AFFTC TR-60-19

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HYDROGEN HANDBOOK

A Compilation of Properties, Handling and Testing Procedures, Compatibility with Materials, and Behavior at Low Temperatures

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by

ARTHUR D. LITTLE, INC.
Cambridge, Massachusetts

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Under Contract With
PARKER AIRCRAFT CO.
Los Angeles, California
(A Division of Parker-Hannifin Corp.)

7-60-4-3

Contract No. AF 33 (616)-6710
April 1960

Prepared For
AIR FORCE FLIGHT TEST CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
Edwards Air Force Base, California

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FOREWORD

Liquid hydrogen has long been recognized as one of the most promising liquid propellants. In recent months more effort is being made to develop rocket propulsion systems for use with liquid hydrogen.

As in the past, one of the biggest problems in the development of new systems which involve new fluids is the concurrent development of components to handle the fluids; that is, valves, regulators, disconnects, etc.

Contract AF33(616)-6710, sponsored by the Directorate of Rocket Propulsion and Missiles, Air Force Flight Test Center, Edwards Air Force Base, California, with Parker Aircraft Co., Los Angeles, California, provides for the design, development, and test of two valves, one for use with liquid hydrogen and one for use with cryogenic gaseous hydrogen.

In the accomplishment of the contract, Parker Aircraft Co. solicited the technical services of Arthur D. Little, Inc., Cambridge, Massachusetts to gather data on the properties, handling and testing procedures, capability with materials and behavior at low temperatures for use in the development of cryogenic hydrogen valves. This is the report submitted by A. D. Little, Inc. to Parker Aircraft Co. and fulfills the requirements of Contract AF 33(616)-6710 for a compilation of data pertinent to the development of cryogenic hydrogen valves.

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I. SUMMARY

This report summarizes (1) our experience with and the available technical information on the development of two prototype valves, one for a cryogenic gas service and the other for a cryogenic liquid service (these valves are under development by Parker Aircraft Co. for a Government agency); (2) bibliographical information on the physical and mechanical properties of specific construction materials for a temperature range of -420°F to +200°F (these materials include some austenitic stainless steels and Teflon plastics); (3) the thermodynamic properties of helium, hydrogen, and nitrogen fluids with which the valves may be used or tested; (4) the hazards associated with the transportation and storage of hydrogen and with its use for testing the prototype valves for leakage across the seats; and (5) the sources and availability of hydrogen, and the Los Angeles regulations that apply to its transportation and use.

II. PROCEDURES AND EQUIPMENT FOR TESTING VALVES

The valves to be tested by Parker Aircraft Co. range from 1 inch to 2 inches in size. The liquid valve will operate on line pressures of 0 to 1200 psig over a temperature range of -420°F to +220°F. The gas valve will operate on pressures of 0 to 21 psia over the same temperature range. We describe tests by which the gas leakage rate across the valve seat can be determined over the pressure and temperature operating ranges. We discuss the means of obtaining the various temperature levels required for the tests, the gas or gases that will serve to establish leakage rates, and the equipment and procedures associated with some of the tests, especially those which use liquid hydrogen.

A. TEMPERATURE ENVIRONMENTS

The gas leakage rates of the prototype valves will be obtained over their -420 to 200°F operating range by placement of the valves in a controlled temperature environment. Within this range five temperature levels can be obtained as follows:

1. 200°F - temperature-controlled electric oven
2. 85°F - natural environment
3. -100°F - solid carbon dioxide
4. -320°F - immersion or cooling with liquid nitrogen
5. -423°F - immersion or cooling with liquid hydrogen

Temperature levels from ambient to 200°F can be easily obtained with temperature-controlled ovens heated by gas or electricity. Wall ovens of the type installed in new homes should provide a suitable environmental test chamber for the tests in this range. With minor alterations an oven can be adapted so that its atmosphere is inerted during tests. Gas lines and other connections to the test article can be made through the wall of the oven.

Steady-state valve-body temperatures of approximately -100°F are easily obtained if the valve is surrounded with dry ice. Steady-state temperature levels of -320°F can be obtained by the immersion of the valve in a liquid nitrogen bath. One can obtain unsteady-state and special distributions of temperatures within the valve by placing it in a vacuum-insulated chamber and cooling the interior to the desired temperature level with liquid nitrogen. Leak tests on the valve would be made with the liquid nitrogen removed. The length of time that a temperature level of -320 to -300°F could be maintained with this method is directly dependent on the efficiency of the insulation surrounding the valve.

A steady-state valve temperature of -420°F, the lowest temperature required, can be obtained by the immersion of the valve in a bath of liquid hydrogen. With such immersion, however, the rate of liquid hydrogen boiloff cannot be controlled easily when the valve is cooling, and the results can be hazardous. Furthermore, the complete or even the partial immersion of the test article in the liquid will usually result in complete cooldown of the entire unit. Such cooldown is not acceptable where portions of the valve are not designed for operation at the same temperature as the valve body. The large size of the liquid hydrogen container, and of the openings in this container required to admit the test article, will add materially to the cost of testing. Unless specific conditions make the immersion of a valve in liquid hydrogen desirable, we do not recommend it, because of the hazard and the cost of the equipment.

The -420°F temperature level can also be obtained by admittance of liquid hydrogen to the interior of the valve. One may also cool the valve to low temperature by jacketing it with a coil of copper tubing through which liquid hydrogen or liquid helium is circulated. These methods are discussed in greater detail in Section II-G.

B. LEAK-TEST GAS

When the desired temperature level has been established in the valve under test, the upstream side of the valve will be pressurized with gas from a high-pressure manifold. The downstream side will be connected to a volumetric flow meter so that the leakage rate of the gas across the valve seat can be determined as a function of temperature, pressure, and the design characteristics of the valve.

We recommend that leakage rates be established over the full range of pressure and temperatures for which the valves are designed, and that helium gas be used for the leak tests. Helium is a logical choice, because it is one of the two fluids with which the valve is designed to operate. Furthermore, it will not condense in the valve during the low-temperature, high-pressure tests. Since only small quantities are required for the tests, the limited availability and high cost of helium should not preclude its use here.

Since the valves will also be used with liquid hydrogen, their leakage rates with this fluid are to be established. These rates can be established from tests similar to those for helium, or from an analytical determination of hydrogen-helium equivalent rates. Recent tests performed at ADL* to establish hydrogen-nitrogen equivalent leakage rates at ambient temperatures did not produce the expected results. For example, the theoretical ratio of the volume rate of flow of gaseous hydrogen to that of gaseous nitrogen varies from 3.74 to 2.04, depending upon whether the flow across the valve seat is isentropic or isothermal. The actual ratio of the flows varied from 5.0 to 0.5 This discrepancy is explained by changes in valve seating position that occurred from one test to the other when the valve was cycled.

We believe that although nitrogen is an inert and readily available fluid, its use for establishing gas leakage rates is neither necessary nor desirable, for the following reasons:

1. Nitrogen can be used at only three of the five previously indicated temperature levels. For example, if nitrogen is used as the test gas, it will condense when admitted at a pressure above atmospheric to a test valve having a temperature of -320°F. It is conceivable that the wetting of the valve seat by the condensate can result in leakage rates different from the rates obtained with a dry valve seat.

2. Heat-transfer rates between the valve walls and the test gas are greater when condensation occurs than when the test gas experiences only sensible heat loss. Thus if the valve is internally precooled with liquid, the formation of condensate will result in rapid warmup of the valve during the test and a subsequent reduction in the available length of the test period.

3. Leakage rates obtained with nitrogen are useful only if they can be expressed in equivalent rates of helium or hydrogen. An experimental effort to establish such equivalence may be as great as that required to obtain the gas-leak information directly.

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*Storage, Transfer, and Servicing Equipment for Liquid Hydrogen, WADC Technical Report 59-386, September 1959, Contract AF 33 (616)-5641.

C. HYDROGEN DEWARS AND ACCESSORIES

Small low-loss containers for the storage of liquid hydrogen and liquid helium during shipment and use are manufactured in capacities of 5 to 100 liters. In a typical container, the stored liquid is insulated from the environment by two vacuum jackets and one liquid nitrogen jacket. The list price for a 25-liter dewar is approximately $750, and deliveries of three to four weeks are considered reasonable. The daily loss of liquid helium from this container is given by one manufacturer as 225 cubic centimeters. Daily loss from the nitrogen jacket for the same unit is given as 2.75 liters. Additional information, including approximate dimensions and nitrogen-jacket capacities, is given in Appendix A.

To fill or empty a liquid hydrogen dewar properly or to hold liquid in the dewar for extended periods of time, one must use special accessories, including (1) filling tube, (2) withdrawing tube, and (3) pressurized vent. Before liquid hydrogen is placed in a dewar, the liquid nitrogen jacket is filled and cooled. Often the innermost vessel is also precooled with liquid nitrogen to reduce the liquid hydrogen boiloff during filling. Regardless of the precooling, when liquid hydrogen is first admitted to the dewar, a partial vacuum is temporarily created in the innermost shell, and as a result, air will be admitted to the dewar if precautions are not taken. After repeated fillings, sufficient air crystals can accumulate in the liquid hydrogen space to produce an explosion hazard.

A pressurizing and venting manifold of the type shown in Figure A-1 has been successfully used by ADL to prevent the admission of air to the dewar hydrogen space. At the filling nozzle, three concentric spaces are formed by the filling tube and manifold: the center space is the flow path for the liquid hydrogen; the outer space is used to admit pressurizing helium gas or to vent boiloff gases, depending upon the pressure indicated by the compound pressure gage; the center space forms the vacuum insulation around the hydrogen tube. During the filling operation, the pressure gage is observed very closely. When it indicates pressures above atmospheric, the vent valve is held open; when the gage indicates a vacuum, the vent is closed and the valve in the pressurizing line is opened. Thus, only helium gas and hydrogen are admitted to, or vented from, the hydrogen space during the filling operation.

Liquid hydrogen is removed from the dewar by pressurization of the gas space with hydrogen or helium gas. The liquid passes out through a vacuum-insulated tube that is inserted through the nozzle at the top of the dewar until it nearly touches the bottom. Details of the withdrawing tube used successfully by ADL are shown in Figure A-2. The withdrawing and filling ends of the transfer tube are very similar in construction, except for the depth in the dewar to which each is inserted.

The flow of liquid hydrogen from the storage dewar can be controlled by adjustment of its ullage pressure or by adjustment of the setting of a valve in the transfer line. The details of a valve that ADL has used for liquid flow control are shown in Figure A-2.

On standing, a dewar that is filled with liquid hydrogen and open to the atmosphere will collect liquid air though hydrogen is being vented. Since the vented flow of gaseous hydrogen is quite small, air can penetrate to the hydrogen space by diffusion and gravity. As we have said, the accumulation of frozen air inside the dewar can create an explosion hazard. The stored liquid is allowed to become saturated at a pressure slightly (1/4 psig) above atmosphere pressure, so that the intake of air is prevented. This saturation can be accomplished if one end of a coil of copper tubing is attached to the dewar nozzle and the other end is attached to a small, spring-loaded check valve that will allow gas in the dewar to escape as its pressure rises. The tubing is usually attached to the dewar with rubber or tygon hose. When a dewar filled with liquid hydrogen is transported in an enclosed vehicle, the vent line should extend outside the enclosure, to prevent a combustible mixture from forming in the vehicle.

D. SOURCES OF LIQUID HYDROGEN

Hydrogen is produced at seven facilities in Southern California. These facilities and the one at Boulder, Colorado are listed in Table I as probable sources of liquid hydrogen. At the first six facilities, ADL cryostats having approximate capacities of 8-10 liters of hydrogen per hour are used. Since these cryostats are also capable of producing liquid helium, they may be used for the alternative production of liquid helium and liquid hydrogen. The units known to have ortho-para converters are noted in the table.

Liquid hydrogen is produced in large quantities at the Stearns-Rogers plant under operation for the Air Force at Bakersfield, California. Parker can probably obtain liquid from this source by providing its own dewar and the adapter for connecting to the 28,000-gallon storage tank at the production facilities. Authorization to use this liquid must be obtained from Major J. R. Brill at AFBMD.

Large-quantity users of liquid hydrogen are known to be located in the Los Angeles area. Facilities (such as Rocketdyne's) for the flow testing of components are supplied with liquid hydrogen from Air Force sources. Because of the proximity of some of these facilities to Parker, it is advisable that the availability of hydrogen from them be investigated. Authorization for the procurement of liquid hydrogen undoubtedly must be obtained from Major Brill as well as from the facility operator.

TABLE I

WEST COAST FACILITIES HAVING LIQUID HYDROGEN PRODUCTION CAPABILITY

	Facility	Location	Production Capacity (liters/hour)	Para-Hydrogen Produced
1.	Rocketdyne Div. of North American	Canoga Park, Calif.	8-10	Not Known
2.	California Institute of Technology	Pasadena, Calif.	8-10	Yes
3.	Aerojet-General	Azusa, Calif.	8-10	Not Known
4.	Convair	San Diego, Calif.	8-10	Not Known
5.	Stanford University	Palo Alto, Calif.	8-10	Not Known
6.	General Atomics	San Diego, Calif.	8-10	Yes
7.	Stearns-Rogers	Bakersfield, Calif.	Large but not known	Yes
8.	National Bureau of Standards	Boulder, Colo.	Moderate	Yes

E. HAZARDS ASSOCIATED WITH USE OF LIQUID HYDROGEN

The principal physical and thermodynamic properties of gaseous and liquid hydrogen are presented in Section IV-A. To summarize these properties: Hydrogen is a colorless and odorless gas at atmospheric pressure and temperature. At -422.9°F it becomes a transparent and odorless liquid having a density of 4.4 lb/ft^3. Its heat of vaporization at atmospheric pressure is 194.5 Btu/lb. The critical point for hydrogen is 188 psia and -399.8°F. The heat capacity of the gas is approximately 15 times that of oxygen or nitrogen; the heat capacity of the liquid at one atmosphere is approximately four times that of liquid oxygen or liquid nitrogen at the same pressure.

Liquid hydrogen is hazardous to handle. Because of its low temperature, prolonged contact with it can cause the temporary embrittlement and possible failure of certain metallic structural materials, and the destruction of living tissue. Furthermore, hydrogen in both the liquid and the gaseous state burns vigorously, and sometimes explosively, in the presence of oxidizers such as oxygen and fluorine. Liquid hydrogen is easily contaminated by contact with any gas except helium, because its temperature (-423°F) is below the solidification point of all other gases. The contamination of liquid or gaseous hydrogen with oxygen gives rise to a great potential for fire or explosion. Hydrogen is not hypergolic in the presence of oxygen crystals, but static electric discharges can initiate an exothermic chemical reaction. At atmospheric conditions, the combustion limits of hydrogen in air are 4.1 and 74 volume-percent.

Sufficient experimental information has been obtained to establish the nature of the hydrogen hazard and to recommend procedures for equipment design and operation. The following sources provide the most recent information available in this area:

1. Storage, Transfer, and Servicing Equipment for Liquid Hydrogen, WADC Technical Report 59-386, September 1959, Contract AF 33(616)-5641.

2. L.H. Cassutt, F.E. Maddocks, and W.A. Sawyer, A Study of the Hazards in Storage and Handling of Liquid Hydrogen. This paper was presented at the 1959 Cryogenic Engineering Conference, and a preprint is included in this report as Appendix C.

3. Liquid Hydrogen Safety Manual (preliminary), prepared for ARDC under Contract AF 18(600)-1687. Appendix B is a copy of this manual.

F. LOS ANGELES CITY REQUIREMENTS FOR TRANSPORTATION, STORAGE, AND USE OF LIQUID HYDROGEN

The city requirements that must be met so that Parker may store and use liquid hydrogen at its Century Boulevard location were reviewed with representatives of the Los Angeles Fire Department. No special permits are required for transportation of liquid hydrogen in quantities of less than 100 gallons. Transportation by a licensed public carrier is required, and the container should be approved by the ICC. Standard liquid hydrogen dewars such as those manufactured by Superior Air or Hoffman should meet the ICC standards. If Parker plans to move liquid hydrogen in its own vehicles, it should check with Captain Buxton before doing so. Captain Harold K. Bordner is responsible for approval of the facilities for storage and use. The Los Angeles Fire Code does not have special provisions covering the use of liquid hydrogen. Instead, each case is handled individually. The storage building should conform to that specified for E-1 occupancy in the Los Angeles City Building Code. A cursory check of this code indicates that these requirements are not severe. Ventilation of six changes of air per hour is required and a sprinkler system should be installed. If the building is separated from adjacent structures by 20 feet or more, the construction requirements are not severe and Parker's standard building construction will meet the requirements.

When Parker is ready to implement its testing program, it might adopt the following suggested procedure: Prepare a sketch of the storage area, showing the location relative to adjacent buildings and the type of construction to be used. Prepare a sketch of the test setup and a description of how the material is to be transferred from the storage area to the test area. Provide details of the planned use of the material. Submit these plans to Captain Bordner, who will give tentative approval of the arrangements if they are satisfactory to the department. Before bringing liquid hydrogen onto the premises, contact the Fire Department; Inspector Frank Wells will look over the setup and issue a permit if it meets his approval.

In general, the Fire Department has a very constructive attitude toward the use of this material in the manner planned by Parker and will present no obstacles that would preclude the use of liquid hydrogen in the planned test program.

G. LEAK-TEST PROCEDURE

We shall make no attempt to prescribe complete, specific testing equipment or procedures, but it may be helpful to illustrate how leak tests may be carried out. The test apparatus, shown schematically in Figure 1, consists of a vacuum pump, a high-pressure helium supply bottle with a regulator, and a water-displacement volumetric measuring system. The temperature environment is established by one of the means suggested previously. Valves V-1 through V-6 are located as shown.

Vacuum pumps similar to Kinney Model No. KS-13 or Welch Model No. 1403-13, which are capable of producing approximately 10 microns of vacuum, are adequate for removing the system air. The Kinney pump has a displacement of 13 cfm, and is capable of evacuating the small test system envisioned here in one to three minutes to a vacuum of 100 microns or less.

Starting with V-2, 5, and 6 in the closed position, and V-1, 3, and 4 in the open position, the chambers in both ends of the valve and the piping system are evacuated with the mechanical pump. Next, V-1 is closed and V-2 is opened; thus the vacuum is broken with helium gas. The valves are returned to the previously indicated positions, and vacuum is again established in both chambers of the valve with the mechanical pump. This vacuum is again broken with low-pressure helium. Next, V-6 is opened and helium vented through it to atmosphere for a short time; V-4 and V-3 are closed; V-5 is opened; and the vented line from V-6 is placed in the volumetric displacement apparatus as shown. The system is allowed to stand for a brief period so that the gas may come into temperature equilibrium with metal portions of the system. Next, the helium pressure on the upstream side of the valve is adjusted to the desired level and the leak-through rate is obtained with the volumetric measuring system.

H. EQUIPMENT AND PROCEDURE FOR ESTABLISHING -423°F TEMPERATURE ENVIRONMENT

A temperature level of -423°F can be obtained in the valve under test by one of four methods: (1) the valve can be immersed in liquid hydrogen, (2) the valve can be insulated and the interior cooled with liquid hydrogen, (3) the valve can be surrounded with a jacket through which liquid hydrogen is circulated, and (4) the valve can be surrounded with a jacket through which helium from a helium refrigerator is recirculated. The principal criteria for evaluation of these four

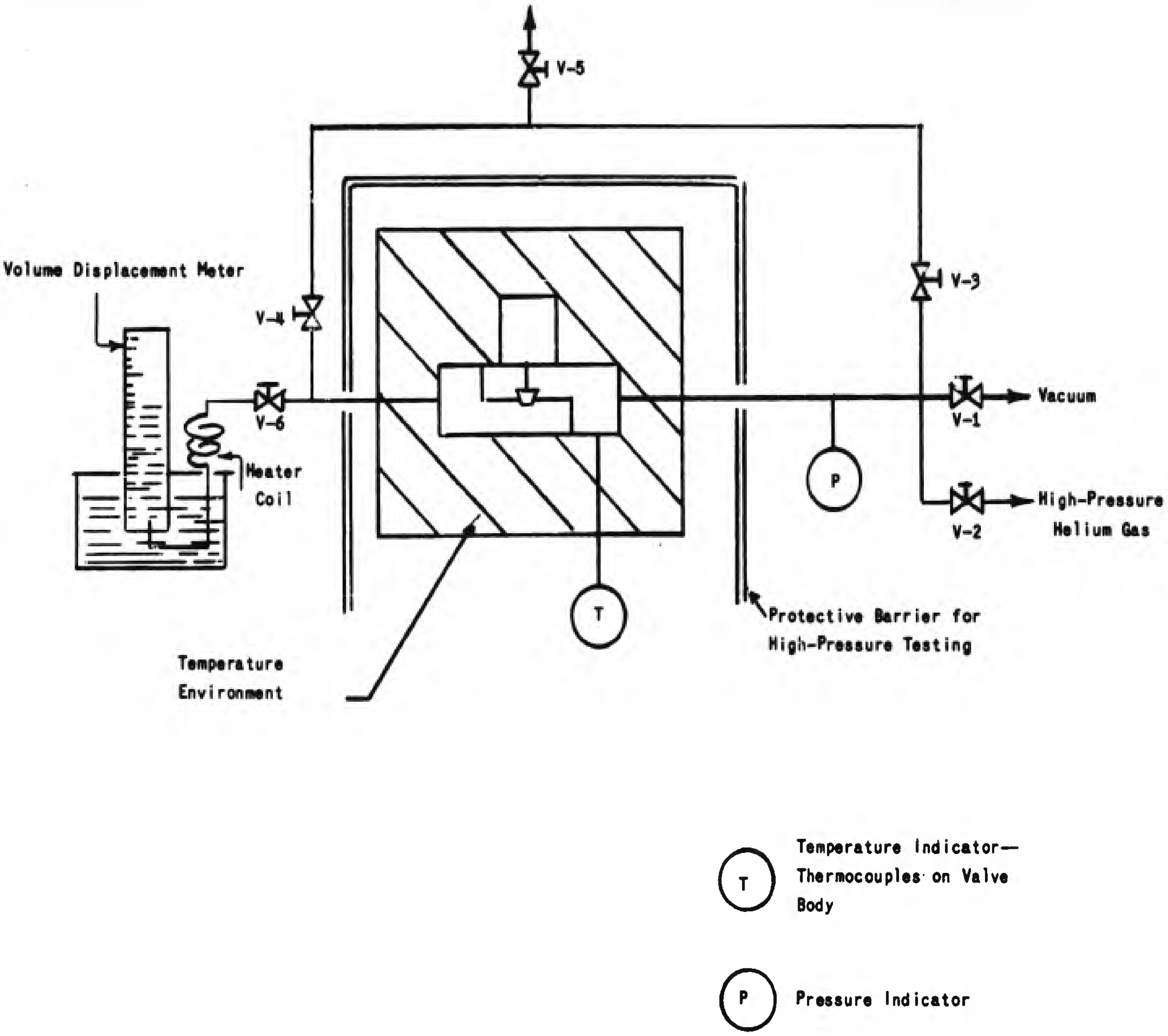

Figure I

FLOW SCHEMATIC OF LEAK-TEST SYSTEM

methods are the cost of the equipment and the test fluid, and the hazard associated with the operation of the equipment. Because of the hazard associated with method 1 and the cost of the equipment associated with method 4, we recommend the use of method 2 or method 3 or a combination of the two.

If cooling is accomplished with either method 2 or method 3, the quantity of the liquid hydrogen required is materially reduced by the use of insulation. Foamglas, foamed-in-place polyurethane, and vacuum-type insulations are recommended on the basis of low thermal conductivity, ready availability, acceptable cost, ease of use, low-temperature properties, and other factors discussed in WADC Technical Report 59-386.* The vacuum-type insulation will be most suited to testing the Parker valves for two principal reasons: (1) The liquid valve will undergo a low-temperature structural test when leakage rates at 1200 psig are investigated, and the vacuum jacket will serve as a test chamber to protect personnel from flying debris in the event of failure of the valve metal. (2) Accessibility to the prototype valves for inspection and modification during the progress of the testing will undoubtedly be required and can be accomplished easily with a vacuum-insulated container.

Figure 2 is an equipment flow sheet of the low-temperature-environment test system. As we have noted, the experimental equipment consists of a gaseous helium manifold, a vacuum-insulated test chamber, liquid hydrogen and nitrogen dewars, a vacuum pump, a volume-displacement meter, and interconnecting liquid and gas piping.

Three separate gas supply systems are shown in Figure 2. The low-pressure (approximately 3 psig) supply provides helium for purging the liquid hydrogen systems and pressurizing the dewars. One of the high-pressure supplies provides helium or hydrogen gas at pressures ranging from 0 to 1200 psig. This gas supply is connected to the upstream side of the test valve, so that pressure is maintained at the desired level during the leak test. The third supply is used for actuating the valves; the pressures required for this function range from 0 to 1000 psig.

The vacuum chamber can be cylindrical as shown, or spherical, or of any other shape, provided that it is designed for internal vacuum. The vessel can be constructed of carbon steel -- except for the top head,

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*Storage, Transfer, and Servicing Equipment for Liquid Hydrogen, September 1959.

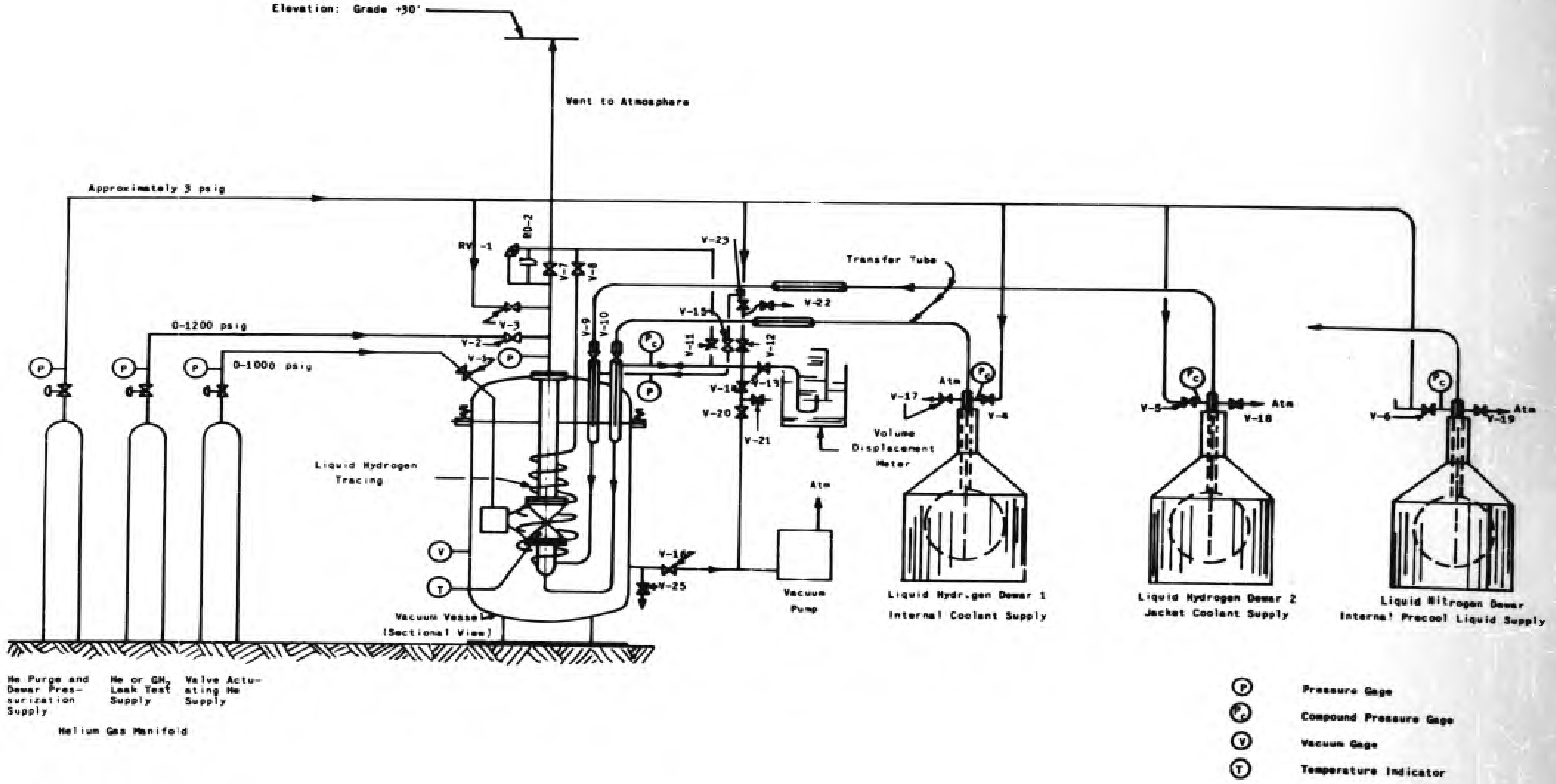

Figure 2

FLOW SCHEMATIC OF SYSTEM FOR LOW-TEMPERATURE TESTS which must be constructed of 304 stainless steel or its equivalent. When the tank is under vacuum, no bolts are required to form a seal between the top and bottom tank section if an O-ring seal is provided and if the flange faces are covered with a film of vacuum grease. Several spring-loaded bolts spaced around the flange limit the motion of the top head in the event that the chamber is pressurized above atmospheric pressure (e.g., as would occur from a valve failure or a liquid hydrogen leak into the vacuum chamber). For reducing the heat transfer by radiation from the vacuum-chamber wall to the test-valve assembly, the interior of the chamber should be lined with aluminum foil. The test valve should be supported from the top head. All gas and liquid lines, electrical connections, and thermocouple leads should pass through the top head so that removal of the test valve from the chamber will be facilitated. Accessibility will be improved if the chamber is designed so that the bottom section can be dropped down and out of the way.

As for the other items of equipment, the dewars and the liquid hydrogen transfer tubes are fully described in Appendix A. The volume meter consists of a calibrated flask inverted in water. The required vacuum capabilities of the evacuating system depend upon the size of the test chamber, on the duration of the leak test, and on whether the hydrogen trace is used. For example, for short leak tests, tolerable limits on the temperature rise of the valve can be obtained with heat-transfer rates higher than those for long tests. Thus, a relatively poor insulation--such as might be obtained with mechanical-type vacuum pump equipment capable of 5-10 microns--may be sufficient. If the hydrogen trace is used, it not only provides a radiation shield around the valve, but condenses residual oxygen and nitrogen such that a vacuum is obtained that corresponds to the sum of their solid vapor pressure at -423°F.

To minimize the fire hazard that results when hydrogen is allowed to accumulate in enclosed spaces, we recommend that the leak tests be performed in the open with no more than a vented overhead shelter. The hydrogen gases from the test facility should be vented at a point at least 30 ft above grade. The point of venting must be higher if there is any possibility that the vented gases will be drawn into the air-circulation systems of nearby buildings. In the period between tests, the liquid hydrogen dewars must be stored about 30 ft to 40 ft from the test facility. They should be protected by a storage shelter that like the test shelter is accessible only to qualified personnel. The separation between storage and test areas should not be so great that transportation of the liquid between the two sites becomes a problem. During the performance of tests, the movement of all vehicles in the test area must be restricted.

The following procedure is suggested for the use of the equipment shown in Figure 2. It is assumed that the hydrogen dewars are at the storage area, and that the liquid nitrogen dewar is connected to the test-valve internal feed line. Furthermore, all valves except V-10 are assumed to be initially in their closed position.

First, the test chamber is evacuated with the vacuum pump to 5 to 10 microns with V-16 open. The test valve and V-7 are placed in their open positions, and transfer of liquid nitrogen is initiated by the opening of V-6, the dewar-pressurizing valve. Since the transfer losses are quite small, the quantity of liquid nitrogen to cool and fill the valve section is easily determined, and sufficient liquid storage capacity can therefore be made available in advance. The use of nitrogen for precooling reduces the liquid hydrogen requirements.

When the liquid nitrogen cooldown is complete, the dewar is vented through V-19 with V-6 closed, and the transfer line is removed from the feed tube at V-10. With V-7 closed, low-pressure helium is admitted to the test valve through V-3. The test valve and liquid feed line are purged of nitrogen liquid and gas. V-3 and V-10 are closed and V-14 and V-20 are opened to vacuum-purge the test-valve interior. Shutting V-14 and V-20 and opening V-3 for a second time breaks the vacuum with helium. This procedure may be repeated several times so that residual nitrogen is completely removed. If residual nitrogen is present, it will become crystallized when hydrogen is admitted to the valve.

A hydrogen dewar is brought to the test site and its vent line is removed. A transfer tube is slowly inserted in the dewar, and the vent and pressurizing connections are made. Pressurize the dewar through V-5 to 1/4 psig or less so that the transfer tube is slowly purged with vaporized liquid. With V-3 opened to provide a bleed through the test valve, open V-10 and insert and connect the discharge end of the transfer tube to the test-valve feed connection. Shut V-3, open V-7, and slowly open V-4, pressurizing dewar No. 1 so that liquid hydrogen can pass into the test valve. Observe the pressure gage P_c and open valve V-12 if the pressure drops temporarily below atmospheric. Continue the liquid hydrogen transfer until the thermocouples connected to the valve body indicate that it has cooled to liquid hydrogen temperatures. At this time, close V-7 and after removing the transfer tube, close V-10. Next purge all liquid hydrogen from the test valve by opening V-3 and venting it through V-11. The helium purge may also be supplemented with a vacuum purge.

While helium is slowly purging the valve, liquid hydrogen dewar No. 2 is connected to its transfer tube by the method described for the connection of dewar No. 1. With V-8 open and V-9 closed, the trace line is purged with helium by the opening of V-15. While this line is being purged, V-9 is opened after a short time, and the discharge end of the transfer tube is inserted in the trace inlet at V-9. V-15 is then shut and V-5, the pressurizing valve for dewar No. 2, is opened. Liquid that is now passing through the trace line cools it. At this point, V-16 is shut, and if the system is vacuum-tight, the chamber vacuum should increase.

In the final steps, V-12, 23, 14, and 20 are shut; V-13, 21, and 22 are opened. The line inserted under the water-displacement measuring flask is vented to atmosphere for a short period and then inserted under the water in its appropriate position for measuring. V-3 is then shut, and the test valve is shut through its helium supply. The leak test can now commence. The pressure regulator on the leak test supply is adjusted to the desired pressure level, and the leakage through the valve is measured with the displacement meter as a function of time.

For shutdown of the system, V-2 and V-13 are shut and V-7 is opened so as to remove pressure from the upstream side of the valve. When the pressure is relieved, V-7 is shut and V-3 opened. V-4 is shut and V-17 opened to stop liquid hydrogen transfer to the trace line. The transfer tube is withdrawn at V-9, and V-9 is immediately closed. V-15 is opened to purge the liquid hydrogen from the trace line. When this is complete, V-8 is shut. The dewars are removed to the storage area. V-25 is opened to break the vacuum on the chamber. When the system has warmed, valves V-23 and V-3 are shut. The bottom of the vacuum chamber can now be removed to allow inspection or removal of the test valve.

III. LOW-TEMPERATURE STRUCTURAL MATERIALS[*]

A. FUNDAMENTAL SELECTION CRITERIA (CRYSTALLINE STRUCTURE)

The selection of materials for low-temperature application must be based primarily on their structural properties--i.e., yield and tensile strength, ductility, impact strength, and notch insensitivity. The possession of certain minimum values of these physical characteristics over the entire temperature range of operation is mandatory. The materials must be metallurgically stable, moreover, so that phase changes in the crystalline structure will not occur with time or under repeated thermal cycling. Furthermore, low heat conductivity, low coefficient of thermal expansion, and low emissivity are properties that can be used to advantage in applications for storage vessels, vacuum transfer lines, and other structural components.

The alloy behavior of practical interest falls into three main classes: (1) the transition from ductility to brittleness as a function of temperature and other factors; (2) the modes of plastic deformation, particularly certain unconventional modes encountered at very low temperatures; (3) the influence of metallurgical instability and phase transformations in the crystalline structure on mechanical properties.

It is known that the so-called body-centered cubic-lattice structure in metals is associated with a rapid increase in yield strength or resistance to plastic flow as the temperature is reduced below a certain range. As the difference between the yield strength and the ultimate strength becomes small, so does the amount of plastic flow between yield and fracture. Brittle failures in such metals occur at low temperatures. Among these metals are most of the low-alloy carbon steels. The temperature range at which each becomes brittle varies with the alloy content and with other factors, but it is usually well above the liquid hydrogen temperature.

It is also known that the metals having a face-centered cubic-lattice structure do not show so pronounced a rise in yield point with lowered temperature, although the tensile strength rises markedly. There is normally no ductile-to-brittle transition and the ductility tends to be large. At low temperatures, these alloys must be subjected to a large change in stress to go from the yield point to fracture, and this

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[*] Sections A, B, C, and D are reprinted (with minor changes) from WADC Technical Report 59-386.

change is accompanied by a large amount of plastic flow. There are exceptions, but some undesirable and avoidable metallurgical condition is generally the case. The face-centered structure is represented in common structural alloys by the 300-series stainless steels and other austenitic materials, and we should naturally look to these for critical structural elements in cryogenic service.

Unstable plastic flow, which is pronounced in a number of materials at low temperature, is described(25)* as being associated with the ability of the material to work-harden. Since body-centered metals lose their ability to undergo continuous work hardening, there are large fluctuations in their load-carrying capacity in the plastic range. Face-centered metals retain the ability to undergo continuous work hardening and the fluctuations in load-carrying capacity are much less severe. The 18-8 stainless steels, again because they have a face-centered structure, would be qualified on this basis.

E. T. Wessel(25) warns that a face-centered material whose yield strength is raised by alloying or precipitation hardening will tend to behave more like the body-centered types and might well exhibit their characteristic instability. Hence, new materials designed to have a yield strength higher than that of conventional 18-8 alloys should be regarded with reservations until proper testing has proved them satisfactory.

Stability against phase transformations in the crystalline structure should also be taken into account. For reasons given above, materials having a face-centered lattice are preferable, but materials that undergo a transformation from the face-centered to the body-centered structure would not be safe in the region of the phase change or below. On the other hand, some materials change in the opposite direction. The fact that a material is face-centered at room temperature is no guarantee that it will remain so at cryogenic temperatures.

B. SERVICE EXPERIENCE

The actual service background of metals and alloys in liquid hydrogen systems is confined largely to the 300-series stainless steels. Aluminum has been used to some extent, and copper, brass, bronze, and monel have all proved serviceable in special applications to small storage vessels, valves, transfer lines, etc.

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*Numbers in parentheses correspond to references listed at the end of this section.

C. STAINLESS STEEL

There are three general types of stainless steel:

1. Austenitic (nonhardenable by heat treatment--300 series)
2. Martensitic (hardenable by heat treatment--400 series)
3. Ferritic (nonhardenable by heat treatment--400 series)

Some stainless steels do not fall into these types; the 17-4PH, 17-7PH, AL-350, and Type W are typical of this group.

The ferritic and martensitic stainless steels are not recommended for cryogenic use, because of poor ductility at low temperatures; they are also less corrosion resistant than the austenitic types.

The 300-series stainless steels meet the requisites for low-temperature service. They remain ductile at liquid hydrogen temperatures, and their coefficients of thermal expansion and thermal conductivities are less than those of other materials suitable for cryogenic service. Most of these steels show a relatively small increase in yield strength as the temperature is lowered, but their tensile strength increases a great deal. Both the yield and the tensile strength of these types can be markedly increased by cold work, at some loss in ductility. In a welded structure, however, the maximum strength obtainable near the weld is approximately equal to the annealed yield point. Since this is about 30,000 to 40,000 psi (0.2% offset) for most of these materials, it limits the design of welded structures accordingly.

Of the austenitic stainless steels, type 304 is probably the most popular commercially and therefore has some definite advantages as far as procurement is concerned. It is compatible for welding and brazing with a variety of austenitic alloys, and can be welded to the ferritic steels as well. The properties that must be considered by the designer in material selection are corrosion resistance, strength, machinability, castability, weldability, thermal conductivity, specific heat, cost, and availability. Many of these properties are quite similar in all the 300-series stainless steels. We shall not recommend a particular 300-series stainless steel here, since the way in which the properties are evaluated will be different for different design criteria.

Another property that has received considerable attention in the past few years is the carbide precipitation associated with the welding of certain types of stainless steel, notably 304. When type 304 stainless steel having more than approximately 0.03% carbon is exposed to temperatures of 800°F-1600°F, some of the carbon goes out of solution and combines with the chromium at the grain boundaries. Such precipitation reduces the local corrosion resistance and makes the part notch-sensitive. Where the environment is highly corrosive, areas of reduced corrosion resistance are penetrated rather quickly, deep cracks are formed, and the structure is weakened. If the system is to be continuously inerted, local corrosion should not be a problem. If the system is to be exposed to atmospheric environment for long periods and if no products of corrosion can be tolerated, carbide precipitation can be minimized in the following ways:

1. Use only the stabilized grades of stainless steel. Stabilizing is accomplished by the addition of small quantities of titanium and columbium. Types 321 and 347 are treated in this respect. Note that type 347 is rather difficult to weld.

2. Use the Extra Low Carbon grade of stainless steel, such as AISI type 304L.

3. Heat-treat after welding. This procedure is suitable for manufacturing small items, but obviously not suitable for integrating components into the system by welding.

4. Restrict the carbon content in conformity with the thickness of the welded section:

Section Thickness (inches)	Carbon Content (Maximum) (%)
1/2	.06
3/4	.05
1	.04

It is known that phase transformation--for instance, austenitic to martensitic structure--occur in some metals at low temperatures. E. T. Wessel(25) notes that transformation is influenced by many variables, such as the rate of heating or cooling, the amount of associated plastic strain, the general composition, and the effect of impurities. Some experimental work(4, 16) suggests that the degree of the transformation in some commonly used austenitic stainless steels does not result in severe brittleness. Wessel tested a commercial type 347 stainless steel at 7.2°R in notch tension and observed no embrittlement even though 25% of the material in the region of the notch had been transformed.

D. ALUMINUM

In terms of its weight-to-strength (yield or ultimate) ratio, ductility, emissivity, impact strength, weldability, formability, and oxidation resistance, aluminum is a good material at low temperatures. Furthermore, since the diffusion of hydrogen through a metal is associated with its solubility and since hydrogen is less soluble in aluminum than in stainless steel, there would be an advantage in using aluminum for storage vessels. The nonheat-treatable types, however, lack the absolute strength of stainless, and would be less applicable in some places. In some applications, the high thermal conductivity and coefficient of thermal expansion of aluminum are additional disadvantages. Recently, aluminum has been successfully used for the inner vessel of double-wall insulated tanks at the temperatures of liquid nitrogen and oxygen. Its use in place of stainless steel apparently yields some reduction in the cost. So far as we know, there is little experience in the use of aluminum for storing liquid hydrogen, but such use appears to have promise. A liquid hydrogen storage vessel of aluminum can be designed so that the difference in the thermal expansion between the inner and the outer vessel is accommodated, and the high heat leak along aluminum lines is circumvented. Wherever aluminum is used with other metals, its coefficient of thermal expansion and its lack of compatibility in respect to joining (i.e., welding or brazing) present problems sometimes difficult to overcome.

The types of aluminum that appear most suitable for liquid hydrogen ground servicing equipment are the readily weldable alloys having high strength in the annealed condition. The aluminum-magnesium alloys 5052, 5083, 5086, 5154, 5356, and 5456 form such a group. These materials(2) have been extensively tested at liquid nitrogen temperature and have been shown to be useful at this temperature. On the basis of this information and Reference 26, we believe they are usable at liquid hydrogen temperature; however, they should be thoroughly screened for use at this temperature before they are adopted for general service.

E. LOW-TEMPERATURE PROPERTIES

In Tables II-XII, properties of materials are listed in the first column. Values of these properties for the temperature ranges specified in subsequent columns can be found in the publication designated by the numbers within parentheses. The numbers correspond to the numbers in the list of references. Tables for the following materials are presented.

2024 - T4 Aluminum

303 Stainless Steel

304 Stainless Steel

321 Stainless Steel

AM-350 Stainless Steel

17-4PH Stainless Steel

17-7PH Stainless Steel

K-Monel

Inconel

Teflon

Kel-F

TABLE II

PROPERTIES OF 2024-T4 (Formerly 24S-T4) ALUMINUM

1. MATERIAL SPECIFICATION		
Analysis	Si: 0.16; Fe: 0.43; Cu: 3.8 to 4.4; Mn: 0.6 to 0.9; Mg: 1.2 to 1.7; Zn: 0.10; Ni: 0.05; Bi: 0.05; Al: bal. (15)	
2. PHYSICAL PROPERTIES		
a. Melting Range		
b. Density	0.100 lb/in.^{3}	
c. Specific Heat	-423 to 80°F(5)*	
d. Thermal Conductivity	-420 to 80°F(19)	
e. Coefficient of Linear Thermal Expansion	-420 to 80°F(5)*	
3. MECHANICAL PROPERTIES		
a. Structure		
b. Yield Strength	-423 to 80°F(4, 13)	-423 to 500°F(6)
c. Ultimate Strength	-423 to 80°F(4, 13)	-423 to 500°F(6)
d. Elongation	-423 to 80 F(11, 13)	
e. Reduction in Area	-423 to 80°F(11)	
f. Hardness	-314, -108, 77°F(29)	
g. Modulus of Elasticity	-320 to 77°F(15)	
h. Impact Strength	-423 to 80°F(13, 15)	
i. Fatigue Strength	-320 to 75°F(15)	-320, -108, 77°F(29)
j. Compressive Yield Strength	-314, -108, 77°F(29)	
4. ELECTRICAL PROPERTIES		
a. Magnetic Permeability		
b. Electrical Resistivity		
5. WEAR CHARACTERISTICS		
6. MANUFACTURING TECHNIQUES		
7. MATERIAL COST AND AVAILABILITY		

* For aluminum.

TABLE III

PROPERTIES OF 303 STAINLESS STEEL

1.	MATERIAL SPECIFICATION		
	Analysis	C: 0. 15 max. ; Cr: 17 to 19; Ni: 8 to 10; Mn: 2, 00 max. ; Si: 1. 00 max. ; P, S, or Se: 0. 07 min. ; Mo or Zr: 0,60 max.(1)	
2.	PHYSICAL PROPERTIES		
	a. Melting Range	2550 to 2590°F(1)	
	b. Density	0. 29 lb/in^3 (1)	
	c. Specific Heat	32 to 212°F(1)	
	d. Thermal Conductivity	-450 to 420°F(19)	
	e. Coefficient of Linear Thermal Expansion		
3.	MECHANICAL PROPERTIES		
	a. Structure	Austenitic(7)	
	b. Yield Strength	-423 to 80°F(4, 13)	
	c. Ultimate Strength	-423 to 80°F(4, 13)	
	d. Elongation	-423 to 80°F(11, 13)	-320, 80°F(8)
	e. Reduction in Area	-423 to 80°F(9, 11)	
	f. Hardness	B 80 min. (1)	
	g. Modulus of Elasticity	29, 000, 000 lb/in.^{2} (1)	
	h. Impact Strength	-324 to 80°F(9, 13)	
	i. Fatigue Strength		
	j. Compressive Yield Strength	-423 to 80°F(24)	
4.	ELECTRICAL PROPERTIES		
	a. Magnetic Permeability	1. 02(1)	
	b. Electrical Resistivity	68°F(1)	
5.	WEAR CHARACTERISTICS		
6.	MANUFACTURING TECHNIQUES(7)		
7.	MATERIAL COST AND AVAILABILITY		

TABLE IV

PROPERTIES OF 304 STAINLESS STEEL*

1.	MATERIAL SPECIFICATION			
	Analysis	Cr: 18-20; Ni: 8 - 11; C: 0.08 max.; **Mn: 2.00 max.;** Si: 1.00 max.(1)		
2.	PHYSICAL PROPERTIES			
	a. Melting Range	2550 to 2650°F(1)		
	b. Density	0.29 lb/in.^{3} (1)		
	c. Specific Heat	32 to 212°F(1)		
	d. Thermal Conductivity	-423 to 80°F (19)		
	e. Coefficient of Linear Thermal Expansion	-460 to 80°F(5)		
3.	MECHANICAL PROPERTIES			
	a. Structure	Austenitic(7)		
	b. Yield Strength	-423 to 80°F(4, 13)		
	c. Ultimate Strength	-423 to 80°F(4, 13)	-290 to 70°F(8)	
	d. Elongation	-423 to 80°F(9, 13)	-320 to 80°F(8)	
	e. Reduction in Area	-423 to 80°F(9)		
	f. Hardness	B 90 max. (1)		
	g. Modulus of Elasticity	-320, 80°F(8)		
	h. Impact Strength	-423 to 80°F(4, 13)	-112 to 4°F(8)	**-320 to 70°F(8)**
	i. Fatigue Strength	-320, -108, 77°F(29)		
	j. Compressive Yield Strength	-423 to 80°F(24)		
4.	ELECTRICAL PROPERTIES			
	a. Magnetic Permeability	1.02(1)		
	b. Electrical Resistivity	68°F(1)	-423 to 20°F(21)	
5.	WEAR CHARACTERISTICS(1, 7, 27, 28)			
6.	MANUFACTURING TECHNIQUES(1, 7)			
7.	MATERIAL COST AND AVAILABILITY(7)			

* Designated 18 - 85 by Allegheny Ludlum Steel Corporation.

