NACA

RESEARCH MEMORANDUM

AIRCRAFT-FUEL-TANK DESIGN FOR LIQUID HYDROGEN

By T. W. Reynolds

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

Declassified October 25, 1962

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

August 9, 1955
Reclassified May 29, 1959

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

AIRCRAFT-FUEL-TANK DESIGN FOR LIQUID HYDROGEN *

By T. W. Reynolds

SUMMARY

Some of the considerations involved in the design of aircraft fuel tanks for liquid hydrogen are discussed herein. Several of the physical properties of metals and thermal insulators in the temperature range from ambient to liquid-hydrogen temperatures are assembled. Calculations based on these properties indicate that it is possible to build a large-size liquid-hydrogen fuel tank which (1) will weigh less than 15 percent of the fuel weight, (2) will have a hydrogen vaporization rate less than 30 percent of the cruise fuel-flow rate, and (3) can be held in a stand-by condition and readied for flight in a short time.

INTRODUCTION

Recent performance analyses have indicated that liquid hydrogen offers promising advantages as a fuel for both long- and short-range, high-altitude aircraft operation (ref. 1). In order to obtain these advantages, however, the fuel-tank weight must be kept to a small fraction of the fuel weight.

To keep the tank weight light with a fuel of the very low density (4.42 lb/cu ft) and low boiling-point temperature (37° R) of liquid hydrogen causes problems not encountered with ordinary liquid fuels. Recent experience in the liquefaction of hydrogen and in the storage and transfer of liquid hydrogen has indicated that the problems involved in its use as an aircraft fuel are not insurmountable. Concepts of fuel-tank design different from those used for ground storage are required for aircraft fuel tanks. Ground storage Dewar vessels, designed for low heat-leak rates, are multiple-shell units and have much too high a ratio of tank weight to fuel weight to be considered for flight use.

In this report are assembled some of the physical properties of materials and other considerations involved in the design of a liquid-hydrogen aircraft fuel tank. In addition, some details of the design and anticipated performance of a particular fuel tank for a long-range aircraft are reported.

GENERAL DESIGN CONSIDERATIONS

Values of some of the physical properties of hydrogen which are presented in references 2 and 3 have been reproduced in table I and figures 1 and 2.

The major considerations involved in the design of a fuel tank for an airplane using hydrogen as fuel are (1) it must be light weight, (2) it should not have a heat-leak rate such that fuel will vaporize faster then the engines will burn it at cruise conditions, and (3) it should be capable of storing fuel on the ground for a reasonable length of time without loss of fuel.

Present designs of ground storage Dewar vessels for liquid hydrogen employ a triple-jacketed construction. The inner shell, which contains the liquid hydrogen, is surrounded by a vacuum space, a liquid-nitrogen-cooled radiation shield, another vacuum space, and an outer shell. This construction, besides having multiple shells, requires the outer wall, at least, to withstand a full vacuum. Such construction, while necessary to maintain the low losses required for long-time storage of liquid hydrogen, is obviously too heavy for a flight fuel tank.

In order to maintain the tank weight to a small fraction of the fuel weight, it will be impossible to use more than a single-shell tank with an extremely light-weight insulation around it. Such a tank cannot be built to have a very low heat-leak rate or fuel-loss rate such as the storage Dewar vessels have.

The following principal specifications were assumed for the tank design reported herein:

(1) The fuel-tank weight shall be no more than about 15 percent of the fuel weight.

(2) The heat-leak rate will be such that fuel will vaporize no faster than about one-third of the fuel-flow rate for normal rated engine speed.

Rather than specify a no-loss time on the ground after filling a tank, the time was determined after meeting the preceding two requirements.

MATERIALS OF CONSTRUCTION

Metals

Only limited data are available on the strength of metals and alloys at the temperature of liquid hydrogen (37° R). The tensile and yield strengths of most metals increase as the temperature is lowered. However, some materials, for example the ferritic steels, become very brittle at subzero temperatures and are unsatisfactory as structural materials. Recent work (refs. 4 to 6) has indicated that the austenitic stainless steels, monels, and aluminum alloys have satisfactory properties for use at liquid-hydrogen temperatures. Yield strength of some of the metals increases from 50 to 100 percent of their room-temperature value in decreasing to these low temperatures. At the same time the ductility remains at usable values and the impact strength does not change much from room temperature values.

Recent data on the yield strength and ductility of stainless steels 303, 310, and 316, 24ST aluminum, and monel (ref. 5) are shown in figures 3 and 4. Data for stainless steel type 301 (ref. 6) are also shown on figure 3. These extrapolated data indicate that yield-strength values in excess of 150,000 pounds per square inch may be attained by certain hardened stainless steel alloys at 37° R.

At a yield strength of 150,000 pounds per square inch for steel, the strength-to-weight ratio for the stainless steel is still only about three-fourths of that for the 24ST aluminum. A lighter weight tank could be made from the aluminum alloy. However, stainless steel may still be the desirable material for construction because of its superior impact and welding properties.

When a fuel tank using liquid hydrogen is cooled from ambient temperatures to 37° R, the heat capacity of the metals will be of interest in calculating the cooling load. Figure 5 shows the heat capacity of several metals in this temperature range (ref. 7). These data have been integrated to give enthalpy values above 0° R (fig. 6) for more convenient use in heat-load calculations.

The large temperature range through which the tank materials operate causes thermal expansion and contraction problems. Linear coefficients of thermal expansion of several metals (refs. 8 to 10) in the range from 0° to 300° K (0° to 540° R) are shown in figure 7. The integrated values of expansion coefficients from 300° to 0° K are presented in figure 8.

Data on thermal conductivities and emissivities of various metals in this temperature range may be found in references 11 to 14.

Insulating Materials

A discussion of the problems of low-temperature insulation is presented in references 15 to 20. In general, the characteristics of an insulator which are desirable for this particular application are

(1) Low thermal conductivity

(2) Low vapor penetration

(3) Good compressive strength

(4) Low density

The thermal conductivity of a number of insulators at liquid-hydrogen temperature and at liquid-nitrogen temperature both in vacuum and in the presence of hydrogen and nitrogen gas is given in reference 21. Santocel has one of the lowest thermal conductivities of known insulators. It is used extensively in evacuated shells for insulation of liquified-gas storage containers. Santocel is a granular insulator, however, requiring a supporting container. It is subject to settling and has a higher density-conductivity product than several other insulators of interest. Kapok and several fibrous glass insulations have been produced that have both low thermal conductivity and low density. However, the fibrous nature of these materials, which gives them poor vapor barrier qualities and lack of compressive strength, makes them poor choices for this application.

The type of material that seems to offer the best insulating possibilities is a foamed plastic. Typical of this type is Styrofoam (a polystyrene foam). This plastic is cellular in structure with the cells discontinuous. Styrofoam has negligible vapor penetration and good compressive strength. It can be made in various shapes and densities. Its physical properties are dependent on the density of the material. Some of the physical properties of Styrofoam at 77° F (ref. 22) are given in the following table:

Foam density, lb/cu ft	1.3	1.6	2.0
Compressive yield strength, psi	10-20	15-25	25-35
Tensile strength, psi	30-45	50-70	80-100
Shear strength, psi	15-25	25-35	35-45
Impact strength, 3/8" by 1/8" section, in.-lb	0.5-1.2	1.1-1.8	2.1-2.7
Thermal conductivity, Btu/(sq ft)(hr)(°F/in.)	0.23-0.30		
Coefficient of linear expansion, (in.)/(in.)(°F)	$2-5\times10^{-5}$		
Specific heat, Btu/(lb)(°F) at 40° F	0.27		
Water vapor transmission, grains/(sq ft)(hr)(in. of thickness)(in. Hg vapor pressure difference)	1.5-3.0		

The compressive strength is about 50 percent greater at liquid-nitrogen temperature (78° R) than it is at room temperature. The variation of the thermal conductivity with temperature for Styrofoam (ref. 23) is shown in figure 9.

Other types of expanded plastic foam might also prove of interest. Isocyanate foams, for example, can be foamed in place (ref. 24), and may have the advantage of ease of installation.

DESIGN CALCULATIONS

The characteristics and performance of a tank to hold nominally 25,000 pounds of liquid hydrogen are presented in the following paragraphs. This tank is the approximate size selected for the 5500-nautical-mile-range subsonic bomber discussed in reference 1. The cruise fuel-flow rate is assumed to be 1350 pounds per hour.

Tank Shell

The tank will be pressurized, the pressure aiding in maintaining the fuel-tank shape. As noted in figure 2, the density of the saturated liquid varies considerably with the equilibrium pressure. Liquid expansion may be considerable as the liquid heats until the vapor pressure reaches the tank design pressure. For example, at 30 pounds per square inch absolute, expansion is about 5 percent, at 60 pounds per square inch it is 12 percent, and at 150 pounds per square inch it is nearly 40 percent. Allowance must be made for an expansion volume greater than the anticipated liquid expansion. Since the fuel-tank weight will also increase as the design pressure is increased, it is desirable to keep the tank pressure as low as possible.

It was pointed out in reference 1 that a tank pressure of 2 atmospheres would be adequate for pumping the fuel at the high-altitude cruise condition. A cylindrical tank 10 feet in diameter and 81.6 feet long, including hemispherical ends, has a volume of 6151 cubic feet. This is nearly 9 percent over the nominal volume of 25,000 pounds of liquid at 1-atmosphere pressure. This expansion volume is adequate for a working pressure of 2 atmospheres.

