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MATERIALS MANUAL

For Use With TRW Space Radiator-Condenser Design and Performance Analysis Computer Programs

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INTRODUCTION

The purpose of this manual is to provide a compact reference for the thermophysical properties required in the design of space radiator-condensers. This effort was performed as part of the Space Radiator-Condenser Design and Performance Computer Program under contract NAS 9-4884 with the NASA Manned Spacecraft Center. It is intended that this manual supplement these computer programs by providing, in one report, the fluid and construction materials properties required as inputs.

SUMMARY

Section 1.0 presents the results of a power system survey undertaken to assess the utilization of working fluids and materials on actual and proposed space electric power systems employing direct condenser-radiators.

Section 2.0 contains data on five working fluids. Their selection is based on a survey of their current use in actual direct condensing systems or contemplated future systems.

Section 3.0 contains the properties of candidate radiator materials. Materials other than those in current or proposed use have been included to extend the usefulness of the computer program as bonding and joining technology advances. Materials fabrication compatibility and working fluid compatibility are indicated to aid in the selection of suitable radiator-condenser materials for a given application.

Section 4.0 presents the emittance coatings which would be suitable for extended service in space-vacuum conditions. Solar and thermal absorptivity values are

included where available from the literature. Coating bonding compatibility with substrates, methods of application, and service temperature limitations are tabulated to aid in the proper coating selection for the intended application.

Section 5.0 presents some of the areas which, upon searching the literature, were found to be in need of further study.

1.0 POWER SYSTEM SURVEY

A survey of space electrical power systems employing direct condenser-radiators presently being investigated and those considered as primary or candidate systems for spacecraft applications is summarized in Table 1. Only those systems which have received serious developmental attention or extensive study were included. Since the only sources utilized in this survey were exoteric company and government reports, some systems may have inadvertently been overlooked. With these qualifications, the fluids selected are: mercury, potassium, water, rubidium and the organics, Dowtherm-A, ortho-xylene and ethylbenzene.

1.1 Mercury

During the last decade, mercury rose as the most prominent Rankine cycle working fluid for electrical generation space application. The SNAP 1 (SPUD), the thermal reactor powered SNAP 2 and SNAP 8, and the solar powered Sunflower accelerated mercury to the forefront as a space system working fluid. The cancellation of the intended mission spelled the end of the SNAP 1 (SPUD) system. The SNAP 2 system, originally space oriented, has been redirected to a study-type system test program due to lack of specific application. The SNAP 8 program suffered a similar fate, being relegated to a component development program as emphasis shifted from high to low output power generation systems. The highly successful solar powered Sunflower system has been bypassed for lack of a mission and waning interest in solar powered mercury systems. Regardless of these events, mercury still remains as one of the more prominent working fluids for Rankine cycle power plants with outputs ranging from 3 to 300 KW.

Radiator materials in direct mercury radiator-condensers varied depending on intended application. The SNAP 1 (SPUD) radiator was fabricated from 316 stainless steel throughout. Two types of SNAP 2 radiator-condensers were considered: Haynes Alloy No. 25 tubing and aluminum fins and 17.7 molybdenum tubes and copper fins. The Sunflower system used a radiator-condenser composed of 347 stainless steel tubes and 1100-0 (non-structural) aluminum fins. One of the SNAP 8 direct radiator-condenser designs utilized Haynes Alloy No. 25 tubing and aluminum fins.

1.2 Potassium

Potassium found application as a working fluid in the SPUR/SNAP 50 system which has also been reduced to component development. The use of potassium is still very attractive for future space applications pending fast reactor revival and the availability of container materials suitable for 10,000 hours or more service at the higher temperatures seen in these systems. In 1965, TRW prepared a potassium Rankine cycle test capsule to evaluate the boiling and condensing properties of potassium in space. A failure of the boost vehicle during launch led to an abrupt conclusion to the experiment. Another test capsule is being built to repeat the experiment, indicating a continuing interest in potassium as a cycle working fluid.

The radiator materials proposed for the SPUR/SNAP 50 direct condenser were 316 stainless steel tubing and 316 stainless steel clad copper fins. The TRW heat transfer test capsule radiator-condenser utilized 316 stainless steel tubing with copper fins brazed to the tubing (88).

1.3 Water

A steam system was investigated utilizing the SNAP 8 reactor by ASTRA, Inc. (73). The proposed systems utilized nuclear and solar heat sources. Radiator-condensers were initially considered to be aluminum (tube and fins) with beryllium as the ultimate material. TRW and other companies have sponsored internally funded studies in this area.

1.4 Rubidium

The initial working fluid of the ASTEC program (Advanced Solar Turbo Electric Concept) was rubidium. The program was redirected before reaching the system stage.

A radiator-condenser test segment (tubes and fins) was fabricated from Inconel. Beryllium tubes and fins would have been the ultimate radiator-condenser materials. Rubidium is not considered to be a likely working fluid for the space applications presently under investigation.

1.5 Organics

Interest in organic fluids for space power applications has developed rapidly in the last five years. Sundstrand (74) is currently involved in a development program for the Navy and Air Force for a 1.5 KW solar power plant using Dowtherm-A. No details are available as to the materials being considered. TRW has concluded that Dowtherm-A is the most favorable working fluid for an isotope-heated system as a part of the Manned Mars Mission Study (75). TRW has recently been awarded a contract to build a system for a Multi-tube Orbital Rankine Experiment (77) using Dowtherm-A as the working fluid. Tubes and headers for this system will be 347 stainless steel. Fins will be 5083 aluminum. Various Binary systems proposed included ortho-xylene or ethylbenzene as the bottom cycle fluid. Aluminum tubes and fins were proposed in most cases.

A comparison of various organic working fluids and their properties is shown in Table 2. From this chart, ethylbenzene, ortho-xylene and Dowtherm-A were chosen as the most promising for space systems, based on favorable combinations of their vapor pressure/temperature relationships, freezing point, corrosive nature, and thermal stability.

2.0 THERMO-PHYSICAL PROPERTIES OF WORKING FLUIDS

The thermo-physical properties of eight primary and candidate working fluids have been prepared as a function of temperature. These include water, mercury, rubidium, potassium and three organics (ortho-xylene, ethylbenzene and Dowtherm-A). The working fluids, their respective properties and a reference figure number for each property are summarized in Table 3.

The properties compiled for each working fluid are those necessary as inputs to the computer programs and are as follows: molecular weight, heat of vaporization, specific heat, specific heat ratio, density, absolute viscosity, liquid-vapor surface tension, thermal conductivity and vapor pressure. These appear on Figures 1 through 49. Single valued quantities are given for molecular weight, freezing point, critical temperature, critical pressure, specific heat ratio and, in some cases, specific heat. All data is presented in the units required by the design and performance analysis radiator computer programs.

In most instances, the information is the result of the latest test data available in the literature, but in some cases, most notably rubidium, the curves represent calculated values since no test data could be found.

3.0 CONSTRUCTION MATERIALS PROPERTIES

3.1 Tube, Header and Fin Thermo-Physical Properties

Seven properties were selected and tabulated for each of the candidate radiator materials. These properties include density, tension moudules of elasticity, thermal conductivity, specific heat, thermal expansion, yield strength (.2%), and melting temperature. Only the density, tension modulus of elasticity and thermal conductivity are required as inputs to the computer program, but thermal expansion was included to assess fin/tube compatibility, yield strength and melting temperature to establish service limits, and specific heat to facilitate transient study. A cross-reference between each candidate material and the respective property curves is given in Table 4 including figure number and the reference numbers. Where important and available, the information is presented as a function of temperature in the referenced figures. Otherwise, a single value is contained directly in Table 4. Materials properties as a function of temperature are found on Figures 50 through 58. All data is presented in the units required by the design and performance analysis radiator computer programs.

Some of the properties listed vary widely depending on the form of the material, i.e., sheet or bar, heat-treated or unheat-treated, etc. This is especially true of the yield strength. In each case, the form most representative of that usable in condenser-radiators was listed or, in some cases, a range if more than one form is applicable.

3.2 Materials Compatibility with Working Fluids

A literature search was conducted to obtain materials/working fluid compatibility information. The working fluids considered were those found to be candidate fluids for space systems as a result of the system survey (section 1.0), namely, mercury, water, rubidium, potassium and selected organics. The materials considered included, but were not limited to, those candidate materials of section 2.0. Tables 5(a) and 5(b) are a summary of the information.

The temperatures on this table represent (a) the test temperature at which little or no corrosion (loss or gain in weight) was detected, (b) acceptable corrosion temperature limit extrapolated from test data at lower temperatures, or (c) temperature limits based on tests of similar fluids. In each case, the test duration is less than 1000 hours, more than 10,000 hours, or in some cases as noted. Where no data is presented either (1) none could be found, (2) the normal condenser operating temperature for that fluid is higher than the service temperature of the material or (3) the combination of fluid and container material is illogical.

3.2.1 Water

The temperatures given in Tables 5(a) and 5(b) are based on the results of both static and dynamic tests.

The static corrosion rates were determined as a byproduct of autoclave tests conducted at temperatures below 500°F. The tests were performed for such purposes as crevice corrosion and bearing combination studies in connection with water-cooled reactor systems.

Dynamic testing was carried out at temperatures between 500 and 600°F which is the normal operating range of water-cooled reactors. Velocities ranged from 1/60 to 30 fps. The dynamic corrosion rates of materials studies at 500°F is increased between 5 and 20 times when tested at 600°F (17).

The effects of water velocity on the corrosion rate of 300 series stainless steel are delineated in reference (19). A weight loss of 10 mg/cm^2 at 10 ft/sec solution velocity was established after 400 test hours. The rate increased 3 to 15 times that amount as velocities were tripled and quadrupled for the same number of hours tested.

Studies (18) on high purity water corrosion indicated that the use of water with a pH above 10 caused the corrosion rate of mild steel to decrease with exposure time. The corrosion of aluminum and its alloys above 200°F took the form of serious intergranular attack. Decreasing the pH to 2 could extend the operating temperature range to about 600°F (19). However, regulation of pH to 2 (acidic condition) may not be feasible in fuel cell radiators using hydrogen and H_2O mixtures.

Aluminum alloys containing nickel, iron, titanium, silicon, beryllium and zirconium tend to displace the cathodic reaction from the aluminum surface and make the alloys less sensitive to corrosion. The addition of hydrogen to the water was also found to be beneficial.

A considerable increase of corrosion in flowing as against static water was noted by researchers (19) and increasing the ratio of area of aluminum exposed to volume of water was found to reduce dynamic corrosion.

Beryllium and its alloys showed good resistance to corrosion below 200°F (about one mil penetration per year). Above this temperature the corrosion rate increased rapidly and became more unpredictable (19).

Magnesium alloys had high corrosion rates (0.1 mil/day) at 300°F (19). Their use should be restricted below 150°F for long duration operation.

Dynamic corrosion studies on copper-nickel (70-30) indicated that low corrosion rates could be maintained at 200°F with 30 fps water velocity. At 500°F the same rate could be maintained by the addition of hydrogen into the water. Corrosion rates at 500°F and 30 fps without the presence of hydrogen increase about 200 times compared to the 200°F rate of 34 mg/in^2-yr. The water pH was maintained at 7 throughout the tests (17). The corrosion rate of copper tubing increases rapidly with increasing water velocity and temperature. No water corrosion data was immediately available on the refractory metals.

3.2.2 Mercury

The temperatures indicated in Tables 5(a) and 5(b) are a result of extensive mercury materials compatibility work done at TRW (30,31,32). Refluxing capsules and circulation loops operating between 700 and 1100°F provided the basis for most corrosion temperature limitations. These tests were corroborated to 1300°F on selected materials by NASA-Lewis. Studies at Brookhaven National Laboratory have provided endurance testing data for boiling systems in the SNAP 8 temperature range and higher (86).

3.2.3 Rubidium

Materials compatibility data with rubidium include beryllium, cobalt alloys, nickel alloys, some refractories, stainless steels and vanadium. Testing duration has been in the 1000 hour range. The temperature range investigated is a direct result of the normal condensing temperature range associated with rubidium cycles (1000-1500°F). Compatibility studies have generally been aimed at screening only those materials that can structurally withstand the temperature range. Refluxing liquid vapor capsules and some dynamic loop testing provided the bulk of information available in the literature.

3.2.4 Potassium

Refluxing capsules and dynamic loop tests of 1000 hours or less dominate the current investigations and provide the basis for the corrosion temperature limits shown in Table 5. Dynamic 5000 hours 316 stainless steel loop tests with low velocity potassium at 4 in/sec indicated corrosion rates of about 0.12 mils per year (14).

3.2.5 Hydrocarbons

3.2.5.1 Dowtherm-A

Corrosion data for Dowtherm is limited. The fluid is not corrosive and does not scale with standard materials of construction. The materials containing temperatures in Table 5 are considered to be standard. The refractory metals show no compatibility temperatures but probably are compatible to the operating limits of Dowtherm-A.

When contaminated with water, Dowtherm reacts to form highly corrosive hydrocholoric acid. In this respect, where contamination with water is possible, materials subject to corrosion by the acid should be used with caution.

3.2.5.2 Ortho-xylene and Ethylbenzene

Over 1000 hours of testing indicated that 300 series stainless steel was not attacked when suspended in liquid ortho-xylene at 550°F. Low temperature tests at 180°F on 347 stainless steel, 406 stainless steel, 1010 carbon steel, pure aluminum, aluminum alloys, Inconel, Vanadium alloy (T_1 - 6Al - 4V) and Haynes 25 showed no evidence of attack (24). Capsule tests of 304 stainless steel and 1010 carbon steel at about 700°F for almost 1000 hours indicated no effects on either material (25). The remainder of the corrosion data listed for ortho-xylene and ethylbenzene are actually for biphenyl and isoproplybiphenyl. This substitution was made because of the similarity in their corrosion characteristics and the availability of data.

Extensive static corrosion tests (26) were made with biphenyl at 500°F for 4500 hours and 750°F for 4700 hours. Most of the general material categories listed on Tables 5(a) and 5(b) were covered by the tests. Dynamic corrosion rates were available for isoproplybiphenyl at velocities from 0 to 27 fps. Corrosion rates increased by a factor of 20 at 27 fps over static corrosion rates for 300 series stainless.

3.3 Tube and Header Material Meteoroid Protection Capability

Meteoroid collision represents the greatest potential hazard to fluid radiators in space. Data from unmanned earth orbiting satellites has reinforced early theories used to predict armor thickness requirements. Correlations are presently based on material properties (modules of elasticity, hardness and density) as well as some evaluation of meteoroid flux. The correlation currently advocated by NASA-Lewis utilizes the modulus of elasticity and density of the armor.

This approach is used by TRW to determine the meteoroid armor thickness in the radiator design programs.

The following expression is a form of that resulting from the work by Loeffler, Lieblein, Clough of NASA-Lewis and Whipple, Cook and others at Harvard (84):

$$t_a = 3.31 \left[\frac{A \ \tau}{- \ln P(o)} \right]^{.25} (\rho \ E^2)^{-\frac{1}{6}}$$

where t_a = armor thickness, inches

A = vulnerable area, ft^2 (taken as the inside tube area)

$P(o)$ = probability of no meteoroid penetrations

ρ = armor density, lb/in.

E = modulus of elasticity of armor, psi

τ = mission time, days

The properties of density (ρ) and modulus of elasticity (E) for all radiator materials are referenced in Table 4. Armor weight is proportional to the term $\rho^{5/6} E^{-1/3}$.

Recent hypervelocity impact investigations of advanced armor and/or fin materials such as beryllium and pyrolytic graphite have indicated that these materials exhibit brittle characteristics which make them unsuitable as space radiator structural members (115). In this respect, the present approach advanced by NASA to determine meteoroid armor should be used with restraint. The theory will have to be modified to account for the very brittle radiator materials which offer very attractive, but possibly erroneous, weight advantages over more conventional materials such as aluminum and steel under the present method of armor determination.

3.4 Compatibility of Radiator Fin Materials to Tube Materials

Table 6 lists combinations of possible space radiator tube and fin materials. These have been compared from the standpoint of bonding and joining techniques, thermal expansion limitations and susceptibility to galvanic corrosion. The fin tube material combinations marked with a dash (-) indicate that the combination is either not applicable, not feasible, or no information is available on the union.

3.4.1 Bonding and Joining Techniques

The method(s) by which fin materials can be fastened to tube materials is highly dependent on the types of material involved and the radiator operating temperature. A detailed discussion of each possible method is beyond the scope of this manual. However, the major techniques are delineated below.

1. Welding
   a) heliarc
   b) arc
   c) electron beam
2. Brazing
   a) torch
   b) furnace
3. Mechanical
   a) casting
   b) clamping and crimping (interference joints)
   c) pressure lamination

d) extrusions

4. Chemical

Another important aspect of joining dissimilar fin-tube materials is the consideration of thermal resistance (82, 83). This is especially important when mechanical techniques have been employed. The presence of a gap between a tube wall and a fin converts the mechanism of heat transmission from highly efficient conduction to radiation. An increase in this thermal resistance from tube wall to fin increases the condensing temperature.

3.4.2 Thermal Expansion Limitations

Large differences in thermal expansion coefficients between tube and fin radiator materials subjected to large temperature variations require special attention. The use of these combinations is normally not recommended from a practical or an economic standpoint. If a requirement for such combinations exists, the bond can be made by building up layers of different thermal expansion materials, maintaining the difference in thermal expansion coefficients small between adjacent layers. Thermal expansion coefficients for various radiator material as a function of temperature are compared in Figures 57 and 58.

3.4.3 Galvanic Corrosion

Direct contact between dissimilar metals such as copper and aluminum or aluminum and steel are susceptible to galvanic corrosion (35). Salt water is considered to be one of these environments. Excessive exposure (usually during ground testing) of radiators of these types without adequate protection should be avoided. Galvanic corrosion normally takes the form of severe pitting.

4.0 RADIATOR COATINGS

Radiator coatings provide protection for the substrate metal from vacuum conditions of space as well as providing control of the thermal radiative and absorptive properties of the surface. An effective radiator coating must have a high infra-red or thermal emittance and, in the case of a low temperature radiator, low solar absorptance. Coatings meeting these requirements have been developed and, in many cases, extensively tested under simulated vacuum conditions of space.

A literature survey was conducted to determine the most effective coatings, their applicable temperature range, the methods of application, the substrates applicable, and the testing duration. The results of this survey are shown in Tables 7(a) through 7(g).

4.1 Emittance

The tabulation of total hemispherical emittance values in Tables 7(a) through 7(g) includes only those coatings or surfaces with values greater than .7 as determined at test temperatures above 300°F for a minimum of 20 hours in a simulated space environment.

The results of extensive emittance coating studies by Pratt and Whitney Aircraft (54) are reproduced in Figure 59. (Total Hemispherical Emittance versus Temperature.) Only those coatings possessing high emittances and good high temperature stability under vacuum conditions are shown. In the above testing program, temperatures were measured on the metal substrates. This eliminated the need for temperature drop and opaqueness corrections and allows direct use of the emittances in radiator design.

4.2 Absorptivity

There are two types of thermal radiation in space. The first is solar, either direct or reflected from planets (albedo), with a wave length of 0.2 to 3.0 microns. The second is infra-red or thermal being emitted from planets and other astronomical bodies with a wave length of 5 to 50 microns. Due to this wave length difference, almost all surfaces have difference absorptances to the two types of radiation.

Thermal absorptance is taken as being equal to thermal emittance and is usually high as a result of a desire for a high thermal emittance. Solar absorptance, on the other hand, is somewhat independent of thermal emittance and a balance between high thermal emittance and low solar absorptance can be obtained and is desirable, especially for a low temperature radiator. The importance of the solar absorptivity is a function of the temperature level of the radiator and the intensity of the incident solar energy. Solar absorptivity values have been determined in the laboratory for various structural materials and coatings. These have been included as part of Tables 7(a) through 7(g).

4.3 Comparison Parameter (α_S / ϵ_H)

The ratio of solar absorptivity to total hemispherical emittance (α_S / ϵ_H) is an important parameter for comparing the performance characteristics of various radiator materials. The ideal radiator surface would have an $\alpha_S / \epsilon_H = 0$. Since the ideal is unattainable in reality, materials with α_S / ϵ_H ratios less than .3 are considered acceptable (66). Values for (α_S / ϵ_H) are shown in

Tables 7(a) through 7(g) for some coatings and surfaces.

4.4 Coating Thickness

Thickness plays an important role in determining the emissivity and solar absorptivity characteristics of a coating. Studies made with high emissivity, low absorptivity inorganic paints (66) indicated that about 3 to 5 mils coating thickness was required to cover metallic surfaces. The study also found that solar absorptivity (α_S) and the solar absorptivity-emittance ratio (α_S/ϵ_H) reached a minimum value with a 5 mil or greater coating thickness (Figure 60). Multiple coats of 1 to 2 mils built up to 5 mils gave indications of having superior bonding properties than a single 5 mil coat.

4.5 Coatings and Substrates

4.5.1 Coatings

Coatings are classified as single oxides, multiple oxides, non-oxides, stably oxided alloys and paints. The high emittance members of each group are shown as part of Tables 7(a) through 7(g).

4.5.1.1 Single Oxides

The single oxides coatings screened by P.W.A. (54) are listed below. Total hemispherical emittance values are shown for temperatures ranging from 300°F minimum to 2200°F maximum.

Single Oxides		Total Hemispherical Emittance
1. Aluminum Oxide	(Al_2O_3)	.69 - .63
2. Ceric Oxide		.75 - .65
3. Chromic Oxide	($Cr2O_3$)	.71 - .84

4.	Cobalt Oxide	(C_oO)	.88 - .90
5.	Manganese Oxide	(M_n2O_3)	.75 - .85
6.	Nickel Oxide	(N_iO)	.45 - .82
7.	Silicon Dioxide	(S_iO_2)	.87 - .70
8.	Stannic Oxide	(S_nO_2)	.92 - .85
9.	Titania	($T_{i2}O_3$)	.77 - .82
10.	"Titania Base" Powder		.83 - .88
11.	Zirconium Oxide	(Z_rO_2)	.88 - .86

4.5.1.2 Multiple Oxides

The multiple oxide coatings screened by P.W.A. (54) are listed below. Total hemispherical emittance values are shown for temperatures ranging from 300°F minimum to 2200°F maximum.

	Multiple Oxides	Total Hemispherical Emittance
1.	Silicates - Zirconium Silicate	.83 - .51
2.	Spinels	
	a) Magnesium Aluminate (M_gO - Al_2O_3)	.80 - .60
	b) 40% Nickel Chrome Spinel 60% Silicon Dioxide	.88 - .82
3.	Titanates	
	a) Barium Titanate ($B_aT_iO_3$)	.75 - .64
	b) Calcium Titanate (C_aO T_i O_2)	.81 - .92
	c) Iron - Titanium Oxide	.85 - .87
	d) Iron - Titanium-Aluminum Oxide	.83 - .88
4.	Zirconates - Calcium Zirconate	.62 - .56

Minimum and maximum values of total hemispherical emittance are indicated for all substrates tested regardless of substrate or coating thickness.

4.5.1.3 Non-Oxides

The non-oxide coatings screened by P.W.A. (54) are listed below. Total hemispherical emittance values are shown below for temperatures ranging from 300°F minimum to 2200°F maximum.

Non-Oxides	Total Hemispherical Emittance
1. Borides	
a) Crystalline Boron	.70 - .88
b) Boron and Silica	.78 - .79
c) Molybdenum Diboride	.42 - .64
d) Tantalum Boride	.49 - .59
e) Zirconium Boride	.43 - .60
2. Carbides	
a) Acetylene Black in Xylol	.72 - .92
b) Boron Carbide	.76 - .80
c) Graphite Varnish	.56 - .62
d) Hafnium Carbide	.52 - .62
e) Molybdenum Carbide	.42 - .49
f) Silicon Carbide	.80 - .92
g) Silicon Carbide and Silicon Dioxide	.85 - .87
h) Tantalum Carbide	.44 - .59
i) Titanium Carbide	.42 - .62
j) Vanadium Carbide	.48 - .60

3. Fluorides - Calcium Fluoride .68 - .47

4. Nitrides - Boron Nitride in Synar .82 - .69

4.5.1.4 Stably Oxided Metals and Alloys

Some oxidized metals and their alloys exhibit total hemispherical emittance values above .7. Unfortunately, their solar absorptivity values are in the same range making an oxided metal surface unfavorable for use in low temperature radiator-condensers.

In high temperature (above 1200°F) radiator-condenser applications (systems condensing potassium or rubidium vapor), the effects of higher solar absorptivities are not as pronounced and the use of oxided metal surfaces may be warranted.

Oxided metal surfaces require heating to high temperatures to accomplish the oxidation process. Typical oxidizing temperatures required for stainless steels are 1800°F with similar levels for Inconel, Inconel X and Haynes Alloy 25.

The stably oxided metals surfaces screened by P.W.A. (54) are listed below. Total hemispherical emittance values are shown for 300°F and 2200°F.

Metallic and Oxidized Metallic Surfaces	Total Hemispherical Emittance
1. Columbium and Oxidized Columbium	.26 - .69
2. Columbium - 1% Zirconium Alloy	.11 - .30
3. Cupric Oxide	.86 - .46
4. Molybdenum	.28 - .34
5. Oxidized Nichrome	.73 - .82

6.	Lithiated and Oxidized Nickel	.63 - .86
7.	Oxidized AISI-310 Stainless Steel	.47 - .84
8.	Tantalum	-- --
9.	Tungsten	.03 - .17
10.	Chromium Black	.72 - .88
11.	Platinum Black	.41 - .74

4.5.1.5 Paints

Organic Enamels

High emittance organic enamels are attractive from the standpoint that they are easily applied and can be applied to any substrate.

Organic enamels were found to be unfit for long duration space applications since most of the coatings exhibit appreciable vapor pressures in a vacuum at room temperature (68). The effect is even more pronounced at elevated temperatures. The lowest temperatures expected would be about 200°F in the indirect fuel cell radiator.

At best, organic paints may be used where short duration thermal control applications (weeks-months) are required below 575°F. Typical paints, their emittance and absorptivities are shown in Table 7(f) and 7(g).

Water Glass Enamels

Silicate base paints are also known as water glass enamels. Extensive testing of inorganic coatings indicates that alkali-metal silicates, pigmented with refractory silicate materials, were found to possess low absorptivity-emissivity ratios and high emissivities (66). These coatings have the advantage of application by standard spray, dip or brush techniques. Stabilization of the coating can be accomplished by low temperature curing cycles between 200 to 400°F. The coatings are flexible and ductile, have excellent thermal stability characteristics under 950°F and are resistant to thermal shocks. These coatings have been applied on aluminum and magnesium based substrates which makes them excellent candidates for low temperature water or organic radiator-condensers. Typical radiative properties of inorganic coatings are included in Tables 7(a) through 7(d).

4.5.2 Substrate Materials

High temperature coatings (above 1200°F) have been successfully bonded to a wide range of substrates. These include aluminum (1010, 6061) 310 stainless steel, columbium-1% zirconium, nickel, columbium and molybdenum. Substrate materials such as beryllium and copper can accept some coatings applicable to 310 stainless steel (49) due to the similarity in expansion coefficients.

Where large differences in thermal expansion coefficients exist between substrate and desired coating, the difference can be reduced by multiple layering of several coatings.

Low temperature organic and silicone coatings (below 1000°F) can be bonded to most materials with adequate surface preparation. Magnesium and aluminum substrates can be coated with inorganic pigmented, alkali metal silicate vehicle coatings.

4.6 Application Methods

4.6.1 Thermal Spraying

High emittance coatings may be applied to radiator surfaces by the plasma-arc and the Rokide thermal spraying processes.

The plasma-arc spraying process uses an electric arc to heat and ionize a vehicle gas. The ionized gas is then combined with a second gas carrying the coating material in powder form. The coating material powder is melted or softened by the union and the combination impinges on the radiator surface. Inert gases (argon, nitrogen) are generally used in the plasma-arc spraying process.

The major advantage of the plasma-arc spraying technique is the ability to protect the coated material from an oxidizing atmosphere. The substrate material can be maintained below $400^{\circ}F$ while controlling coating thickness, finish and density.

The Rokide spraying process uses an ignited mixture of combustible gases and a solid rod of coating material. The coating material rod vaporizes as it is fed into the flame and is carried by the gas stream to the surface to be coated. This process yields a more porous coating than the plasma-arc process because of the lower gas velocities and temperatures used.

Plasma-arc and Rokide techniques are applicable to stainless steels, aluminum alloys, refractory metals and their alloys, beryllium, copper alloys and cobalt alloys.

The Rokide process requires the use of a coating rod material that matches the thermal expansion characteristics of the substrate material for high temperature applications.

4.6.2 Slurries

Coating material may be applied in slurry form.

A slurry is a finely divided coating material suspended in a liquid binder. It may be applied to the radiator surface by spraying, brushing or dipping. The coating is air- and oven-dried to remove volatile liquid. The slurry technique finds application where substrate materials cannot withstand the extreme temperatures of thermal spraying. The more promising slurries considered are listed below:

Slurry	Curing Temperature
Aluminum phosphate	500 to 800°F
Synar	500°F
Xylol	Room temperature

4.6.3 Electrodeposition

Electroplating is another method of applying a high emissivity coating to a radiator surface. The method is extremely useful in controlling the thickness of the desired coating. Metals and alloys that can be electroplated from aqueous solutions include chromium, copper, nickel and platinum. Titanium, refractory metals and aluminum are electroplated from fused-salt electrolytes. Organic solutions can also be used to electroplate aluminum.

Electrodeposition has many advantages. Thermally stable pure metal coatings can be deposited at near zero stress. Surface defects and roughness may be leveled by applications of bright copper and nickel. The thickness of a coating may be controlled from a few millionths of an inch to 100 mils.

Electroplating finds extensive use in plating chromium black and platinum black on beryllium, stainless steels and nickel. Chromium black can be applied to any surface that can be plated with nickel or chromium.

4.6.4 Vapor Phase Deposition

Surface catalysis, thermal decomposition or reduction of a coating's volatile compound are used to produce both metallic and non-metallic deposits on metal substrates (69). Thermal decomposition of metal organic compounds produce deposits of aluminum, chromium and nickel. Pyrolytic graphites can be produced by thermal decomposition of methane and acetylene on a heated surface at temperatures between 1832 to 4532°F (69). The deposition temperatures required make high emittance pyrolytic graphite coatings applicable only to low thermal expansion substrates. The high total solar absorptances (70) ranging from .85 to .91 of graphite in general make them applicable only to high temperature potassium or rubidium radiator condensers.

The major application of vapor phase deposition for space radiator-condensers is limited. It may be used as an intermediate layer of material between a metal substrate and a high emittance - low solar absorptance coating when electroplating is impractical. The technique produces good coverage of the surface, a pore-free coating, and has a high deposition rate (to 20 mils per hour) (69).

4.6.5 Other Coating Methods

Chemical deposition, vacuum metallizing and painting are also techniques for coating materials. Chemical deposition finds application where the use of anodes and currents are not feasible. Platinum black is coated on beryllium by an immersion or displacement type coating process.

Vacuum metallizing consists of evaporating the coating metal and condensing it on the surface to be coated. The process is accomplished in a vacuum environment and the coating thickness is generally less than 1 mil thick. The process is not considered practical for large radiators and at the present time is relatively undeveloped.

Organic and inorganic coatings using volatile vehicles can be applied by the conventional painting methods of brush, dip or spraying. Curing is done at room temperature or in an oven at temperatures up to 400°F depending on the type of coating being applied.

5.0 RECOMMENDATIONS

Based on the readily available data in the literature, the following areas of work appear to warrant further attention to more reliably and accurately design and analyze condenser-radiators for space power systems:

1. Low temperature ($< 300^{\circ}F$) emittance coating testing. Most of this work has been in the higher temperature ranges, and as a result some coatings unacceptable at high temperatures that may be acceptable at fuel cell temperature levels, for instance, have been neglected.

2. Atmospheric testing of emittance coatings. Since almost all radiators will be ground operated prior to flight, the effect of this operation is important.

3. Compatibility of fin materials, tube materials and emittance coatings. Information on a wider range of combinations, including beryllium, is needed.

4. Meteoroid protection capability. Develop an expression for armor protection thickness that accounts for the ductility of armor material in addition to density and elastic modulus.

II.

Tables

TABLE 1 RESULTS OF POWER SYSTEM SURVEY

POWER SYSTEM	RADIATOR TYPE	WORKING FLUID	RADIATOR MATERIALS		PRIME AND/OR SUBCONTRACTOR	PRESENT OR FINAL STATUS
			TUBES AND HEADERS	FINS		
SNAP 1 (SPUD)	DIRECT	MERCURY	316 S. St.	316 S. St.	TRW	FLIGHT TESTED
SNAP 2	DIRECT	MERCURY	HAYNES 25 17.7 Mo	ALUMINUM COPPER	AI/TRW	ADVANCED DEVELOPMENT
SUNFLOWER	DIRECT	MERCURY	347 S. St.	1100-0 ALUMINUM	TRW (79)	SYSTEM TESTING
SNAP 8	DIRECT & INDIRECT	MERCURY	HAYNES 25	ALUMINUM	AEROJET GENERAL	DEVELOPMENT
SPUR/SNAP 50	DIRECT & INDIRECT	POTASSIUM	316 S. St.	316 S. St. CLAD COPPER	AIRESEARCH (6)	DEVELOPMENT
HEAT TRANSFER TEST CAPSULE	DIRECT	POTASSIUM	316 S. St.	COPPER	TRW (88)	FLIGHT TESTED
ASTEC	DIRECT	RUBIDIUM	INCONEL BERYLLIUM	INCONEL BERYLLIUM	SUNDSTRAND (76)	DEVELOPMENT
1.5 KW POWER SYSTEM	DIRECT	DOWTHERM-A	N/A	N/A	SUNDSTRAND (74)	DEVELOPMENT
NUMEROUS ORGANIC STUDIES	INDIRECT	ORTHO-XYLENE ETHYL BENZENE DOWTHERM-A	ALUMINUM	ALUMINUM	TRW (90) & OTHERS	DEVELOPMENT
FUEL CELLS	INDIRECT (DIRECT UNDER STUDY)	H_2, O_2	NICKEL-PLATED MAGNESIUM	MAGNESIUM OR ALUMINUM		SYSTEM TESTING
MULTI-TUBE ORBITAL RANKINE EXPERIMENT	DIRECT	DOWTHERM-A	347 S. St.	5083 ALUMINUM	TRW (77)	CONTRACT FOR FLIGHT
NUMEROUS STEAM CYCLE STUDIES	DIRECT	WATER	ALUMINUM BERYLLIUM	ALUMINUM BERYLLIUM	ASTRA (73) & OTHERS	ADVANCED STUDY

NUMBERS IN PARENTHESIS ARE REFERENCE NUMBERS.

TABLE 2 PROPERTIES OF ORGANIC WORKING FLUIDS (90)

WORKING FLUIDS	BENZENE C_8H_6	ETHYLBENZENE C_8H_{10}	ORTHO-XYLENE C_8H_{10}	META-XYLENE C_8H_{10}	TOLUENE C_7H_8	PYRIDINE C_5H_5N	CHLOROBENZENE $C_8H_5C_1$	O-DICHLOROBENZENE $C_8H_4Cl_2$	METHOXYPROPANOL	PERCHLORETHYLENE C_2Cl_4	BIPHENYL $C_{12}H_{10}$	DOWTHERM-A $C_{12}H_{10}C_{12}H_{10}O$	FC-75 $C_8F_{18}O$	FREON-113 $CCl_2F\text{-}CClF_2$	TITANIUM TETRACHLORIDE $TiCl_4$	HEXACHLORODISILANE Si_2Cl_8	ALUMINUM BROMIDE $AlBr_3$	WATER H_2O
BOILING POINT, °F	176.2	277.1	291.9	282.4	231.1	239.5	269.6	352.0	248 F	252	491	498.8	217.5	117.6	277.5	282.2	485.0	212
FREEZING POINT, °F	42.0	-139.0	-13.3	-54.2	-139.0	-43.6	-67.0	-7.0	-50	-8.2	156	53.6	-80	-31.0	-22	30.2	207.5	32
CRITICAL TEMPERATURE, °F	553.0	655.8	678.3	654.9	609.5	651	680	927		656.8	930.4	927	441	417.4	696		923	705.2
MOLECULAR WEIGHT, Lb_m/Lb_{mole}	78.1	106.2	106.2	106.2	92.1	79.1	112.6	147.0	90.1	165.8	154.2	165.66	332	187.4	189.7	288.9	266.7	18
DENSITY, LB/FT³ AT 70°F	54.8	54.1	54.9	53.9	54.1	61.3	69.1	81.7	61.7	101.3	60.8 @ 200°F	66.7	110.4	97.0	107.7	98.6	142 @ NEP	62.3
SPECIFIC HEAT-Cp. BTU/LB °F (LIQUID)	0.406	0.423	0.405	0.397	0.405	0.406	0.315	0.269	.56	0.205	.422 @ 200°F	0.524 Btu/Lb °F -Liquid at NBP	248	0.218	0.192		0.095 @ NEP	1.0
LATENT HEAT, BTU/LB AT NBP	169.3	145.7	149.1	147.4	156.2	193.3	139.8	116.1	600	90	285.2	125	37.8	63.1	79.2		40.8	970
DECOMPOSITION RATE, % YEAR (c)		(4.5/575)	(0.5/575)	(0.5/575)	(0.5/575)									6/400°F				0
COMPATIBILITY WITH: ALUM.	OK	OK	OK	OK	OK	OK	Varies	Poor		Varies	OK	OK	OK	Fair	Poor	Poor		OK
STAINLESS STEEL	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK				OK
COPPER	OK	OK	OK	OK	OK	OK	OK	OK	OK	Varies	OK	OK	OK	OK	Poor	Poor		OK
ELASTOMERS (a)	Viton	Viton	Viton	Viton	Viton	Ethylene Propylene	Viton	Fluoro-silicone	Neoprene	Viton	Fluoro-silicone	Fluoro-silicone	Buna-N	Buna-N	Viton	Viton	Neoprene	Fluoro-silicone
FLASH POINT, °F CLOSED CUP	12	59	63	77	40	68	90	156	122	None	235	255	None		(b)	(b)	(b)	None
AUTO IGNITION POINT, °F	1076	870	924		1026	1065	1295	932	878	None	1000	1150	None	1256	(b)	(b)	(b)	None
EXPLOSIVE RANGE	Mod.		Slight	Mod.	Mod.	Several	Mod.			None			None		(b)	(b)	(b)	None
TOXICITY-MAXIMUM	25 PPM	220 PPM	200 PPM	200 PPM	200 PPM	5 PPM	75 PPM	50 PPM		100 PPM			Very Low	1000 PPM				None

(a) Elastomers Compatibility is Temperature Dependent. Compounds Listed are Those which will Give Highest Temperature Service.