TABLE V

PROPERTIES OF 321 STAINLESS STEEL

1. MATERIAL SPECIFICATION		
Analysis	Cr: 17 to 19; Ni: 8 to 11; Ti: 5 x C min.; C: 0.08 max.; Mn: 2.00 max.; Si: 1.00 max.(1)	
2. PHYSICAL PROPERTIES		
a. Melting Range	2550 to 2600°F(1)	
b. Density	0.29 lb/in.^{3} (1)	
c. Specific Heat	32 to 212°F(1)	
d. Thermal Conductivity		
e. Coefficient of Linear Thermal Expansion	68 to 212°F(1)	
3. MECHANICAL PROPERTIES		
a. Structure	Austenitic(7)	
b. Yield Strength	-423 to 80°F(13)	
c. Ultimate Strength	-423 to 80°F(13)	
d. Elongation	-423 to 80°F(13)	-100 to 70°F(8)
e. Reduction in Area	-423 to 80°F(9)	-320, 80°F(8)
f. Hardness	B 95 max. (1)	
g. Modulus of Elasticity	29,000,000 lb/in.^{2} (1)	
h. Impact Strength	-324 to 80°F(9, 13)	
i. Fatigue Strength		-112 to 32°F(8)
j. Compressive Yield Strength		
4. ELECTRICAL PROPERTIES		
a. Magnetic Permeability	1.02(1)	
b. Electrical Resistivity	68°F(1)	
5. WEAR CHARACTERISTICS(1)		
6. MANUFACTURING TECHNIQUES(7)		
7. MATERIAL COST AND AVAILABILITY(1)		

TABLE VI

PROPERTIES OF AM-350 STAINLESS STEEL

1. MATERIAL SPECIFICATION	
Analysis	Ni: 4.0 - 4.5; Cr: 16.25 - 17.25; Mo: 2.5 - 3.0; C: 0.10 max.(20)
2. PHYSICAL PROPERTIES	
a. Melting Range	
b. Density	0.286 lb/in.^{3} (20)
c. Specific Heat	
d. Thermal Conductivity	
e. Coefficient of Linear Thermal Expansion	
3. MECHANICAL PROPERTIES	
a. Structure	Semi-austenitic (ferritic in aged condition, austenitic as annealed)
b. Yield Strength	-423 to 80°F(13, 14)
c. Ultimate Strength	-423 to 80°F(13, 14)
d. Elongation	-423 to 80°F(13, 14)
e. Reduction in Area	-423 to 80°F(14)
f. Hardness	-423 to 80°F(14)
g. Modulus of Elasticity	-423 to 80°F(14)
h. Impact Strength	-324 to 80°F(13)
i. Fatigue Strength	
j. Compressive Yield Strength	
4. ELECTRICAL PROPERTIES	
a. Magnetic Permeability(20)	
b. Electrical Resistivity(20)	
5. WEAR CHARACTERISTICS(20)	
6. MANUFACTURING TECHNIQUES(20)	
7. MATERIAL COST AND AVAILABILITY(20)	

TABLE VII

PROPERTIES OF 17-4PH STAINLESS STEEL

1.	MATERIAL SPECIFICATION	
	Analysis	C: 0.07; Cr: 15.5 - 17.5; Ni: 3.0 - 5.0; Cu: 3.0 - 5.0; Cb + Ta: 0.25 - 0.45(20)
2.	PHYSICAL PROPERTIES	
	a. Melting Range	
	b. Density	0. 280 - 0. 282 lb/in.^{3} (20)
	c. Specific Heat	
	d. Thermal Conductivity	
	e. Coefficient of Linear Thermal Expansion	
3.	MECHANICAL PROPERTIES	
	a. Structure	Ferritic in aged condition, martenitic as annealed(20)
	b. Yield Strength	-320 to 80°F(20)
	c. Ultimate Strength	-320 to 80°F(20)
	d. Elongation	-320 to 80°F(20)
	e. Reduction in Area(20)	
	f. Hardness(20)	
	g. Modulus of Elasticity(20)	
	h. Impact Strength	-320 to 75°F(20)
	i. Fatigue Strength(20)	
	j. Compressive Yield Strength(20)	
4.	ELECTRICAL PROPERTIES	
	a. Magnetic Permeability(20)	
	b. Electrical Resistivity	77 - 98(20)
5.	WEAR CHARACTERISTICS	
6.	MANUFACTURING TECHNIQUES(20)	
7.	MATERIAL COST AND AVAILABILITY(20)	

TABLE VIII

PROPERTIES OF 17-7PH STAINLESS STEEL

1. MATERIAL SPECIFICATION			
Analysis	C: 0. 9 max.; Cr: 16.0 - 18.0; Ni: 6.5 - 7.75; Al: 0.75 - 1.50(20)		
2. PHYSICAL PROPERTIES			
a. Melting Range			
b. Density	0. 276 - 0. 282 lb/in.^{3} (20)		
c. Specific Heat			
d. Thermal Conductivity			
e. Coefficient of Linear Thermal Expansion			
3. MECHANICAL PROPERTIES			
a. Structure	Semi-austenitic 'erritic in aged condition, austenitic as annealed)(20)		
b. Yield Strength	-423 to 77°F(14)	-100 to 70°F(20)	-460 to 500°F(6)
c. Ultimate Strength	-423 to 77°F(14)	-100 to 70°F(20)	-460 to 500°F(6)
d. Elongation	-423 to 77°F(14)	-100 to 70°F(20)	
e. Reduction in Area	-423 to 77°F(14)		
f. Hardness	-423 to 77°F(14)		
g. Modulus of Elasticity	-423 to 77°F(14)		
h. Impact Strength	-320 to 75°F(20)		
i. Fatigue Strength			
j. Compressive Yield Strength			
4. ELECTRICAL PROPERTIES			
a. Magnetic Permeability	At room temp. (20)		
b. Electrical Resistivity	81 - 85(20)	At room temp.	
5. WEAR CHARACTERISTICS(20)			
6. MANUFACTURING TECHNIQUES(20)			
7. MATERIAL COST AND AVAILABILITY(20)			

TABLE IX

PROPERTIES OF K-MONEL

1. MATERIAL SPECIFICATION		
Analysis	Ni (+Co): 65.3; C: 0.15; Mn: 0.60; Fe: 1.0; S: 0.005; Si: 0.15; Cu: 29.5; Al: 2.8; Ti: 0.5(22)	
2. PHYSICAL PROPERTIES		
a. Melting Range	2400 - 2460°F	
b. Density	6 (annealed)	
c. Specific Heat		
d. Thermal Conductivity	-212 to 32°F(22)	
e. Coefficient of Linear Thermal Expansion	-423 to 440°F(22)	
3. MECHANICAL PROPERTIES		
a. Structure		
b. Yield Strength	-423 to 80°F(10, 13)	-300 to 80°F(22)
c. Ultimate Strength	-423 to 80°F(10, 13)	-300 to 80°F(22)
d. Elongation	-423 to 80°F(10, 13)	-300 to 80°F(22)
e. Reduction in Area	-423 to 80°F(10)	-300 to 80°F(22)
f. Hardness	-110 to 80°F(22)	
g. Modulus of Elasticity	31,000,000 lb/in.^{2}	
h. Impact Strength	-100 to 80°F(10)	
i. Fatigue Strength		
j. Compressive Yield Strength		
4. ELECTRICAL PROPERTIES		
a. Magnetic Permeability	Aged(22)	
b. Electrical Resistivity	For various conditions(22)	
5. WEAR CHARACTERISTICS		
6 MANUFACTURING TECHNIQUES		
7. MATERIAL COST AND AVAILABILITY		

TABLE X

PROPERTIES OF INCONEL

1.	MATERIAL SPECIFICATION		
	Analysis	Ni (+Co): 76.4; C: 0.04; Mn: 0.20; Fe: 7.2; S: 0.007; Si: 0.20; Cu: 0.10; Cr: 15.8(22)	
2.	PHYSICAL PROPERTIES		
	a. Melting Range	2540 - 2600°F	
	b. Density	For various conditions(22)	
	c. Specific Heat		
	d. Thermal Conductivity	-450 to 80°F(19)	-212 to 32°F(22)
	e. Coefficient of Linear Thermal Expansion	-423 to 440°F(22)	-460 to 80°F(5)
3.	MECHANICAL PROPERTIES		
	a. Structure		
	b. Yield Strength	-423 to 80°F(10, 13)	-110 to 80°F(22)
	c. Ultimate Strength	-423 to 80°F(10, 13)	-315 to 80°F(22)
	d. Elongation	-423 to 80°F(10, 13)	-315 to 80°F(22)
	e. Reduction in Area	-423 to 80°F(10)	-315 to 80°F(22)
	f. Hardness	-110 to 80°F(22)	
	g. Modulus of Elasticity	80°F(22)	
	h. Impact Strength	-324 to 80°F(13)	-315 to 80°F(10, 22)
	i. Fatigue Strength		
	j. Compressive Yield Strength		
4.	ELECTRICAL PROPERTIES		
	a. Magnetic Permeability(22)		
	b. Electrical Resistivity	For various conditions(22)	
5.	WEAR CHARACTERISTICS		
6.	MANUFACTURING TECHNIQUES		
7.	MATERIAL COST AND AVAILABILITY		

TABLE XI

PROPERTIES OF TEFLON

1.	MATERIAL SPECIFICATION		
	Analysis	Polytetrafluorethylene	
2.	PHYSICAL PROPERTIES		
	a. Melting Range	500 to 600°F(3)	
	b. Density	0.0786 lb/in.^{3} (23)	
	c. Specific Heat	-423 to 45°F(5)	
	d. Thermal Conductivity	-423 to -100°F(4)	-450 to 80°F(5)
	e. Coefficient of Linear Thermal Expansion	-460 to 32°F(4)	-460 to 80°F(5)
3.	MECHANICAL PROPERTIES		
	a. Structure	Nonrigid	
	b. Yield Strength		
	c. Ultimate Strength	-324 to 80°F(13)	-320 to 70°F(5)
	d. Elongation	-324 to 80°F(13)	
	e. Reduction in Area		
	f. Hardness	D 55 Shore hardness(12)	
	g. Modulus of Elasticity	-450 to 70°F(5)	
	h. Impact Strength	2.5 - 4.5 ft-lb/in. Izod impact(12)	
	i. Fatigue Strength		
	j. Compressive Yield Strength	-450 to 80°F(13, 23)	-450 to 185°F(5)
4.	ELECTRICAL PROPERTIES		
	a. Magnetic Permeability		
	b. Electrical Resistivity		
5.	WEAR CHARACTERISTICS(26, 27)		
6.	MANUFACTURING TECHNIQUES		
7.	MATERIAL COST AND AVAILABILITY		

TABLE XII

PROPERTIES OF KEL-F

1. MATERIAL SPECIFICATION		
Analysis	Polytrifluoromonochloroethylene	
2. PHYSICAL PROPERTIES		
a. Melting Range	~ 400°F(12)	
b. Density		
c. Specific Heat	0.22 Btu/lb -°F(12)	
d. Thermal Conductivity	0.413 Btu-in./ft^2-hr-°F(12)	
e. Coefficient of Linear Thermal Expansion	-110 to 80°F(12)	
3. MECHANICAL PROPERTIES		
a. Structure	Rigid	
b. Yield Strength		
c. Ultimate Strength	-324 to 80°F(13)	-310 to 70°F(5)
d. Elongation	-328 to -100°F(13)	
e. Reduction in Area		
f. Hardness	75 to 80 Shore hardness(12)	
g. Modulus of Elasticity	-310 to 70°F(5)	
h. Impact Strength	3.0 - 4.0 ft-lb/in. Izod impact(12)	
i. Fatigue Strength		
j. Compressive Yield Strength	-450°F(5, 23)	
4. ELECTRICAL PROPERTIES		
a. Magnetic Permeability		
b. Electrical Resistivity		
5. WEAR CHARACTERISTICS(26)		
6. MANUFACTURING TECHNIQUES		
7. MATERIAL COST AND AVAILABILITY		

F. HYDROGEN EMBRITTLEMENT

In our search of the literature we found no experimental data relating the embrittlement of 17-7PH, 17-4PH, and other stainless steels to temperature and hydrogen contents. However, the opinion of our metallurgist, Dr. R. S. Davis, is that if a stainless steel does not show hydrogen embrittlement at room temperature, it will not be hydrogen-embrittled at any lower temperature--provided that the metal is never placed in a bath where electrolytic dissociation of hydrogen can take place on the metal surface. Furthermore, contact of the stainless metals with liquid or gascous hydrogen in the range of -420 to 200°F will not produce hydrogen embrittlement, because of the low solubility of the hydrogen in the metal and the low atomic-hydrogen activity at the metal surfaces.

In regard to the use of 17-7PH and 17-4PH stainless steels for springs, McClintock and Gibbons(13) point out that the ductility criterion is not applicable for selecting materials to be used as springs in low-temperature service. Since spring coils are designed to function purely as elastic members and are smoothly shaped so that stress concentration in the metal is minimized, material ductility is not required. The authors point out that carbon steel valve springs have been used by Professor Collins at the Massachusetts Institute of Technology and have given excellent service in a liquid nitrogen expansion engine.

G. BRAZING

In the fabrication of helium and hydrogen cryostats and other low-temperature equipment at ADL, brazing is used extensively for joining copper and stainless steel. Silver and copper-phosphorus brazing metal are used for making copper-to-copper joints. Silver is used for brazing copper to 300-series stainless steel. Stainless-to-stainless joints are normally formed by argon-shielded arc welding when the metal thicknesses are greater than 0.015 inch. For thicknesses less than this, soft soldering is normally used. These types of joints have given excellent performance at temperatures ranging from 4.2°K to ambient over periods of many years.

When copper is silver-brazed to stainless steel, the joint is apt to fail unless it is designed so that the braze metal is in compression. One can form a tube joint so that the braze metal is in compression by inserting the stainless steel in the copper. Since the expansion coefficient of copper is greater than that of stainless steel, the copper sheath will be in tension when the lowering of the joint temperature causes a different expansion of the two metals. If the position of the copper and the stainless steel is reversed in the joints, the copper will separate from the wall and the joint will fail as its temperature is lowered.

The fluxing agents used in silver brazing are highly corrosive. When thin metal sections are joined, the brazing operation should be performed quickly, so that the flux will contact the metal only briefly. The brazing operation must be quickly followed by a thorough hot-water wash for the removal of all traces of the flux. On occasion, it may be necessary to shield the component from flux splatter and fumes during the brazing operation so that corrosion of the more sensitive areas of the fabricated items will be prevented.

Stainless-to-stainless joints can also be formed by copper brazing. This is a furnace operation that utilizes a hydrogen atmosphere. The elements to be joined must have a zero clearance or be press-fit if high strength in the joint is to be achieved. The joint areas are cleaned with emery cloth or by an acid dip. A copper ring or washer is attached to the article to be brazed in the area of the joint. When the article is placed in the furnace, the copper melts and flows into the joint without the use of a flux.

The furnace temperature for copper brazing is near 2200°F, the melting point of the copper. Some stainless steels undergo carbide precipitation at a lower temperature. If copper-brazed, such steels become embrittled at low temperature. The furnace atmosphere also causes the stainless steel and the copper to become saturated with hydrogen; this saturation itself can bring about embrittlement of the metal, if hydrogen is not removed by proper quenching. Thin metal sections may retain hydrogen even though they are air-quenched, since their heat capacity is small. Whether hydrogen embrittlement will occur can be determined with confidence only by trial.

The factors that affect the design of copper- and silver-brazed joints for service in temperatures above 0°F are adequately presented in the 1954 Supplement to the Metals Handbook published by the American Society for Metals. Only limited information is available regarding strength and ductile properties of these brazed joints at temperatures below 0°F. At -321°F, ultimate strengths of 18,000 to 22,000 psi have been obtained(18) in single-lap joints of deoxidized copper brazed with copper-phosphorus alloy. These values are slightly above their room-temperature values and less than half the strength of the parent metal.

H. HYDROGEN DIFFUSION

It is known that hydrogen diffuses through many metals. This diffusion takes place atomically along the interstitial sites of the crystal lattice. The diffusion rate is greatly influenced by the temperature of the metal membrane, the differential hydrogen pressure across the membrane, the diffusion properties of the metal, and the metal surface condition. When hydrogen is confined in an enclosure formed by a metallic membrane (e.g., a pressure bellows), the diffusion of the gas through the walls will result in the gradual depletion of the contents of the confined space. The temperature-pressure-length response of the bellows device will be altered as it loses gas to its surroundings. The determination of the magnitude of the response change in a hydrogen bellows system over a given period of time rests upon a knowledge of the diffusion rate.

No reliable data is presently available for determining hydrogen diffusion rates at temperatures below 100°C--the temperatures of interest here. Data is available, however, for various hydrogen-metal systems above 400°C. These can be cautiously extrapolated to low temperatures so that order-of-magnitude estimates of the diffusion rates can be made. Actual diffusion rates, however, must be determined experimentally. Where the system is a completely sealed bellows, the diffusion rate can be easily established over one to two months.

S. Dushman* has reviewed the available experimental information on the solubility of gas in metals and the diffusion of gas through metal membranes. He develops the general equation that correlates many of the data and presents the various empirical constants required for its use in predicting diffusion rates.

The equation takes the form

$$Q_{ul} = 45{,}600 \frac{K_o}{d} \sqrt{P_{mm}} \; \varepsilon^{-E_o/2R_oT}$$

---

*S. Dushman, Scientific Foundations of Vacuum Technique, New York, 1949.

where

Q_{ul} = liters of gas diffused at one micron of pressure and 0°C, per minute, per millimeter of membrane thickness, per cm^2

K_o = dimensionless characteristic of the gas-metal system

d = membrane thickness in millimeters

P_{mm} = differential pressure across the membrane in millimeters of mercury

E_o = heat of diffusion in g-calories per molecule

R_o = gas constant

T = absolute temperature in °K

The heat of diffusion, E_o, as determined from the literature for a 300-series stainless steel, is 38,000 g-calories per mole. This value is independent of the chromium-nickel content of the steel. Because information for evaluating K_o was not available in the literature for the 300-series stainless steels, we have chosen a value of 10^{-2}, which corresponds very closely to the value for nickel. We believe that with this value of K_o, we shall calculate rates that are higher than the actual rates.

As we have said, atomic rather than molecular hydrogen diffuses through metals; molecular hydrogen must therefore convert to atomic hydrogen at the surface of the metal through which it diffuses. At temperatures below 400°C, the rate of the conversion begins to influence the rate of diffusion through the membrane. The conversion rate decreases with decreasing temperature. Thus, the diffusion rates that are calculated by use of the above equation for a given hydrogen-metal system will always give values that are higher than actual.

The diffusion equation can be written in logarithmic form as follows:

$$\log Q_{ul} = C - B/T$$

where the constants C and B are defined by the Dushman equations

$$C = \log K_0 + 6.0994$$

$$B = E_0/9.148$$

and are determined to be 4.0994 and 4150°K, respectively, for a 300-series stainless steel having the values of K_0 and E_0 established above.

For a cylindrical bellows having a 2-inch mean diameter and a 2-inch length, the calculated volume is 103 cm^3. At an ambient temperature of 80°F and one atmosphere, the bellows contains 4.18×10^{-3} g-moles of hydrogen. The area of the corrugated sides of the bellows is taken as four times the product of the mean circumference and bellows length. The total area including the ends is calculated to be 367 cm^2. From Table XIII the diffusion rate is given as

$$5.75 \times 10^{-12} \frac{\text{g-mole}}{\text{yr-cm}^2/\text{mm}}$$

The total rate of diffusion at 300°K through a bellows with a 0.006-inch (0.153-mm) wall thickness is

$$Q = 5.75 \times 10^{-12} \frac{\text{g-mole}}{\text{yr-cm}^2/\text{mm}} \times 367 \text{ cm}^2 \times \frac{1}{0.153 \text{ mm}}$$

$$= 138 \times 10^{-10} \frac{\text{g-mole}}{\text{yr}}$$

TABLE XIII

HYDROGEN DIFFUSION RATES

Temperature (°K)	Diffusion Rate $\left(\frac{\text{g-mole}}{\text{yr-cm}^2/\text{mm}}\right)$
21	9.76×10^{-196}
100	1.23×10^{-39}
200	6.91×10^{-19}
300	5.75×10^{-12}
373	2.82×10^{-9}

Thus the change in the hydrogen mass of the bellows over a year's time as a result of diffusion through the wall will not be greater than 0.00033%. For the bellows chosen, diffusion would have a negligible effect on its calibration. From Table XIII it can be seen that for membrane temperatures below 200°K, the diffusion rates become insignificant.

For pressures, temperatures, and bellows surface-to-volume ratios much higher than those chosen in the example, the effects of diffusion can become noticeable and the use of hydrogen may no longer be acceptable. For such designs, the bellows wall thickness can be increased, or helium gas can be substituted for the hydrogen. Since helium will not diffuse through metal membranes, there is no diffusion problem attending its use.

I. FRICTION AND WEAR

Metal surfaces in sliding contact produce heat at the points of contact, even in the presence of water or lubricants. For steel on steel, local junctions may reach temperatures as high as 1000°C if the relative speed of the sliding parts is high. When two dissimilar metals are made to slide together, the local temperatures can be as high as the melting point of the lower-melting metal. If the thermal conductivity of either or both metals is low, the tendency to become welded increases.

At the heated regions of contact the metals deform plastically and become welded to the opposing surfaces. As the surfaces continue to translate relative to one another, the welds tear and the surfaces become plowed and scored. Sometimes the welding is such that the surfaces cannot be moved relative to one another. In some instances, 304 stainless steel bolts and nuts are known to weld to the extent that the bolts fail in torsion when an attempt is made to loosen the nuts. Our recent experience with gate valves having seats and wedges of 304 material is similar.

The results obtained with liquid nitrogen environments in recent studies by Wisander et al.(28) show that severe surface failure takes place when two parts of 304 stainless steel are made to slide against each other. Under the test conditions at sliding speeds of 2300 ft/min, the surface welding that occurred resulted in metal transfer, severe surface scoring, friction coefficients of the order of 0.78, and wear rates of about 6.2×10^{-3} in.^{3}/hr. By coating one of the surfaces with Teflon or Kel-F, Wisander et al.(27) obtained friction coefficients of about 0.05 and wear rates less than 0.001×10^{-3} in.^{3}/hr. In References 26, 27, and 28, Wisander et al. report the friction and wear rates of a variety of materials that have suitable mechanical properties at liquid nitrogen temperatures.

J. LIST OF BIBLIOGRAPHIES

1. Janies, Katherine, Bibliography on Low Temperature Characteristics of Steels, 1904-1954, with Author Index, New York, International Nickel Company, Inc.

   This bibliography contains 564 references; it gives no abstracts.

2. Kropschot, R. H., and D. McColon, A Bibliography on the Effects of Low Temperature on the Mechanical Properties of Materials, National Bureau of Standards Report No. 5058, April 15, 1957.

   This survey of the mechanical properties of metals at low temperatures (i. e., below 0°C) covers the period 1945 to July 1955. It contains 386 references, listed chronologically by the year in which they appeared in the literature. A brief abstract of each article indicates the scope of the work and sometimes the outstanding results. A subject-and-author index serves as a guide for quickly identifying the data sources. This bibliography is incomplete as regards information pertaining to the impact sensitivity of metals at low temperatures.

3. Teed, P. L., The Properties of Metallic Materials at Low Temperatures, New York, John Wiley & Sons, 1950.

   This comprehensive technical treatise on the behavior of metals at low temperatures is divided into 10 chapters, each well documented with bibliographical references. The author analyzes the major properties of alloys of aluminum, iron, magnesium, copper, nickel, zinc, tin, and lead. He finds that aluminum alloys do not deteriorate at low temperatures; in fact, they generally improve. A number of austenitic steels can be safely used at the lowest temperatures, while some ferritic steels are extremely dangerous at temperatures close to the freezing point of water. Zinc-rich alloys become extremely brittle at moderately low temperatures. The author also discusses the behavior of notched specimens and welds with decreasing temperature.

K. LIST OF REFERENCES

1. Allegheny Ludlum Steel Corporation, Stainless Steel Handbook, Pittsburgh, 1951.

2. Arthur D. Little, Inc., internal memorandum, 1959.

3. Cheney, A. J., Jr., W. B. Happoldt, and K. G. Swayne, "Zytel and Teflon Resins as Bearing Materials," Plastics Technology, 2, No. 4, 221-225, 230 (April 1956).

   The properties making Zytel and Teflon resins advantageous for bearing applications are discussed. The general properties of molded Teflon are tabulated.

4. Chilton, D. B., and D. B. Mann, Cryogenic Data Book, National Bureau of Standards, WADC Technical Report 59-8, March 1959.

   This report is a compilation of the physical properties of several liquefied gases and a number of structural and thermal insulating materials for temperatures of 550°R and below. Specifically, the density, vapor pressure, heat of vaporization and conversion, specific heat, viscosity, and thermal conductivity of hydrogen, deuterium, nitrogen, oxygen, and helium liquids are presented graphically as a function of temperature. Data for the gaseous phases of these liquids are also presented. The physical properties (such as specific heat, thermal conductivity, and thermal expansion) and the mechanical properties (such as tensile and yield strengths and impact resistance) of selected low-temperature metals and metal alloys are also given. The report includes information on the thermal conductivity of several insulations and on radiant heat transfer. It contains 141 figures.

5. Corruccini, R. J., "Properties of Materials at Low Temperature," Chem. Eng. Prog., 53, Numbers 6, 7, and 8 (June, July, and August 1957).

   Experimental and calculated values of heat capacity, coefficient of thermal expansion, and thermal conductivity for several materials suited to low-temperature application are presented. The application of several insulations to cryogenic service is discussed and a comparison of their mean thermal conductiveness is presented. The tensile strength, compressive yield strength, and Young's modulus are tabulated as functions of temperature for Teflon, Kel-F, Nylon, and other plastics. Some mechanical properties of metals are also presented. The article contains 46 literature references.

6. Cryogenic Engineering Laboratory Cryogenic Materials Data Handbook, Boulder, Colorado, September 1959.

   Data on solid materials at low temperature was distributed as an advance part of the Second Quarterly Report of Air Force Contract No. AF 04(647)-59-3.

7. Everhart, J. I., "How To Select a Stainless Steel," Materials in Design Engineering, 49, No. 1, 95-110 (January 1959). Available as Materials in Design Engineering Manual, No. 155.

   The resistance of different stainless steels to various types of corrosive attack at ordinary and high temperatures, and their mechanical properties at low, ordinary, and high temperatures are discussed. Information on hardenability, nominal compositions, and fabricating processes is presented. Details on the use of the various grades, their specific applications, and their relative cost conclude the article.

8. Krivobok, V. N., Properties of Austenitic Stainless Steels at Low Temperatures, New York, International Nickel Company, Inc.; bulletin reprinted from NBS Circular 520, entitled Mechanical Properties of Metals at Low Temperatures, 1952.

   This paper presents a study and summary of published and unpublished information on the strength characteristics of austenitic stainless steels at various subzero temperatures. The effect of composition on the mechanical properties at room and subzero temperatures, values of true strength calculated from test results, and the influence of heat treatments (especially those which might result in either carbide precipitation or sigma formation) on the mechanical properties at low temperatures are discussed in some detail. The important beneficial influence of extra low carbon content is pointed out.

   Data on the modulus of elasticity, the fatigue, impact, and tensile impact strengths, the effect of notches, the distribution of ductility at the notch, and the beneficial effects of low temperature on ductility are summarized and appraised.

9. Kropschot, R. H., and W. F. Graham, Mechanical Properties of the Austenitic Stainless Steels at Low Temperatures, Technical Memorandum 39, Cryogenic Engineering Laboratory, National Bureau of Standards, Boulder, Colorado, August 30, 1956.

   This paper presents measurements on the mechanical properties of the austenitic stainless steels for temperatures down to 20°K. In addition, it includes data compiled from various sources. The properties included are chemical composition, tensile strength, yield strength, elongation, reduction of area, Young's modulus, impact strength, weld properties, effect of sensitization and sigma formation, and hardness after various amounts of cold work.

10. Kropschot, R. H., and W. F. Graham, The Mechanical Properties of Nickel and Some Nickel Alloys at Low Temperature, Technical Memorandum 40, Cryogenic Engineering Laboratory, National Bureau of Standards, Boulder, Colorado, October 25, 1956.

    This paper presents some measured mechanical properties of Monel, "K" Monel, and Inconel down to 20°K. In addition, it includes data from other sources of these alloys and commercially pure nickel. The properties covered are tensile and yield strength, elongation, reduction of area, impact strength, and the relation between hardness and various amounts of cold work.

11. Kropschot, R. H., C. R. Parkerson, J. O'Donel, and M. G. Crum, Low Temperature Tensile Testing Equipment and Results (300° - 20°K), Technical Memorandum 21, Cryogenic Engineering Laboratory, National Bureau of Standards, Boulder, Colorado, July 1, 1953.

    A 20,000-lb tensile-testing machine for use at temperatures as low as 20°K is described, with detailed emphasis on design considerations. The technique for obtaining near-axial pull is discussed. Results are given on the tensile behavior of 303, 310, and 316 stainless steels, Monel, and 24S-T4 aluminum alloy in the range 300°K to 20°K. The yield and tensile strengths of all materials tested increased with decreasing temperature without serious decreases in ductility. In one instance, the tensile strength increased 2-1/2 times between 300°K and 20°K.

12. Lee, H., "Fluorocarbon Plastics Today," Product Engineering, 25, No. 10, 168-173 (October 1954).

    The significant differences between Teflon and Kel-F are stressed. The properties of Kel-F are discussed in detail.

13. McClintock, R. M., and H. P. Gibbons, A Compilation of Mechanical Properties of Metals at Cryogenic Temperatures, National Bureau of Standards Report No. 6064, July 1, 1959.

    This is now the most extensive compilation of the low-temperature properties of metals. The tensile and yield strength, percent elongation, and impact energy of 12 classes of materials are presented in graphical form. Some of the reported properties are for temperatures as low as 20°K. The material classes are:

1. Aluminum
2. Copper
3. Nickel
4. Titanium
5. Magnesium
6. Austenitic Stainless Steel
7. Ferritic and Hardenable Stainless Steels
8. Low-Alloy Construction Steels
9. Superalloys (Alloys of Co, Ni, Cr, W, Mo)
10. Brazing and Soldering Metals
11. Miscellaneous Alloys and Pure Metals
12. Nonmetallic Materials

The graphic information is referenced to 104 data sources listed in a bibliography at the end of the report.

This report was compiled for the Air Force on Contract 04(647)-59-3 and formed the first quarterly report prepared by NBS. Requests for copies should be addressed to AFBMD, AF Unit Post Office, Los Angeles 45, California, Attention Col. John R. Browning, WDSOT. The report is also being reprinted as an NBS Monograph and will be available from the U. S. Government Printing Office this year.

The second quarterly report is being prepared for issue in handbook binder form. Successive quarterly reports will consist of additional data sheets to be inserted in the binder. Requests for copies of the handbook should be addressed to Col. Browning.

14. McGee, R. L., J. E. Campbell, R. L. Carlson, and G. K. Manning of the Battelle Memorial Institute, The Mechanical Properties of Certain Aircraft Structural Metals at Very Low Temperatures, WADC Technical Report 58-386, Astia Document 204422, November 1958.

New aircraft developments have required the use of structural metals at very low temperatures. In this investigation, tensile and hardness properties of nine alloys of interest to the aircraft industry were determined at four temperature levels ranging from room temperature to -253°C (liquid hydrogen). These alloys were 17-7PH and AM-350 stainless steels, AISI 4340 and Tricent steels, 7079-T6 aluminum and ZK60A-T5 magnesium alloys, and A110AT, C110M, and 6Al-4V titanium alloys. Notched-impact energies were determined on the two steels and the aluminum and magnesium alloys at the low temperatures.

Values for hardness, elastic modulus, yield strength, and tensile strength of these materials tended to increase as the temperature was reduced to -253°C. However, only the 17-7PH stainless steel, the aluminum and magnesium alloys, and the A110AT and 6Al-4V titanium alloys reached 0.2% offset for yield-strength determination at -253°C before fracturing. Of these, the titanium alloys had much higher ratios of yield strength to density than the other alloys at the low temperatures. Tensile and impact tests on notched bars showed the tendency of the nine alloys to become embrittled at low temperatures.

15. "Mechanical Properties of Metals at Low Temperatures," Proceedings of the National Bureau of Standards Semicentennial Symposium on Mechanical Properties of Metals at Low Temperatures (held at the National Bureau of Standards on May 14 and 15, 1951); National Bureau of Standards Circular 520, issued May 7, 1952.

    The papers in this volume present some of the then latest results of studies conducted in both industry and government. They were initially presented at the Symposium on the Influence of Low Temperatures on the Mechanical Properties of Metals, the second of 12 symposiums held by the National Bureau of Standards during its Semicentennial in 1951.

16. Mikesell, R. P., and R. P. Reed, "The Stability of Austenitic Stainless Steels at Low Temperatures as Determined by Magnetic Measurements," Proceedings of the 1958 Cryogenic Engineering Conference, National Bureau of Standards, Boulder, Colorado, January 1959.

17. Mikesell, R. P., and R. P. Reed, "The Tensile and Impact Strength of Annealed and Welded 5086 Aluminum Down to 20°K," Proceedings of the 1958 Cryogenic Engineering Conference, National Bureau of Standards, Boulder, Colorado, January 1959.

18. Munse, W., and D. Crawford, Strength of Brazed Joints in Copper and Copper Alloys, paper presented to 1954 meeting of AWS, University of Illinois, Engineering Experiment Station, Reprint No. 57.

19. Powell, R. L., and W. A. Blanpied, Thermal Conductivity of Metals and Alloys at Low Temperature, A Review of the Literature, National Bureau of Standards Circular 556, September 1, 1954.

    This is a compilation of the measured values of thermal conductivity for metals and alloys from room temperature down to approximately 0°K. The more extensive and important data are plotted in 48 graphs. The tables and graphs for the metallic elements and alloys are essentially complete for the literature from 1900 to early 1954. For comparison, several graphs and tables are given for some representative dielectrics.

20. Roach, D. B., and A. M. Hall, The Engineering Properties of Precipitation-Hardenable Stainless Steels, Titanium Metallurgical Laboratory, Battelle Memorial Institute, TML Report 48, July 20, 1956.

    Properties of the precipitation-hardenable stainless steels, which are considered competitive with titanium for aircraft applications, are evaluated.

21. Scott, Russel B., Cryogenic Engineering, New York, D. Van Nostrand, 1959.

22. Some Properties of Inco Nickel Alloys at Low Temperatures, New York, International Nickel Company, Inc., September 1957.

    This bulletin presents tabular summaries of some physical and mechanical properties of nickel and its alloys for various conditions of treatment over a maximum temperature range from room temperature to -423°F. The physical properties include density, melting range, electrical resistivity, magnetic-transformation temperature, thermal conductivity, and coefficient of thermal expansion. The mechanical properties include yield and tensile strength, elongation, reduction of area, and hardness and impact strength. The magnetic permeability of nickel and its principal alloys is presented.

23. Swenson, C. A., "Mechanical Properties of Teflon at Low Temperatures," The Review of Scientific Instruments, 25, No. 8, 834-35 (August 1954).

    This brief report on the mechanical properties of Teflon in compression between 4°K and 300°K states that Teflon did not exhibit brittle behavior, while Kel-F showed brittle fracture at 44,000 psi when tested at 4°K.

24. Swenson, C. A., "The Compressive Strengths of Some Technical Metals Between 4.2° and 300°K," Proceedings of The 1954 Cryogenic Engineering Conference, National Bureau of Standards, Boulder, Colorado, February 1955.

    Compressive-test data as a function of temperature were obtained by use of a hydraulic press constructed for high-pressure work at liquid helium temperatures. Graphs show the small change in compressive yield strength with temperature for austenitic stainless steels 303 and 304.

    It is concluded that the 303 and 304 stainless steels remain ductile and retain their excellent impact strengths at very low temperatures.

25. Wessel, E. T., The Relationship of the Low Temperature Behavior of Metals to the Structural and Mechanical Effects of Repeated Cooling, Westinghouse Research Laboratories November 1958.

26. Wisander, D., W. Hody, and R. Johnson, "Friction Studies of Various Materials in Liquid Nitrogen," Proceedings of the 1957 Cryogenic Engineering Conference, National Bureau of Standards, Boulder, Colorado, 1958.

27. Wisander, D., and R. Johnson, "Wear and Friction in Liquid Nitrogen With Austenitic Stainless Steel Having Various Surface Coatings," Proceedings of the 1958 Cryogenic Engineering Conference, National Bureau of Standards, Boulder, Colorado, January 1959.

28. Wisander, D., C. Maley, and R. Johnson, "Wear and Friction of Filled Teflon Compositions in Liquid Nitrogen," ASME-ASLE Lubrication Conference, Los Angeles, California, 1958.

29. Zambrow, J. L., and M. G. Fontana, "Mechanical Properties Including Fatigue, Of Aircraft Alloys At Very Low Temperatures," Transactions of American Society for Metals, 41, 480-518 (1959).

    Aluminum and aluminum alloys, a magnesium alloy, low-alloy steels, 18-8S stainless steel, Stainless "W," an 8-1/2% nickel steel, and aluminum bronze were subjected to mechanical tests from room temperature to -253°C (-423°F). Data from the following tests are reported: fatigue tests at 25°, -78°, and -196°C, impact tests at 25°, -78°, -127°, -192°, and -253°C; hardness tests at 25°, 78°, and -192°C; and tensile tests at 25°, -78°, and -196°C. Equipment, techniques, and precautions used in performing these tests are described.

IV. PHYSICAL AND THERMODYNAMIC PROPERTIES OF HYDROGEN

A. GENERAL CONSIDERATIONS

1. Critical Properties

Critical Pressure, atm	12.8
psia	188.0
Critical Temperature, °F	-399.8
°K	33.2
Critical Volume, cu ft/lb	0.531
cu cm/gm	33.1

References: International Critical Tables, New York, McGraw-Hill Book Co., Inc., 1926.

Johnston, H. L., D. White, and A. S. Friedman, Journal of American Chemical Society, 72, 3565 (1950).

Woolley, H. W., R. B. Scott, and F. G. Brickwedde, "Compilations of Thermal Properties of Hydrogen in its Various Isotope and Ortho-Para Modifications," Journal of Research of National Bureau of Standards, 41, 379 (1948).

2. Molecular Weight

Isotope	Natural Abundance (%)	Atomic Mass Physical Scale	Atomic Mass Chemical Scale
H^1	99.9844	1.00813	1.00785
H^2	0.0156	2.01473	2.01418
H^3		3.01695	3.01613
H (natural)		1.00827	1.00800

Reference: Handbook of Chemistry and Physics, ed. C.D. Hodgman, 36th Edition, Chemical Rubber Publishing Co., Cleveland, Ohio, 1954.

3. Triple Point

Form	Temperature (°K)	Pressure (mm of Hg)	Pressure (psia)
20.4°K Equilibrium Mixture (99.79% $p-H_2$, 0.21% $O-H_2$)	13.81	52.8	0.694
38% $O-H_2$, 62% $p-H_2$	13.86	53.0	0.697
Normal Hydrogen (75% $O-H_2$, 25% $p-H_2$)	13.95	54.0	0.710
Pure $O-H_2$	14.05	55.1	0.725

Reference: Woolley, H. W., R. B. Scott, and F. G. Brickwedde, "Compilation of the Thermal Properties of Hydrogen in its Various Isotopic and Ortho-Para Modifications," Journal of Research of National Bureau of Standards, 41, 379 (1948).

B. VAPOR PRESSURE

1. Freezing Points

Atmospheric Pressure -259.14°C

or 14.0 °K

or 25.2 °R

or -434.8 °F

2. Effect of Pressure on Freezing Points

Freezing Point (°K)	Pressure (psia)
13.96	0.99
14	19.9
15	472
16	957
17	1,472
18	2,024
19	2,611
20	3,229
22	4,530
24	5,901
26	7,370
28	8,930
30	10,600
32	12,300
34	14,200
36	16,100
38	18,100
40	20,220
45	25,890
50	32,110
55	38,890
60	46,200
65	54,050
70	62,410
75	71,300
80	80,680

See Figure 3.

Reference: Woolley, H. W., R. B. Scott, and F. G. Brickwedde, "Compilation of the Thermal Properties of Hydrogen in its Various Isotopic and Ortho-Para Modifications," Journal of Research of National Bureau of Standards, 41, 379 (1948).

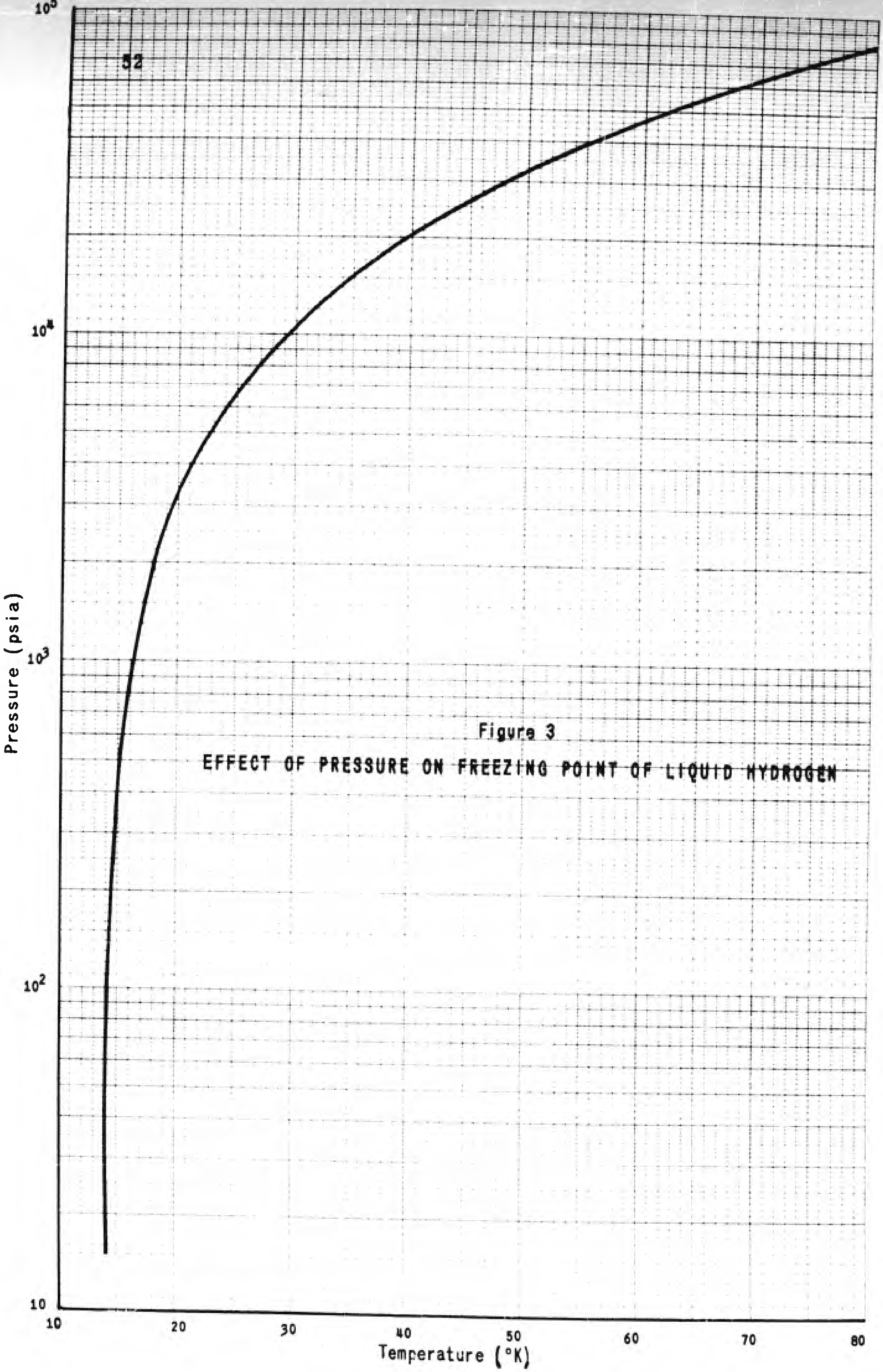


Figure 3

EFFECT OF PRESSURE ON FREEZING POINT OF LIQUID HYDROGEN

3. Vapor Pressure of Solid Hydrogen

See Figure 4.

Reference: Woolley, H. W., R. B. Scott, and F. G. Brickwedde, "Compilations of Thermal Properties of Hydrogen in its Various Isotopic and Ortho-Para Modifications," Journal of Research of National Bureau of Standards, 41, 379 (1948).

4. Vapor Pressure of Normal Liquid Hydrogen

T (°K)	T (°R)	Vapor Pressure atm	Vapor Pressure psia
14	25.2	0.0653	0.960
15	27.0	0.1164	1.711
16	28.8	0.1931	2.838
17	30.6	0.3018	4.435
18	32.4	0.4492	6.601
19	34.2	0.6421	9.436
20	36.0	0.8870	13.04
21	37.8	1.190	17.49
22	39.6	1.559	22.91
23	41.4	1.999	29.38
24	43.2	2.518	37.00
25	45.0	3.123	45.90
26	46.8	3.824	56.20
27	48.6	4.629	68.03
28	50.4	5.549	81.55
29	52.2	6.593	96.89
30	54.0	7.777	114.3
31	55.8	9.120	134.0
32	57.6	10.62	156.1
33.2	59.7	12.8	188.0

Vapor pressures were calculated from the equation

$$\log P = 3.0683 - \frac{55.256}{T} - 3.1282 \times 10^{-2} T + 6.6989 \times 10^{-4} T^2$$

T = temperature, °K

P = vapor pressure, atm

Notes:
1. Vapor pressures are plotted in Figures 5 and 6.
2. Data pertains to normal hydrogen (75% O, 25% P).
3. If hydrogen is 100% ortho or equilibrium (0.21% O, 99.79% P), multiply the vapor pressures of normal hydrogen by the correction factor plotted in Figure 7.

References: White, D., A. S. Friedman, and H. L. Johnston, Journal of American Chemical Society, 72, 3927 (1950).

Woolley, H. W., R. B. Scott, and F. G. Brickwedde, "Compilations of Thermal Properties of Hydrogen in Its Various Isotopic and Ortho-Para Modifications," Journal of Research of National Bureau of Standards, 41, 379 (1948).

C. LIQUID AND SOLID DENSITIES

1. Density of Solid Normal Hydrogen

At the Melting Point

See Figure 8.

As a Function of Pressure at 4.2°K

Temperature (°K)	Pressure (psia)	Density (lb/ft3)
4.2	0	5.558
	142	5.598
	355	5.646
	711	5.715
	1060	5.775
	1420	5.829

Reference: Woolley, H. W., R. B. Scott, and F. G. Brickwedde, "Compilations of the Thermal Properties of Hydrogen in its Various Isotopic and Ortho-Para Modifications," Journal of Research of National Bureau of Standards, 41, 379 (1948).

