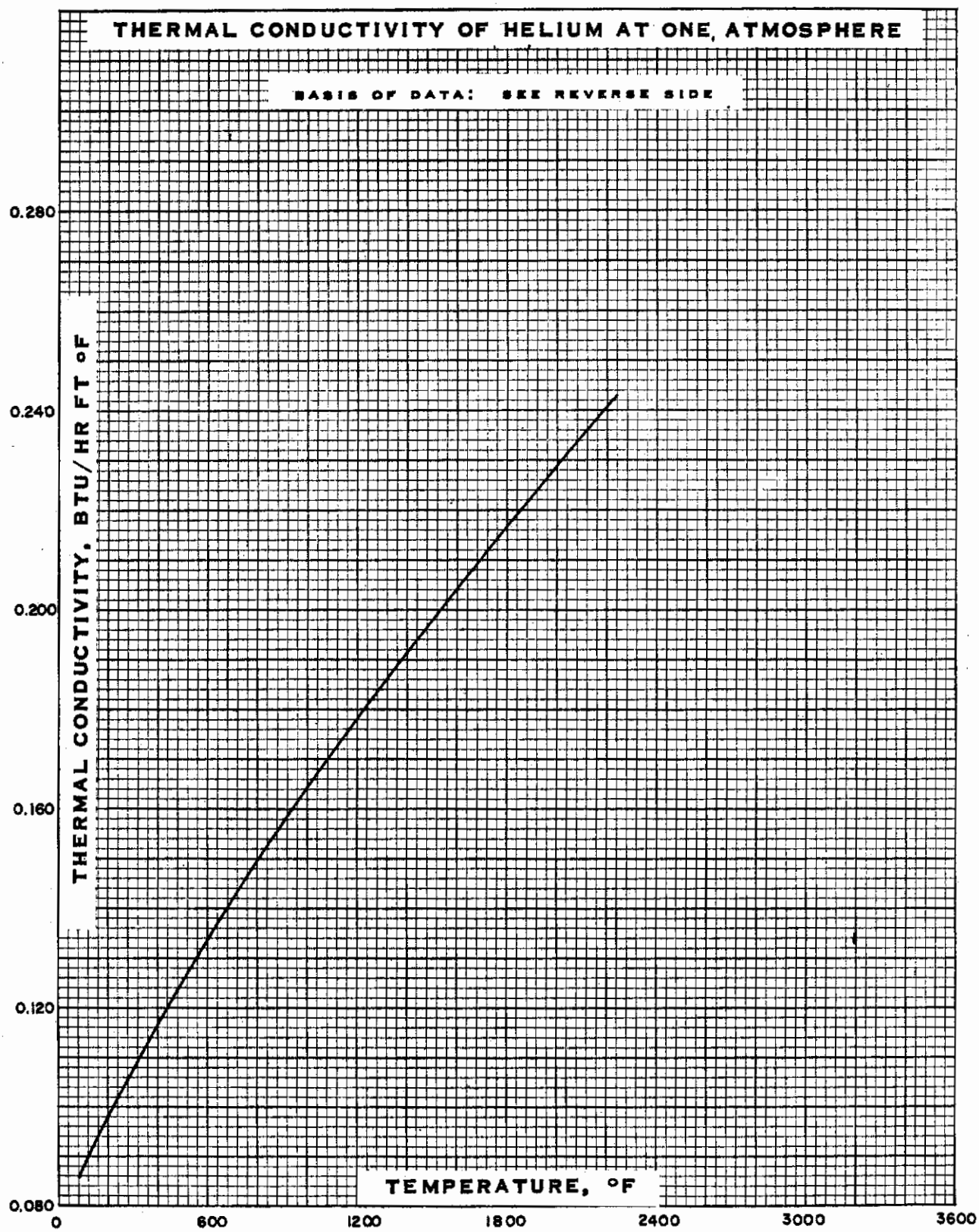
d. Working Charts for Helium

He-μ-a



He-μ-a (basis)

Basis of Data	Known References Consistent with Recommended Values	Temperature Range (° F)	Remarks
Unknown	5-4-9	0-1200	Survey



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretically Extrapolated	5-9-9	80-2240	Calculated according to Hirschfelder, using force constants determined from experimental thermal conductivity data.

e. Data Sources for Helium

Code No.	Source
5-4-9	Eckert, E. R. G. and Drake, R. M., Jr., "Heat and Mass Transfer," New York, McGraw-Hill Book Co., Inc., 1959.
5-9-9	Eckert, E. R. G., Ibele, W. E. and Irvine, T. F., Jr., Thermodynamic and Transport Properties of Gases, Liquids and Solids, McGraw-Hill Book Co., Inc., New York, February 23-26, 1959. pp 295-300.
8-0-8	Hodgman, C. D., Editor, "Handbook of Chemistry and Physics," Cleveland, Chemical Rubber Publishing Co., 1958.
11-12-3	Kobe, Kenneth A. and Lynn, Emerson, Jr., Chem. Rev. 52, No. 1, 117-236 (1953).
11-15-7	Kirk, R. E., Othmer, D. F., Editors, "Encyclopedia of Chemical Technology," Vol. 1, 10, 13, First Sup. Vol., New York, The Interscience Encyclopedia, Inc., 1947.
19-19-6	Stull, D. R. and Sinke, G. C., "Thermodynamic Properties of the Elements," Washington, American Chemical Society, 1956.

HYDROGEN

a. General Discussion of Hydrogen. Hydrogen is the first element in the periodic table. Under normal conditions, it exists as a colorless, odorless, tasteless, diatomic gas.

At temperatures higher than 1000° F, hydrogen reacts with oxygen with explosive violence. Hydrogen is produced commercially by various means such as (a) steam-hydrocarbon process, (b) steam-water-gas process, (c) electrolysis of water, (d) steam-iron process and (e) thermal decomposition of hydrocarbon. The most common impurities in hydrogen are carbon dioxide, carbon monoxide, oxygen and water vapor.