(b) Reacts with Moisture in Air to Form Metal Oxide & Corresponding Mineral Acid.

(c) Values in Parentheses are Estimated.

TABLE 3 THERMO-PHYSICAL PROPERTIES OF WORKING FLUIDS

PROPERTY	UNITS	WORKING FLUIDS													
		WATER		MERCURY		POTASSIUM		RUBIDIUM		ORGANICS					
										DOWTHERM-A		ORTHO-XYLENE		ETHYL BENZENE	
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor
MOLECULAR WEIGHT	Lb_m/Lb_{mole}	18	N/A	200.61	N/A	39.10	N/A	85.48	N/A	165.7	N/A	106.16	N/A	106.17	N/A
				(67)		(67)		(67)		(67)		(63)		(64)	
DENSITY	Lb/Ft^3	Fig. 1	N/A	Fig. 11	N/A	Fig. 19	N/A	Fig. 29	N/A	Fig. 38	N/A	Fig. 38	N/A	Fig. 38	N/A
SPECIFIC HEAT	Btu/Lb - °F	Fig. 2	Fig. 7	Fig. 12	.0249	Fig. 20	Fig. 25	.0877	Fig. 34	Fig. 39	Fig. 44	Fig. 39	Fig. 44	Fig. 39	Fig. 44
					(64)			(62)							
SPECIFIC HEAT RATIO	N/A	1.31	N/A	1.66	N/A	1.61	N/A	1.60	N/A	1.031	N/A	1.046	N/A	1.046	N/A
		(64)		(64)		(62)		(62)		(63)		(63)		(63)a	
HEAT OF EVAPORATION	Btu/Lb	Fig. 3	N/A	127.0	N/A	Fig. 21	N/A	Fig. 30	N/A	Fig. 40	N/A	Fig. 40	N/A	Fig. 40	N/A
				(64)											
THERMAL CONDUCTIVITY	Btu/Hr-Ft-°F	Fig. 4	Fig. 8	Fig. 13	Fig. 16	Fig. 22	Fig. 26	Fig. 31	Fig. 35	Fig. 41	Fig. 45	Fig. 41	Fig. 45	Fig. 41	Fig. 45
VISCOSITY (ABSOLUTE)	Lb/Ft-Sec	Fig. 5	Fig. 9	Fig. 14	Fig. 17	Fig. 23	Fig. 27	Fig. 32	Fig. 36	Fig. 42	Fig. 46	Fig. 48	Fig. 46	Fig. 48	Fig. 46
SURFACE TENSION (LIQUID-VAPOR)	Lb/Ft	Fig. 6	N/A	Fig. 15	N/A	Fig. 24	N/A	Fig. 33	N/A	Fig. 43	N/A	Fig. 43	N/A	Fig. 43	N/A
VAPOR PRESSURE	PSIA	N/A	Fig. 10	N/A	Fig. 18	N/A	Fig. 28	N/A	Fig. 37	N/A	Fig. 47	N/A	Fig. 49	N/A	Fig. 49
FREEZING POINT	°F	32	N/A	-37.97	N/A	144.1	N/A	101.3	N/A	53.6	N/A	-13.3	N/A	-139.0	N/A
		(7)		(67)		(67)		(67)		(67)		(67)		(67)	
CRITICAL TEMPERATURE	°F	705.2	N/A	>2822	N/A	3092	N/A	3032	N/A	927	N/A	678.3	N/A	655.8	N/A
		(67)		(67)		(67)		(67)		(23)		(90)		(90)	
CRITICAL PRESSURE	Atm.	217.7	N/A	>200	N/A	170	N/A	190	N/A	31.62	N/A	37	N/A	38	N/A
		(67)		(67)		(67)		(67)		(23)		(61)		(61)	

Numbers in Parenthesis are Reference Numbers; (a) Similar Composition; (N/A)- Not Applicable; All Vapor Properties at Saturated Conditions.

TABLE 4 THERMO-PHYSICAL PROPERTIES OF RADIATOR MATERIALS

PROPERTY / MATERIAL	DENSITY (b) Lb/In^3	DENSITY (b) Lb/Ft^3	MODULUS OF ELASTICITY PSI	THERMAL CONDUCTIVITY Btu/Hr-Ft-°F	SPECIFIC HEAT Btu/Lb-°F	.2% YIELD STRESS PSI	COEFFICIENT OF THERMAL EXPANSION In/In - °F	MELTING TEMPERATURE RANGE °F
ALUMINUM (2024)	.100 (1)	172.8	Fig. 50	Fig. 52	.195 (1)	Fig. 54	Fig. 57	935-1180 (1)
ALUMINUM (7075)	.101 (1)	174.5	Fig. 50	Fig. 53	.23 (1)	Fig. 54	Fig. 57	890-1180 (39)
BERYLLIUM (1-1/2-3% BeO)	.067 (2)	116.8	Fig. 51	Fig. 52	.43 (2)	Fig. 54	Fig. 57	2345 (2)
COPPER (PURE)	.323 (39)	558	Fig. 50	Fig. 53	.092 (39)	Fig. 55	Fig. 57	1981 (39)
COPPER (D.H.)	.317 (6)	548	Fig. 50	Fig. 53	.092 (39)	Fig. 55		1981 (39)
COBOLT ALLOYS (L605)	.330 (16)	570	Fig. 50	Fig. 52	.092 (16)	Fig. 54	Fig. 57	2425-2570 (16)
MAGNESIUM (HK 31A)	.065 (39)	112.2	Fig. 51	Fig. 53	.245 (39	Fig. 55	-	1092-1195 (39)
MAGNESIUM (AZ 31B)	.064 (39)	110.5	Fig. 51	Fig. 53	.245 (39)	Fig. 55	Fig. 57	1050-1170 (39)
NICKEL ALLOYS (INCONEL-X)	.298 (1)	515	Fig. 51	Fig. 52	.10-.11 (1)	Fig. 56	Fig. 58	2540-2600 (1)
NICKEL ALLOYS (INCONEL-718)	.296 (6)	512	Fig. 50	Fig. 52	.10-.11 (1)	Fig. 56	Fig. 58	2540-2600 (1)
300 SERIES (STAINLESS)	.290 (39)	501	Fig. 50	Fig. 53	.12 (39)	Fig. 54	Fig. 57	2500-2650 (39)
400 SERIES (STAINLESS)	.280 (1)	484	Fig. 51	Fig. 53	.11 (39)	Fig. 55	Fig. 57	2700-2790 (1)
SUPERALLOYS (A-286)	.286 (39)	494	Fig. 50	Fig. 52	.10-.11 (39)	Fig. 55	Fig. 58	2500-2600 (39)
COLUMBIUM ALLOYS (Cb-1 Zr)	.310 (39)	536	Fig. 51	Fig. 52	.065 (41)	Fig. 55	(a)	4474 (39)
MOLYBDENUM (Mo-0.5 Ti)	.369 (39)	638	Fig. 50	Fig. 53	.061 (39)	Fig. 56	Fig. 57	4750 (39)
TITANIUM ALLOYS (T_i-6 Al - 4V)	.160 (1)	277	Fig. 51	Fig. 52	.135 (39)	Fig. 56	Fig. 58	2800-3000 (1)
ZIRCONIUM ALLOYS (ZIRCALOY-2)	.237 (39)	410	Fig. 51	Fig. 53	.077 (Est.) (1)	Fig. 55	Fig. 57	3300 (39)
GRAPHITE (PYROLYTIC)	.0793 (89)	137	Fig. 50	Fig. 52	.14-.15 (38)	Fig. 54	Fig. 57	~ 6400 (67)

NUMBERS IN PARENTHESIS ARE REFERENCE NUMBERS

(a) 3.8×10^{-6} °F^{-1} @ 70°F (39)

(b) At Room Temperature

TABLE 5A MATERIALS COMPATIBILITY WITH WORKING FLUIDS

WORKING FLUID / MATERIAL	CORROSION TEMPERATURE LIMIT													
	WATER		MERCURY		RUBIDIUM		POTASSIUM		ORGANICS					
									Dowtherm-A (23)		Ortho-Xylene (26) (87)		Ethylbenzene (26) (87)	
	Less Than 1000 Hrs.	10,000 Hrs. or More	Less Than 1000 Hrs.	10,000 Hrs. or More	Less Than 1000 Hrs.	10,000 Hrs. or More	Less Than 1000 Hrs.	10,000 Hrs. or More	Less Than 1000 Hrs.	10,000 Hrs. or More	Less Than 1000 Hrs.	10,000 Hrs. or More	Less Than 1000 Hrs.	10,000 Hrs. or More
	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F
ALUMINUM		(17) 200	(30) N/C							750		500		500
ALUMINUM ALLOYS		(19) 200	(30) N/C							750		750		750
BERYLLIUM		(7) 200	(30) 900	(30)(31) 800	(14) 1000		(34) 1200							
		(36 500			(14) 1400[a]									
COBOLT ALLOYS HAYNES-25		(17) 500+		(86) 1250 (5000 Hrs.)	(14) 1400/ 1700	(14) 1700[a]	(12) 1800			750				
COPPER			(69) N/C							750				
COPPER-NICKEL	(17) 200/500		N/C							750				
MAGNESIUM			(30) N/C							750		500		500
MAGNESIUM ALLOYS		(17) 150								750				
NICKEL ALLOYS					(62) 1500		(12)(33) 1535					750		750
INCONEL		(17) 600		(30) (N/C)	(12) ~1700		~1700			750				
MONEL		(19) 500+		(30) (N/C)						750				
HASTELLOY-B		(69) <800			(12) ~1700		(12) 1700			750				
<u>REFRACTORY METALS</u>														
COLUMBIUM			(30) 1200				(62) ~1700							
Cb - 1% Zr				(86) 1200 (7800 Hrs	(14) 1400/ 2000		(14) 1500/ 2200	(86) 1600 (3000 Hrs)						
Mo - 5% Ti					(14) 1400/ 2000									
MOLYBDENUM			(30) 900				(62) ~1700							
TANTALUM			(30) 1100	(86) 1365 (20,000 Hrs.)			(62) 1700							
Cb-1OW-1 Zr			(30) 900				(29)(14) 2000 2000 Hrs							
AS-55							(29)(14) 2000							

NUMBERS IN PARENTHESIS ARE REFERENCE NUMBERS.

TEMPERATURES SHOWN INDICATE NO OR LOW AMOUNTS OF CORROSION.

(a) MORE TESTING REQUIRED TO CHECK OUT LONG TERM CORROSION EFFECTS.

(N/C) NOT COMPATIBLE (VERY HIGH CORROSION RATE OR DISSOLVES)

TABLE 5B MATERIALS COMPATIBILITY WITH WORKING FLUIDS

WORKING FLUID / MATERIAL	CORROSION TEMPERATURE LIMIT													
	WATER		MERCURY		RUBIDIUM		POTASSIUM		ORGANICS					
									Dowtherm-A (23)		Ortho-Xylene (26) (87)		Ethylbenzene (26) (87)	
	Less Than 1000 Hrs.	10,000 Hrs. or More	Less Than 1000 Hrs.	10,000 Hrs. or More	Less Than 1000 Hrs.	10,000 Hrs. or More	Less Than 1000 Hrs.	10,000 Hrs. or More	Less Than 1000 Hrs.	10,000 Hrs. or More	Less Than 1000 Hrs.	10,000 Hrs. or More	Less Than 1000 Hrs.	10,000 Hrs. or More
	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F
FERROUS METALS														
300 SERIES		(17) 500/600		(30) (31) 750	(12) 1400/1600		(33) (62) 1600	(14) 1575 (5000 Hrs)		750		750		750
400 SERIES		(17) 500/600		(30) 1100			(62) 1600			750				
LOW CARBON		(14) 480/570		(30) 1050	(62) 900		(62) 900			750		500		500
IRON BASE SUPER-ALLOY A286			(30) 900							750				
PRECIPITATION HARDENING (17-4PH, AM350, PH 15-7 Mo)		(19) 800/1350		(30)(22) 1050						750				
SICROMO 5S				(30)(22) 1200										
TITANIUM		(19) 570					(62) 1100							
VANADIUM			(30) 900		(14) 1000/1400		(62) 1700							
NIOBIUM-VANADIUM ALLOY		(19) ~900												
ZIRCALOY-2	(19) 750	(19) 750										<500		<500
ZIRCONIUM	(17) 500+						(62) 1100							

NUMBERS IN PARENTHESIS ARE REFERENCE NUMBERS.

TEMPERATURES SHOWN INDICATE NO OR LOW AMOUNTS OF CORROSION.

TABLE 6 RADIATOR FIN AND TUBE MATERIAL COMPATIBILITY

REFERENCE	FIN ARMOR OR CLADDING MATERIALS	APPLICATION			TUBE MATERIALS																
											FERROUS METALS					REFRACTORY METALS					
		Fins	Armor	Cladding	Al & Alloys	Be & Alloys	Cu & Alloys	Cobolt & Alloys	Mg & Alloys	Ni & Alloys	300 Series	400 Series	Low Carbon	Super Alloys	Prec. Hardening	Cb Cb-1% Zr	Mo	Ta	Ti & Alloys	Va & Alloys	Zr & Alloys
(35)	ALUMINUM AND ALLOYS	X	X	O	A	A	A, D	C	A, D	C	A	A	A, D	A	A	C	C	C	C	C	C
(6)	BERYLLIUM AND ALLOYS	X	X	O	A	A	A	B, C	A	B, C	B, C	B, C	B, C	B, C	B, C	B, C	B, C	B, C	C	C	C
(6)	COPPER & ALLOYS	X	O	O	A, D	A	A	C	A, D	C	A	A	A	A	A	C	C	A	C	C	C
	COBOLT (ALLOYS)	O	X	X	C	C	C	A	-	A	A	A	A	A	A	C	A	C	C	C	C
(66)	MAGNESIUM AND ALLOYS	X	O	O	A, D	A	A, D	-	A	A, D	A, D	A, D	A, D	C	C	C	C	C	A, D	C	C
	NICKEL & ALLOYS	X	X	X	C	B, C	C	-	A, D	A	C	A	C	C	A	B, C	B, C	B, C	C	C	C
	FERROUS METALS																				
(6)	300 SERIES	X	X	X	A	B, C	B, C	A	A, D	A	A	C	A	A	A	C	C	-	A	C	C
(6)	A-286	O	X	X	A	B, C	B, C	B, C	A, D	B, C	A	C	A	A	A	C	C	-	A	C	C
	REFRACTORY METALS																				
(85), (6)	Cb - 1% Zr	X	X	X	-	B, C	C	-	B, C	B, C	C	-	B, C	-	B, C	A	-	-	C	-	-
(85)	TANTALUM	-	X	-	-	B, C	A	-	B, C	B, C	-	-	-	-	-	-	-	A	C	-	-
(85)	COLUMBIUM	X	X	X	-	B, C	C	B, C	B, C	B, C	C	-	B, C	-	B, C	A	-	-	C	-	-
(37), (40)	TITANIUM & ALLOYS	O	X	X	C	C	C	C	A, D	C	A	A	A	A	C	C	C	C	A	C	C
(85), (10)	GRAPHITE (PYROLYTIC)	X	X	O	B, C	B, C	B, C	B, C	B, C	B, C	B, C	B, C	B, C	B, C	B, C	B	B	B	B	B	B

BLANK SPACES INDICATE NOT APPLICABLE OR NO INFORMATION AVAILABLE

A - COMPATIBLE WITH EXISTING JOINING & BONDING TECHNIQUES
B - BONDING OR JOINING PROBLEM
C - NOT RECOMMENDED (LARGE THERMAL EXPANSION DIFFERENCE)
D - SUSCEPTIBLE TO GALVANIC CORROSION (PROTECTION REQ'D) (35) (66)
X - APPLICABLE
O - NOT APPLICABLE

TABLE 7 (a) RADIATOR EMITTANCE COATINGS

COATING	SUBSTRATE BASE	APPLICATION METHOD	THICKNESS (MILS)	EFFECTIVE TEMPERATURE RANGE °F	TOTAL HEMISPHERICAL EMITTANCE		SOLAR ABSORPTIVITY α_s	$\alpha_s/\mathcal{E}_H$	REFERENCE
					DURATION TESTED (HRS) IN HARD VAC.	$\mathcal{E}_H$			
<u>SINGLE OXIDES</u>									
CHROMIC OXIDE (Cr_2O_3)	Cb 1% Zr	PLASMA-ARC SPRAYED	4	500-2100	8	.82 - .70			47
STABILIZED TITANIUM OXIDE	"	" " "	4	1700	400	.87			43
TITANIA (T_iO_2)	"	ALUM. PHOSPHATE BONDED	1 5	300-1000 300-1000	3 5	.80 - .83 .76 - .88			47 47
	ALUMINUM 1100	PLASMA-ARC SPRAYED		700	15,000				53
	ALUMINUM 6061	" " "		700	15,000				53
	347 S. ST.	" " "		650	13,000				53
TITANIA (50%) ALUMINA (50%)	ALUMINUM	" " "		300-900	35	.70 - .80			49, 54
	310 S. ST.	" " "	2.4	300-1340	150	.84 - .89			49, 54
	Cb 1% Zr	" " "		1450	300	.82			49
SILICA (SiO_2)	"	ALUM. PHOSPHATE BONDED	5	300-1000	4	.86 - .70			47
	MAGNESIUM		5			.83	.210	.25	68, 92
SILICON MONOXIDE (SiO)	ALUMINUM					.70	.51	.73	92
BERYLLIUM OXIDE (BeO)								.421	70
MAGNESIUM OXIDE (MgO)								.168	70
ALUMINUM OXIDE (Al_2O_3)								.16	20
ZIRCONIUM OXIDE (ZrO_2)								.14	20
NICKEL OXIDE (N_iO)	Cb 1% Zr	PLASMA-ARC SPRAYED	3	1000-2100	2	.74 - .86			47
COBALT OXIDE (C_oO)	"	" " "	4	300-2200	5	.79 - .87			47
STANNIC OXIDE	COPPER	ALUM. PHOSPHATE BONDED	3	500-700		.87 - .84			114
	"	POTASSIUM SILICATE BINDER	3	500-700		.88			114
ZINC OXIDE (Z_nO)	"	" " "	2	600-700		.79 - .77			114

TABLE 7 (b) RADIATOR EMISSIVITY COATINGS

COATING	SUBSTRATE BASE	APPLICATION METHOD	THICKNESS (MILS)	EFFECTIVE TEMPERATURE RANGE °F	TOTAL HEMISPHERICAL EMITTANCE		SOLAR ABSORPTIVITY α_s	α_s/ε_H	REFERENCE
					DURATION TESTED (HRS) IN HARD VAC.	ε_H			
MULTIPLE OXIDES									
IRON TITANATE	310 S. ST.	PLASMA-ARC SPRAYED	4	1350	5300	.88			43
	Cb 1% Zr	" " "	4	1700	6250	.85			43
IRON TITANATE, ALUM. TITANATE	"	" " "	5	1000-2200	4	.82-.89			47
ALUM. OXIDE - ALUM. TITANATE	"	" " "	4	1700	1000	.83			43
BARIUM TITANATE (Ba Ti O_3)	"	" " "	4	1700	100	.71			43
	ALUMINUM	" " "	1	440		.75	.65	.86	50
	"	" " "	3	440		.82	.61	.74	50
	"	" " "	5	440		.87	.74	.85	50
CALCIUM TITANATE (CaO TiO_2)	"	" " "	2	440		.75	.72	.96	50
	"	" " "	3.5	440		.82	.70	.85	50
	"	" " "	4.5	440		.88	.70	.795	50
	310 S. ST.	" " "	4	1350	6300	.90			43
	COLUMBIUM	" " "	4	1450	300	.92			48
	Cb 1% Zr	" " "	4	1000-1800		.89-.85			48
STRONTIUM TITANATE (SrO TiO_2)	"	" " "	4	900-1400	21	.76-.88			47
	STAINLESS STEEL	" " "		1450	17	.89			49
	ALUMINUM	" " "	1.4	440		.81	.73	.90	50
	"	" " "	3.4	440		.82	.76	.93	50
	"	" " "	5.0	440		.83	.64	.77	50
ZIRCONIUM TITANATE	Cb 1% Zr	" " "	4	1700	312	.82			43
	ALUMINUM	" " "	2.4	440		.83	.46	.55	50
	"	" " "	2.9	440		.83	.38	.46	50
	"	" " "	5.0	440		.86	.37	.43	50
SILICON CARBIDE AND SILICON DIOXIDE MIXTURE	1100 ALUMINUM 6061 "	ALUMIMUM PHOSPHATE BONDED		700	12800				53

TABLE 7(c) RADIATOR EMITTANCE COATINGS

COATING	SUBSTRATE BASE	APPLICATION METHOD	THICKNESS (MILS)	EFFECTIVE TEMPERATURE RANGE °F	TOTAL HEMISPHERICAL EMITTANCE		SOLAR ABSORPTIVITY α_s	α_s / ε_H	REFERENCE
					DURATION TESTED (HRS) IN HARD VAC.	ε_H			
MULTUPLE OXIDES (CON'T)									
NICKEL-CHROME SPINEL	Cb 1% Zr	PLASMA-ARC SPRAYED	4	1000-1800	30	.7			45
	"	" " "	2	1000-2100	5	.87			46
	310 S. ST.	ALUMINUM PHOSPHATE BONDED	3	1000-1450		.88			48
	"	" " "	2	1450	550	.83			48
	"	" " "	2	1000-1350		.88			49
	ALUMINUM 1100	" " "		700	15,000				53
	ALUMINUM 6061	" " "		700	15,000				53
ROKIDE-A	ALUMINUM	ROKIDE PROCESS			570 SUN HRS.			.59	91
	STAINLESS STEEL	" "				.80	.21	.26	68
ROKIDE-C	310 S. ST.	" "		1450	300	.85			49
			5			.789	.898	1.14	92
ROKIDE-MA	ALUMINUM	ROKIDE PROCESS	1	440		.55	.55	1.00	50
	"	" "	2.5	440		.71	.58	.82	50
	"	" "	5.5	440		.82	.41	.50	50
ROKIDE-ZS	"	" "	2	440		.79	.54	.68	50
	"	" "	7.5	440		.89	.45	.51	50
	310 S. ST.	" "	4	1000-2200	6	.64-.56			94
	Cb 1% Zr	" "	5	300-1450	300	.78-.83			94
CHROME, COBALT, NICKEL SPINEL	COPPER	ALUMINUM PHOSPHATE BONDED	2	500-700		.86			114

TABLE 7 (d) RADIATOR EMITTANCE COATINGS

COATING	SUBSTRATE BASE	APPLICATION METHOD	THICKNESS (MILS)	EFFECTIVE TEMPERATURE RANGE °F	TOTAL HEMISPHERICAL EMITTANCE		SOLAR ABSORPTIVITY α_s	α_s/ε_H	REFERENCE
					DURATION TESTED (HRS) IN HARD VAC.	ε_H			
NON-OXIDES									
CRYSTALLINE BORON	Cb 1% Zr	PLASMA-ARC SPRAYED	1	1300-1700	6	.70 - .76			46, 48
	COLUMBIUM	" " "	3	1000-1350		.85			48
	MOLYBDENUM	" " "	3	1000-1500		.88			48
ZIRCONIUM DIBORIDE - MOLYBDENUM DISILICIDE (BORIDE-Z)	Cb 1% Zr	" " "	4			.85			44
ACETYLENE BLACK		XYLOL BONDED				.72 - .92			54
SILICON CARBIDE (SiC)	310 S. ST.	ALUMINUM PHOSPHATE BONDED		1000-1300		.88 - .85			48
	1100, 6061	" " "		700	15,000				53
	Cb 1% Zr	" " "	4-8	300-1450	350	.92 - .90			44, 47, 48
	"	" " "		1000-1400		.87 - .88			44, 47, 48
	374 S. ST.	" " "		700	1,500				53
BORON CARBIDE (B_4C)	Cb 1% Zr	" " "	6	900-1400	3	.90 - .95			47
ATJ GRAPHITE				1700-2900		.87 - .82			70
ACHESON GRAPHITE				1600-3400		.72 - .83			70
BORON NITRIDE	TANTALUM	SYNAR BONDED	3	300-1200	27	.82 - .682			54
BORON NITRIDE (POTASSIUM SILICATE BINDER)	COPPER		2	500 600 700		.83 .80 .78			114

TABLE 7 (e) RADIATOR EMITTANCE COATINGS

COATING	SUBSTRATE BASE	APPLICATION METHOD	THICKNESS (MILS)	EFFECTIVE TEMPERATURE RANGE °F	TOTAL HEMISPHERICAL EMITTANCE		SOLAR ABSORPTIVITY α_s	α_s/ε_H	REFERENCE
					DURATION TESTED (HRS) IN HARD VAC.	ε_H			
STABLY OXIDED METALLIC SURFACES									
LITHIATED NICKEL OXIDE	310 S. ST.	SLURRY SPRAY & SINTER		300-1450	375	.81 - .85			49
CHROMIUM BLACK	"	ELECTROPLATED		1450	300	.89			48, 49
	NICKEL	"		1450	800	.90			48, 49
OXIDED KENNAMETAL K-151-A	310 S. ST.	PLASMA-ARC SPRAYED	4	700-1600	24	.85 - .82			47
OXIDIZED 310 S. ST.	"	GRIT BLAST, OXIDIZE @ 1800°F		300-1450	330	.83			49
DOW-1	MAGNESIUM					.53	.64	1.2	68
DOW-10	"					.85	.89	1.05	68
DOW-15	"					.08	.19	2.4	68
DOW-17	"					.82	.72	1.25	68
COATING SYSTEMS									
Al 93 (NA 0109-023) SUBCOAT (C_r Co N_i SPINEL) TOPCOAT (STANNIC OXIDE)	COPPER	ALUMINUM PHOSPHATE BONDED	3	600	2000	.91	.35	.387	114
Al 93 (NA 0109-020/022)	ALUMINUM AND ALLOYS	ALUMINUM PHOSPHATE BONDED	3	600	2000	.91 - .92			
Al 93 (NA 0109-014)	TITANIUM	" " "	3						

TABLE 7 (f) RADIATOR EMITTANCE COATINGS

COATING	SUBSTRATE BASE	APPLICATION METHOD	THICKNESS (MILS)	EFFECTIVE TEMPERATURE RANGE °F	TOTAL HEMISPHERICAL EMITTANCE		SOLAR ABSORPTIVITY α_s	α_s / ε_H	REFERENCE
					DURATION TESTED (HRS) IN HARD VAC.	ε_H			
WHITE PAINTS									
PRATT & LAMBERT (91-1524)	TITANIUM	DIP OR SPRAY	.5-1 0	400-1500		.21 - .70			22
TITANIUM DIOXIDE (T_iO_2)	ALL	" " "				.90	.15	.167	66
WHITE ORGANICS	"	" " "		400-750		.90		.2 - .3	55
T_iO_2 UNTINTED (SILICONE VEHICLE)					50	.84	.33	.393	71
T_iO_2 TINTED (SILICONE VEHICLE)					50	.83	.37	.446	71
SPO 500 Z_mO (PS 7 POTASSIUM SILICATES)					1000	.926	.204	.22	71
SPO 500 Z_mO (GE 81932 SILICONE RESIN)					1000	.864	.332	.385	71
TILE COAT PAINT	ALUMINUM	DIP OR SPRAY				.89	.34 - .38	.382 - .426	50
SICON 7X1153	DOW 17 ON HM-21A Mg	" " "			600 SUN HRS.			.45 - .67	91
SKYSPAR A-423	"	" " "			276 SUN HRS.			.4	91
KEMACRYL M49 WC 17	"	" " "			600 SUN HRS.			.4	91
FULLER 517-W-1 SILICONE	"	" " "			276 SUN HRS.			.34	91
SKYSPAR EPOXY (UNTINTED WHITE)		" " "		440		.860	.260	.30	92
FULLER GLOSS WHITE SILICONE		" " "		440		.870	.18	.21	92
WHITE HAE 65V	MAGNESIUM AZ 31B	" " "				.5 - .7			93

TABLE 7 (g) RADIATOR EMITTANCE COATINGS

COATING	SUBSTRATE BASE	APPLICATION METHOD	THICKNESS (MILS)	EFFECTIVE TEMPERATURE RANGE °F	TOTAL HEMISPHERICAL EMITTANCE DURATION TESTED (HRS) IN HARD VAC.	TOTAL HEMISPHERICAL EMITTANCE ε_H	SOLAR ABSORPTIVITY α_s	α_s/ε_H	REFERENCE
BLACK PAINTS	.								
KEMACRYL	DOW 17, HM-21A Mg	DIP OR SPRAY			600 SUN HRS.			1.10	91
M49 BC12		" " "				.750	.260	.35	92
MICO BOND	DOW 17, HM-21A Mg	" " "			630 SUN HRS.	.844	.936	1.04-1.11	91, 92
10043 ALUM. SILICONE FULLER 171-A-152		" " "			600 SUN HRS.			1.48	91
FULLER GLOSS - BK. SILICONE		" " "		440		.890	.810	.91	92
DULL BLACK MICO BOND VINYL (PHENOLIC)		" " "		440		.840	.930	1.10	92
BLACK ORGANIC		" " "		400-750		.9	.81	.9	55
46 H47 BLACK	A-286	" " "		600-1800		.8			72, 22
KRYLON BLACK	310 S. ST.	" " "	1.3	300-600	30	.89			54
	"	" " "	3	300-1800	50	.89-.62			
CARBON BLACK PIGMENT						.780	.908	1.16	92
OTHER PAINTS									
ALUMINUM PAINT		" " "		0-575		.3-.4	.3-.4	1.0	55
WATER GLASS ENAMEL		" " "		950		.8		.2-.3	72
LITHIATED ALUM. SILICATE INORGANIC PAINT		" " "		440		.870	.180	.21	92
FULLER ALUM. SILICONE		" " "		440		.200	.230	1.15	92
MIL-E-7729 ENAMEL	321 S. ST.	" " "					.5		93

III.

Figures

LIQUID WATER DENSITY
(59)

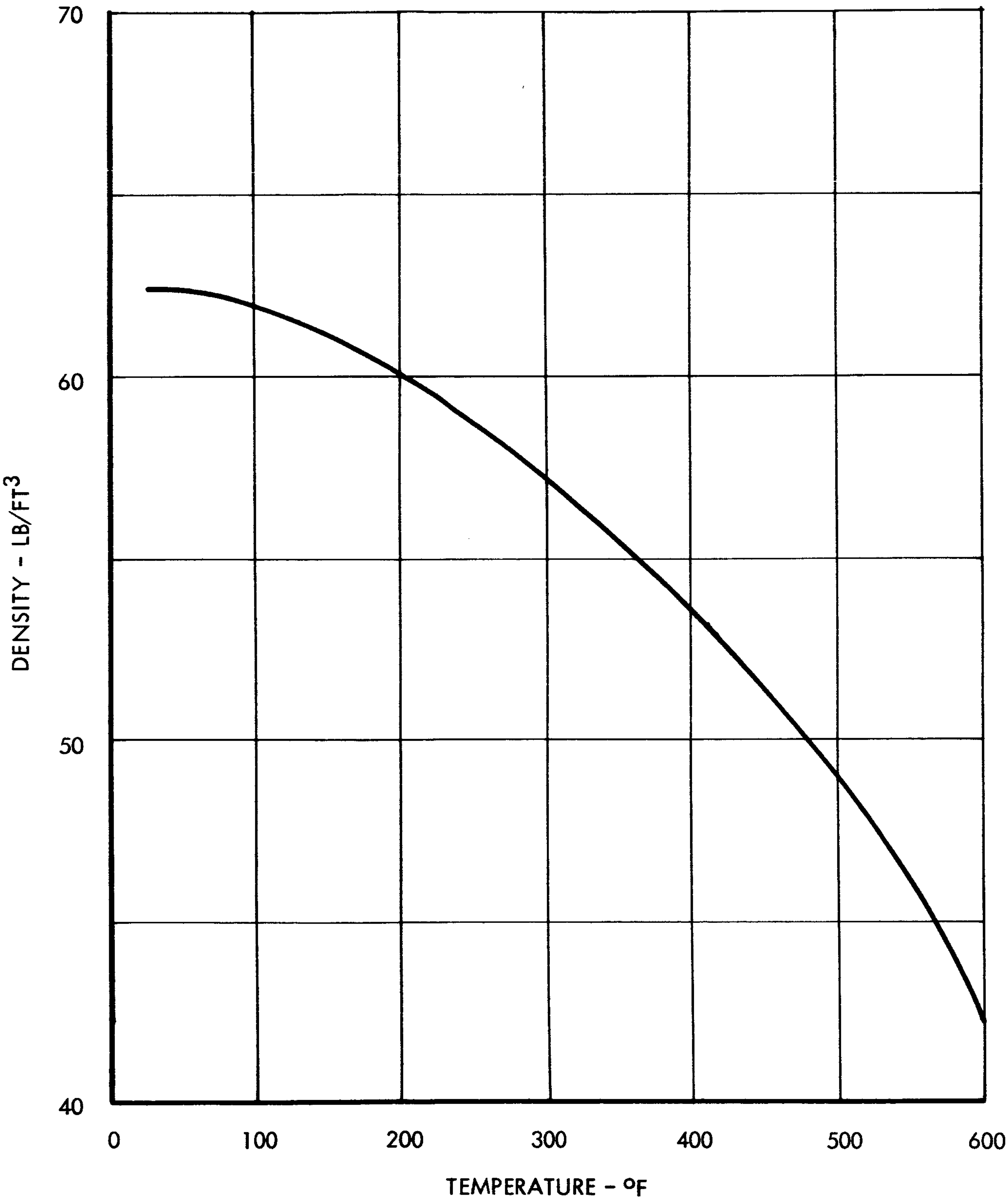


FIGURE 1

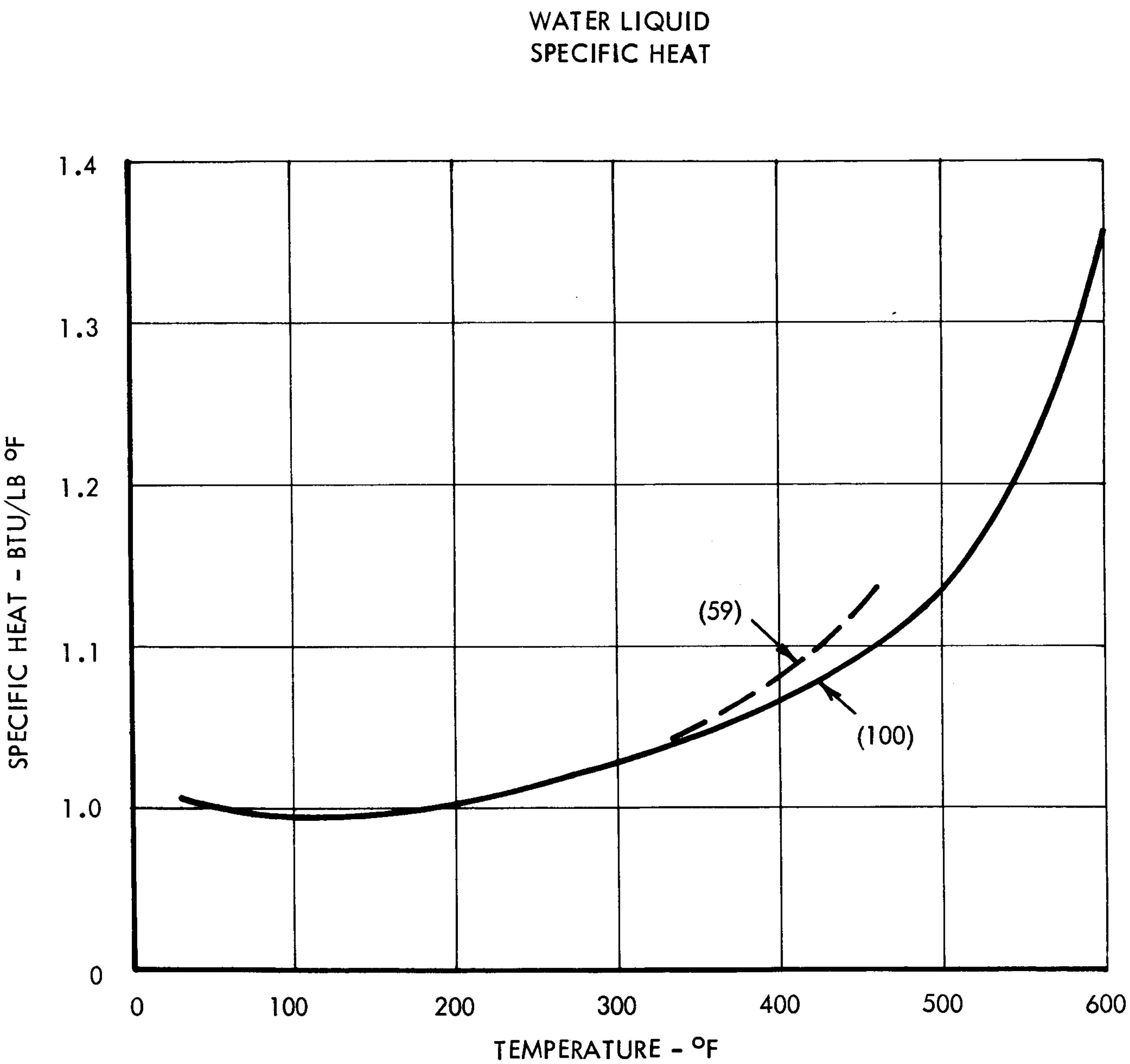

WATER LIQUID
SPECIFIC HEAT
SPECIFIC HEAT - BTU/LB °F
1.4
1.3
1.2
1.1
1.0
0
0
100
200
300
400
500
600
TEMPERATURE - °F
(59)
(100)