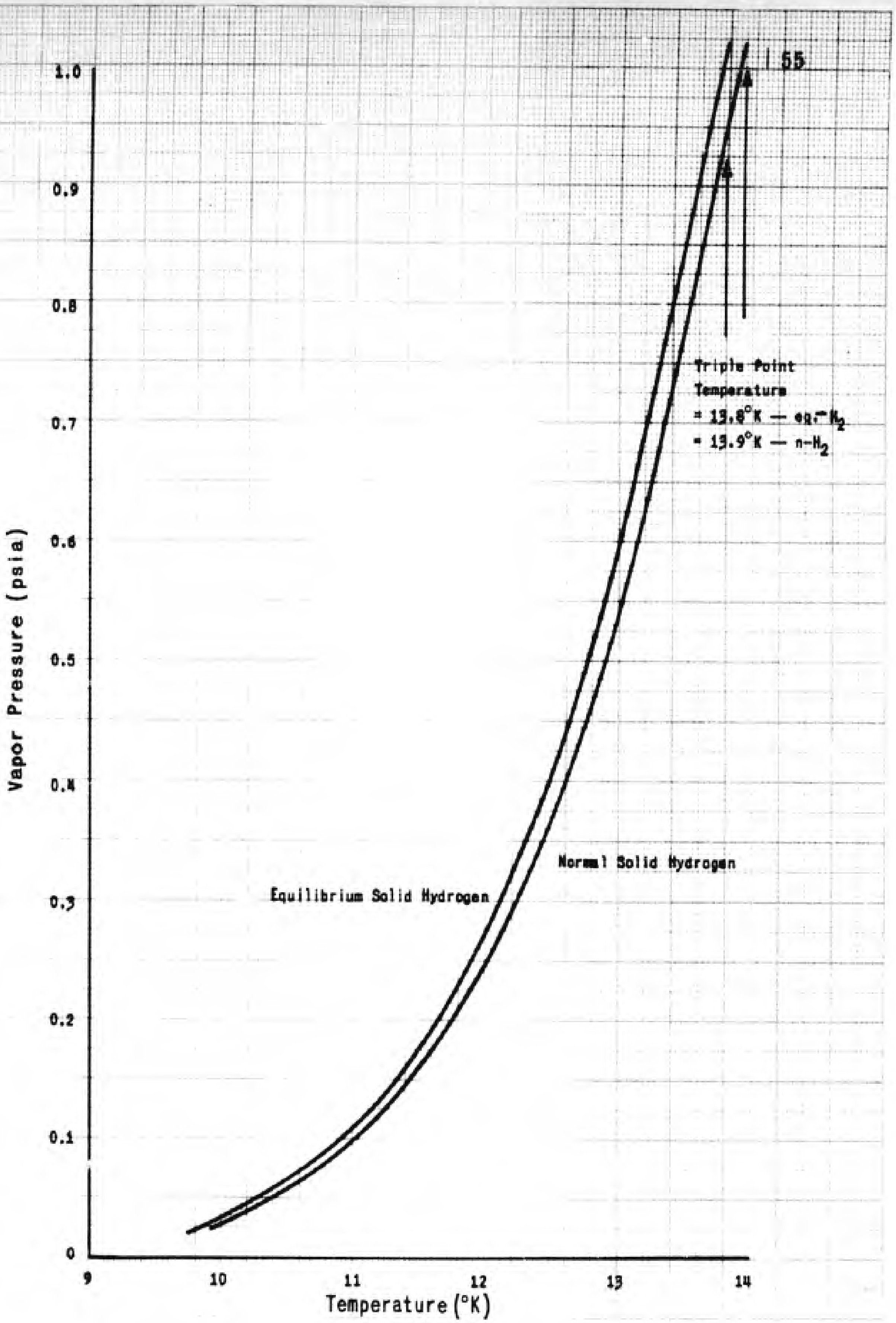


Figure 4

VAPOR PRESSURE VS TEMPERATURE -- SOLID HYDROGEN

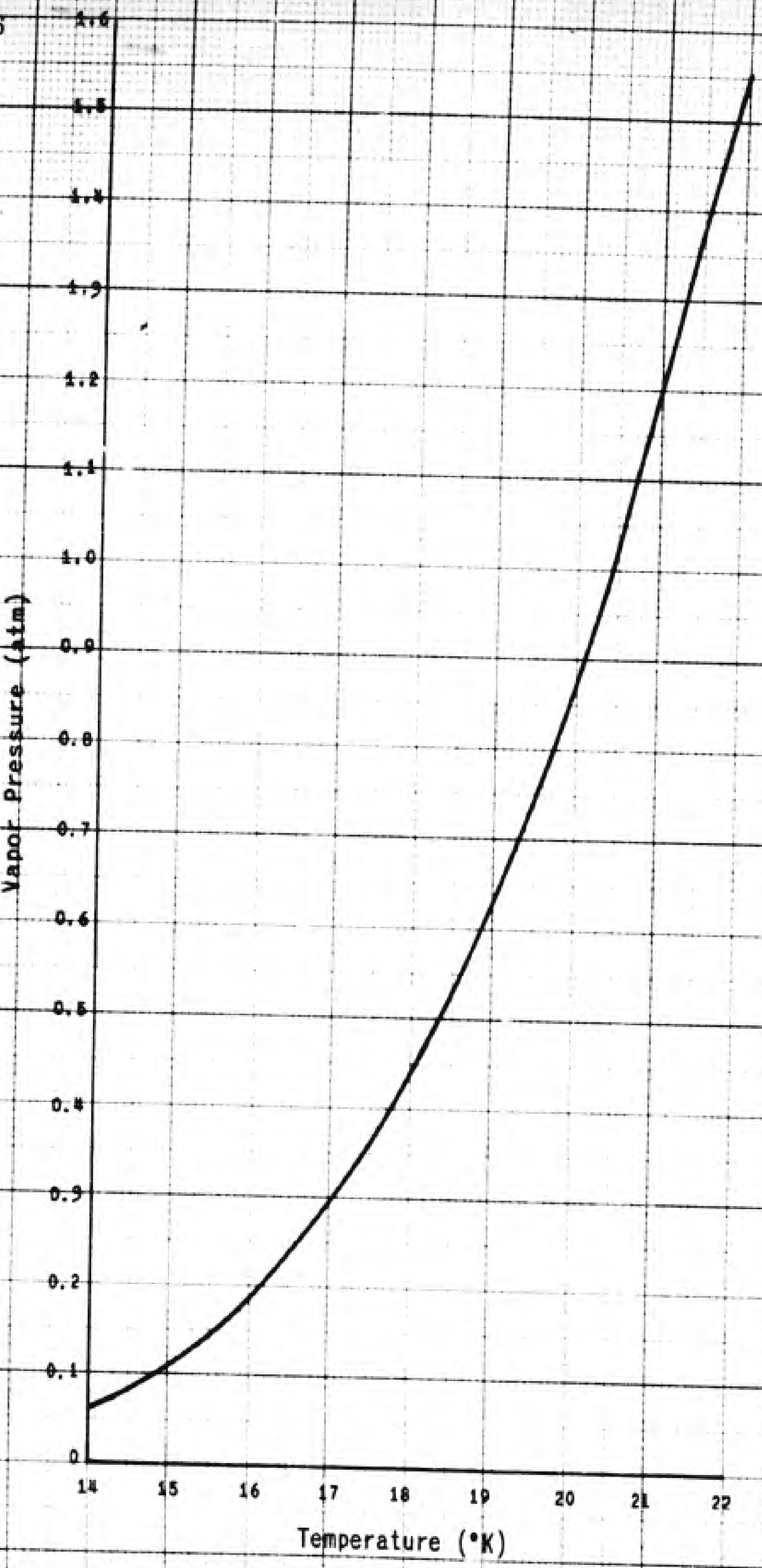


Figure 5

VAPOR PRESSURE VS TEMPERATURE -- NORMAL LIQUID HYDROGEN
(LOW-PRESSURE RANGE)

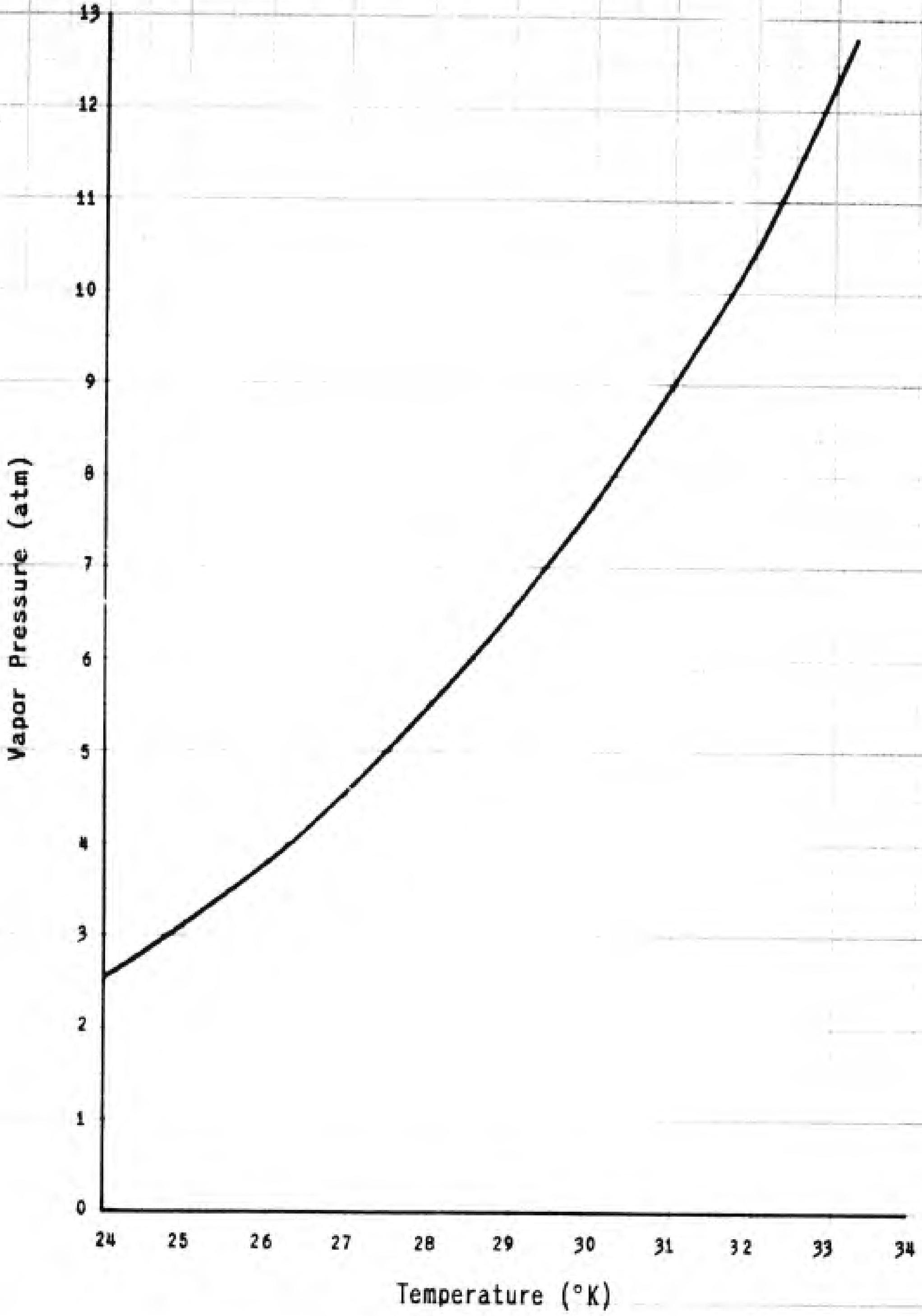


Figure 6

VAPOR PRESSURE VS TEMPERATURE -- NORMAL LIQUID HYDROGEN
(HIGH-PRESSURE RANGE)

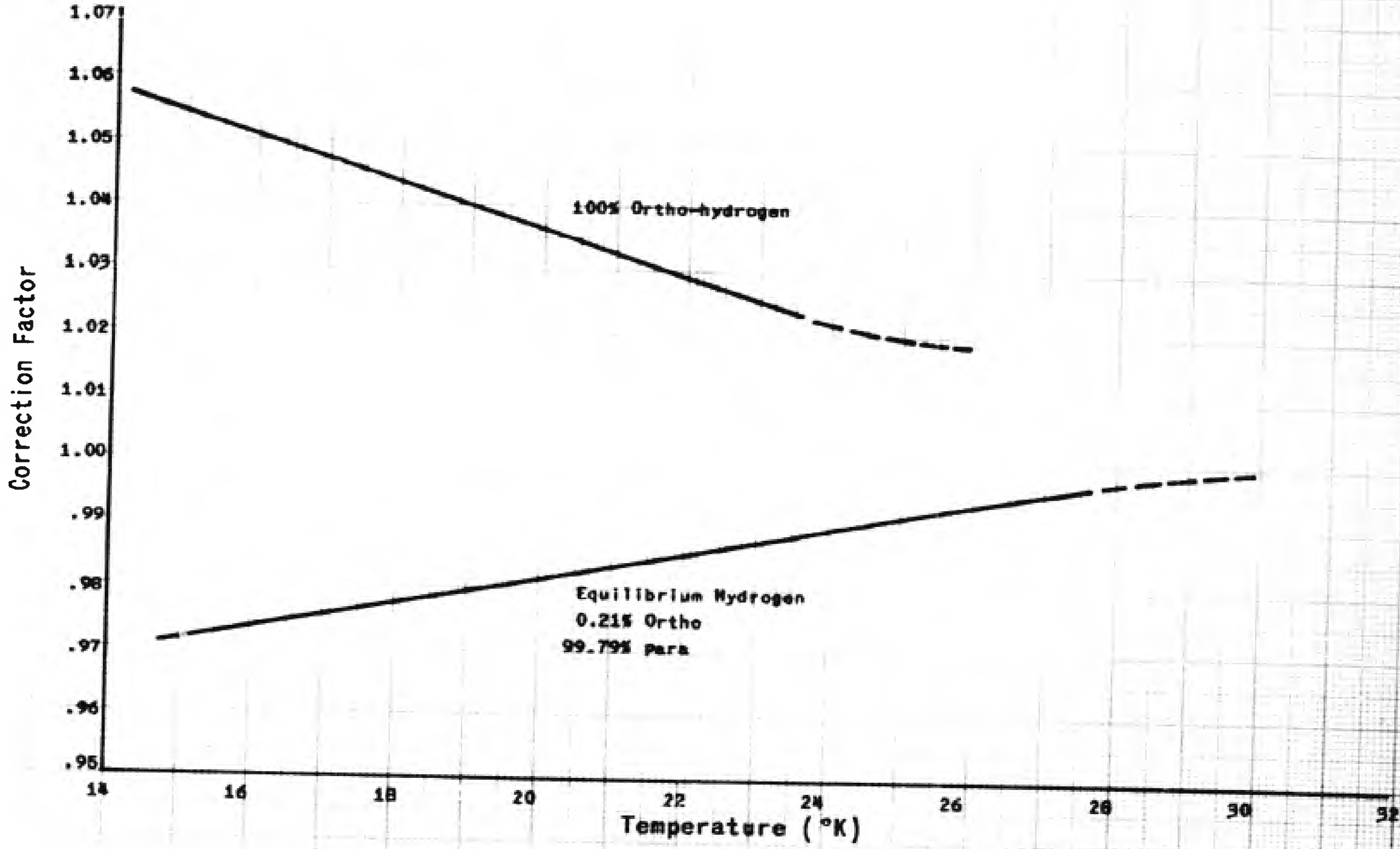


Figure 7

CORRECTION FACTOR FOR NORMAL HYDROGEN VAPOR PRESSURE

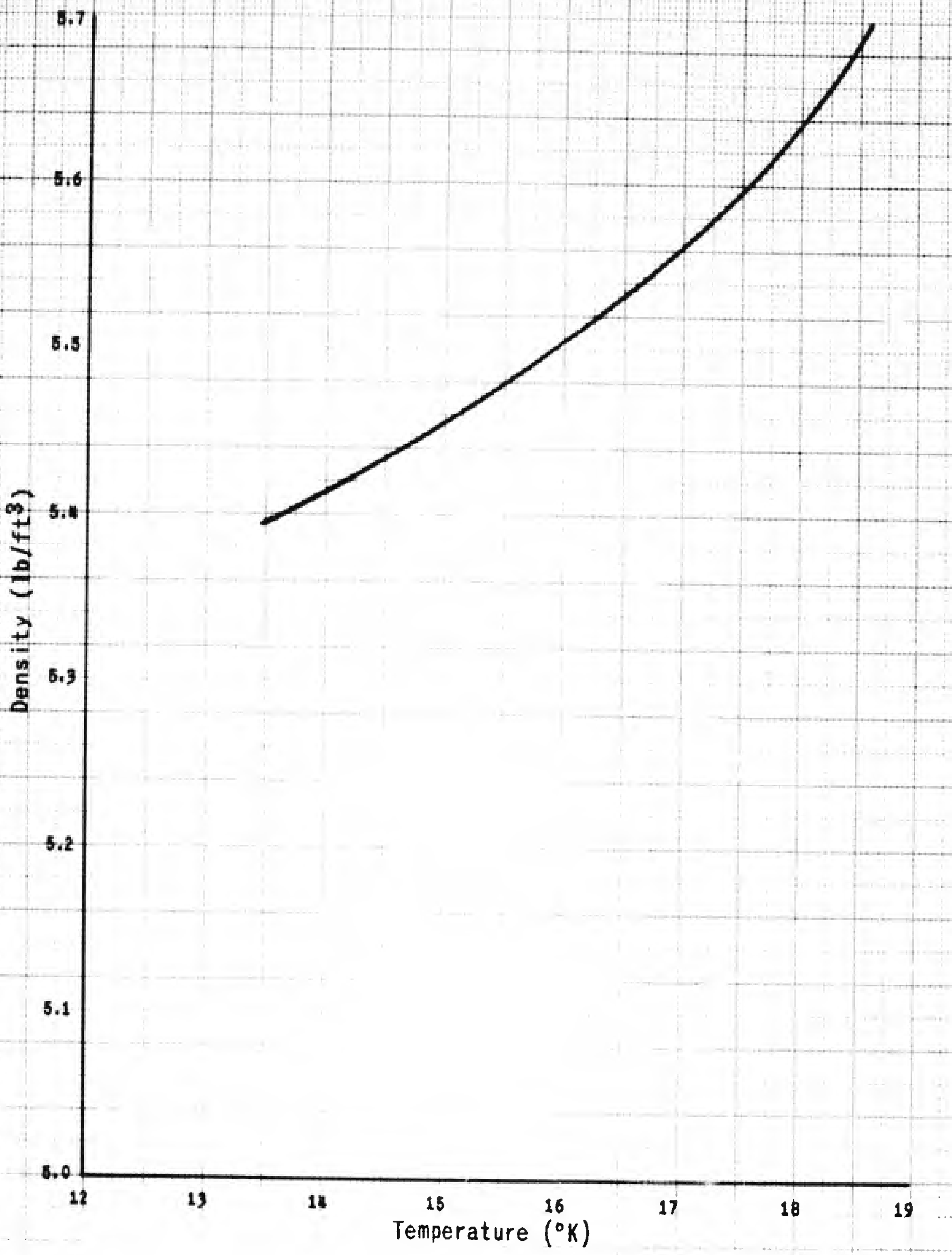


Figure 8

DENSITY OF SOLID NORMAL HYDROGEN AT MELTING POINT

2. Volume Change on Fusion (Normal Hydrogen)

T (°K)	Volume Change (cm^3/g-mole)	(ft^3/lb)	Pressure (psia)
13.96	2.85	0.0227	1.00
16.43	2.30	0.0183	1170.0
18.24	2.03	0.0161	2160.0

Reference: Woolley, H. W., R. B. Scott, and F. G. Brickwedde, "Compilation of the Thermal Properties of Hydrogen in its Various Isotopic and Ortho-Para Modifications," Journal of Research of National Bureau of Standards, 41, 379 (1948).

3. Density of Liquid Normal Hydrogen

Saturated Liquid

Temperature (°K)	Density (lb/ft^3)
13.95	4.822
14	4.820
15	4.767
16	4.712
17	4.652
18	4.591
19	4.526
20	4.459
22	4.307
24	4.135
26	3.935
28	3.697
30	3.390
32	2.914
33.2 (critical point)	1.88

See Figure 9 and Table XIV.

References: van Itterbeek, A., and O. van Paemel, Physica, 8, 133 (1941).

Woolley, H. W., R. B. Scott, and F. G. Brickwedde, "Compilation of the Thermal Properties of Hydrogen in Its Various Isotopic and Ortho-Para Modifications," Journal of Research of National Bureau of Standards, 41, 379 (1948).

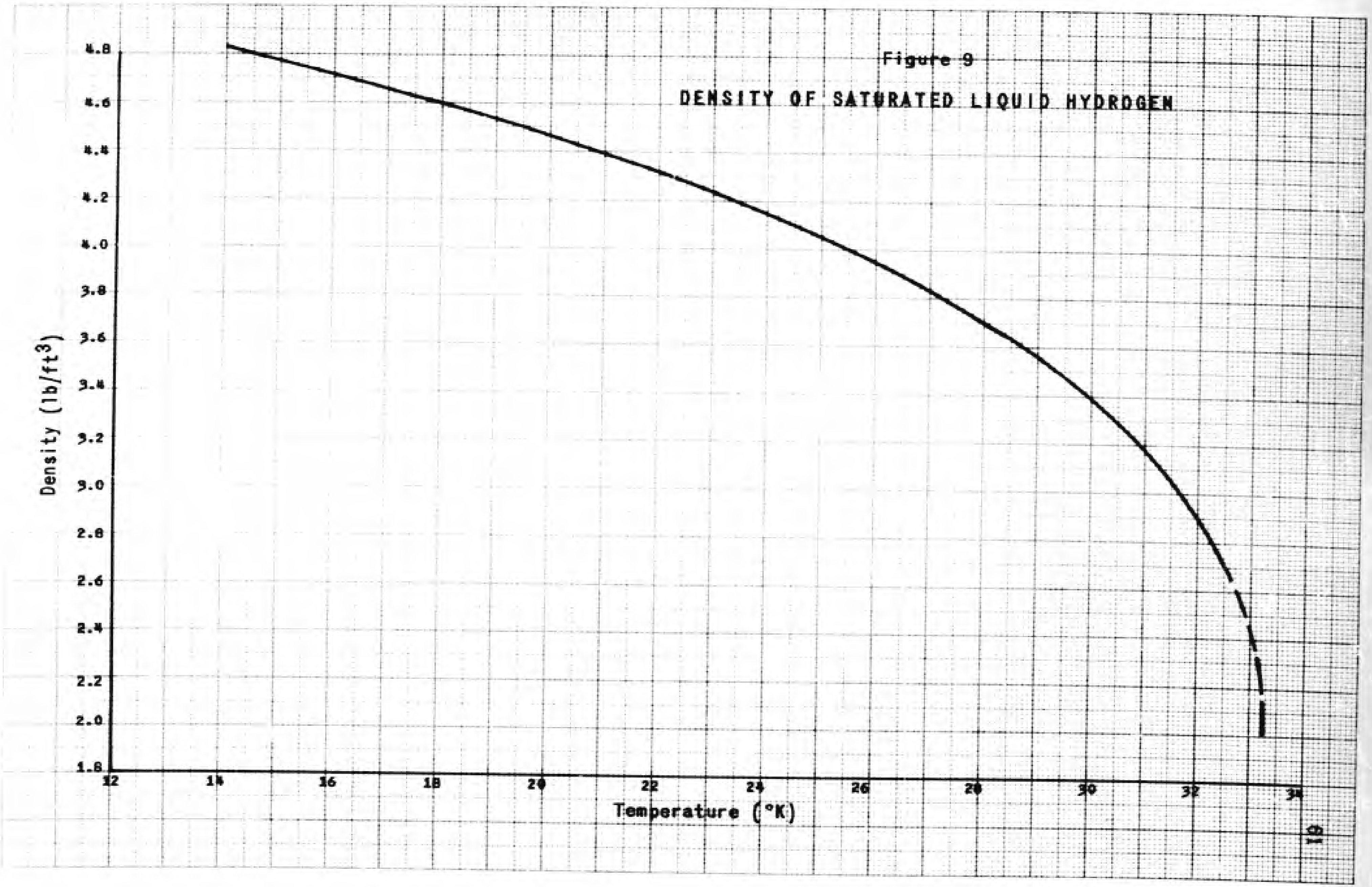


Figure 9

DENSITY OF SATURATED LIQUID HYDROGEN

TABLE XIV

DENSITIES OF SUBCOOLED LIQUID NORMAL HYDROGEN
(lb/ft^3)

Pressure (atm)	20° K	21° K	22° K	23° K	24° K	25° K	26° K	27° K	28° K	29° K	30° K	31° K	32° K	33° K
2	4.461	4.388	4.310											
4	4.479	4.405	4.329	4.249	4.161	4.059	3.944							
6	4.493	4.427	4.353	4.274	4.170	4.088	3.982	3.864	3.725					
8	4.509	4.444	4.373	4.295	4.212	4.120	4.019	3.908	3.780	3.620	3.410			
10	4.529	4.461	4.391	4.318	4.236	4.147	4.050	3.944	3.827	3.685	3.502	3.259		
12	4.543	4.477	4.410	4.338	4.261	4.173	4.078	3.975	3.866	3.738	3.583	3.390	3.104	
14	4.560	4.498	4.432	4.359	4.279	4.191	4.104	4.008	3.903	3.780	3.636	3.467	3.268	3.031
16	4.573	4.514	4.449	4.378	4.300	4.218	4.131	4.037	3.936	3.822	3.691	3.539	3.364	3.166
20	4.598	4.542	4.479	4.411	4.503	4.259	4.176	4.088	3.994	3.892	3.777	3.648	3.508	3.358
30	4.660	4.610	4.553	4.492	4.424	4.353	4.281	4.204	4.124	4.035	3.943	3.843	3.737	3.619
40	4.721	4.672	4.618	4.563	4.503	4.438	4.370	4.300	4.226	4.150	4.069	3.987	3.901	3.814
50	4.778	4.728	4.676	4.624	4.567	4.509	4.449	4.387	4.321	4.249	4.177	4.104	4.030	3.955
60	4.826	4.780	4.731	4.682	4.630	4.577	4.519	4.461	4.399	4.335	4.271	4.202	4.133	4.063
70	4.872	4.829	4.783	4.737	4.682	4.637	4.583	4.527	4.471	4.411	4.350	4.288	4.225	4.158
80	4.922	4.880	4.835	4.789	4.740	4.691	4.641	4.588	4.535	4.480	4.424	4.365	4.306	4.245
90	4.966	4.924	4.880	4.835	4.789	4.742	4.694	4.644	4.593	4.542	4.488	4.433	4.379	4.325
100	5.006	4.966	4.937	4.882	4.837	4.793	4.746	4.700	4.651	4.600	4.548	4.496	4.444	4.393
110	5.034	5.000	4.963	4.924	4.882	4.839	4.794	4.749	4.701	4.654	4.605	4.555	4.506	4.458
120	5.066	5.034	4.998	4.961	4.922	4.880	4.837	4.793	4.747	4.700	4.653	4.608	4.563	4.519

Reference: Johnston, H. L., and D. White, The Thermodynamic Properties of Liquid Normal Hydrogen Between the Boiling Point and Critical Temperature and up to 150 Atmospheres Pressure, O. S. U. Research Foundation, Technical Report TR-264-23, Cryogenic Laboratory, Columbus, Ohio, February 1, 1953.

4. Isothermal Compressibility of Solid Normal Hydrogen

$$\beta = \frac{-1}{V}\left(\frac{\partial V}{\partial P}\right)_T$$

β = isothermal compressibility, atm^{-1}
V = specific volume
P = pressure, atm
T = temperature

Pressure (atm)	Isothermal Compressibility (atm^{-1})
0	7×10^{-4}
97	3.3×10^{-4}

Reference: Woolley, H. W., R. B. Scott, and F. G. Brickwedde, "Compilation of the Thermal Properties of Hydrogen in its Various Isotopic and Ortho-Para Modifications," Journal of Research of National Bureau of Standards, 41, 379 (1948).

5. Coefficient of Thermal Expansion of Solid Normal Hydrogen

$$\alpha = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_p$$

α = coefficient, $°K^{-1}$
V = specific volume
T = temperature, °K
p = pressure

T (°K)	α ($°K^{-1}$)
4.2	0.0024
11.0	0.0051

Reference: Woolley, H. W., R. B. Scott, and F. G. Brickwedde, "Compilation of the Thermal Properties of Hydrogen in its Various Isotopic and Ortho-Para Modifications," Journal of Research of National Bureau of Standards, 41, 379 (1948).

6. Isothermal Compressibility of Liquid Normal Hydrogen

$$\beta = \frac{-1}{V} \left(\frac{\partial V}{\partial P}\right)_T$$

β = isothermal compressibility, atm^{-1}
V = specific volume
P = pressure, atm
T = temperature

See Table XV.

Reference: Johnston, H. L. , and D. White, The Thermodynamic Properties of Liquid Normal Hydrogen Between the Boiling Point and Critical Temperature and up to 150 Atmospheres Pressure. O. S. U. Research Foundation, Technical Report TR-264-23, Cryogenic Laboratory, Columbus, Ohio, February 1, 1953.

7. Coefficient of Thermal Expansion of Liquid Normal Hydrogen

$$\alpha = \frac{1}{V} \left(\frac{\partial V}{\partial T}\right)_p$$

α = coefficient of thermal expansion, °K^{-1}
V = specific volume
T = temperature, °K
p = pressure

See Table XVI and Figure 10.

Reference: Johnston, H. L. , and D. White, The Thermodynamic Properties of Liquid Normal Hydrogen Between the Boiling Point and Critical Temperature and up to 150 Atmospheres Pressure, O. S. U. Research Foundation, Technical Report TR-264-23, Cryogenic Laboratory, Columbus, Ohio, February 1, 1953.

TABLE XV

COEFFICIENT OF COMPRESSIBILITY β, 1/atm

Pressure (atm)	20°K	21°K	22°K	23°K	24°K	25°K	26°K	27°K	28°K	29°K	30°K	31°K	32°K	33°K
2	0.00186	0.00209	0.00236											
4	0.00179	0.00202	0.00227	0.00260	0.00314	0.00378	0.00470							
6	0.00172	0.00194	0.00219	0.00250	0.00298	0.00350	0.00426	0.00517	0.00720					
8	0.00165	0.00186	0.00212	0.00241	0.00282	0.00327	0.00392	0.00466	0.00619	0.00926	0.01475			
10	0.00159	0.00180	0.00204	0.00231	0.00269	0.00308	0.00364	0.00427	0.00543	0.00764	0.01159	0.02168		
12	0.00152	0.00173	0.00198	0.00223	0.00255	0.00291	0.00341	0.00396	0.00485	0.00636	0.00903	0.01386	0.03382	
14	0.00147	0.00167	0.00190	0.00216	0.00244	0.00277	0.00321	0.00369	0.00443	0.00582	0.00778	0.00871	0.01566	0.02513
16	0.00143	0.00161	0.00185	0.00208	0.00234	0.00264	0.00303	0.00348	0.00411	0.00516	0.00673	0.00896	0.01216	0.01624
20	0.00133	0.00150	0.00173	0.00195	0.00218	0.00244	0.00276	0.00312	0.00361	0.00434	0.00536	0.00667	0.00819	0.00998
30	0.00118	0.00132	0.00150	0.00167	0.00187	0.00206	0.00228	0.00251	0.00283	0.00323	0.00371	0.00426	0.00511	0.00636
40	0.00110	0.00120	0.00133	0.00148	0.00162	0.00180	0.00196	0.00211	0.00234	0.00259	0.00285	0.00312	0.00343	0.00380
50	0.00103	0.00112	0.00122	0.00133	0.00142	0.00156	0.00169	0.00182	0.00199	0.00216	0.00236	0.00257	0.00277	0.00297
60	0.00097	0.00105	0.00112	0.00120	0.00127	0.00138	0.00150	0.00161	0.00174	0.00189	0.00203	0.00218	0.00234	0.00252
70	0.00093	0.00098	0.00103	0.00110	0.00117	0.00126	0.00136	0.00145	0.00155	0.00167	0.00176	0.00189	0.00204	0.00222
80	0.00087	0.00092	0.00097	0.00103	0.00109	0.00117	0.00123	0.00130	0.00139	0.00149	0.00157	0.00168	0.00185	0.00194
90	0.00082	0.00086	0.00090	0.00096	0.00102	0.00108	0.00112	0.00119	0.00127	0.00136	0.00141	0.00148	0.00154	0.00162
100	0.00076	0.00081	0.00085	0.00089	0.00095	0.00101	0.00105	0.00111	0.00118	0.00125	0.00133	0.00137	0.00138	0.00140
110	0.00070	0.00075	0.00079	0.00084	0.00088	0.00094	0.00098	0.00104	0.00110	0.00116	0.00121	0.00124	0.00126	0.00127
120	0.00064	0.00069	0.00074	0.00080	0.00084	0.00088	0.00093	0.00100	0.00105	0.00109	0.00110	0.00110	0.00111	0.00112

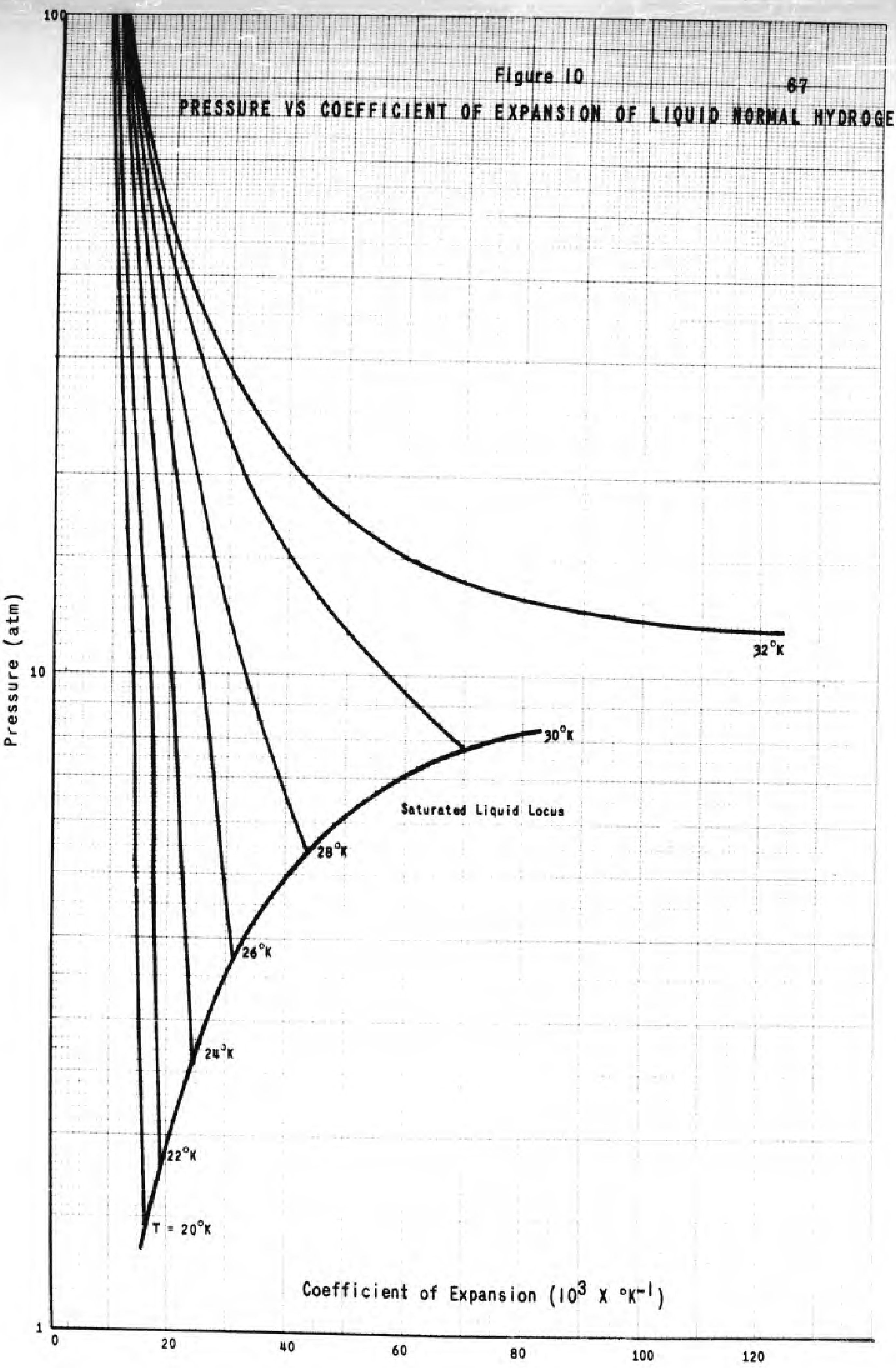
TABLE XVI

COEFFICIENT OF THERMAL EXPANSION, α, 1/°K

Pressure (atm)	20°K	21°K	22°K	23°K	24°K	25°K	26°K	27°K	28°K	29°K	30°K	31°K	32°K	33°K
2	0.0156	0.0170	0.0185											
4	0.0151	0.0165	0.0180	0.0199	0.0230	0.0264	0.0309							
6	0.0146	0.0160	0.0175	0.0193	0.0221	0.0248	0.0286	0.0326	0.0419					
8	0.0141	0.0155	0.0171	0.0188	0.0212	0.0235	0.0268	0.0301	0.0372	0.0505	0.0697			
10	0.0137	0.0151	0.0166	0.0182	0.0204	0.0224	0.0253	0.0281	0.0335	0.0434	0.0585	0.0911		
12	0.0132	0.0146	0.0162	0.0177	0.0196	0.0215	0.0240	0.0265	0.0306	0.0373	0.0481	0.0645	0.1239	
14	0.0128	0.0142	0.0157	0.0173	0.0189	0.0206	0.0229	0.0251	0.0285	0.0350	0.0429	0.0526	0.0663	
16	0.0125	0.0138	0.0154	0.0168	0.0183	0.0199	0.0219	0.0240	0.0269	0.0318	0.0384	0.0463	0.0555	0.0857
20	0.0118	0.0130	0.0146	0.0160	0.0173	0.0187	0.0204	0.0221	0.0244	0.0278	0.0322	0.0370	0.0415	0.0630
30	0.0107	0.0117	0.0130	0.0142	0.0154	0.0165	0.0177	0.0188	0.0204	0.0223	0.0244	0.0266	0.0300	0.0454
40	0.0102	0.0109	0.0119	0.0129	0.0138	0.0149	0.0158	0.0165	0.0177	0.0189	0.0200	0.0210	0.0221	0.0347
50	0.0098	0.0104	0.0111	0.0119	0.0124	0.0133	0.0144	0.0148	0.0157	0.0165	0.0175	0.0183	0.0190	0.0233
60	0.0094	0.0100	0.0104	0.0110	0.0114	0.0121	0.0129	0.0135	0.0142	0.0150	0.0156	0.0163	0.0170	0.0196
70	0.0091	0.0095	0.0098	0.0103	0.0107	0.0113	0.0120	0.0125	0.0130	0.0137	0.0141	0.0147	0.0154	0.0176
80	0.0087	0.0090	0.0094	0.0098	0.0102	0.0107	0.0111	0.0115	0.0120	0.0126	0.0129	0.0135	0.0142	0.0162
90	0.0083	0.0086	0.0089	0.0093	0.0097	0.0101	0.0103	0.0107	0.0112	0.0118	0.0119	0.0122	0.0125	0.0148
100	0.0078	0.0082	0.0085	0.0088	0.0092	0.0096	0.0098	0.0102	0.0107	0.0111	0.0115	0.0116	0.0115	0.0128
110	0.0072	0.0077	0.0080	0.0084	0.0087	0.0091	0.0093	0.0098	0.0101	0.0105	0.0108	0.0108	0.0107	0.0114
120	0.0067	0.0072	0.0076	0.0081	0.0084	0.0086	0.0090	0.0095	0.0098	0.0100	0.0099	0.0098	0.0097	0.0106

Figure 10

PRESSURE VS COEFFICIENT OF EXPANSION OF LIQUID NORMAL HYDROGEN



8. Density of Saturated Vapor--Normal Hydrogen

T (°K)	T (°R)	ρ (lb/ft^3)	V (ft^3/lb)
14	25.2	0.00812	123.
16	28.8	0.0200	50.
18	32.4	0.0411	24.3
20	36.0	0.0748	13.4
22	39.6	0.1249	8.006
24	43.2	0.1968	5.081
26	46.8	0.2980	3.356
28	50.4	0.4413	2.266
30	54.0	0.6540	1.529
32	57.6	1.018	0.9823
33.2	59.7	1.884	0.531

See Figure 11.

Reference: Woolley, H. W., R. B. Scott, and F. G. Brickwedde, "Compilations of Thermal Properties of Hydrogen in its Various Isotopic and Ortho-Para Modifications," Journal of Research of National Bureau of Standards, 41, 379 (1948).

D. PRESSURE - VOLUME - TEMPERATURE RELATIONS FOR HYDROGEN* GAS

1. Density and Specific Volume of Saturated Vapor

Graphical Representation

For accuracy within 1%, if the temperature does not exceed 300°K and the pressure 100 atm, use the accompanying graphs (Figures 12,13) of Z = -(T, P),

---

[*] Normal or any ortho-para composition.

where $Z = \frac{PV}{RT}$

If

P = atm

V = ft^3/lb

T = °K

$R = 0.6526 \frac{atm\text{-}ft^3}{°K\text{-}lb}$

Analytical Representation

Beattie-Bridgeman equation:

$$P = \frac{RT}{V^2}\left(1 - \frac{c}{VT^3}\right)\left[V + B_o\left(1 - \frac{b}{V}\right)\right] - \frac{A_o}{V^2}\left(1 - \frac{a}{V}\right)$$

where:

P = pressure, atm

$R = 0.08206 \frac{liter\text{-}atm}{g\text{-}mole\text{-}°K}$

T = temperature, °K

V = specific volume, liters/g-mole

A_o, a, B_o, b, and c are constants whose values can be determined from the following table:

	A_o	a	B_o	b	$c \times 10^{-4}$
$P < 100$ atm; $T < 600$°K	0.1975	-0.00506	0.02096	-0.04359	0.0504
$P < 1000$ atm; $200°K < T < 700°K$ $\rho < 1.88\ lb/ft^3$ *	0.1240	0.05618	0.02022	-0.00722	2.00
$P < 1000$ atm; $200°K < T < 700°K$ $\rho > 1.88\ lb/ft^3$ *	0.1240	0.05618	0.01750	-0.01968	2.00

---

* The critical density is 188 lb/ft^3.

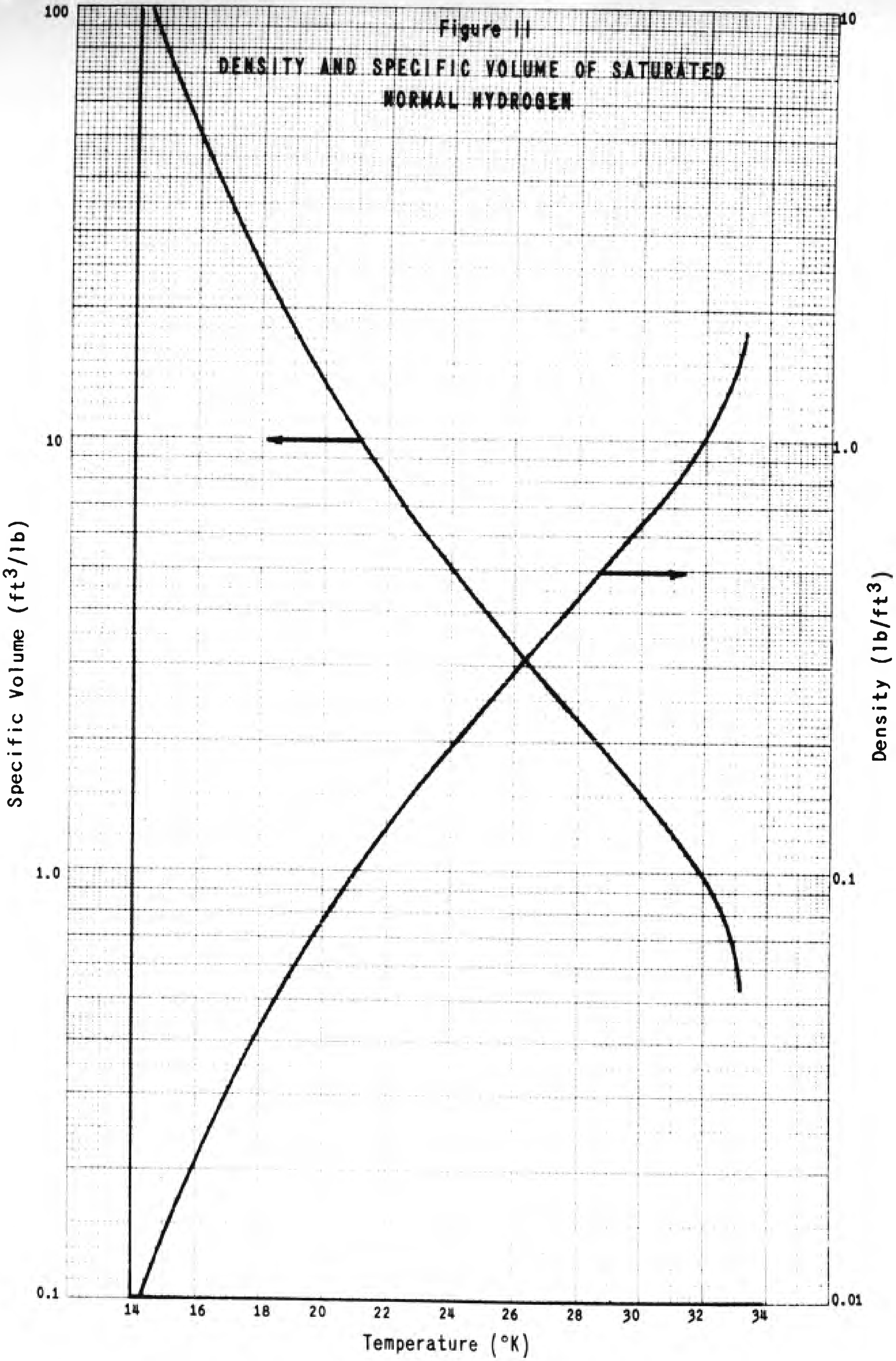


Figure 11

DENSITY AND SPECIFIC VOLUME OF SATURATED NORMAL HYDROGEN

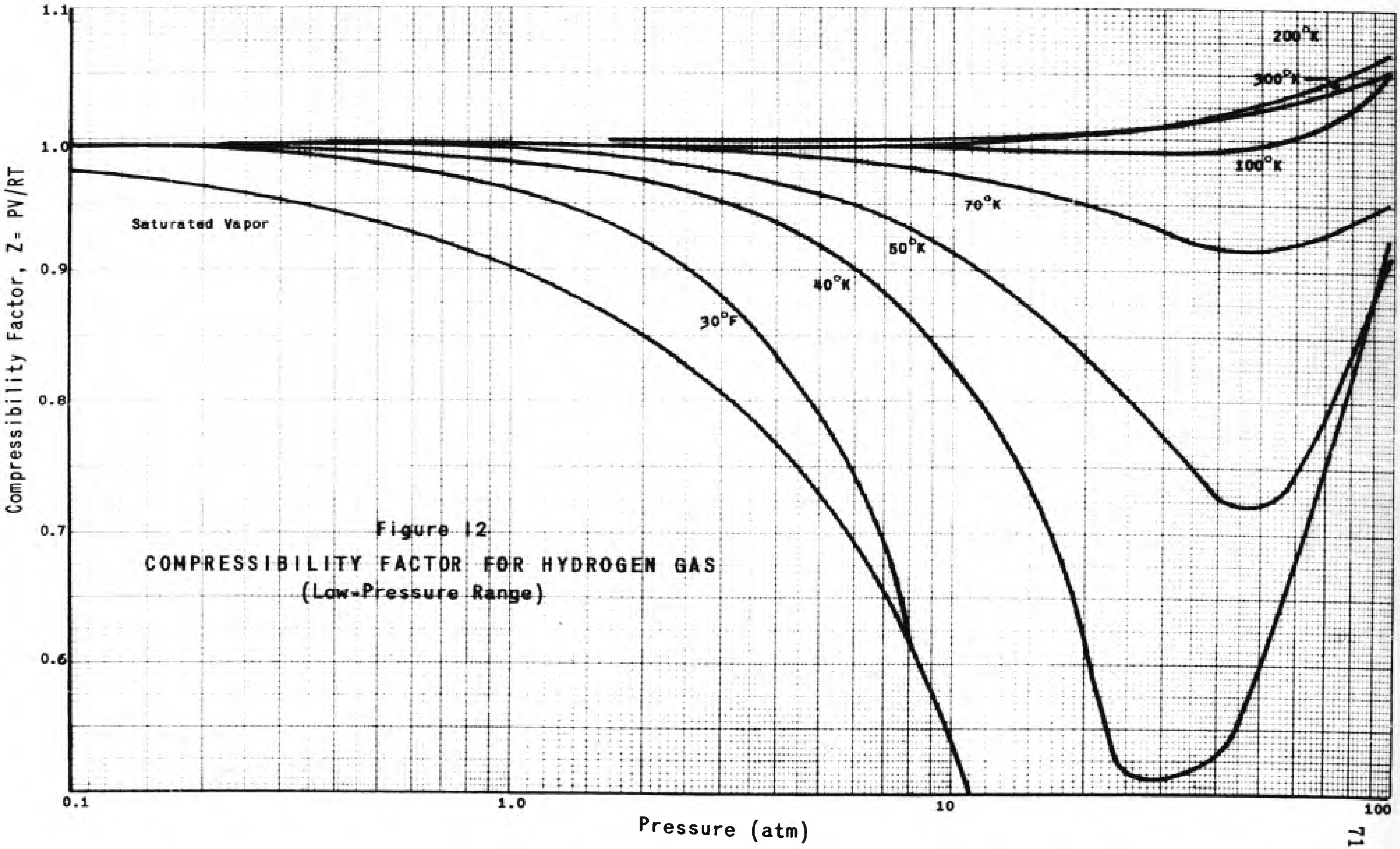
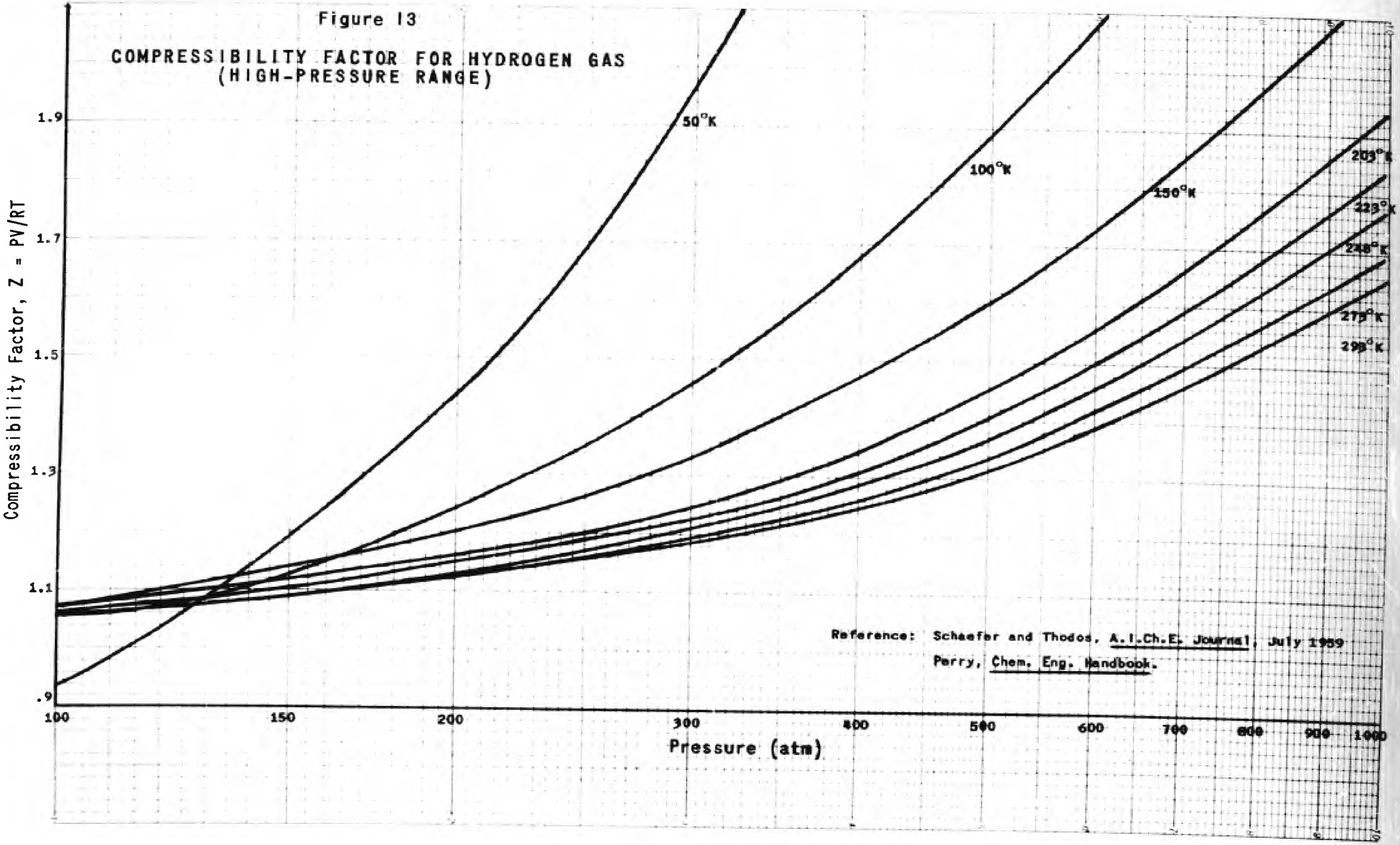


Figure 12
COMPRESSIBILITY FACTOR FOR HYDROGEN GAS
(Low-Pressure Range)

Figure 13

COMPRESSIBILITY FACTOR FOR HYDROGEN GAS
(HIGH-PRESSURE RANGE)



Reference: Schaefer and Thodos, A.I.Ch.E. Journal, July 1959
Perry, Chem. Eng. Handbook.

For specific volume given in cubic feet per pound, the Beattie-Bridgeman equation can be used if a value of 0.6526 $\frac{\text{atm-ft}^3}{\text{lb-°K}}$ is used for R, and if the values of the constants in the above table are revised as follows: Multiply A_o by 63.5; Multiply a, B_o, b, and c by 7.97.

References: Beattie, J. A., O. C. Bridgeman, Proceedings of the American Academy of Arts and Science, 63, 229 (1928).

Deming, W. E., L. G. Shupe, Journal of American Chemical Society, 53, 843 (1931).

Hilsenrath, J., *et al.*, Tables of Thermal Properties of Gases, U. S. Dept. of Commerce, National Bureau of Standards, Circular 564, U. S. Government Printing Office, Washington, D. C., November 1, 1955.

Holley, C. E., W. J. Worlton, and R. K. Zeigler, "Compressibility Factors and Fugacity Coefficients Calculated from the Beattie-Bridgeman Equation of State for Hydrogen, Nitrogen, Oxygen, Carbon Dioxide, Ammonia, Methane, and Helium," LA-2271, March 17, 1959.

Johnston, H. L., and D. White, Transactions of the American Society of Mechanical Engineers, 72, 785 (1950).

Woolley, H. W., R. B. Scott, and F. G. Brickwedde, "Compilations of Thermal Properties of Hydrogen in its Various Isotopic and Ortho-Para Modifications," Journal of Research of National Bureau of Standards, 41, 379 (1948).

2. Compressibility Factor of Normal Hydrogen

See tabulation on page 74.

Temperature (°K)	Temperature (°R)	0.01 atm	0.1 atm	1 atm	4 atm	7 atm	10 atm	40 atm	70 atm	100 atm	150 atm	200 atm
20	36	.9991	.9909									
30	54	.9997	.9967	.9662								
40	72	.9998	.9985	.9845	.9362	.8853	.8317					
50	90	.9999	.9992	.9919	.9675	.9431	.9186			.9264		
60	108	1.0000	.9995	.9955	.9822	.9691	.9564	.8757	.8700	.9395	1.1982	1.4669
70	126	1.0000	.9997	.9975	.9901	.9830	.9760	.9338	.9361	.9831		
80	144	1.0000	.9999	.9986	.9946	.9908	.9872	.9682	.9782	1.0174		
90	162		.9999	.9993	.9973	.9956	.9940	.9894	1.0050	1.0407		
100	180		1.0000	.9998	.9992	.9987	.9983	1.0029	1.0222	1.0560		
110	198		1.0000	1.0001	1.0001	1.0005	1.0011	1.0117	1.0332	1.0663	1.1330	1.2279
120	216			1.0003	1.0012	1.0021	1.0030	1.0176	1.0405	1.0726		
130	234			1.0004	1.0016	1.0029	1.0043	1.0216	1.0457	1.0765		
140	252			1.0005	1.0020	1.0036	1.0052	1.0243	1.0488	1.0786		
150	270			1.0006	1.0024	1.0041	1.0058	1.0260	1.0507	1.0796		
160	288			1.0005	1.0024	1.0043	1.0062	1.0271	1.0516	1.0798	1.3258	1.1928
170	306			1.0006	1.0025	1.0044	1.0065	1.0279	1.0522	1.0794		
180	324			1.0007	1.0028	1.0048	1.0067	1.0283	1.0523	1.0785		
190	342			1.0007	1.0028	1.0048	1.0068	1.0284	1.0519	1.0773		
200	360			1.0007	1.0028	1.0048	1.0068	1.0283	1.0513	1.0760		
210	378			1.0007	1.0028	1.0048	1.0068	1.0281	1.0506	1.0745	1.1195	
220	396			1.0007	1.0028	1.0048	1.0067	1.0276	1.0497	1.0730		
230	414			1.0007	1.0028	1.0048	1.0067	1.0274	1.0489	1.0714		
240	432			1.0007	1.0027	1.0047	1.0066	1.0269	1.0480	1.0698		
250	450			1.0006	1.0025	1.0044	1.0065	1.0264	1.0469	1.0682		
260	468			1.0006	1.0024	1.0044	1.0064	1.0259	1.0459	1.0667	1.0929	2.1425
270	486			1.0006	1.0024	1.0043	1.0063	1.0255	1.0450	1.0651		
280	504			1.0006	1.0024	1.0042	1.0061	1.0247	1.0439	1.0636		
290	522			1.0006	1.0024	1.0042	1.0060	1.0242	1.0429	1.0621		
300	540			1.0006	1.0024	1.0042	1.0059	1.0238	1.0420	1.0607	1.0929	1.1426

E. SPECIFIC HEATS

1. Heat Capacity of Liquid and Solid Under Saturation Pressure

See Figure 14. Data plotted represent compositions ranging between pure para and pure ortho. The differences in heat capacity between the forms are less than the experimental scatter.

References: Gutsche, H., Z. Physik Chemistry, A184, 45 (1939).