Hydrogen is ordinarily shipped in steel cylinders; however, most of the hydrogen consumed in the U. S. is produced "in situ." Hydrogen is available in cylinder quantities at prices ranging from $6.50 to $45.00 per 190 cu ft cylinder.

b. Synopsis of Properties of Hydrogen.

Property	Value	Temp (°F)	Data Basis	Reference
Physical:*				
Molecular Weight	2.016	---	Handbook	8-0-8
Melting Point, F	-434	---	Handbook	8-0-8
Boiling Point, °F	-423	---	Handbook	8-0-8
Critical Point, psia	188	-400	Handbook	11-12-3
Density, lb/ft^3	0.00260	600	Handbook	5-4-9
	0.00143	1500	Handbook	5-4-9
Viscosity, lb/ft hr	0.0342	600	Experimental	Page H_2-μ-a
	0.0516	1500	Experimental	Page H_2-μ-a
Thermal:*				
Thermal Conductivity, BTU/hr ft °F	0.1790	600	Experimental	Page H_2-k-a
	0.2675	1500	Experimental	Page H_2-k-a
Specific Heat, BTU/lb °F	3.504 (0 atm)	600	Theoretical	Page H_2-C-a
	3.651 (0 atm)	1500	Theoretical	Page H_2-C-a
Ratio of Specific Heats	1.391	600	Theoretical	Page H_2-γ-a
	1.366	1500	Theoretical	Page H_2-γ-a
Electrical and Magnetic:				
Ionization Potential, volts	13.595	---	Experimental	11-0-60
Magnetic Susceptibility, fps electromagnetic units/unit mass	-0.83014	68	Handbook	8-0-8
Dielectric Constant	1.0003	32	Handbook	8-0-8

*All properties are at atmospheric pressure unless otherwise specified.

Property	Value	Temp (°F)	Data Basis	Reference
Thermal Neutron Cross Section (2200 m/s):				
Absorption, barns:	0.330 ± .003	---	Handbook	8-0-8
Scattering, barns	38 ± 4	---	Handbook	8-0-8

c. Property Tables for Hydrogen.

INFLUENCE OF PRESSURE ON SPECIFIC HEAT RATIO OF HYDROGEN

(Ref: 8-2-5)

Temperature (°R)	Pressure		
	1 atm	10 atm	100 atm
468	1.413	1.416	1.431
540	1.405	1.406	1.417
720	1.398	1.398	1.403
900	1.397	1.397	1.398
1080	1.396	1.396	1.396

THERMODYNAMIC PROPERTIES OF HYDROGEN

Ideal Monatomic Gas: $H^{\circ}_{536.67} - H^{\circ}_{o} = 2,666$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^{\circ} - H^{\circ}_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^{\circ} - H^{\circ}_{536.67})/T$ (BTU/lb mole °R)
537	0	27.39	27.39
540	16.2	27.42	27.39
720	910.8	28.85	27.59
900	1805	29.96	27.96
1080	2700	30.87	28.37
1260	3593	31.63	28.78
1440	4487	32.30	29.19
1620	5382	32.88	29.56
1800	6277	33.40	29.92
1980	7169	33.88	30.26
2160	8064	34.31	30.58
2340	8959	34.71	30.89
2520	9853	35.08	31.17
2700	10748	35.42	31.44
2880	11642	35.74	31.70
3060	12535	36.04	31.95
3240	13430	36.32	32.18
3420	14324	36.59	32.41
3600	15219	36.85	32.63
3780	16114	37.09	32.83
3960	17008	37.32	33.03

THERMODYNAMIC PROPERTIES OF HYDROGEN

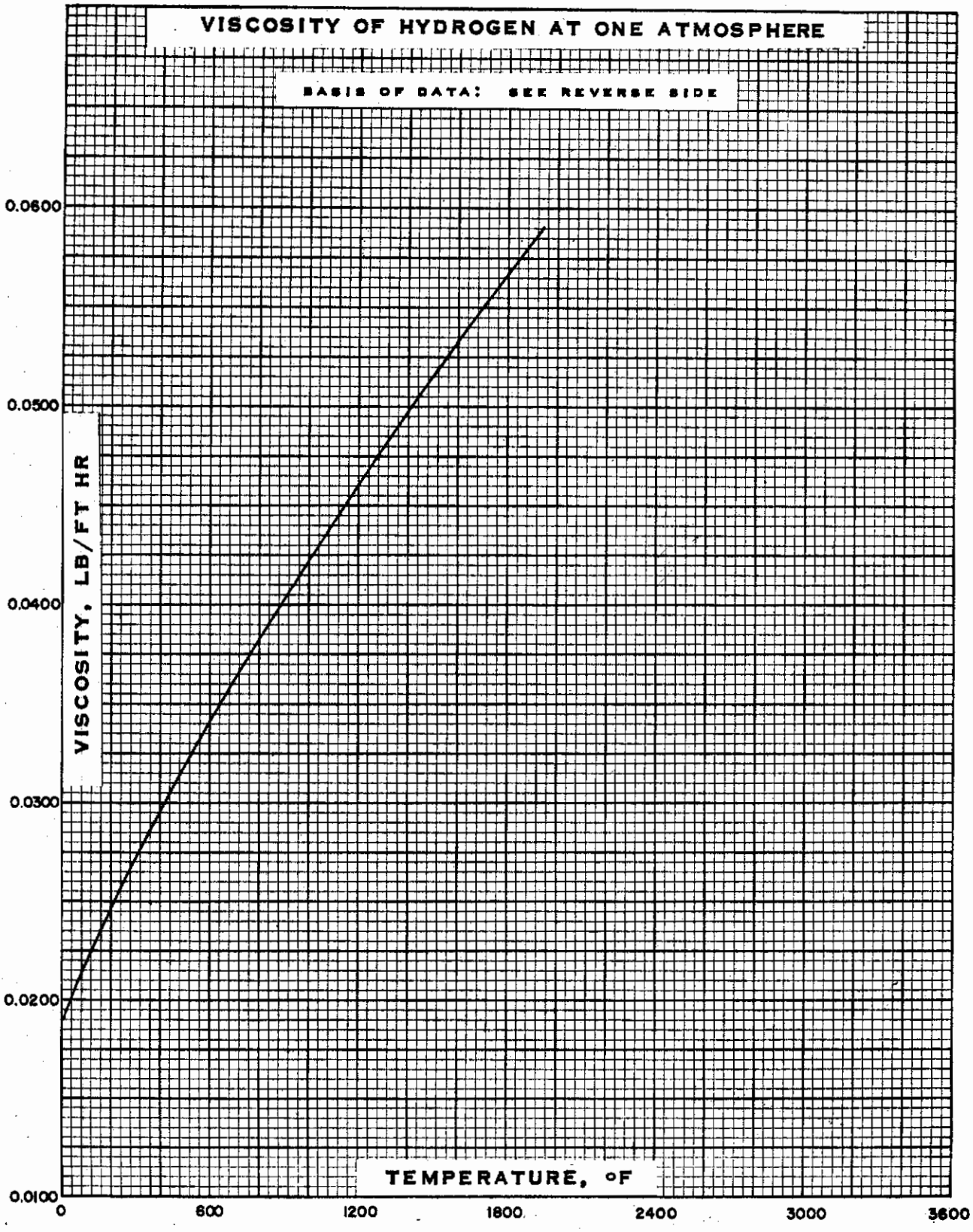
Ideal Diatomic Gas: $H^\circ_{536.67} - H^\circ_0 = 3,643$ BTU/lb mole