FIGURE 2

WATER HEAT OF EVAPORIZATION
(59)

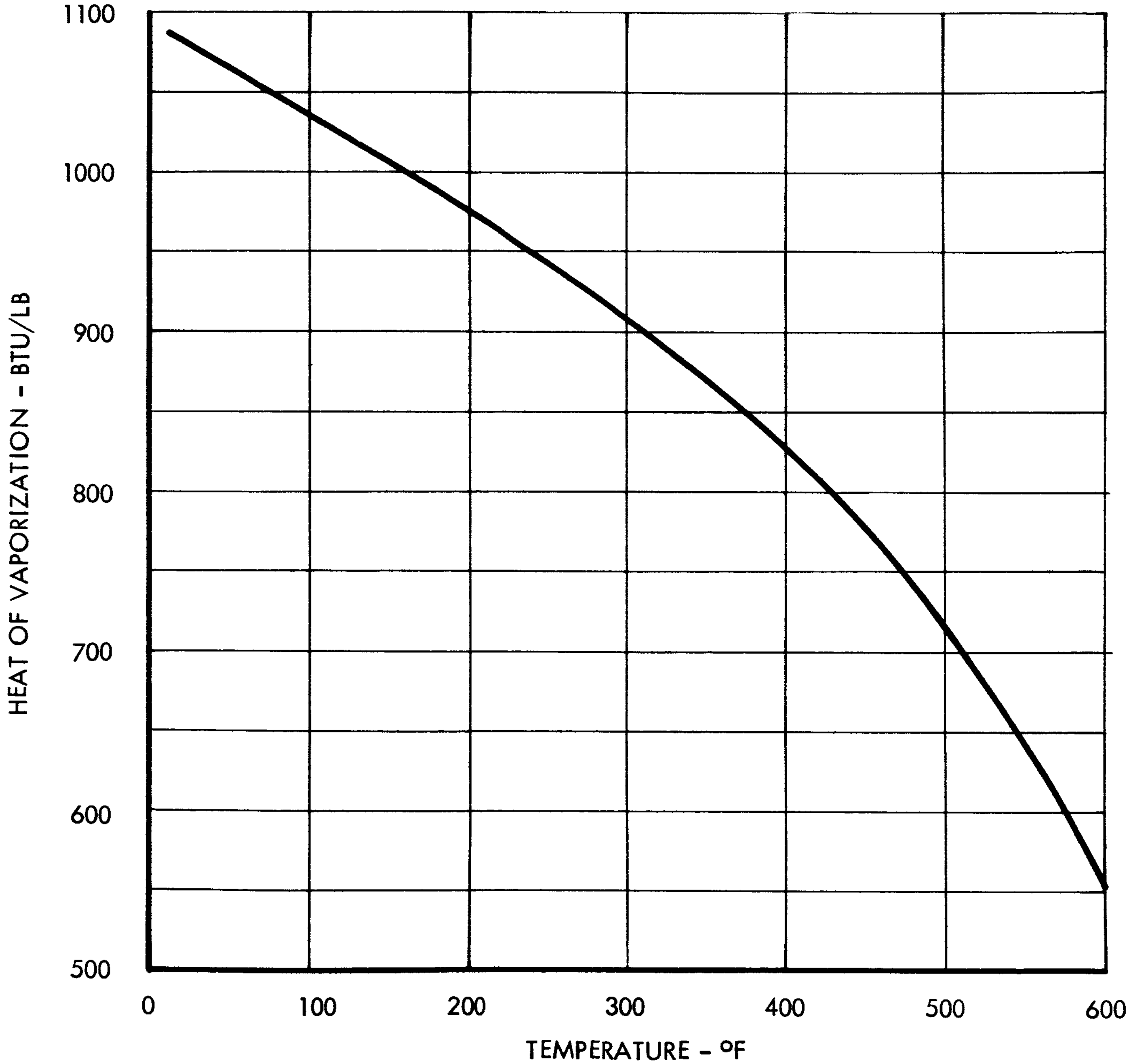


FIGURE 3

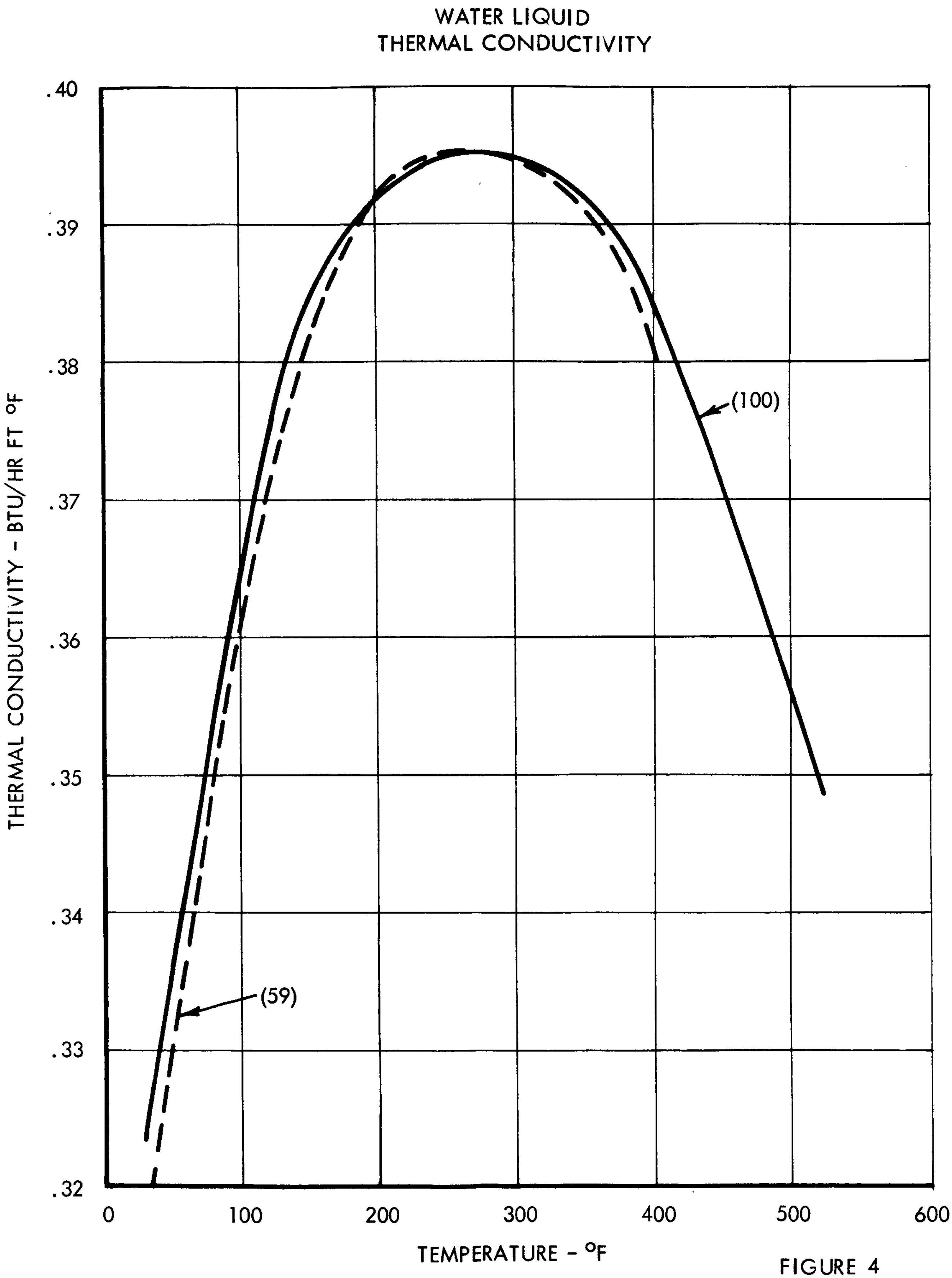

WATER LIQUID
THERMAL CONDUCTIVITY
THERMAL CONDUCTIVITY - BTU/HR FT °F
.40
.39
.38
.37
.36
.35
.34
.33
.32
0
100
200
300
400
500
600
TEMPERATURE - °F
(100)
(59)

FIGURE 4

LIQUID WATER VISCOSITY
(ABSOLUTE)
(59)

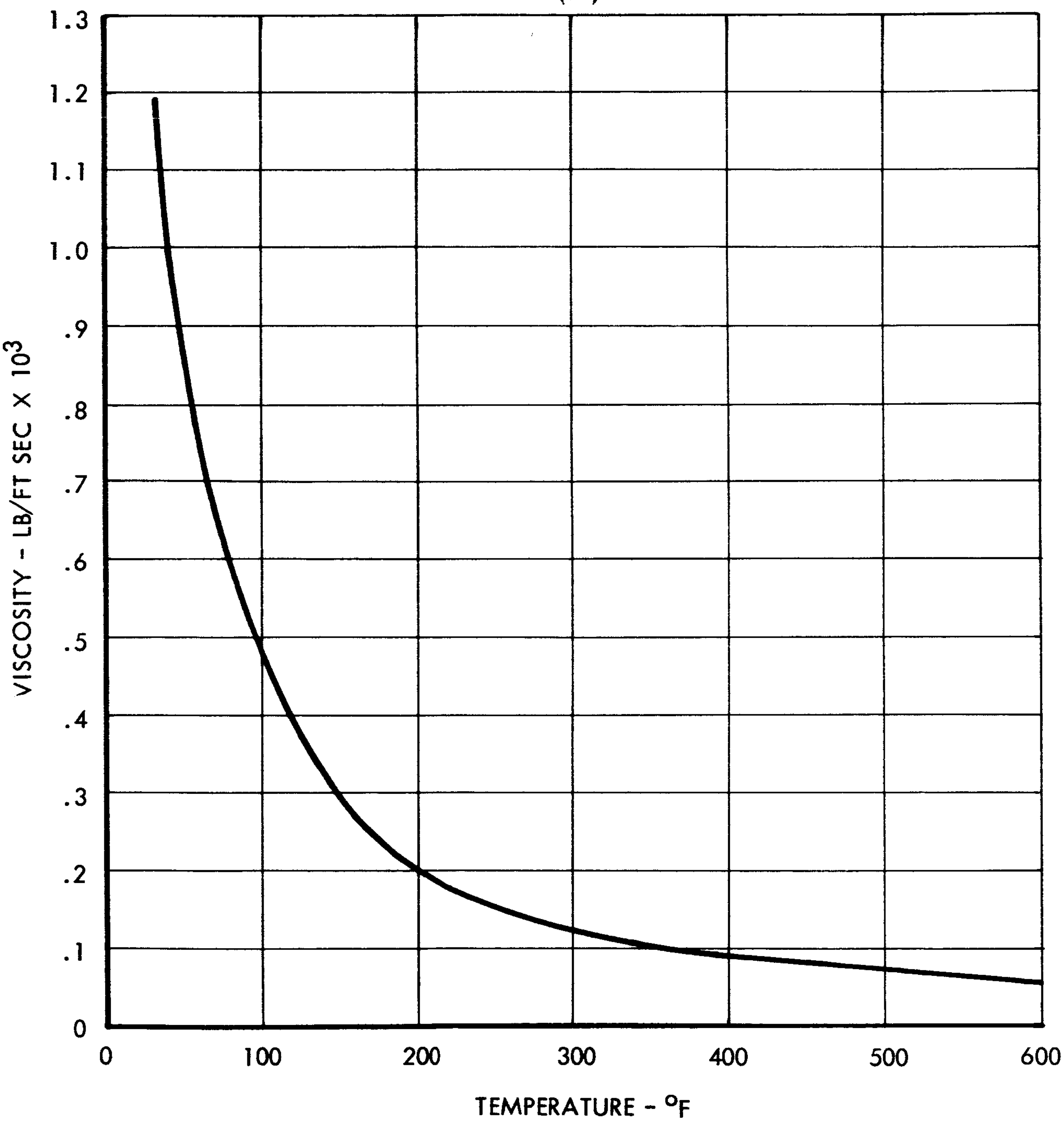


FIGURE 5

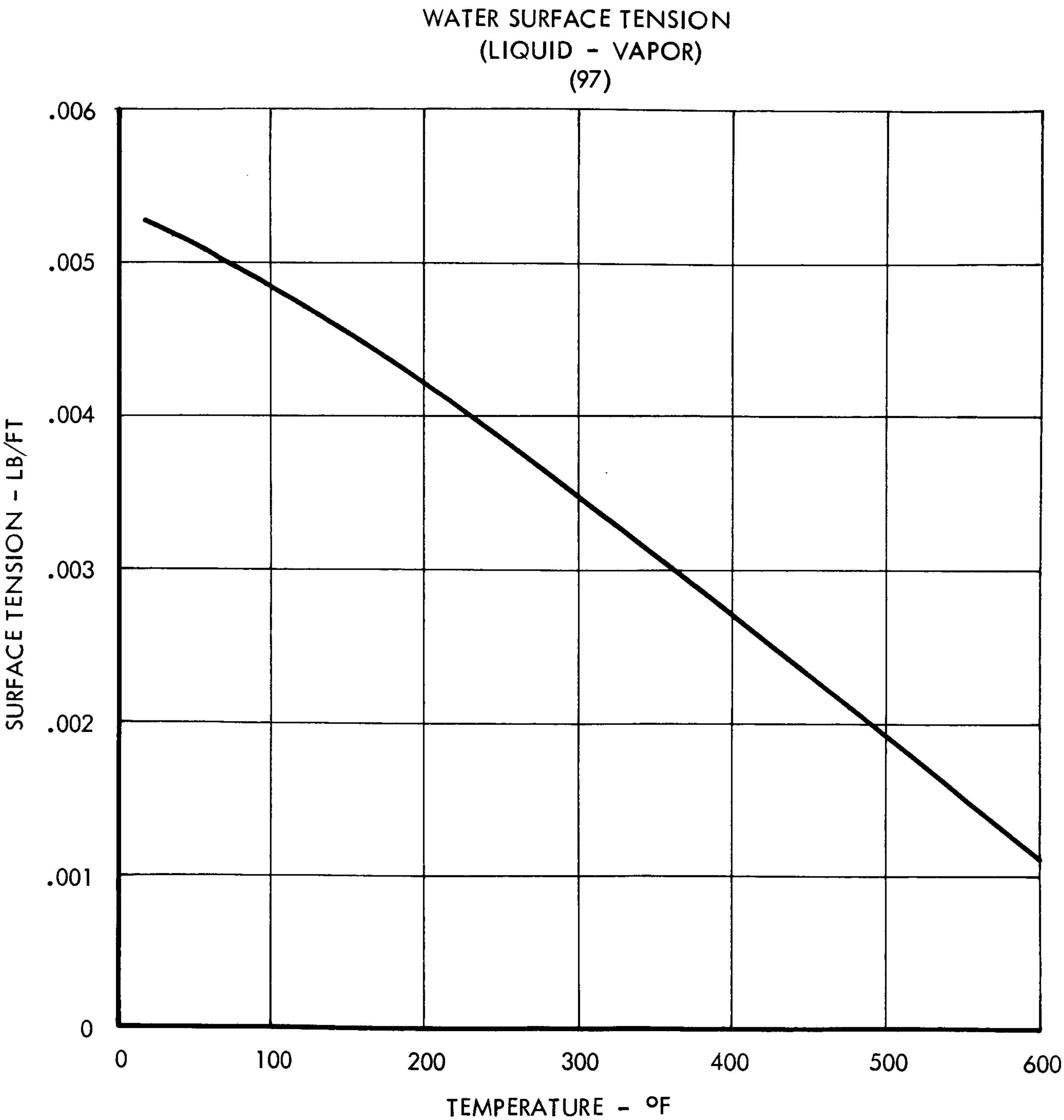

WATER SURFACE TENSION
(LIQUID - VAPOR)
(97)
.006
.005
.004
.003
.002
.001
0
SURFACE TENSION - LB/FT
0
100
200
300
400
500
600
TEMPERATURE - °F

FIGURE 6

WATER VAPOR SPECIFIC HEAT (CONST P) (59)

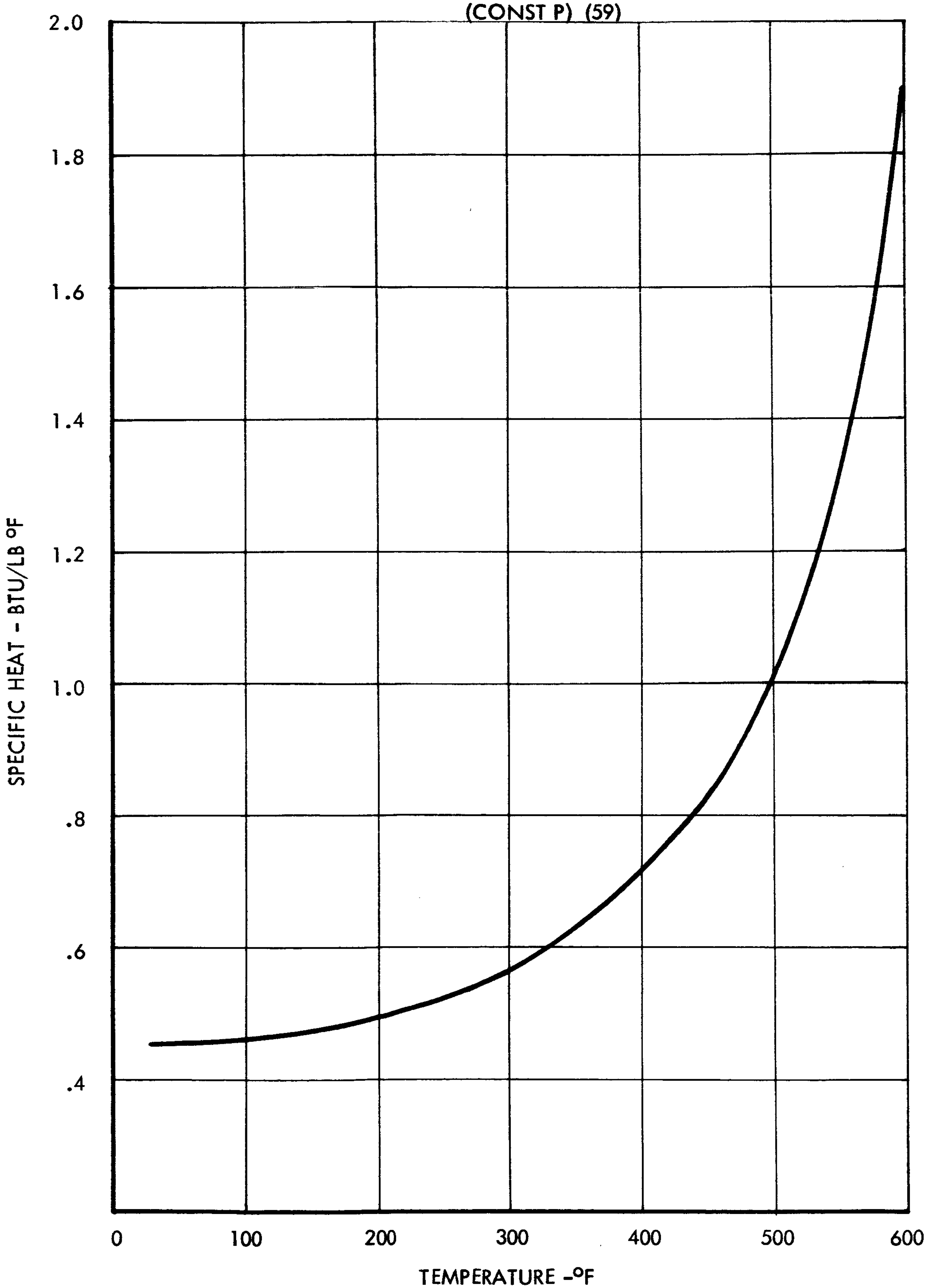


FIGURE 7

WATER VAPOR THERMAL CONDUCTIVITY

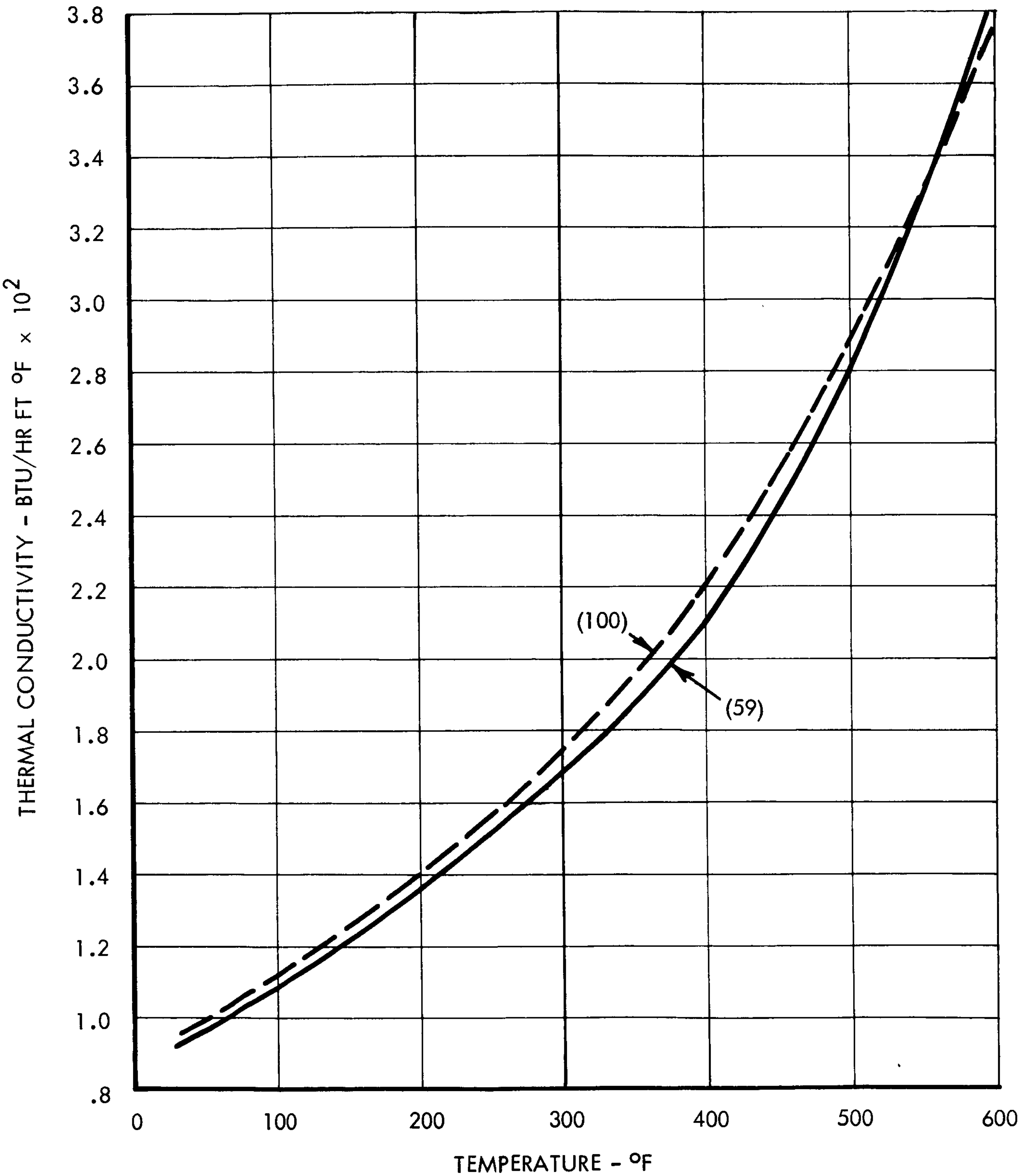


FIGURE 8

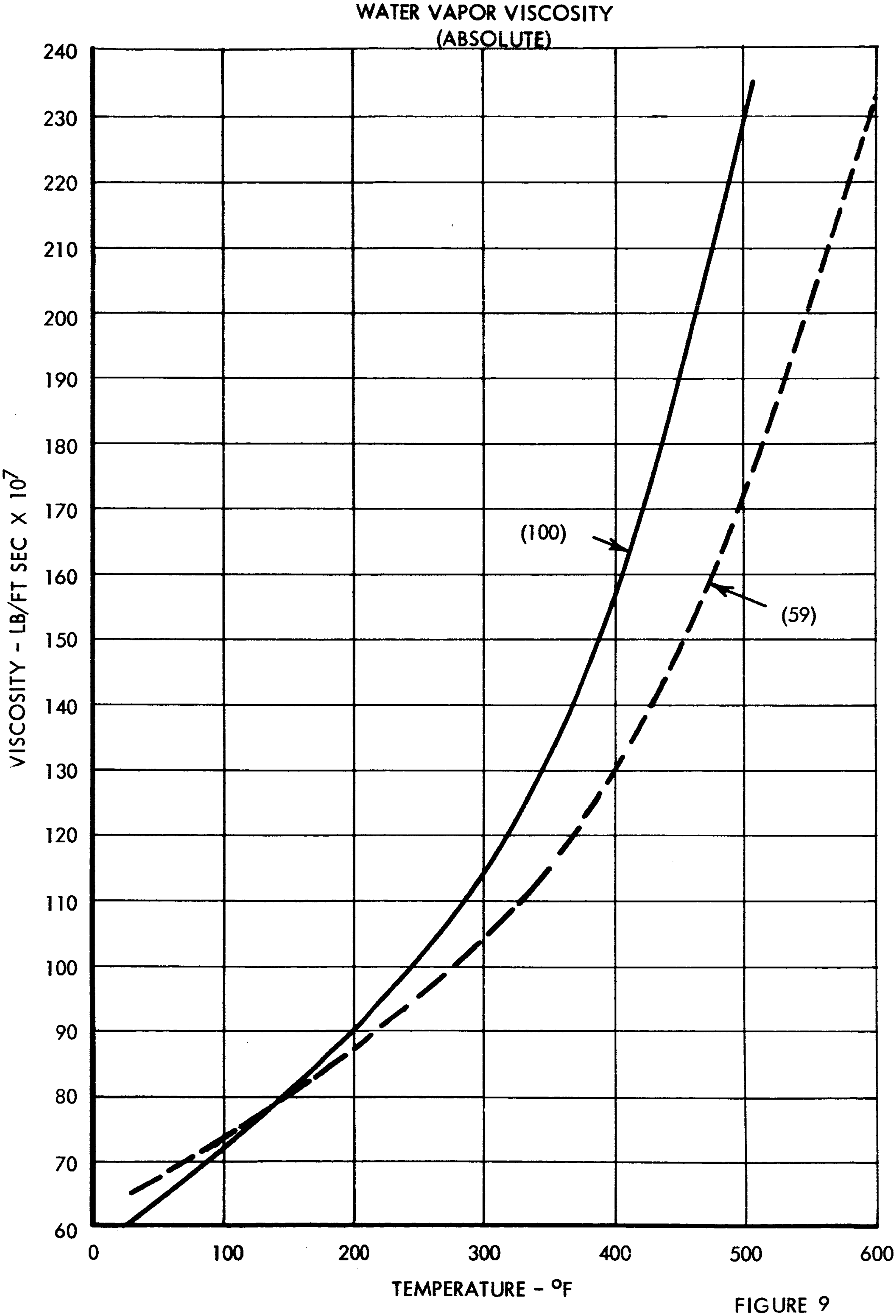

WATER VAPOR VISCOSITY
(ABSOLUTE)
VISCOSITY - LB/FT SEC X 10^7
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
0
100
200
300
400
500
600
TEMPERATURE - °F
(100)
(59)

FIGURE 9

WATER VAPOR PRESSURE
(59)