Johnston, H. L., and D. White, "The Thermodynamic Properties of Liquid Normal Hydrogen Between the Boiling Point and Critical Temperature and Up to 150 Atmospheres Pressure," Q. S. U. Research Foundation, Technical Report TR-264-23, Cryogenic Laboratory, Columbus, Ohio, February 1, 1953.

Woolley, H. W., R. B. Scott, and F. G. Brickwedde, "Compilations of Thermal Properties of Hydrogen in its Various Isotope and Ortho-Para Modifications," Journal of Research of National Bureau of Standards, 41, 379 (1948).

2. Heat Capacity of Liquid Normal Hydrogen

See Figure 15.

Reference: Gutsche, H., Z. Physik Chemistry, A184, 45 (1939).

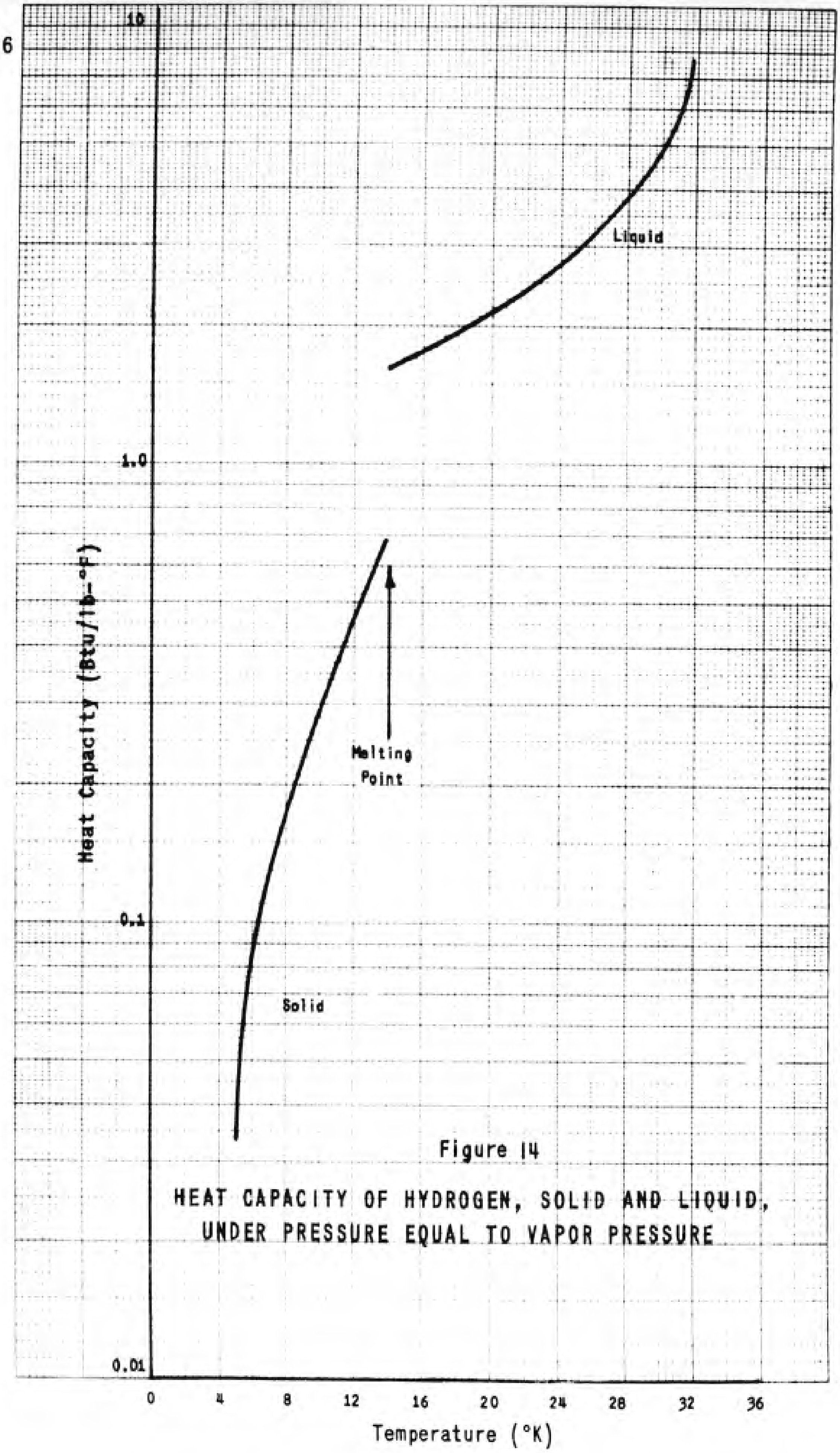


Figure 14

HEAT CAPACITY OF HYDROGEN, SOLID AND LIQUID, UNDER PRESSURE EQUAL TO VAPOR PRESSURE

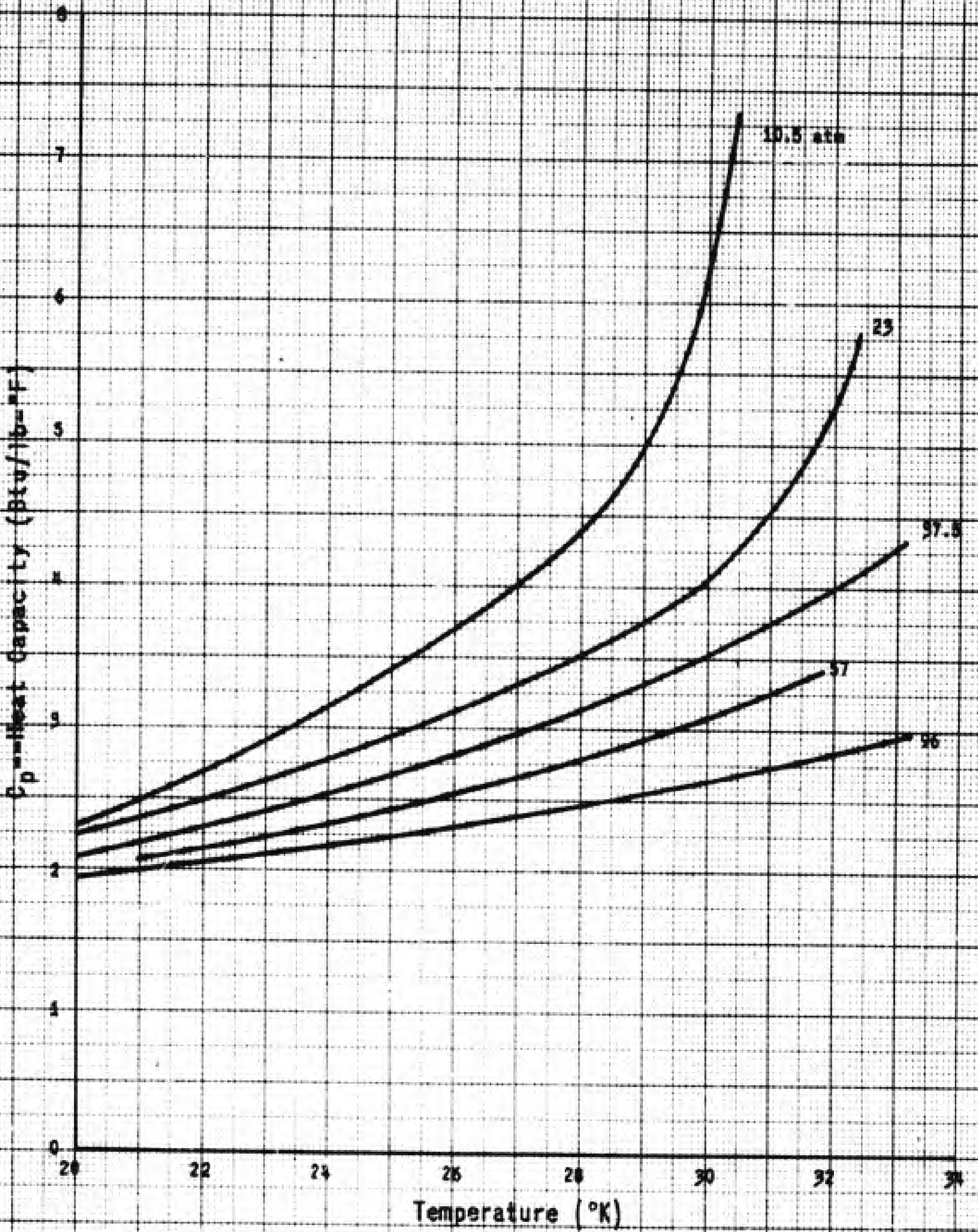


Figure 15
HEAT CAPACITY OF NORMAL LIQUID HYDROGEN

3. Heat Capacity of Hydrogen Gas (Btu/lb-°F)

Temperature (°R)	Temperature (°K)	1 atm	10 atm	100 atm
36	20	2.		
72	40	2.53	3.42	
108	60	2.51	2.74	3.90
144	80	2.57	2.69	3.52
180	100	2.68	2.75	3.25
216	120	2.82	2.86	3.20
252	140	2.96	2.98	3.22
288	160	3.07	3.10	3.28
324	180	3.16	3.18	3.33
360	200	3.24	3.25	3.37
396	220	3.30	3.31	3.41
432	240	3.34	3.35	3.44
468	260	3.38	3.38	3.46
504	280	3.40	3.42	3.47
540	300	3.42	3.43	3.48

See Figure 16.

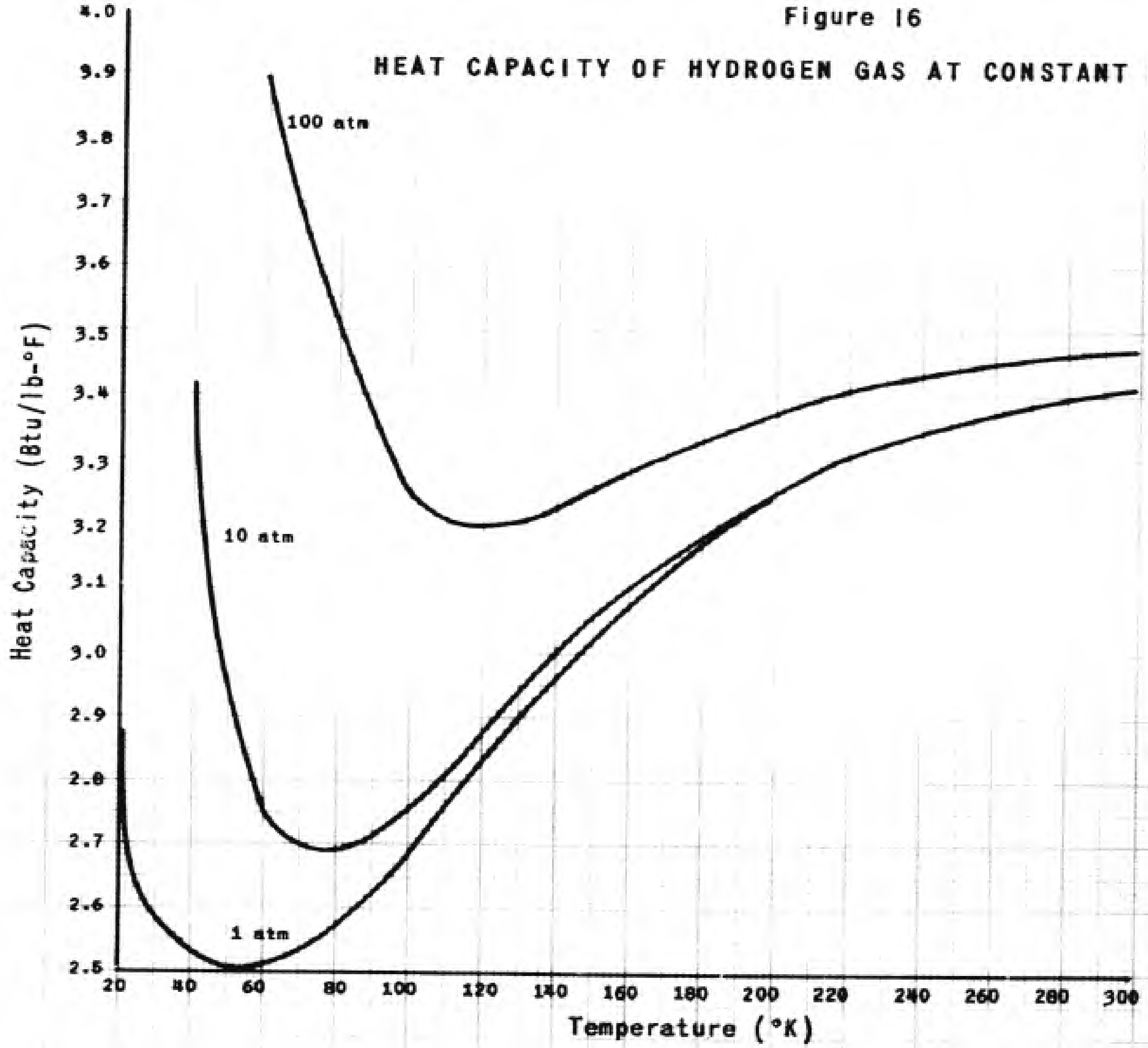
4. Ratio of Heat Capacities

See Figure 17.

Reference: Hilsenrath, J., *et al.*, *Tables of Thermal Properties of Gases*, U. S. Department of Commerce, National Bureau of Standards, Circular 564, U. S. Government Printing Office, Washington, D. C., November 1, 1955.

Figure 16

HEAT CAPACITY OF HYDROGEN GAS AT CONSTANT PRESSURE



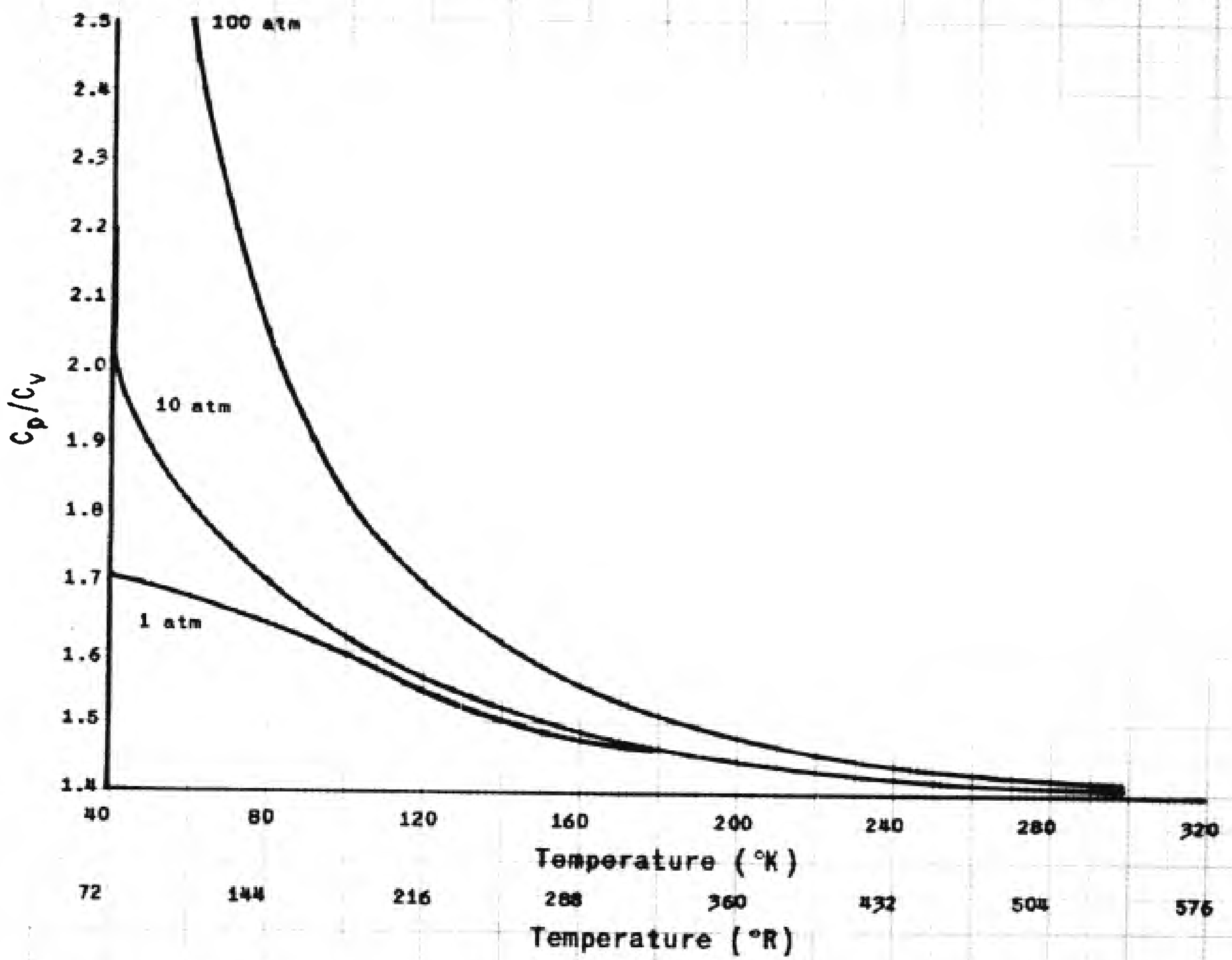


Figure 17

RATIO OF HEAT CAPACITIES OF NORMAL HYDROGEN GAS

F. LATENT HEATS

1. Heat of Fusion at Triple Point

	Temperature		Pressure		Heat of Fusion
	(°K)	(°R)	(mm of Hg)	(psia)	(Btu/lb)
Normal Hydrogen	13.95	25.11	54.0	1.04	25.0
Para Hydrogen	13.81	24.86	52.8	1.02	25.0

Reference: Woolley, H. W., R. B. Scott, and F. G. Brickwedde, "Compilations of Thermal Properties of Hydrogen in its Various Isotope and Ortho-Para Modifications," Journal of Research of National Bureau of Standards, 41, 379 (1948).

2. Heat of Vaporization of Normal Liquid Hydrogen

Temperature		Pressure		Heat of Vaporization
(°K)	(°R)	(atm)	(psia)	(Btu/lb)
20.4	36.7	1.0	14.7	195.3
22	39.6	1.559	22.91	189.9
24	43.2	2.518	37.00	181.3
26	46.8	3.824	56.20	170.3
28	50.4	5.549	81.55	155.0
29	52.2	6.593	96.89	144.9
30	54.0	7.777	114.3	132.5
31	55.8	9.120	134.0	115.9
32	57.6	10.62	156.1	91.3
32.5	58.5			72.0
33	59.4			36.0
33.1	59.6			30.0
33.2	59.7	12.8	188.0	0

See Figure 18.

References: Chelton, D. B., and D. B. Mann, Cryogenic Data Book, University of California Radiation Laboratory, Berkeley, California, UCRL-3421, May 15, 1956.

White, D., A. S. Friedman, and H. L. Johnston, Journal of American Chemical Society, 72, 3927 (1950).

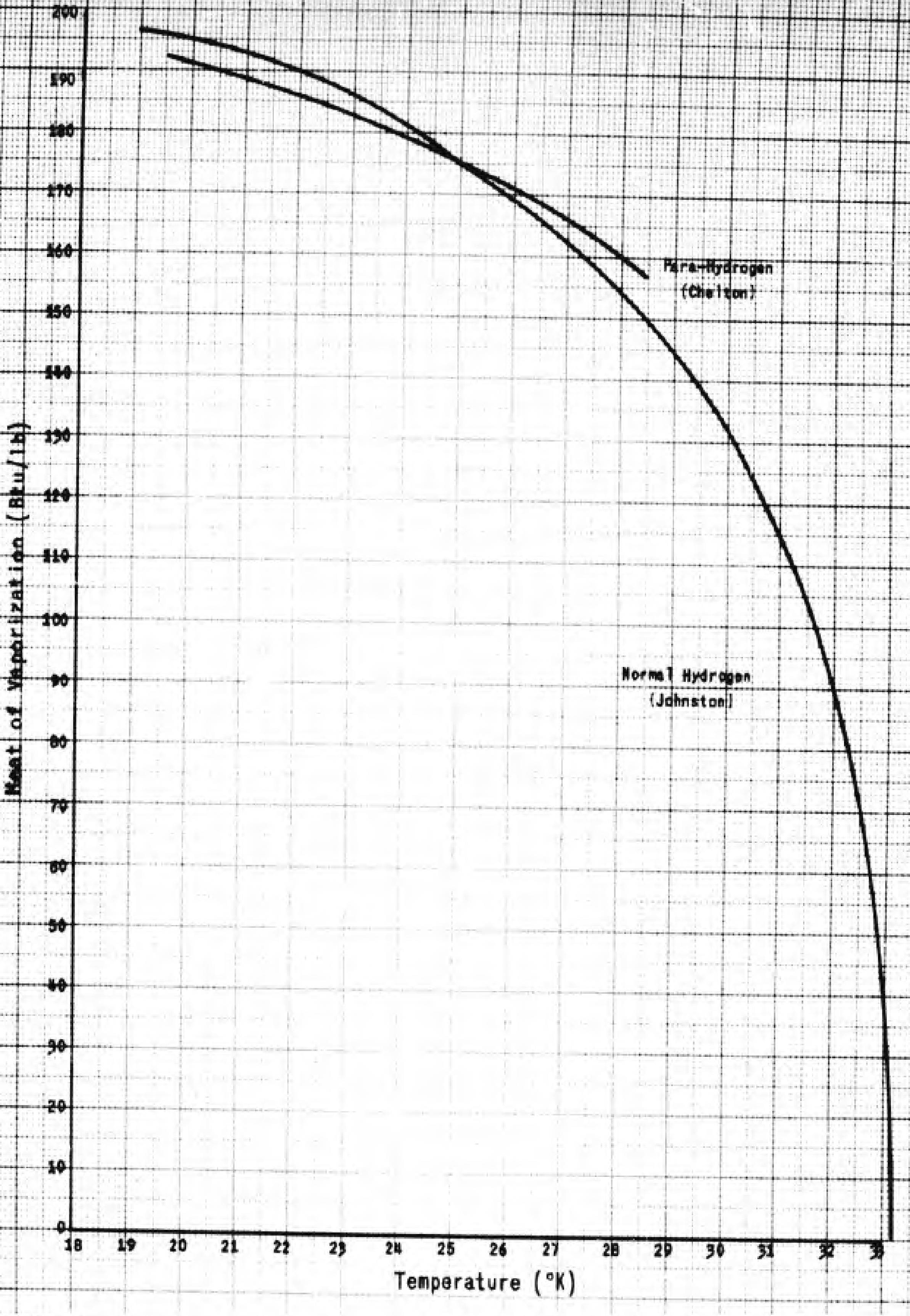


Figure 18

HEAT OF VAPORIZATION OF HYDROGEN

3. Ortho-Para Transitions

The heat of transition of 1 lb of liquid ortho-hydrogen to liquid para-hydrogen under equilibrium conditions at its boiling point (20.4°K) is 302 Btu/lb.

See Figure 19.

References: Chelton, D. B., and D. B. Mann, Cryogenic Data Book, University of California Radiation Laboratory, Berkeley, California UCRL-30421, May 15, 1956.

Coplen, H. L., J. Am. Rocket Soc., 22, 309 (1952).

G. THERMODYNAMIC PROPERTIES

1. Enthalpy and Entropy of Saturated Normal Hydrogen

P (atm)	T (°K)	Enthalpy (Btu/lb) L	Enthalpy (Btu/lb) G	Entropy (Btu/lb-°F) L	Entropy (Btu/lb-°F) G
.92	20	86.0	282.3	2.05	7.51
1.0	20.4	88.1	283.4	2.11	7.43
1.19	21	90.4	284.4	2.17	7.33
1.56	22	94.8	284.8	2.28	7.07
2.00	23	99.5	285.3	2.40	6.88
2.52	24	104.9	285.9	2.51	6.70
3.12	25	110.7	286.8	2.64	6.56
3.82	26	116.9	287.1	2.76	6.40
4.63	27	123.6	286.9	2.89	6.25
5.55	28	131.0	286.0	3.03	6.11
6.59	29	139.1	284.6	3.17	5.95
7.78	30	148.1	280.8	3.33	5.78
9.12	31	157.8	273.3	3.50	5.57
12.8	33.25	250.2	250.2	4.59	4.59

See Figure 20.

References: Chelton, D. B., and D. B. Mann, Cryogenic Data Book, University of California Radiation Laboratory, Berkeley, California, UCRL-3421, May 15, 1956.

Moore, R., private communication, Arthur D. Little, Inc.

White, D., A. S. Friedman, and H. L. Johnston, J. Am Chem. Soc., 72, 3927 (1950).

Woolley, H. W., R. B. Scott, and F. G. Brickwedde, Journal of Research of National Bureau of Standards, 41, 379 (1948).

2. Enthalpy of Liquid Hydrogen (in Btu/lb)

P (atm)	20°K	23°K	26°K	29°K	33°K
10	90	102	118	139	247
30	99	110	124	140	240
50	108	118	131	146	242
70	117	127	140	154	248
100	131	140	152	165	259
120	140	149	161	172	267
150	154	162	174	185	279

See Figure 21.

Reference: Johnston, H. L., and D. White, The Thermodynamic Properties of Liquid Normal Hydrogen Between the Boiling Point and Critical Temperature and Up to 150 Atmospheres Pressure, O. S. U. Research Foundation, Technical Report TR-264-18, Cryogenic Laboratory, Columbus, Ohio, May 15, 1952.

3. Entropy of Liquid Hydrogen (in Btu/lb-°F)

P (atm)	20°K	23°K	26°K	29°K	33°K
10	2.00	2.34	2.70	3.10	
30	1.92	2.24	2.54	2.87	4.09
50	1.85	2.15	2.43	2.73	3.88
70	1.79	2.08	2.35	2.63	3.74
100	1.72	1.99	2.25	2.50	3.60
120	1.68	1.94	2.19	2.43	3.53
150	1.62	1.87	2.10	2.35	3.44

See Figure 21.

Reference: Johnston, H. L., and D. White, The Thermodynamic Properties of Liquid Normal Hydrogen Between the Boiling Point and Critical Temperature and Up to 150 Atmospheres Pressure, O. S. U. Research Foundation, Technical Report TR-264-18, Cryogenic Laboratory, Columbus, Ohio, May 15, 1952.

4. Enthalpy of Normal Hydrogen (in Btu/lb)

See tabulation on page 86.

Temperature (°K)	Temperature (°R)	0.01 atm	1 atm	10 atm	20 atm	30 atm	40 atm	50 atm	60 atm	70 atm	80 atm	90 atm	100 atm	150 atm	200 atm
60	108	492	491	476											
70	126	538	535	525	510	497	485	475	467	460	455	451	447	442	450
80	144	583	582	573	561	552	542	534	527	521	516	512	509	502	506
90	162	630	628	622	614	607	600	594	589	584	579	576	573	565	569
100	180	675	675	671											
110	198	726	726	721											
120	216	776	776	772	769	776	763	760	757	755	753	751	749	747	751
130	234	826	826	824											
140	252	879	879	877	374	872	870	869	867	866	865	865	863	863	868
150	270	933	933	931											
160	288	986	986	984	983	982	981	981	980	980	979	979	979	981	987
170	306	1041	1041	1040											
180	324	1100	1100	1100	1099	1099	1099	1099	1099	1099	1099	1099	1099	1105	1114
190	344	1157	1157	1157	1156	1156	1156	1156	1155	1155	1154	1154	1153	1148	1141
200	360	1214	1214	1214	1213	1213	1213	1212	1211	1211	1210	1209	1208	1202	1196
210	378	1272	1272	1272	1271	1270	1270	1269	1268	1267	1267	1266	1264	1258	1250
220	396	1331	1331	1331											
230	414	1390	1390	1390	1388	1387	1386	1385	1384	1383	1381	1380	1379	1371	1360
240	432	1450	1450	1450	1447	1446	1445	1443	1442	1441	1439	1438	1436	1427	1417
250	450	1511	1511	1511											
260	468	1571	1571	1571											
270	486	1631	1631	1631											
280	504	1692	1692	1692											
290	522	1755	1755	1756											
300	540	1818	1818	1819	1814	1811	1809	1807	1805	1803	1801	1799	1796	1786	1774

See Figures 22-24.

References. Hilsenrath, J., et al., Tables of Thermal Properties of Gases, U.S. Department of Commerce, National Bureau of Standards, Circular 564, U.S. Government Printing Office, Washington, D.C., November 1, 1955.

Johnston, H.L., D. White, and P. Camky, O.S.U. Research Foundation, Technical Report TR-264-18, Cryogenic Laboratory, Columbus, Ohio, May 15, 1952.

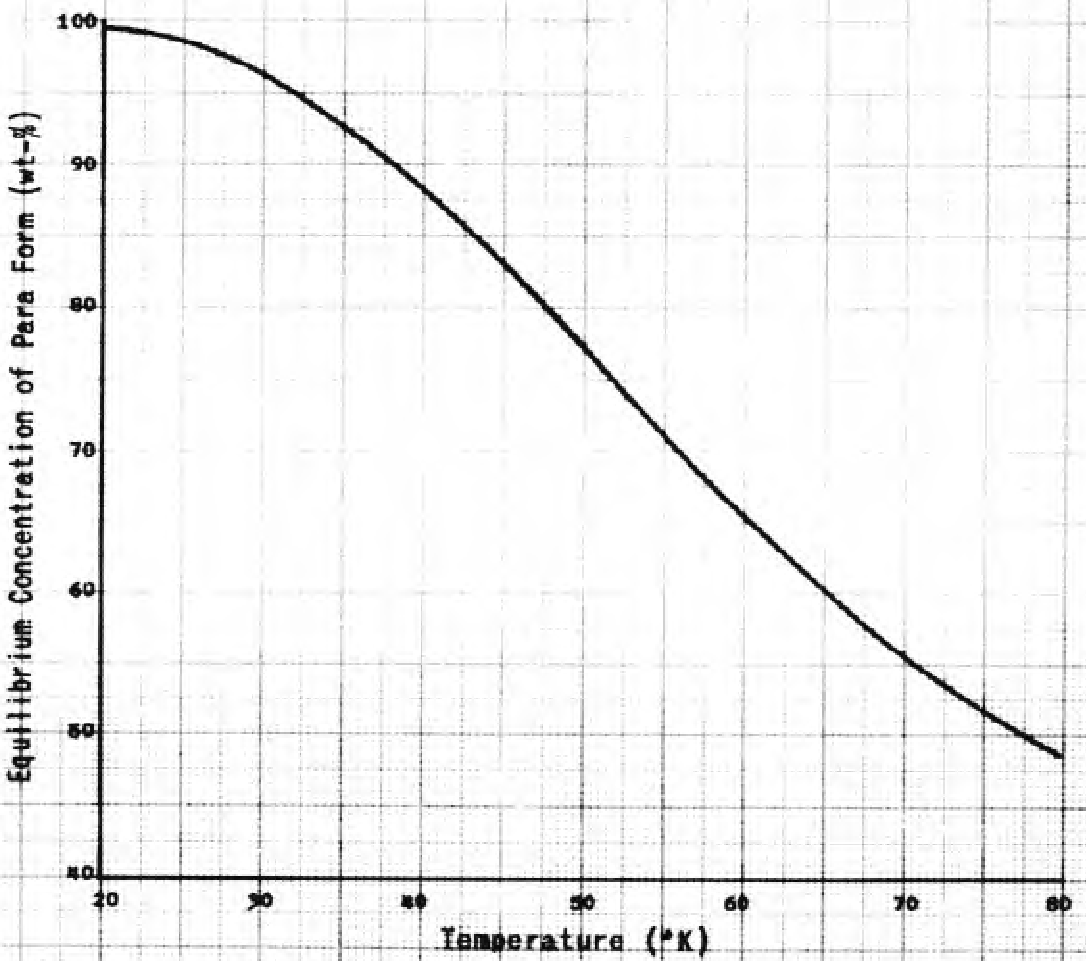


Figure 19

ORTHO-PARA CONCENTRATION OF HYDROGEN AT EQUILIBRIUM

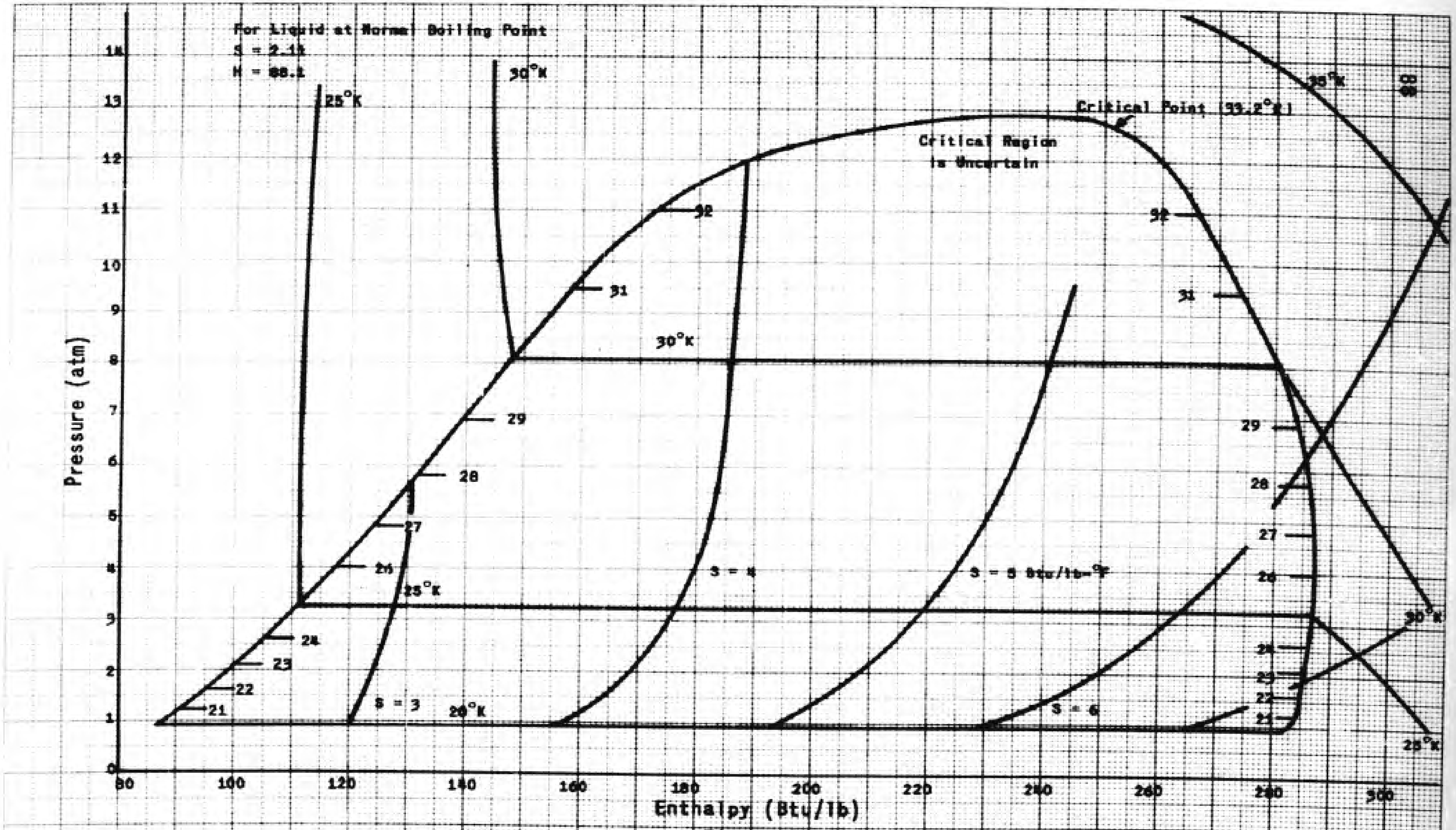


Figure 20
PRESSURE VS ENTHALPY OF NORMAL HYDROGEN

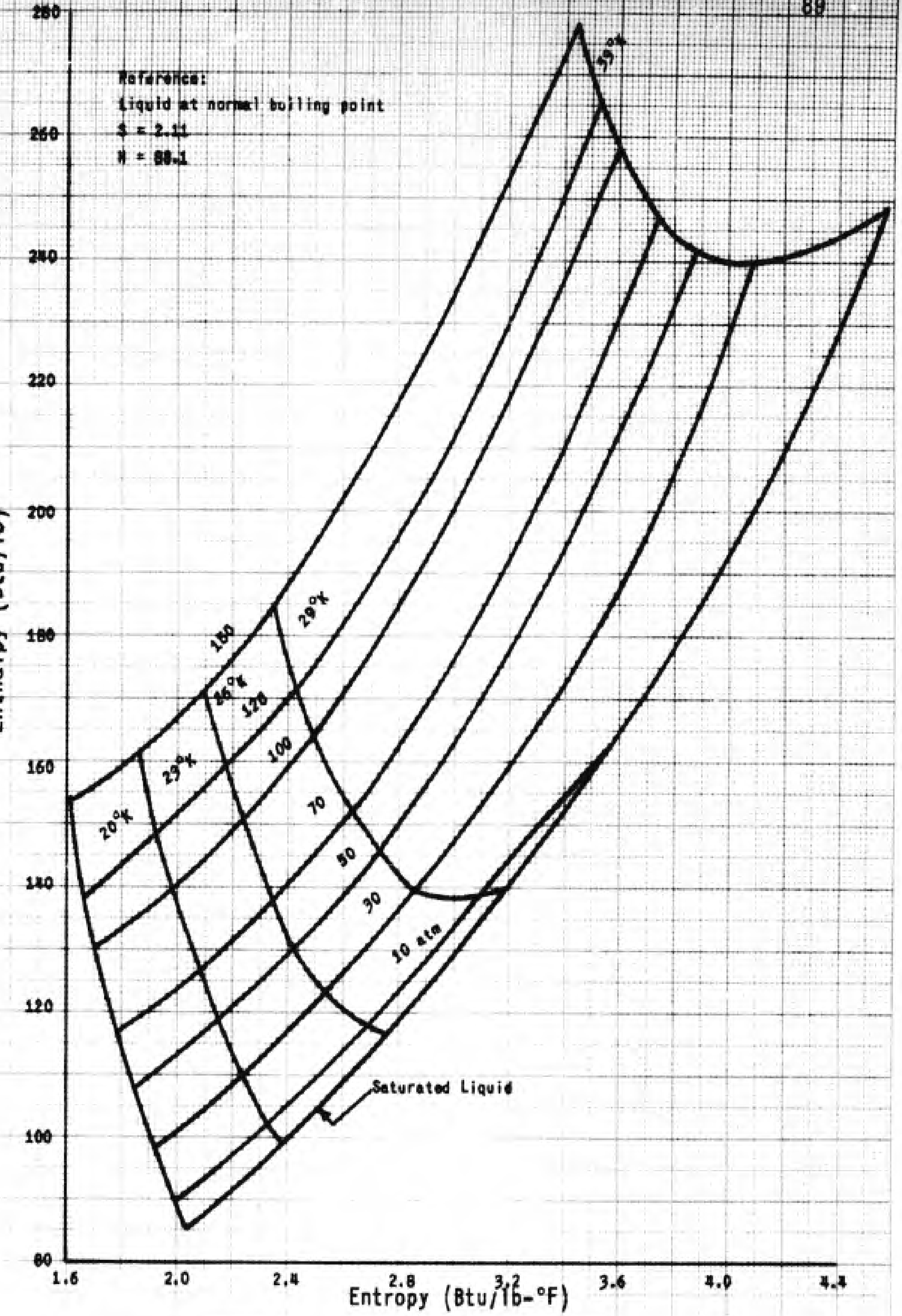


Figure 21

ENTHALPY-ENTROPY FOR NORMAL LIQUID HYDROGEN

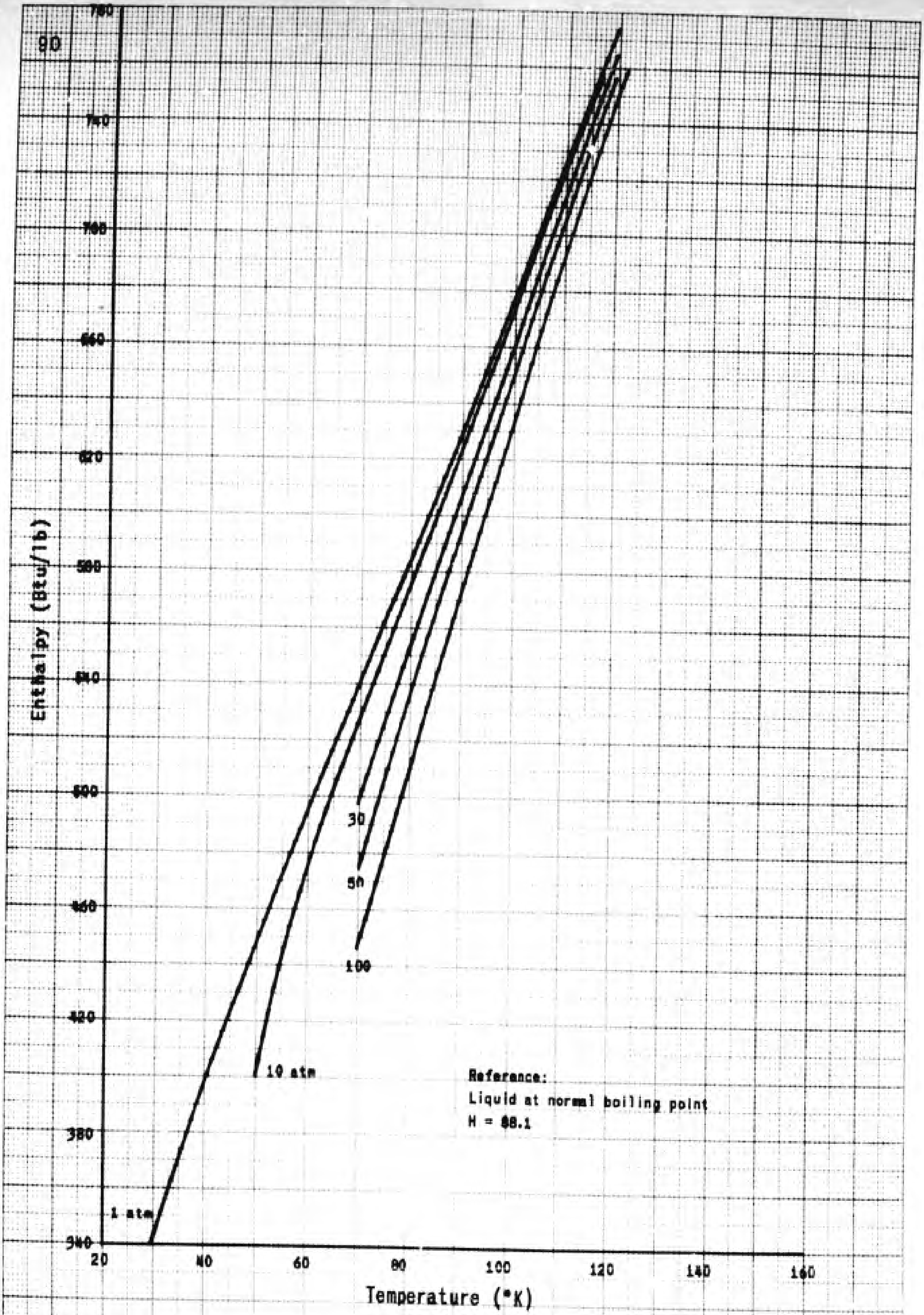


Figure 22

ENTHALPY OF NORMAL HYDROGEN FOR TEMPERATURES FROM 30 TO 120°K AND PRESSURES FROM 1 TO 100 ATM

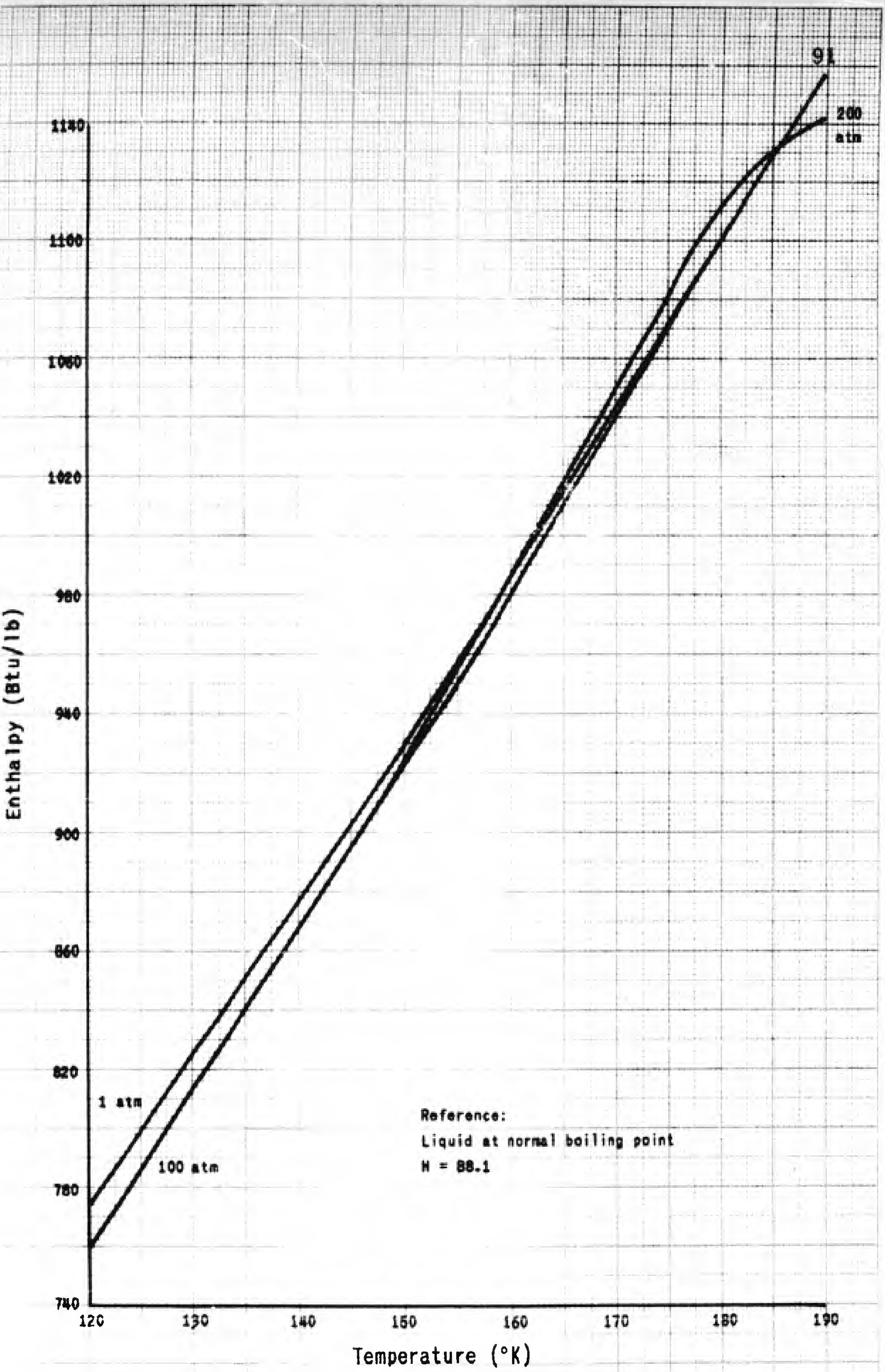
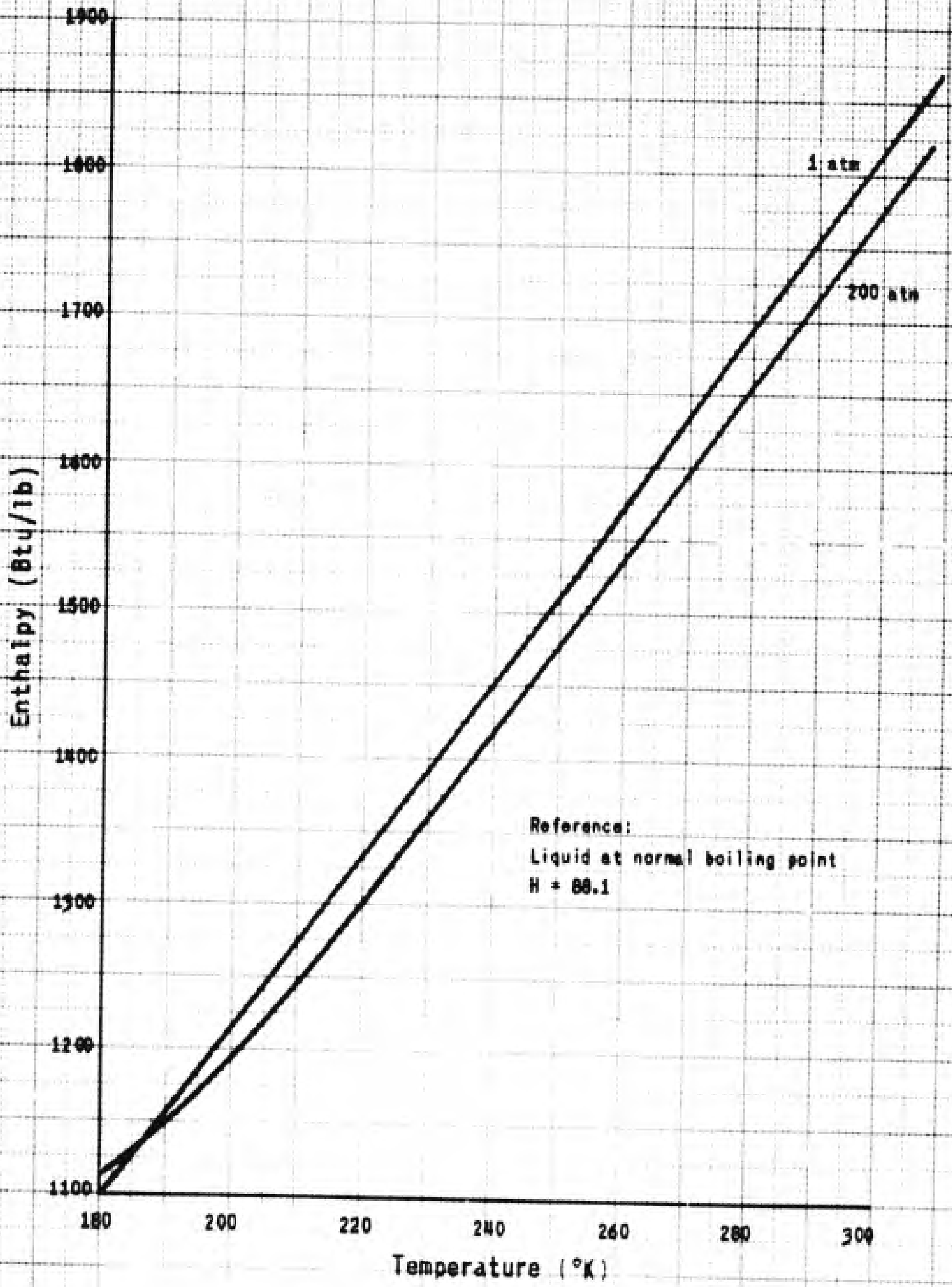


Figure 23

ENTHALPY OF NORMAL HYDROGEN FOR TEMPERATURES FROM 120 TO 180°K AND PRESSURES FROM 1 TO 200 ATM



Reference:
Liquid at normal boiling point
H = 88.1

Figure 24
ENTHALPY OF NORMAL HYDROGEN FOR TEMPERATURES FROM 180 TO 300°K AND PRESSURES OF 1 AND 200 ATM

5. Entropy of Normal Hydrogen (in Btu/lb-°F)

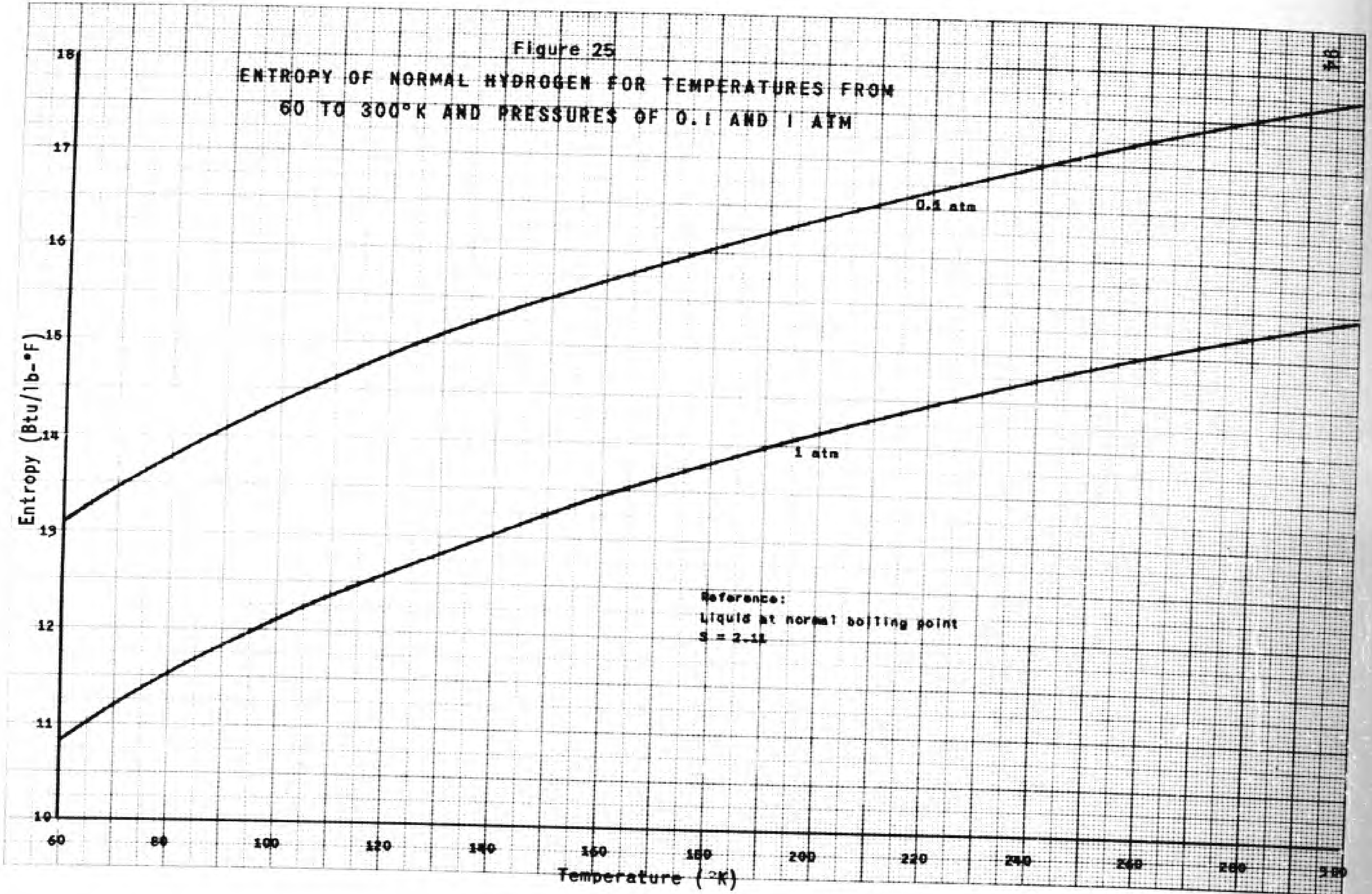
Temperature		0.1 atm	1 atm	10 atm	100 atm
(°K)	(°R)				
60	108	13.06	10.79	8.40	5.48
70	126	13.42	11.18	8.84	6.07
80	144	13.77	11.50	9.19	6.54
90	162	14.06	11.80	9.49	6.94
100	180	14.32	12.08	9.80	7.29
110	198	14.62	12.36	10.08	7.60
120	216	14.82	12.59	10.30	7.88
130	234	15.10	12.81	10.51	8.13
140	252	15.31	13.03	10.75	8.37
150	270	15.51	13.25	10.97	8.59
160	288	15.70	13.44	11.18	8.80
170	306	15.90	13.63	11.38	9.00
180	324	16.09	13.81	11.51	9.19
190	342	16.22	13.97	11.69	9.37
200	360	16.40	14.14	11.88	9.55
210	378	16.59	14.30	12.02	9.71
220	396	16.70	14.43	12.19	9.87
230	414	16.89	14.61	12.32	10.00
240	432	17.00	14.72	12.47	10.19
250	450	17.12	14.89	12.59	10.30
260	468	17.30	15.01	12.74	10.42
270	486	17.40	15.12	12.85	10.59
280	504	17.50	15.24	12.98	10.70
290	522	17.65	15.40	13.10	10.80
300	540	17.79	15.50	13.22	10.92

See Figures 25 and 26.