(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^\circ - H^\circ_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^\circ - H^\circ_{536.67})/T$ (BTU/lb mole °R)
537	0	31.21	31.21
540	21.6	31.25	31.21
720	1271	33.25	31.49
900	2531	34.81	32.00
1080	3789	36.08	32.58
1260	5054	37.17	33.16
1440	6325	38.11	33.72
1620	7603	38.95	34.26
1800	8896	39.70	34.76
1980	10204	40.40	35.25
2160	11533	41.04	35.71
2340	12877	41.64	36.14
2520	14240	42.20	36.55
2700	15620	42.73	36.95
2880	17020	43.23	37.32
3060	18436	43.70	37.68
3240	19868	44.16	38.03
3420	21316	44.59	38.36
3600	22784	45.01	38.69
3780	24268	45.41	38.99
3960	25769	45.80	39.30

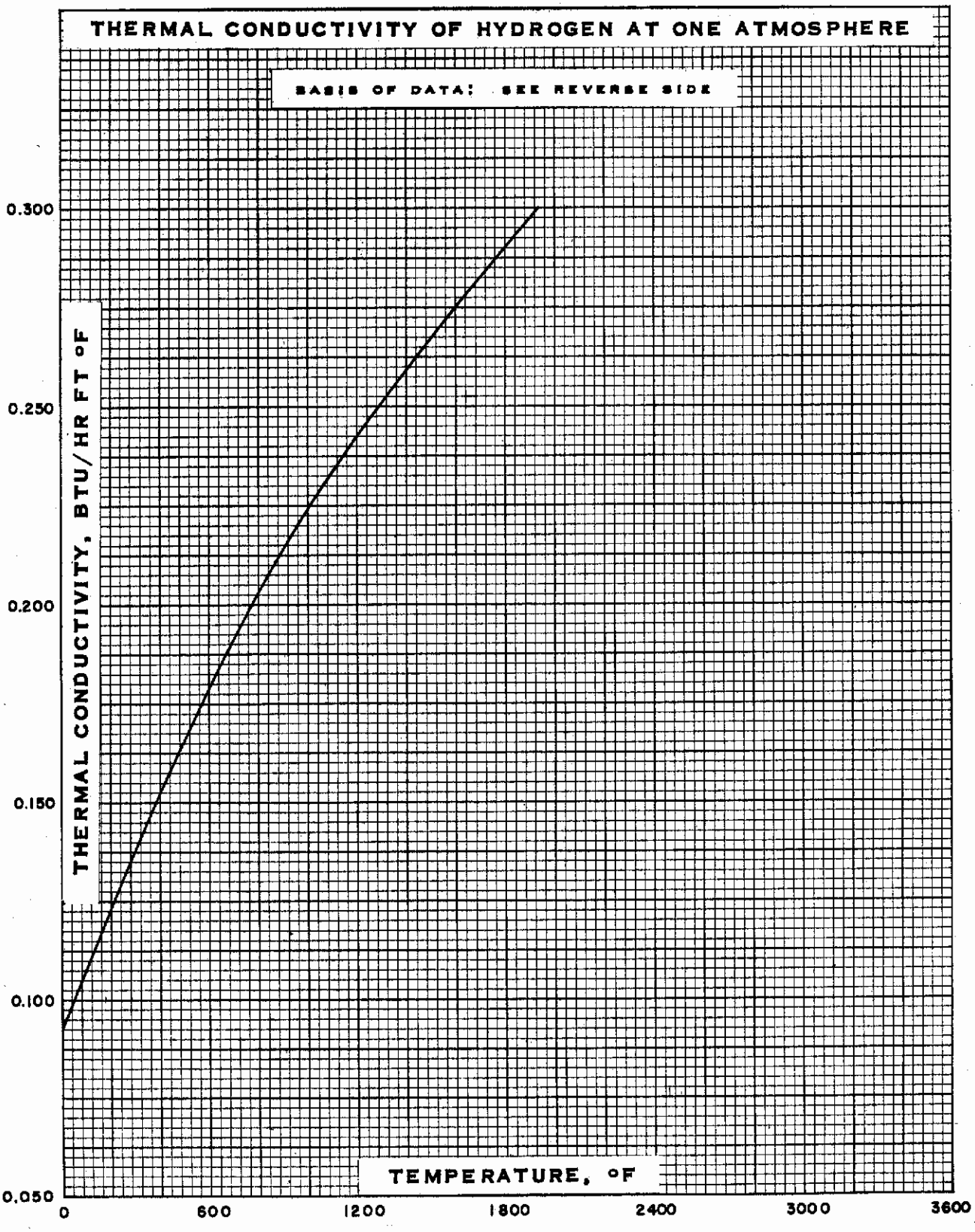
d. Working Charts for Hydrogen.