If a yield strength of 150,000 pounds per square inch for a hardened 300-series stainless steel at 37° R and a safety factor of 2 are assumed, the shell thickness will be 0.024 inch. The surface area of this shell is 2564 square feet and the weight 2564 pounds.

Heat-Leak and Surface Temperatures

The tank is insulated with a layer of Styrofoam, which is covered with laminated Mylar-aluminum foil. A schematic cross section of the tank is shown in figure 10. An estimate of the heat leak and surface temperatures was made in the following manner: The heat transferred through the Styrofoam insulation was set equal to that transferred from the surroundings to the surface by radiation and natural convection:

$$\frac{q}{\theta} = h_c A_s(t_a - t_s) + h_r \varepsilon A_s(t_a - t_s) = \frac{k}{L} A_m[t_s - (-423)] \qquad (1)$$

where

A_m logarithm of mean area of inner and outer insulation surfaces, sq ft (A_m differs from A_s by only about 2 percent and is therefore assumed equal to A_s in the calculations.)

A_s surface area of tank, sq ft

D_0 diameter, in.

Δt $t_a - t_s$

ε emissivity of surface, assumed equal to 0.06

h_c free convection coefficient, Btu/(hr)(sq ft)($^{\circ}$F) (Estimated from $h_c = 0.27\left(\frac{\Delta t}{D_0}\right)^{0.25}$ (ref. 25))

h_r radiation coefficient for emissivity of 1.0

k thermal conductivity of insulation, Btu/(hr)(sq ft)($^{\circ}$F/ft) (A mean value of 0.015 was assumed for the calculations; see fig. 9)

L thickness of insulation, ft

q heat leak, Btu/hr

t_a ambient-air temperature, $^{\circ}$F

θ time, hr

t_s equilibrium surface temperature, $^{\circ}$F

Surface temperatures were determined for insulation thicknesses of 3/4, $1\frac{1}{2}$, $2\frac{1}{4}$, and 3 inches, and for ambient temperatures of 80° and -67° F. At the -67° F ambient temperature, a pressure of 0.1 atmosphere was assumed. The natural convection coefficient was assumed to vary with the square root of the pressure, $h_c = 0.27\left(\frac{\Delta t}{D_0}\right)^{0.25} p^{0.5}$ where p is pressure in atmospheres.

The following table summarizes the results of these surface-temperature calculations:

Insulation thickness, in.	Total insulation weight, lb	Surface temperature, °F, at ambient temperature of -	
		80° F	-67° F
3/4	209	-70	-271
$1\frac{1}{2}$	417	-15	-209
$2\frac{1}{4}$	625	10	-182
3	835	23	-162

3745

These data are plotted in figure 11.

Once the surface temperatures have been determined, the heat-leak rate is easily calculated from the equation

$$\frac{q}{\theta} = \frac{k}{L} A_m[t_s - (-423)] \qquad (2)$$

Heat-leak rates expressed in Btu per hour and also as pounds of hydrogen evaporated per hour as a function of insulation thickness are shown in figure 12. The vaporization rate at the altitude condition with $2\frac{1}{4}$ inches of insulation is about 255 pounds per hour. The amount of hydrogen gas necessary to maintain the tank pressure while removing liquid at the rate of 1350 pounds per hour is obtained by multiplying the liquid-flow rate by the ratio of vapor to liquid densities at the tank pressure. At 30 pounds per square inch, the ratio of vapor to liquid densities (fig. 1) is about 0.036. Therefore, about 49 pounds per hour of hydrogen gas will maintain the tank pressure. This amount is only about 20 percent of the vaporization rate due to heat leak for the $2\frac{1}{4}$-inch insulation thickness. The heat leak at higher ambient temperatures can be approximated by multiplying the heat leak calculated for the 80° F ambient by the ratio of the over-all temperature differences involved.

These heat-leak calculations have not assumed any additional insulating value that might be obtained through installation of this tank in an aircraft fuselage. The heat-leak calculations should therefore be conservative for this type of installation.

Externally mounted tanks would have higher convective heat-transfer coefficients than the free-convection coefficients assumed in evaluating equation (1). Consequently, with an external installation, these heat-leak calculations will be somewhat low for conditions during flight.

Filling Tank

The problem of filling the tank with liquid hydrogen, when it is at room temperature and filled with air initially, is essentially one of both cooling and purging. The amount of heat that must be removed in cooling the tank and insulation from an ambient temperature of 80° F to liquid-hydrogen temperatures can be estimated by using the integrated heat-capacity curve for iron (fig. 6) and the heat-capacity value for Styrofoam. For an insulation thickness of $2\frac{1}{4}$ inches, this heat amounts to less than 150,000 Btu.

In order to prevent the formation of any solid materials, which might plug fuel lines or orifices, it will be necessary to purge the tank and lines with either helium or hydrogen gas, since any other material will be solid at these temperatures.

There are several alternative schemes for filling the tank:

(1) Flushing with gaseous helium, then filling with liquid hydrogen directly

(2) Cooling with liquid nitrogen, flushing with helium, then filling with liquid hydrogen

(3) Cooling and flushing with helium that has been cooled by liquid nitrogen

(4) Flushing with helium cooled by a mechanical refrigeration cycle

Since the heat capacity of liquid hydrogen is rather high (fig. 13 and ref. 26), the cooling load could be absorbed as sensible heat in the liquid. The tank is designed for a working pressure of 2 atmospheres. The temperature of the saturated liquid at this pressure is 41° R (fig. 2) or about 4° R above the normal boiling point. The average heat capacity of the liquid over this temperature interval is about 2.4 Btu per pound per °R. The heat sink available in the liquid is, then, $wc_p\Delta t = (25{,}000)(2.4)(4) = 240{,}000$ Btu where w is mass in pounds and c_p is heat capacity at constant pressure in Btu per pound per °R. This is more than enough to absorb the full cooling load.

It will be noted from figure 6 that about 95 percent of the cooling load could be extracted by using liquid nitrogen to cool the tank. When the tank is cooled by some other means than using the heat capacity of the liquid hydrogen to absorb the heat load, the filled tank can stand for a longer time without losing any hydrogen through evaporation. The heat sink available in the liquid is used to absorb the heat leak into the tank until the liquid temperature rises to a point where the vapor pressure is equal to the tank design pressure. This time has been called the no-loss time in this report. The variation of no-loss time for the 30-pound-per-square-inch working-pressure tank reported herein is plotted against insulation thickness in figure 14. For the $2\frac{1}{4}$ inch insulation, the no-loss time is about 165 minutes.

It may be desirable to maintain the tanks in a refrigerated, standby condition, ready to be filled with liquid hydrogen. Therefore, it is suggested that a cycling system using helium gas, cooled by liquid nitrogen, may be cycled through the tank until such time as it is desired to fill with liquid hydrogen. The introduction of liquid hydrogen, then, does not impose a great thermal shock on the tank, the loss of hydrogen through vaporization in cooling from liquid-nitrogen to liquid-hydrogen temperature is relatively small, and the system is full of helium gas prior to the introduction of the liquid hydrogen.

SUMMARY OF CALCULATIONS

The results of the foregoing calculations are summarized in the following table:

Size:		
Diameter, ft		10
Length, ft		81.6
Volume, cu ft		6151[a]
gal		45,800
Surface area, sq ft		2564
Working pressure, atm		2
lb/sq in.		30
Styrofoam insulation[b]:		
Thickness, in.		$2\frac{1}{4}$
Density, lb/cu ft		1.3
Weight of tank:		
Shell, lb		2564
Insulation, lb		625
Covering, lb		64
Allowance for baffles and stiffeners, lb		247
Approximate total weight, lb		3500[c]
Estimated performance at ambient temperature, °F:	80	-67
Outer surface temperature, °F	10	-182
Heat-leak rate, Btu/hr	88,000	49,500
Hydrogen-vaporization rate, lb/hr	454	255
No-loss time on ground, min	165	

[a]Holds 25,000 lb liquid hydrogen with 9 percent expansion volume.
[b]Covered with layer of Mylar-aluminum foil.
[c]About 14 percent of fuel weight.

CONDLUDING REMARKS

From a consideration of the physical properties of materials and thermal insulators now available, it appears feasible to design a liquid-hydrogen fuel tank for aircraft use which (1) will weigh less than 15 percent of the fuel weight, (2) will have a hydrogen vaporization rate less than 30 percent of the cruise fuel-flow rate, and (3) can be held in a stand-by condition and readied for flight in a short time.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, June 22, 1955

REFERENCES

1. Silverstein, Abe, and Hall, Eldon W.: Liquid Hydrogen as a Jet Fuel for High-Altitude Aircraft. NACA RM E55C28a, 1955.

2. Woolley, Harold W., Scott, Russell B., and Brickwedde, F. G.: Compilation of Thermal Properties of Hydrogen in Its Various Isotopic and Ortho-Para Modifications. Jour. Res. Nat. Bur. Standards, vol. 41, no. 5, Nov. 1948, pp. 379-475.

3. White, David, and Johnston, Herrick L.: The Thermodynamic Properties of Liquid Normal Hydrogen Between the Boiling Point and the Critical Temperature and up to 150 Atmospheres Pressure. TR 264-23, Cryogenic Lab., Dept. Chem., The Ohio State Univ., Feb. 1, 1953. (AF Contract W33-038 ac 14794 (16243), Proj. RF-264.)