Reference: Hilsenrath, J., et al., Tables of Thermal Properties of Gases, U.S. Department of Commerce, National Bureau of Standards, Circular 564, U.S. Government Printing Office, Washington, D.C., November 1, 1955.

Figure 25

ENTROPY OF NORMAL HYDROGEN FOR TEMPERATURES FROM 60 TO 300°K AND PRESSURES OF 0.1 AND 1 ATM



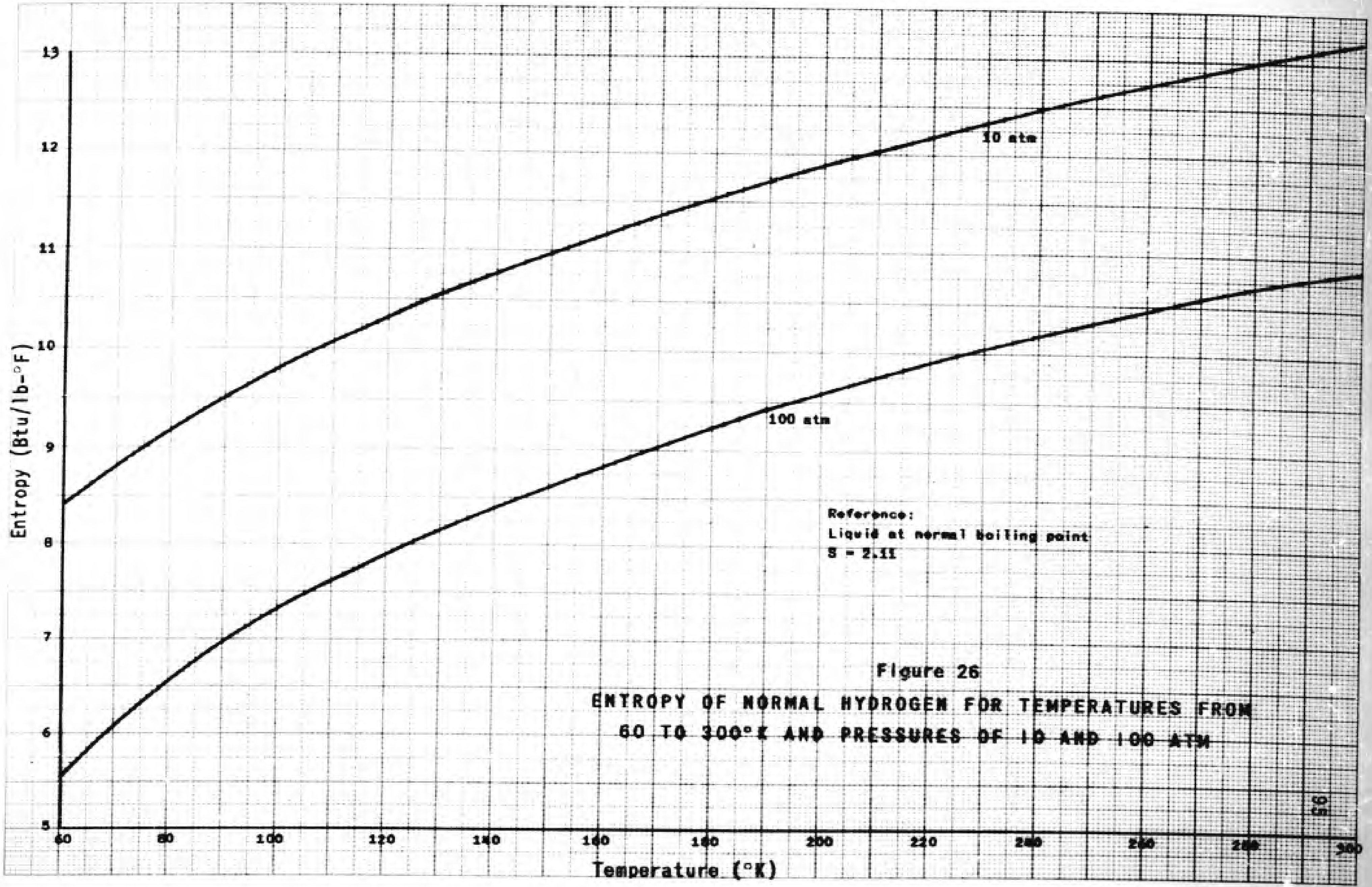


Figure 26

ENTROPY OF NORMAL HYDROGEN FOR TEMPERATURES FROM 60 TO 300°K AND PRESSURES OF 10 AND 100 ATM

H. SURFACE TENSION OF LIQUID NORMAL HYDROGEN

Surface tension in dynes/cm = $5.8[illegible] - 0.18\,T$

where T = temperature, °K

The equation is valid for the interval 15 to 25°K, and is for liquid normal hydrogen against its own vapor.

Reference: Chelton, D. B., and D. B. Mann, Cryogenic Data Book, University of California Radiation Laboratory, Berkeley, California, UCRL-3421, May 5, 1956.

I. TRANSPORT PROPERTIES

1. Viscosity of Liquid Hydrogen

See Figure 27.

Reference: Johns, H. E., "Viscosity of Liquid Hydrogen," Canadian Journal of Research, 17A, 2[illegible] (1939).

Keesom, W. H., and G. E. MacWood, "The Viscosity of Liquid Hydrogen," Physica, 5, 745 (1938).

2. Viscosity of Normal Hydrogen Gas (at 1 atm)

Temperature (°R)	Temperature (°K)	Viscosity (cp)
18	10	0.000510
90	50	0.00249
180	100	0.00421
270	150	0.00560
360	200	0.00681
450	250	0.00793
540	300	0.00896

See Figure 28.

References: Chelton, D. B., and D. B. Mann, Cryogenic Data Book, University of California Radiation Laboratory, Berkeley, California, UCRL-3421, May 15, 1956.

Hilsenrath, J., et al., Tables of Thermal Properties of Gases, U. S. Department of Commerce, National Bureau of Standards, Circular 564, U. S. Government Printing Office, Washington, D. C., November 1, 1958.

3. Thermal Conductivity of Liquid Hydrogen

$$K = .00403 + .000209T$$

where K = thermal conductivity, Btu/ft-hr-°R

T = temperature, °R

The equation is for the temperature interval of 27 to 49°R and may be used for normal and para-hydrogen. The probable accuracy is within 2%.

Reference: Johnston, H. L., R. W. Mattox, and R. W. Powers, J. Am. Chem. Soc., 76, 5972 (1954).

4. Thermal Conductivity of Normal Hydrogen Gas

Temperature (°R)	Temperature (°K)	Thermal Conductivity (Btu/ft-hr°R)
36	20	.00895
72	40	.0172
108	60	.0244
144	80	.0313
180	100	.0384
216	120	.0460
252	140	.0532
288	160	.0603
324	180	.0674
360	200	.0741
396	220	.0809
432	240	.0871
468	260	.0931
504	280	.0995
540	300	.1050

Reference: Johnston, H. L., R. W. Mattox, and R. W. Powers, J. Am. Chem. Soc., 76, 5972 (1954).

See Figure 29.

References: Hilsenrath, J., *et al.* National Bureau of Standards, Circular 564, U. S. Government Printing Office, Washington, D. C., November 1, 1958.

Schaefer, C. A., and G. Thodos, Ind. Eng. Chem., 50, 1092 (1958).

5. Diffusivity

Diffusion coefficient of normal hydrogen gas in air at 273°K:

D = 0.634 sq cm/sec

d = 2.46 ft^2/hour

Reference: Handbook of Chemistry and Physics, ed. C. D. Hodgman, 36th Edition, Chemical Rubber Publishing Company, Cleveland, Ohio, 1954.

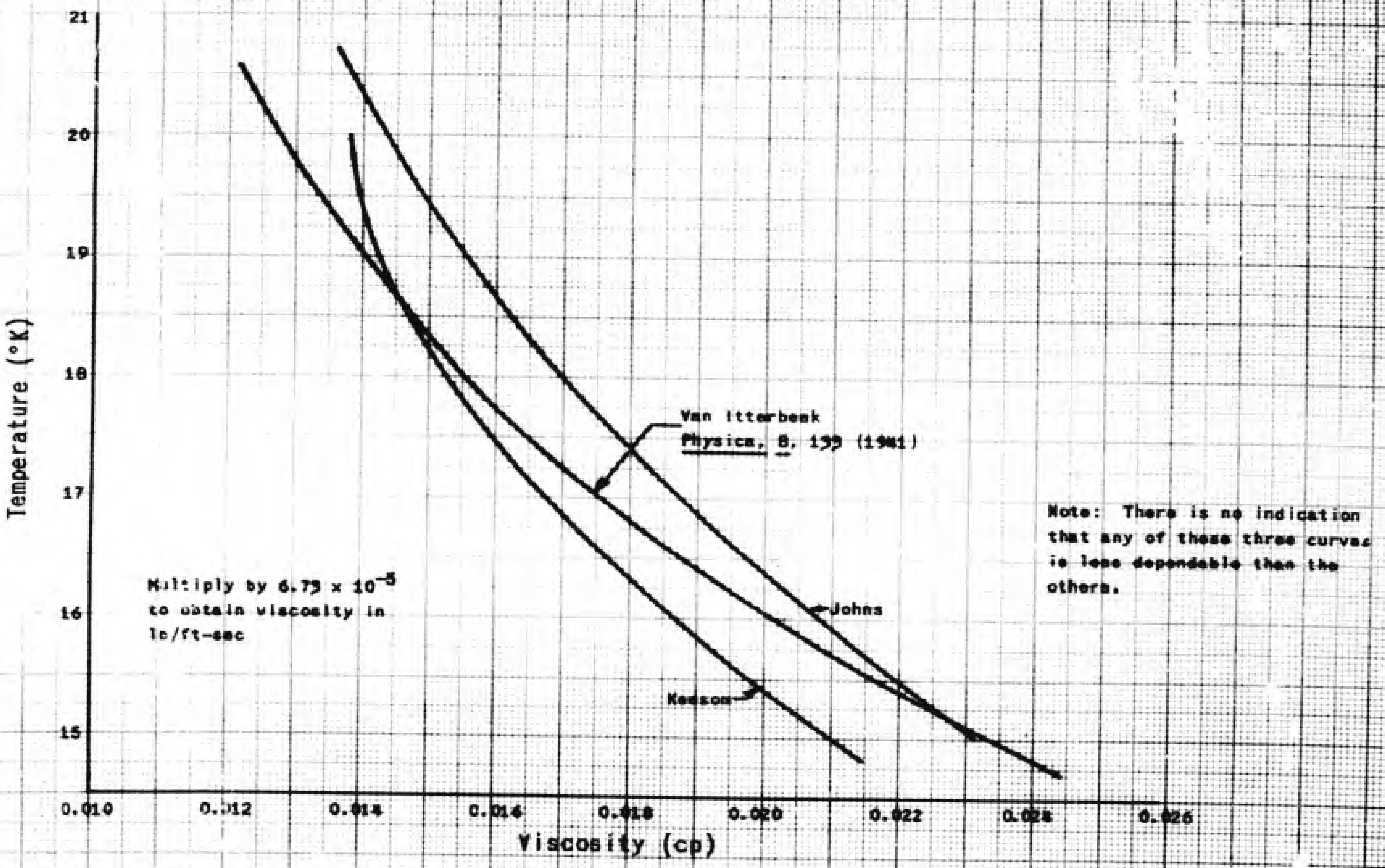
6. Self-Diffusion Coefficient of Hydrogen (at 1 atm)

Temperature (°R)	Self Diffusion Coefficient (ft^2/hr)
36.7	0315
153.	.665
492	4.91

Reference: Hirschfelder, J. O., R. B. Bird, and E. L. Spotz, Trans. ASME, 71, 926 (1949).

7. Prandtl Number of Hydrogen Gas

See Figure 30.

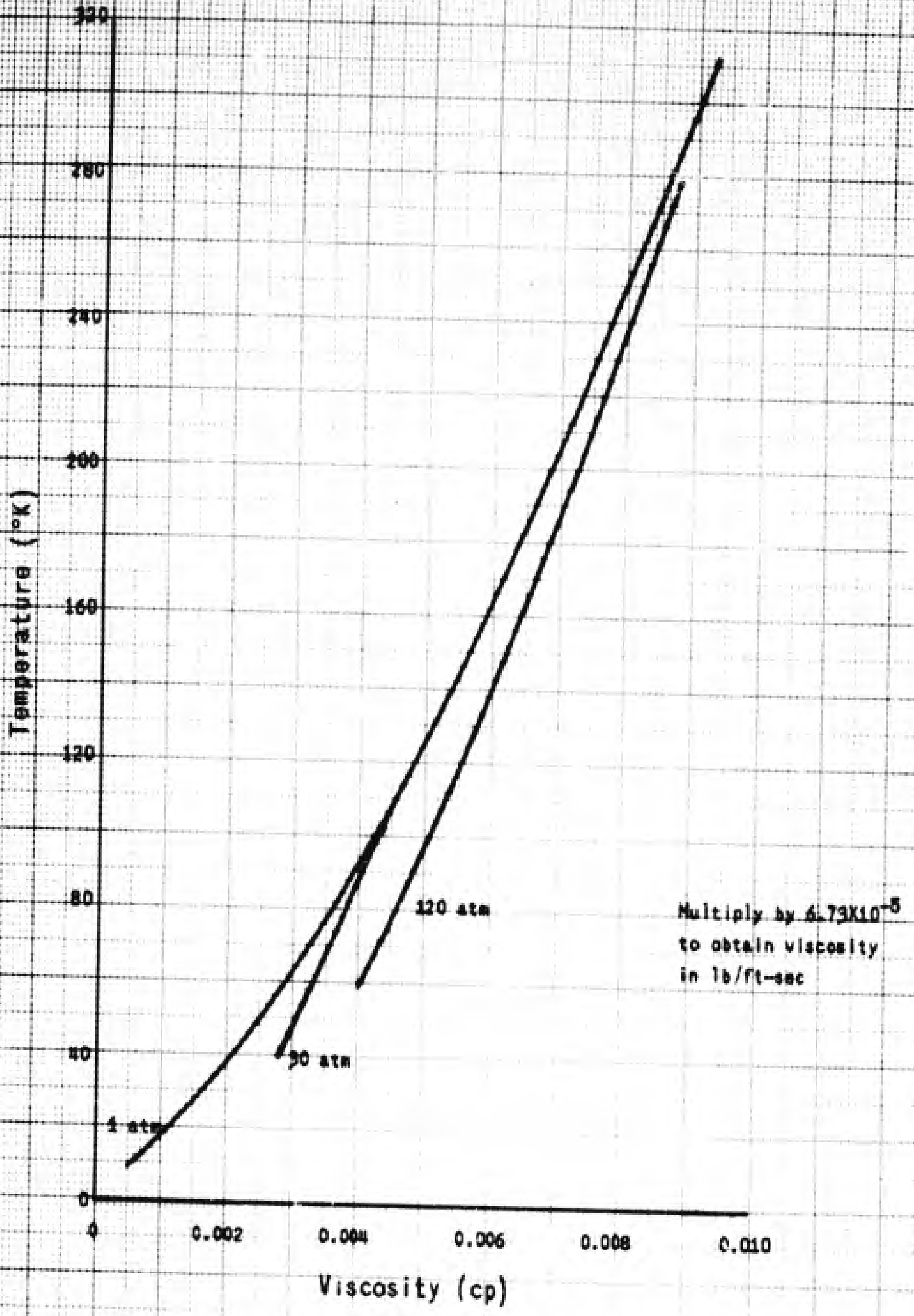


Multiply by 6.73 x 10^{-5} to obtain viscosity in lb/ft-sec

Note: There is no indication that any of these three curves is less dependable than the others.

Figure 27

VISCOSITY OF NORMAL LIQUID HYDROGEN



Multiply by 6.73×10^{-5} to obtain viscosity in lb/ft-sec

Figure 28
VISCOSITY OF HYDROGEN GAS

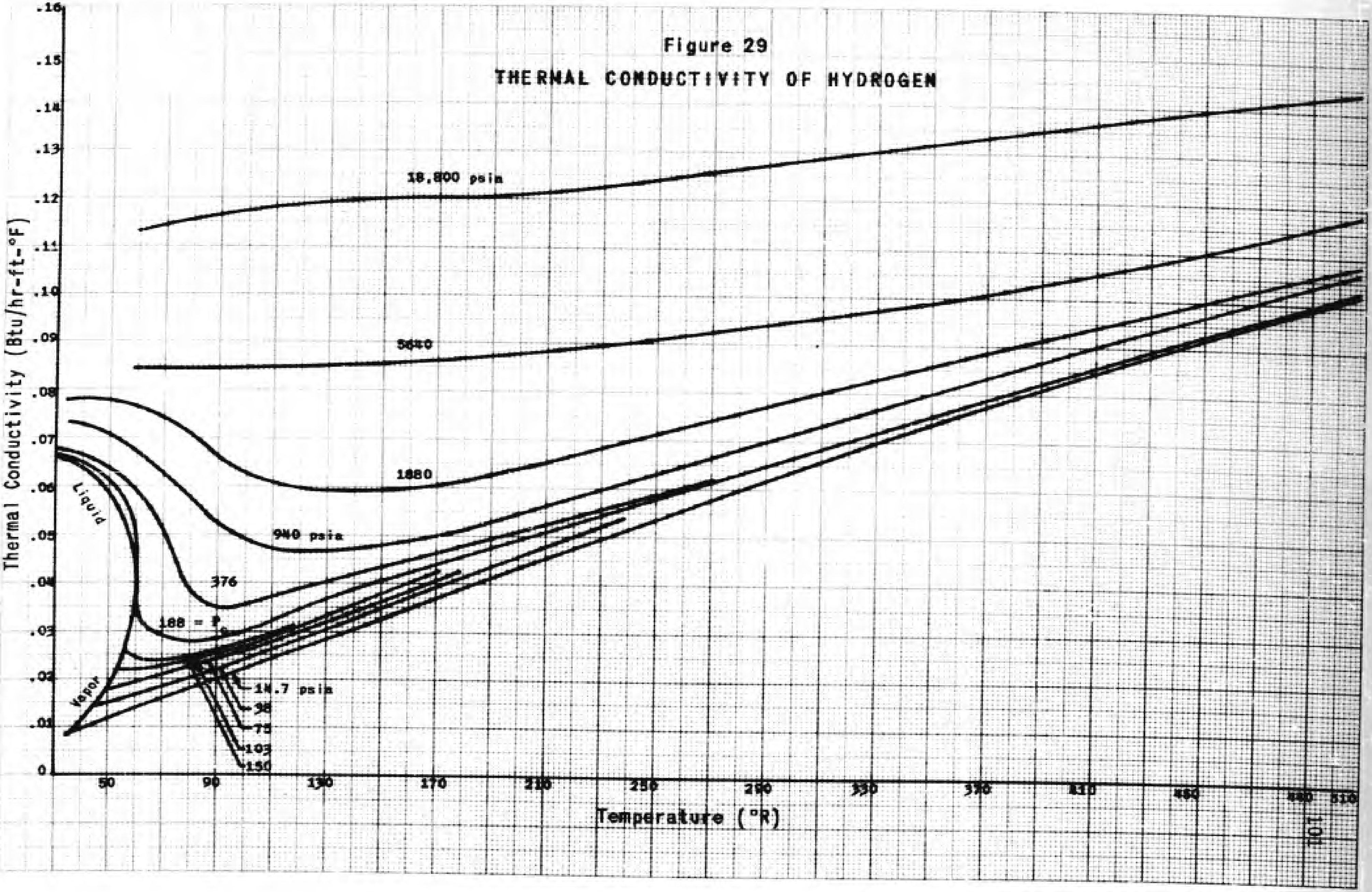


Figure 29

THERMAL CONDUCTIVITY OF HYDROGEN

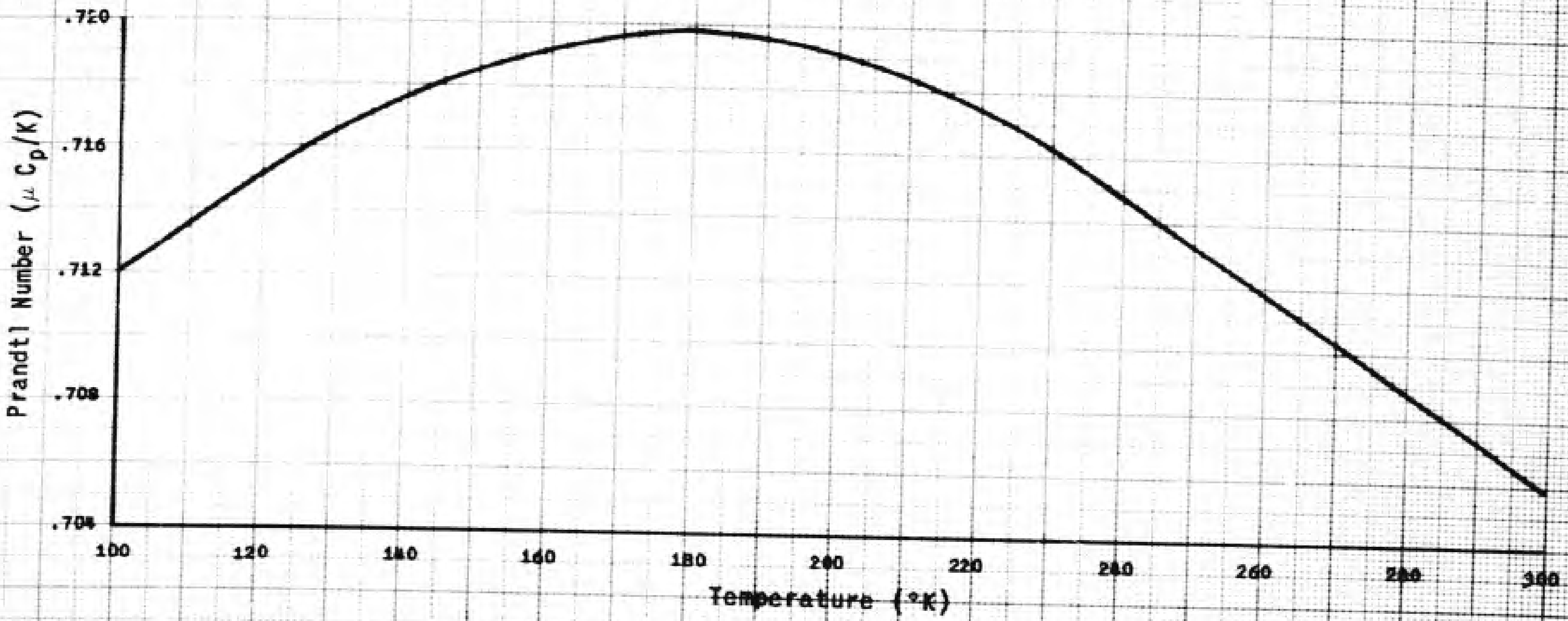


Figure 30

PRANDTL NUMBER OF NORMAL HYDROGEN GAS AT 1 ATM

J. ELECTROMAGNETIC PROPERTIES

1. Index of Refraction of Liquid Normal Hydrogen at Saturation

Temperature (°K)	Wavelength A	Refractive Index
20.39	4358	1.1142
19.56		1.1156
18.96		1.1170
17.97		1.1184
17.22		1.1199
16.01		1.1215
15.58		1.1226
14.01		1.244
20.39	5461	1.1121
19.56		1.1134
18.96		1.1148
18.00		1.1166
17.45		1.1169
17.13		1.1184
16.50		1.1187
16.02		1.1199
14.01		1.1221
20.39	6939	1.1108
19.56		1.1121

Reference: Johns, H. E., and J. O. Wilhelm, "Refractive Indexes of Liquefied Gases," Canadian Journal of Research, 15(A), 107 (1937).

2. Dielectric Constant of Liquid Normal Hydrogen

$$E = 1.296 - 0.00345\ T$$

where E = dielectric constant

T = temperature, °K

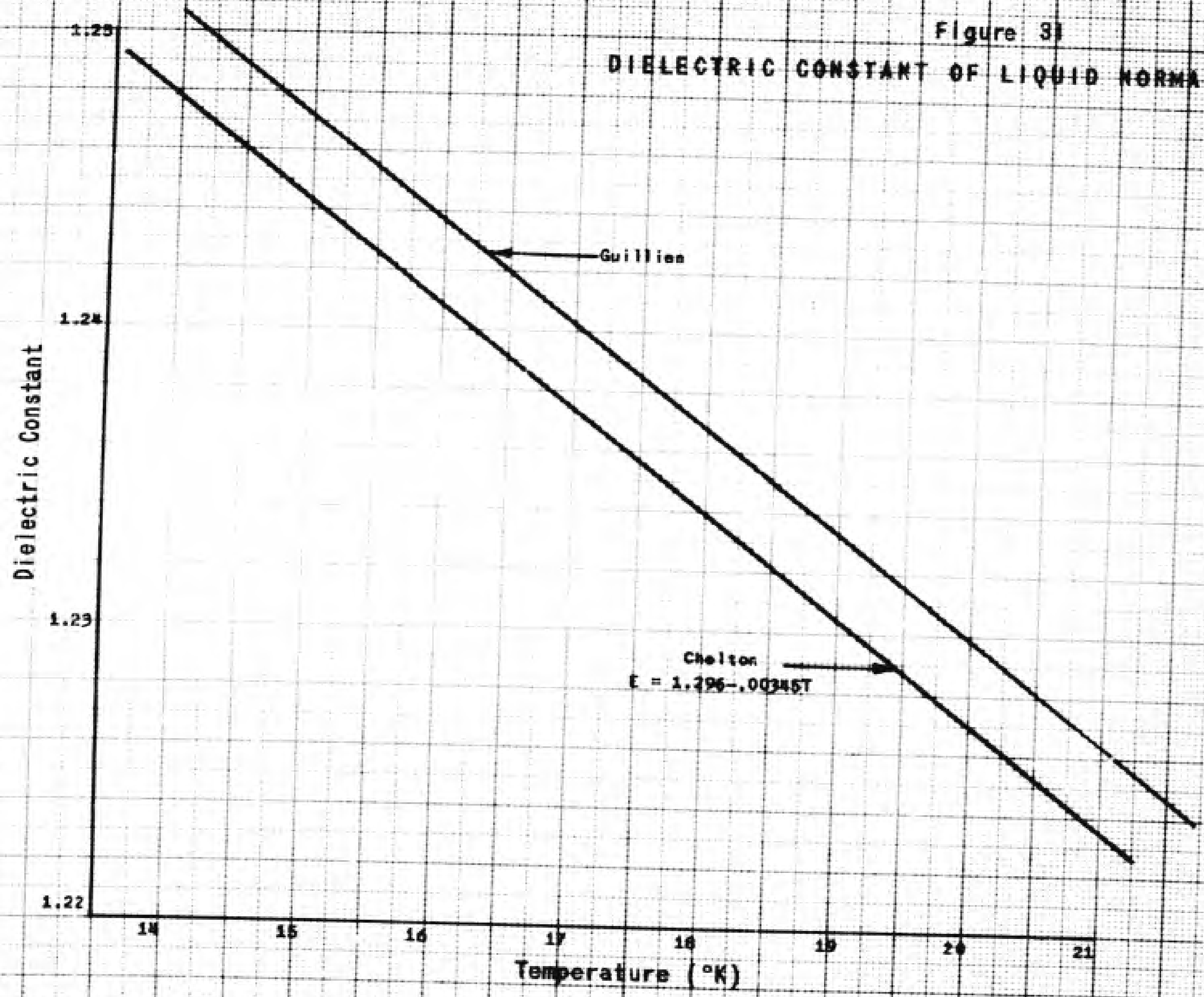
See Figure 31.

References: Chelton, D. B., and D. B. Mann, Cryogenic Data Book, University of California Radiation Laboratory, Berkeley, California, UCRL - 3421, May 15, 1956.

Guillien, R., "The Dielectric Constant of Hydrogen," Revue Scientifique, 77, 575 (1939).

Figure 31

DIELECTRIC CONSTANT OF LIQUID NORMAL HYDROGEN



3. Dielectric Constant of Normal Molecular Hydrogen Gas

At 24.92°C (76°F):

Pressure (atm)	Dielectric Constant
1.15	1.00028
7.96	1.00192
13.47	1.00324
18.95	1.00466
24.53	1.00601
30.03	1.00730
34.68	1.00843
35.52	1.00864
41.00	1.00995
46.42	1.01125
51.89	1.01252
57.36	1.01379
61.53	1.01475
88.13	1.02083
114.67	1.02668
141.36	1.03244
168.07	1.03810
194.87	1.04370
221.41	1.04885
248.15	1.05390
255.04	1.05540
274.88	1.05900
367.15	1.07535
478.78	1.09310
590.53	1.10925
702.20	1.12433
814.62	1.13766
926.05	1.15014
1037.86	1.16157

See Figure 32.

Reference: Micheals, A., P. Sanders, and A. Schipper, "The Dielectric Constant of Hydrogen," Physica, 2, 735 (1935).

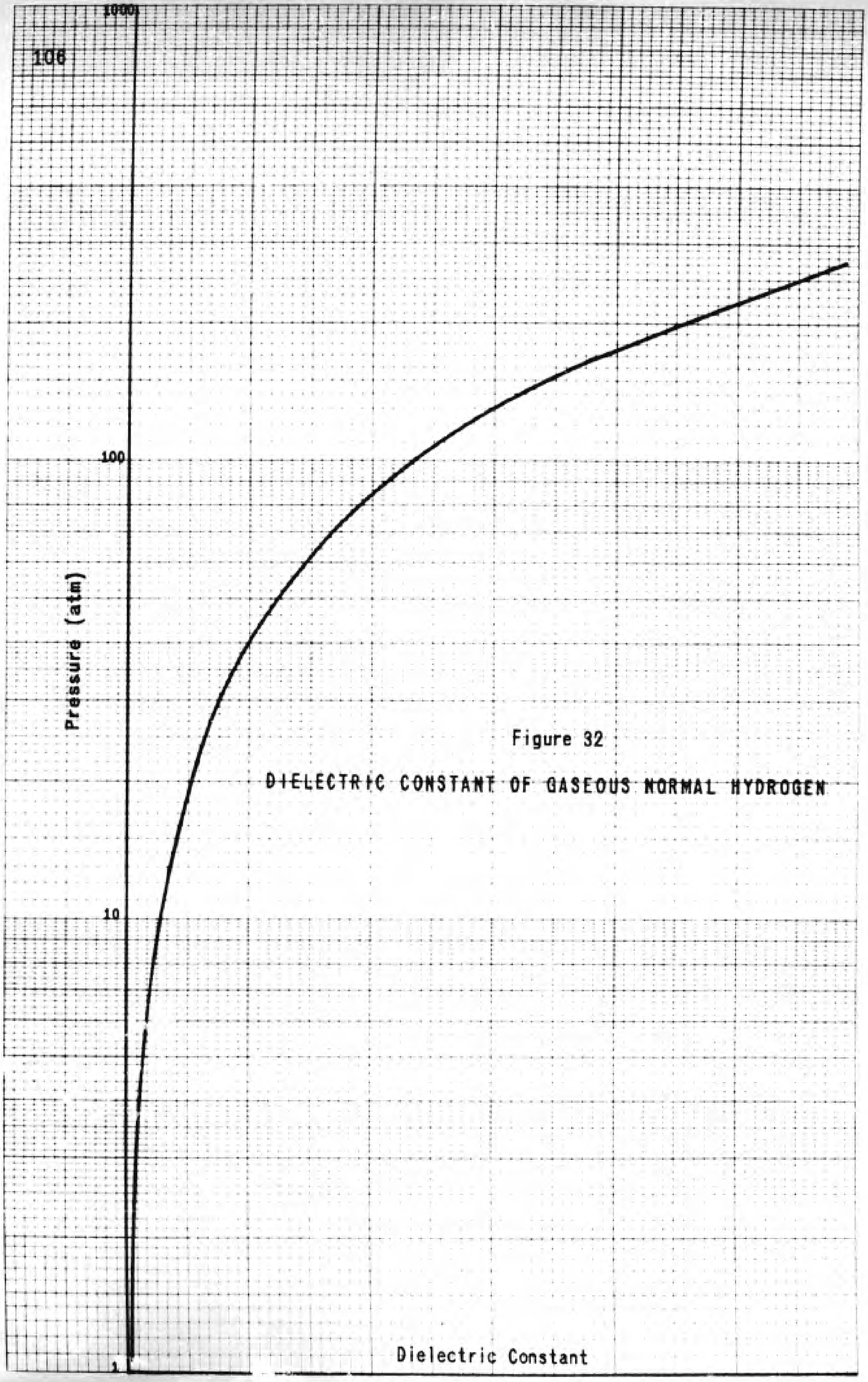


Figure 32

DIELECTRIC CONSTANT OF GASEOUS NORMAL HYDROGEN

V. PHYSICAL AND THERMODYNAMIC PROPERTIES OF HELIUM

A. GENERAL CONSIDERATIONS

1. Atomic Weight and Stable Isotopes

Isotope	Natural Abundance %	Atomic Weight Physical Scale	Atomic Weight Chemical Scale
He^3	~.000134	3.01693	3.01629
He^4	~ 100	4.00388	4.00280

Physical Scale: 0^{16} = 16.0000

Chemical Scale: 0 = 16.0000

Reference: Handbook of Chemistry and Physics, ed. C. D. Hodgman, 36th edition, Chemical Rubber Publishing Company, Cleveland, Ohio, 1954, 3099.

2. Critical Properties

Temperature	Pressure	Density
5.206°K	2.26 atm	0.0693 gm/cc
9.37°R	33.83 psia	4.13 lb/ft^3

References: Berman, R., and C. A. Swenson, Phys. Rev., 95, 311 (1954).
Kamerlingh Onnes, H., Communs. Phys. Lab., University of Leiden, No. 124B (1911).
Kobe, K. A., and R. E. Lynn, Jr., Chem Revs., 52, 117 (1953).

B. VAPOR PRESSURE

Temperature		Vapor Pressure	
(°K)	(°R)	(cm of Hg)	(psia)
2.2	3.96	4.054	.870
2.4	4.32	6.353	1.234
2.6	4.68	9.421	1.820
2.8	5.04	13.37	2.58
3.0	5.40	18.31	3.54
3.2	5.76	24.35	4.70
3.4	6.12	31.60	6.11
3.6	6.48	40.20	7.77
3.8	6.84	50.25	9.71
4.0	7.20	61.89	11.93
4.2	7.56	72.25	13.96
4.4	7.92	90.46	17.48
4.6	8.28	107.71	20.80
4.8	8.64	127.1	24.6
5.0	9.00	148.9	28.8
5.1	9.18	160.7	31.0
5.206	9.37	175.1	33.83

See Figure 33.

Reference: Berman, R., and C. F. Mate, Phil. Mag., 3, 461 (1958).

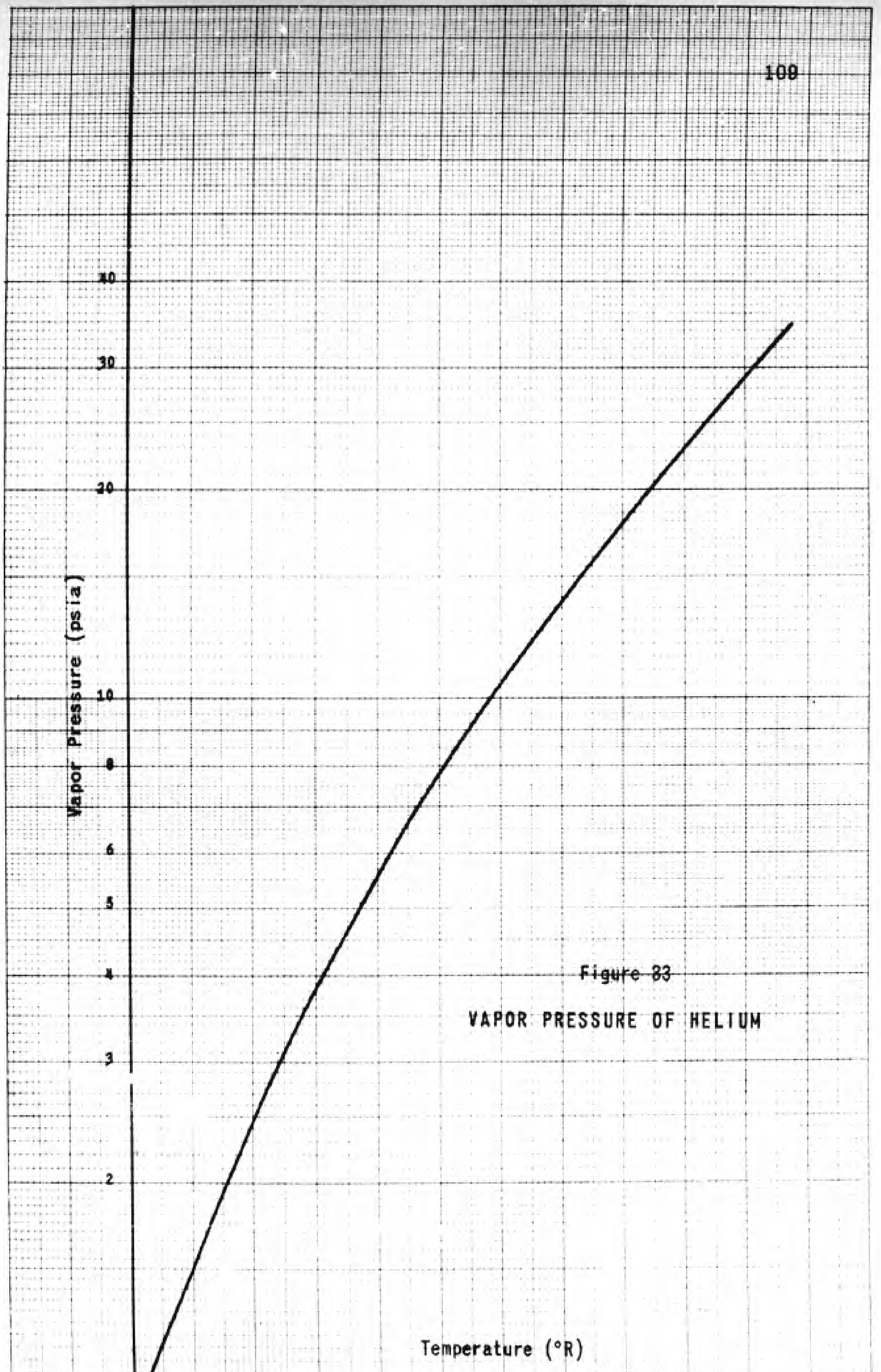


Figure 83

VAPOR PRESSURE OF HELIUM

C. DENSITY OF SATURATED HELIUM

Temperature		Liquid	Vapor
(°K)	(°R)	(lb/ft^3)	
2.2	3.96	9.14	.0773
2.4	4.32	9.07	.1132
2.6	4.68	9.00	.1583
2.8	5.04	8.90	.213
3.0	5.40	8.80	.278
3.2	5.76	8.69	.357
3.4	6.12	8.54	.450
3.6	6.48	8.39	.560
3.8	6.84	8.26	.689
4.0	7.20	8.02	.845
4.2	7.56	7.82	1.029
4.4	7.92	7.58	1.253
4.6	8.28	7.30	1.53
4.8	8.64	6.90	1.89
5.0	9.00	6.27	2.43
5.1	9.18	5.79	2.87
5.206	9.37	4.13	4.13

See Figure 34.

Reference: Berman, R., and C. F. Mate, Phil. Mag., 3, 461 (1958).

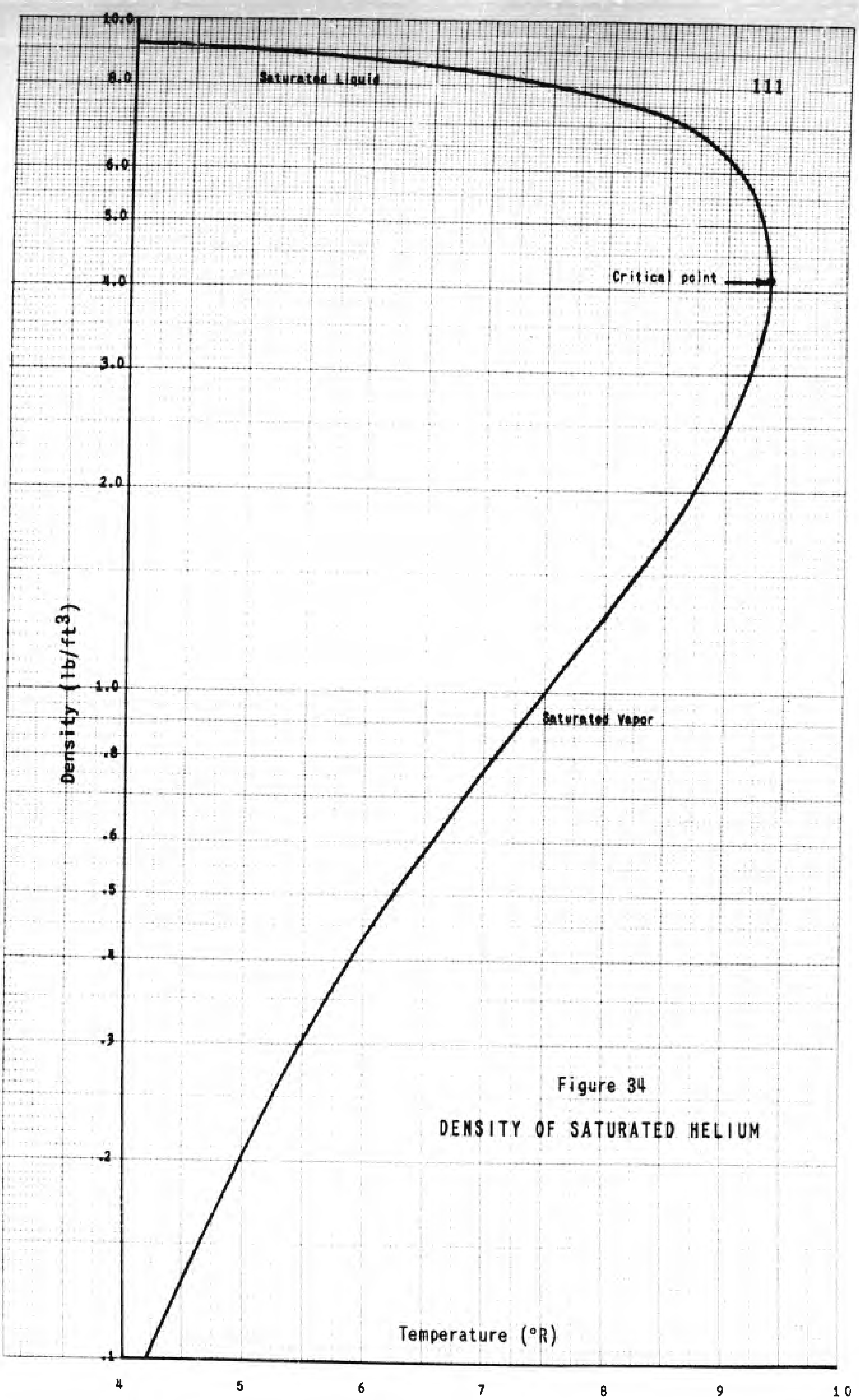


Figure 34

DENSITY OF SATURATED HELIUM

D. PRESSURE-VOLUME-TEMPERATURE RELATIONS FOR GAS

1. Equation of State for Helium

$$P = \frac{RT\,(1-e)\,(V+B)}{V^2} - \frac{A}{V^2}$$

$e = C/VT^3$

$A = A_o\,(1-a/V)$

P = pressure, psia

T = temperature, °R

V = specific volume, ft^3/lb

R = 2.6829 psia-ft^3/lb-°R

A_o = 5.0906

a = 0.23963

B = 0.056063

C = 934.17

Maximum pressure - 1500 psia
Temperature range - 38-1210°R
Maximum density - 2.5 lb/ft^3

References: Akin, S. W., *Trans. ASME*, *72*, 751 (1950).
Beattie, J. A., and O. C. Bridgeman, *Proc. Amer. Acad. Arts Sci.*, *63*, 229 (1928).

2. Compressibility Factor of Helium

See Table XVII and Figures 35 and 36.

TABLE XVII

COMPRESSIBILITY FACTOR OF HELIUM

Temperature (°F)	Temperature (°R)	14.7 psia	50 psia	150 psia	400 psia	600 psia	900 psia	1500 psia	2500 psia	4000 psia
-440	20	.956	.838	.594	1.100					
-425	35	.998	.993	.998	1.086	1.219	1.413	1.774	2.419	3.011
-400	60	1.003	1.008	1.026	1.057	1.115	1.243	1.444	1.719	2.250
-350	110	1.003	1.007	1.021	1.043	1.087	1.134	1.229	1.386	1.619
-300	160	1.003	1.006	1.016	1.034	1.064	1.096	1.156	1.265	1.411
-250	210	1.002	1.005	1.013	1.029	1.051	1.075	1.124	1.209	1.316
-200	260	1.002	1.004	1.011	1.025	1.042	1.062	1.103	1.167	1.255
-150	310	1.002	1.004	1.010	1.022	1.036	1.054	1.088	1.143	1.213
-100	360	1.002	1.003	1.009	1.016	1.029	1.048	1.077	1.125	1.191
- 50	410	1.001	1.003	1.007	1.015	1.026	1.041	1.068	1.109	
0	460	1.001	1.002	1.006	1.014	1.023	1.037	1.061	1.099	1.152
50	510	1.001	1.002	1.005	1.013	1.020	1.034	1.055	1.090	
100	560	1.001	1.002	1.004	1.012	1.019	1.032	1.051	1.083	1.128
150	610	1.001	1.002	1.004	1.012	1.018	1.031	1.047	1.078	
200	660	1.001	1.002	1.003	1.011	1.017	1.031	1.044	1.074	1.110

Reference: Akin, S. W., Trans. ASME, 72, 751 (1950).