H_2-μ-a



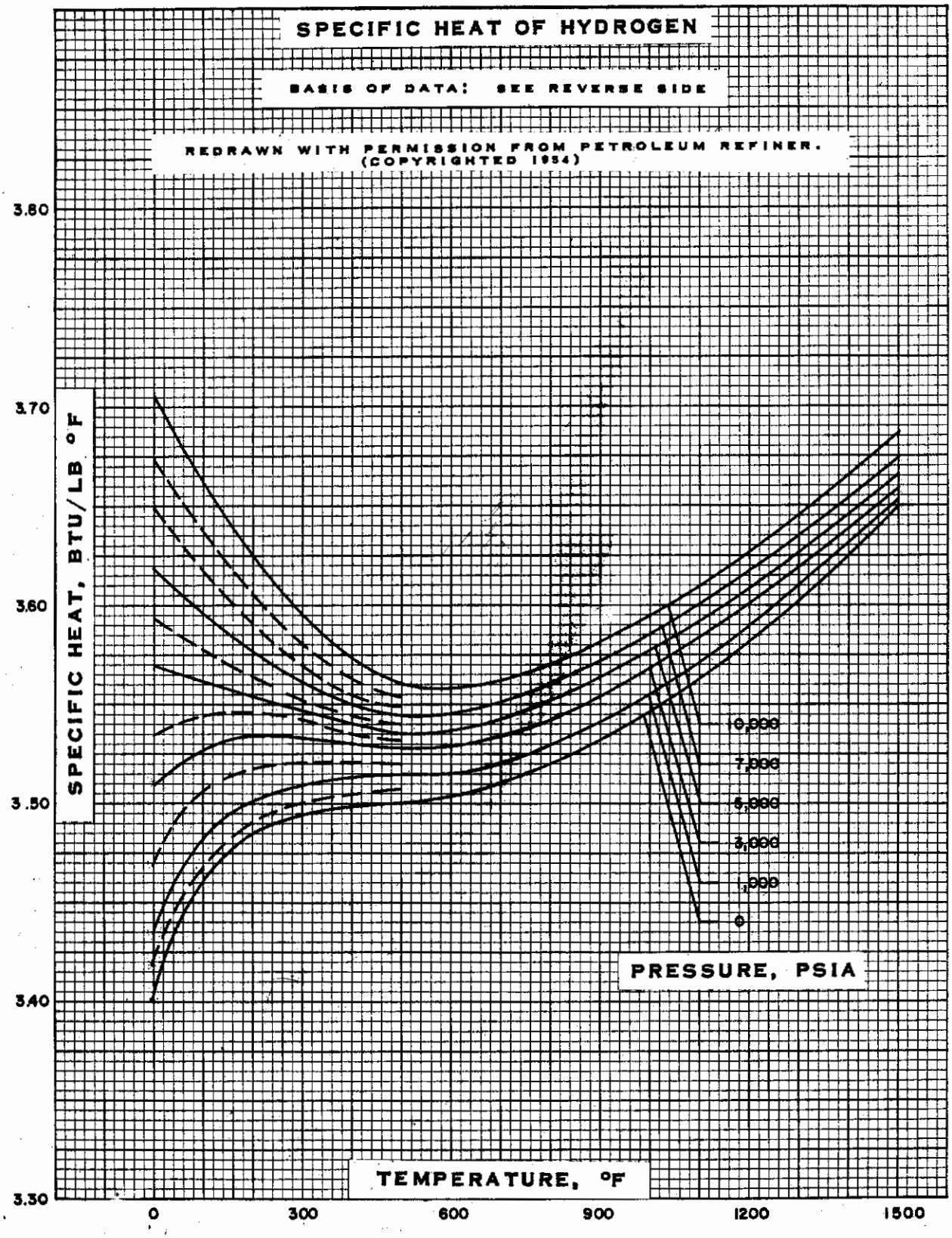
Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	5-4-9, 7-0-4, 8-2-5	0-1520	The viscosity was calculated from an empirical equation. The values are considered reliable to within 0.4% between 0 and 260° F. The calculated values are within 1% of experimental values as high as 1520° F.
Extrapolated	5-4-9	1520-1940	