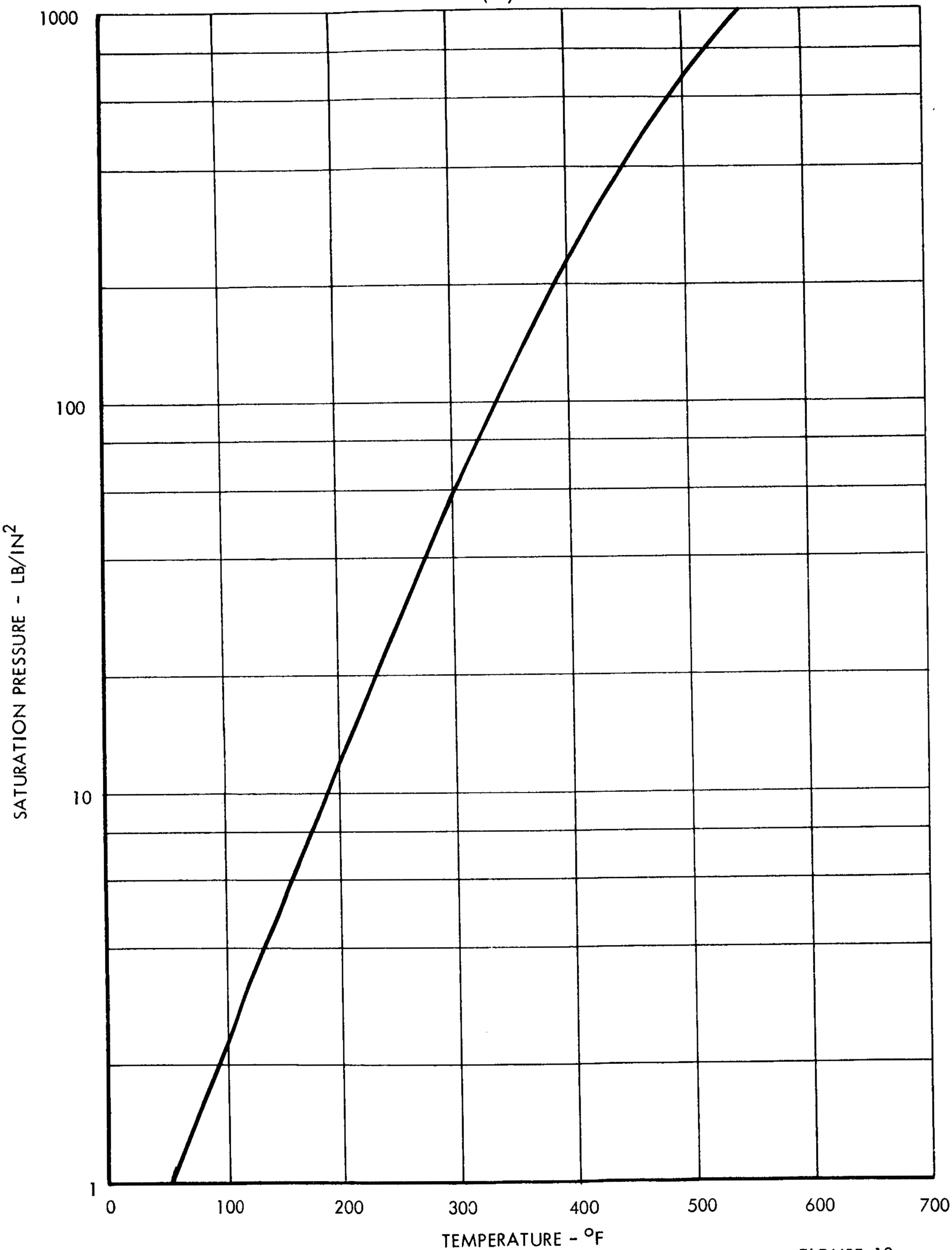


FIGURE 10

MERCURY LIQUID
DENSITY

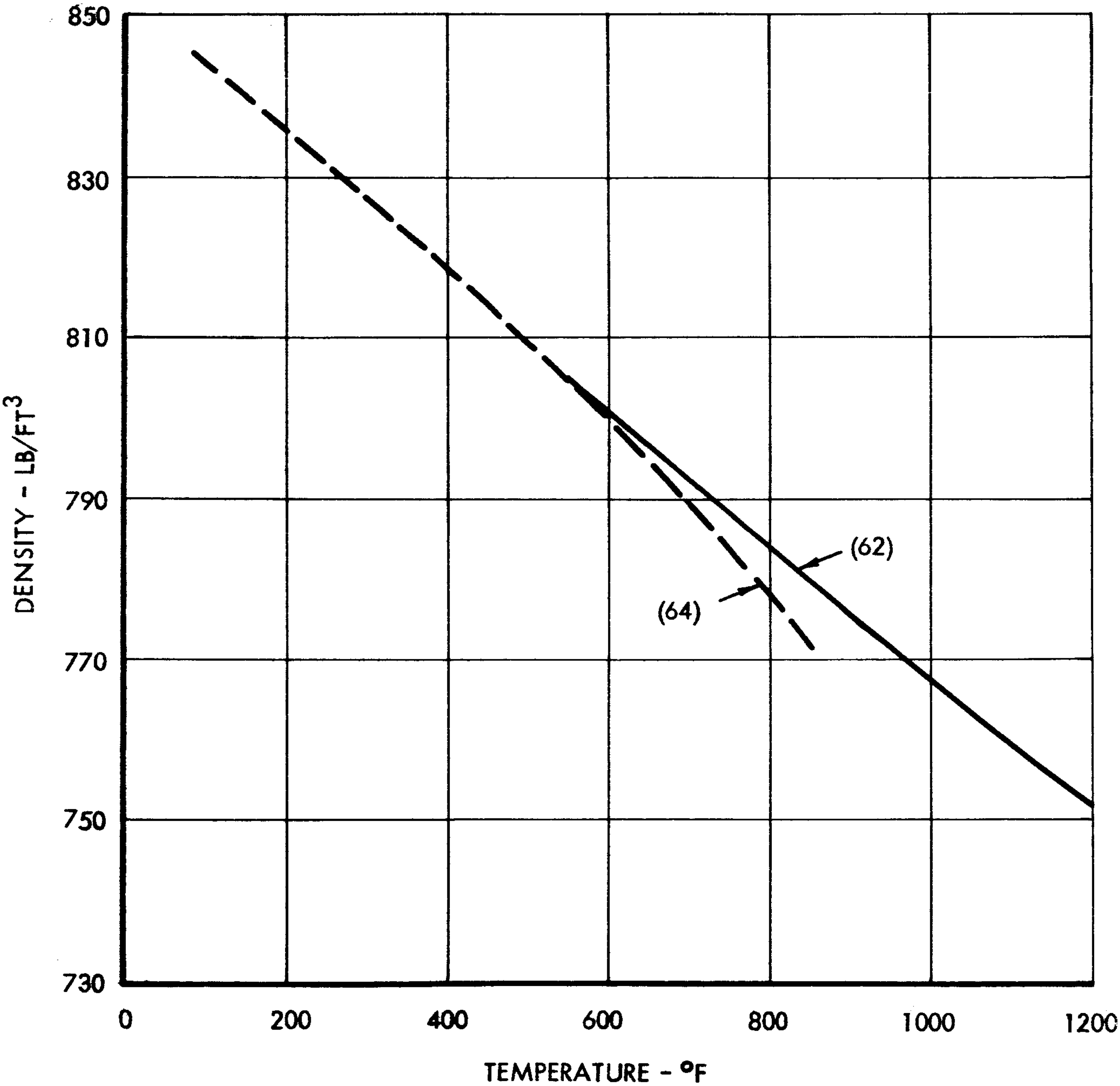


FIGURE 11

MERCURY LIQUID
SPECIFIC HEAT

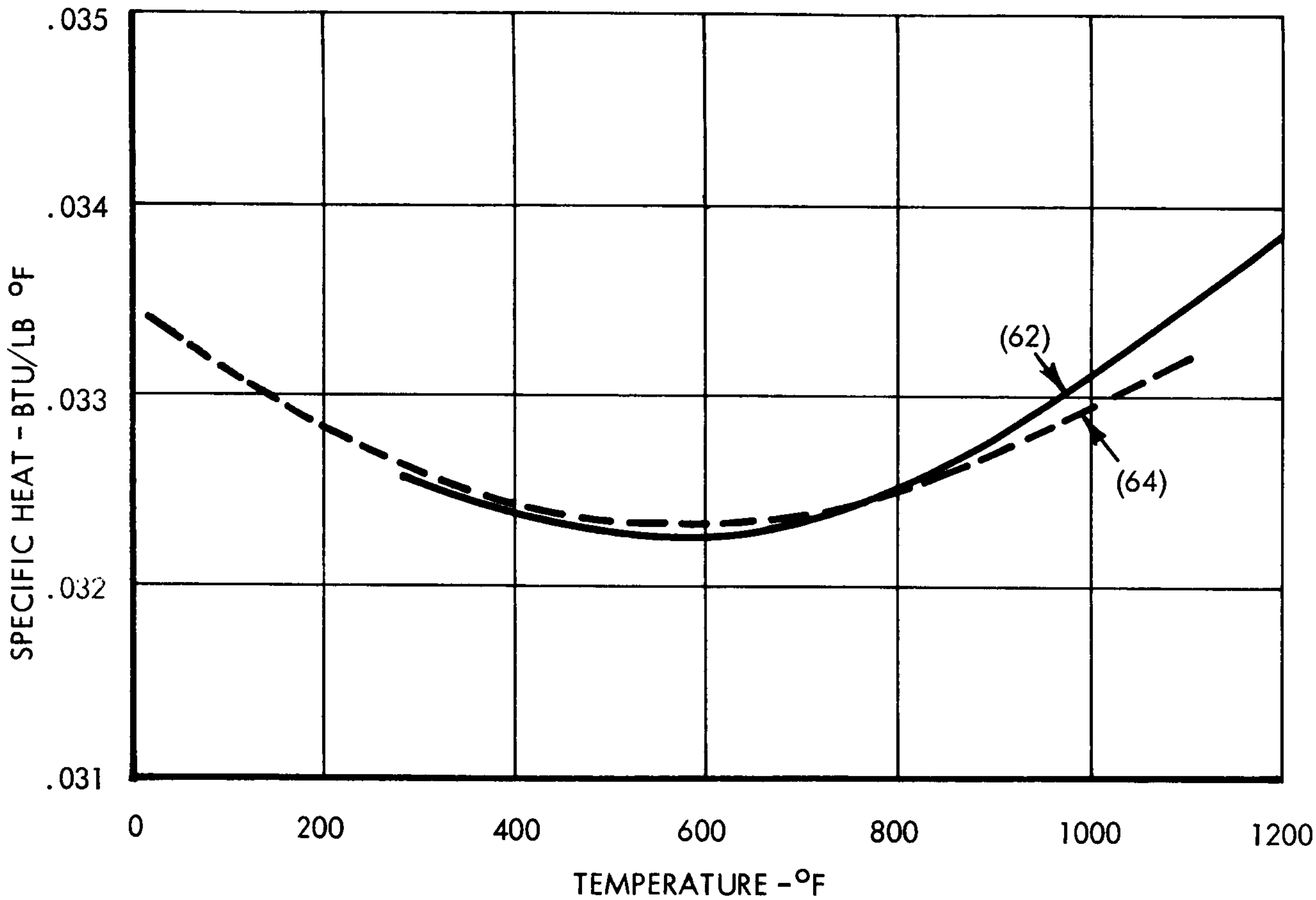


FIGURE 12

MERCURY LIQUID
THERMAL CONDUCTIVITY

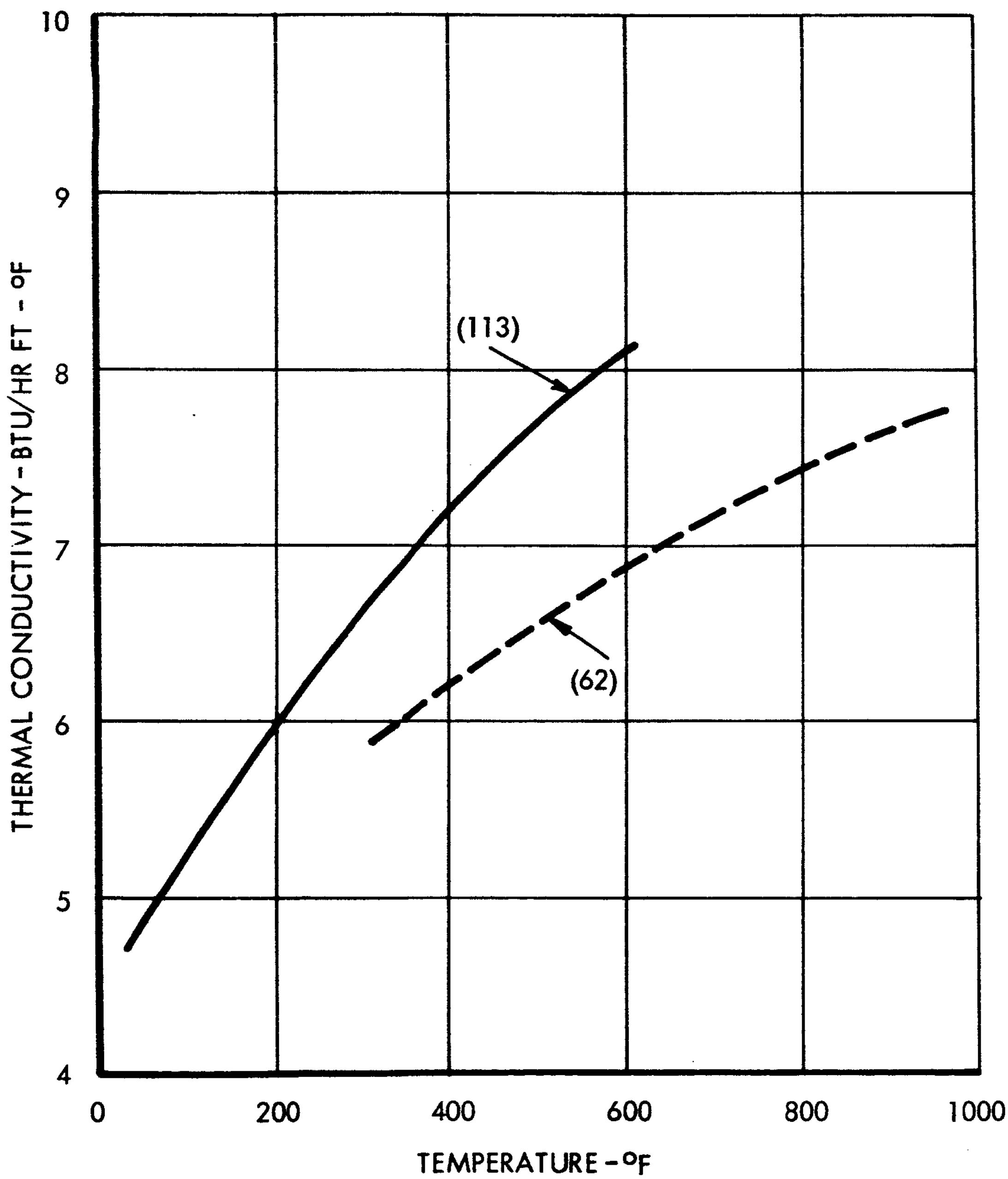


FIGURE 13

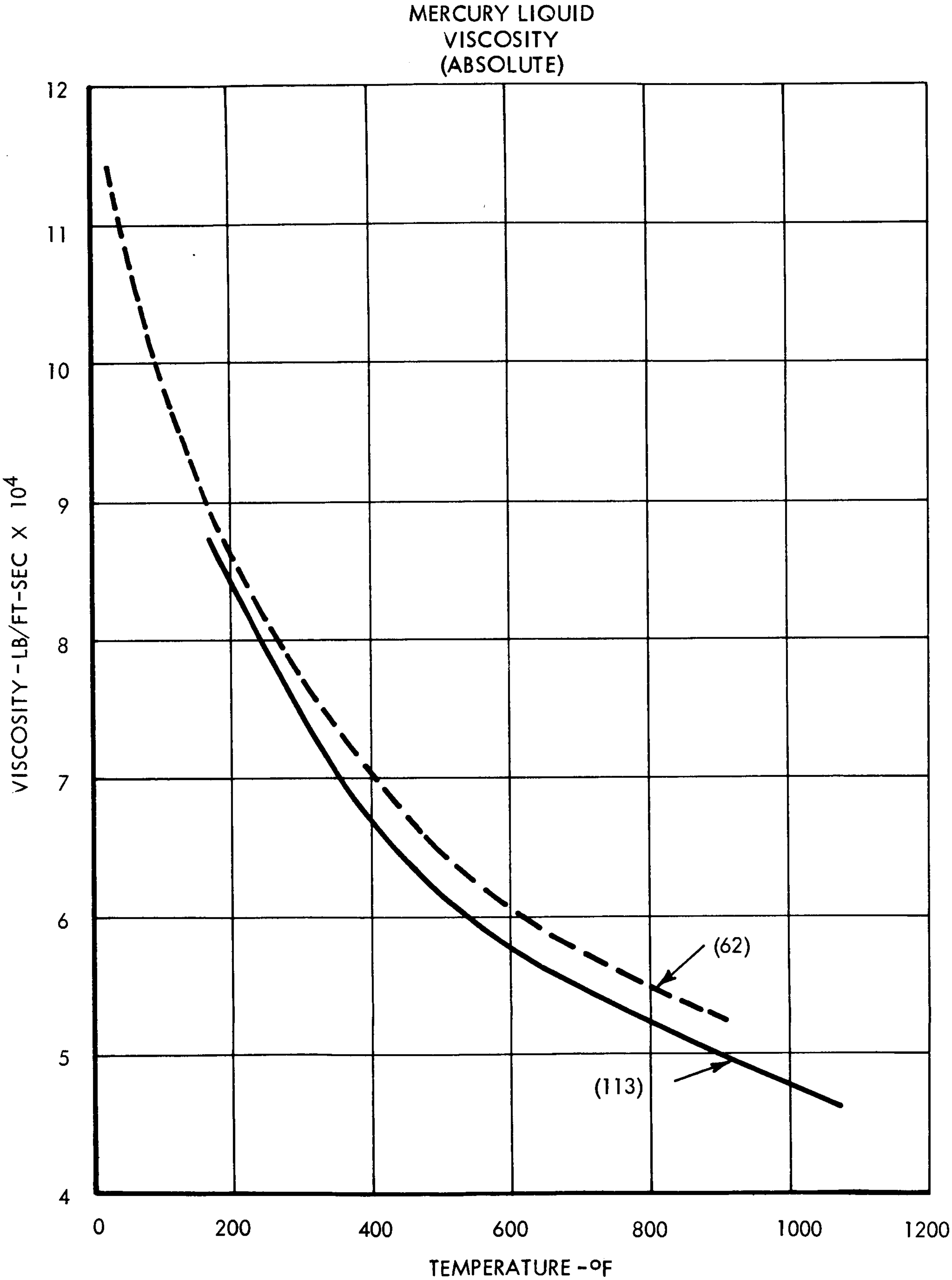

MERCURY LIQUID
VISCOSITY
(ABSOLUTE)
VISCOSITY - LB/FT-SEC X 10^4
12
11
10
9
8
7
6
5
4
0
200
400
600
800
1000
1200
TEMPERATURE - °F
(62)
(113)

FIGURE 14

MERCURY SURFACE TENSION
(LIQUID - VAPOR)

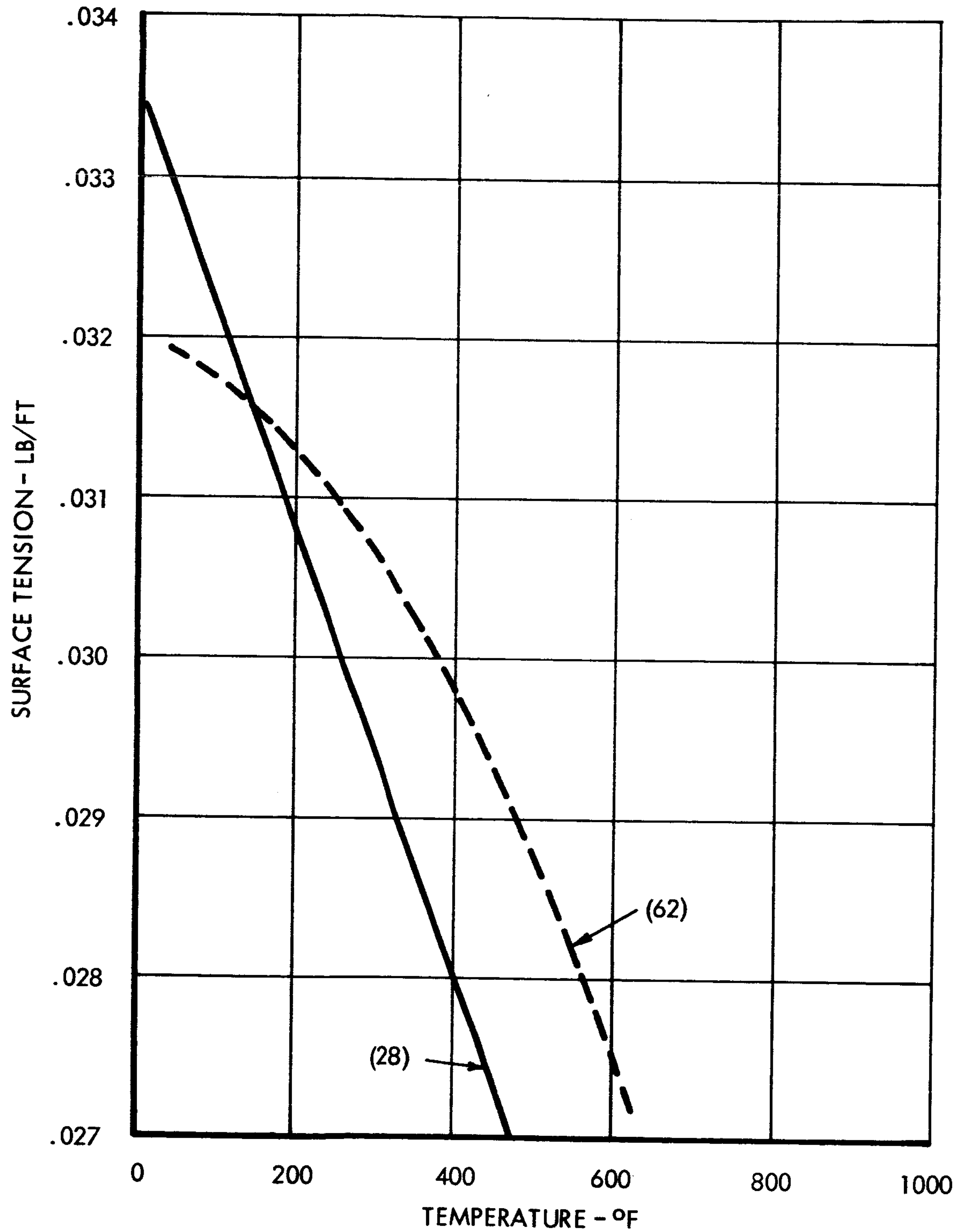


FIGURE 15

MERCURY VAPOR
THERMAL CONDUCTIVITY

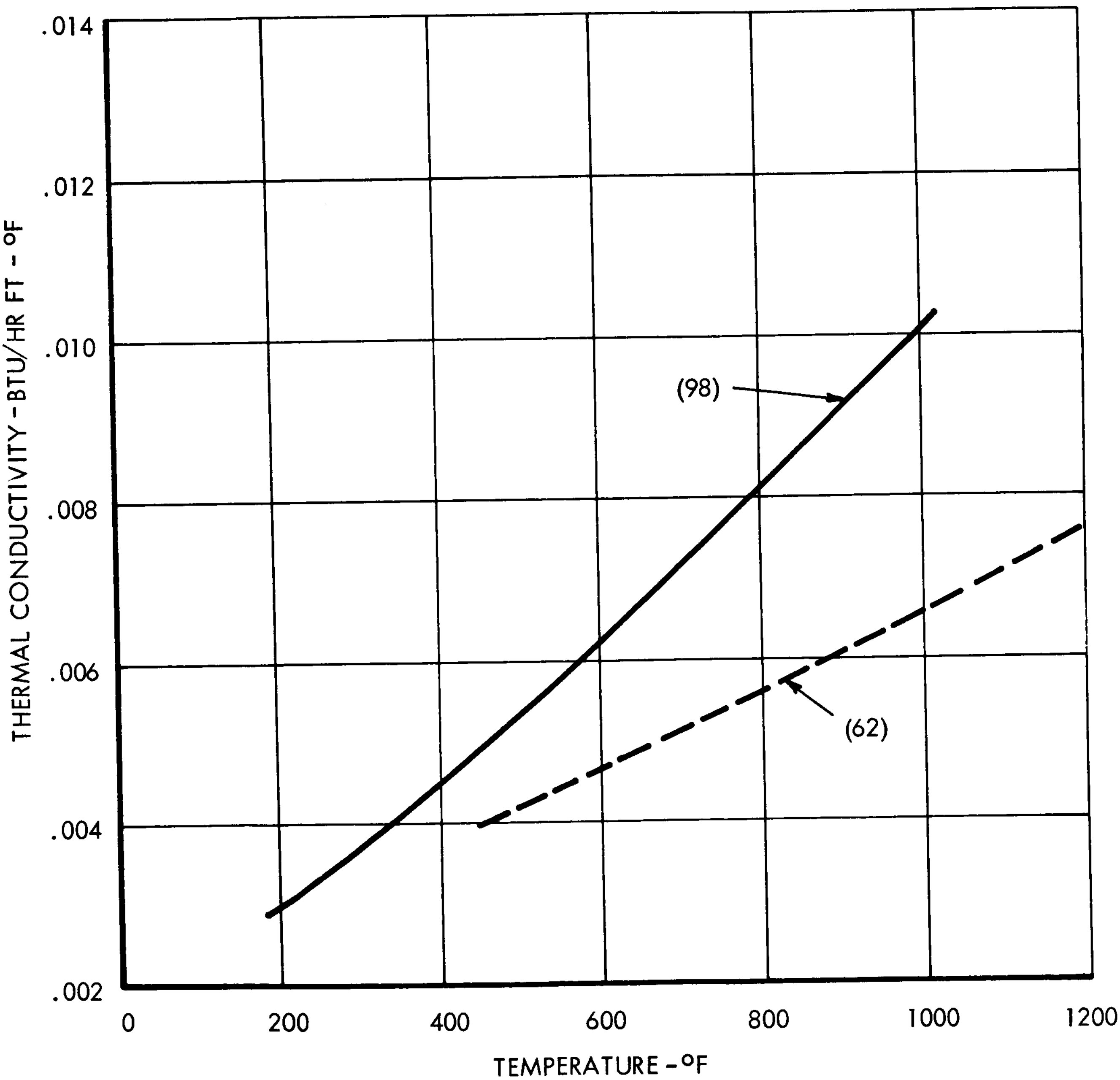


FIGURE 16

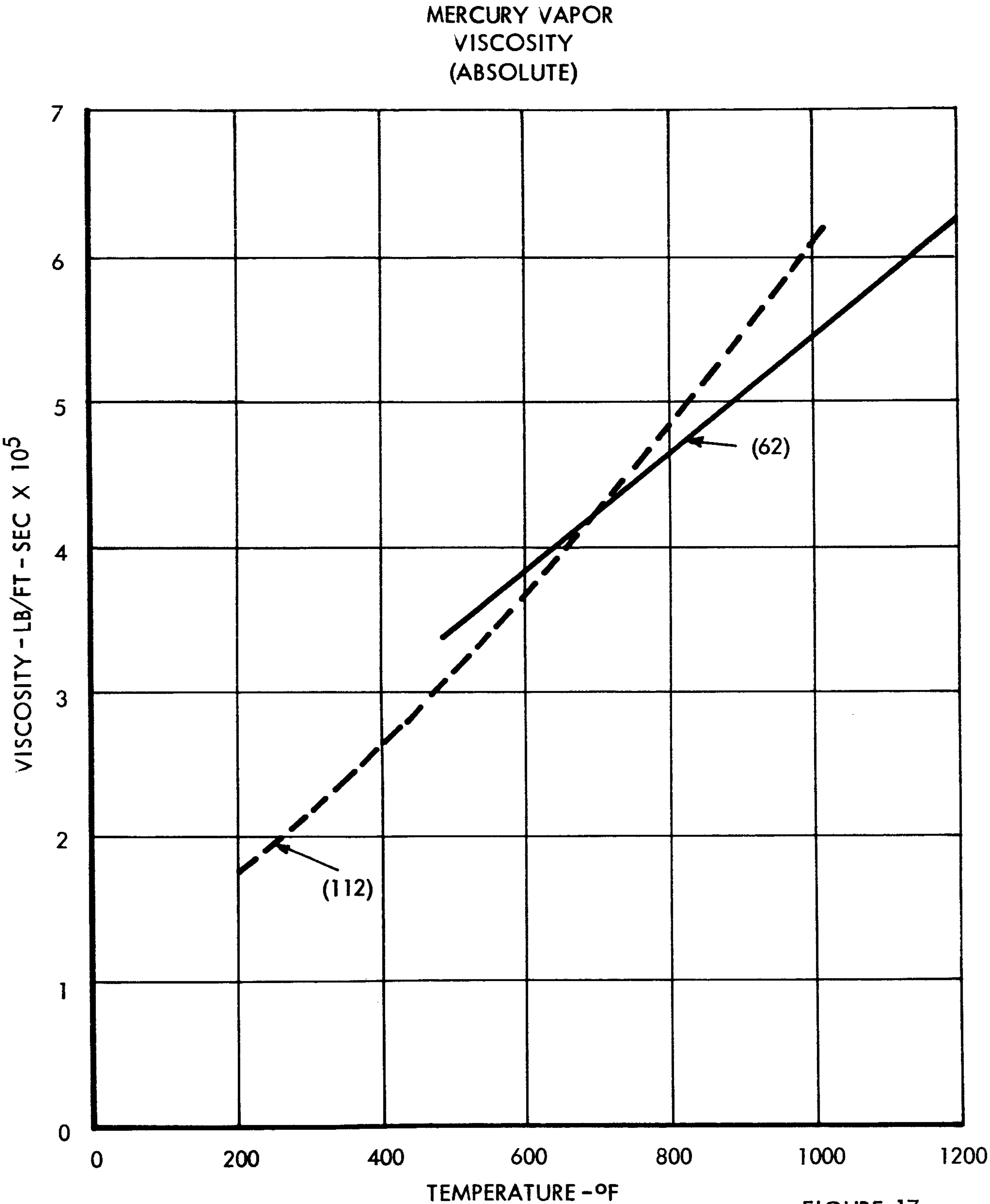

MERCURY VAPOR
VISCOSITY
(ABSOLUTE)
VISCOSITY - LB/FT - SEC X 10^5
0
1
2
3
4
5
6
7
0
200
400
600
800
1000
1200
TEMPERATURE - °F
(62)
(112)

FIGURE 17

MERCURY VAPOR PRESSURE
(111)

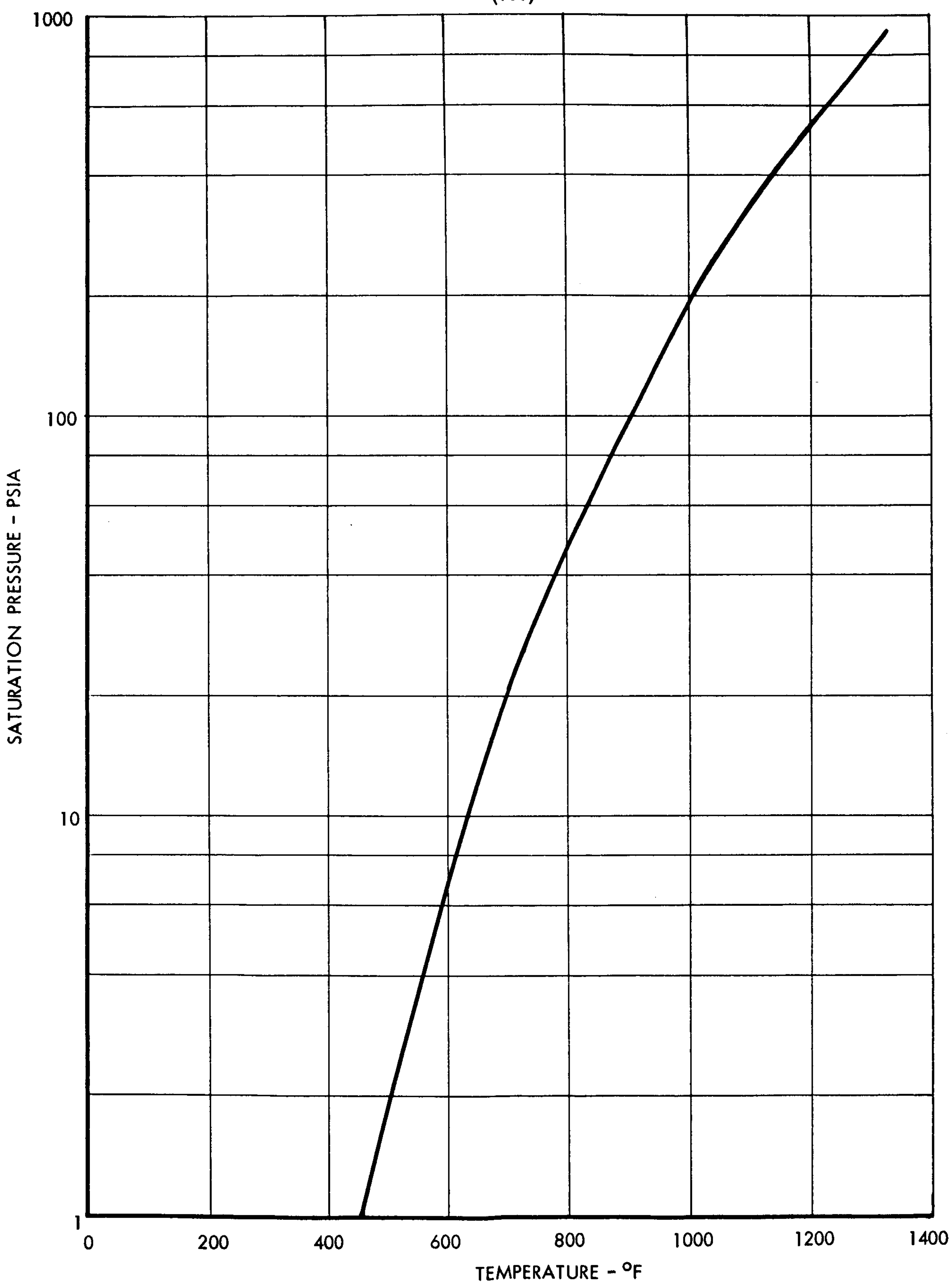


FIGURE 18

POTASSIUM LIQUID DENSITY

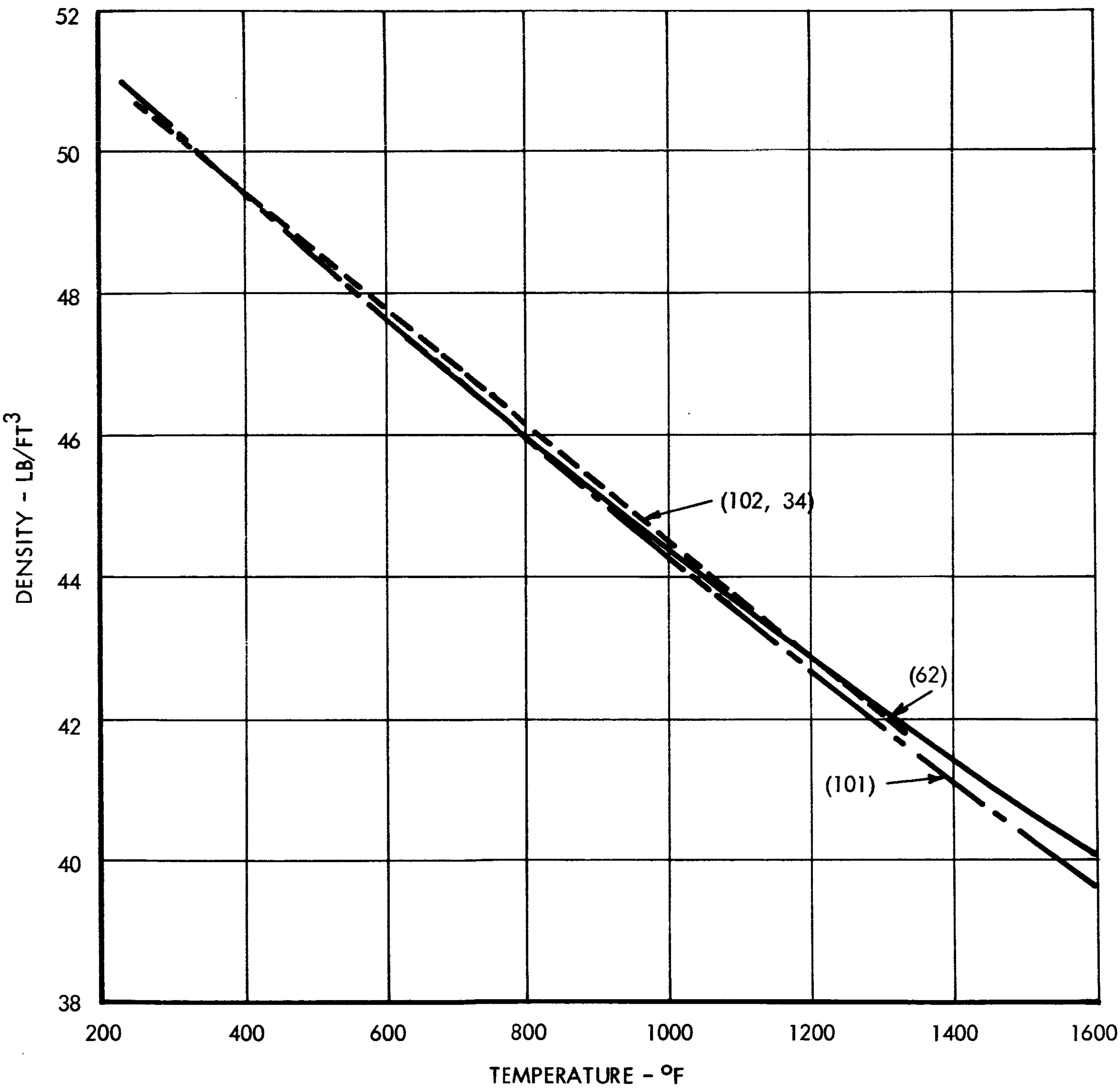


FIGURE 19

POTASSIUM LIQUID
SPECIFIC HEAT

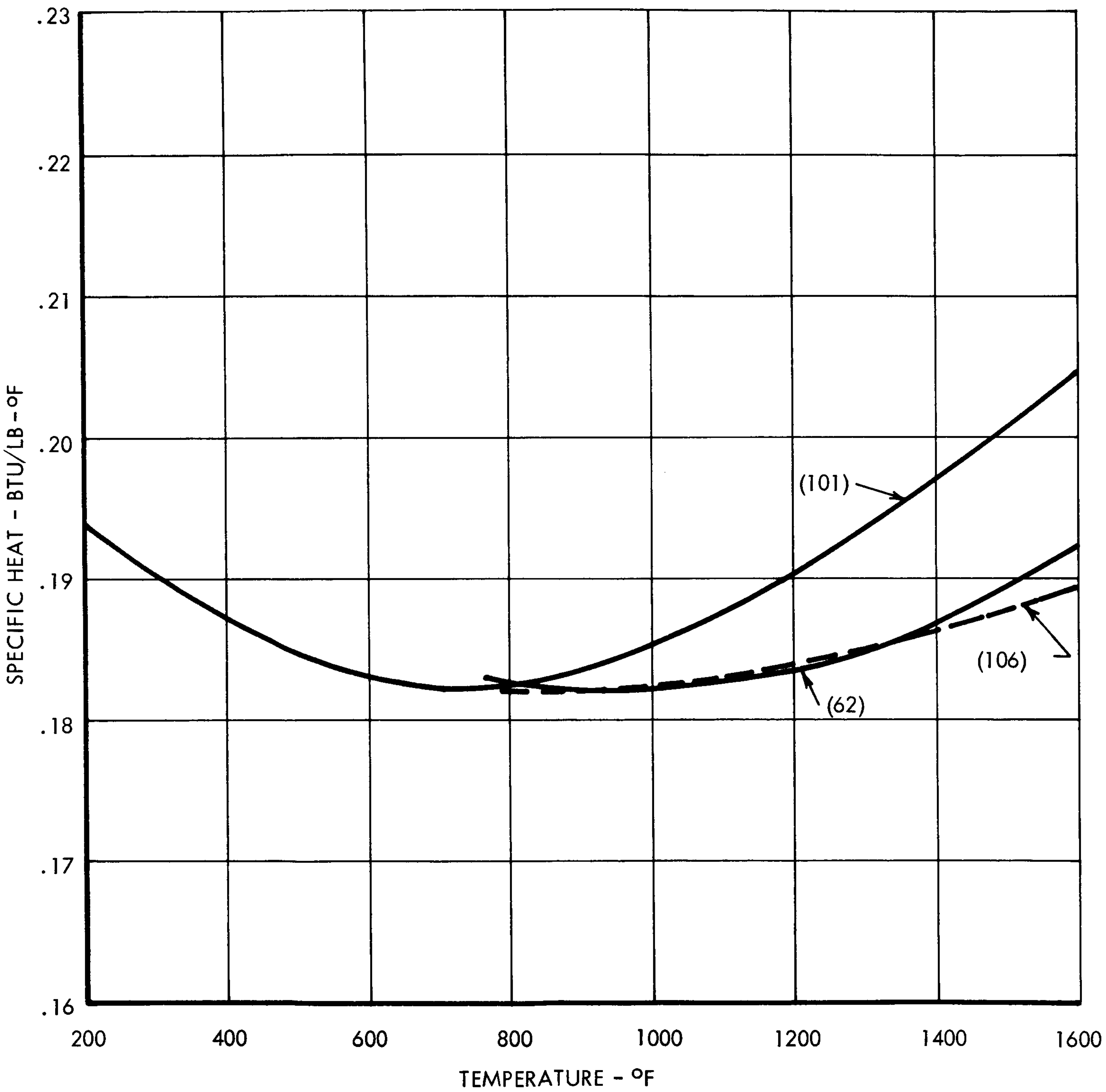


FIGURE 20

POTASSIUM HEAT OF VAPORIZATION

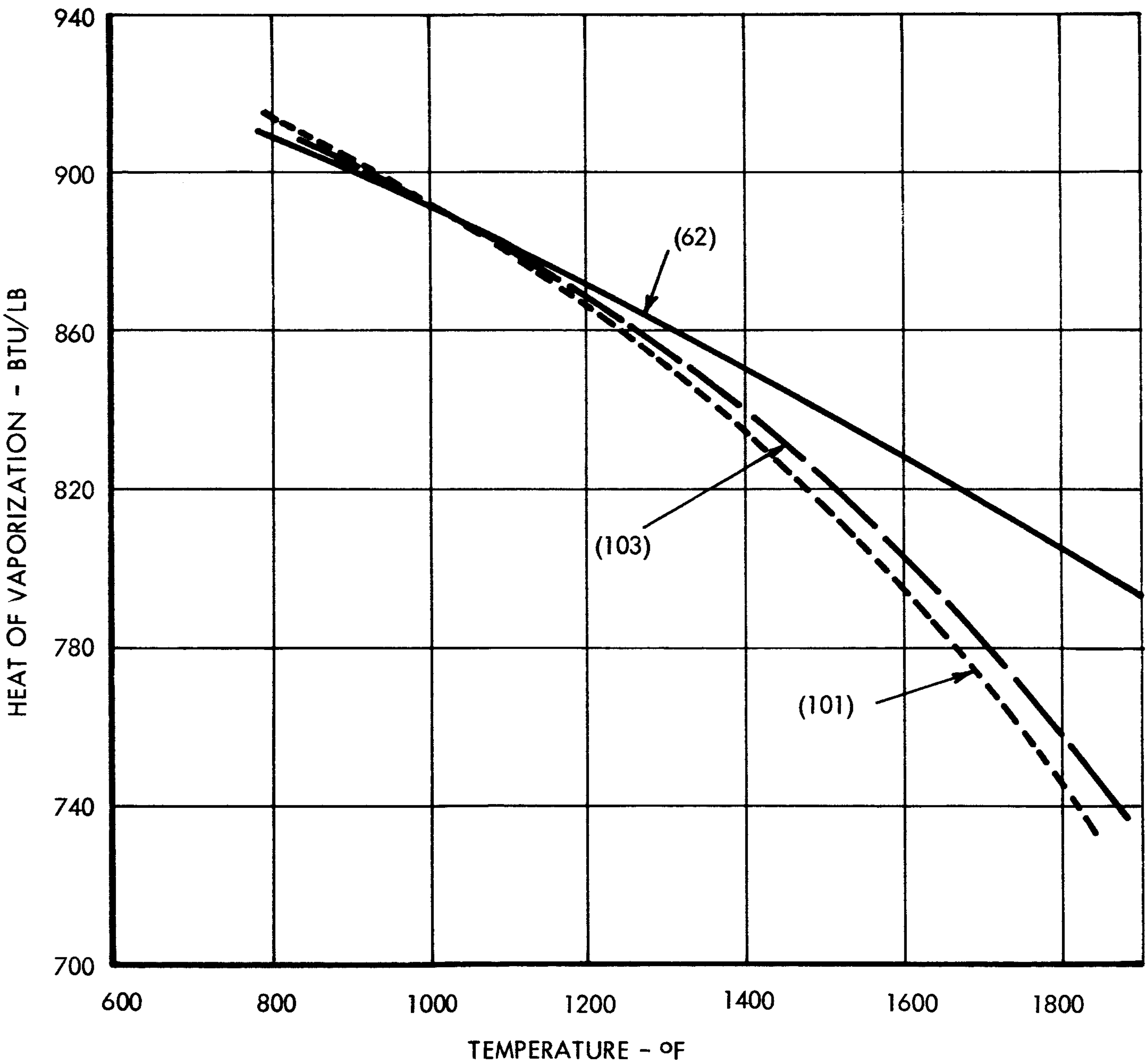


FIGURE 21

POTASSIUM LIQUID
THERMAL CONDUCTIVITY

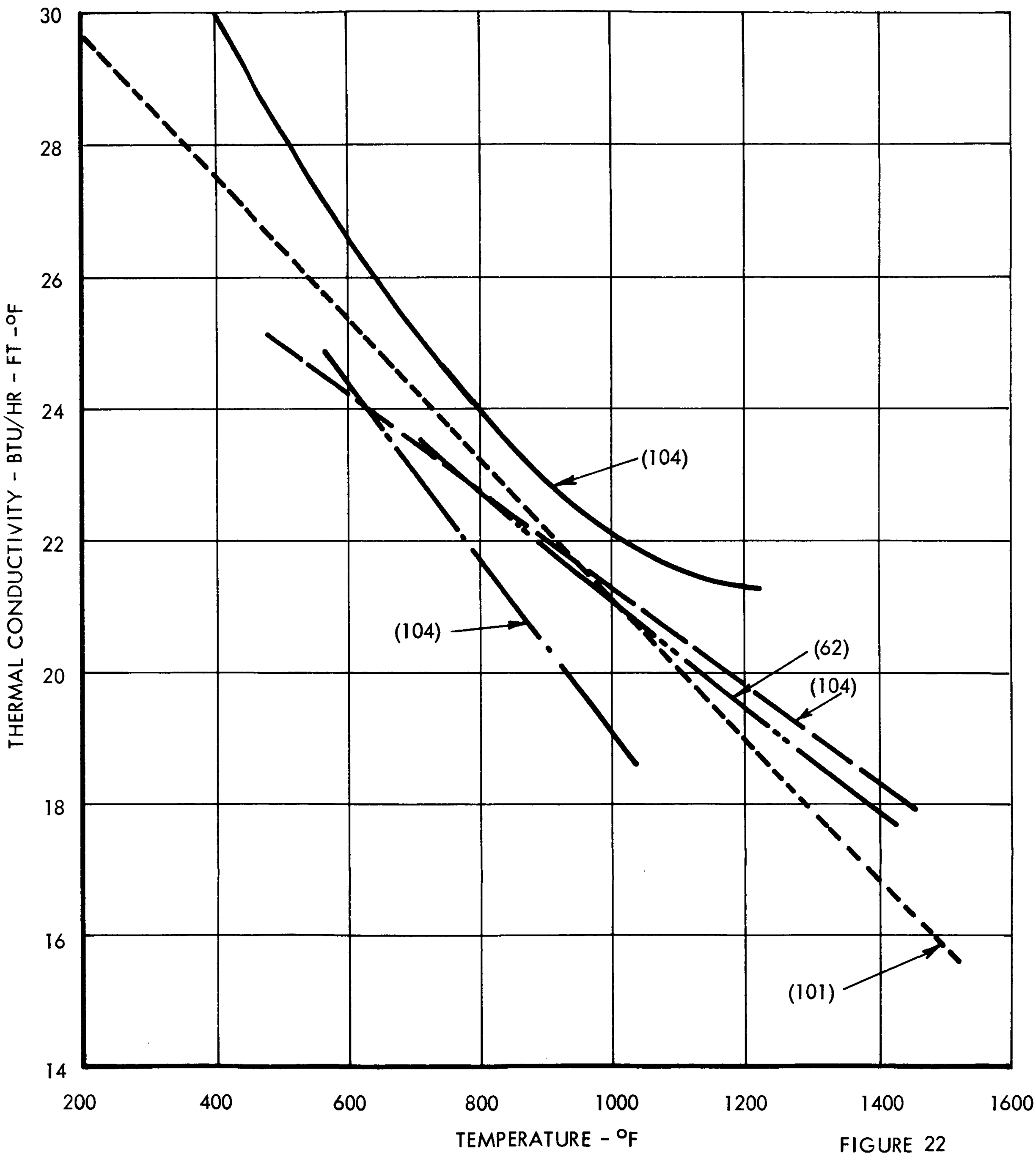


FIGURE 22

POTASSIUM LIQUID VISCOSITY
(ABSOLUTE)