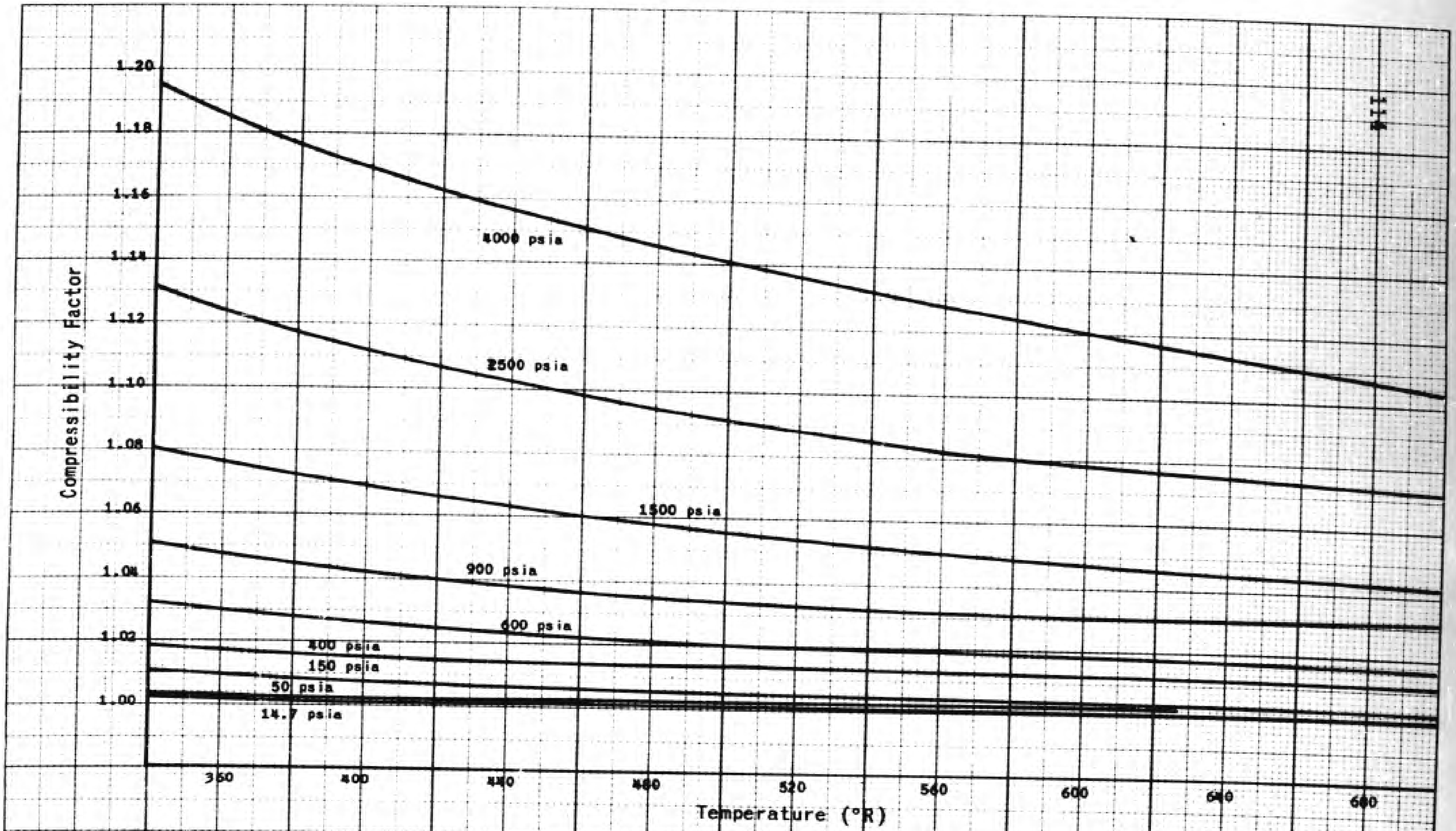


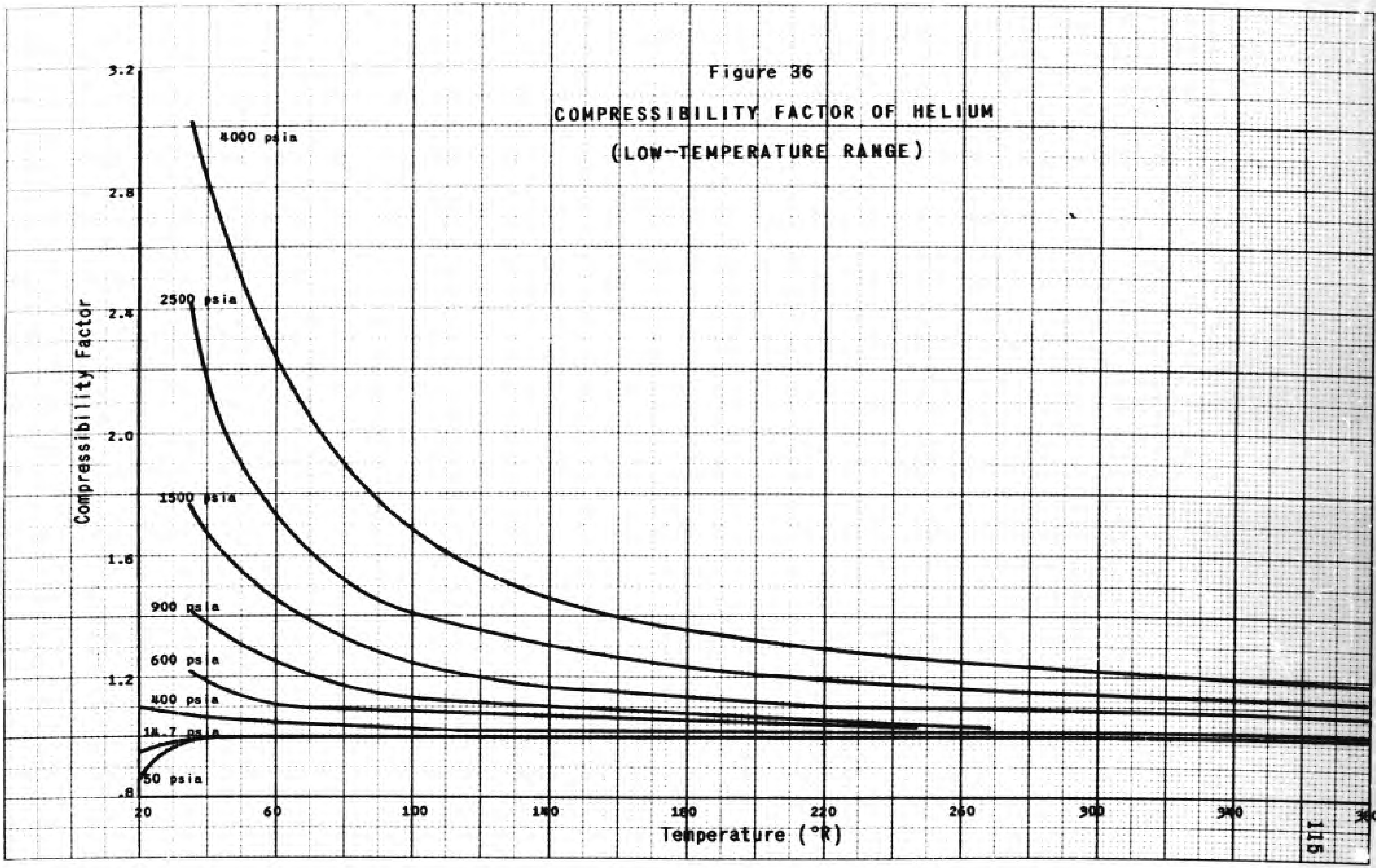
Figure 35

COMPRESSIBILITY FACTOR OF HELIUM
(HIGH-TEMPERATURE RANGE)

Figure 36

COMPRESSIBILITY FACTOR OF HELIUM

(LOW-TEMPERATURE RANGE)



E. HEAT CAPACITY

1. Heat of Vaporization of Helium

Temperature		Latent Heat
(°K)	(°R)	(Btu/lb)
0	0	64.2
1.0	1.8	86.6
1.5	2.7	96.6
2.0	3.6	100.0
2.5	4.5	99.2
3.0	5.4	100.6
3.5	6.3	100.1
4.0	7.2	97.0
4.2	7.56	93.7
4.23	7.61	96.1
4.59	8.26	78.0
4.71	8.45	68.5
5.206	9.37	0

See Figure 37.

Reference: Kistenmaker, J., *Physica* 12, 281 (1946).

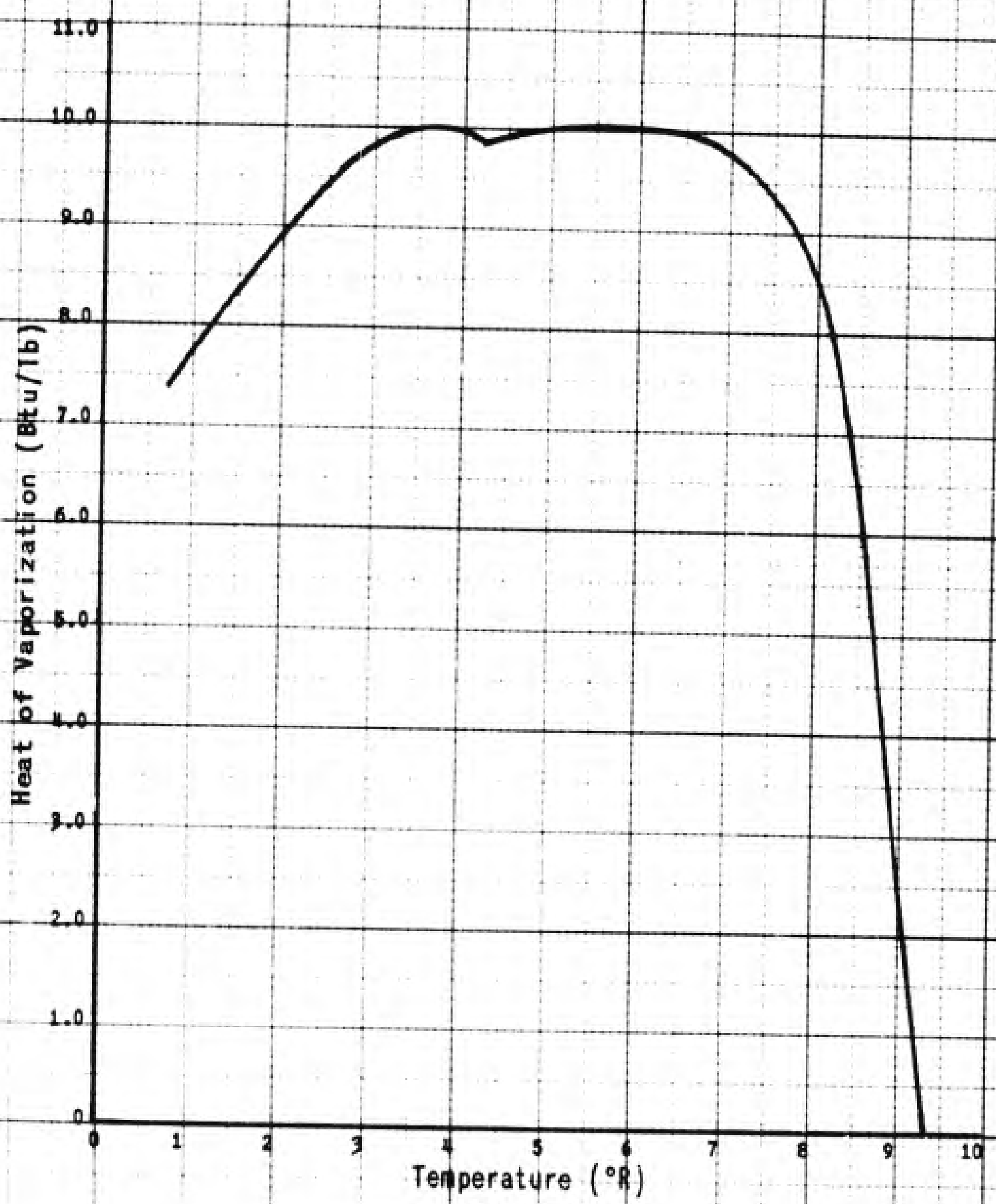


Figure 37

HEAT OF VAPORIZATION OF HELIUM

2. Heat Capacity of Liquid Helium At Saturation

Temperature (°R)	Heat Capacity, C_s (Btu/lb-°F)
3.96	∞
4.0	.96
4.5	.53
5.0	.55
5.5	.62
6.0	.67
6.5	.78
7.0	.91
7.5	1.05
8.0	1.29
8.5	1.67
9.0	2.74

See Figure 38.

Reference: Mann, D. B., and R. B. Stewart, National Bureau of Standards, Technical Note No. 8, May 1959, PB 151367.

3. Ratio of Heat Capacities of Helium Gas

See Figure 39.

Reference: Akin, W. S., Trans. ASME, 72, 751 (1950).

4. Heat Capacity of Helium at Constant Pressure

See Table XVIII and Figure 40.

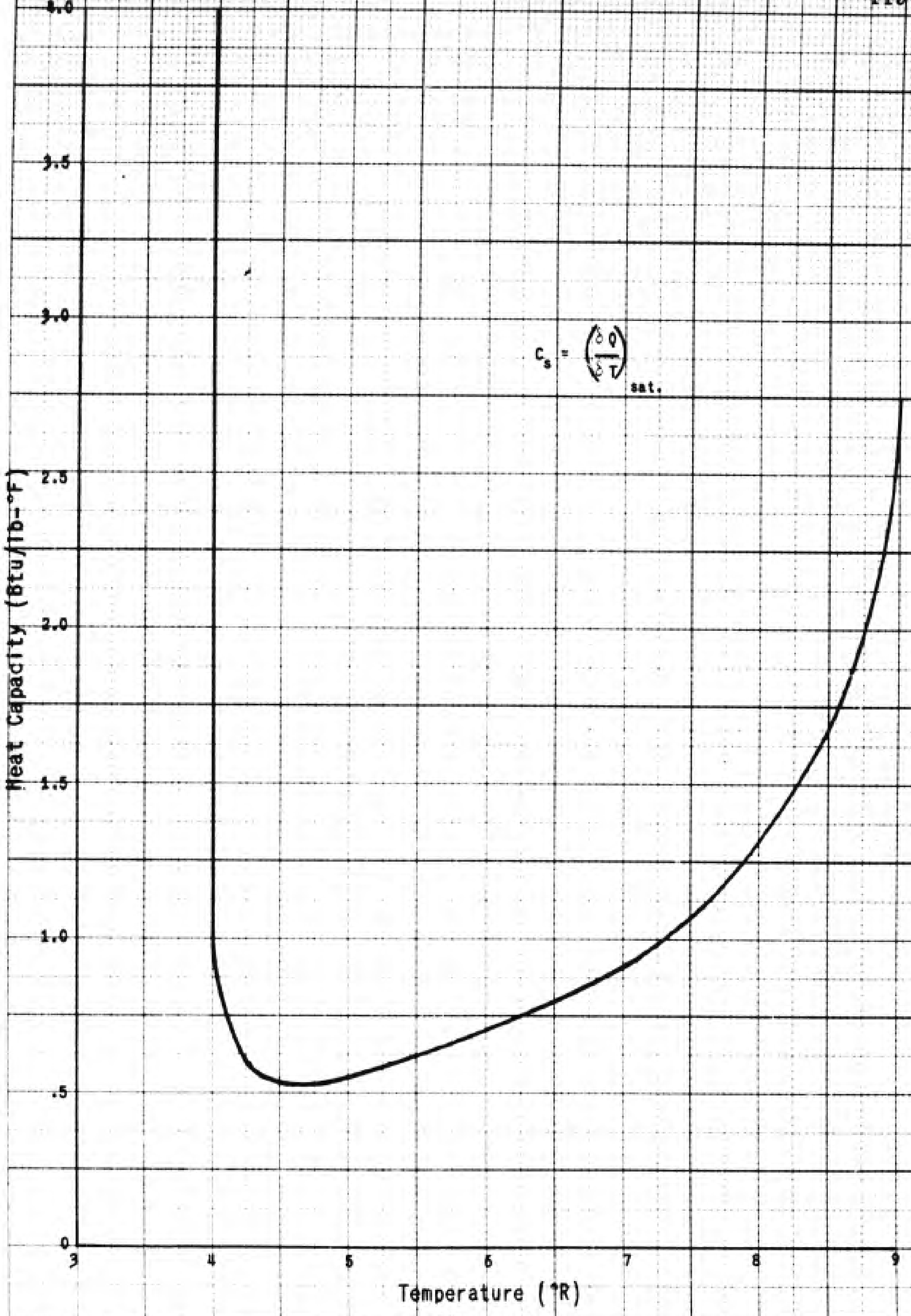


Figure 38

HEAT CAPACITY OF SATURATED LIQUID HELIUM

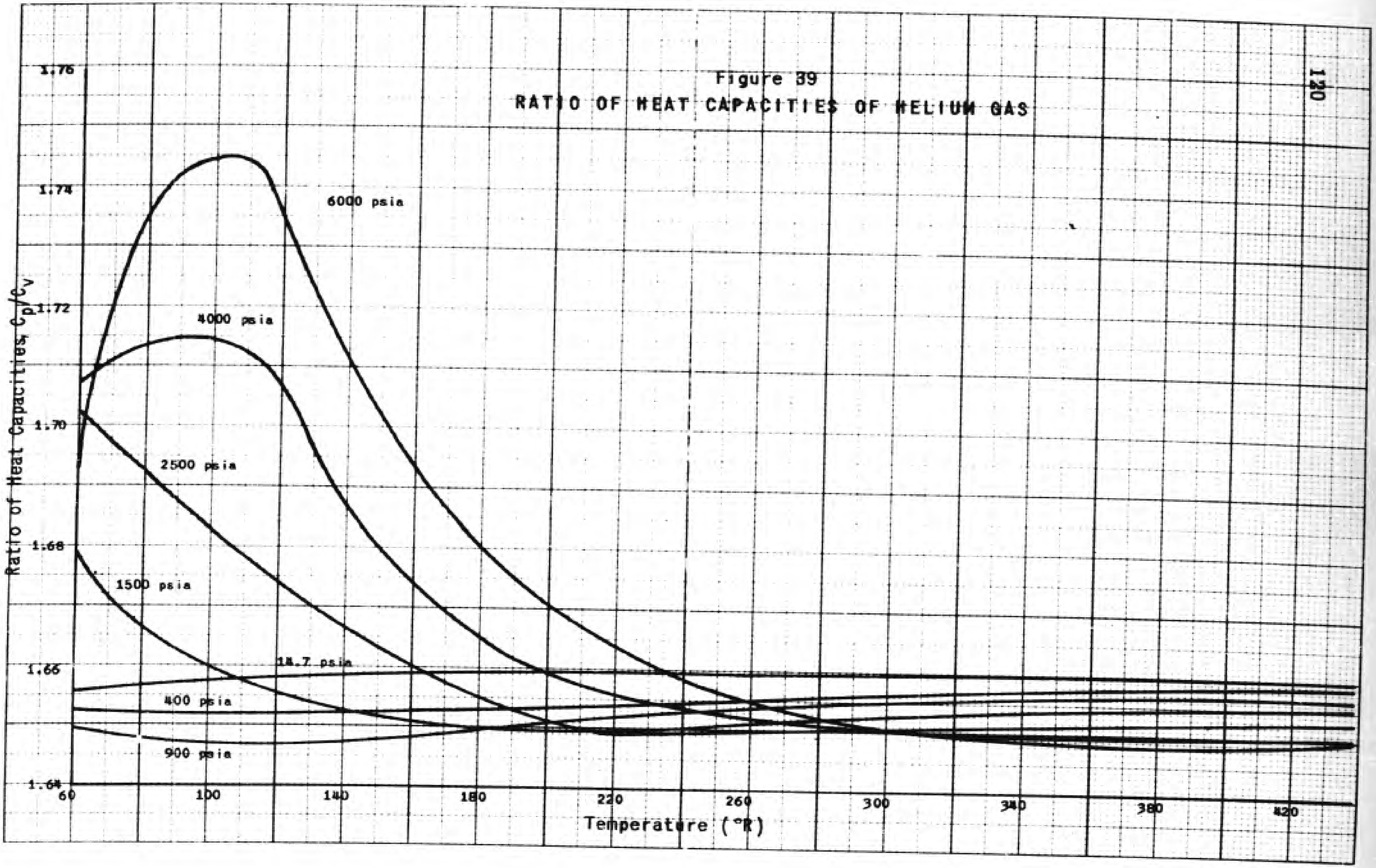


Figure 39

RATIO OF HEAT CAPACITIES OF HELIUM GAS

TABLE XVIII

HEAT CAPACITY OF HELIUM AT CONSTANT PRESSURE

Temperature (°F)	Temperature (°R)	14.7 psia	50 psia	150 psia	400 psia	600 psia	900 psia	1500 psia	2500 psia	4000 psia
-450	10	1.58		1.05						
-440	20	1.36		1.80						
-425	35	1.30		1.33						
-400	60	1.252	1.254	1.255	1.256	1.258	1.259	1.227	1.203	1.197
-350	110	1.250	1.252	1.254	1.256	1.259	1.263	1.250	1.225	1.192
-300	160	1.249	1.251	1.253	1.256	1.258	1.260	1.258	1.248	1.232
-250	210	1.248	1.250	1.252	1.255	1.256	1.257	1.259	1.256	1.250
-200	260	1.248	1.250	1.251	1.253	1.254	1.255	1.259	1.258	1.256
-150	310	1.248	1.249	1.250	1.251	1.253	1.253	1.256	1.258	1.259
-100	360	1.248	1.249	1.250	1.250	1.251	1.252	1.255	1.257	1.260
-50	410			1.249	1.249	1.250	1.252	1.254	1.256	1.259
0	460				1.249	1.250	1.251	1.253	1.255	1.258
50	510						1.250	1.252	1.254	1.257
100	560						1.250	1.252	1.254	1.257
150	610						1.250	1.251	1.253	1.256
200	660	1.248	1.249	1.249	1.249	1.250	1.250	1.251	1.252	1.255

Reference: Mann, D. B., and R. B. Stewart, National Bureau of Standards, Technical Note No. 8, May 1959, PB 151367.

Akin, S. W., Trans. ASME, 72, 751 (1950).

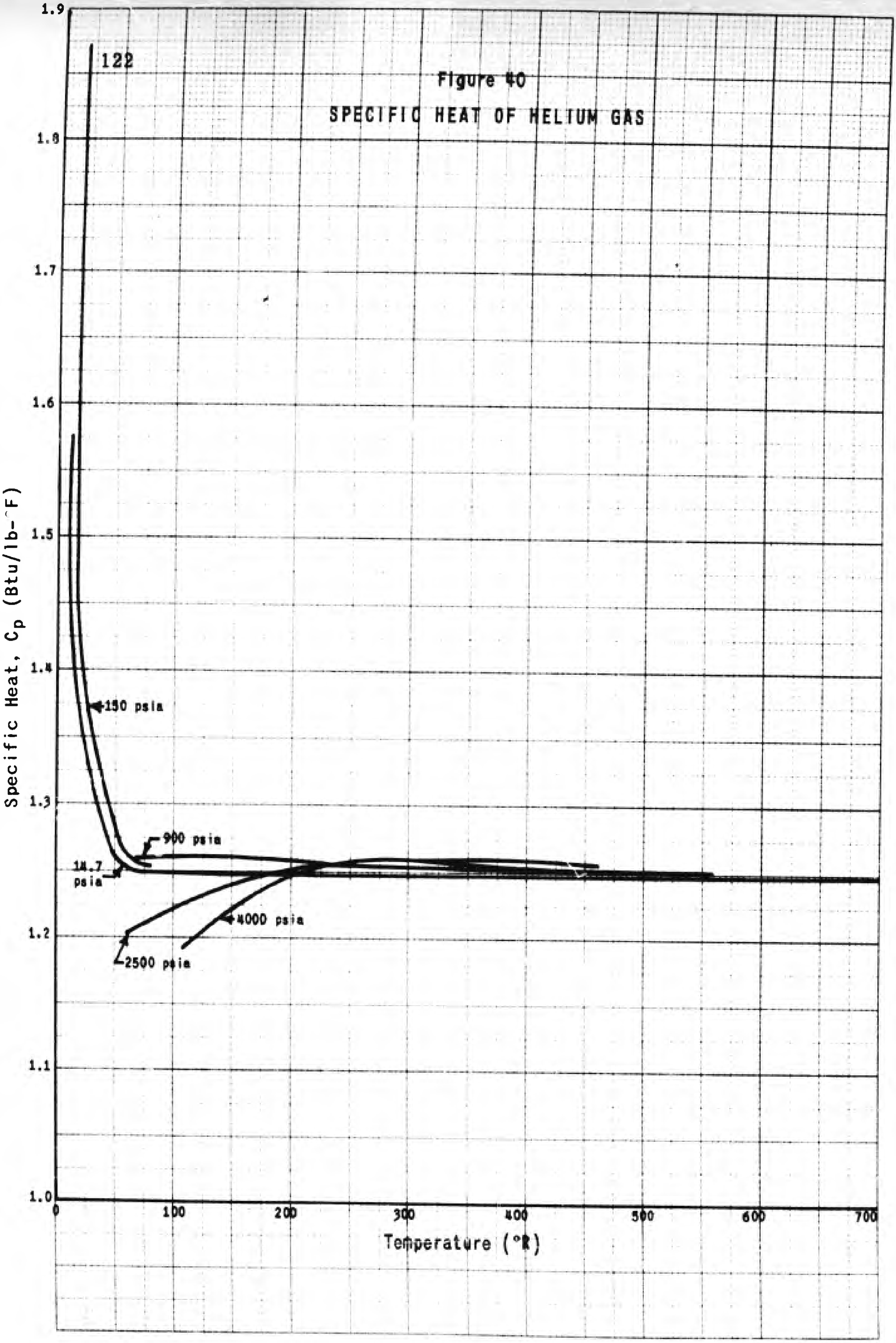


Figure 40

SPECIFIC HEAT OF HELIUM GAS

F. THERMODYNAMIC PROPERTIES

1. Lambda Transition in Liquid Helium

At approximately 2.18°K (3.92°F), liquid helium undergoes a transition that involves no latent heat and no discontinuous change in volume. The term lambda transition arises from the resemblance between the Greek letter lambda (λ) and the shape of the curve of specific heat versus temperature. The transition temperature is referred to as the λ point. The transition temperature decreases as the pressure is increased, until solidification takes place.

The liquid at temperatures above the λ point is known as helium I and below the λ point as helium II. Although helium II has many unique properties, they will not be covered in this report.

Reference: Atkins, K. R., Liquid Helium, London, Cambridge University Press, 1959.

2. Properties of Saturated Helium

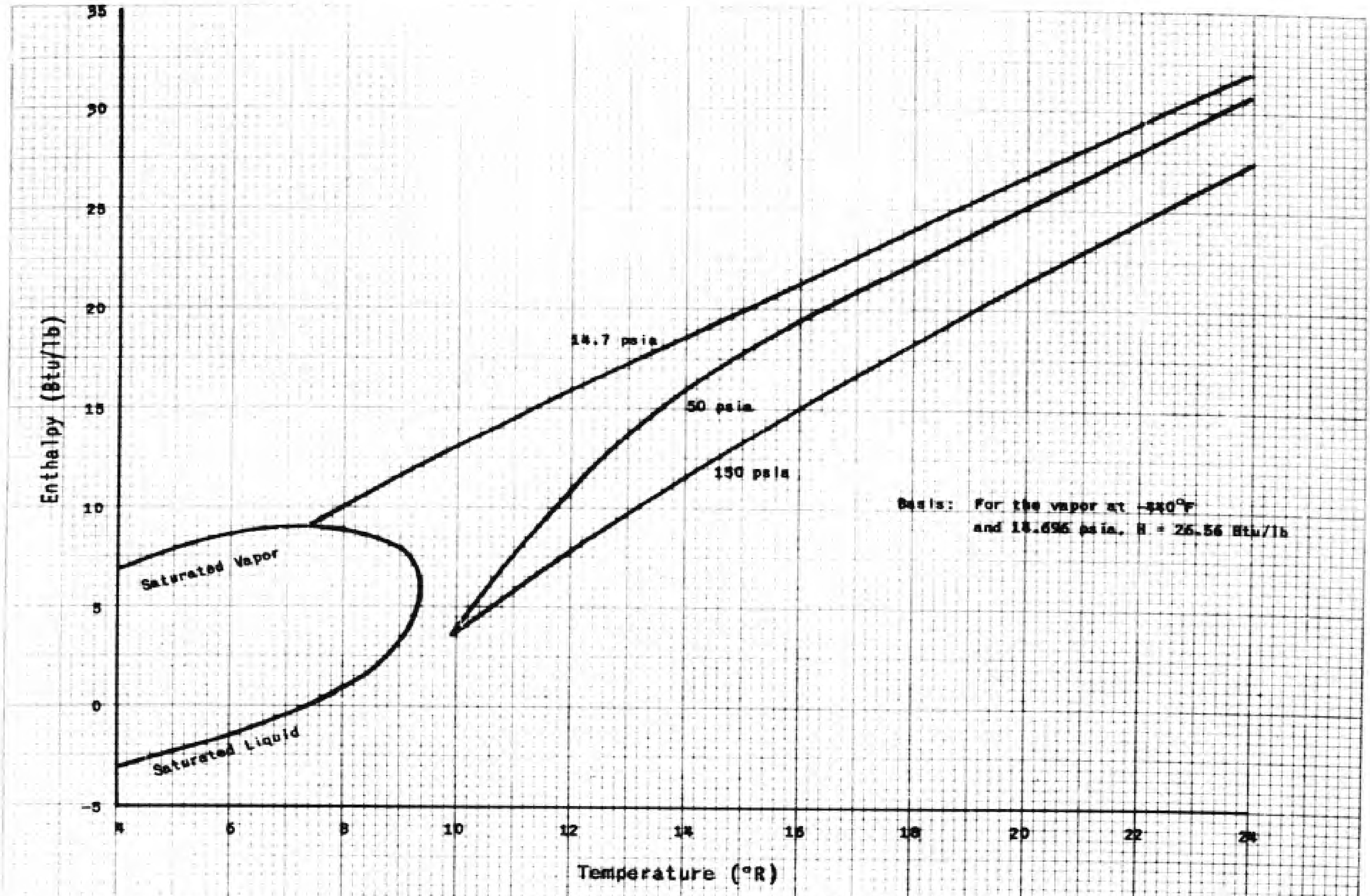
Temperature		Enthalpy (Btu/lb)		Entropy (Btu/lb-°F)	
(°R)	(°F)	Liquid	Vapor	Liquid	Vapor
4	-455.7	-3.2	7.0	-.41	2.04
5	-454.7	-2.3	7.7	-.27	1.73
6	-453.7	-1.6	8.7	-.16	1.55
7	-452.7	-.5	8.9	-.04	1.31
8	-451.7	.8	8.7	+.11	1.10
9	-450.7	3.3	7.8	+.32	.85
9.35	-450.35	5.7	5.7	+.60	.60

Basis: -440°F and 14.696 psia for the vapor
S = 2.602 Btu/lb-°F
H = 26.56 Btu/lb

See Figures 41-49.

Reference: Mann, D. B., and R. B. Stewart, Thermodynamic Properties of Helium at Low Temperatures and High Pressures, National Bureau of Standards, Technical Note No. 8, May 1959, PB 151367.

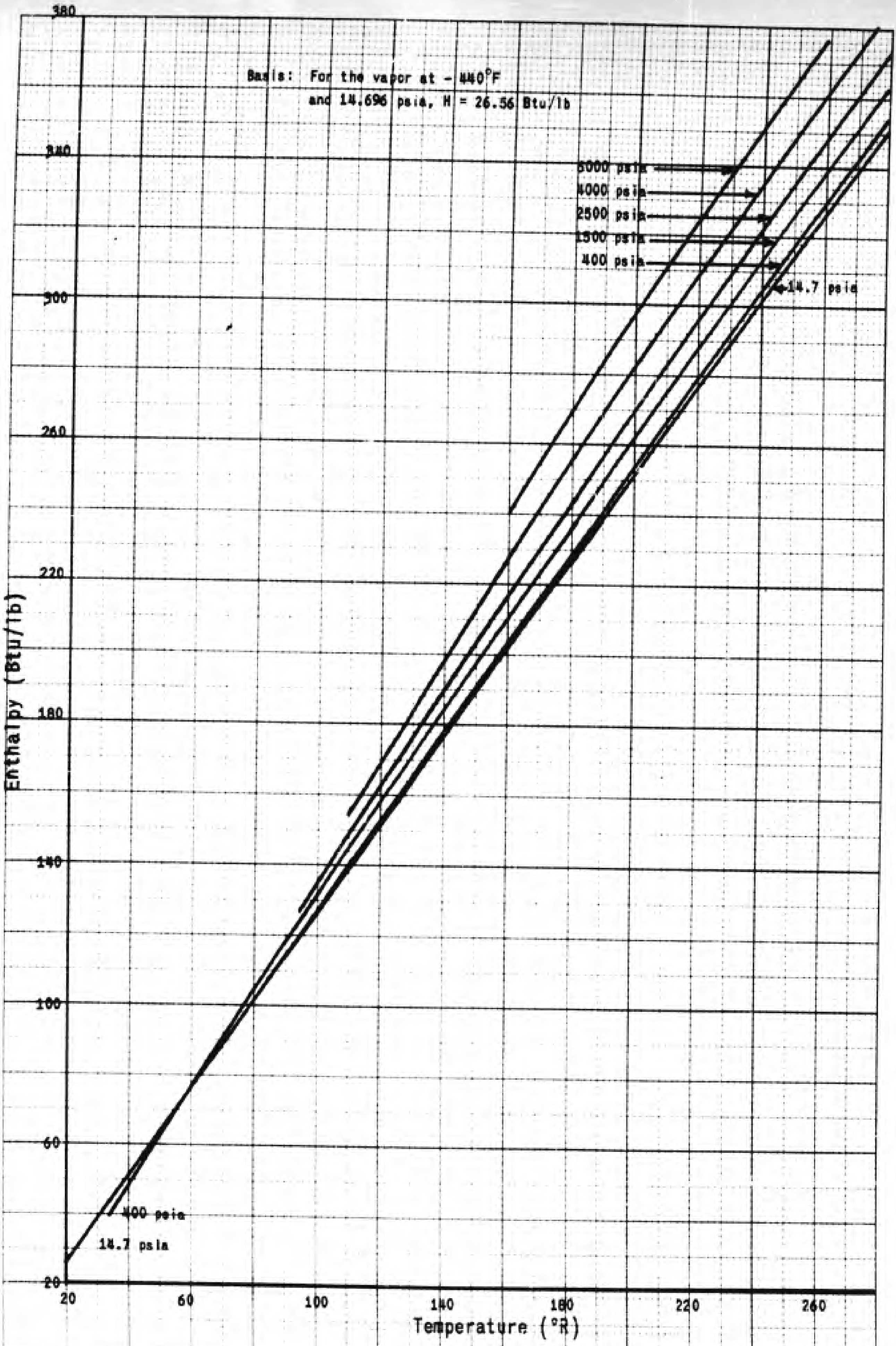
3. Enthalpy and Entropy of Superheated Helium (See Table XIX)



Basis: For the vapor at -440°F
and 14.696 psia, H = 26.56 Btu/lb

Figure 41

ENTHALPY OF SATURATED HELIUM FOR TEMPERATURES FROM 4 TO 24°R AND PRESSURES OF 14.7, 50, AND 150 PSIA



Basis: For the vapor at - 440°F and 14.696 psia, H = 26.56 Btu/lb

Figure 42
ENTHALPY OF HELIUM FOR TEMPERATURES FROM 20 TO 260°R AND PRESSURES FROM 14.7 TO 6000 PSIA

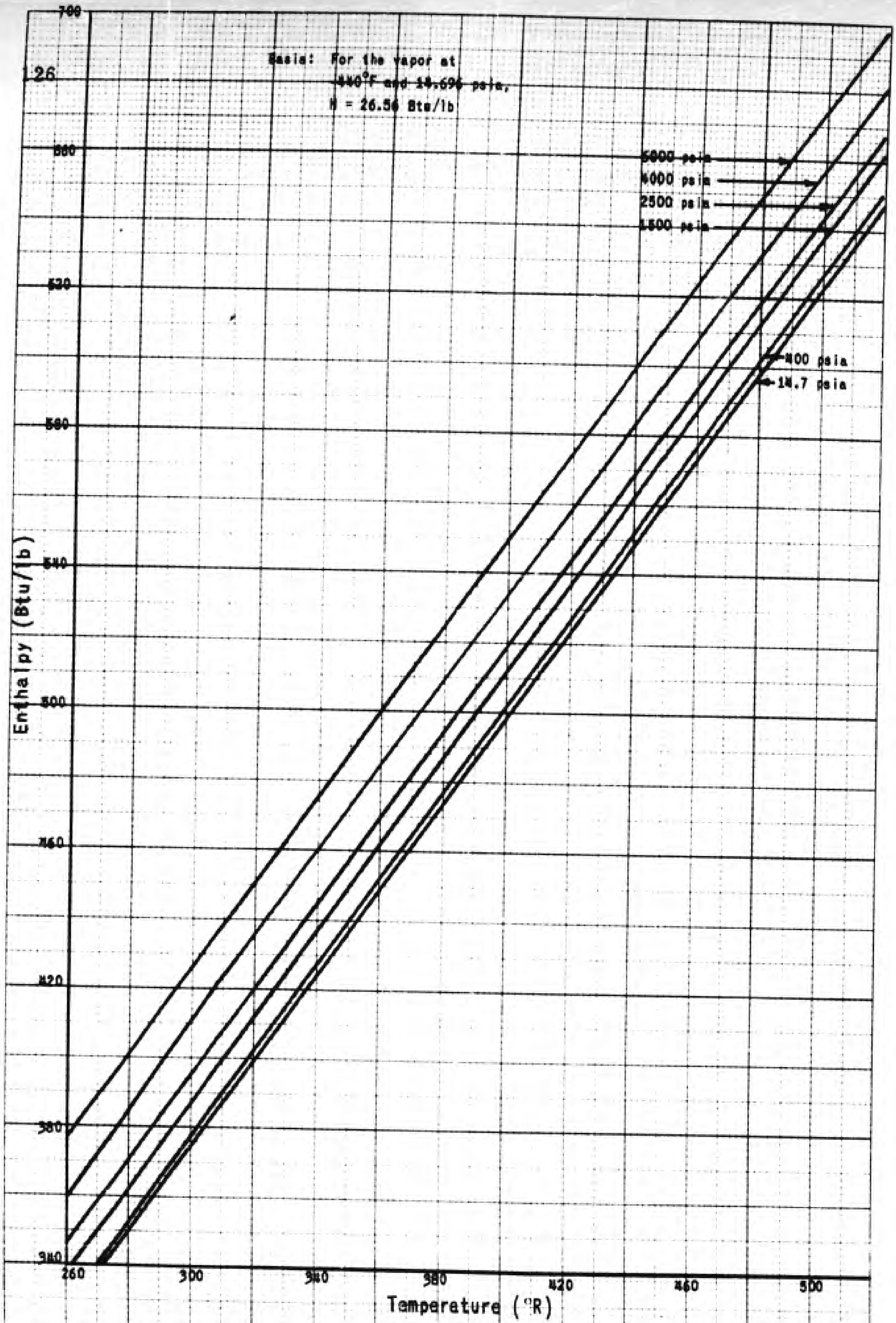


Figure 43

ENTHALPY OF HELIUM FOR TEMPERATURES FROM 260 TO 520 °R AND PRESSURES FROM 14.7 TO 6000 PSIA

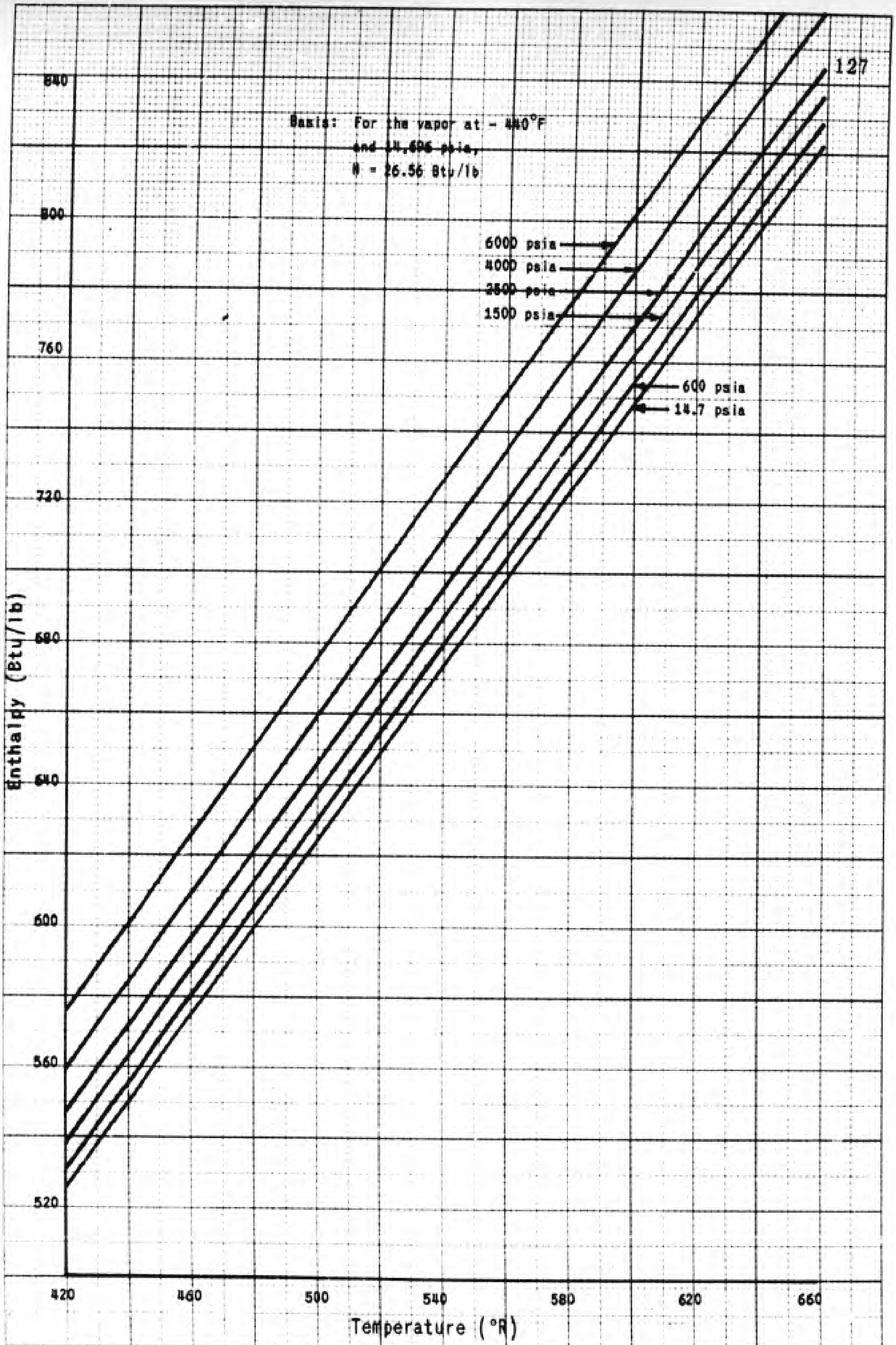


Figure 44

ENTHALPY OF HELIUM FOR TEMPERATURES FROM 420 TO 660°R AND PRESSURES FROM 14.7 TO 6000 PSIA

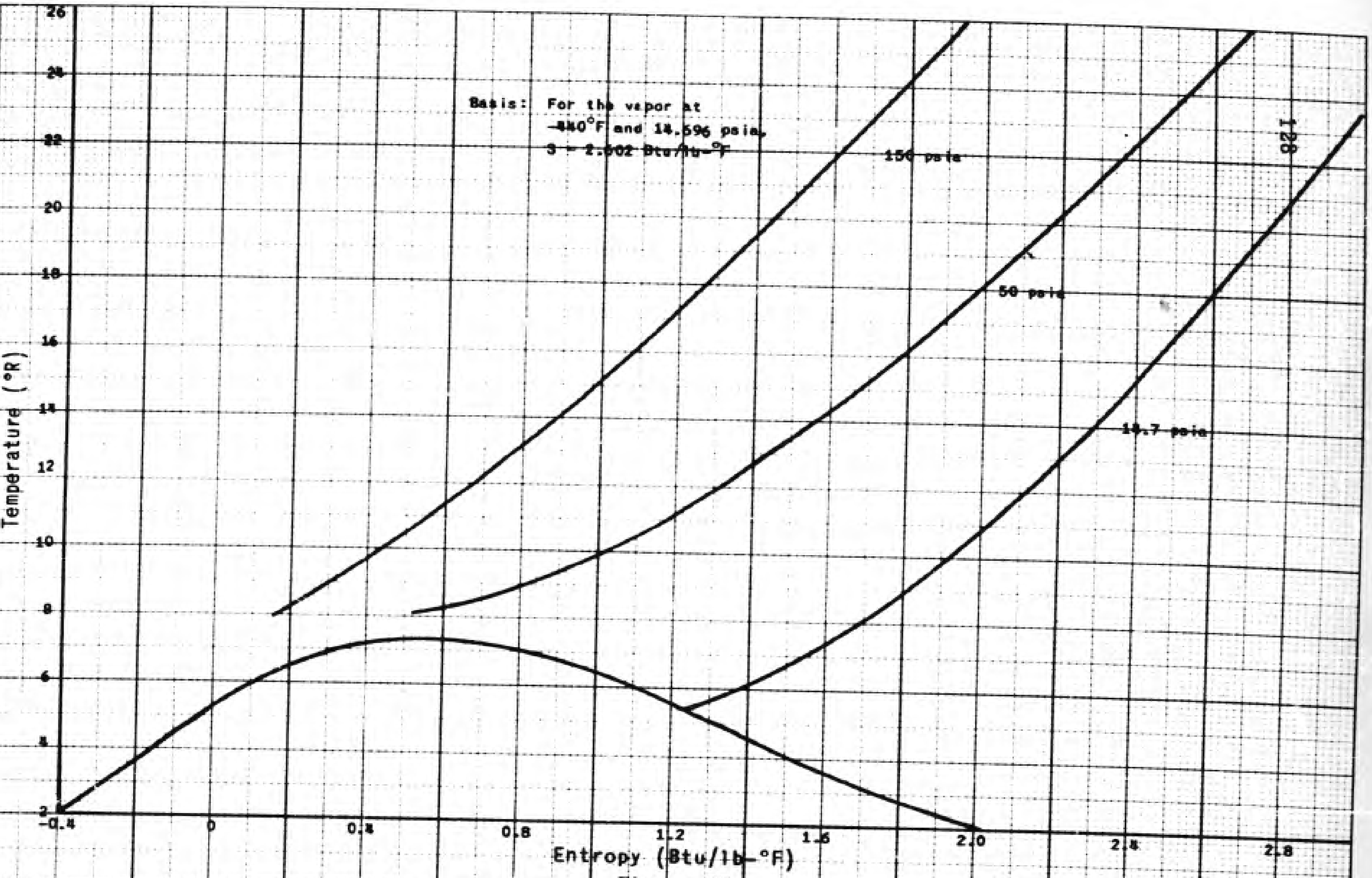
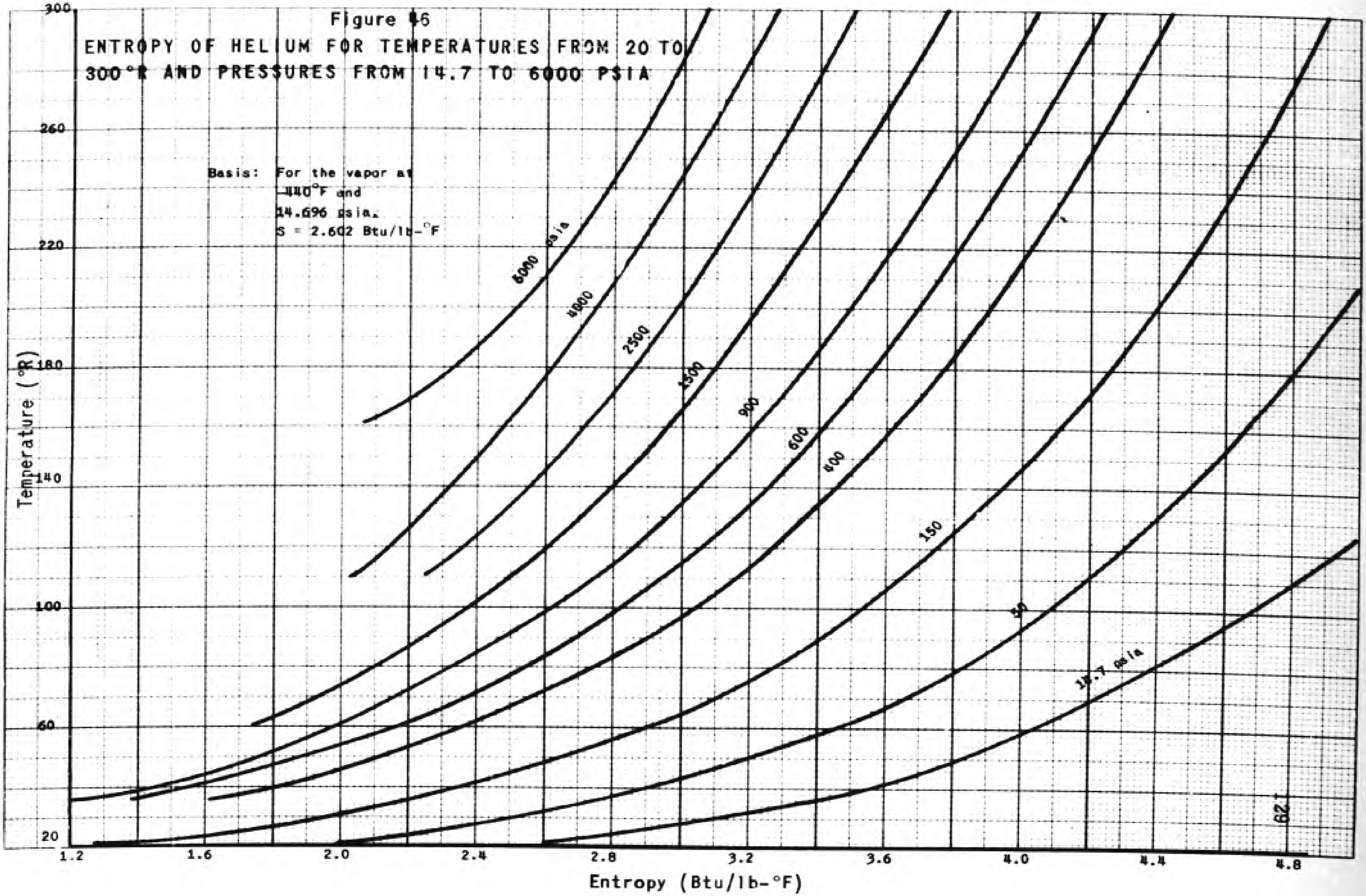