H_2-k-a

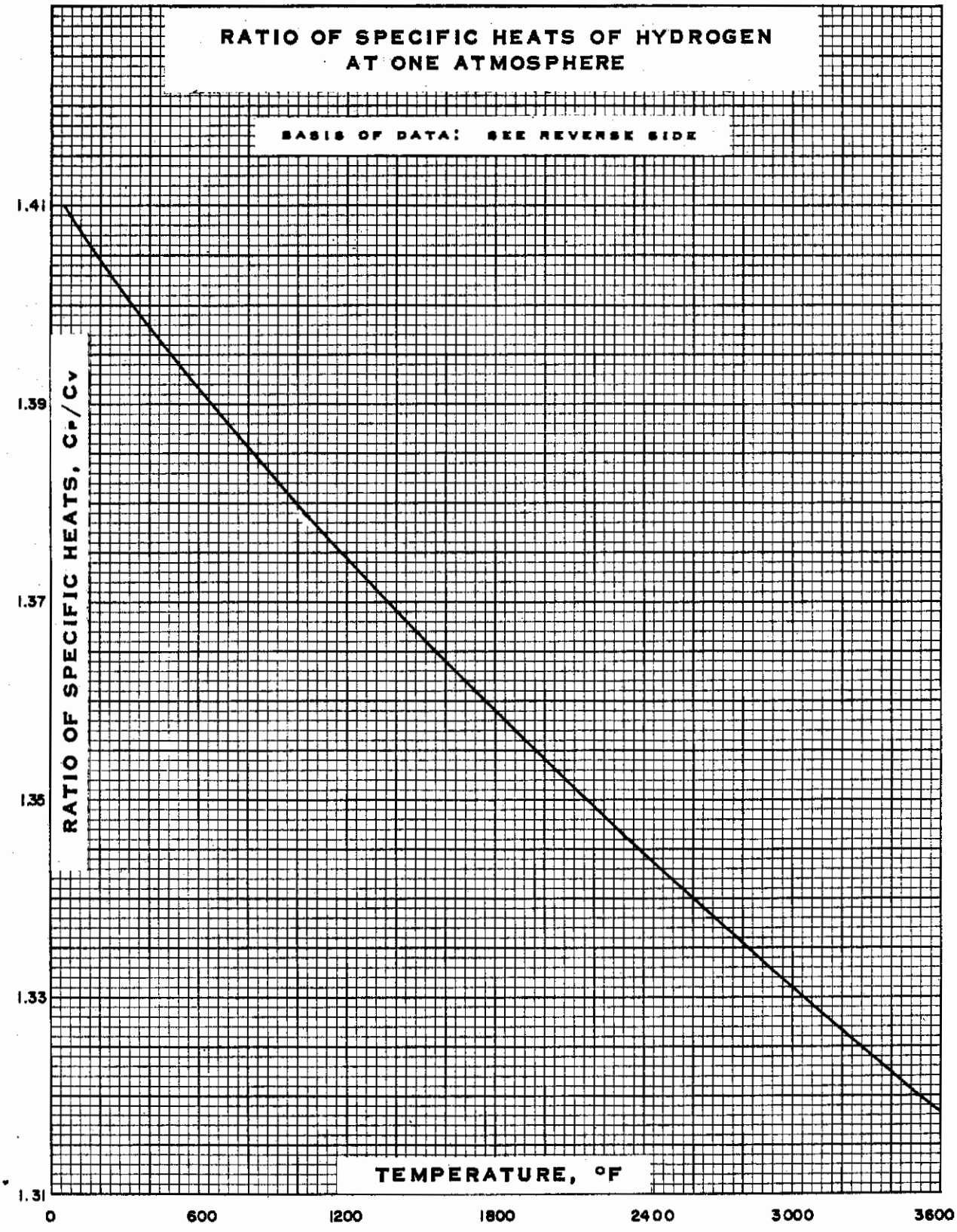


WADD TR 61-96

Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	5-4-9, 8-2-5, 12-0-3	0-1940	The values of thermal conductivity are the smoothed experimental data of all investigators.



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	7-0-4	0-1500	The specific heats of hydrogen are based on spectroscopic measurements and an accurately evaluated equation of state.



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Unknown	8-0-8	60-3600	

e. Data Sources for Hydrogen

Code No.	Source
5-4-9	Eckert, E.R.G., and Drake, R.M., Jr., "Heat and Mass Transfer," New York, McGraw-Hill Book Co., Inc., 1959.
7-0-4	Granet, I., Pet. Ref., 33, No. 5, 205-6 (May 1954).
8-0-8	Hodgman, C. D., Editor, "Handbook of Chemistry and Physics," Cleveland, Chemical Rubber Publishing Co., 1958.
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ARGON

a. General Discussion of Argon. Argon is a colorless gas referred to as a "rare gas," an "inert gas," or a "noble gas." It is a constituent of the atmosphere and is obtained by fractionation of liquid air. Argon does not combine with any other element. It has about the same solubility in water as oxygen and is best recognized by the characteristic lines in the red end of the spectrum.

Argon is available for $31.00 per 224 cu ft cylinder.

b. Synopsis of Properties of Argon.

Property	Value	Temp (°F)	Data Basis	Reference
Physical:				
Atomic Weight	39.44	---	Handbook	8-0-8
Melting Point, °F	-309	---	Handbook	8-0-8
Boiling Point, °F	-302	---	Handbook	8-0-8
Critical Point, psia	705	-188		11-12-3
Density, lb/ft^3	1.1135×10^{-1}	32	Handbook	8-0-8
	5.16×10^{-2}	600	Experimental and theoretical	8-2-5
	1.959×10^{-2}	2500	Experimental and theoretical	8-2-5
Viscosity, lb/ft hr	0.0915	600	Theoretical	Page A-μ-a
	0.1388	1500	Theoretical	Page A-μ-a
Thermal:				
Thermal Conductivity BTU/hr ft°F	0.01725	600	Experimental	Page A-k-a
	0.0261	1500	Experimental	Page A-k-a
Specific Heat	0.1494	600	Experimental and theoretical	8-2-5
BTU/lb °F	0.1243	1500	Experimental and theoretical	8-2-5
Ratio of Specific Heats	1.667	600	Experimental and theoretical	8-2-5
	1.667	1500	Experimental and theoretical	8-2-5
Electrical and Magnetic:				
Ionization Potential, volts	15.68	---	Handbook	8-0-8
Magnetic Susceptibility, fps electromagnetic units/unit mass	-0.1896	68	Handbook	8-0-8
Dielectric Constant	1.0005	32	Handbook	8-0-8
Thermal Neutron Cross Section (2200 m/s):				
Absorption, barns	0.62 ± 0.04	---	Handbook	8-0-8
Scattering, barns	1.5 ± 0.5	---	Handbook	8-0-8

c. Property Tables for Argon.

INFLUENCE OF PRESSURE ON SPECIFIC HEAT RATIO OF ARGON

(Ref: 8-2-5)

Temperature (°R)	Pressure		
	1 atm	10 atm	100 atm
468	1.671	1.709	2.17
540	1.670	1.697	1.96
720	1.668	1.682	1.80
900	1.668	1.676	1.753
1080	1.667	1.673	1.721
1260	1.667	1.671	1.704
1440	1.667	1.669	1.693
1620	1.667	1.669	1.686
1800	1.667	1.668	1.680
1980	1.667	1.668	1.678
2160	1.667	1.668	1.675
2340	1.667	1.667	1.673
2520	1.667	1.667	1.672
2700	1.667	1.667	1.671
2880	1.667	1.667	1.670
3060	1.667	1.667	1.668
3240	1.667	1.667	1.668
3420	1.667	1.667	1.668
3600	1.667	1.667	1.667
3780	1.667	1.667	1.667
3960	1.667	1.667	1.667