4. Krivobok, V. N.: Properties of Austenitic Stainless Steels at Low Temperatures. Mechanical Properties at Low Temperatures, Circular 520, U.S. Dept. Commerce, Nat. Bur. Standards, May 7, 1952, pp. 112-134; discussion, pp. 134-136.

5. Kropschot, R. H., Parkerson, C. R., O'Donel, J., and Crum, M. G.: Low Temperature Tensile Testing Equipment and Results (300°-20° K). Rep. 2708, U.S. Dept. Commerce, Nat. Bur. Standards, July 1, 1953. (NBS Proj. 0306-20-2667.)

6. Anon.: Stainless Steel Handbook. Allegheny Ludlum Steel Corp., Pittsburgh (Pa.), 1951.

7. Anon.: International Critical Tables. Vol. V. McGraw-Hill Book Co., Inc., 1929, p. 83.

8. Altman, Howard W., Rubin, Thor, and Johnston, Herrick L.: Coefficients of Thermal Expansion of Solids at Low Temperatures. II - The Thermal Expansion of Monel, Inconel, Contracid, SAE 1020 Low Carbon Steel and Type 410 Stainless Steel. TR 264-19, Cryogenic Lab., Dept. Chem., The Ohio State Univ., May 1, 1952. (AF Contract W33-038 ac 14794 (16243), Proj. RF-264.)

9. Altman, H. W., Rubin, T., and Johnston, H. L.: Coefficient of Thermal Expansion of Solids at Low Temperature. III - The Thermal Expansion of Pure Metals, with the Data for Aluminum, Nickel, Titanium, and Zironium. TR 264-27, Cryogenic Lab., Dept. Chem., The Ohio State Univ., Feb. 10, 1954. (AF Contract W33-038 ac 14794 (16243), Proj. RF-264.)

10. Altman, Howard W., Rubin, Thor, and Johnston, Herrick L.: Coefficients of Thermal Expansion of Solids at Low Temperatures. IV - The Thermal Expansion of Type 304 Stainless Steel and Yellow Brass. TR 264-28, Cryogenic Lab., Dept. Chem., The Ohio State Univ., Mar. 8, 1954. (AF Contract W33-038 ac 14794 (16243), Proj. RF-264.)

11. Powers, Robert W., Ziegler, John B., and Johnston, Herrick L.: The Thermal Conductivity of Metals and Alloys at Low Temperatures. II - Data on Iron and Several Steels Between 25° and 300° K. Influence of Alloying Constituents. TR 264-6, Cryogenic Lab., Dept. Chem., The Ohio State Univ., Apr. 25, 1951. (AF Contract W33-038 ac 14794 (16243), Proj. RF 264.)

12. Powers, Robert W., Ziegler, John B., and Johnston, Herrick L.: The Thermal Conductivity of Metals and Alloys at Low Temperatures. III - Data for Aluminum Alloys Between 25° and 300° K. TR 264-7, Cryogenic Lab., Dept. Chem., The Ohio State Univ. (AF Contract W33-038 ac 14794 (16243), Proj. RF-264.)

13. Powell, R. L.: Thermal Conductivities of Solids at Low Temperatures. TM No. 17, Cryogenic Eng. Lab., Nat. Bur. Standards, Boulder (Colorado), May 26, 1953.

14. Reynolds, M. M., Fulk, M. M., Weitzel, D. H., and Park, O. E.: A Preliminary Report on the Infrared Absorption of Metals at Low Temperature. TM No. 16, Cryogenic Eng. Lab., Nat. Bur. Standards, Boulder (Colorado), May 26, 1953.

15. White, John F.: Low-Temperature Insulation - Problems and Developments. Chem. Eng. Prog., vol. 44, no. 8, Aug. 1948, pp. 647-652.

16. Palmer, Burton M., and Taylor, Robert B.: Glass-Fiber Insulation at Liquid-Air Temperatures. Chem. Eng. Prog., vol. 44, no. 8, Aug. 1948, pp. 652-654.

17. Bradley, C. B., and Stone, J. F.: Low-Temperature Insulation - Thermal Insulation for Low-Temperature Application. Chem. Eng. Prog., vol. 44, no. 9, Sept. 1948, pp. 723-726.

18. McIntire, O. R., and Kennedy, R. N.: Styrofoam for Low-Temperature Insulation. Chem. Eng. Prog., vol. 44, no. 9, Sept. 1948, pp. 727-730.

19. Van Buskirk, E. C., and Surland, C. C.: Low-Temperature Insulation - A New Plastic Low-Temperature Insulation. Chem. Eng. Prog., vol. 44, no. 10, Oct. 1948, pp. 803-804.

20. Sanders, Victor: Cellular-Glass Insulations for Low-Temperature Equipment. Chem. Eng. Prog., vol. 44, no. 10, Oct. 1948, pp. 804-806.

21. Powers, R. W., Johnston, H. L., Hansen, R. H., and Ziegler, J. B.: Thermal Conductivity of Heat Insulating Materials. TR 264-16, Cryogenic Lab., The Ohio State Univ., May 1, 1953. (AF Contract W33-038 ac 14794 (16243), Proj. RF 264.)

22. Anon.: Styrofoam - Technical Data. Plastics Dept., The Dow Chem. Corp., Midland (Mich.), 1951.

23. Waite, H. J.: Styrofoam (Expanded Polystyrene) Insulation at Low Temperature. Rep. 3517, Proc. 1954 Cryogenic Eng. Conf., U.S. Dept. Commerce, Nat. Bur. Standards, Feb. 1955, pp. 158-163.

24. Witte, P. J.: Foaming Plastics - Cellular Cellulose Acetate. Modern Plastics, Encyclopedia Issue, Sept. 1954, pp. 168-169.

25. McAdams, William H.: Heat Transmission. Second ed., McGraw-Hill Book Co., Inc., 1942, p. 241.

26. Smith, A. Lee, Hallett, Nathan C., and Johnston, Herrick L.: Condensed Gas Calorimetry. VI - The Heat Capacity of Liquid Parahydrogen from the Boiling Point to the Critical Point. Jour. Am. Chem. Soc., vol. 76, no. 6, Mar. 20, 1954, pp. 1486-1488.

TABLE I. - PHYSICAL PROPERTIES OF HYDROGEN

Molecular weight	2.016
Heating value, Btu/lb	51,571
Boiling point at 1 atm, $^{\circ}$R	37
Melting point, $^{\circ}$R	25.2
Critical temperature, $^{\circ}$R	59.6
Critical pressure, atm	12.8
Critical density, lb/cu ft	1.95
Latent heat of melting, Btu/lb	25.2
Latent heat of vaporization, Btu/lb	194
Density, liquid at 1 atm and 37° R, lb/cu ft	4.42
Density, vapor at 1 atm and 492° R, lb/cu ft	0.0056
Viscosity, liquid, centipoises	0.014
Viscosity, vapor, centipoises at T$^{\circ}$ K	$\mu = 0.0084\left(\frac{T}{273.1}\right)^{0.695}$
Heat capacity, liquid parahydrogen at 37° R, Btu/(lb)($^{\circ}$R)	2.25
Heat capacity, vapor at 519° R, Btu/(lb)($^{\circ}$R)	3.4