Figure 45

ENTROPY OF HELIUM FOR TEMPERATURES FROM
8 TO 24°R AND PRESSURES OF 14.7, 50, AND 150 PSIA

Figure 46

ENTROPY OF HELIUM FOR TEMPERATURES FROM 20 TO 300°R AND PRESSURES FROM 14.7 TO 6000 PSIA



Basis: For the vapor at -440°F and 14.696 psia, S = 2.602 Btu/lb-°F

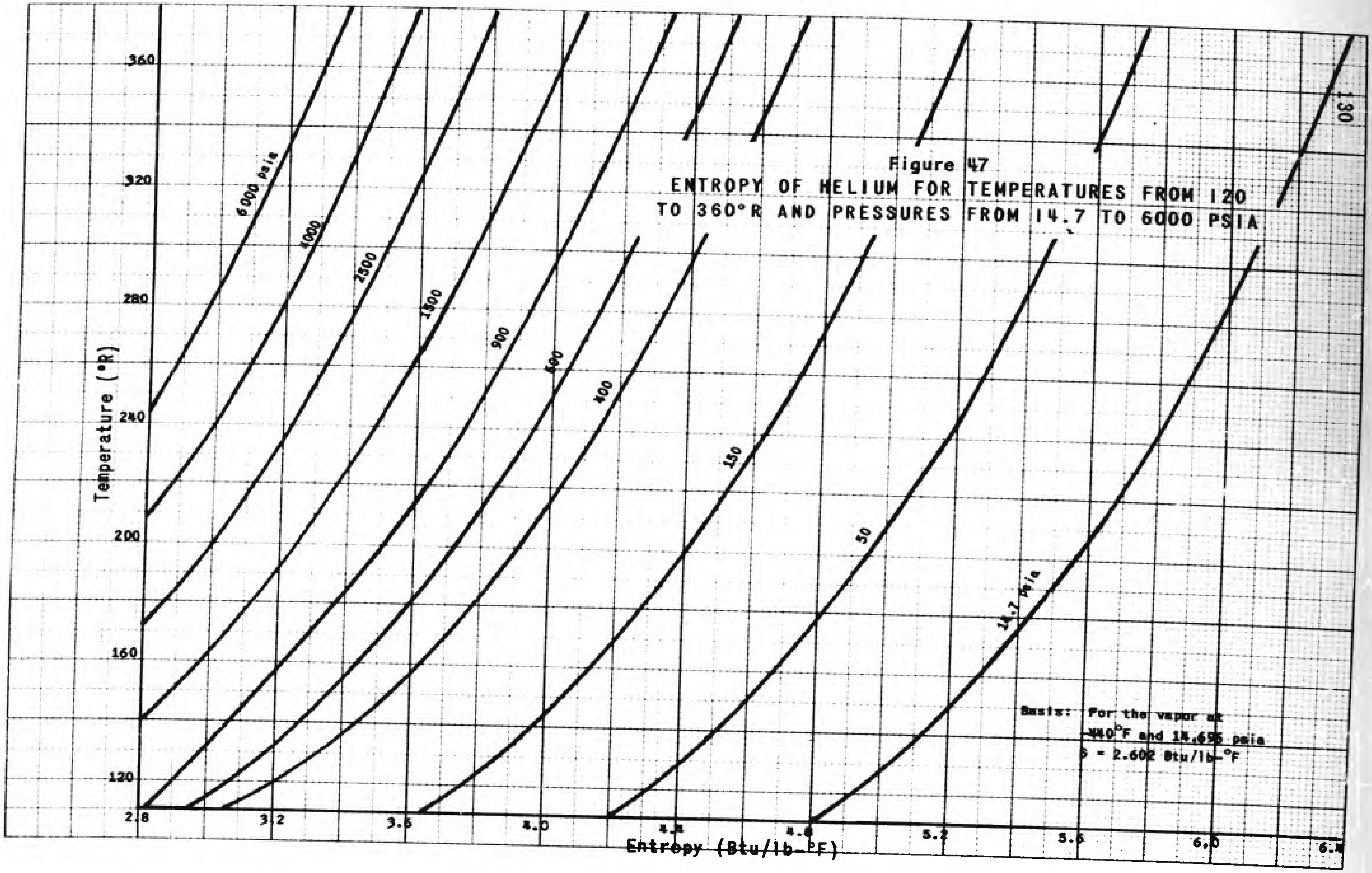


Figure 47

ENTROPY OF HELIUM FOR TEMPERATURES FROM 120 TO 360°R AND PRESSURES FROM 14.7 TO 6000 PSIA

Basis: For the vapor at -440°F and 14.696 psia S = 2.602 Btu/lb-°F

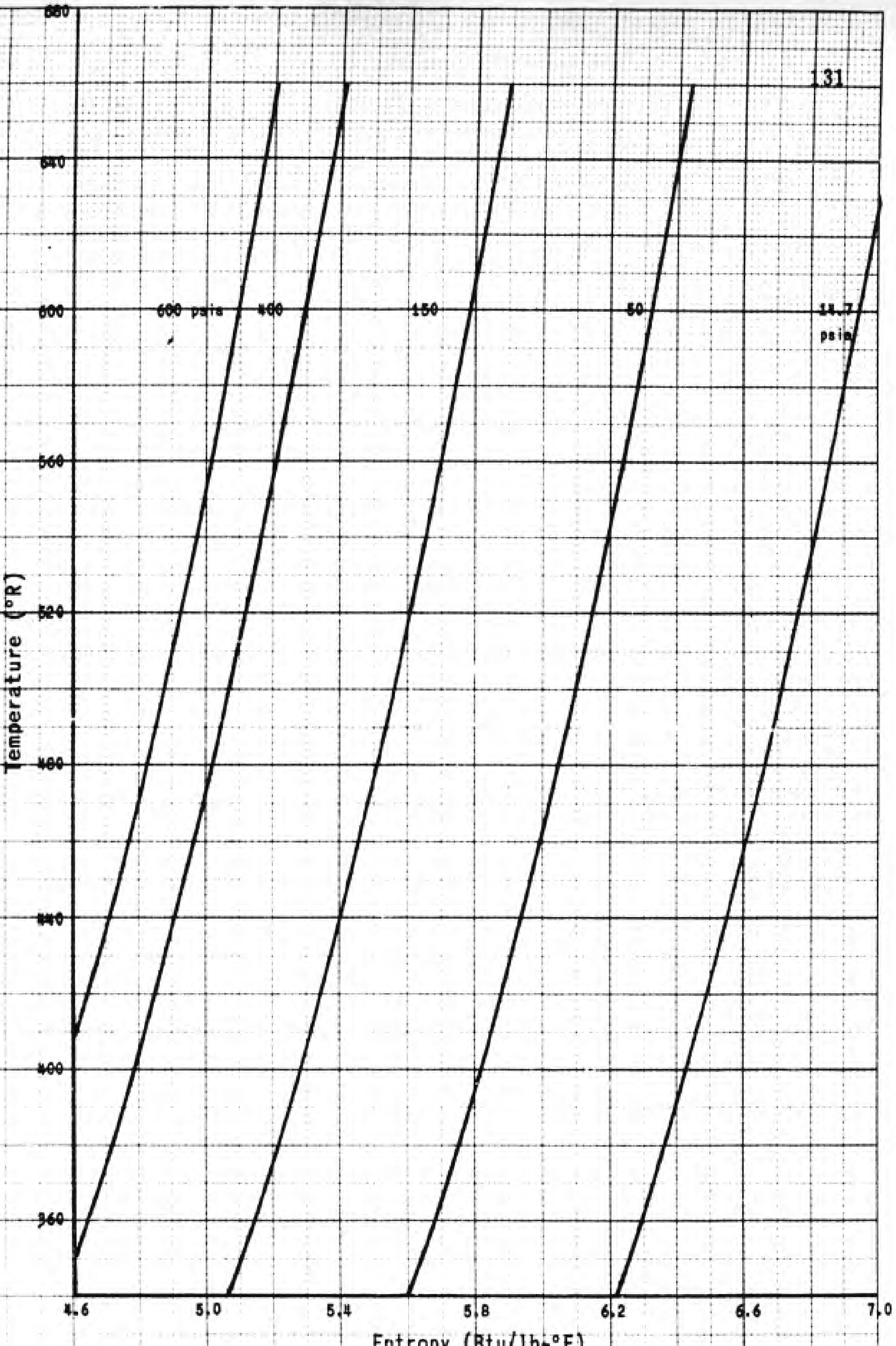


Figure 48

ENTROPY OF HELIUM FOR TEMPERATURES FROM 360 TO 680°R AND PRESSURES FROM 14.7 TO 600 PSIA

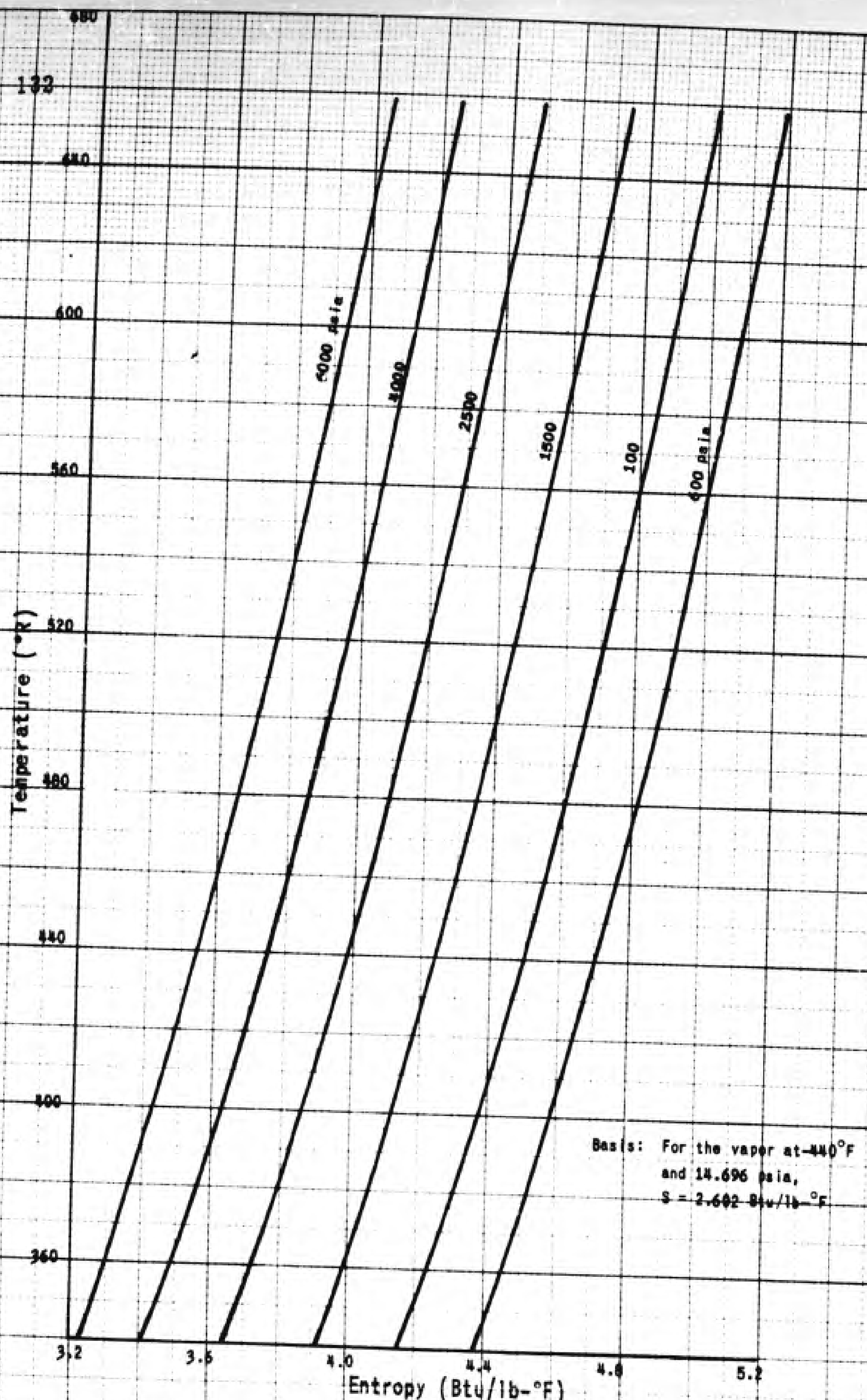


Figure 49

ENTROPY OF HELIUM FOR TEMPERATURES FROM 360 TO 680°R AND PRESSURES FROM 600 TO 6000 PSIA

TABLE XIX

ENTHALPY AND ENTROPY OF SUPERHEATED HELIUM

Temperature (°R)	Temperature (°F)	14.7 psia		50 psia		150 psia		400 psia		600 psia		900 psia		1500 psi	
		H (Btu/lb)	S (Btu/lb -°F)	H (Btu/lb)	S (Btu/lb -°F)	H (Btu/lb)	S (Btu/lb -°F)	H (Btu/lb)	S (Btu/lb -°F)	H (Btu/lb)	S (Btu/lb -°F)	H (Btu/lb)	S (Btu/lb -°F)	H (Btu/lb)	(Bt
8	-42	10.0	1.32												
10	-450	13.3	1.69	3.9	0.51	3.8	0.16								
20	-440	26.56	2.602	24.9	1.987	21.3	1.269								
35	-425	46.2	3.364	45.4	2.749	43.5	2.198	41.5	1.618	41.3	1.396	43.0	1.176		
60	-400	76.9	4.045	76.7	3.435	75.9	2.884	75.7	2.380	75.4	2.176	75.0	1.984	75.2	1
110	-350	138.8	4.807	139.0	4.197	139.3	3.649	140.3	3.158	141.0	2.955	142.1	2.750	144.3	2
160	-300	200.9	5.276	201.1	4.667	201.8	4.121	203.4	3.631	204.7	3.428	206.6	3.224	210.5	2
210	-250	263.0	5.616	263.2	5.008	264.0	4.462	266.0	3.973	267.5	3.770	269.8	3.567	274.5	3
260	-200	325.1	5.883	325.4	5.275	326.2	4.729	328.3	4.241	330.0	4.039	332.5	3.836	337.6	3
310	-150	387.1	6.103	387.4	5.495	388.3	4.949	390.5	4.461	392.3	4.259	395.0	4.057	400.4	3.
360	-100	449.2	6.290	449.5	5.682	450.4	5.137	452.7	4.649	454.5	4.448	457.3	4.245	462.8	3
410	-50	512.0	6.45	512.0	5.85	513.0	5.30	516.0	4.81	518.0	4.61	520.0	4.41	525.0	4.
460	0	573.3	6.597	573.6	5.989	574.6	5.443	576.9	4.956	578.8	4.754	581.7	4.552	588.0	4.
510	50	636.0	6.740	636.0	6.12	637.0	5.59	639.0	5.09	641.0	4.91	644.0	4.70	650.0	4.
560	100	697.4	6.842	697.7	6.234	698.7	5.689	701.1	5.201	703.0	5.0	705.9	4.798	711.7	4.
610	150	760.0	6.96	760.0	6.34	761.0	5.80	763.0	5.30	766.0	5.11	768.0	4.91	773.0	4.
660	200	821.5	7.047	821.8	6.439	822.8	5.894	825.2	5.407	827.1	5.205	830.0	5.004	835.8	4.

Basis: -440°F and 14.696 psia, for the vapor

S = 2.602 Btu/lb-°F

H = 26.56 Btu/lb

Reference: Akin S W, Trans. ASME 72 751 (1950)
Institut International Du Froid Kamerlingh Onnes Laboratory, University of Leiden
Temperature - Entropy Diagram for Helium 1941

TABLE XIX

ENTHALPY AND ENTROPY OF SUPERHEATED HELIUM

150 psia		400 psia		600 psia		900 psia		1500 psia		2500 psia		4000 psia		6000 psia	
H (Btu/lb)	S (Btu/lb-°F)	H (Btu/lb)	S (Btu/lb-°F)	H (Btu/lb)	S (Btu/lb-°F)	H (Btu/lb)	S (Btu/lb-°F)	H (Btu/lb)	S (Btu/lb-°F)	H (Btu/lb)	S (Btu/lb-°F)	H (Btu/lb)	S (Btu/lb-°F)	H (Btu/lb)	S (Btu/lb-°F)
3.8	0.16														
21.3	1.269														
43.5	2.198	41.5	1.618	41.3	1.396	43.0	1.176								
75.9	2.884	75.7	2.380	75.4	2.176	75.0	1.984	75.2	1.752						
139.3	3.649	140.3	3.158	141.0	2.955	142.1	2.750	144.3	2.498	148.0	2.255	154.0	2.036		
201.8	4.121	203.4	3.631	204.7	3.428	206.6	3.224	210.5	2.968	217.0	2.712	227.0	2.479	240.0	2.279
264.0	4.462	266.0	3.973	267.5	3.770	269.8	3.567	274.5	3.311	282.2	3.054	293.9	2.818	309.4	2.614
326.2	4.729	328.3	4.241	330.0	4.039	332.5	3.836	337.6	3.580	346.1	3.324	358.9	3.087	375.9	2.881
388.3	4.949	390.5	4.461	392.3	4.259	395.0	4.057	400.4	3.801	409.0	2.545	422.7	3.308	440.6	3.102
450.4	5.137	452.7	4.649	454.5	4.448	457.3	4.245	462.8	3.990	472.0	3.734	485.9	3.497	504.4	3.292
513.0	5.30	516.0	4.81	518.0	4.61	520.0	4.41	525.0	4.17	534.0	3.91	546.0	3.68	563.0	3.47
574.6	5.443	576.9	4.956	578.8	4.754	581.7	4.552	588.0	4.297	596.9	4.042	608.0	3.806	625.0	3.602
637.0	5.59	639.0	5.09	641.0	4.91	644.0	4.70	650.0	4.42	659.0	4.19	672.0	3.95	688.0	3.73
698.7	5.689	701.1	5.201	703.0	5.0	705.9	4.798	711.7	4.544	721.3	4.289	735.8	4.053	755.2	3.839
761.0	5.80	763.0	5.30	766.0	5.11	768.0	4.91	773.0	4.65	784.0	4.40	799.0	4.16	813.0	3.96
822.8	5.894	825.2	5.407	827.1	5.205	830.0	5.004	835.8	4.748	845.5	4.493	860.1	4.258	879.5	4.054

nnes Laboratory, University of Leiden

4. Surface Tension of Saturated Liquid Helium

See Figure 50.

References: Allen, J. F., and A. D. Misener, Proc. Cambr. Phil. Soc., **34**, 299 (1938).

Van Vrk, A. T., W. H. Keesom, and H. K. Onnes, Proc. Roy. Acad. Amsterdam, **28**, 958 (1925).

G. TRANSPORT PROPERTIES

1. Viscosity of Liquid Helium

See Figure 51.

Reference: Keesom, W. H., and G. E. MacWood, Physica, **5**, 737 (1938).

2. Viscosity of Helium Gas at One Atmosphere

Temperature (°R)	Viscosity (lb/ft-hr)
7.2	.0030
20	.0058
40	.0091
60	.0117
80	.0142
100	.0164
120	.0176
140	.0204
160	.0223
180	.0240
200	.0258
220	.0273
240	.0290
260	.0300
280	.0319
300	.0334
320	.0349
340	.0364
360	.0376
380	.0391
400	.0404
420	.0416
460	.0444
510	.0475
560	.0502
610	.0531
660	.0563

See Figure 52.

References: Akin, S. W., Trans. ASME, 72, 751 (1950); Keesom, W. H., Helium, Elsevier, 1942; Onnes, K., and S. Weber, Proc. Roy. Acad. Amsterdam, 15, 1,396 (1913); Ross, J. F., and G. M. Brown, Ind. Eng. Chem., 49, 2,026 (1957).

3. Thermal Conductivity of Liquid Helium

See Figure 53.

References: Grenier, C., Phys. Rev., 81, 598 (1951)
Keesom, W. H., and A. P. Keesom, Physica, 3, 359 (1936).

4. Thermal Conductivity of Helium Gas At One Atmosphere

Temperature (°R)	Temperature (°F)	Thermal Conductivity (Btu/ft-hr)	Temperature (°R)	Temperature (°F)	Thermal Conductivity (Btu/ft-hr)
4	-456	.0022	410	-50	.0725
10	-450	.0063	460	0	.0782
20	-440	.0106	510	50	.0828
30	-430	.0133	560	100	.0885
40	-420	.0160	610	150	.0939
50	-410	.0186	660	200	.1000
60	-400	.0210			
110	-350	.0320			
160	-300	.0400			
210	-250	.0480			
260	-200	.0550			
310	-150	.0610			
360	-100	.0673			

See Figure 54.

References: Akin, S. W., Trans. ASME, 72, 751 (1950).
Keesom, W. H., Helium, Elsevier, 1942.
Ubbink, J. B., and W. J. de Haas, Physica, 10, 465 (1943).

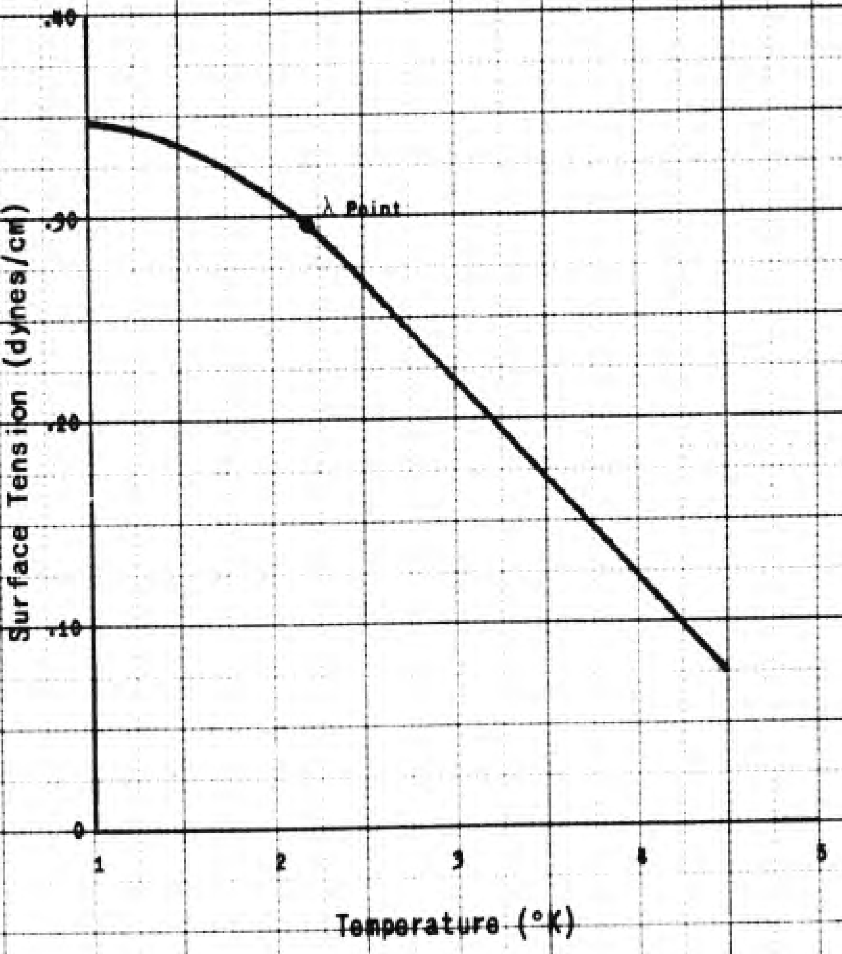


Figure 50

SURFACE TENSION OF LIQUID HELIUM
IN CONTACT WITH SATURATED VAPOR

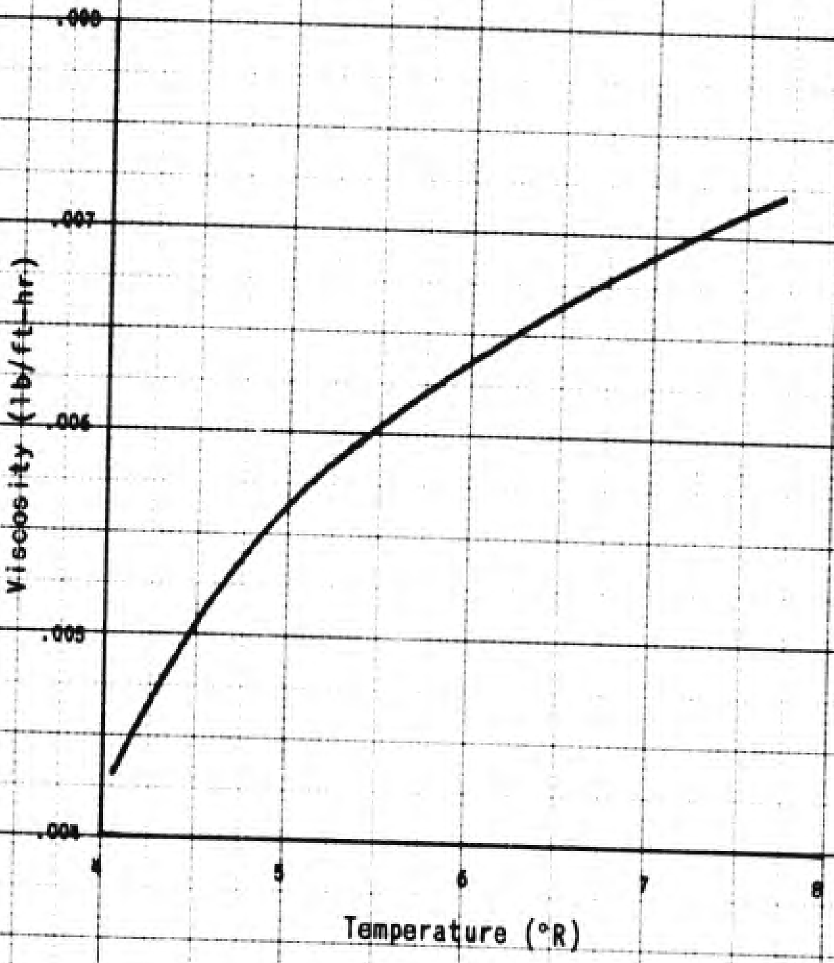


Figure 51

VISCOSITY OF LIQUID HELIUM

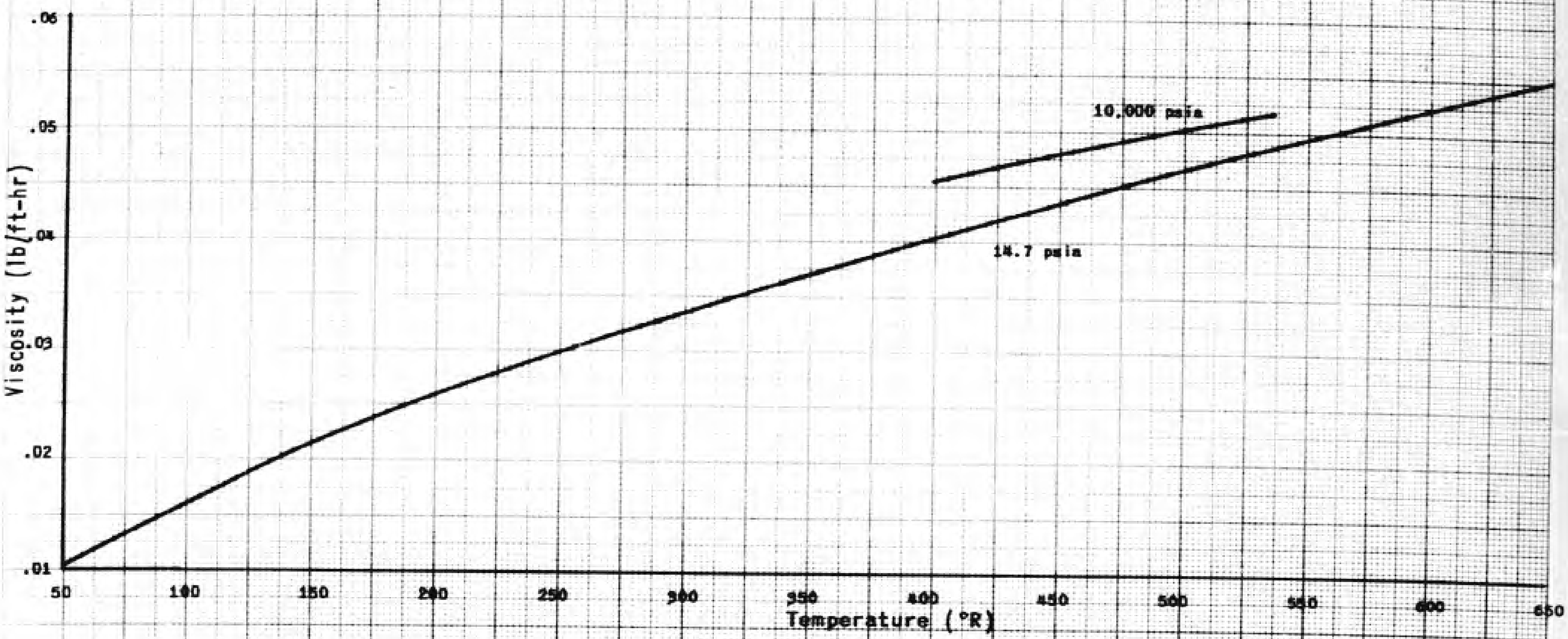


Figure 52
VISCOSITY OF GASEOUS HELIUM

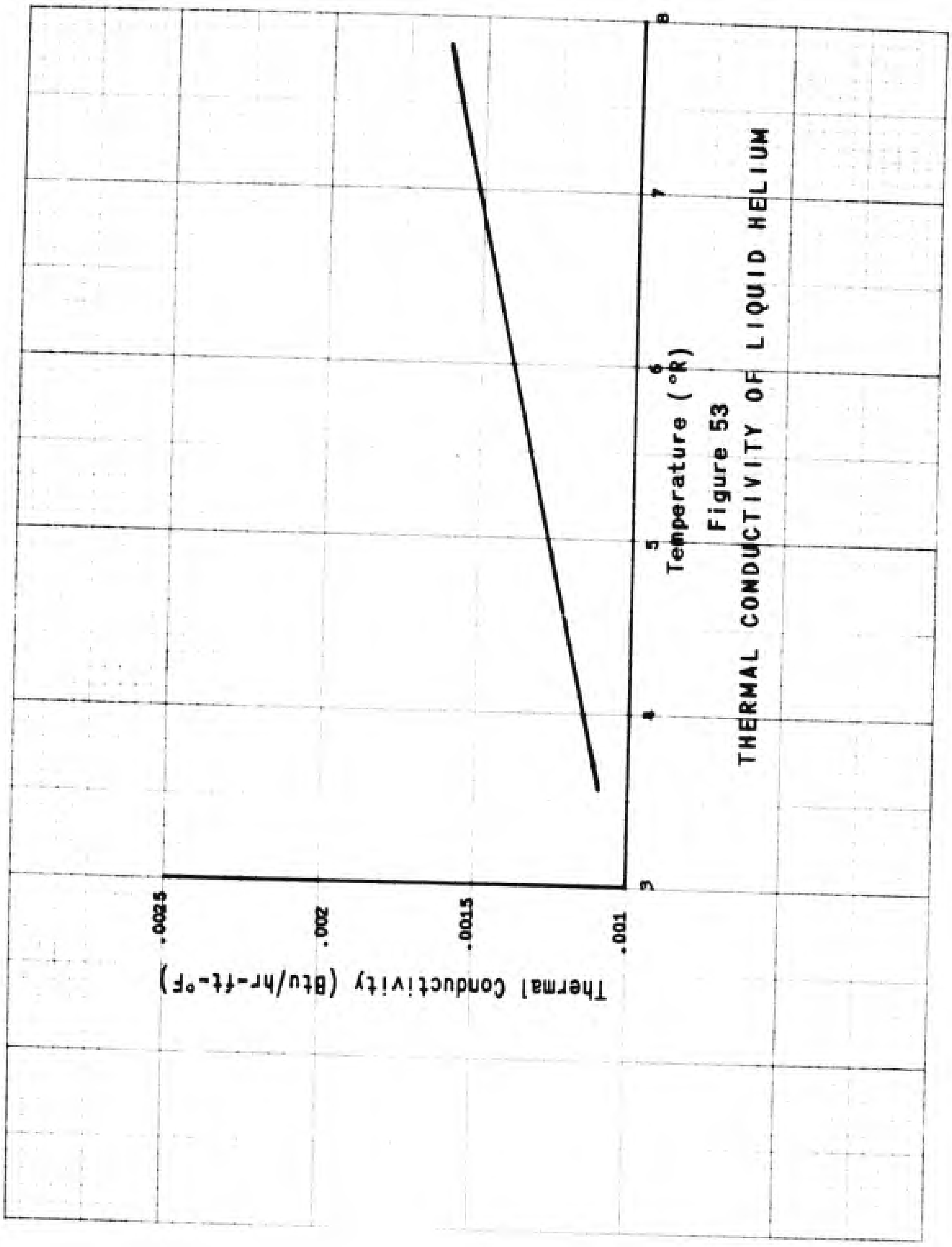


Figure 53
THERMAL CONDUCTIVITY OF LIQUID HELIUM

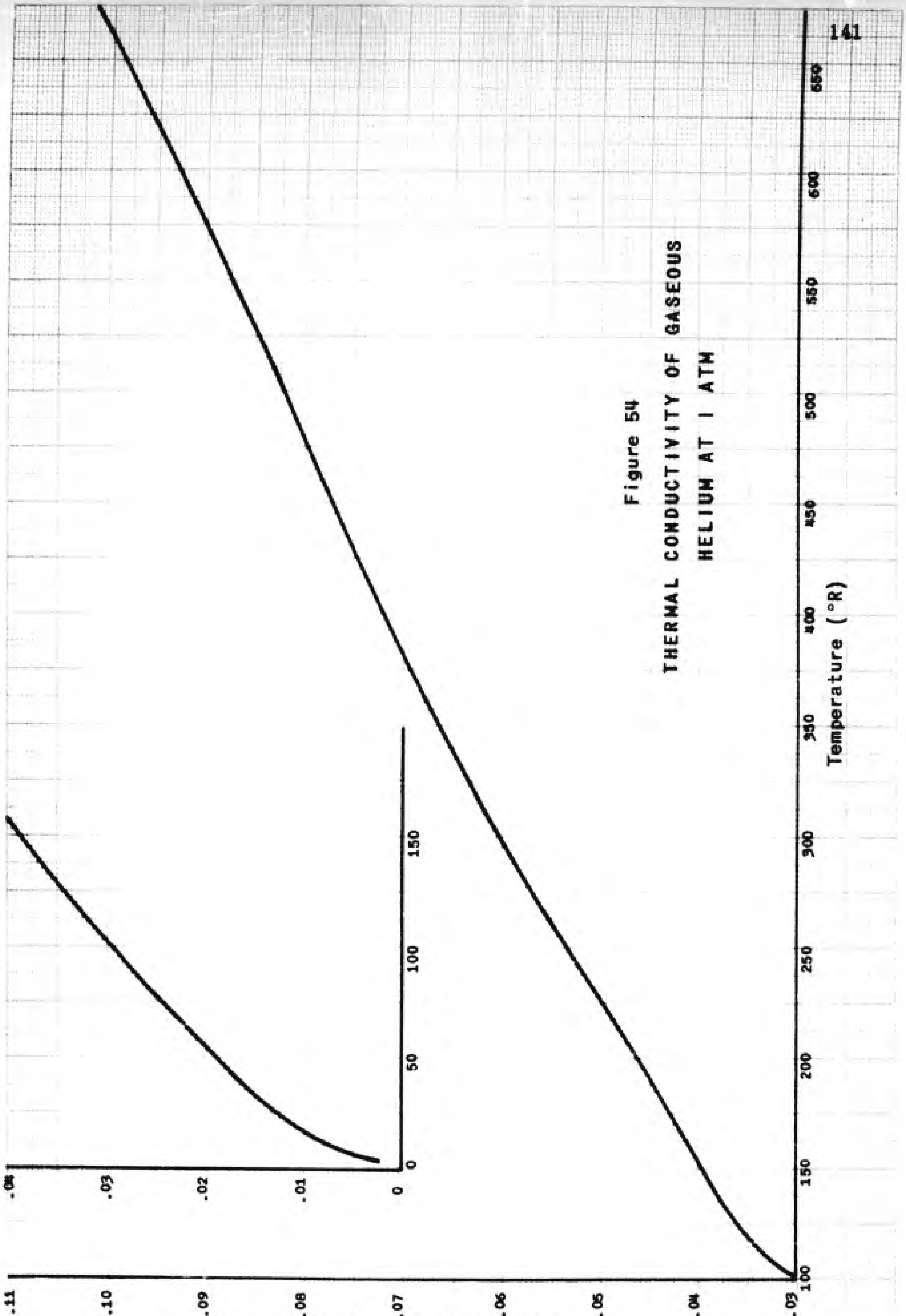


Figure 54

THERMAL CONDUCTIVITY OF GASEOUS HELIUM AT 1 ATM

5. Self-Diffusion Coefficient of Helium

Temperature (°R)	Self-Diffusion Coefficient (ft^3/hr)
25	.113
35	.182
117	1.34
137	1.71
345	7.70
532	15.45

See Figure 55.

Reference: Bendt, P. J., Phys. Rev., 110, 85 (1958).

6. Prandtl Number of Helium Gas

See Figure 56.

Reference: Chelton and Mann, Cryogenic Data Book, University of California Radiation Laboratory, UCRL-3421.

H. ELECTROMAGNETIC PROPERTIES

1. Dielectric Constant of Liquid Helium

See Figure 57.

References: Keesom, W. H., Helium, Elsevier, 1942, p. 323.
Maryott, A. A., and E. R. Smith, National Bureau of Standards Circular 514, 1951.

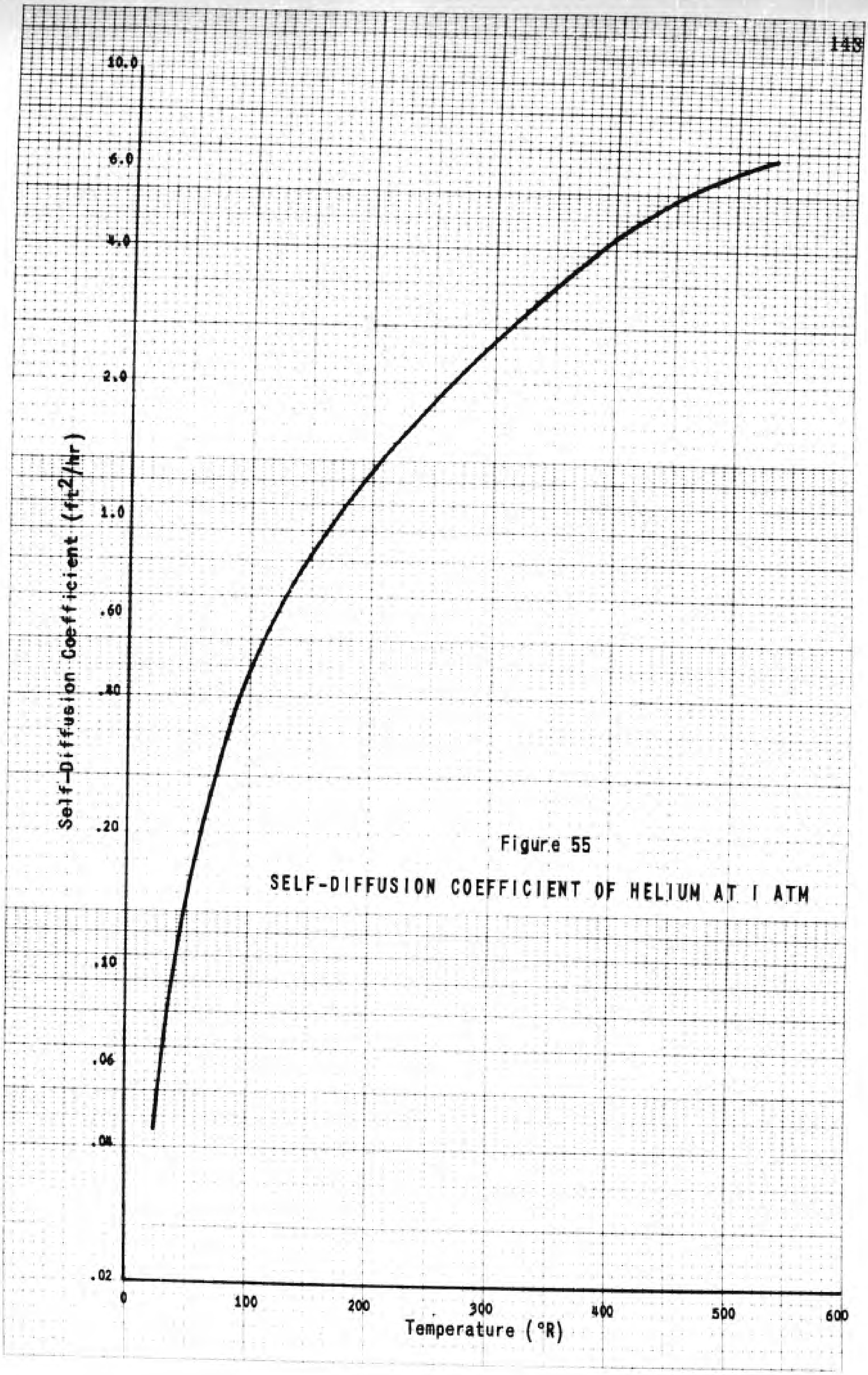


Figure 55

SELF-DIFFUSION COEFFICIENT OF HELIUM AT I ATM

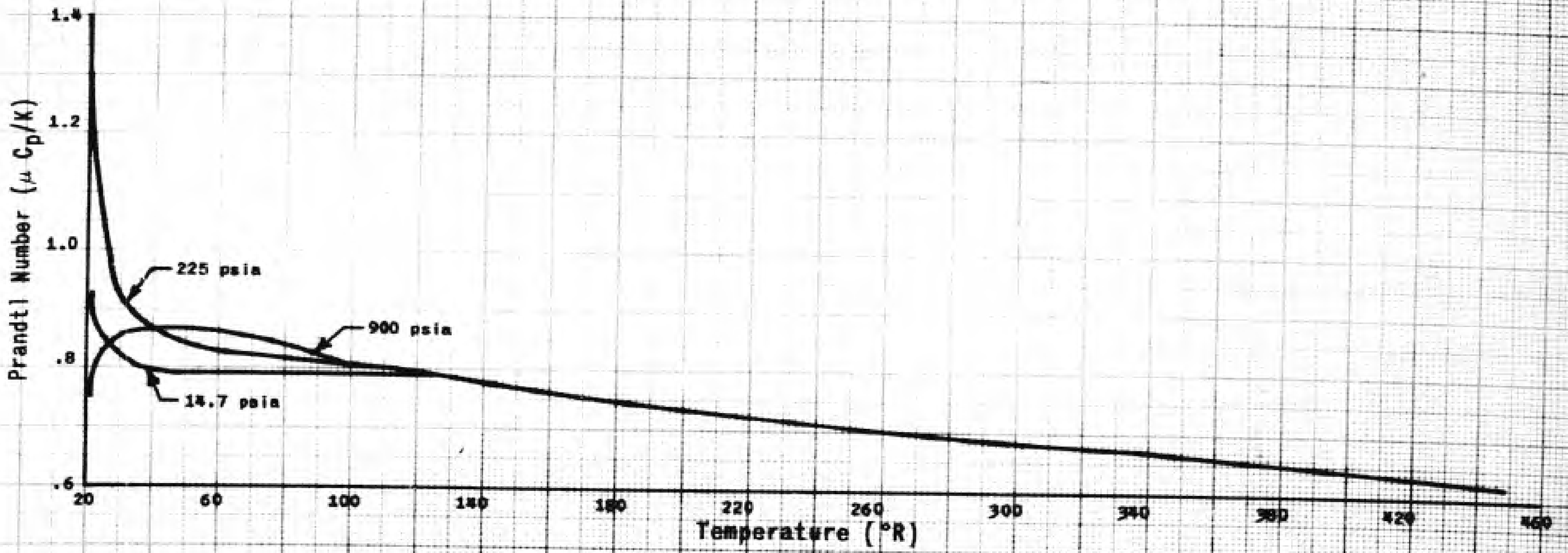


Figure 56
PRANDTL NUMBER OF GASEOUS HELIUM

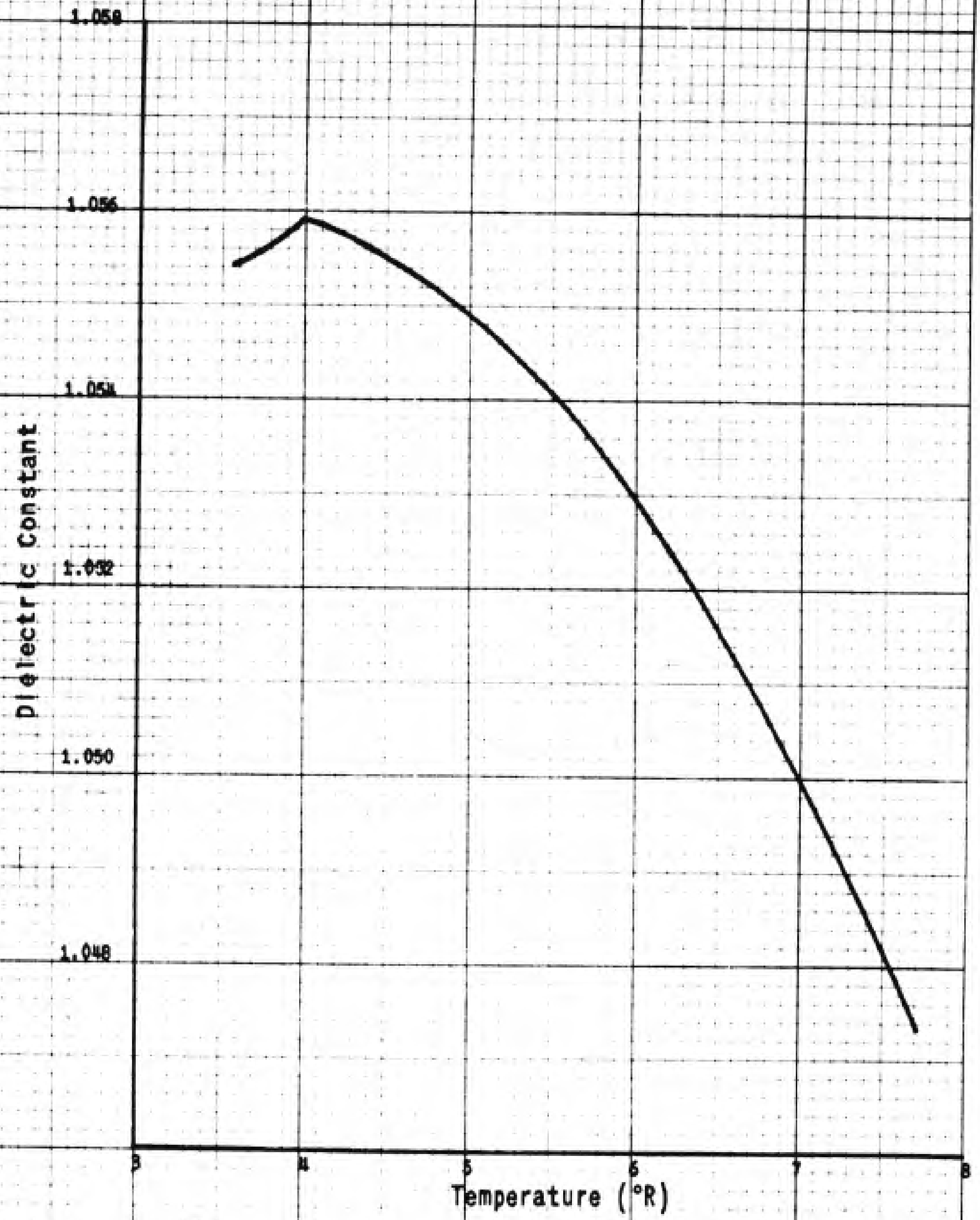


Figure 57

DIELECTRIC CONSTANT OF LIQUID HELIUM

2. Index of Refraction of Saturated Liquid Helium

Temperature		Index of Refraction at 5462.27 Å
(°K)	(°R)	
2.1	3.78	1.028617
2.15	3.87	1.028648
2.1735	3.9123	1.028668
2.2	3.96	1.028654
2.3	4.14	1.028585
2.4	4.32	1.028494
2.5	4.50	1.028382
2.6	4.68	1.028256
2.7	4.86	1.028121
2.8	5.04	1.027975
2.9	5.22	1.027819
3.0	5.40	1.027652
3.1	5.58	1.027473
3.2	5.76	1.027281
3.3	5.94	1.027076
3.4	6.12	1.026859
3.5	6.30	1.026631
3.6	6.48	1.026385
3.7	6.66	1.026124
3.8	6.84	1.025845
3.9	7.02	1.025545
4.0	7.20	1.025223
4.1	7.38	1.024878
4.2	7.56	1.024511

See Figure 58.

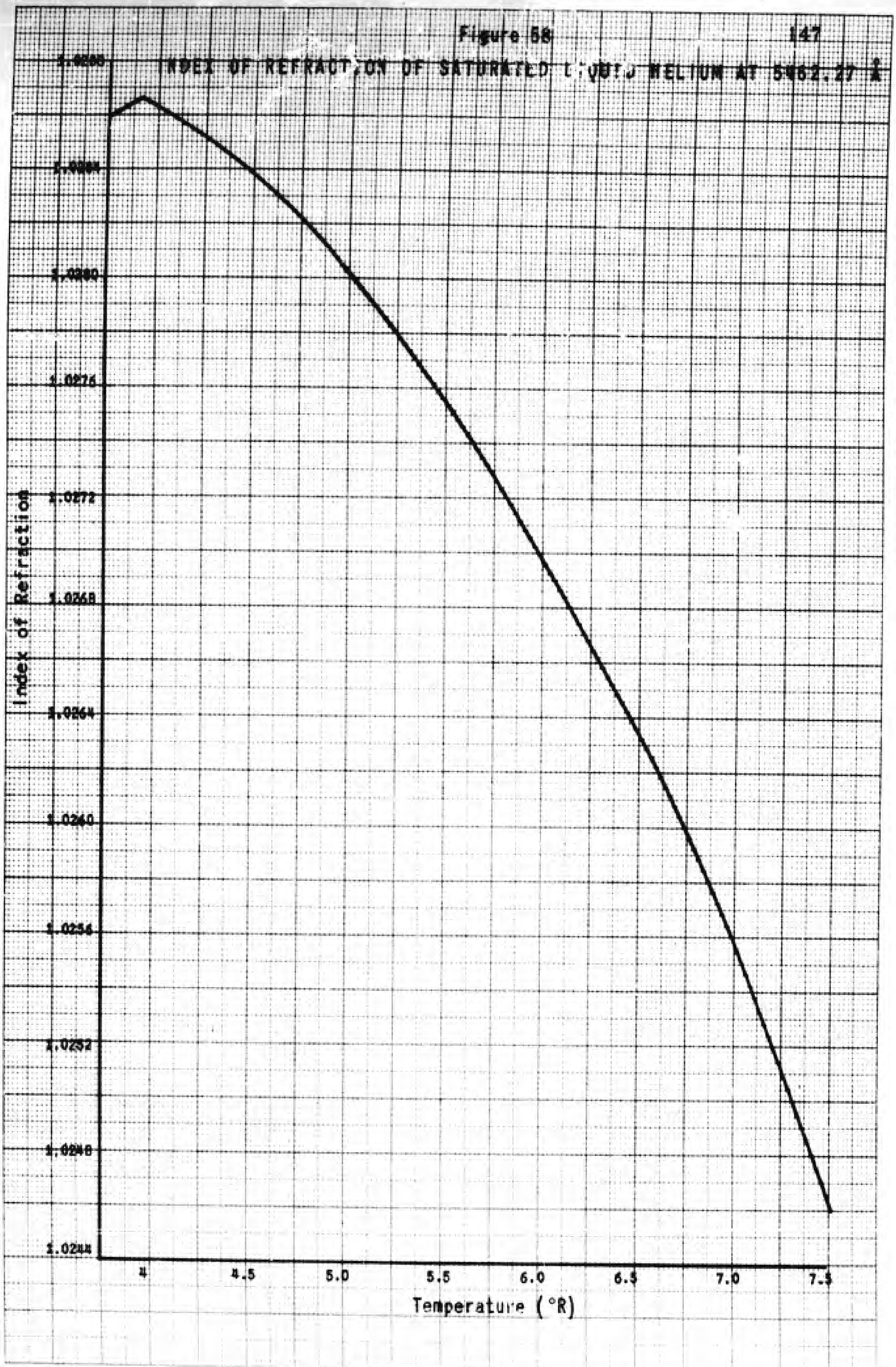
Reference: Edwards, M. H., Canadian Journal of Physics, 36, 884 (1958).

Note: After we completed our work in bringing together the properties of helium, we discovered that the William R. Whittaker Company, Ltd., of Los Angeles, had prepared a similar compilation. The two compilations give much the same information, for they cover much the same source material. The Whittaker report is referenced below:

Simmons, J. T., The Physical and Thermodynamic Properties of Helium, Technical Report D-9027, Engineering and Research Division of William R. Whittaker Company, Ltd., 914 North Citrus Avenue, Los Angeles, California, July 1957.

Figure 58

INDEX OF REFRACTION OF SATURATED LIQUID HELIUM AT 5462.27 Å



VI. PHYSICAL AND THERMODYNAMIC PROPERTIES OF NITROGEN

A. GENERAL CONSIDERATIONS

1. Stable Isotopes and Molecular Weight

Isotope	Natural Abundance (%)	Atomic Weight	
		Chemical Scale	Physical Scale
N^{14}	99.64	14.00740	14.00753
N^{15}	0.36	15.0048	15.0049

The molecular weight of N_2 is taken as 28.02.