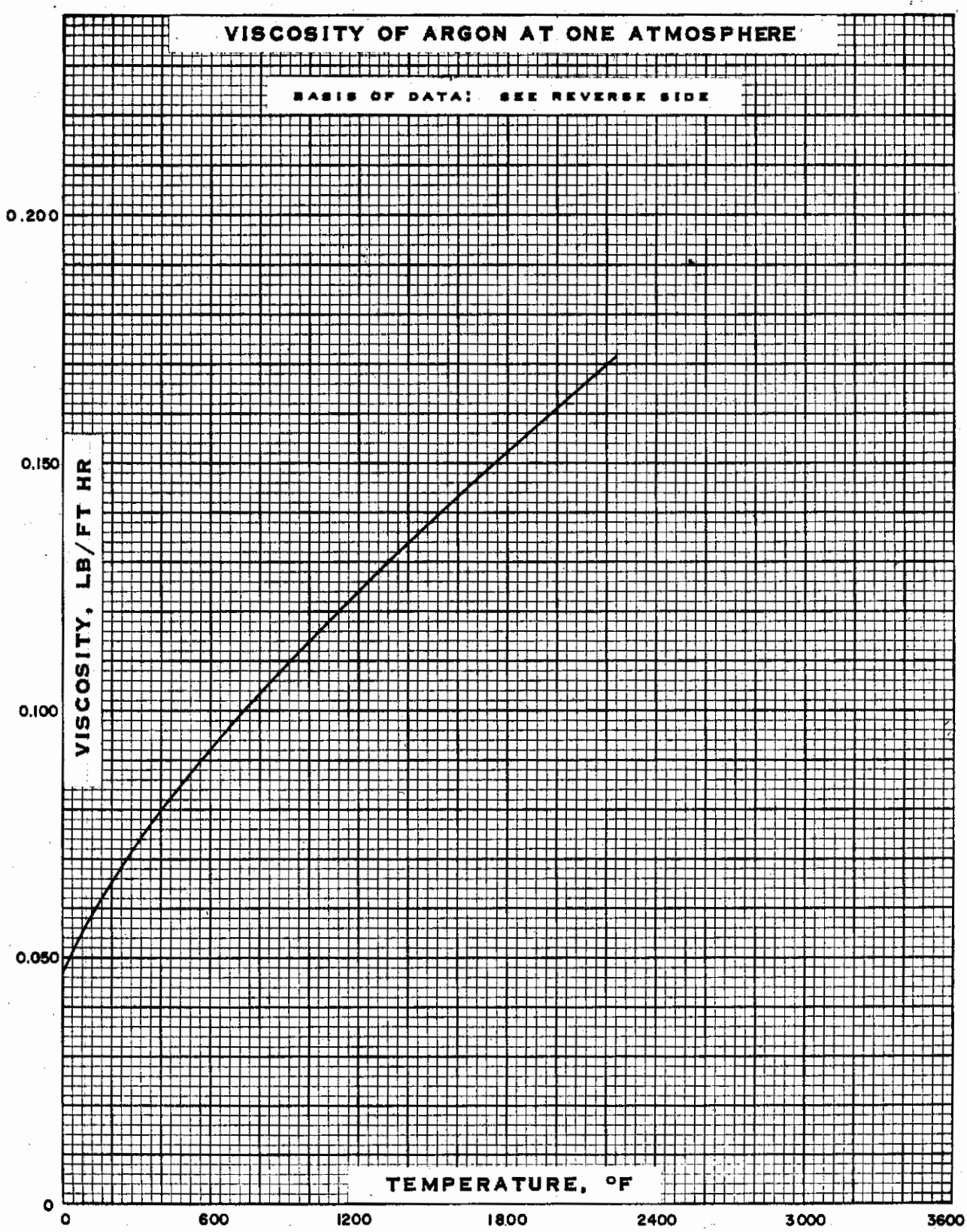
THERMODYNAMIC PROPERTIES OF ARGON

Ideal Monatomic Gas: $H^\circ_{536.67} - H^\circ_o = 2,666$ BTU/lb mole

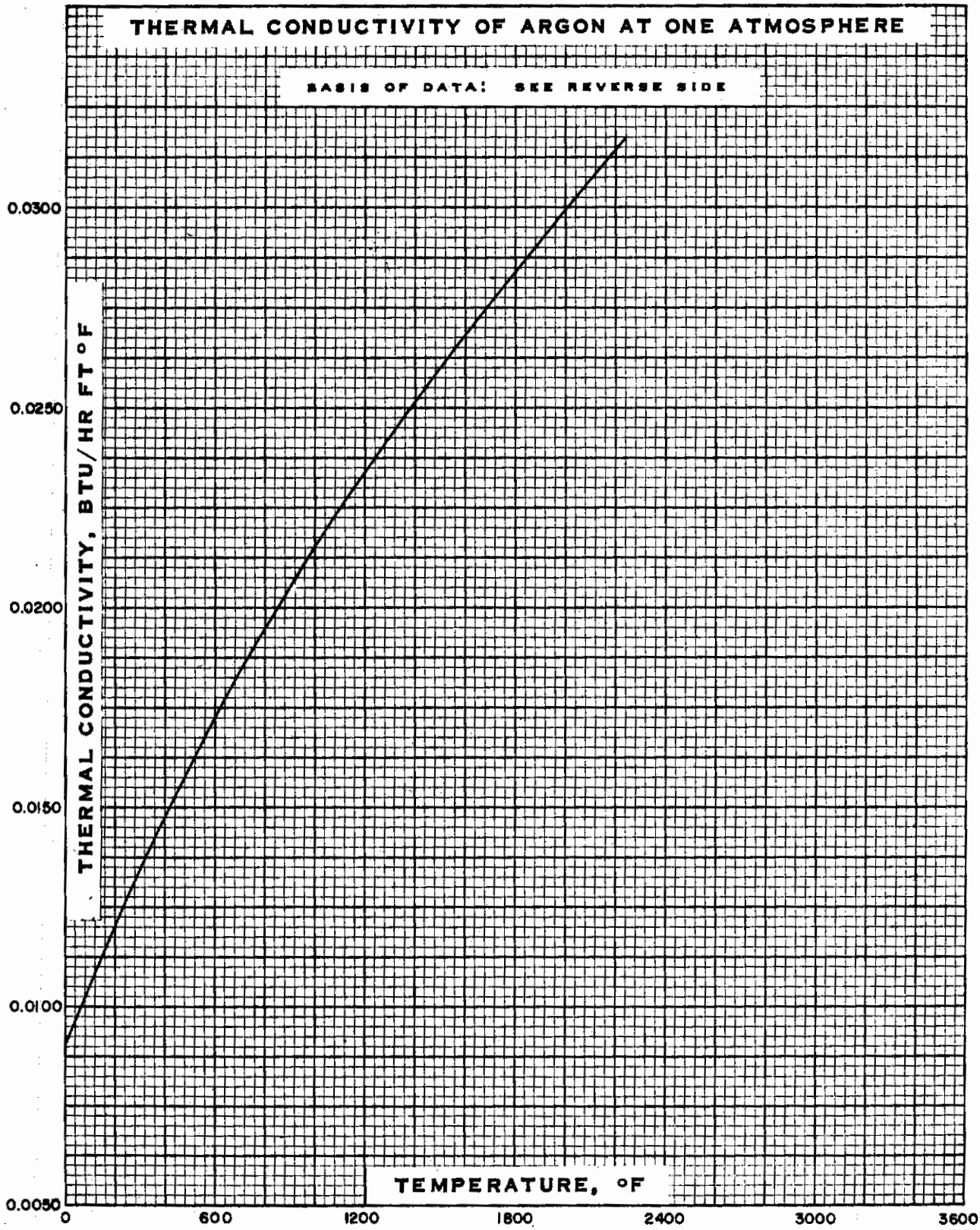
(Ref: 19-19-6)