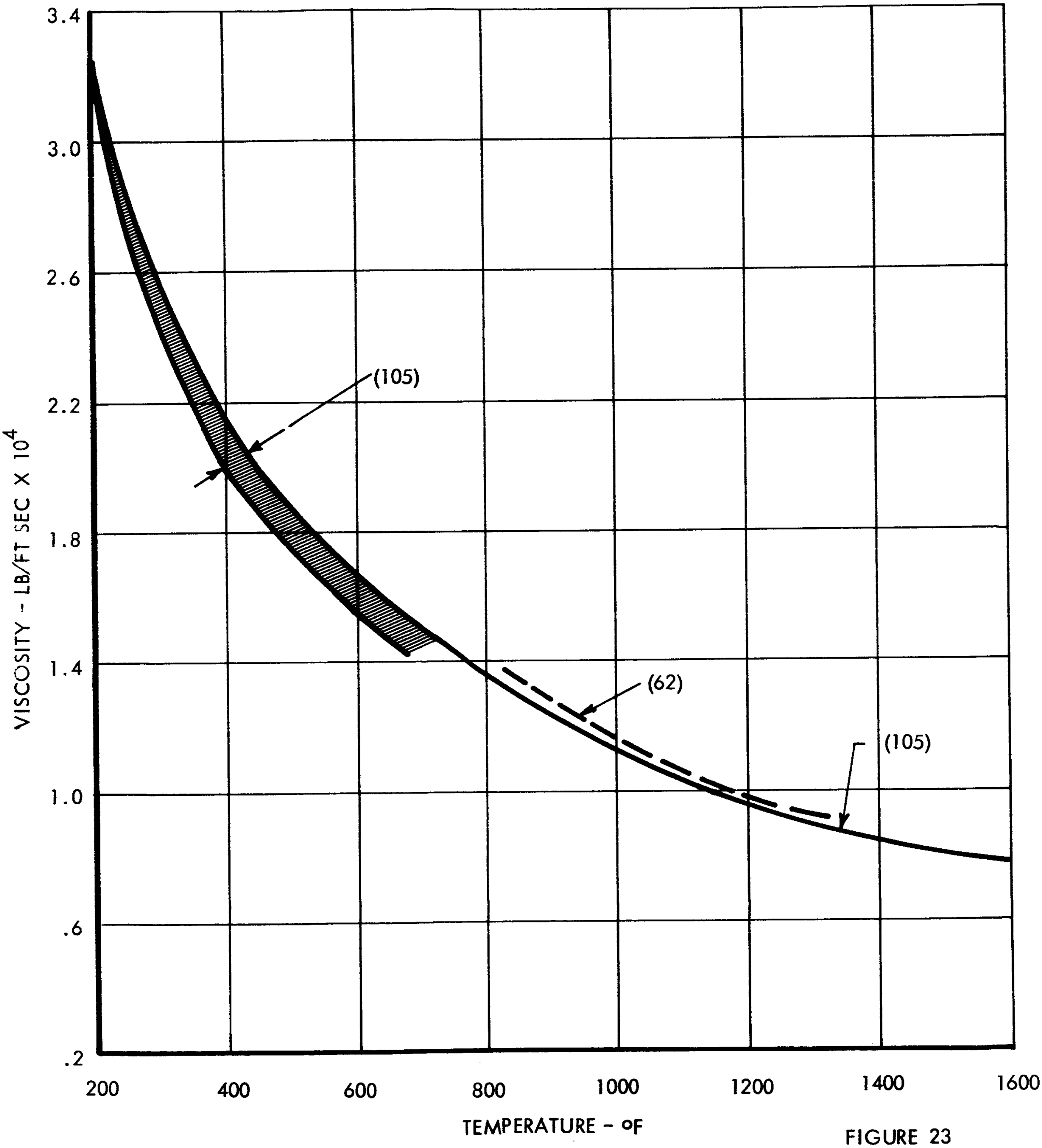


FIGURE 23

POTASSIUM SURFACE TENSION
(LIQUID-VAPOR)

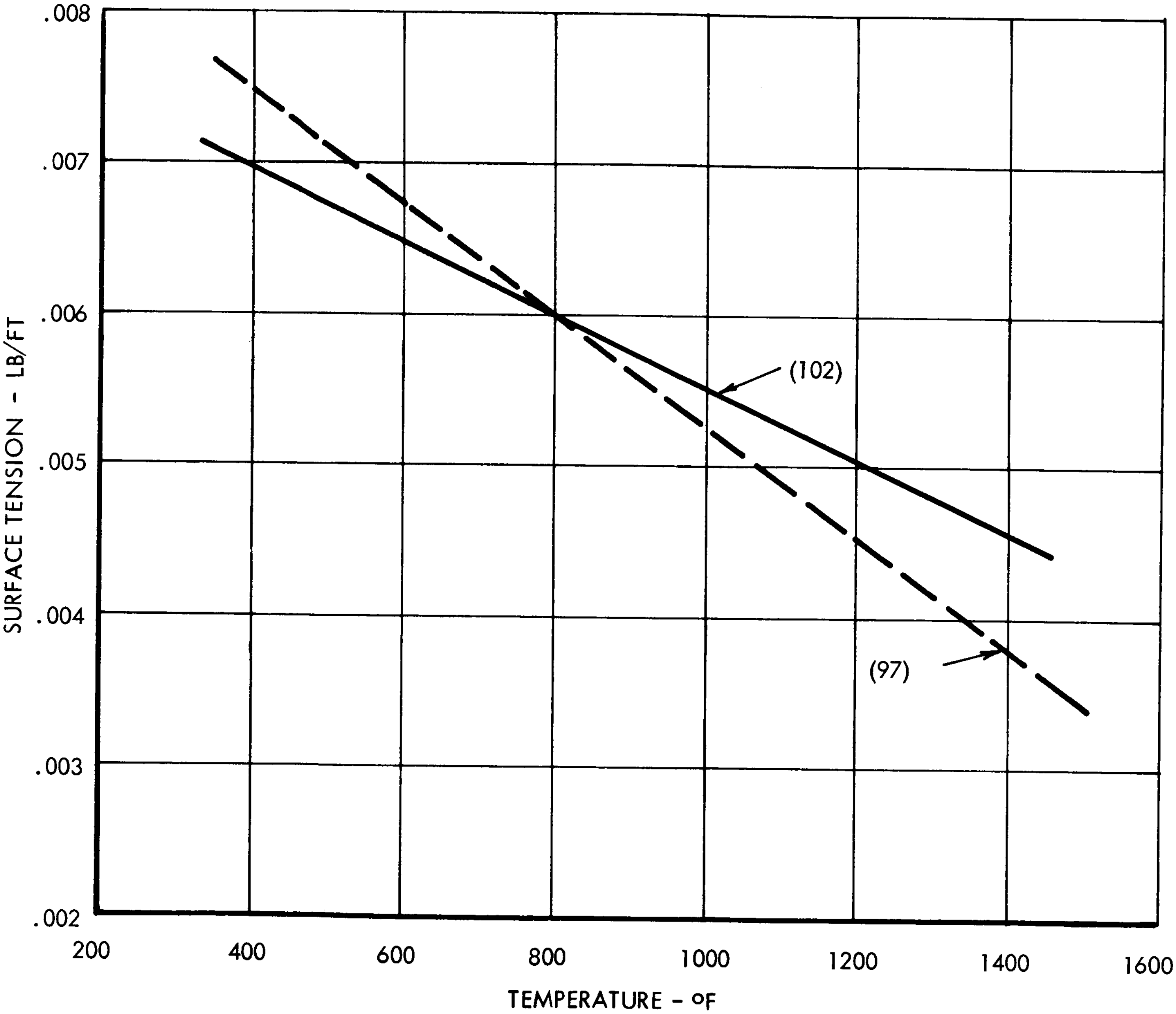


FIGURE 24

POTASSIUM VAPOR SPECIFIC HEAT
(CONST. P)

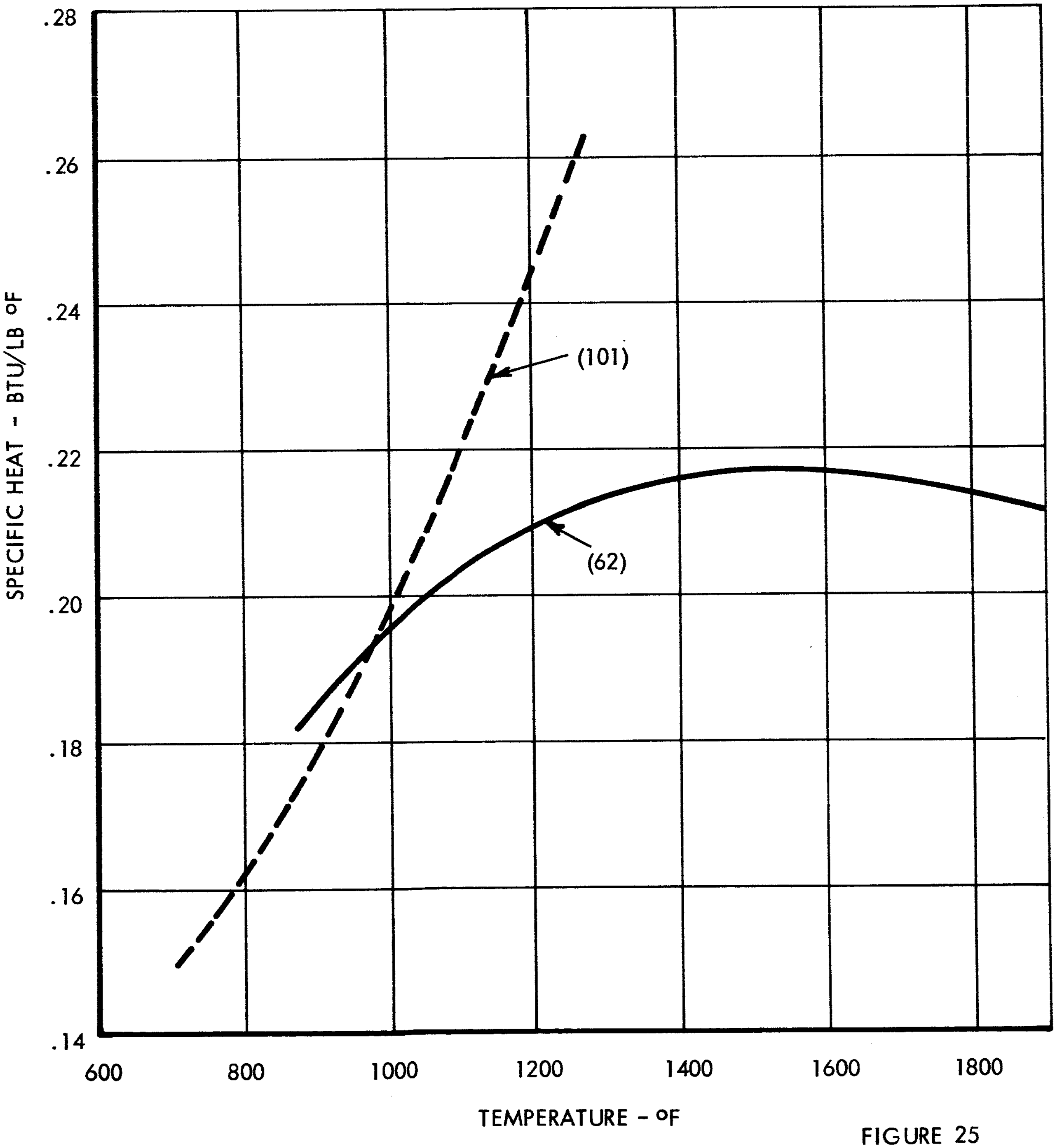


FIGURE 25

POTASSIUM VAPOR THERMAL CONDUCTIVITY
(62)

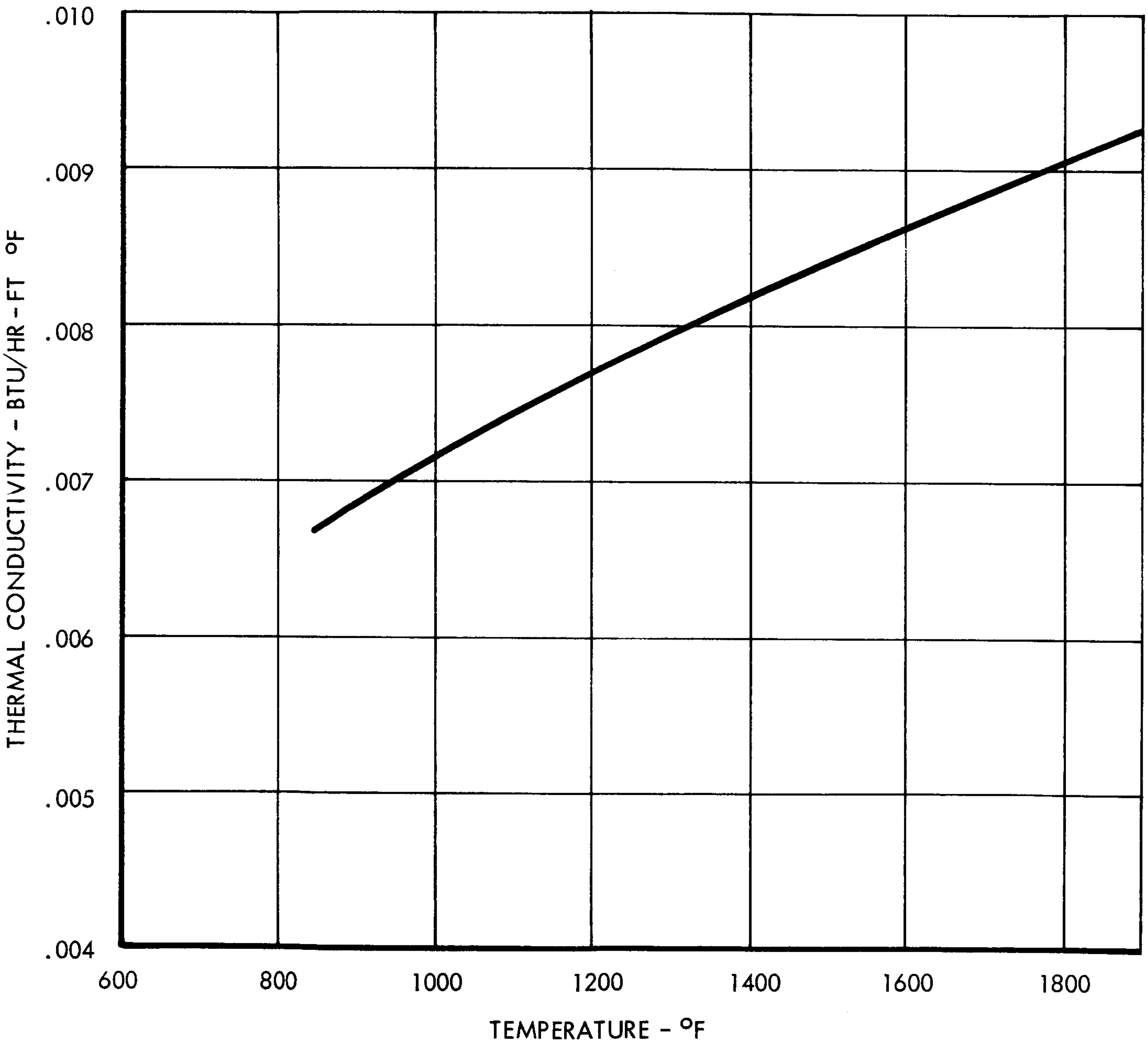
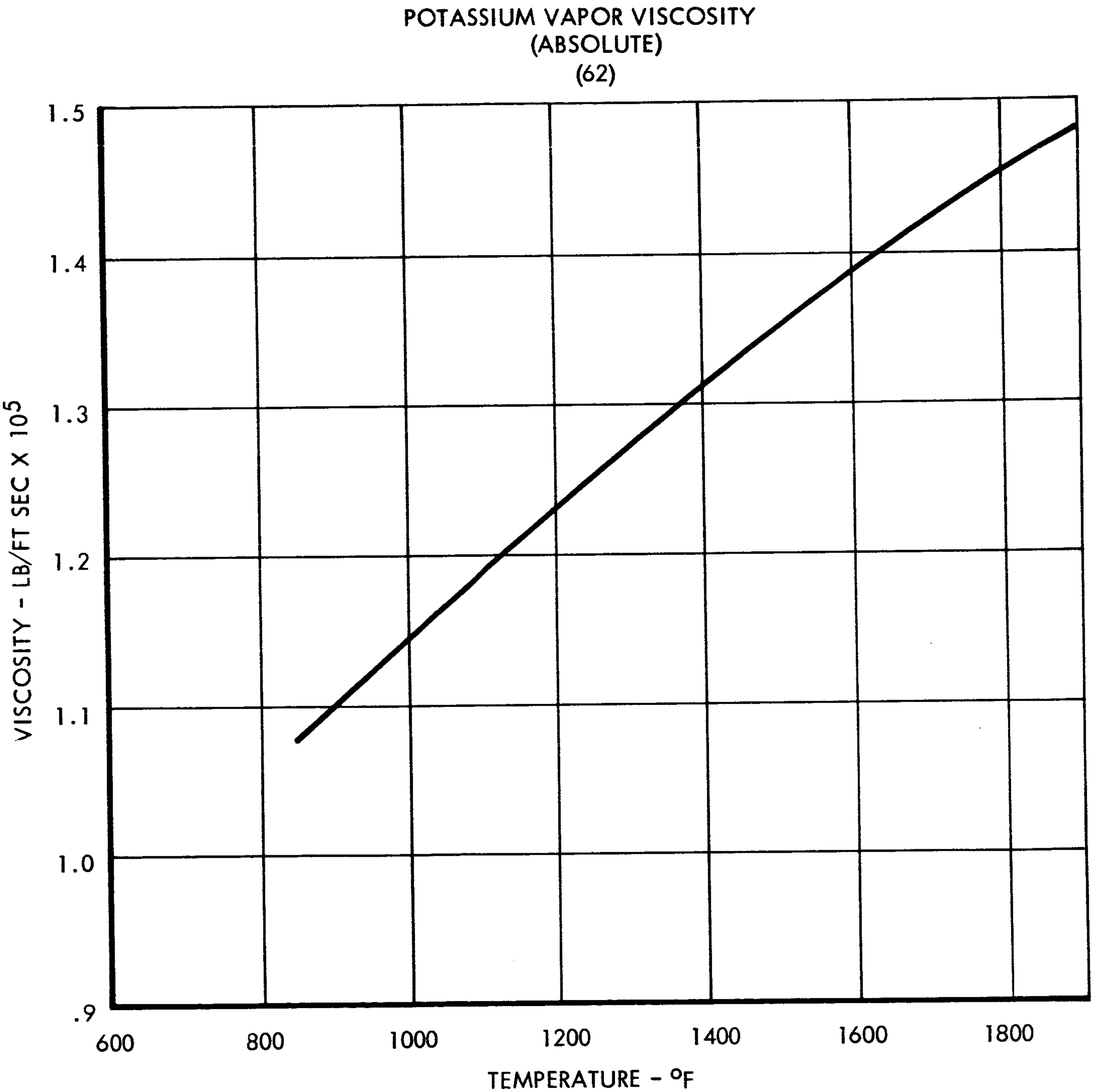


FIGURE 26



POTASSIUM VAPOR VISCOSITY
(ABSOLUTE)
(62)
VISCOSITY - LB/FT SEC X 10^5
1.5
1.4
1.3
1.2
1.1
1.0
.9
600
800
1000
1200
1400
1600
1800
TEMPERATURE - °F

FIGURE 27

POTASSIUM VAPOR PRESSURE

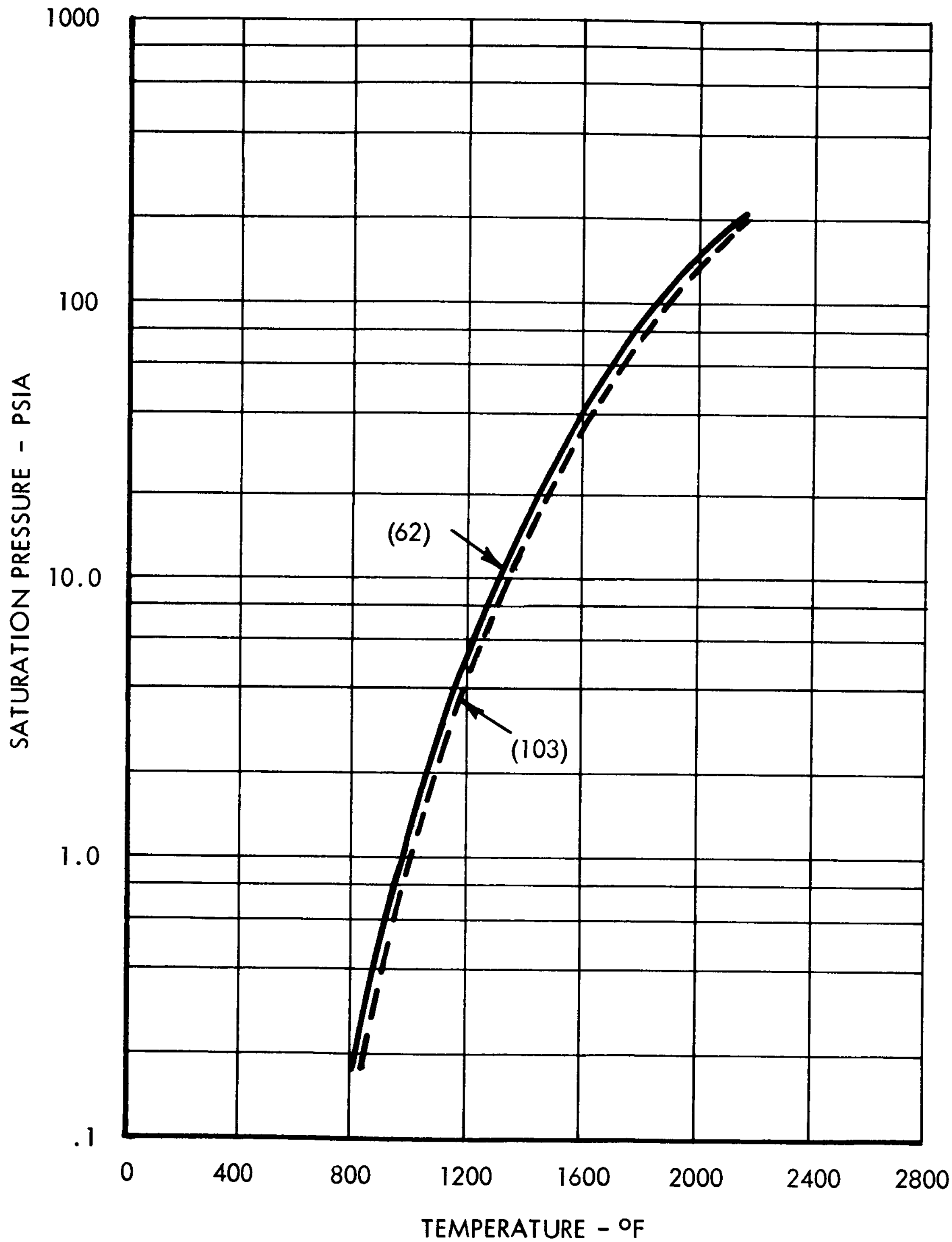


FIGURE 28

RUBIDIUM LIQUID DENSITY

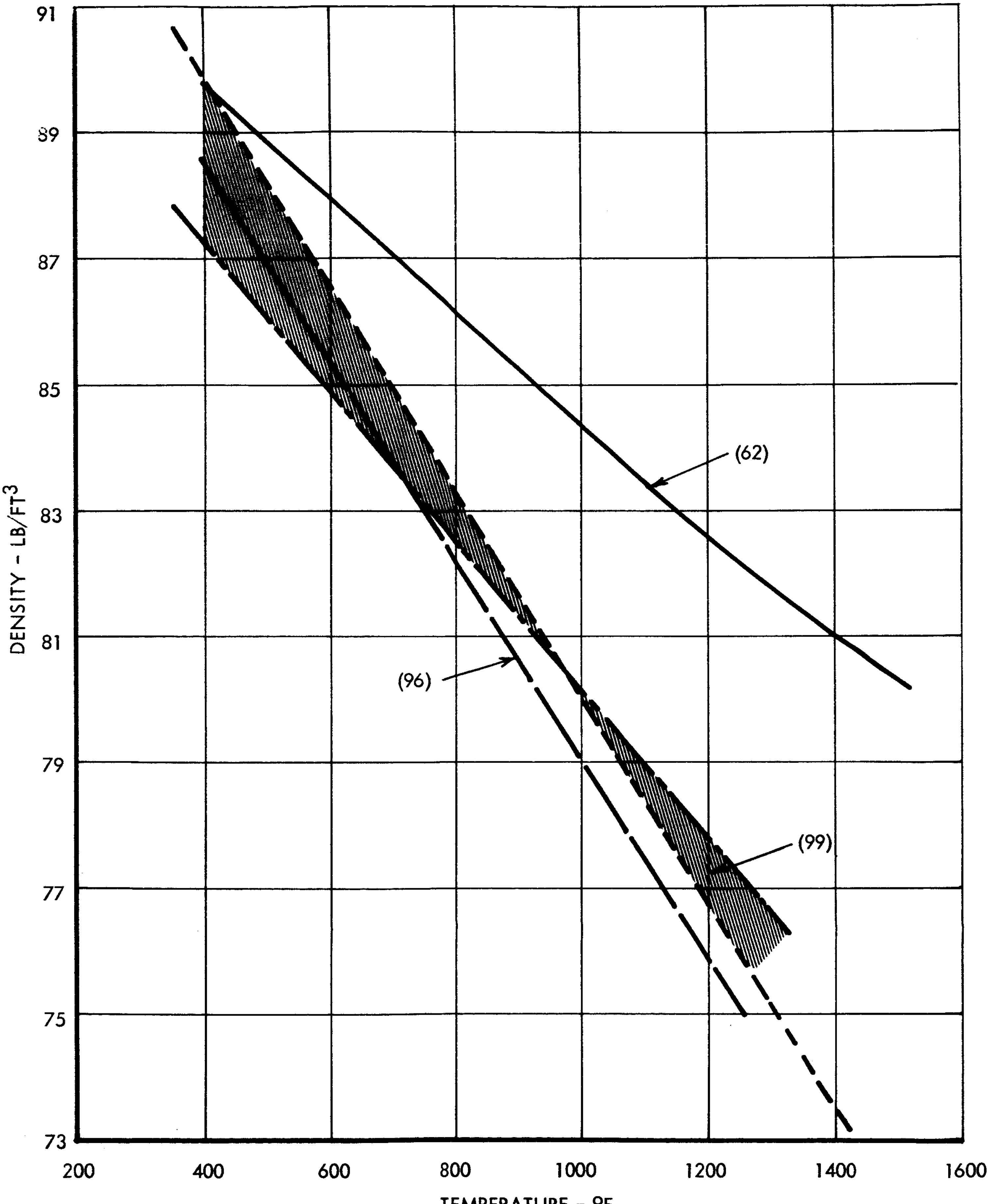


FIGURE 29

RUBIDIUM
HEAT OF VAPORIZATION

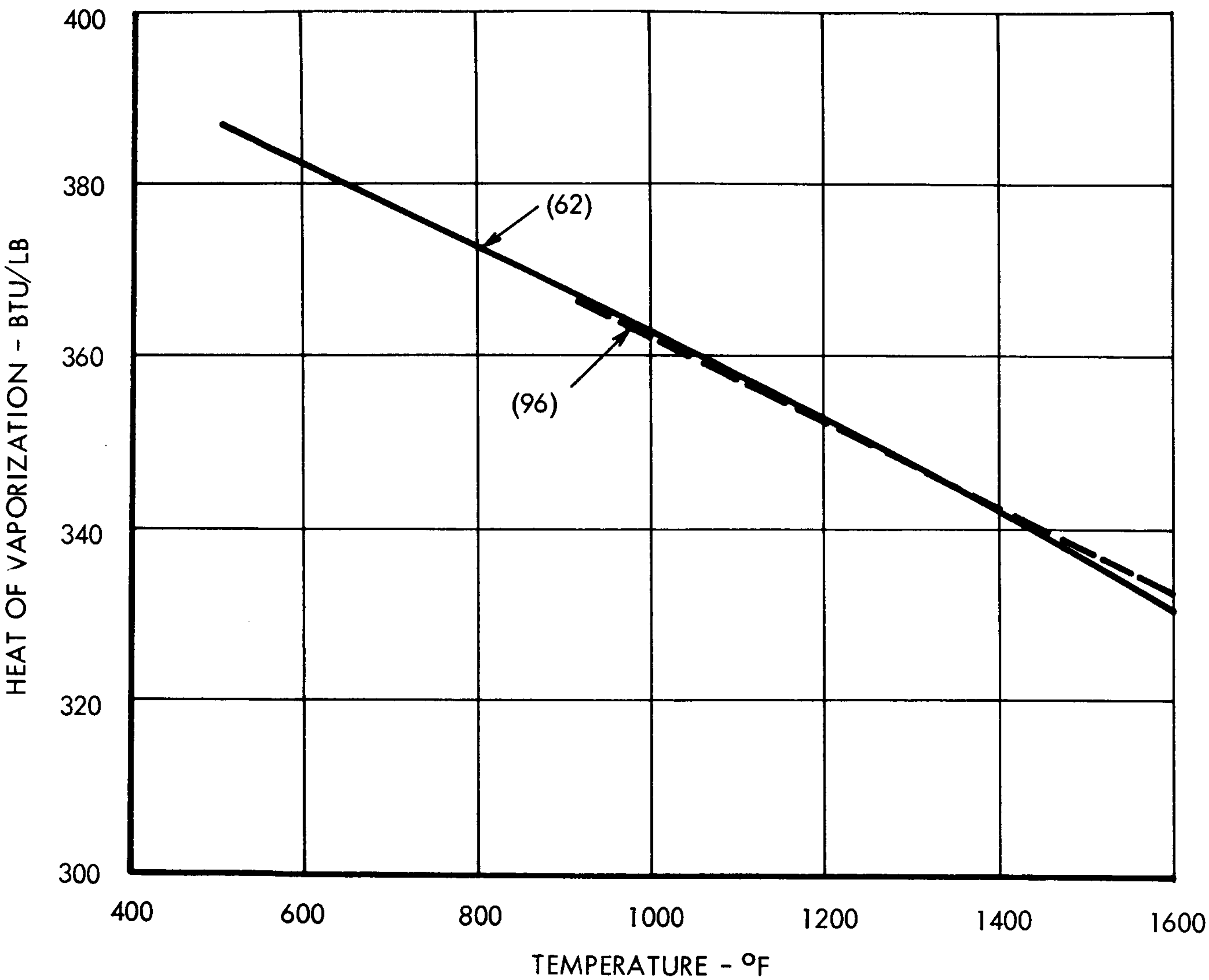


FIGURE 30

RUBIDIUM LIQUID
THERMAL CONDUCTIVITY
(62)

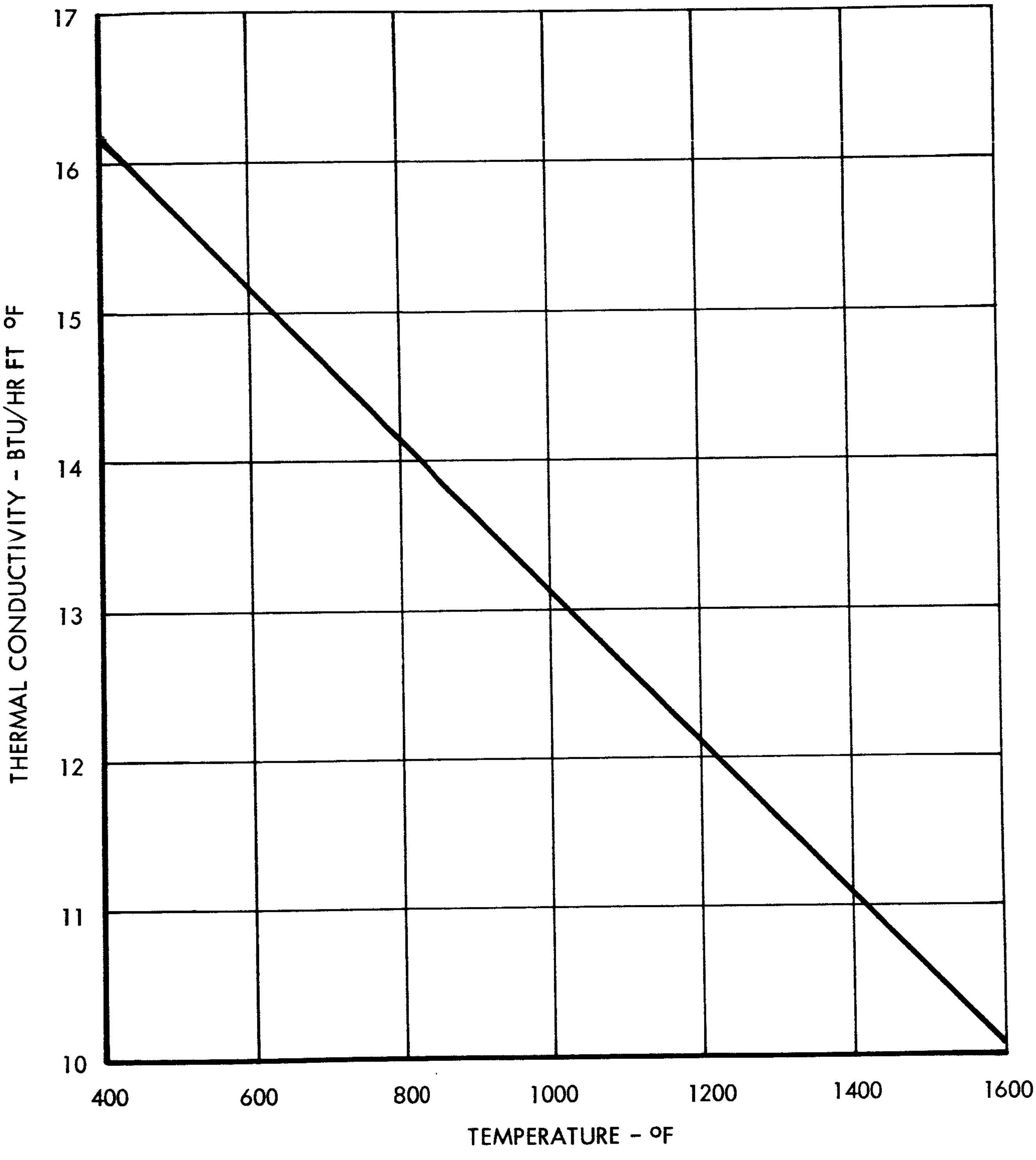


FIGURE 31

RUBIDIUM LIQUID
VISCOSITY
(ABSOLUTE)
(62)