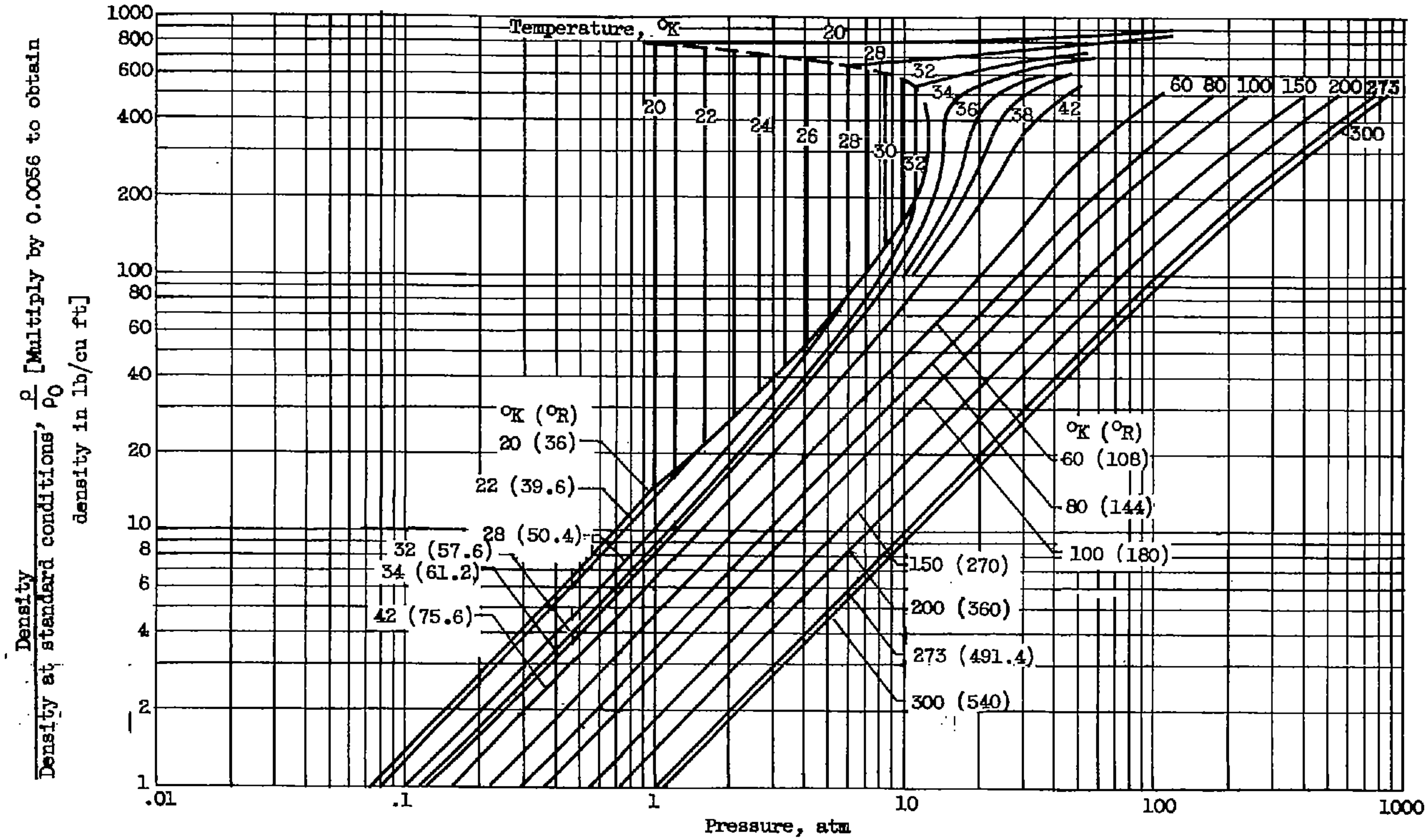

Figure 1. - Pressure-temperature-density relation for hydrogen. Data obtained from references 2 and 3.

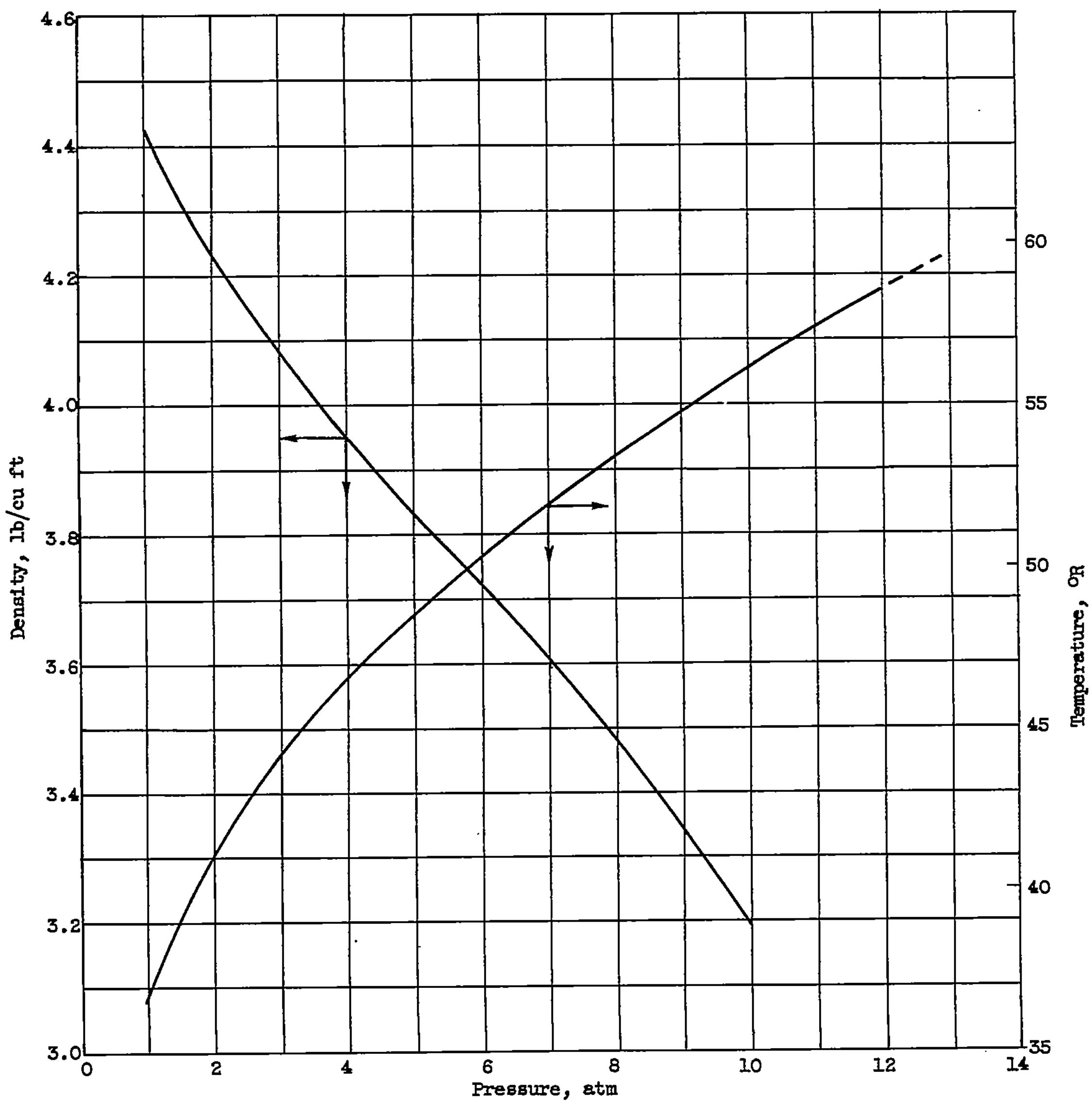

Figure 2. - Pressure-temperature-density relation for saturated liquid hydrogen. Data obtained from reference 3.

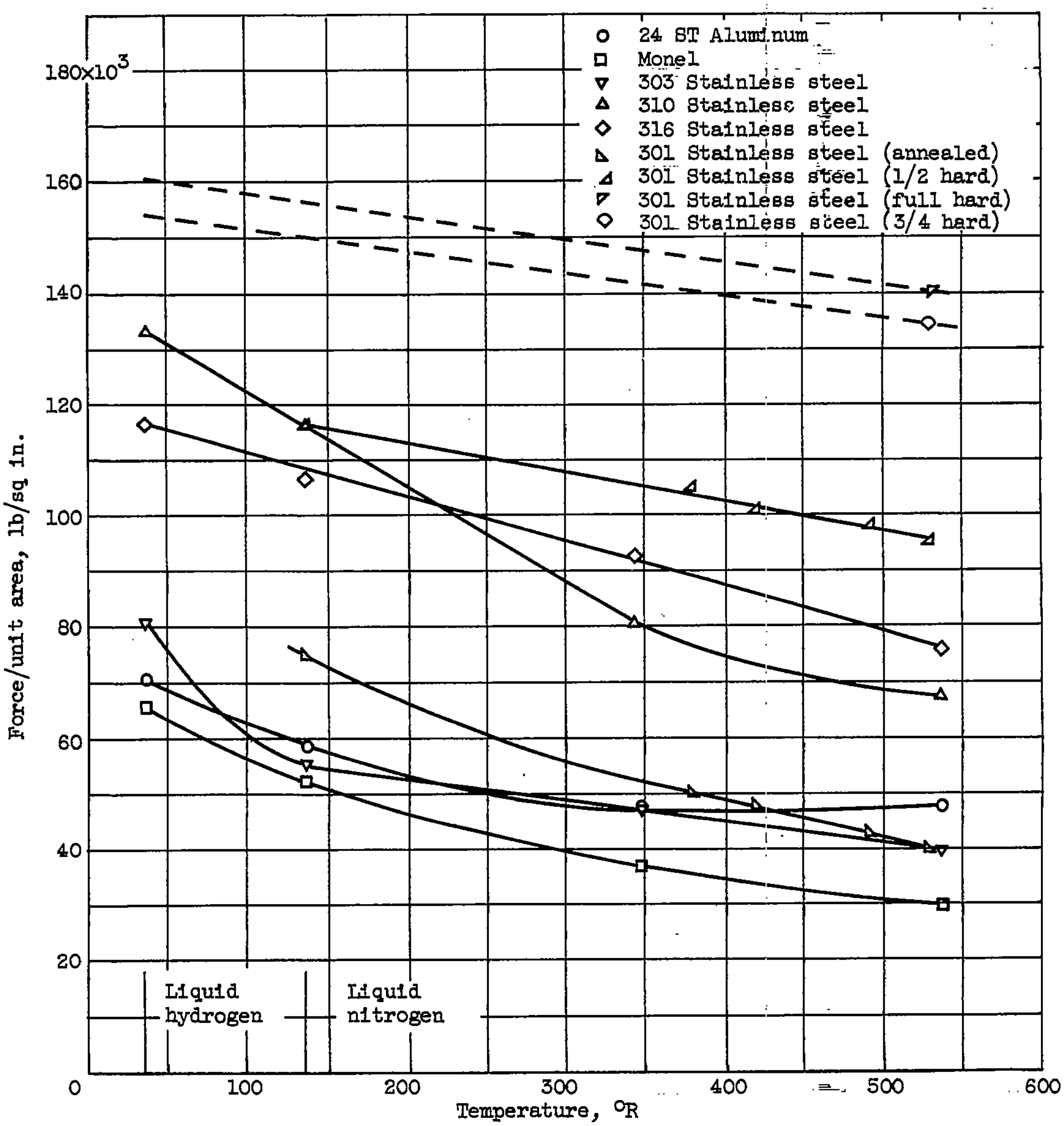

Figure 3. - Yield strength of several alloys at low temperatures. Data obtained from references 5 and 6.