Temperature T (°R)	Enthalpy $H^\circ - H^\circ_{536.67}$ (BTU/lb mole)	Entropy S° (BTU/lb mole °R)	Free Energy Function $-(F^\circ - H^\circ_{536.67})/T$ (BTU/lb mole °R)
537	0	36.98	36.98
540	16.2	37.01	36.98
720	910.8	38.44	37.18
900	1805	39.55	37.55
1080	2700	40.46	37.96
1260	3593	41.22	38.37
1440	4487	41.89	38.78
1620	5382	42.47	39.15
1800	6277	43.00	39.52
1980	7171	43.47	39.85
2160	8064	43.90	40.17
2340	8959	44.30	40.48
2520	9853	44,67	40.76
2700	10748	45.01	41.03
2880	11642	45.33	41.29
3060	12535	45.63	41.54
3240	13430	45.92	41.78
3420	14324	46.18	42.00
3600	15219	46.44	42.22
3780	16114	46.68	42.42
3960	17006	46.91	42.62

d. Working Charts for Argon.



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Theoretical	8-2-5	0-2240	The viscosity was computed on the basis of the Lennard-Jones intermolecular potential with the same force constants as were used for the thermodynamic properties. A graphical comparison of the plotted and experimental viscosities indicates that the plotted values are reliable to within 2% between 0 and 620° F and to within 3% between 620° F and 2240° F.



Basis of Data	Known References Consistent with Recommended Values	Temperature Range (°F)	Remarks
Experimental	8-2-5	0-2240	The thermal conductivities were computed from an empirical fit of the experimental data. The values are considered reliable to within 2 %.

e. Data Sources for Argon

Code No.	Source
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8-2-5	Hilsenrath, J., Beckett, C. W., Benedict, W. S., Fano, L., Hage, H. J., Masi, J. F., Nuttall, R. L., Touloukian, Y. S. and Woolley, H. W., N. B. S. Circular 564, November 1, 1955.
11-12-3	Kobe, Kenneth A. and Lynn, Emerson, Jr., Chem. Rev. 52, No. 1,117-236 (1953).
19-19-6	Stull, D. R. and Sinke, G. C., "Thermodynamic Properties of the Elements," Washington, American Chemical Society, 1956.

IV. CONCLUSIONS

The data presented in this report have been selected on the basis of apparent accuracy and self-consistency where feasible. The compilation should be able to serve as a frame of reference for pointing up inadequacies in available data and for establishing areas where additional research activities are required. Many data gaps still exist, but current research programs should soon provide important additional or corroborative experimental data on many of the fluids of interest. The known pertinent research activities in this country are summarized in the following table:

TABLE 6. SUMMARY OF CURRENT UNCLASSIFIED RESEARCH ON ENERGY-CONVERSION AND HEAT-TRANSFER FLUIDS FOR SPACE APPLICATIONS

Organization and Sponsor	Fluid, Temp., and Time	Construction and Test Material	Remarks
Aerojet-General Nucleonics: AEC, USAF	Rb; to 1800 hrs to 1800°F; 500 hrs	316 SS, Cb-1% ZR	Corrosion studies; capsules, forced-circulation, boiling loop. Thermodynamic properties measurements.
	Hg; to 1200°F	Haynes 25, Cb	Corrosion studies, capsules. Component testing.
AiResearch Manufacturing Co., USAF	K; to 2000°F, 1000 hrs	Mo-1/2% Ti, ceramics, W, K-94, WC-12% Co, Cb-1% Zr, Hastelloy X	Component tests. Corrosion studies: capsules, forced-circulation, boiling loop, liquid loop.
Argonne National Laboratory AEC	Na with 1-20 ppm O_2; to 1200°F; 500 hrs (to 1800 °F; to 5000 hrs)	304, 347 SS, Mo, Cb, W, V	Corrosion studies: capsules, loops. Two-phase heat transfer and fluid flow.
Atomics International; AEC	NaK-78; to 1500°F; to 3500 hrs	304, 316, 347SS, Hastelloys, Haynes 25, Inconel X, Mo, Cb, Rene 41	Corrosion studies: convection loops.