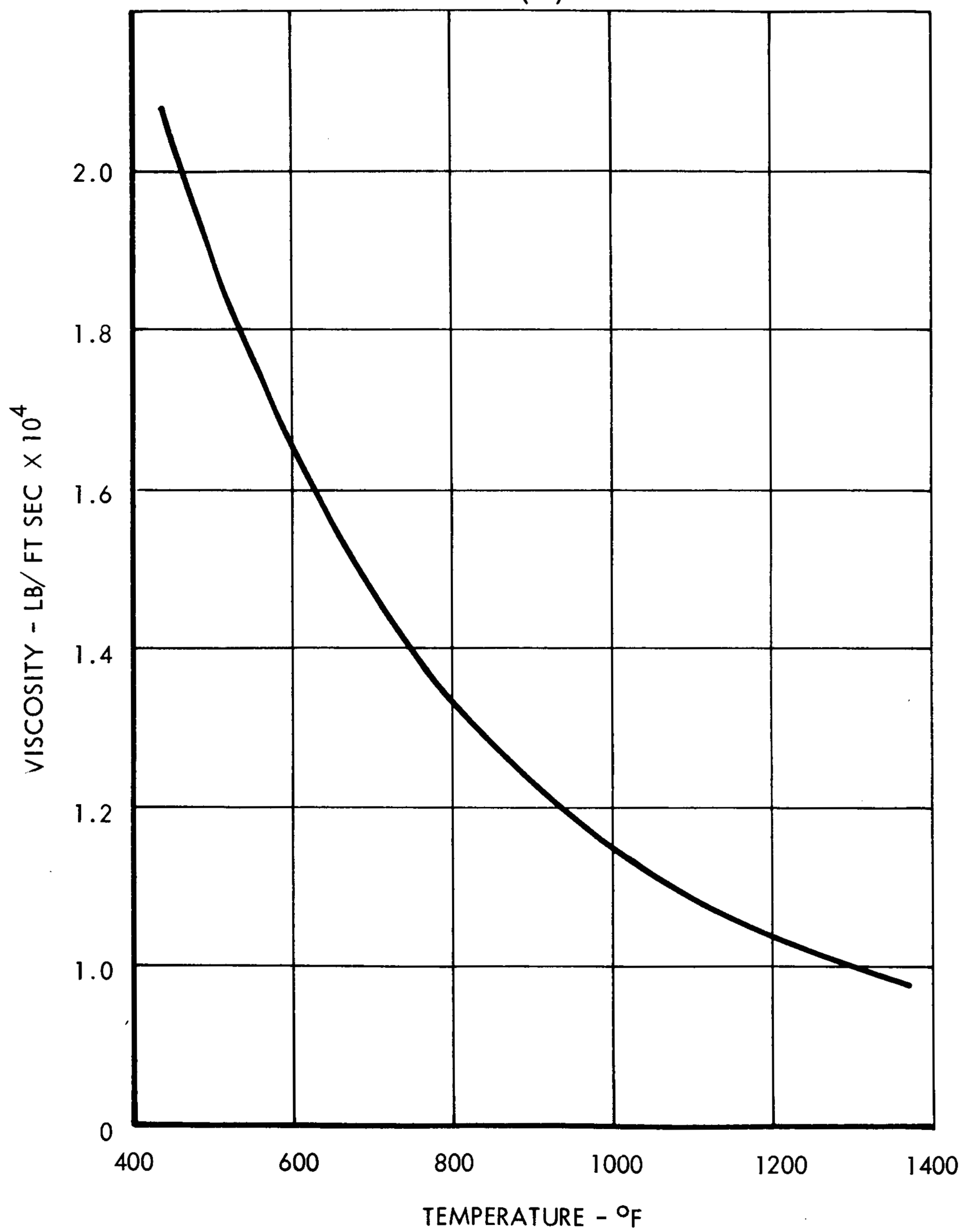


FIGURE 32

RUBIDIUM SURFACE TENSION
(LIQUID - VAPOR)
(97)

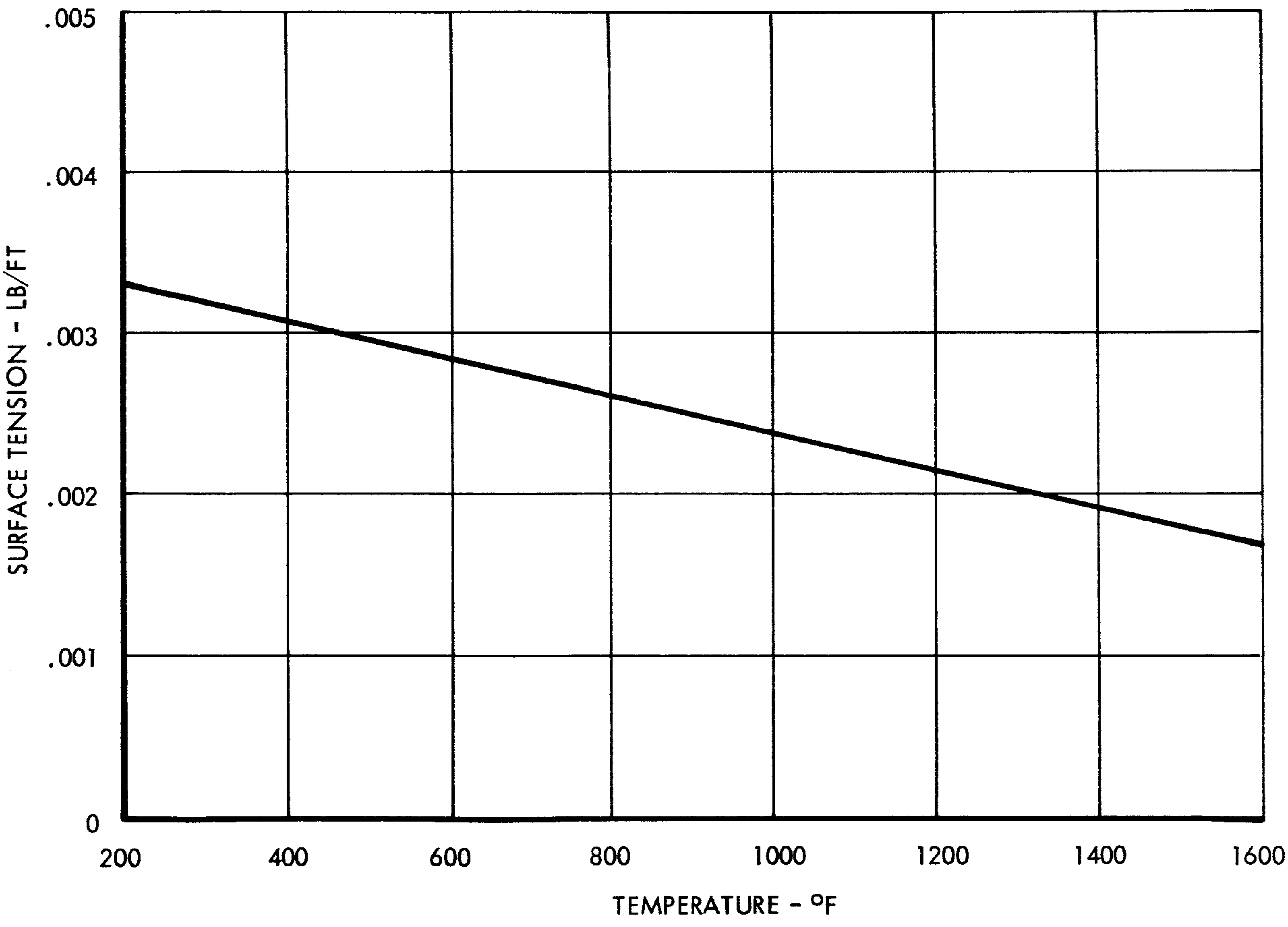


FIGURE 33

RUBIDIUM VAPOR
SPECIFIC HEAT
(CONST. P)
(62)

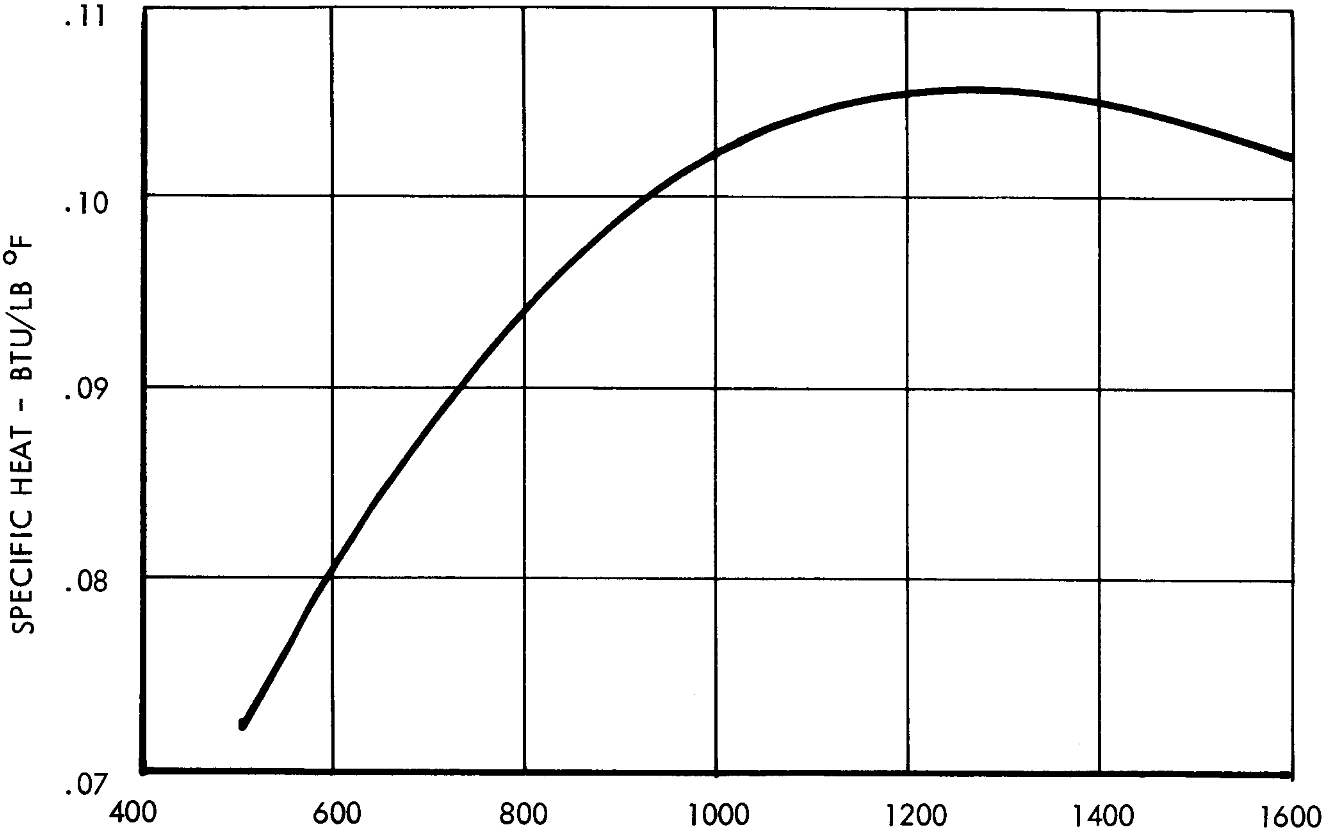


FIGURE 34

RUBIDIUM VAPOR
THERMAL CONDUCTIVITY
(62)

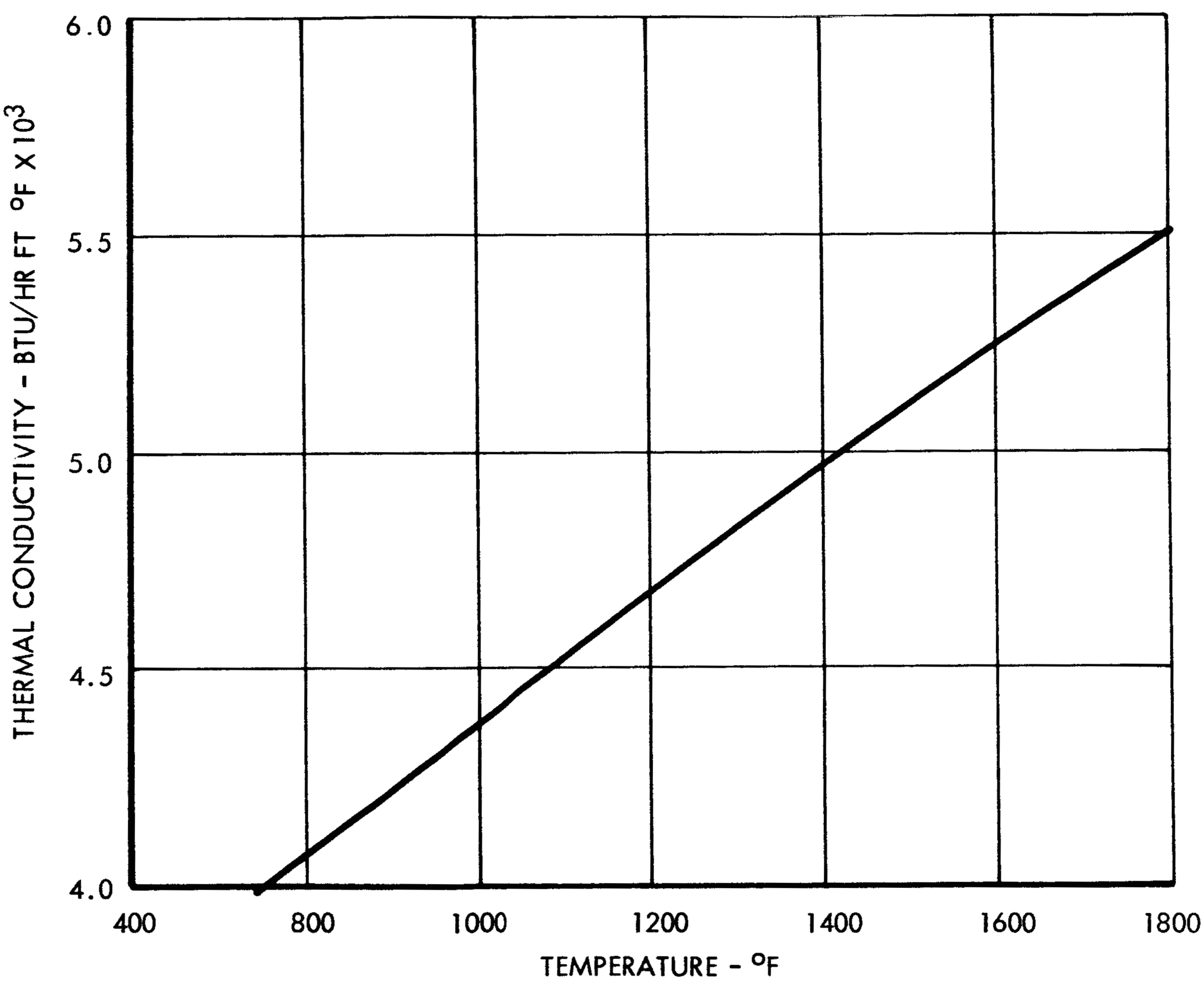


FIGURE 35

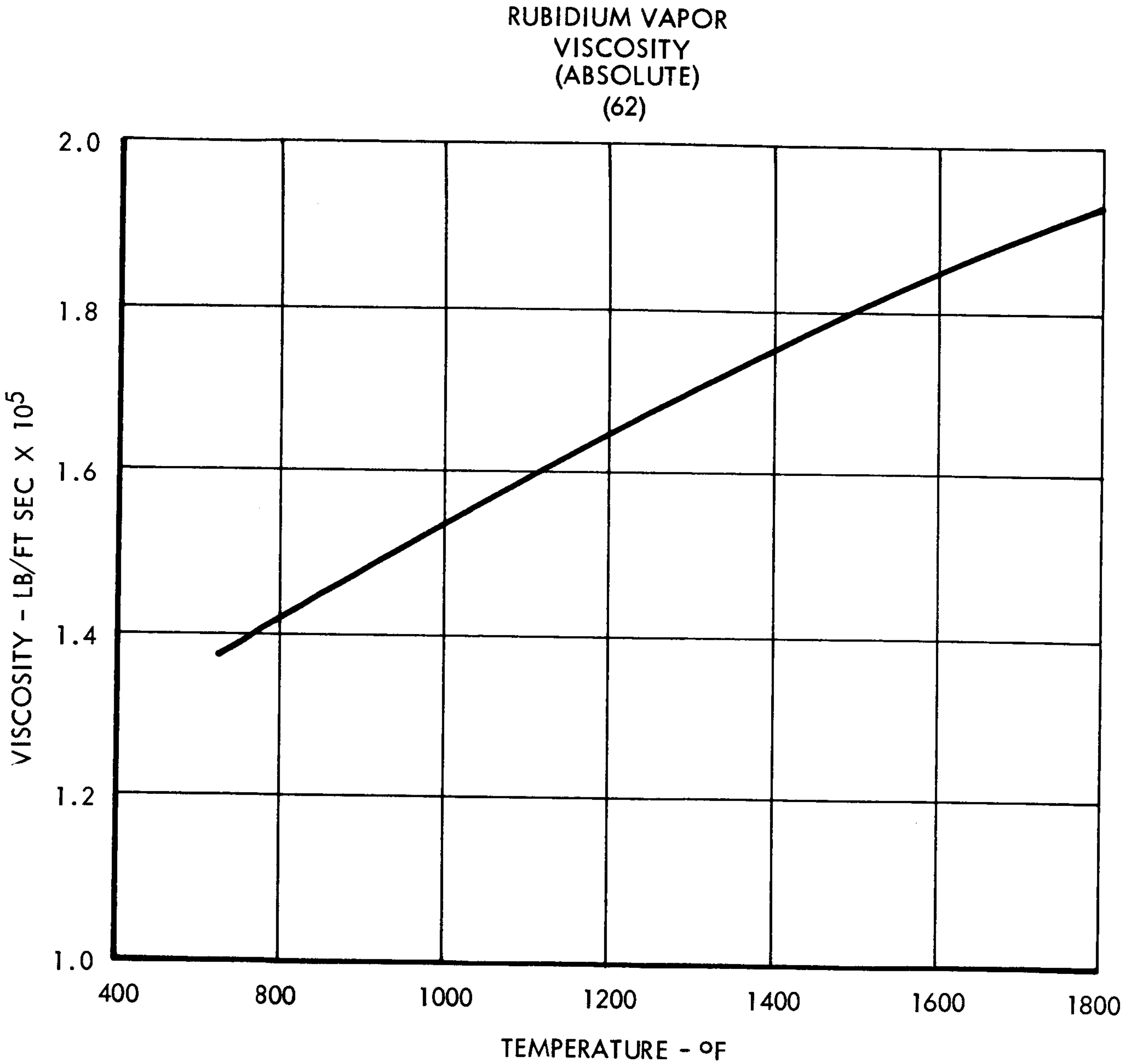

RUBIDIUM VAPOR
VISCOSITY
(ABSOLUTE)
(62)
2.0
1.8
1.6
1.4
1.2
1.0
VISCOSITY - LB/FT SEC X 10^5
400
800
1000
1200
1400
1600
1800
TEMPERATURE - °F

FIGURE 36

RUBIDIUM VAPOR PRESSURE

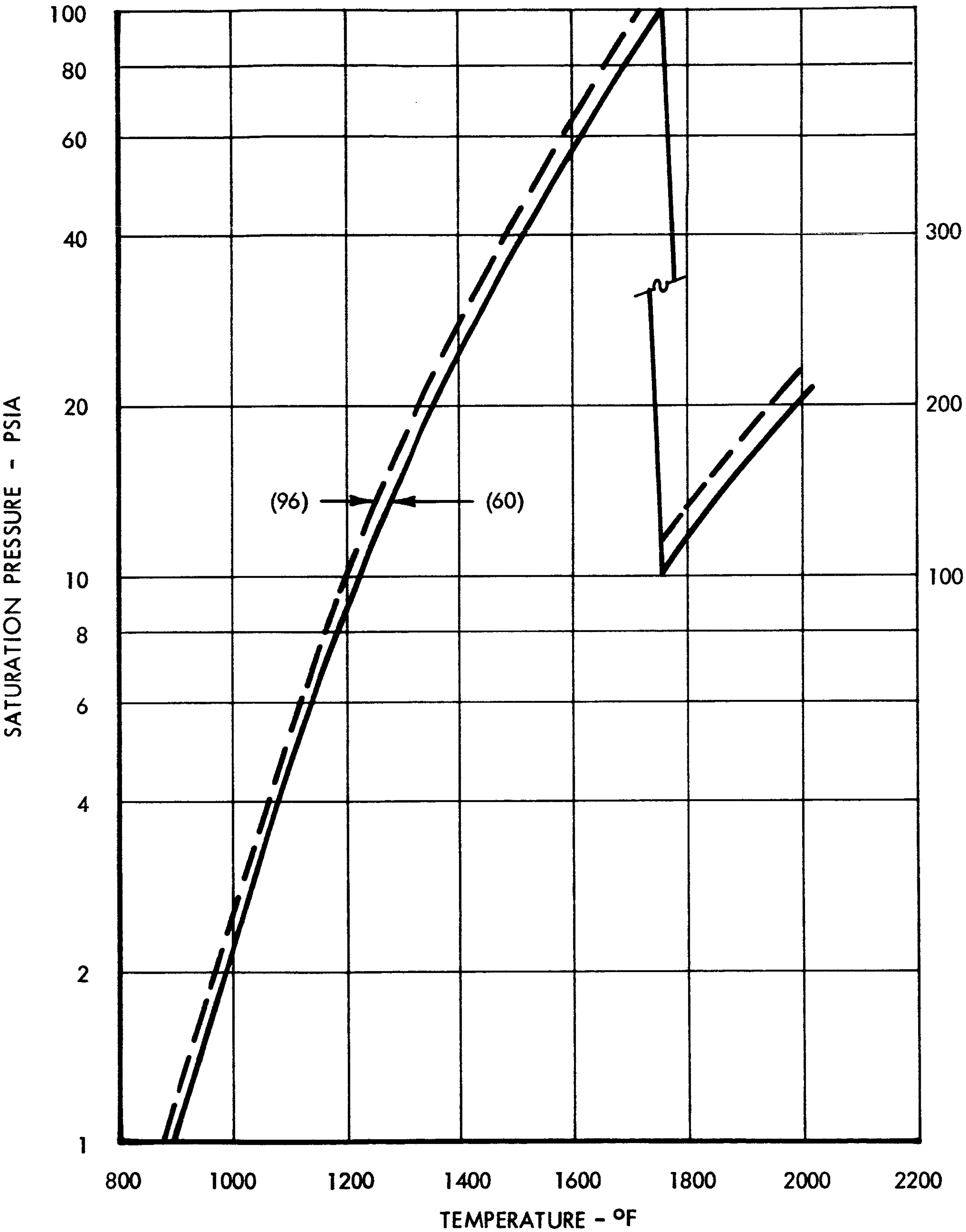


FIGURE 37

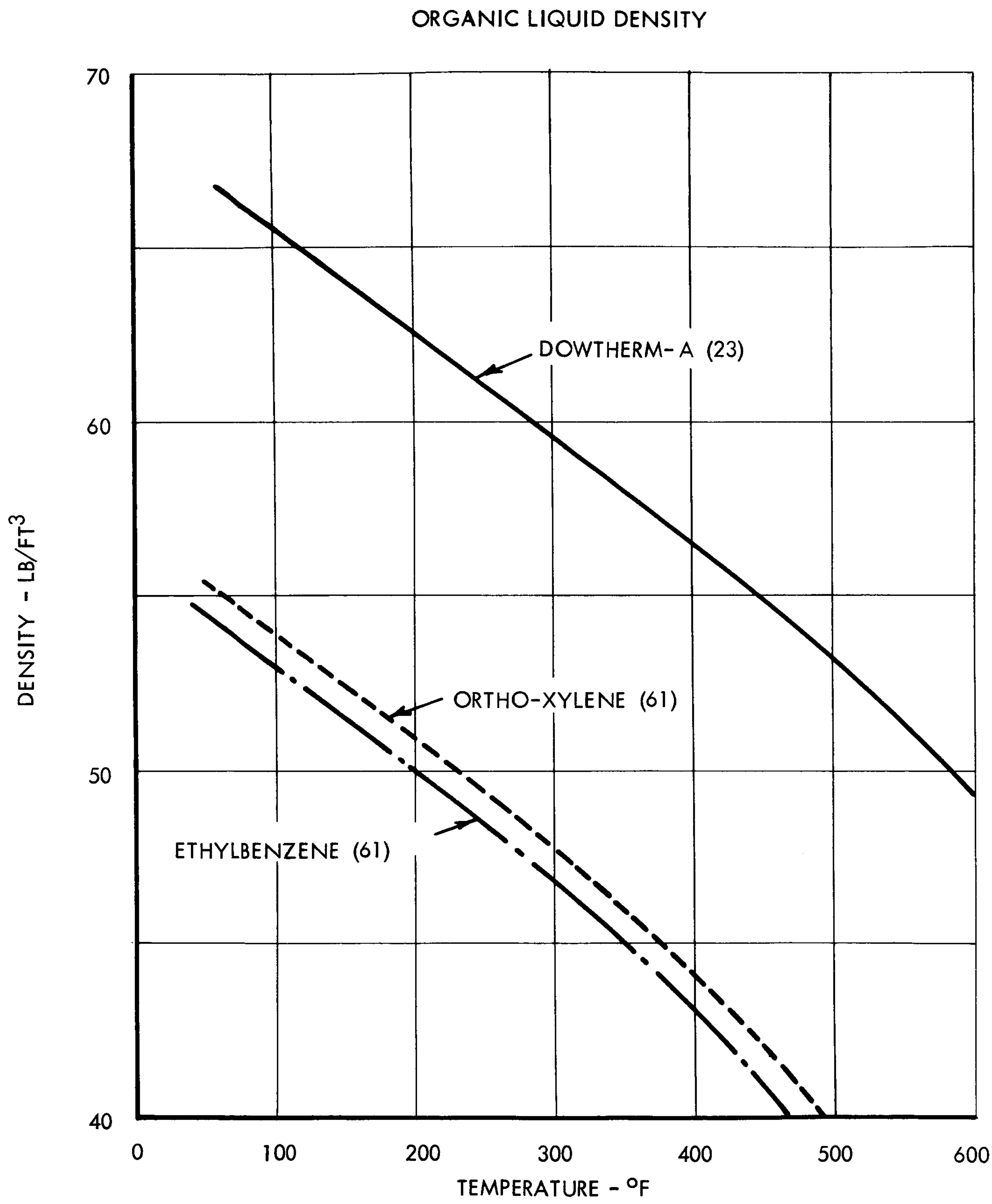

ORGANIC LIQUID DENSITY
70
60
50
40
DENSITY - LB/FT3
DOWTHERM- A (23)
ORTHO-XYLENE (61)
ETHYLBENZENE (61)
0
100
200
300
400
500
600
TEMPERATURE - °F

FIGURE 38

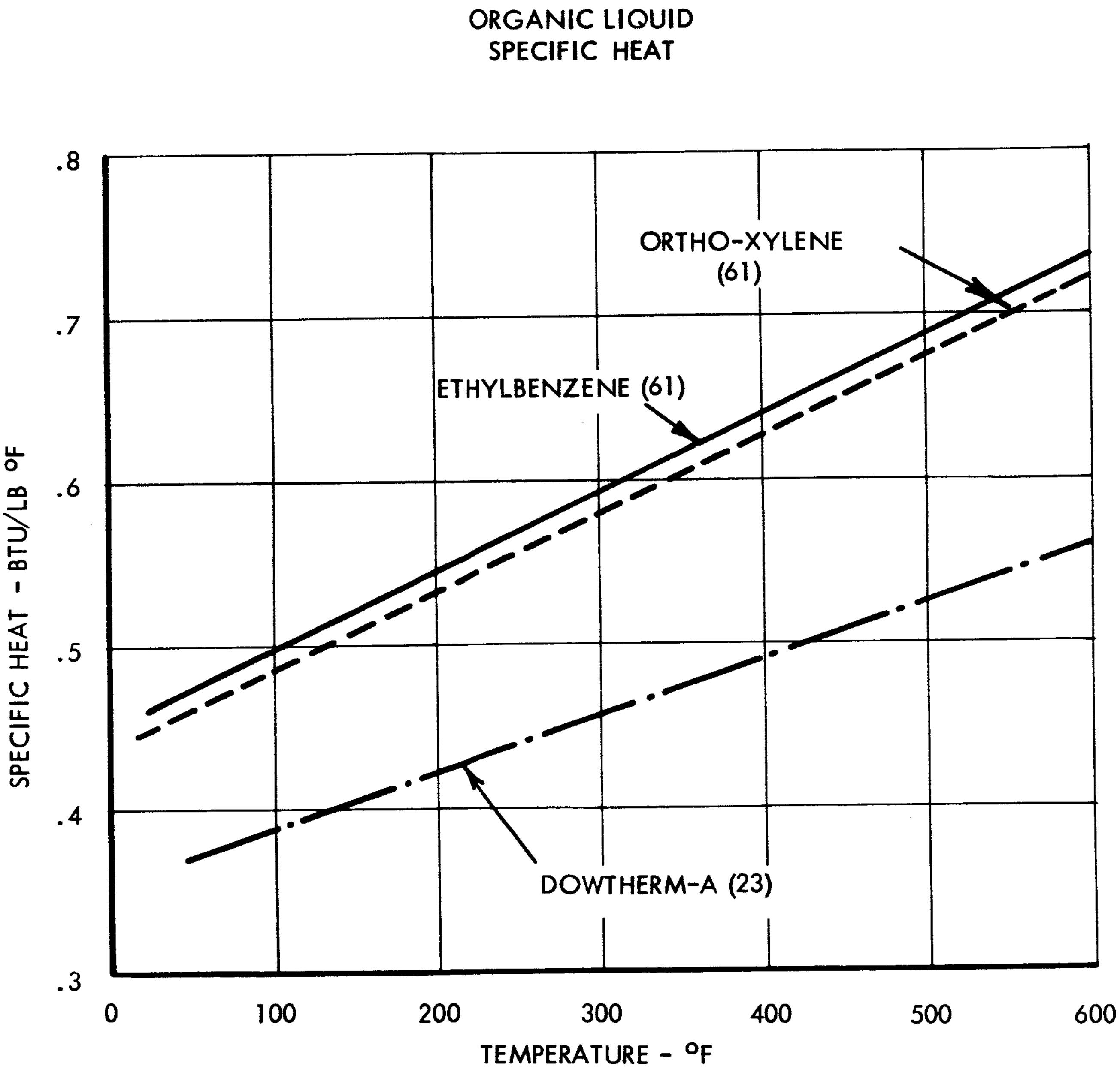

ORGANIC LIQUID
SPECIFIC HEAT
ORTHO-XYLENE (61)
ETHYLBENZENE (61)
DOWTHERM-A (23)
SPECIFIC HEAT - BTU/LB °F
.8
.7
.6
.5
.4
.3
0
100
200
300
400
500
600
TEMPERATURE - °F

FIGURE 39

ORGANIC HEAT OF VAPORIZATION

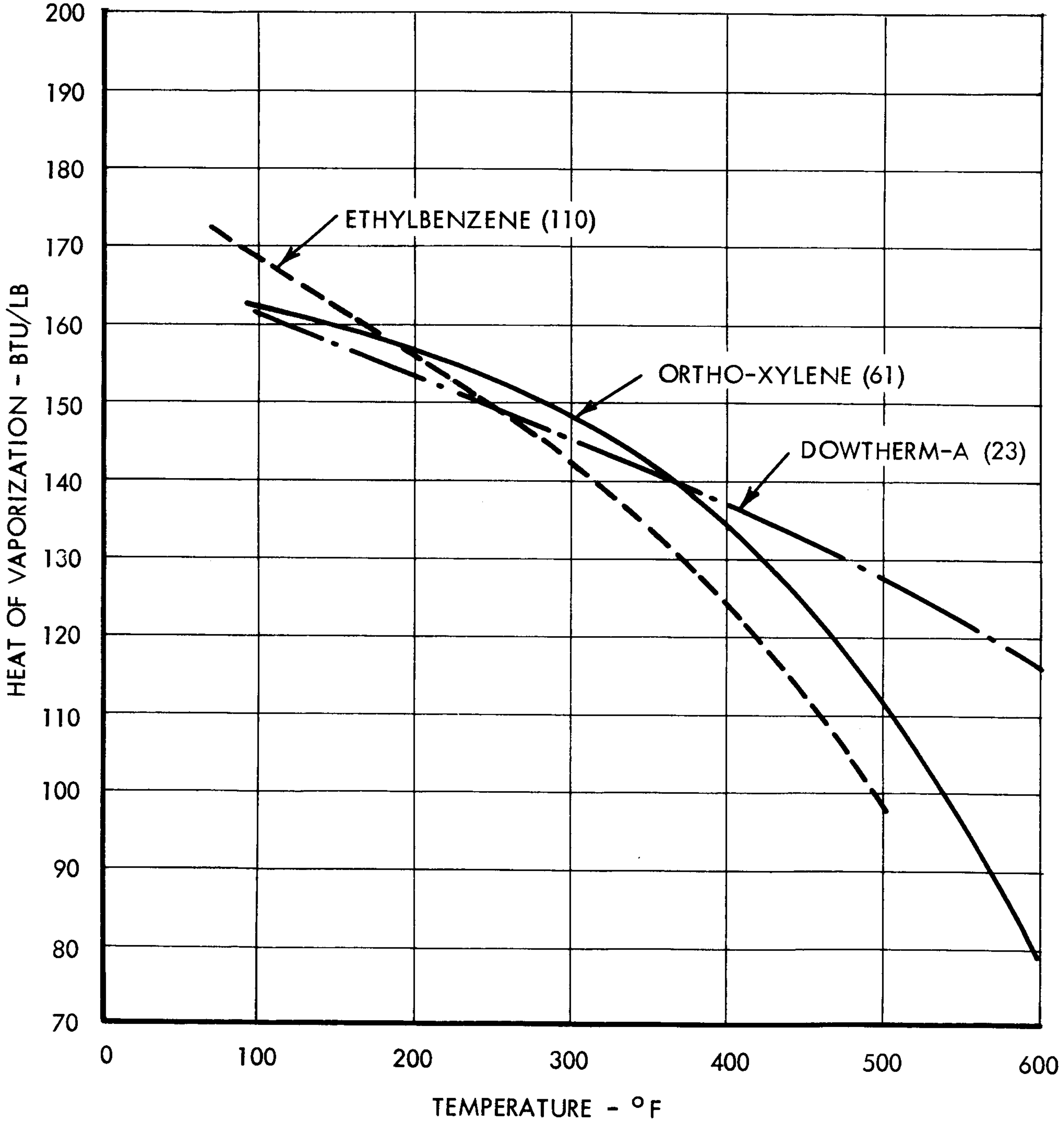


FIGURE 40

ORGANIC LIQUID
THERMAL CONDUCTIVITY

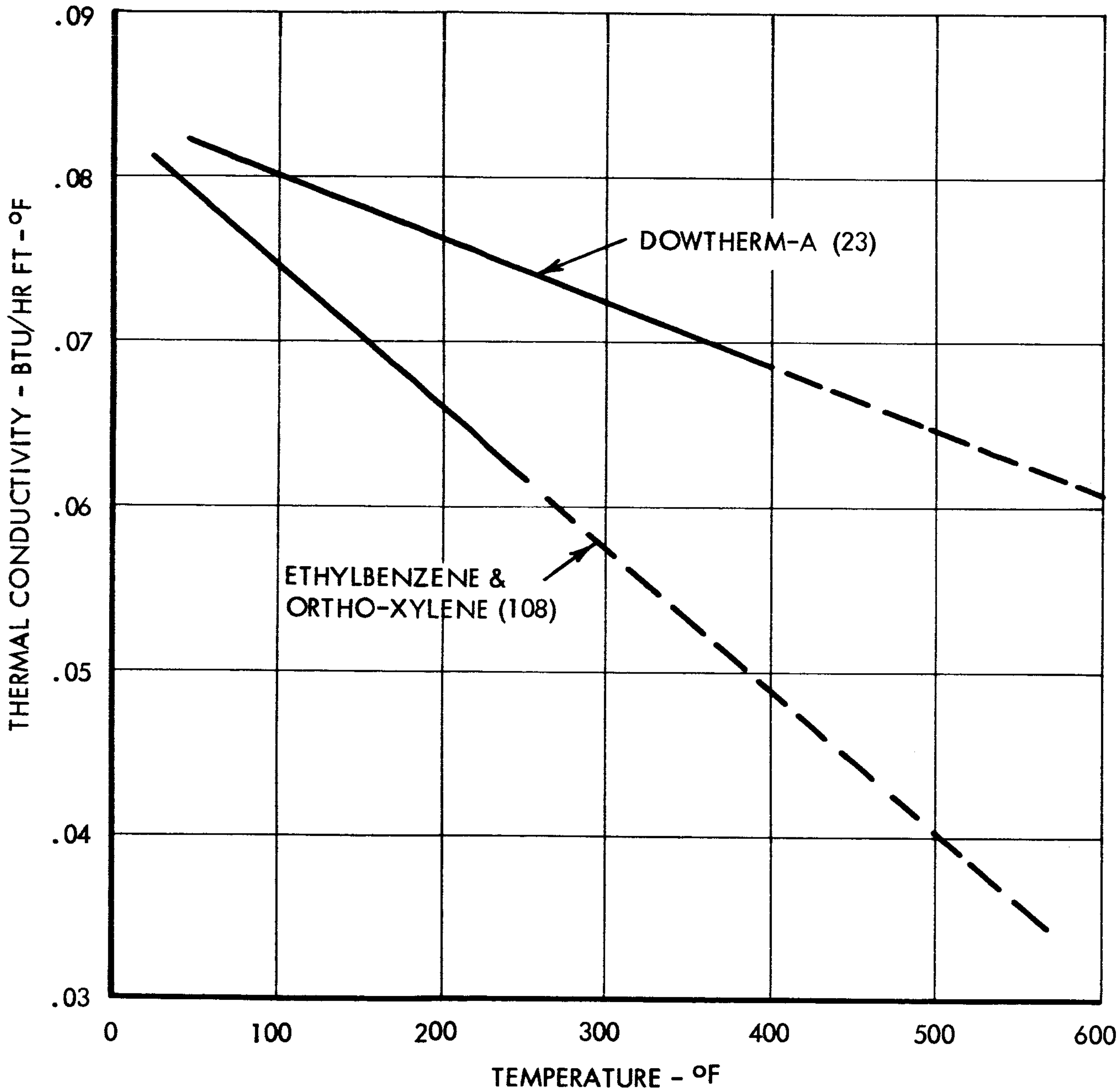


FIGURE 41

ORGANIC LIQUID VISCOSITY
(ABSOLUTE)
(23)