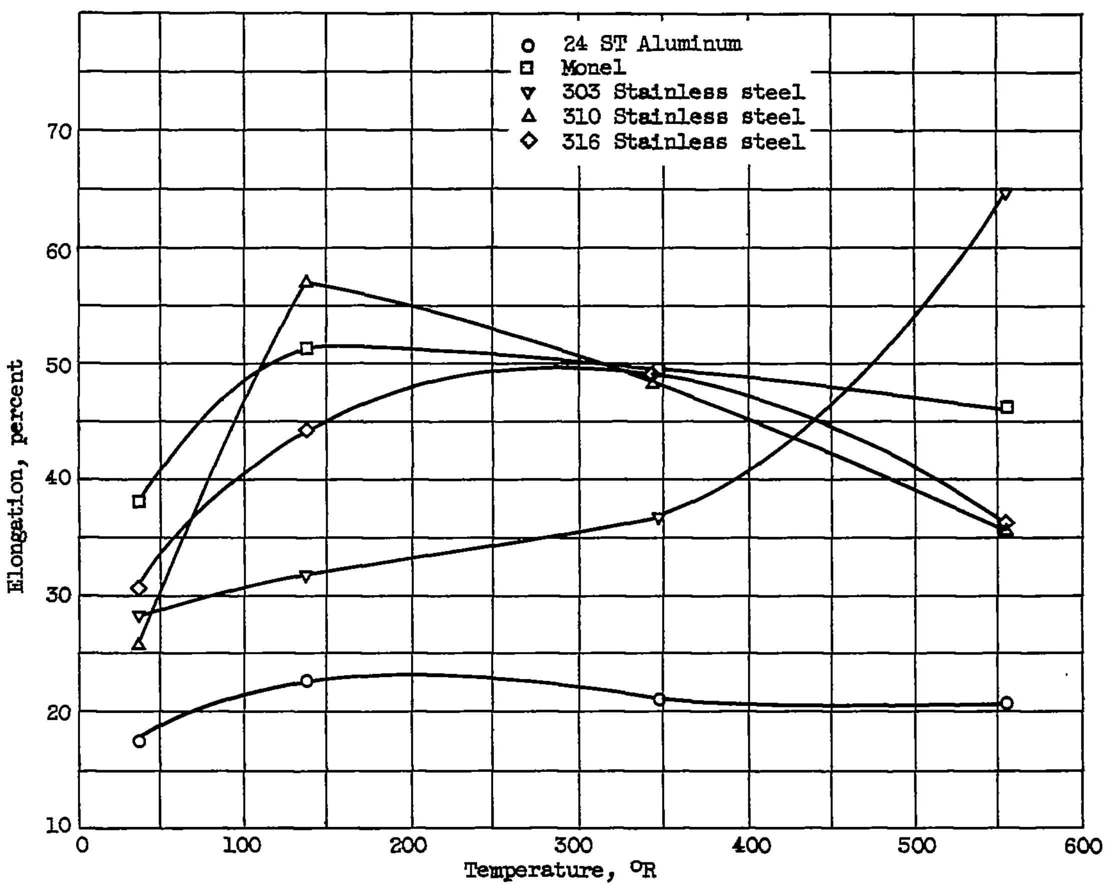

Figure 4. - Elongation of several alloys at low temperatures. Data obtained from reference 5.

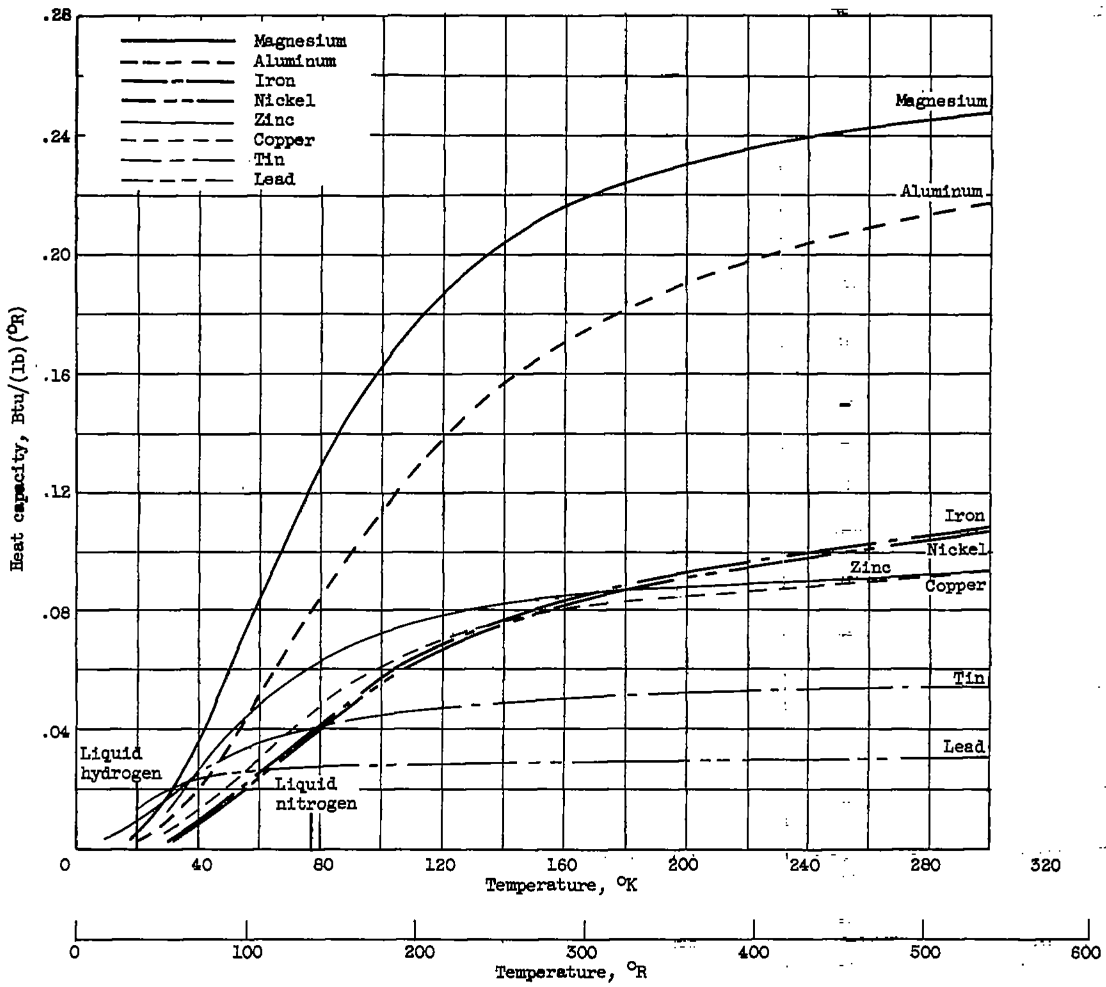

Figure 5. - Heat capacity of several metals at low temperatures. Data obtained from reference 7.