TABLE 6. SUMMARY OF CURRENT UNCLASSIFIED RESEARCH ON ENERGY-CONVERSION AND HEAT-TRANSFER FLUIDS FOR SPACE APPLICATIONS(Cont'd)

Organization and Sponsor	Fluid, Temp., and Time	Construction and Test Material	Remarks
Batelle Memorial Institute, AEC, NASA, USAF	Na		Purity studies.
	Na; to 1300° F	K-91, K-138A, Inconel X, Stellite 3, 347 SS, Mo, W	Friction studies.
	K; to 1900° F; to 1000 hrs	Mo-1/2 Ti in vapor (1000 hrs)	Creep-rupture
	K; to 2100° F	Cb-1% Zr	Thermophysical property measurements.
Brookhaven National Laboratory, AEC	Hg with Ti and Zr inhibitors; to 1400° F; 1000 hrs	C-steel (clad with Inconel or Hastelloy) and refractory metal alloys	Corrosion studies: quartz capsules, convection loops, forced-circulation loops, solubility studies.
	Na with and without inhibitors; to 2400° F	Cb-1% Zr and other refractory metal alloys	Corrosion studies: refluxing capsules, boiling loops, corrosion mechanisms, alloy development.
General Electric Company (FPLD), AEC, USAF	K, Na, to 2200° F	L-605, Cb-1% Zr, Haynes 25, F-48, Mo-1/2% Zr	Heat-transfer studies. Purity studies. Corrosion studies: thermal loops, aging, stress rupture, alloy development.

TABLE 6. SUMMARY OF CURRENT UNCLASSIFIED RESEARCH ON ENERGY-CONVERSION AND HEAT-TRANSFER FLUIDS FOR SPACE APPLICATIONS (Cont'd)

Organization and Sponsor	Fluid, Temp., and Time	Construction and Test Material	Remarks
MSA Research, AEC	Na; 1200°F; to 5000 hrs	316 SS, 2-1/4 Cr-1 Mo	Corrosion studies: purity effects, creep, stress rupture, fatigue, thermal shock.
NASA, Lewis Research Center, NASA	Na, K; to 2500°F; to 1000 hrs	Refractory metal alloys, Inconel	Corrosion studies: welding techniques, capsules, loops, fluid purification. P-T data measurements. Thermocouple drift studies.
Naval Research Laboratory, NASA	Na; to 2500°F	Cb-1% Zr	Corrosion studies. Fluid analysis studies. Thermocouple drift studies. Thermophysical property measurements.
North Carolina State College, USAF	Na; 1000°F	304-SS, Al-bronze	Bearing lubrication studies.
Nuclear Development Corp., US Army, ONR, AEC	Li; to 1600°F	Iron	Corrosion studies: basic solubility data.
	Li: to 2400°F	Ta	Heat-transfer studies.
	Na, NaK, Li		Film cooling studies.

TABLE 6. SUMMARY OF CURRENT UNCLASSIFIED RESEARCH ON ENERGY-CONVERSION AND HEAT-TRANSFER FLUIDS FOR SPACE APPLICATIONS (Cont'd)

Organization and Sponsor	Fluid, Temp., and Time	Construction and Test Material	Remarks
Nuclear Development Corp., US Army, ONR, AEC (Cont'd)	Na; 1400°F	Cb	Corrosion studies: capsules. Fluid analysis studies.
Oak Ridge National Laboratory AEC	K; to 2000°F; to 1000 hrs	Fe-, Ni-, Co-, and Cb-base alloys (1600°F) Haynes -25 alloy (1800°F) Cb-1% Zr(2000°F)	Corrosion studies: purification, purity effects, boiling loops, refluxing capsules.
Pratt & Whitney Aircraft, AEC, USAF	Li		Corrosion studies, pumped nonboiling loops: basic solubility data, effect of N_2 on solubility. Physical property measurements.
Rocketdyne Division (NAA), NASA	K; to 1800°F	321 SS, Haynes 25, Inconel, Mo	Corrosion studies: capsules, forced-circulation boiling loops.
	K; to 2200°F	W, Mo, Cb, Cb-1% Zr	Corrosion studies: tabs, forced-circulation boiling loops.
	Rb; to 2000°F	Refractory metals	Corrosion studies: capsules.

TABLE 6. SUMMARY OF CURRENT UNCLASSIFIED RESEARCH ON ENERGY-CONVERSION AND HEAT-TRANSFER FLUIDS FOR SPACE APPLICATIONS (Cont'd)

Organization and Sponsor	Fluid, Temp., and Time	Construction and Test Material	Remarks
Southwest Research Institute, USAF	Hg; to 1200°F	Loop: 446 SS; various specimen alloys	Corrosion studies: natural circulation boiling loop with turbulent-flow corrosion specimens of variable channel geometry.
	Inorganic fluids		Surveillance and dissemination of information on properties and characteristics of energy-conversion and heat-transfer fluids.
Sundstrand Aviation, USAF	Rb; to 1750°F	Inconel, refractory metal alloys	Corrosion studies: capsules, tabs.
	Hg, Rb, K, $AlBr_3$, S	316 SS	Bearing lubrication studies.
	$AlBr_3$		Power system development.
	LiH, NaF		Thermal energy storage; conceptual design study.
Thompson Ramo Wooldridge, Inc. AEC	Hg; to 1100°F	Pyrex, Ta, W, TiC, WC, Mo-1/2% Ti, carbon steels, 400 series SS, 300 series SS, Ni-alloys, Ti, Pt, Mn, Mg, Al, Zr, Haynes 25	Corrosion studies: refluxing capsules, tabs, convection loops.

TABLE 6. SUMMARY OF CURRENT UNCLASSIFIED RESEARCH ON ENERGY-CONVERSION AND HEAT-TRANSFER FLUIDS FOR SPACE APPLICATIONS (Cont'd)

Organization and Sponsor	Fluid, Temp. and Time	Construction and Test Material	Remarks
WADD Materials Central, USAF	Cs; to 2500° F; 30 days.	Zr, Hf, Cb, Mo, Ta, W, Inconel X, 310 SS, F-80	Corrosion studies: refluxing capsules.

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