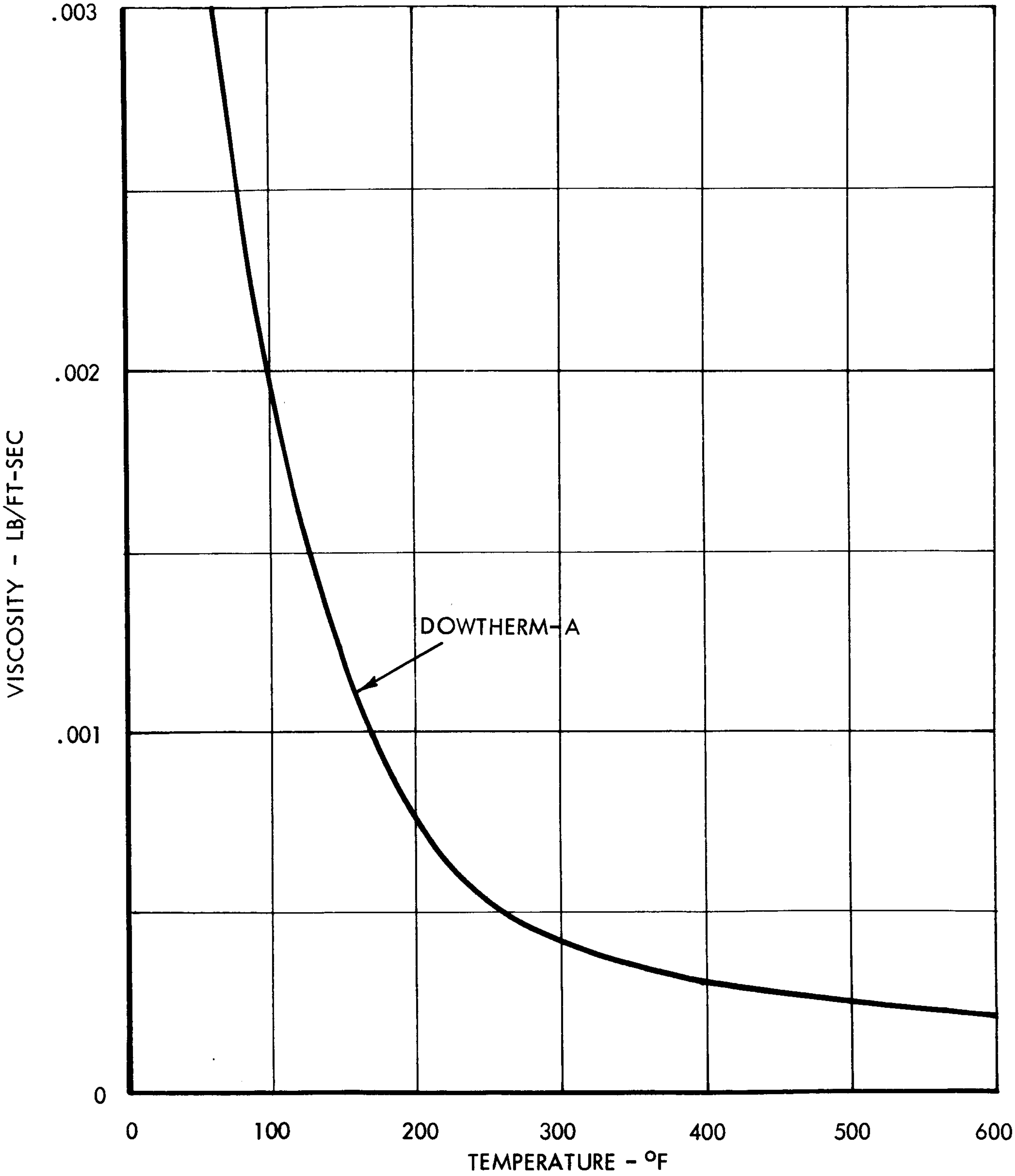


FIGURE 42

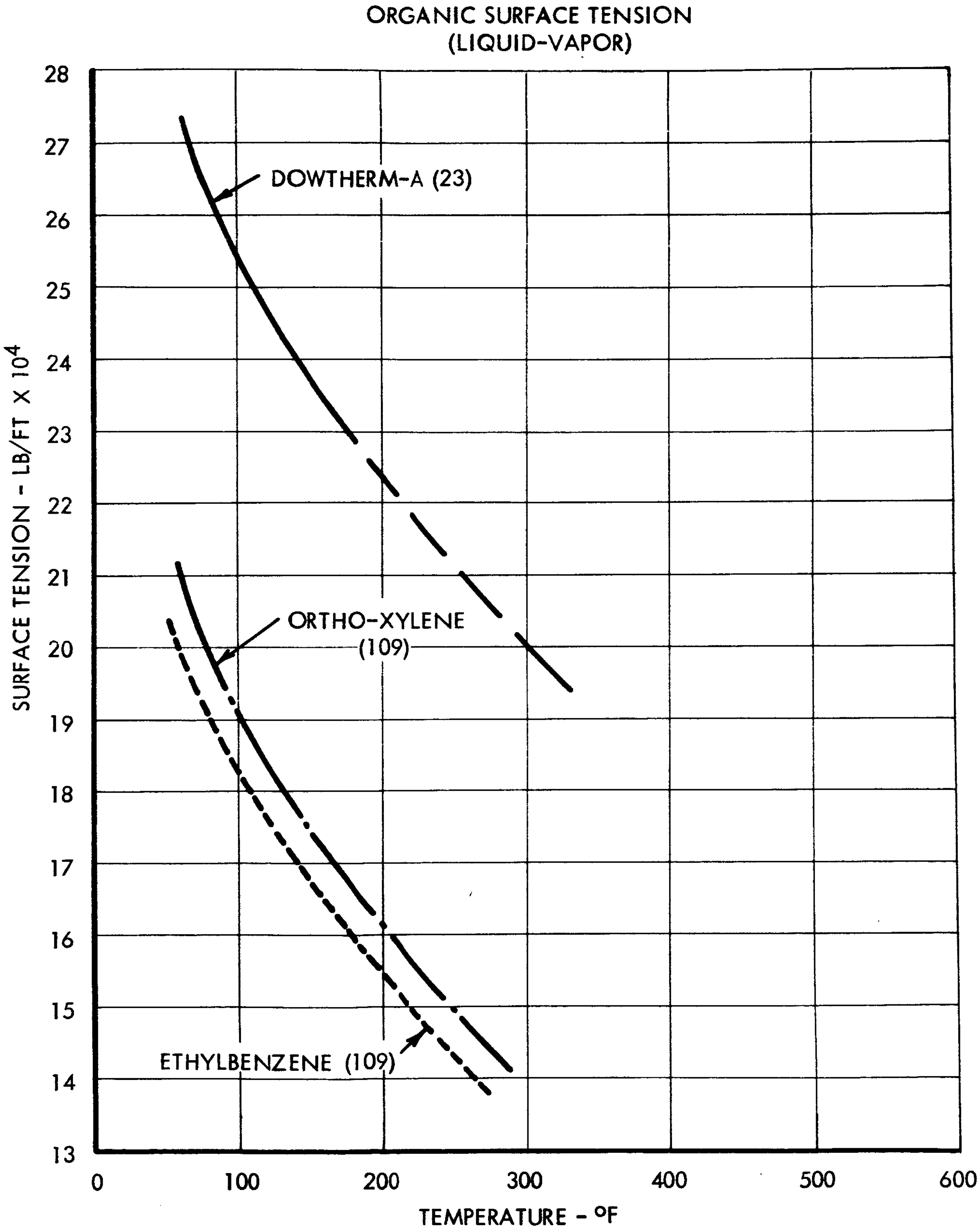

ORGANIC SURFACE TENSION
(LIQUID-VAPOR)
DOWTHERM-A (23)
ORTHO-XYLENE
(109)
ETHYLBENZENE (109)
SURFACE TENSION - LB/FT X 10^4
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
0
100
200
300
400
500
600
TEMPERATURE - °F

FIGURE 43

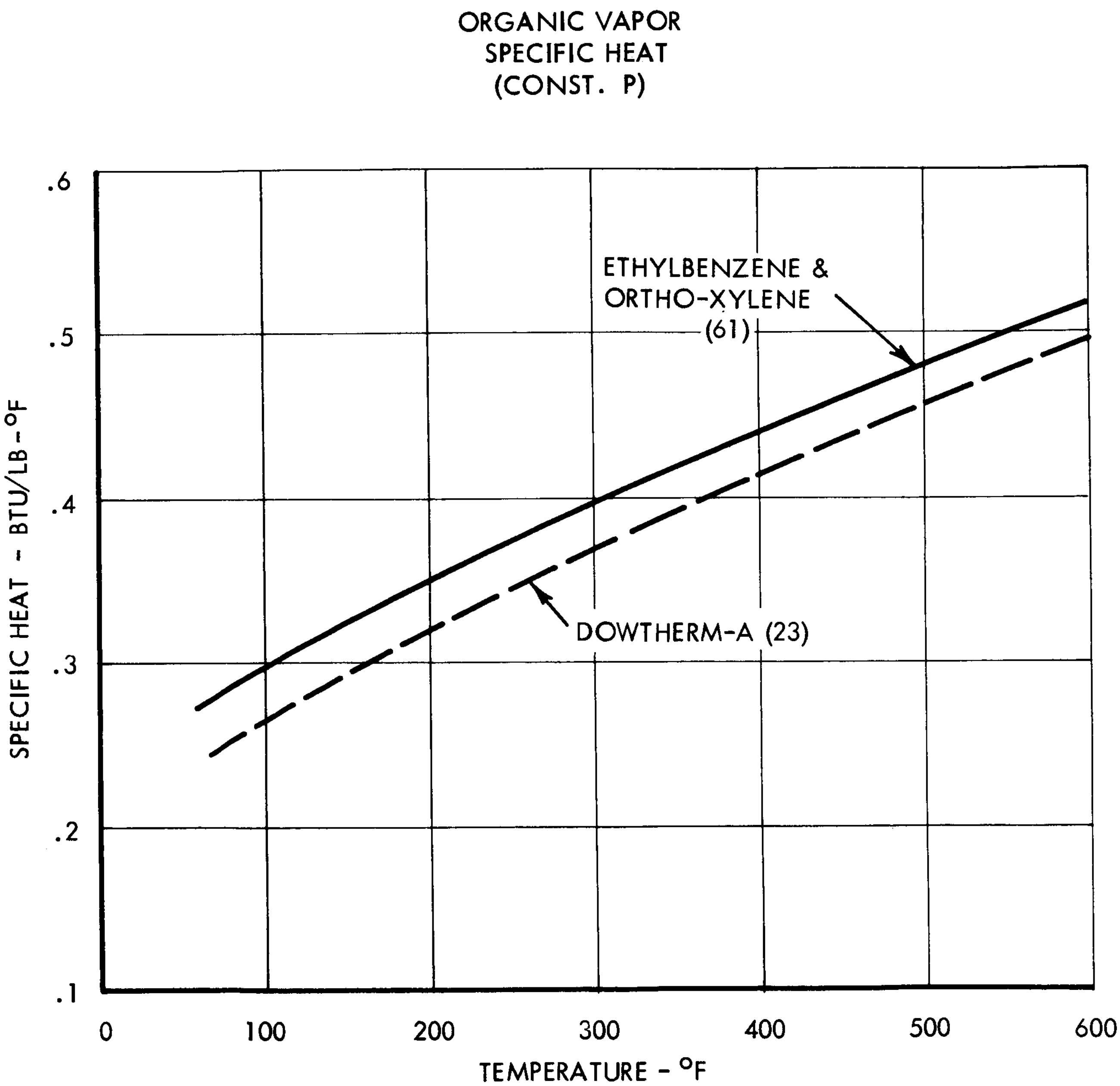

ORGANIC VAPOR
SPECIFIC HEAT
(CONST. P)
.6
.5
.4
.3
.2
.1
0
100
200
300
400
500
600
SPECIFIC HEAT - BTU/LB - °F
TEMPERATURE - °F
ETHYLBENZENE &
ORTHO-XYLENE
(61)
DOWTHERM-A (23)

FIGURE 44

ORGANIC VAPOR
THERMAL CONDUCTIVITY
(61)

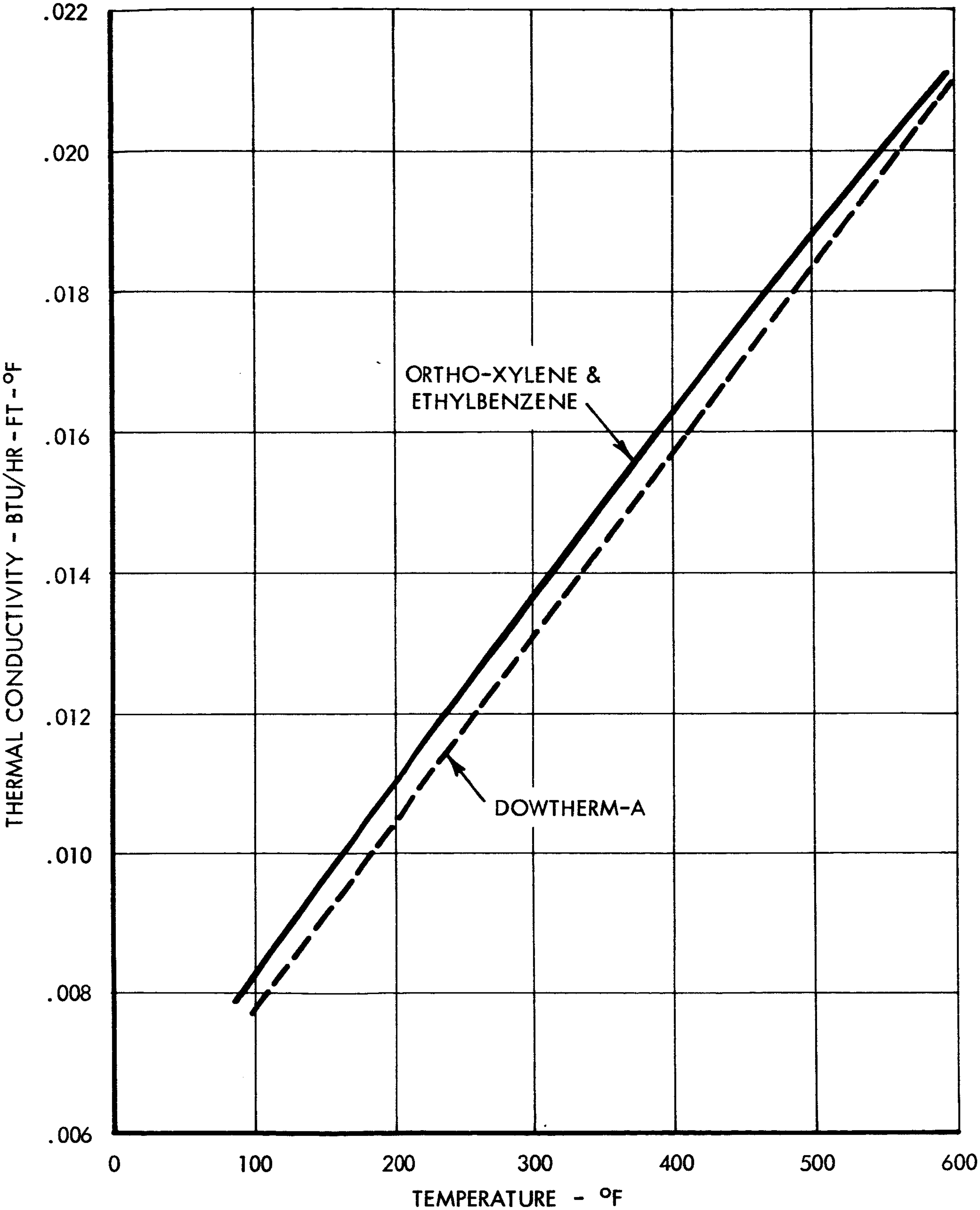


FIGURE 45

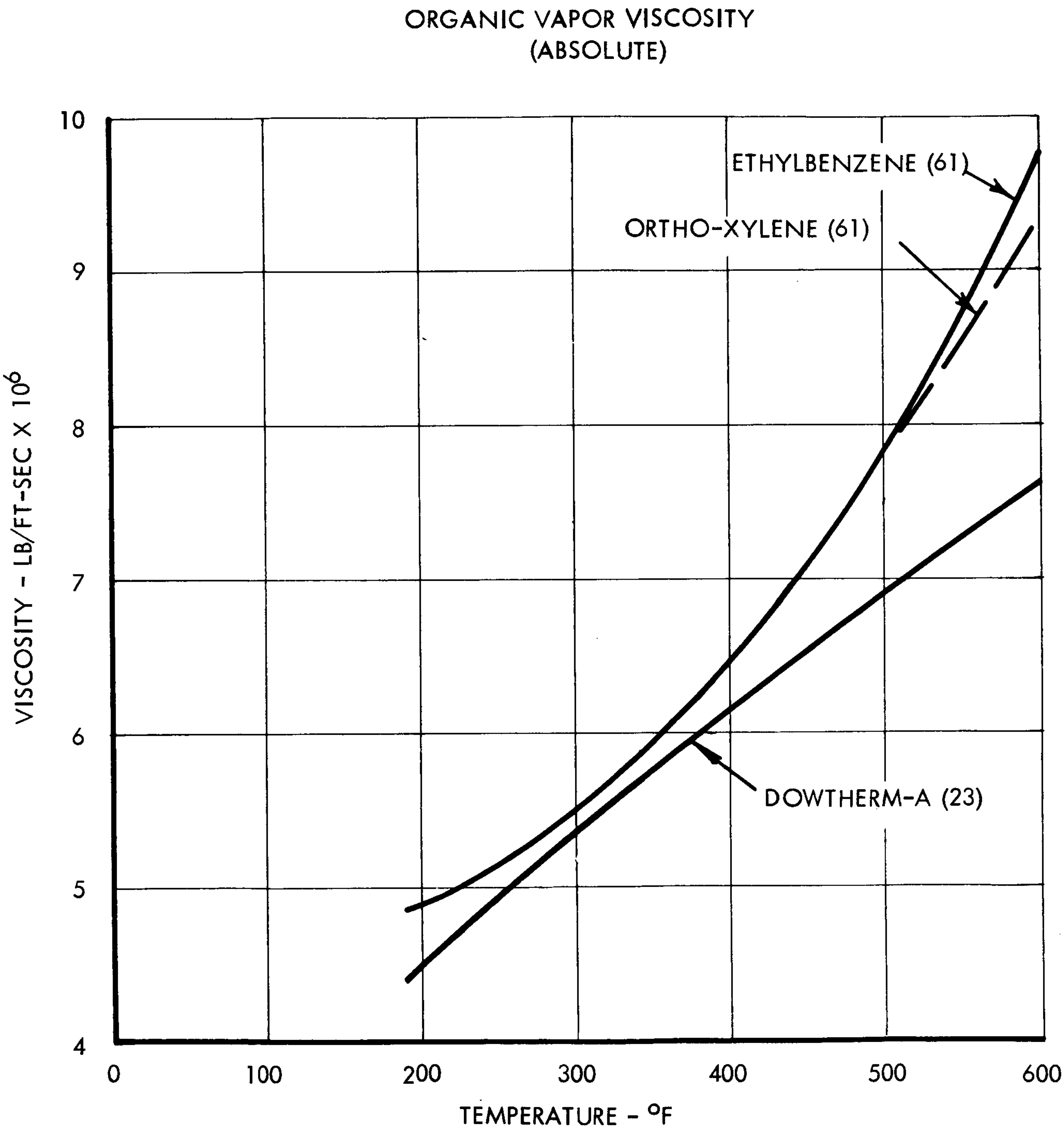

ORGANIC VAPOR VISCOSITY
(ABSOLUTE)
ETHYLBENZENE (61)
ORTHO-XYLENE (61)
DOWTHERM-A (23)
VISCOSITY - LB/FT-SEC X 10^6
TEMPERATURE - °F
10
9
8
7
6
5
4
0
100
200
300
400
500
600

FIGURE 46

ORGANIC VAPOR PRESSURE (23)

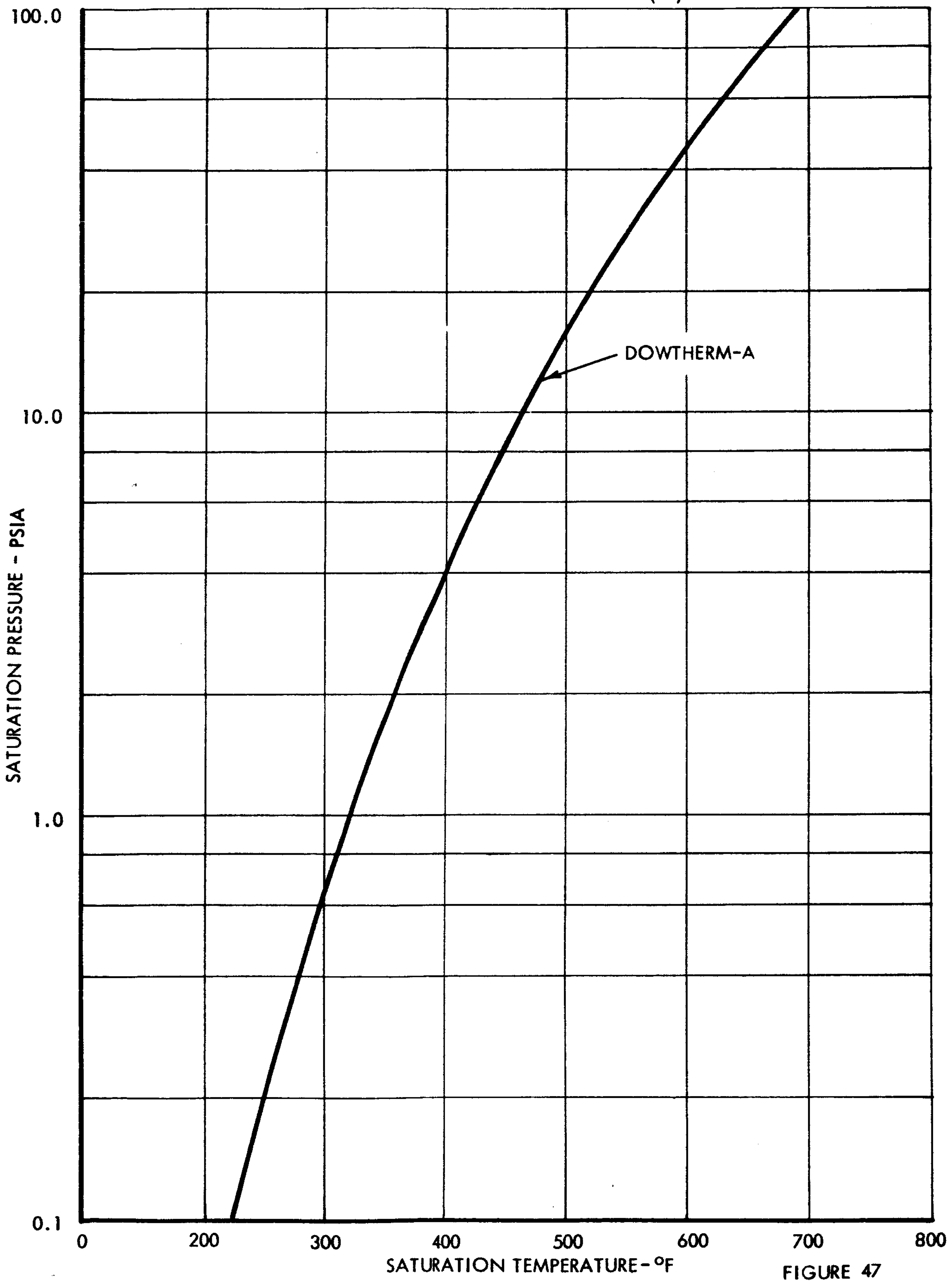
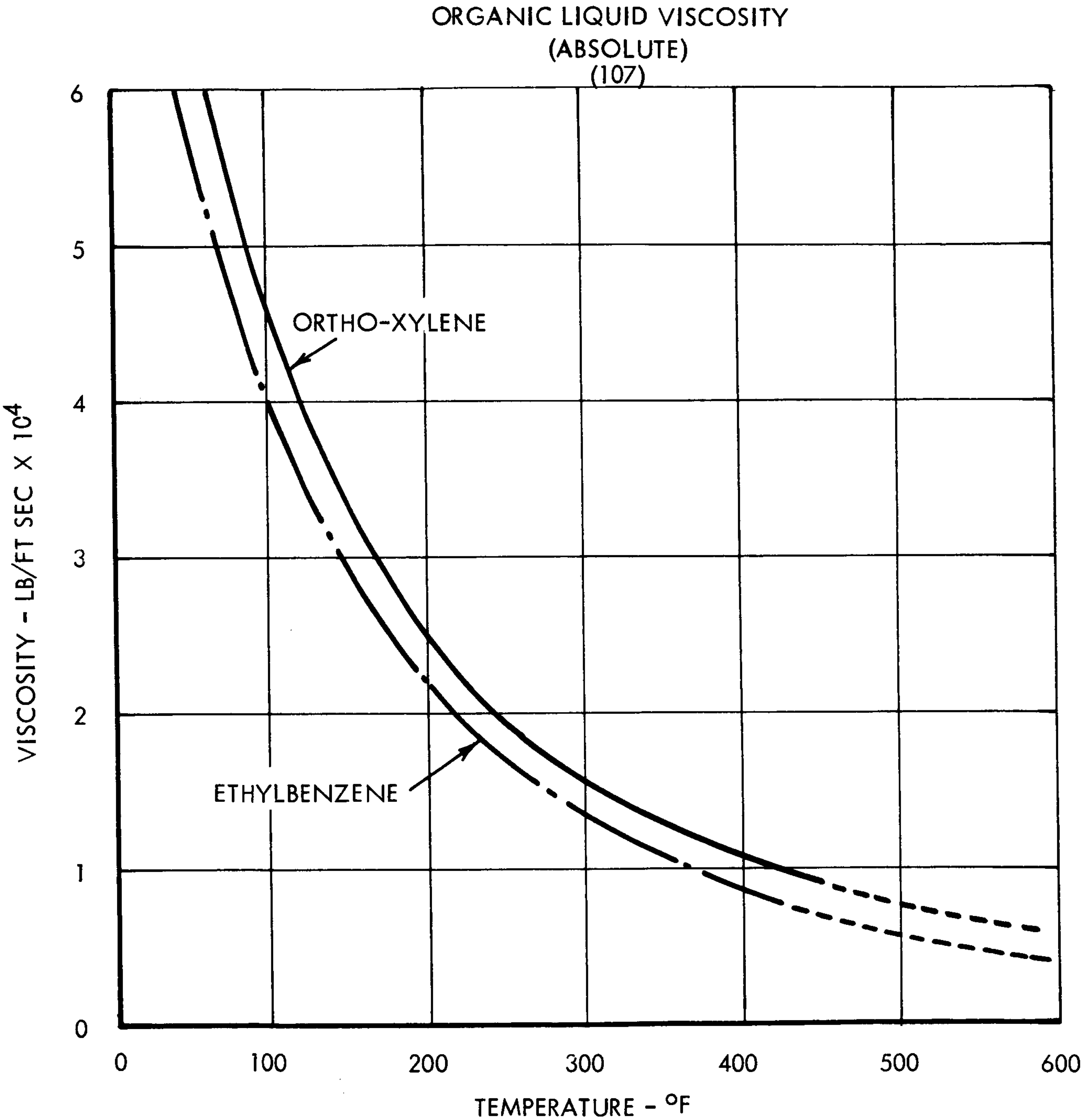


FIGURE 47



ORGANIC LIQUID VISCOSITY
(ABSOLUTE)
(107)
6
5
4
3
2
1
0
0
100
200
300
400
500
600
VISCOSITY - LB/FT SEC X 10^4
TEMPERATURE - °F
ORTHO-XYLENE
ETHYLBENZENE

FIGURE 48

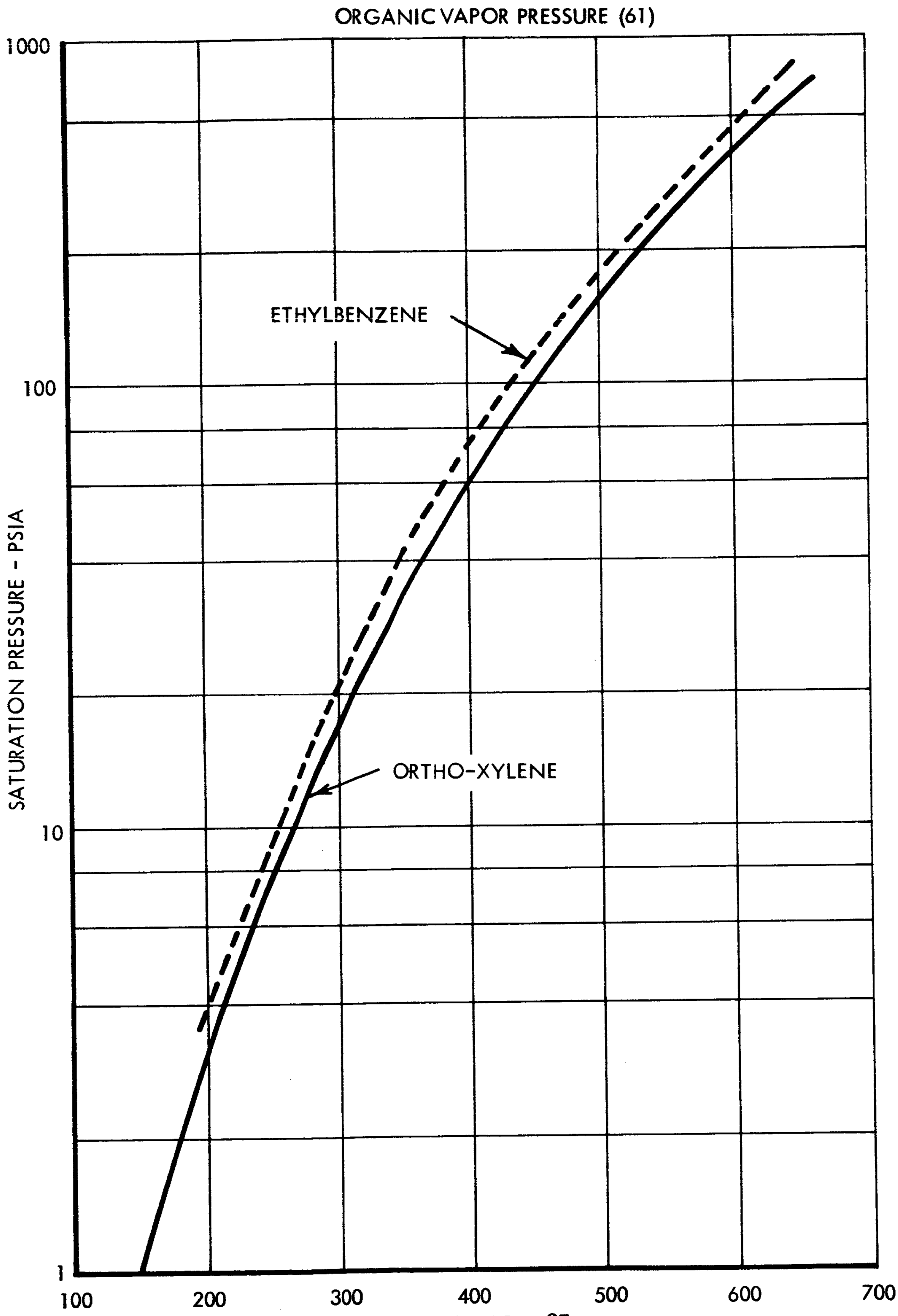

ORGANIC VAPOR PRESSURE (61)
1000
100
10
1
SATURATION PRESSURE - PSIA
100
200
300
400
500
600
700
TEMPERATURE - °F
ETHYLBENZENE
ORTHO-XYLENE