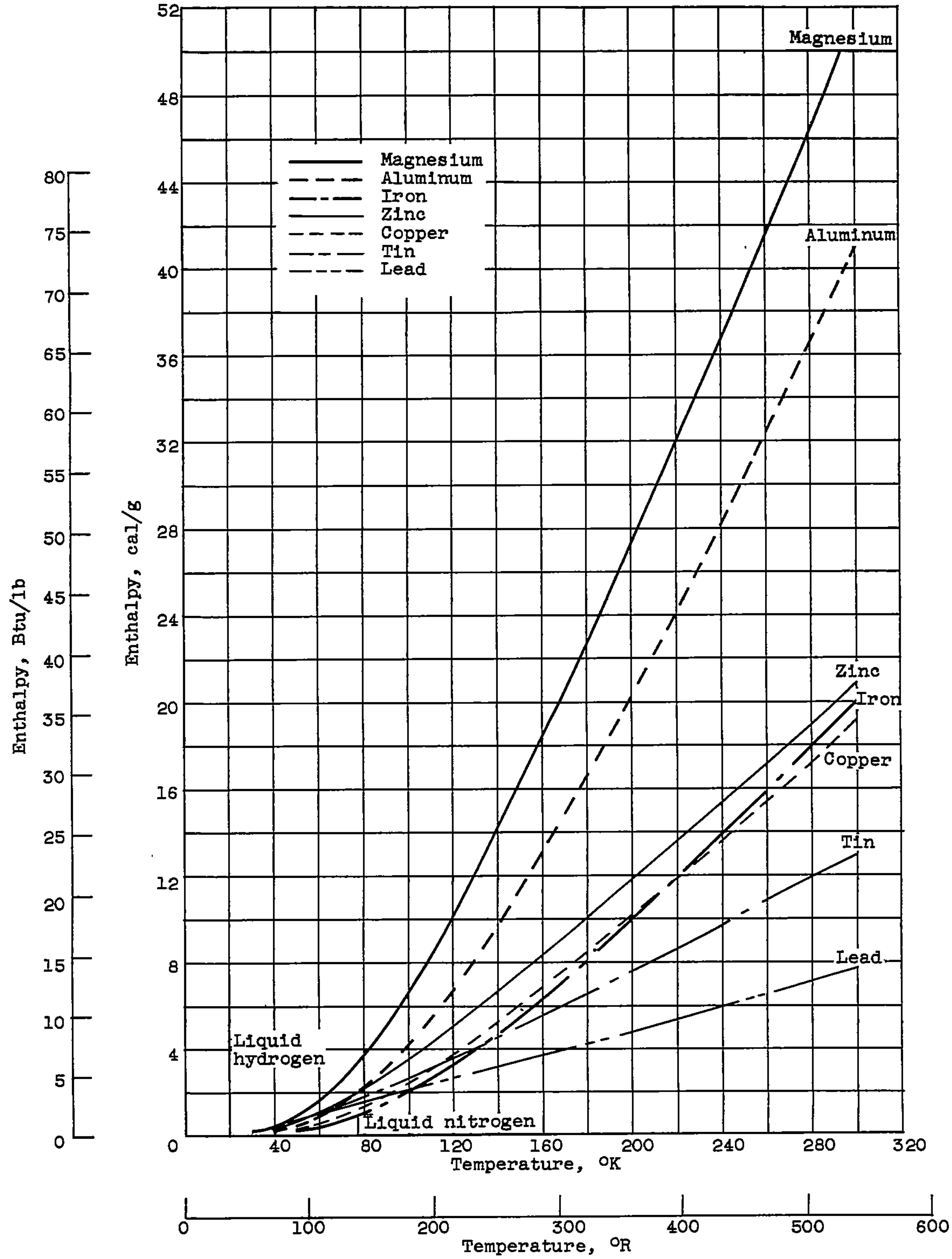

Figure 6. - Integrated heat-capacity curves for several metals above 0° K.

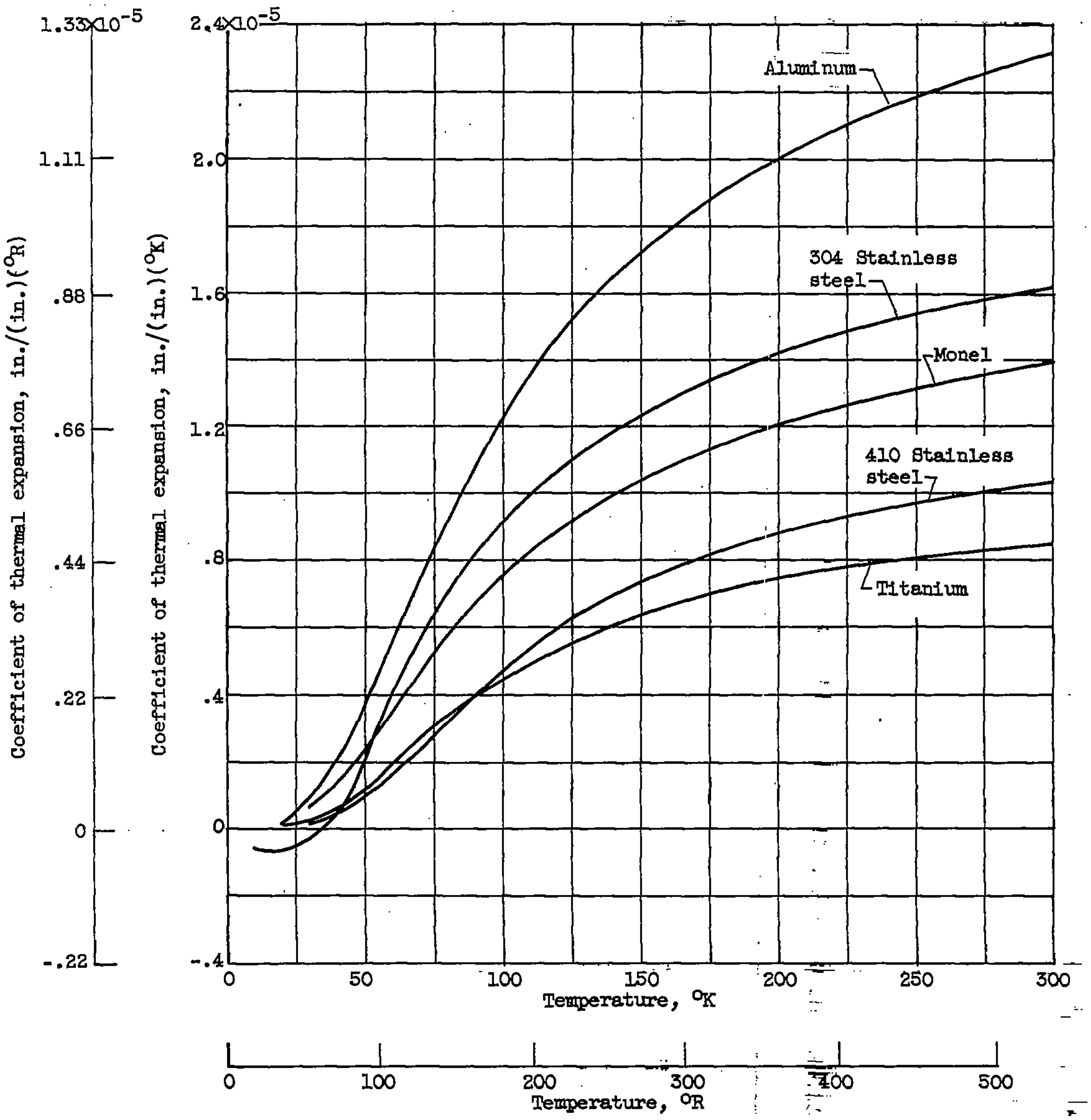

Figure 7. - Linear coefficients of expansion of several metals at low temperatures. Data obtained from references 8 to 10.

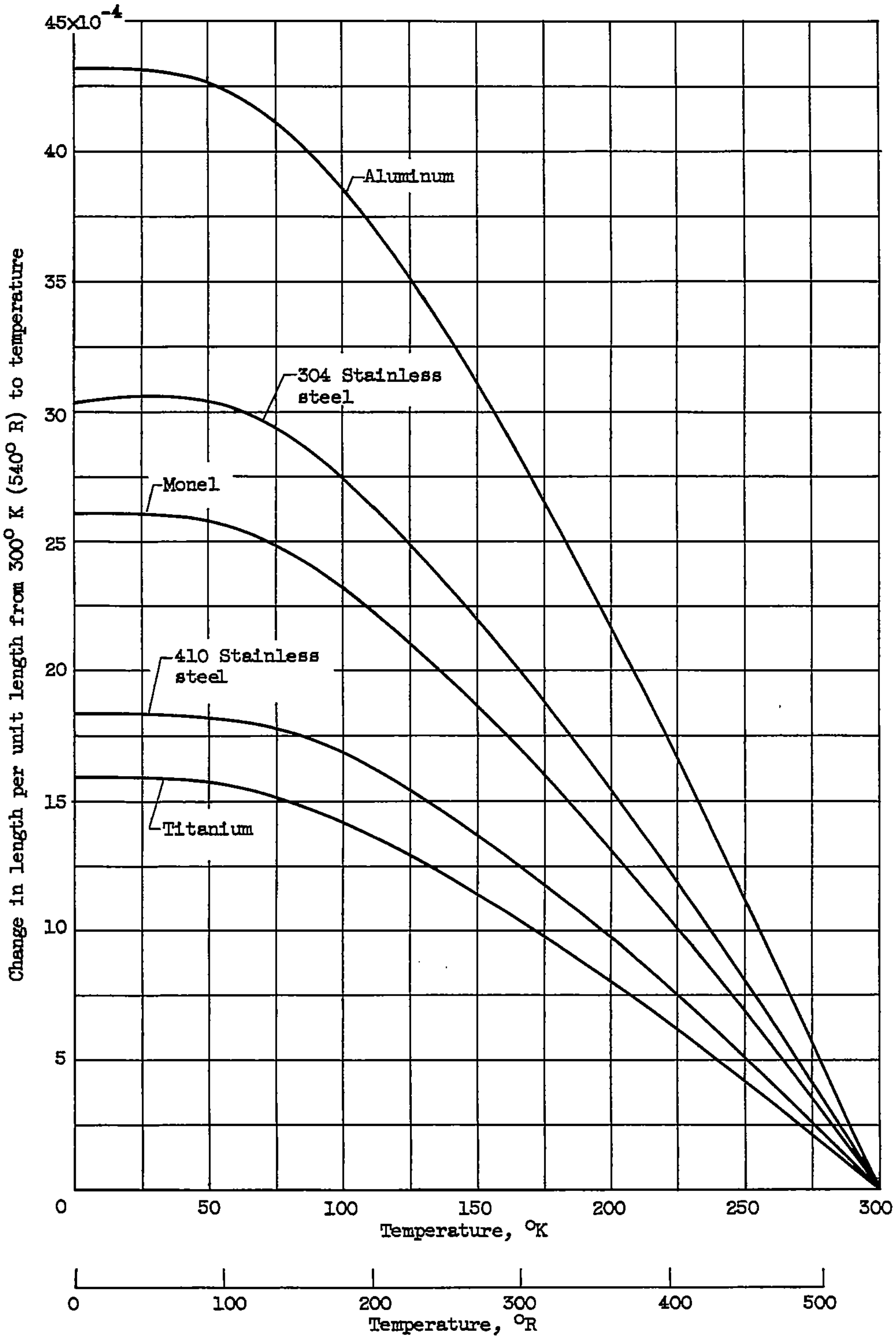

Figure 8. - Integrated values of linear coefficients of expansion for several metals. Data obtained from references 8 to 10.