FIGURE 49

MODULUS OF ELASTICITY OF RADIATOR MATERIALS

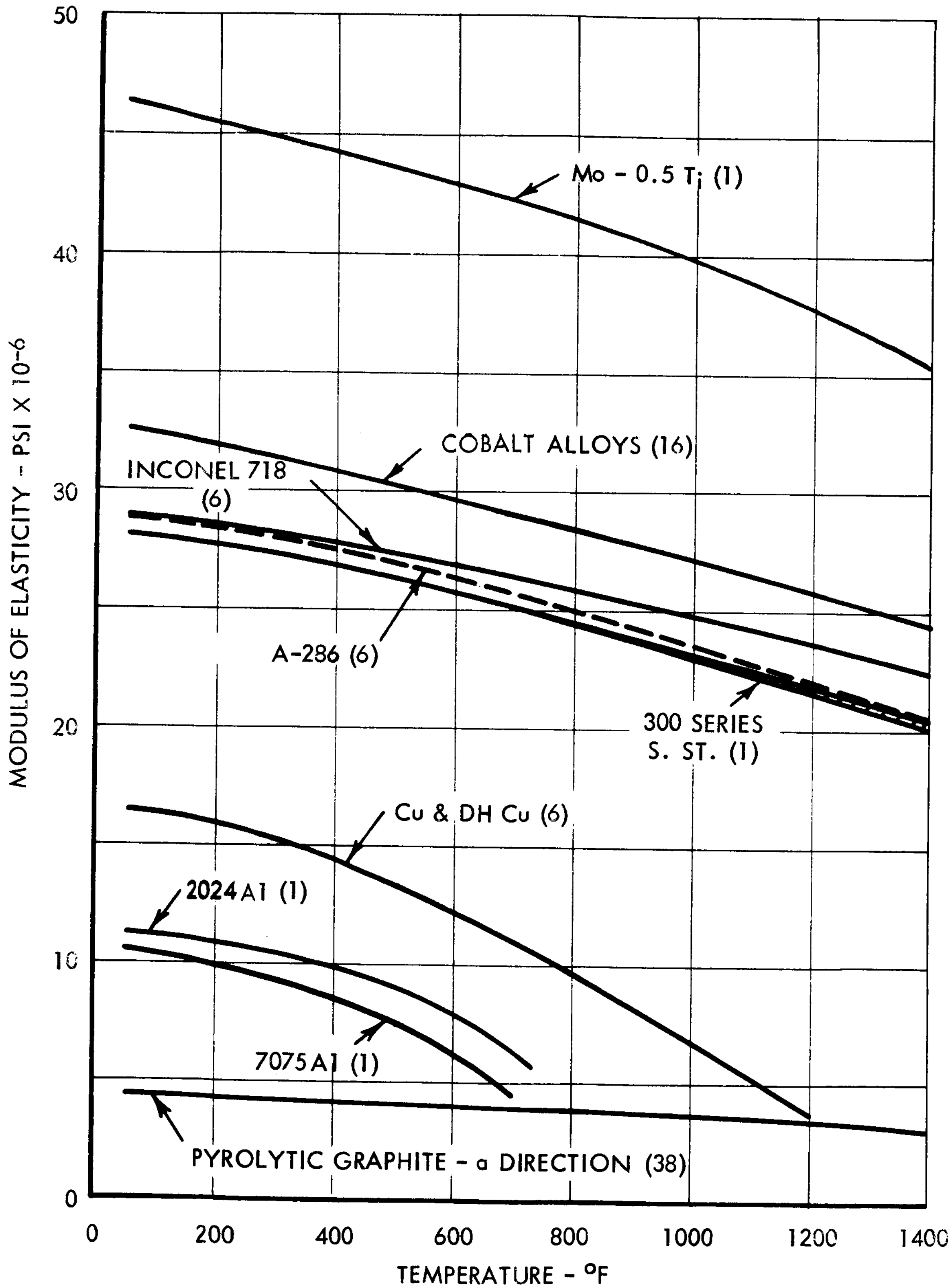


FIGURE 50

MODULUS OF ELASTICITY OF RADIATOR MATERIALS

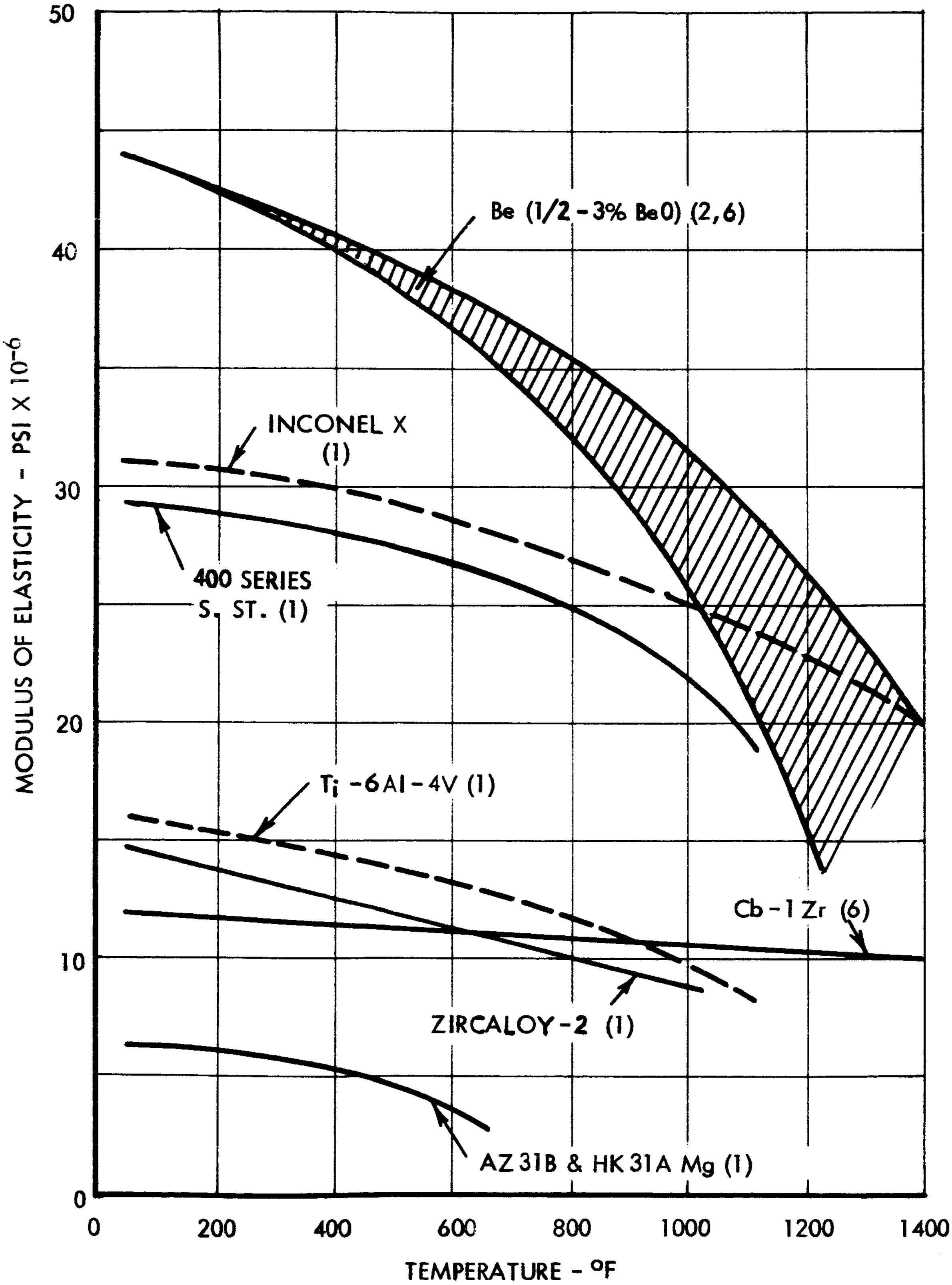


FIGURE 51

THERMAL CONDUCTIVITY OF RADIATOR MATERIALS

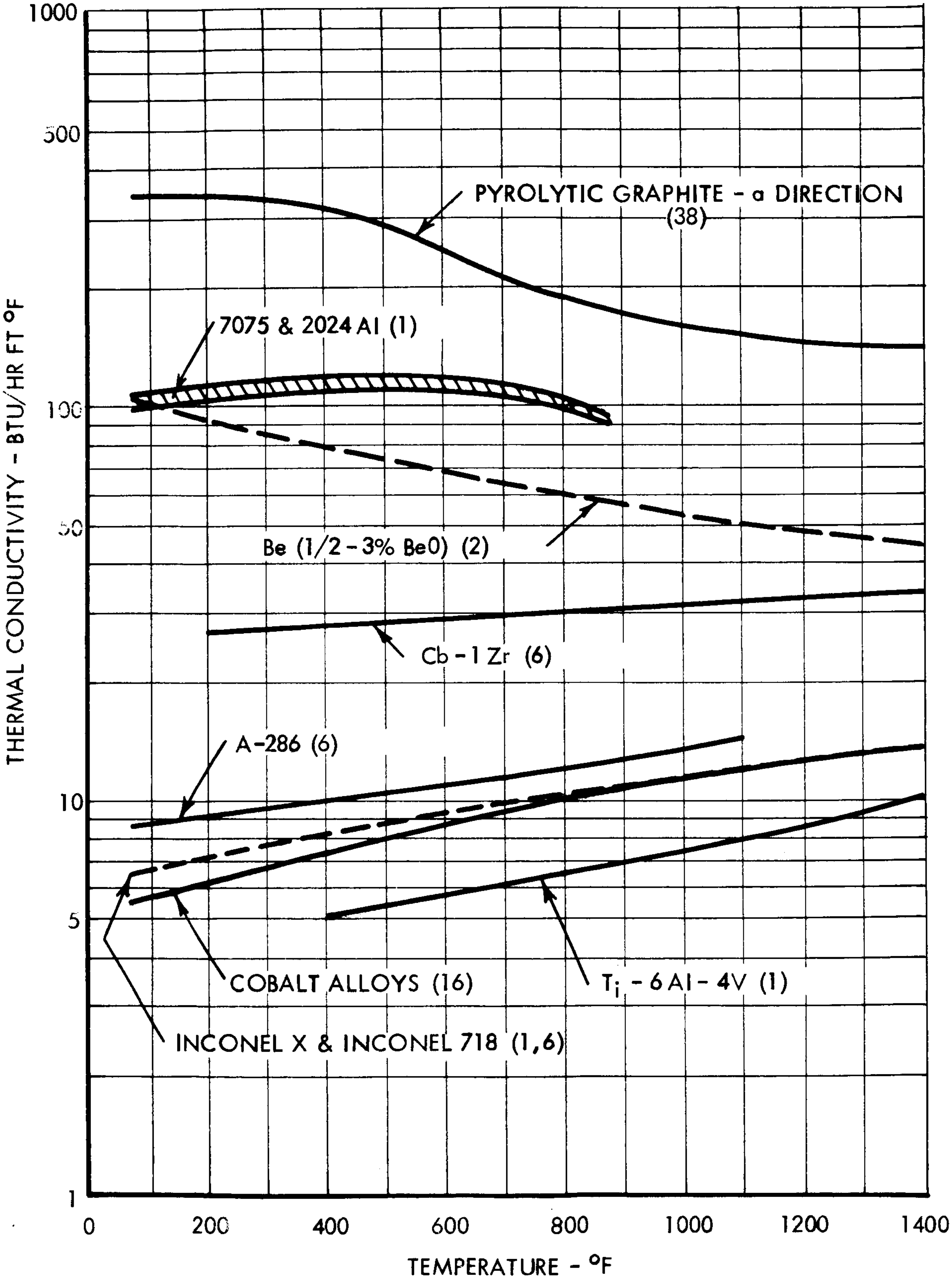


FIGURE 52

THERMAL CONDUCTIVITY OF RADIATOR MATERIALS

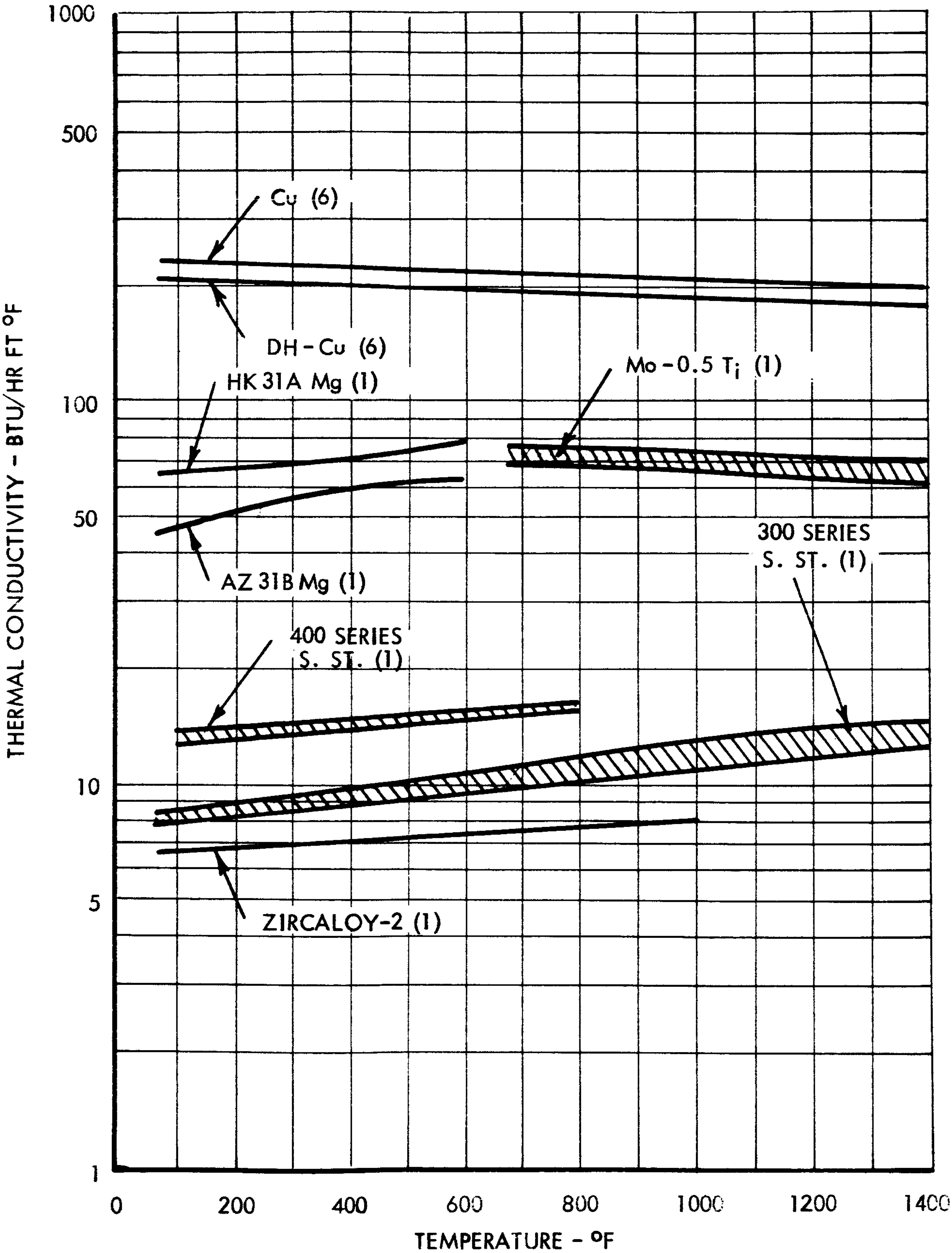


FIGURE 53

.2% YIELD STRENGTH OF RADIATOR MATERIALS

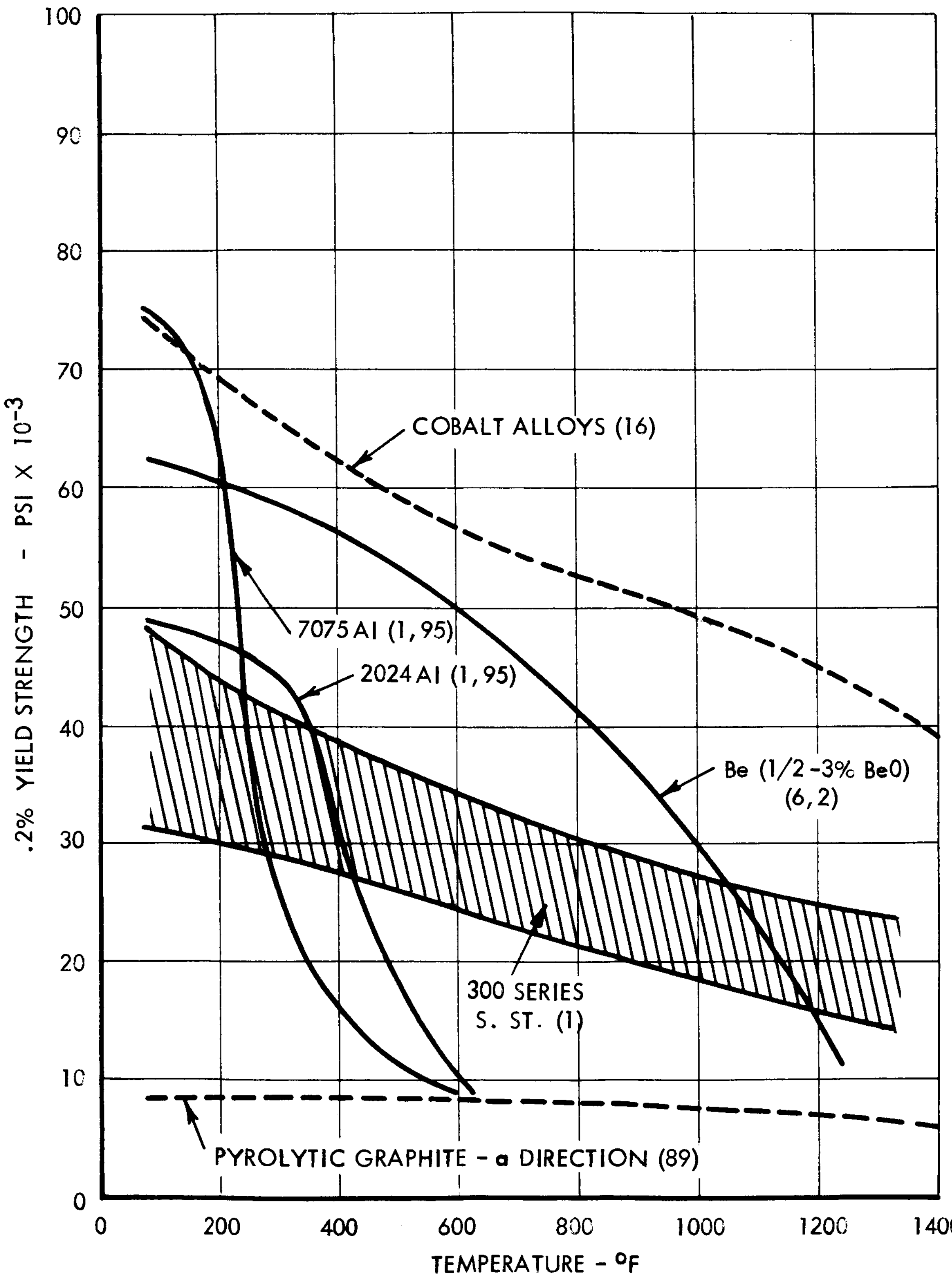


FIGURE 54

.2% YIELD STRENGTH OF RADIATOR MATERIALS

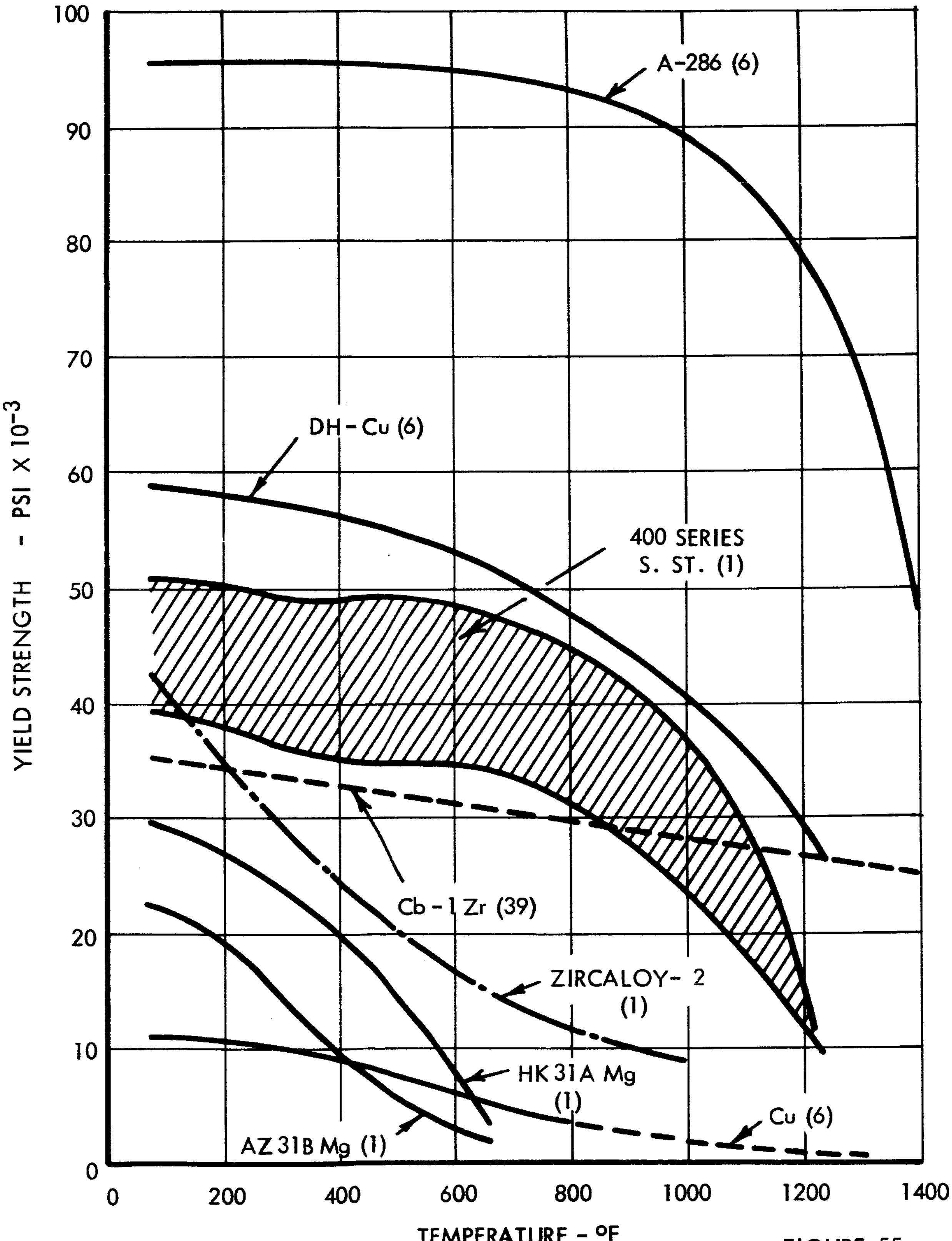


FIGURE 55

.2% YIELD STRENGTH OF RADIATOR MATERIALS

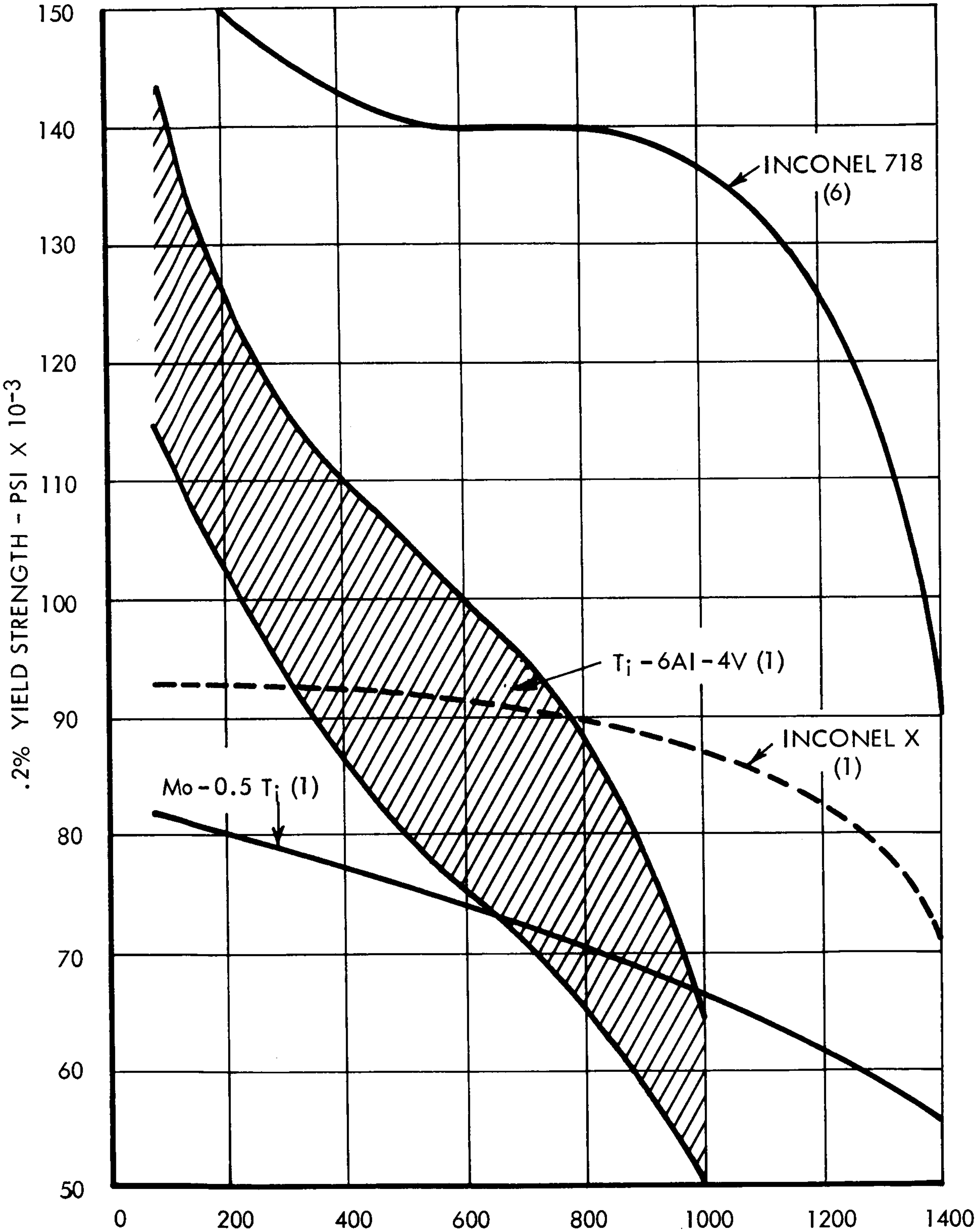


FIGURE 56

THERMAL EXPANSION OF RADIATOR MATERIALS

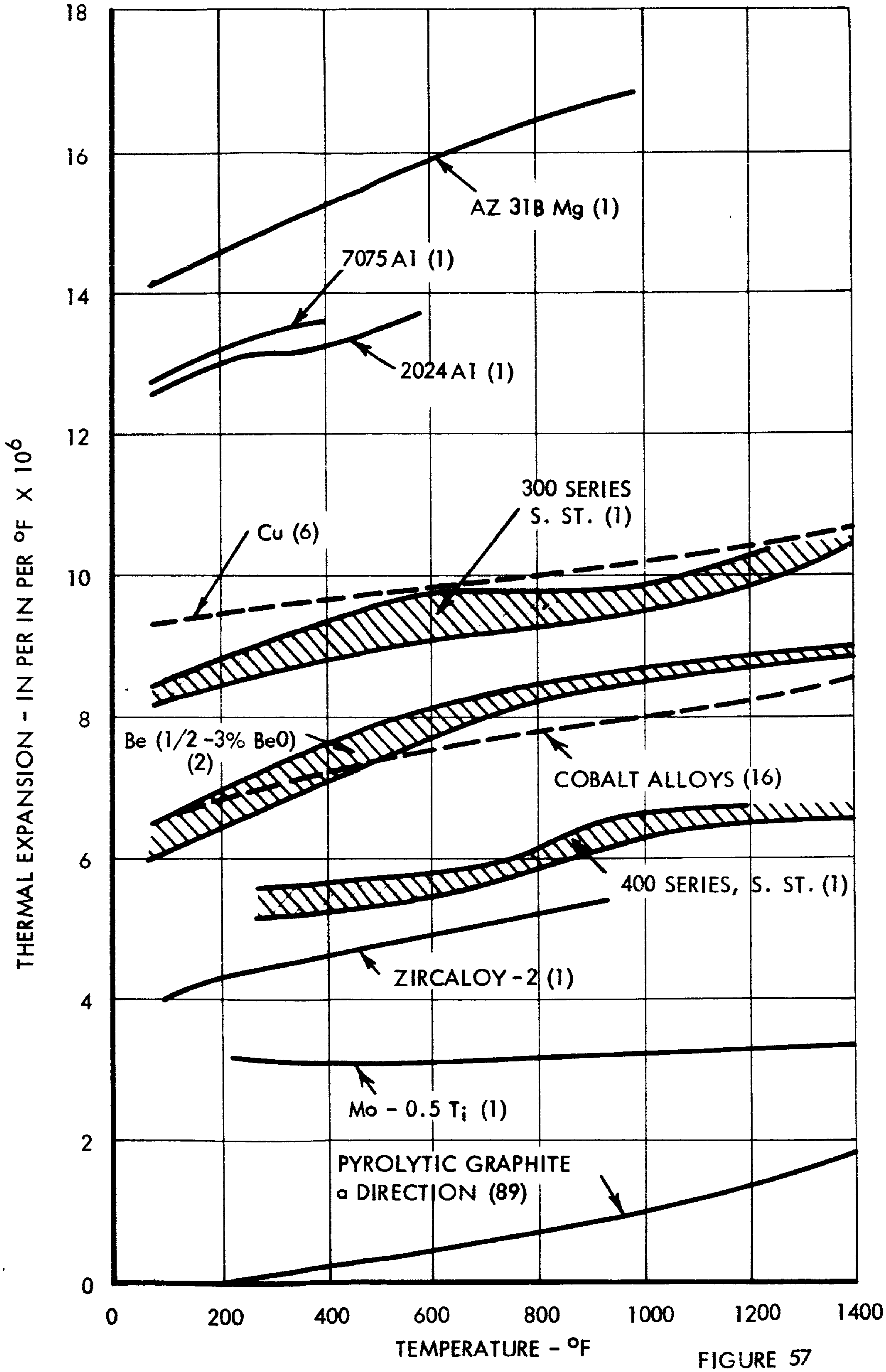


FIGURE 57

THERMAL EXPANSION OF RADIATOR MATERIALS

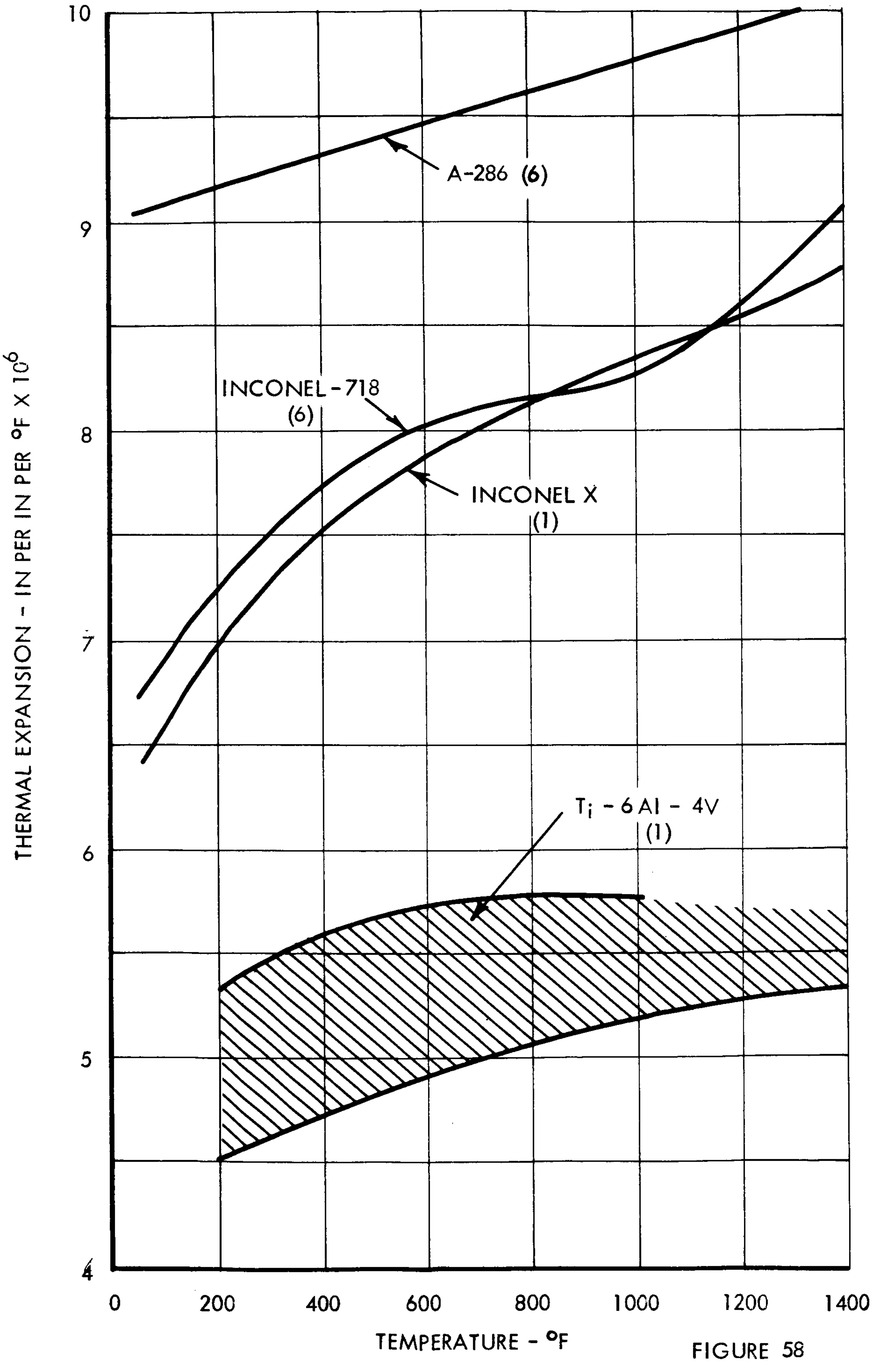


FIGURE 58

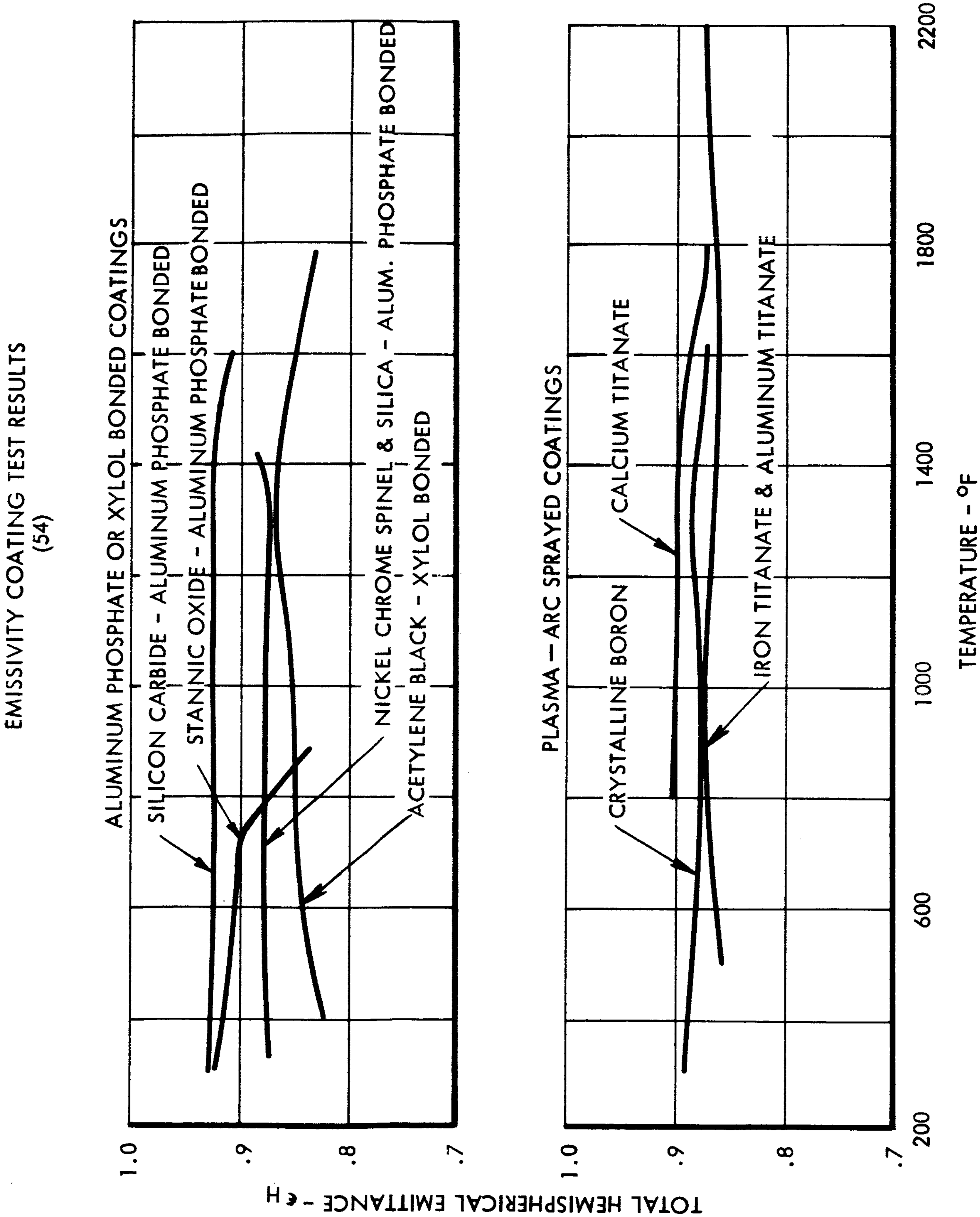

EMISSIVITY COATING TEST RESULTS
(54)
ALUMINUM PHOSPHATE OR XYLOL BONDED COATINGS
SILICON CARBIDE - ALUMINUM PHOSPHATE BONDED
STANNIC OXIDE - ALUMINUM PHOSPHATE BONDED
NICKEL CHROME SPINEL & SILICA - ALUM. PHOSPHATE BONDED
ACETYLENE BLACK - XYLOL BONDED
PLASMA — ARC SPRAYED COATINGS
CRYSTALLINE BORON
CALCIUM TITANATE
IRON TITANATE & ALUMINUM TITANATE
1.0
.9
.8
.7
200
600
1000
1400
1800
2200
TEMPERATURE - °F
TOTAL HEMISPHERICAL EMITTANCE - ϵ_H

FIGURE 59

EFFECT OF COATING THICKNESS ON α_s AND $\alpha_s/\epsilon H$
(68)

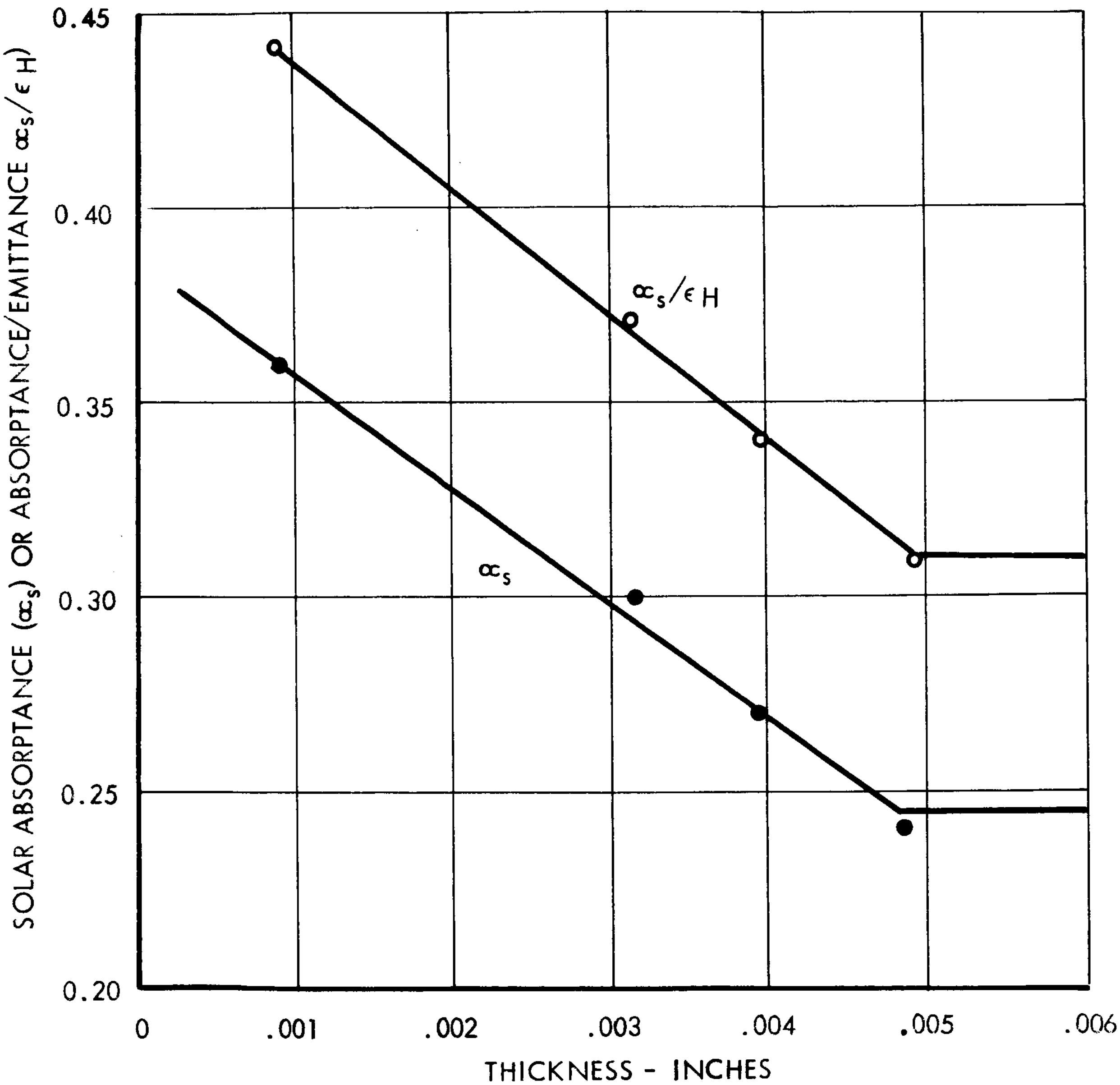


FIGURE 60

IV.

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Note: In some cases, the reference listed is not the primary source of data but rather a publication which referenced the primary source. This substitution kept the number of references to a reasonable number while still enabling the interested user to analyze the primary source of data.

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