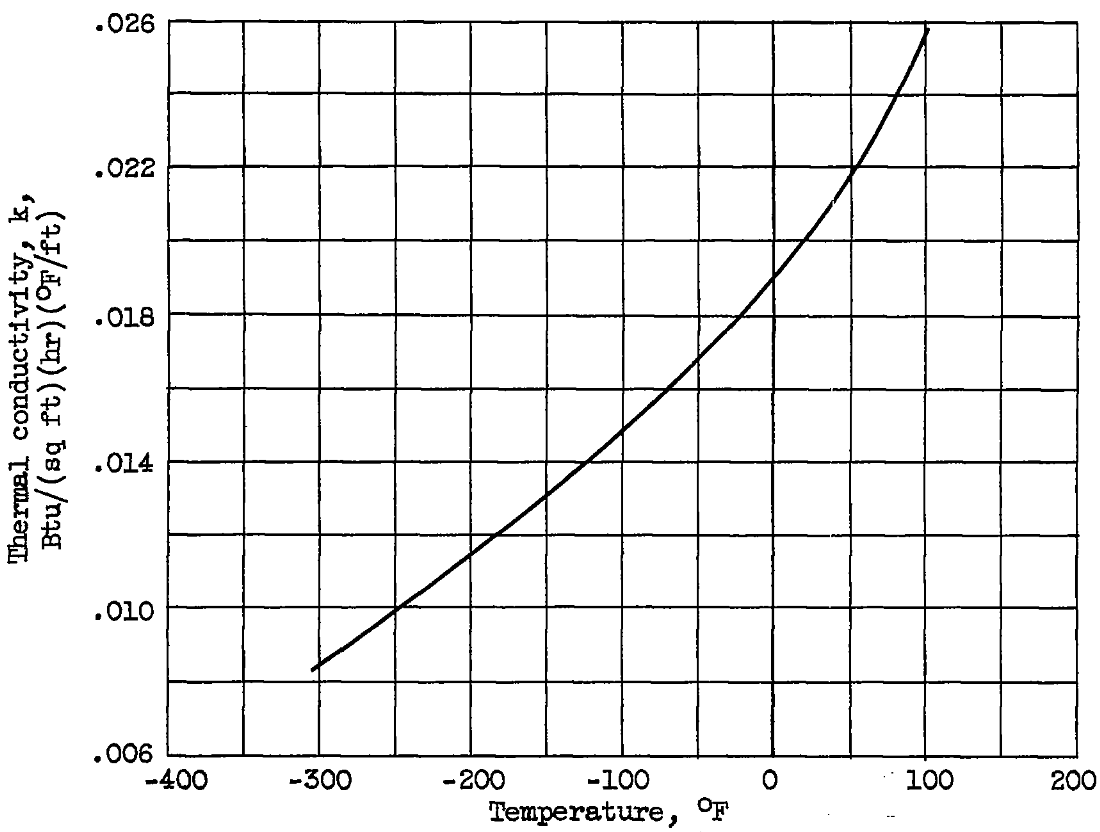

Figure 9. - Variation of thermal conductivity of styrofoam with temperature. Data obtained from reference 23.

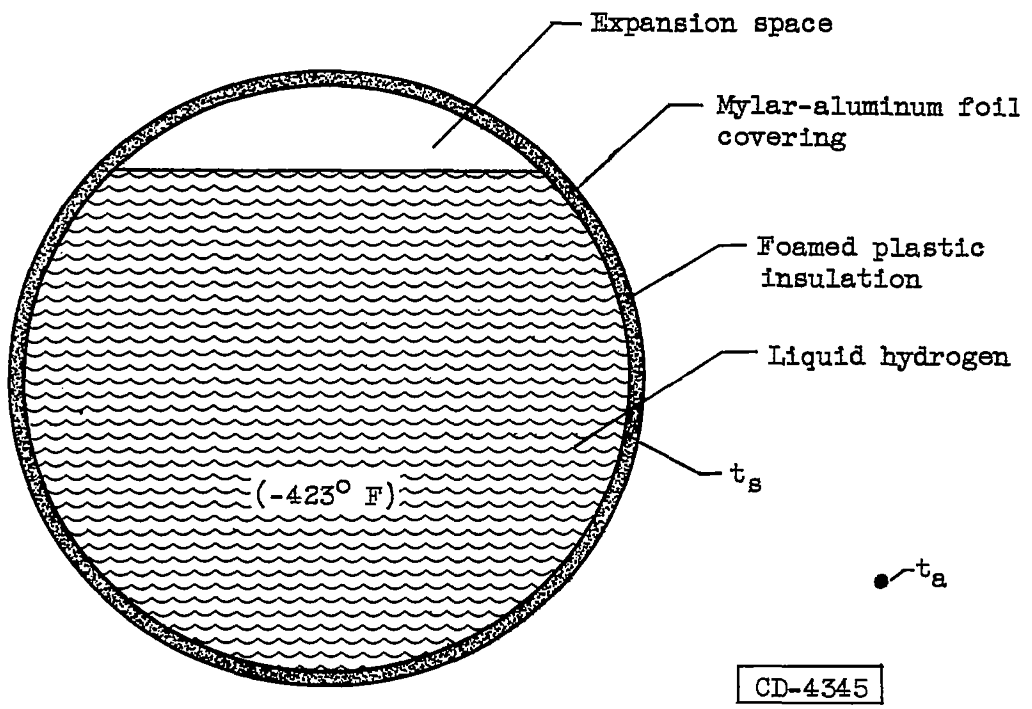

Figure 10. - Liquid-hydrogen fuel tank.

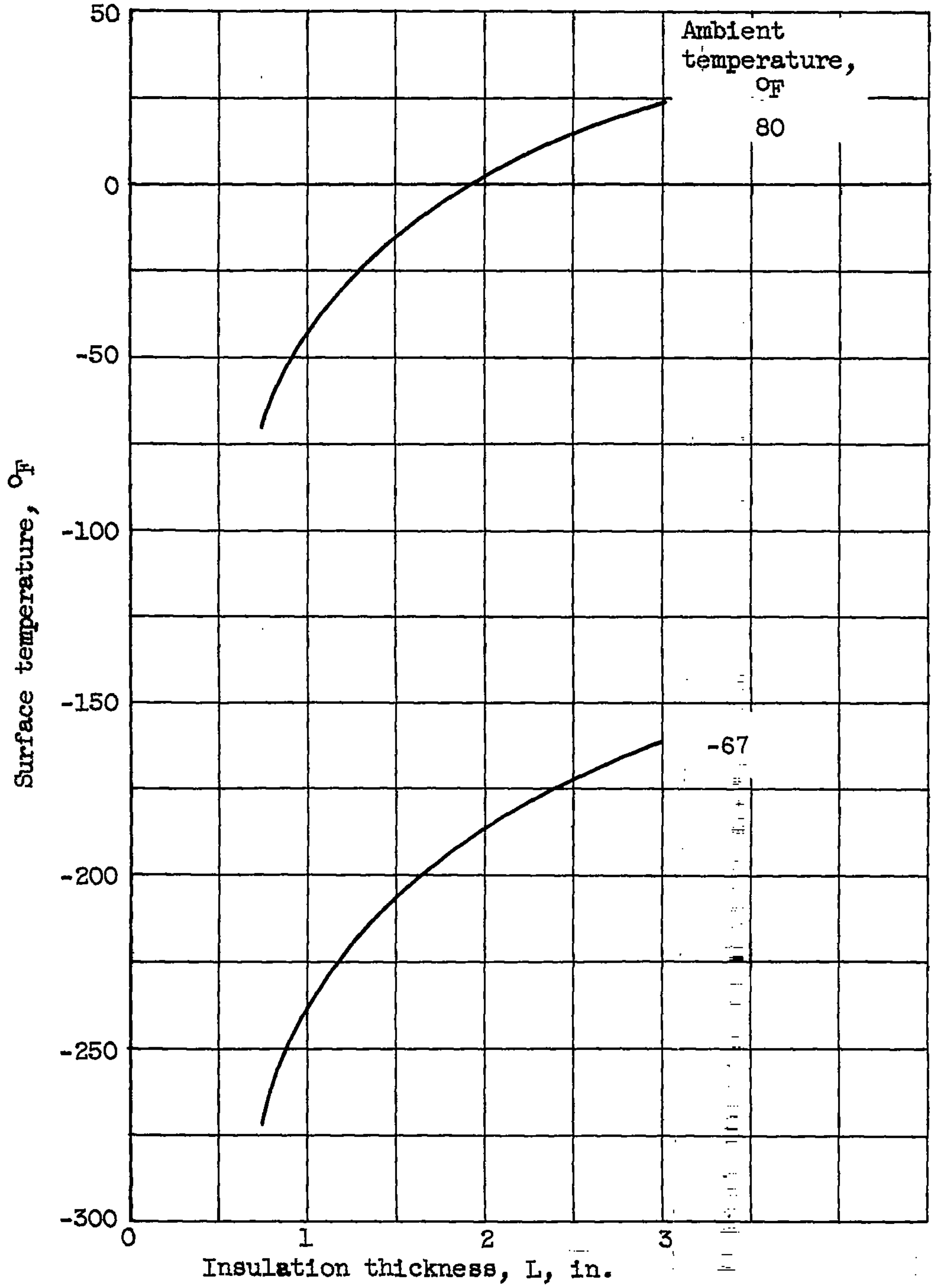

Figure 11. - Variation of surface temperature with insulation thickness for ambient temperatures of 80° and -67° F.

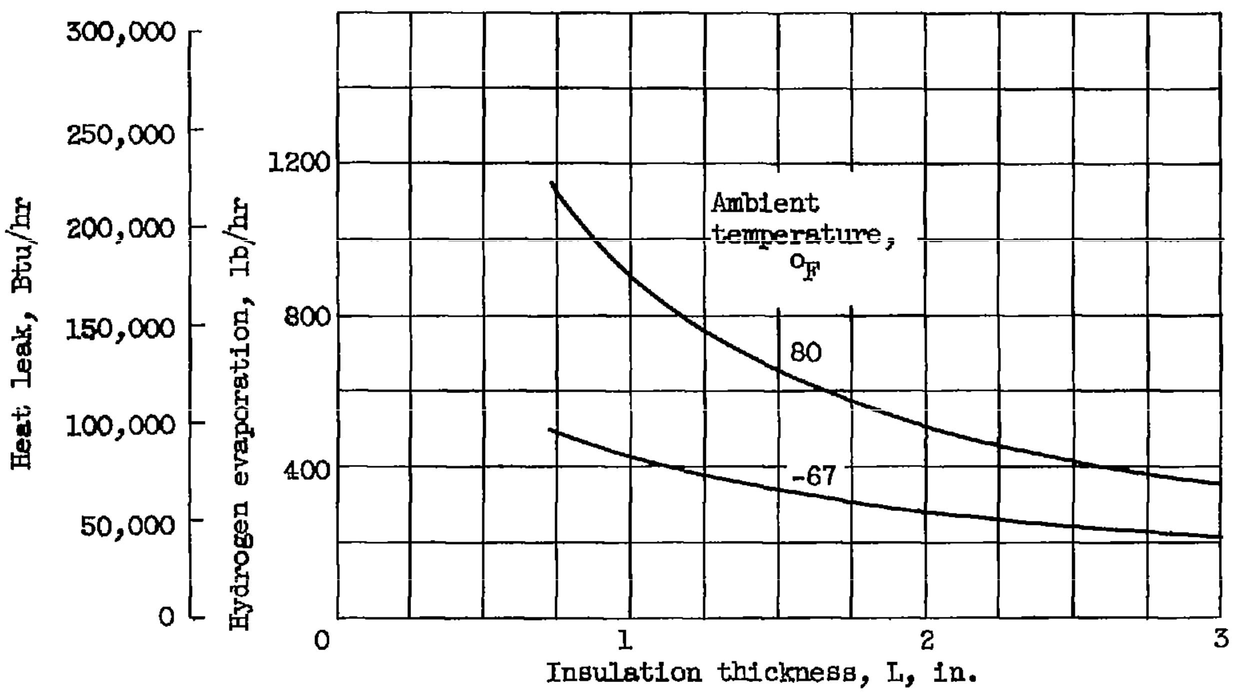

Figure 12. - Variation of heat-leak and hydrogen-evaporation rates with insulation thickness.

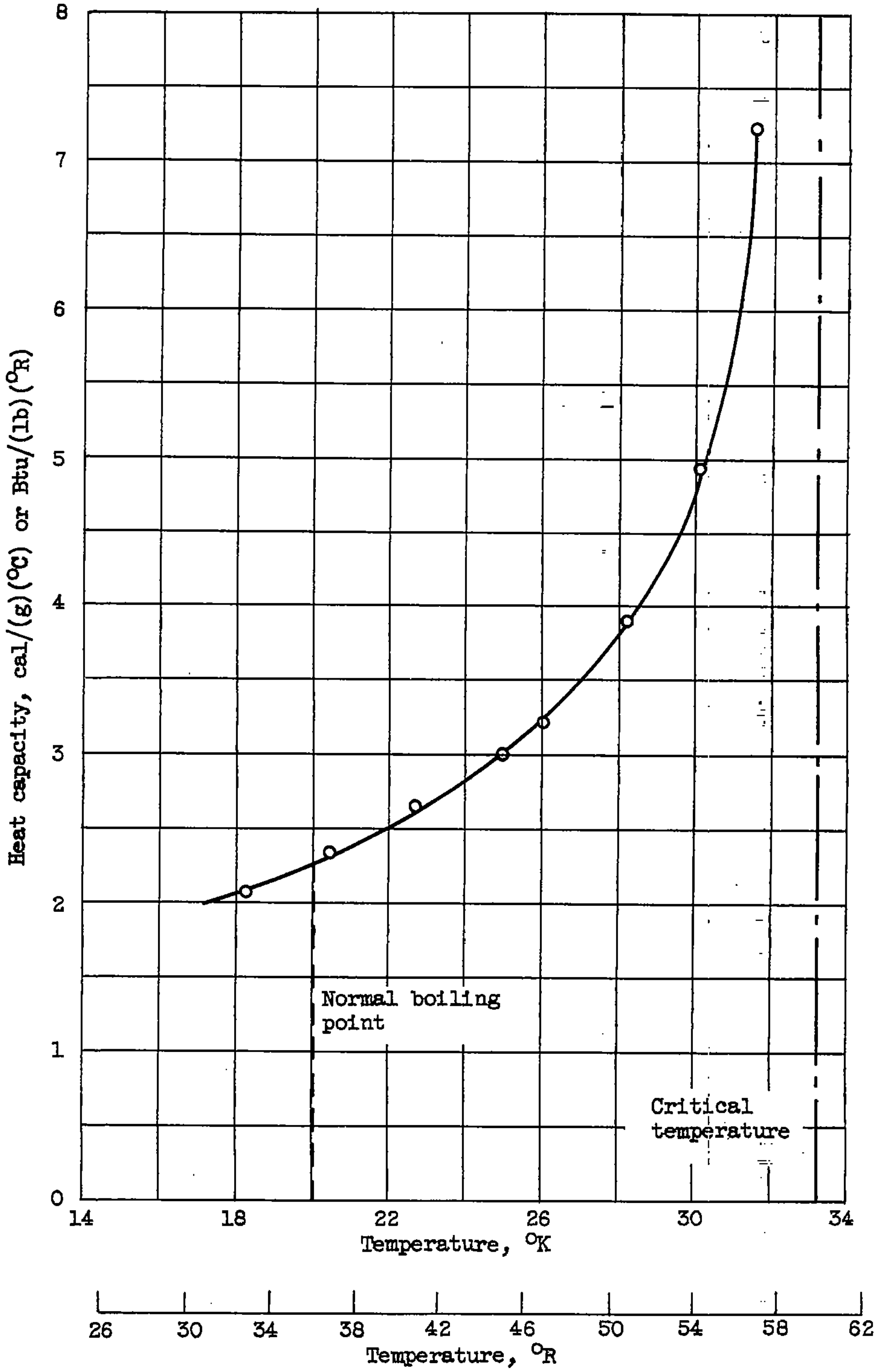

Figure 13. - Heat capacity of liquid parahydrogen. Data obtained from reference 26.

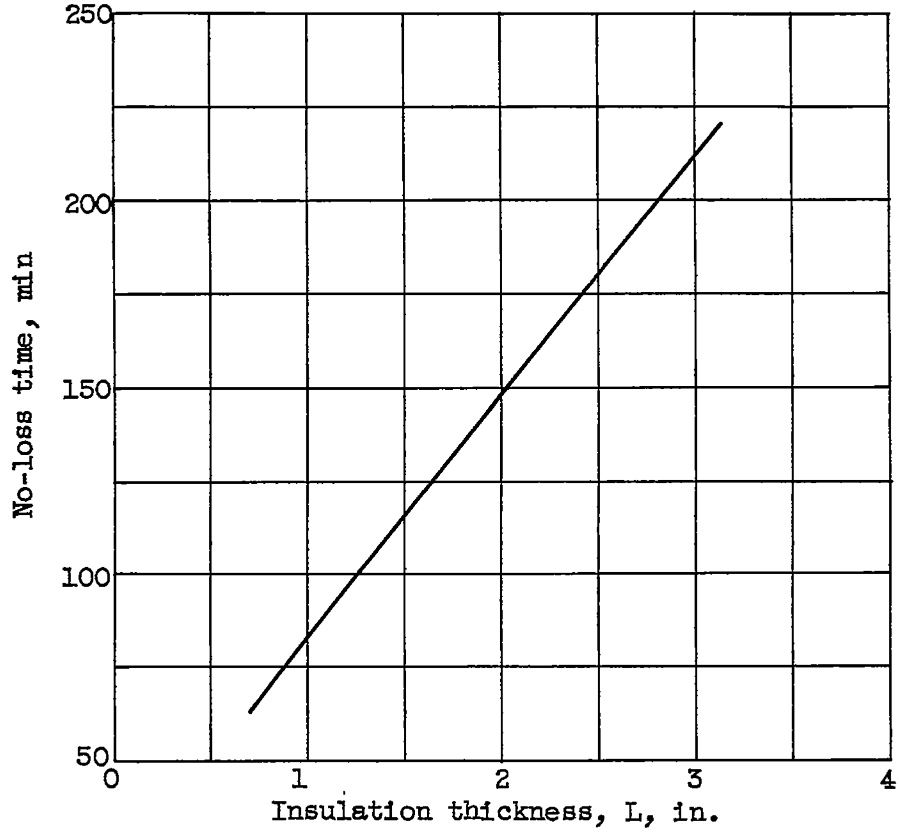

Figure 14. - Variation of no-loss time with insulation thickness. Ambient temperature, 80° F.

NACA - Langley Field, Va.