Reference: Handbook of Chemistry and Physics, ed. C. D. Hodgman, 36th Ed. Chemical Rubber Publishing Co., Cleveland, Ohio. 1954.

2. Melting Point and Triple Point of Nitrogen

Melting Point

-346 °F

113.7°R

63.1°K

-210.1°C

Triple Point

Temperature	Pressure
63.16°K	1.82 psia
-210 °C	.1238 atm
-345.9 °R	93.0 mm of Hg
113.8 °R	

Reference: Hilsenrath, J., et al., National Bureau of Standards Circular 564, November 1, 1955.

3. Critical Properties and Boiling Point

T_c	P_c	D_c
126.1°K	33.5 atm	19.6 lb/ft^3
-147.0°C	492 psia	
-232.7°F		
227.0°R		

Boiling Point at 1 atm

-195.7°C
77.5°K
139.5°R
-320.2°F

Reference: Hilsenrath, J., *et al.*, National Bureau of Standards Circular 564, November 1, 1955.

4. Effect of Pressure on Freezing Point of Liquid Nitrogen

See Figure 59.

Reference: Bridgman, P. W., *Proc. Amer. Acad. Arts Sci.*, *70* 1 (1935).

B. VAPOR PRESSURE

1. Vapor Pressure of Solid Nitrogen

Temperature		Vapor Pressure	
(°K)	(°R)	(mm of Hg)	(psia)
52	93.6	5.7	0.116
54	97.2	10.2	0.197
56	100.8	17.6	0.341
58	104.4	29.4	0.568
60	108.0	47.2	0.913
62	111.6	73.6	1.424
63.14	113.7	94.0	1.820

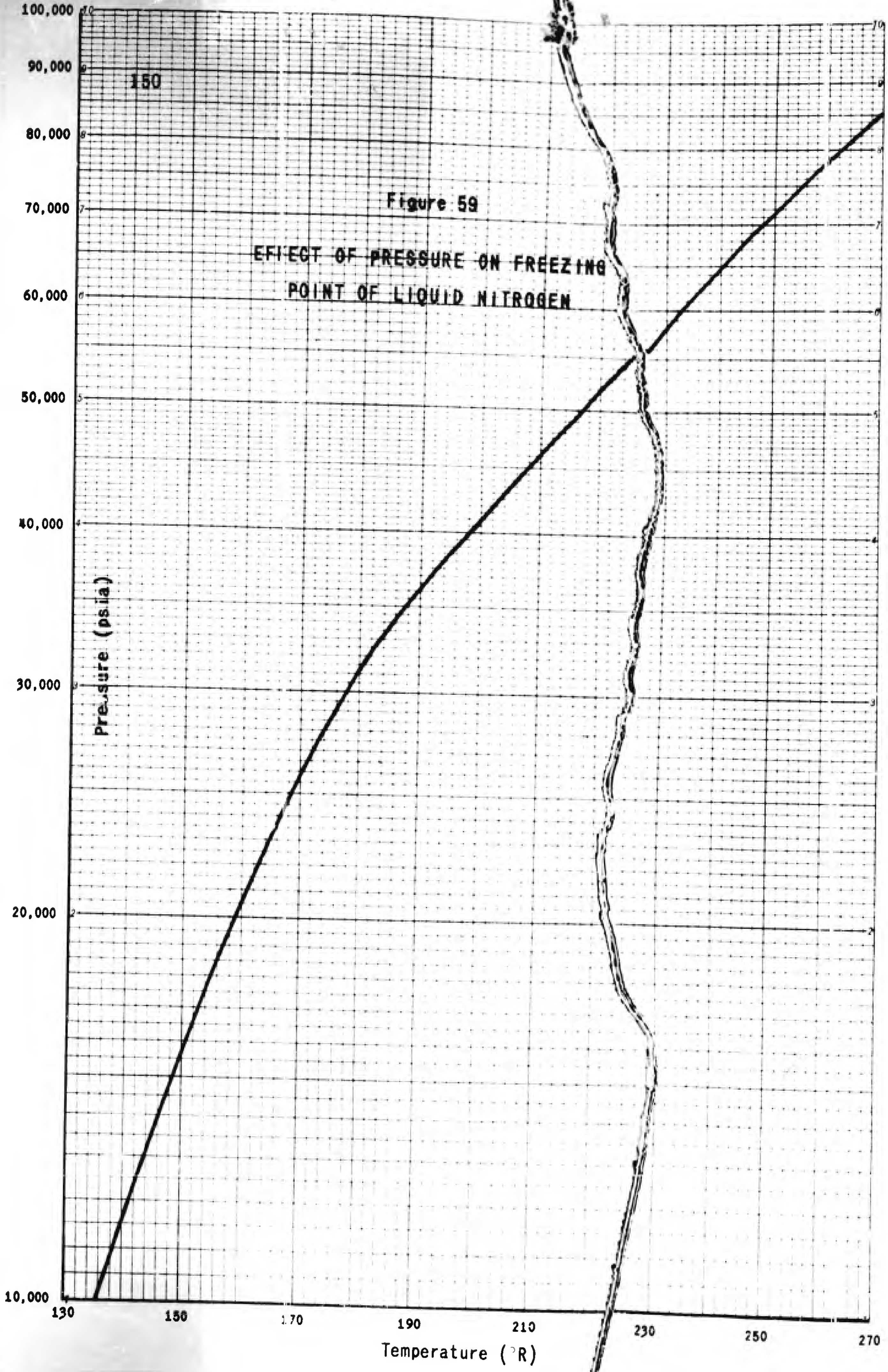


Figure 59

EFFECT OF PRESSURE ON FREEZING POINT OF LIQUID NITROGEN

$$\log P = A - B/T$$

Units of P	A
mm of Hg	7.659
atm	4.778
psia	5.945

Units of T	B
°K	359.1
°R	646.4

See Figure 60.

References: Giauque, W. F., and J. O. Clayton, J. Amer. Chem. Soc., 55, 4875 (1933).

Hilsenrath, J., *et al.*, National Bureau of Standards Circular 564, November 1, 1955.

2. Vapor Pressure of Liquid Nitrogen

Temperature		Vapor Pressure		Temperature		Vapor Pressure	
(°K)	(°R)	(atm)	(psia)	(°K)	(°R)	(atm)	(psia)
64	115.2	.1439	2.115	96	172.8	5.76	84.6
66	118.8	.2028	2.980	98	176.4	6.68	98.1
68	122.4	.2797	4.110	100	180.0	7.70	113.1
70	126.0	.3785	5.56	102	183.6	8.83	129.7
72	129.6	.503	7.40	104	187.2	10.07	147.9
74	133.2	.658	9.67	106	190.8	11.42	167.9
76	136.8	.847	12.44	108	194.4	12.91	189.7
78	140.4	1.073	15.76	110	198.0	14.52	213.3
80	144.0	1.341	19.71	112	201.6	16.26	239.0
82	147.6	1.657	24.35	114	205.2	18.15	266.8
84	151.2	2.026	29.77	116	208.8	20.20	296.8
86	154.8	2.460	36.15	118	212.4	22.41	329.4
88	158.4	2.967	43.60	120	216.0	24.81	364.6
90	162.0	3.548	52.1	122	219.6	27.40	402.7
92	165.6	4.203	61.8	124	223.2	30.21	444.0
94	169.2	4.937	72.5	126	226.8	33.27	489.0

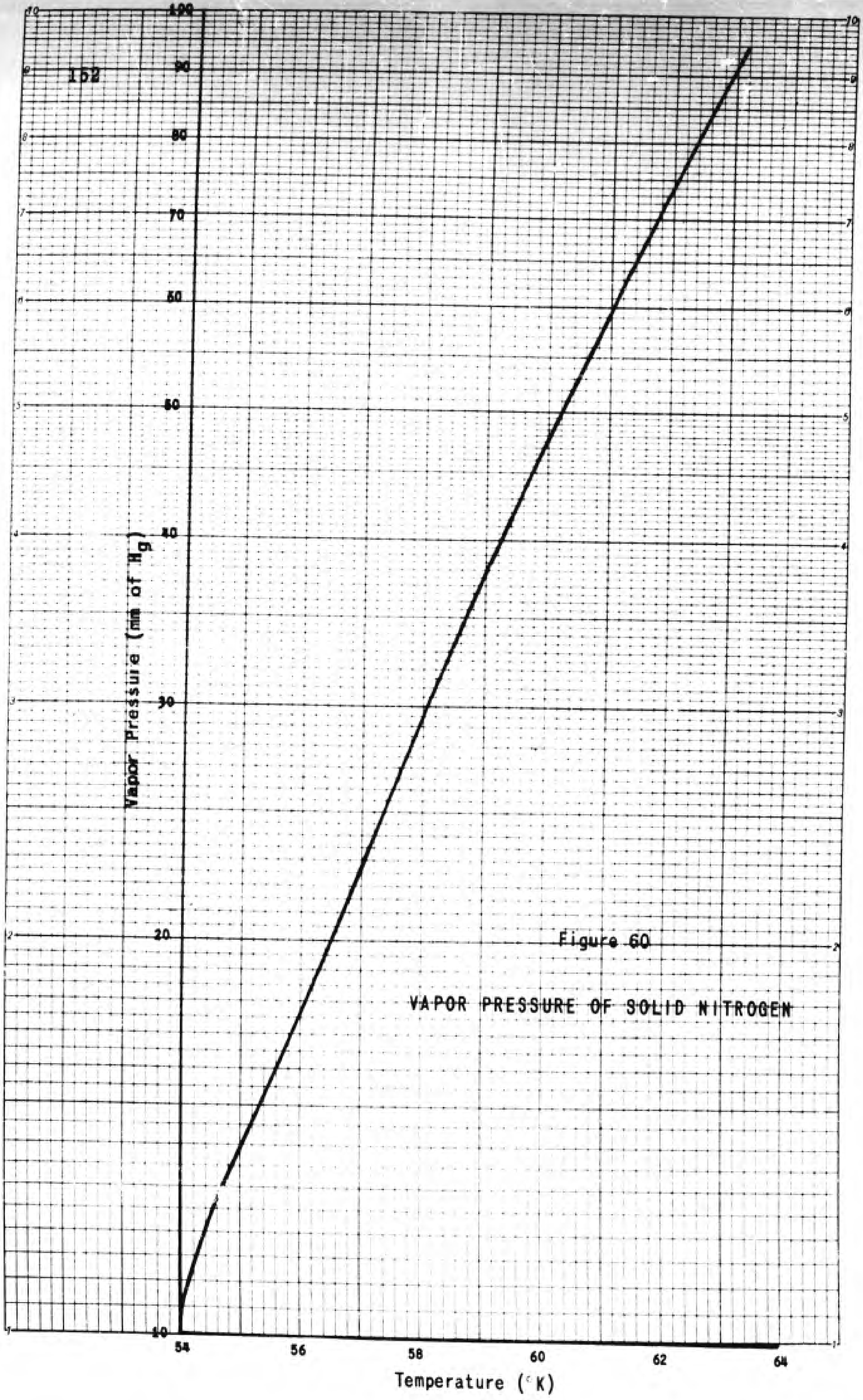


Figure 60

VAPOR PRESSURE OF SOLID NITROGEN

$$\log P = 3.72 - 294/T + .001032T$$

P = pressure, atm

T = temperature, °K

$$\log P = 4.89 - 529/T + .000575T$$

P = pressure, psia

T = temperature, °R

See Figures 61-63.

References: Friedman, A. S., and D. White, J. Amer. Chem. Soc., 72, 3931 (1950).

Hilsenrath, J., et al., National Bureau of Standards Circular 564, November 1, 1955.

C. LIQUID AND SOLID DENSITIES

1. Density of Solid Nitrogen

Temperature (°K)	Density (gm/cc)	(lb/ft³)
20.6	1.0265	64.08
63.0	0.8792	54.89

Note: There is a solid-phase change at 35.6°K.

Reference: Dewar, Proc. Roy. Soc. (London), A73, 251 (1904).

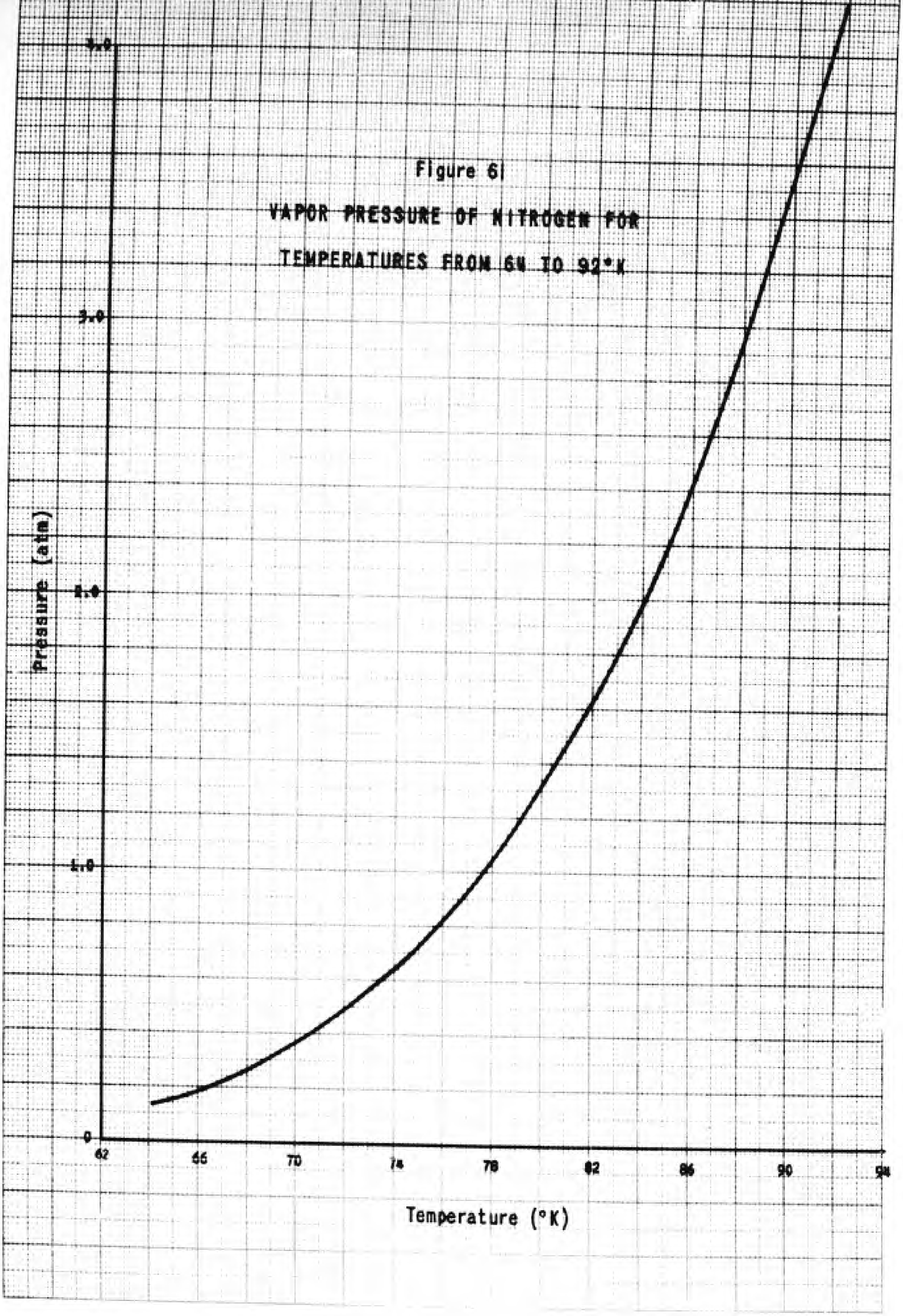


Figure 61

VAPOR PRESSURE OF NITROGEN FOR TEMPERATURES FROM 64 TO 92°K

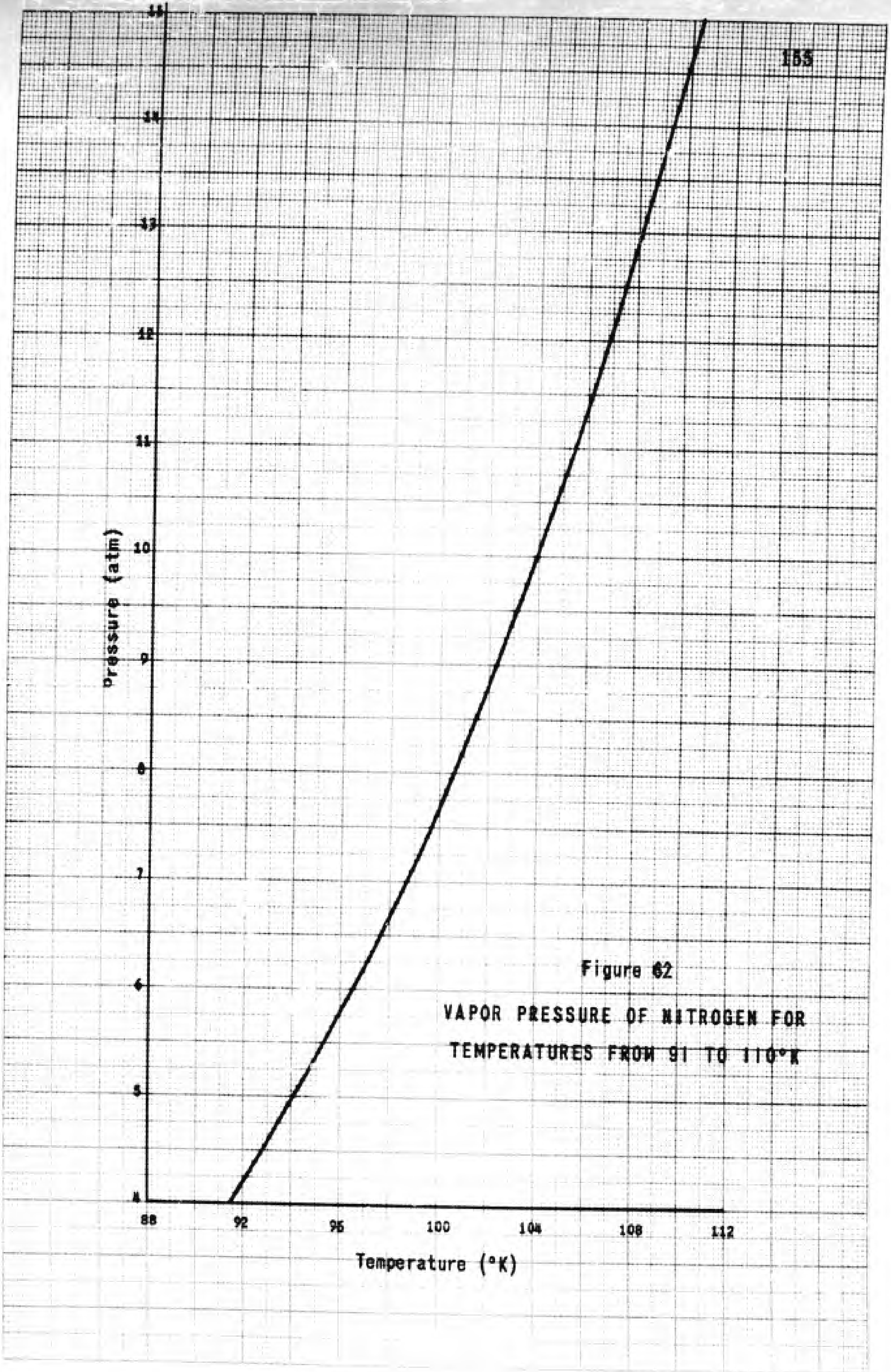


Figure 62

VAPOR PRESSURE OF NITROGEN FOR TEMPERATURES FROM 91 TO 110°K

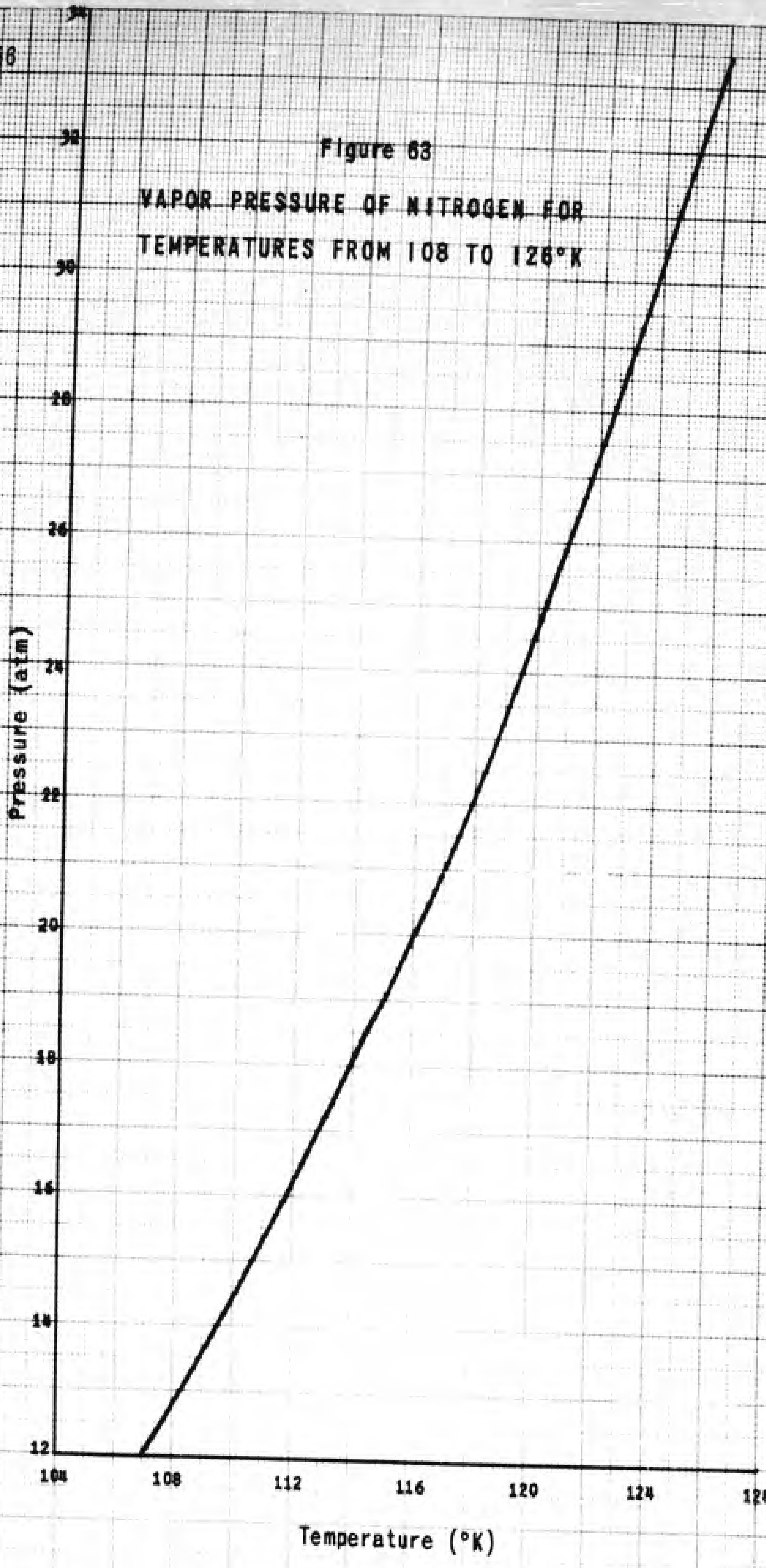


Figure 63

VAPOR PRESSURE OF NITROGEN FOR TEMPERATURES FROM 108 TO 126°K

2. Density of Liquid Nitrogen At One Atmosphere

Reference	Temperature		Density	
	(°R)	(°K)	(lb/ft^3)	(gm/cc)
R & S	115	63.9	54.4	0.872
R & S	115.8	64.3	54.2	0.870
R & S	116.8	64.8	53.9	0.865
I, B, & V	117	65.0	54.1	0.868
I, B, & V	122.3	68.0	53.1	0.854
R & S	124.4	69.1	52.8	0.848
R & S	124.5	69.2	53.1	0.852
I, B, & V	127.9	71.0	52.2	0.839
R & S	128.3	71.4	52.2	0.838
I, B, & V	136.9	74.0	51.4	0.825
R & S	137.0	76.1	51.5	0.816
I, B, & V	138.8	77.0	50.6	0.811
R & S	139.2	77.3	50.5	0.810
B. of Mines	139.3	77.4	50.4	0.807

See Figure 64.

References: Rudenko, N. S., and L. W. Schubnikow, Phys. Z. Sowjetunion, 6, 470 (1934).

U. S. Bureau of Mines, Technical Paper 424, 1928.

van Itterbeek, A., A. de Bock and L. Verhaegen, Physica 15, 624 (1949).

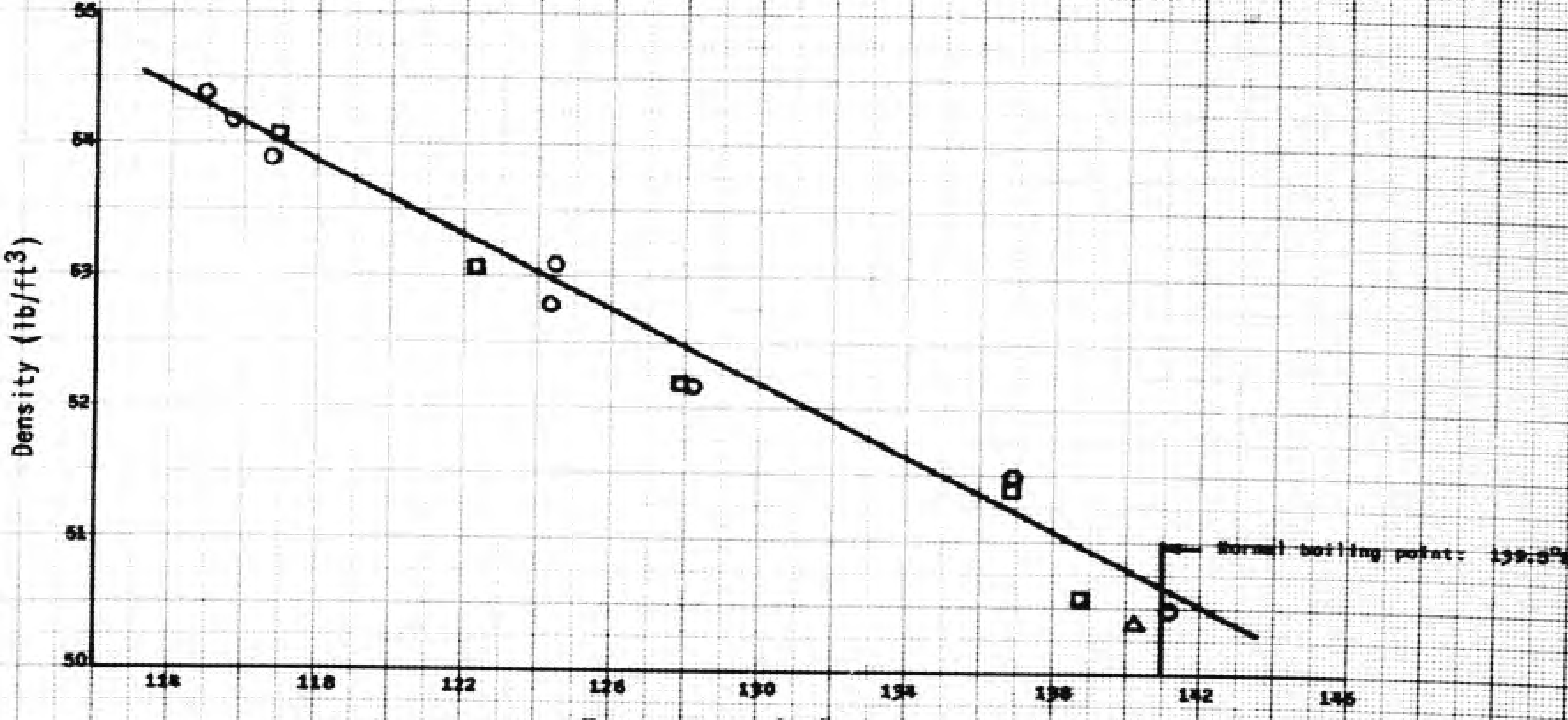


Figure 64

DENSITY OF LIQUID NITROGEN AT 1 ATM

3. Density and Specific Volume of Saturated Liquid Nitrogen

Temperature		Density and Specific Volume		Density and Specific Volume	
(°R)	(°K)	(lb/ft^3)	(ft^3/lb)	(gm/cc)	(cc/g-mole)
139.3	77.4	50.4	.01985	.807	34.8
145	80.5	49.6	.02018	.795	35.3
150	83.3	48.75	.02053	.782	35.9
155	86.1	47.9	.0209	.769	36.5
160	88.8	47.0	.02129	.754	37.2
165	91.7	46.1	.02171	.740	37.9
170	94.4	45.15	.02215	.725	38.7
175	97.2	44.2	.02263	.710	39.5
180	100	43.2	.02316	.694	40.5
185	102.8	42.1	.02376	.675	41.6
190	105.5	40.9	.02444	.655	42.8
195	108.2	39.7	.0252	.636	44.1
200	111.1	38.4	.02604	.616	45.1
205	113.9	37.0	.0270	.594	47.2
210	116.7	35.5	.02820	.569	49.4
215	119.3	33.4	.02997	.535	52.5
220	122.1	30.9	.03238	.495	56.7
225	125.0	27.6	.03623	.442	63.5
227.0	126.1	19.6	.05092	.314	89.4

See Figure 65.

Reference: Bloomer, O. T., and K. N. Rao, Thermodynamic Properties of Nitrogen. Institute of Gas Technology Research Bulletin 18, 1952.

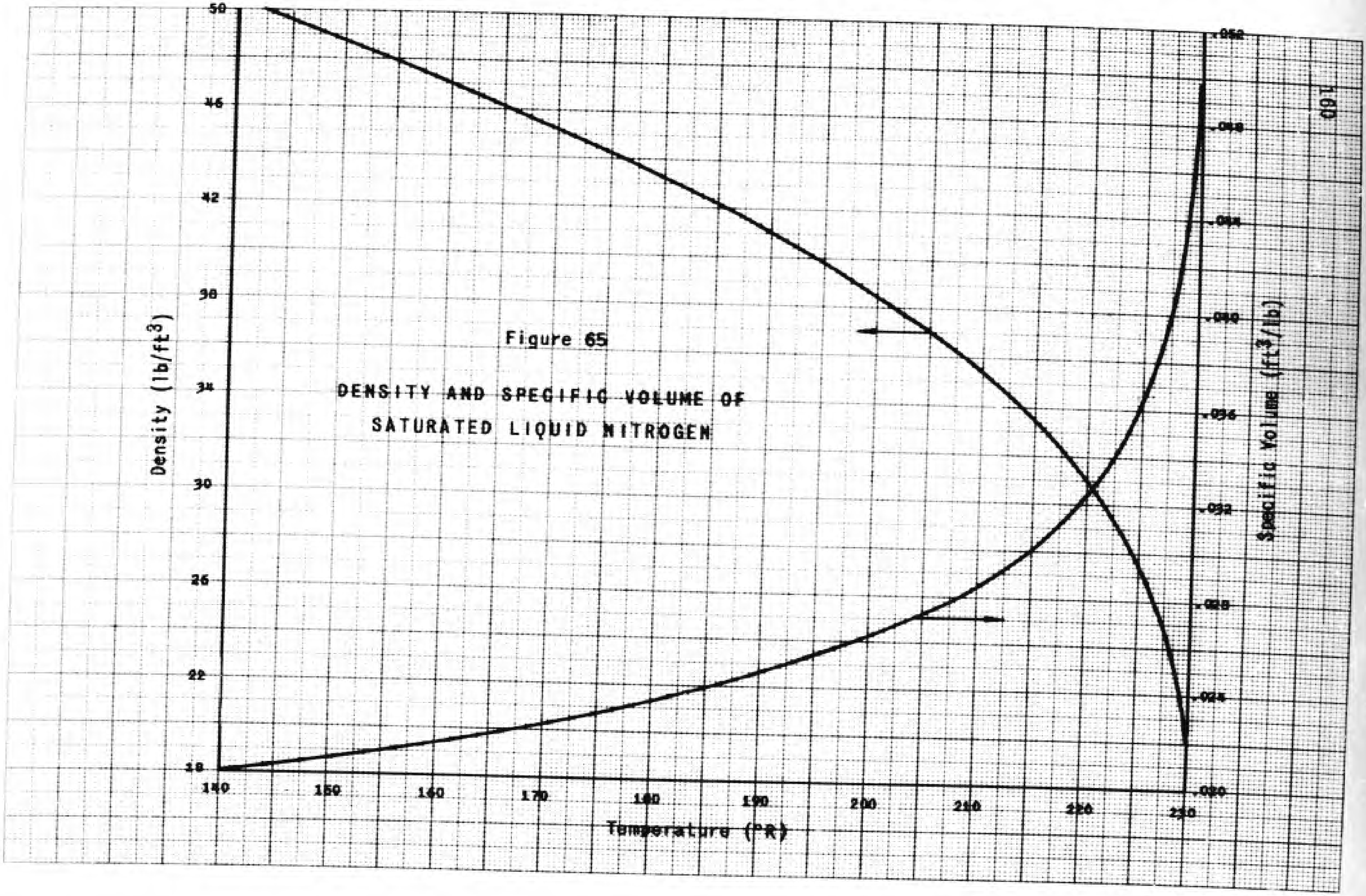


Figure 65

DENSITY AND SPECIFIC VOLUME OF SATURATED LIQUID NITROGEN

4. Adiabatic Coefficient of Compressibility of Liquid Nitrogen

$$\beta_s = \frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_s$$

where

β_s = adiabatic coefficient of compressibility (constant entropy)

V = specific volume

P = pressure

Temperature		Adiabatic Coefficient of Compressibility		
(°R)	(°K)	(cm^2/dyne)	(in.^{2}/lb)	(1/atm)
138.6	77.0	159.2×10^{-12}	10.95×10^{-6}	16.10×10^{-5}
133.0	74.0	146.4	10.09	14.80
127.9	71.0	134.9	9.35	13.60
122.2	68.0	124.4	8.62	12.07
117.0	65.0	114.1	7.86	11.56

See Figure 66.

Reference: van Itterbeek, A., A. de Bock, and L. Verhaegen, *Physica*, 15, 624 (1949).

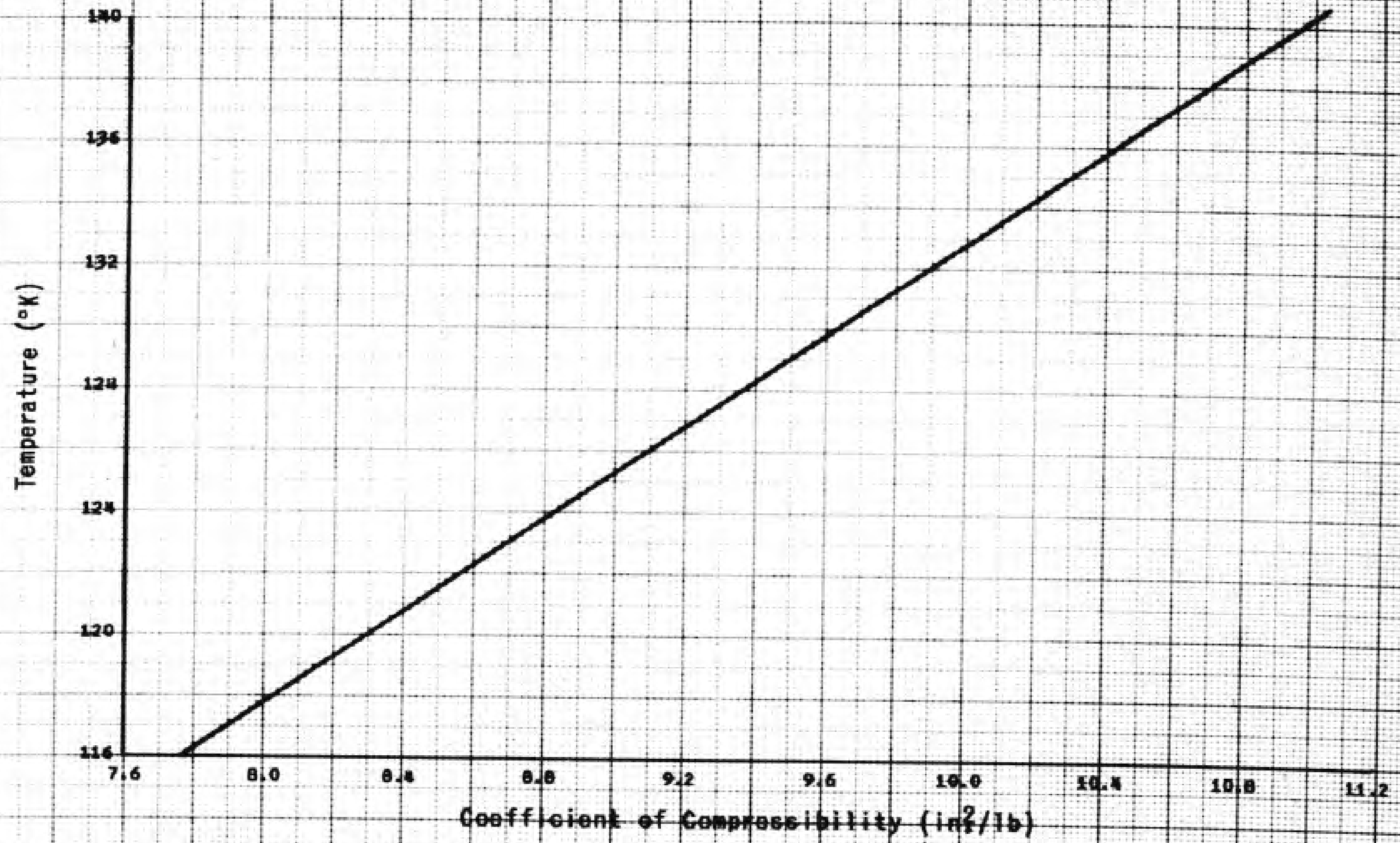


Figure 66

ADIABATIC COEFFICIENT OF COMPRESSIBILITY OF LIQUID NITROGEN

D. PRESSURE-VOLUME-TEMPERATURE RELATIONS FOR GAS

1. Equation of State

Beattie-Bridgeman Equation:

$$PV = \frac{RT^3B_o - A_oT^2 - Rc}{VT^2} + \frac{RT^3B_ob - aA_oT^2 - RB_oC}{V^2T^2} + \frac{RB_obc}{V^3T^2}$$

Maximum pressure	1970 psia (134 atm)
Temperature range	225 - 1200°R (124 - 673°K)
Minimum volume	0.0975 ft^3/lb (182 cc/g-mole)

Constants	Units P - psia V - ft^3/lb T - °R	atm liters/g-mole °K
R	0.3353	.08206
A_o	11.30	1.3445
a	0.01495	0.02617
B_o	0.02885	0.05046
b	-0.00396	-0.00691
c	140,000	42,000

Reference: Beattie, J. A. and O. C. Bridgeman, Proc. Amer. Acad. Arts Sci., 63, 229 (1928).

2. Compressibility Factor of Nitrogen

See Figures 67 and 68.

Reference: Bloomer, O. T., and K. N. Rao Thermodynamic Properties of Nitrogen, Institute of Gas Technology Research Bulletin 18, 1952.

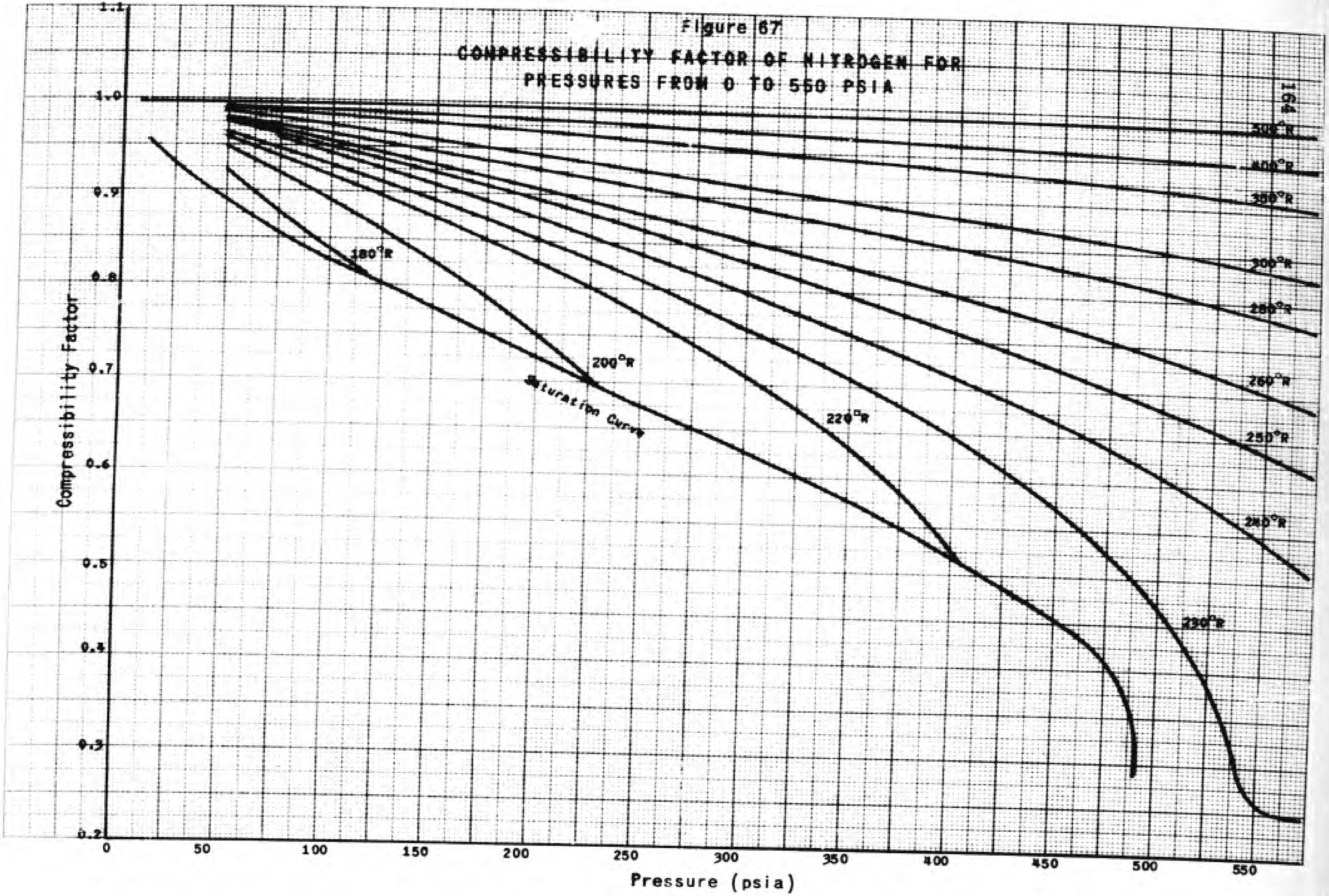


Figure 67

COMPRESSIBILITY FACTOR OF NITROGEN FOR PRESSURES FROM 0 TO 550 PSIA

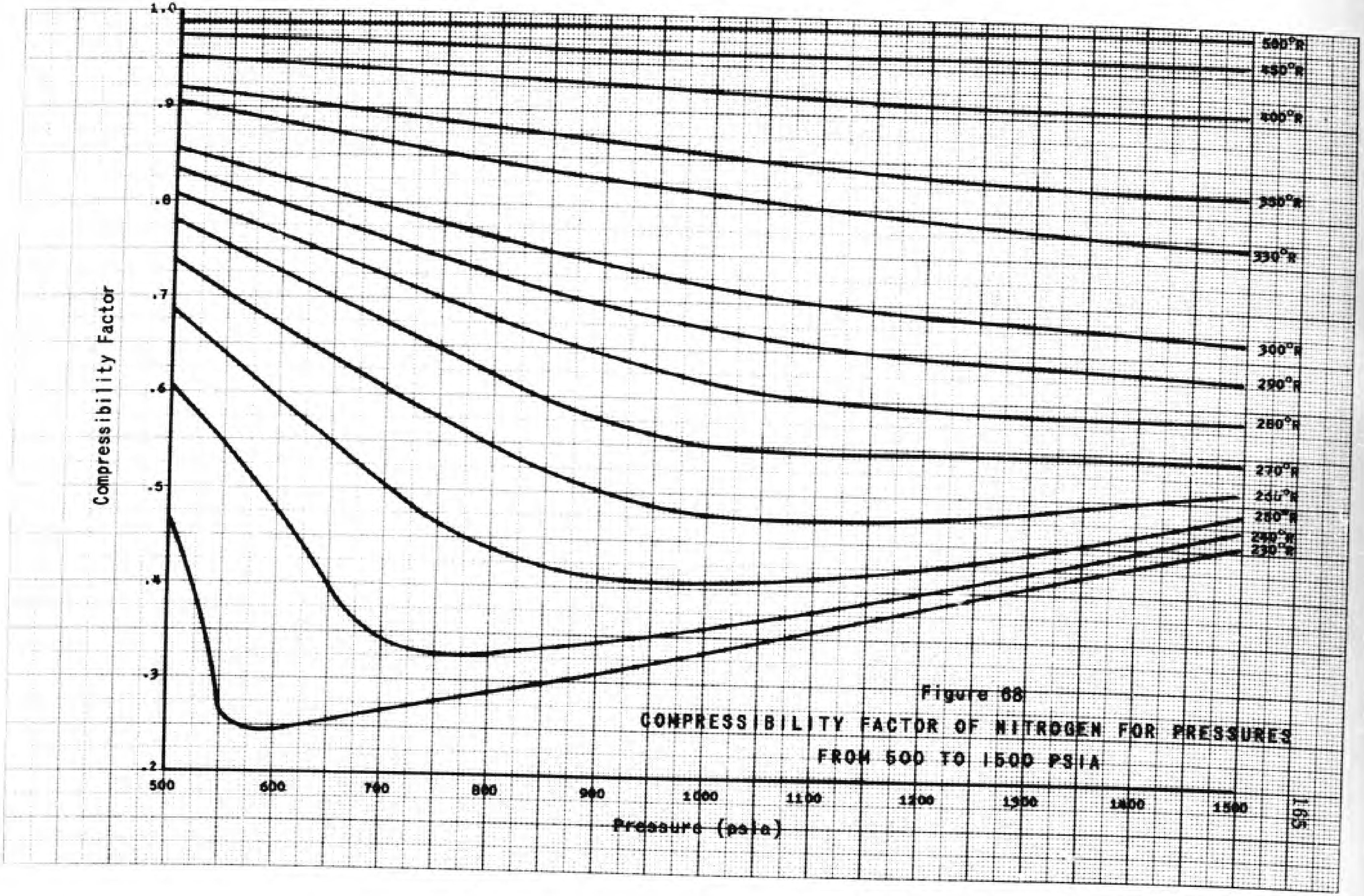


Figure 68

COMPRESSIBILITY FACTOR OF NITROGEN FOR PRESSURES FROM 500 TO 1500 PSIA

E. HEAT CAPACITY

1. Heat Capacity of Solid Nitrogen

Temperature (°R)	Heat Capacity, Cp (Btu/lb-°F)
28.5	0.111
31.8	0.137
35.1	0.163
39.4	0.194
44.1	0.226
48.8	0.256
51.0	0.269
53.8	0.290
56.3	0.308
59.1	0.335
62.0	0.365
63.5	0.380
64.1	transition point
70.4	0.319
77.9	0.332
86.6	0.348
93.4	0.359
96.5	0.365
100.7	0.372
104.3	0.379
110.4	0.394

See Figure 69.

Reference: Giauque, W. F., and J. O. Clayton, J. Am. Chem. Soc., 55, 4875 (1933).

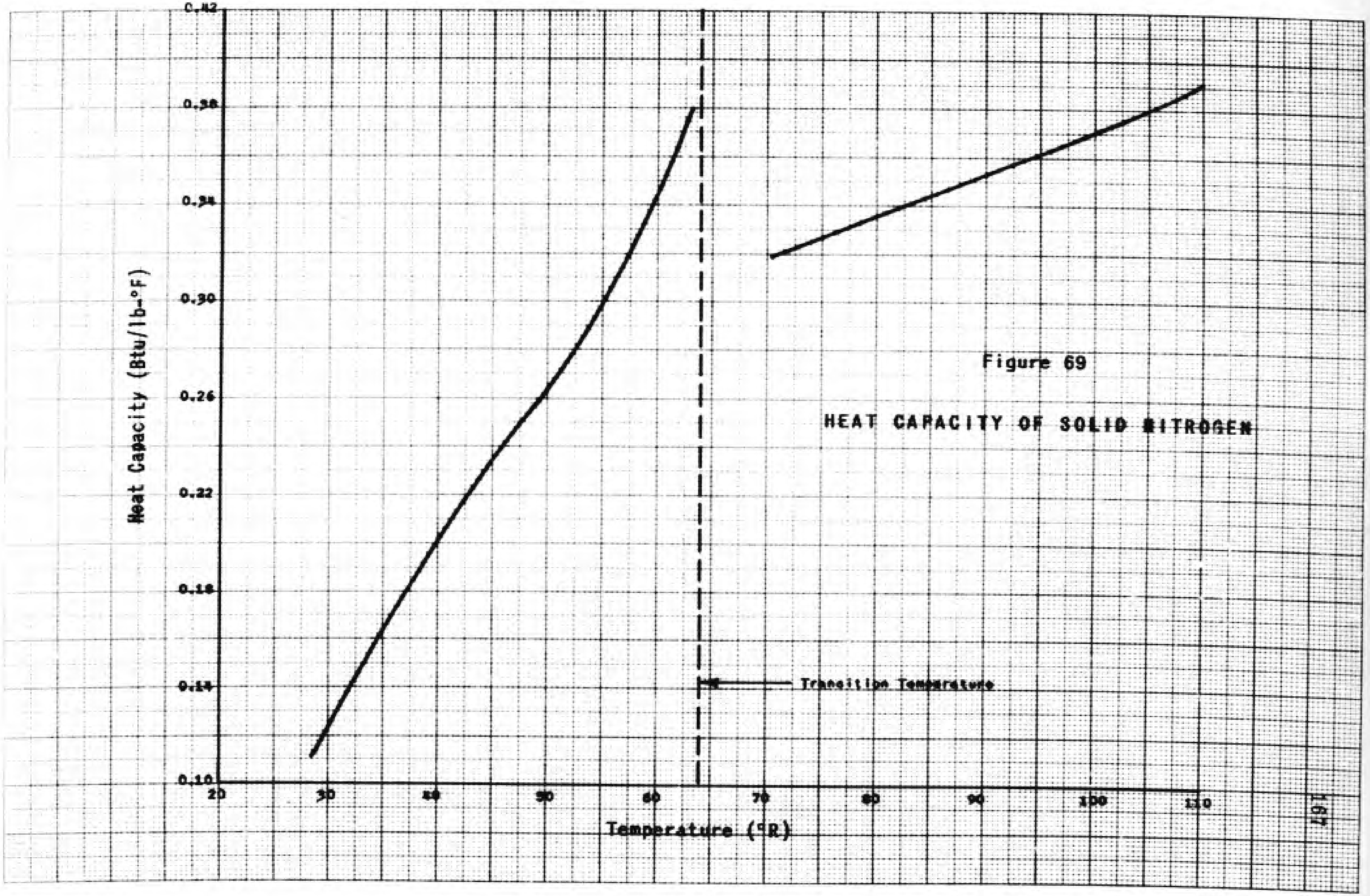


Figure 69

HEAT CAPACITY OF SOLID NITROGEN

2. Heat Capacity of Liquid Nitrogen

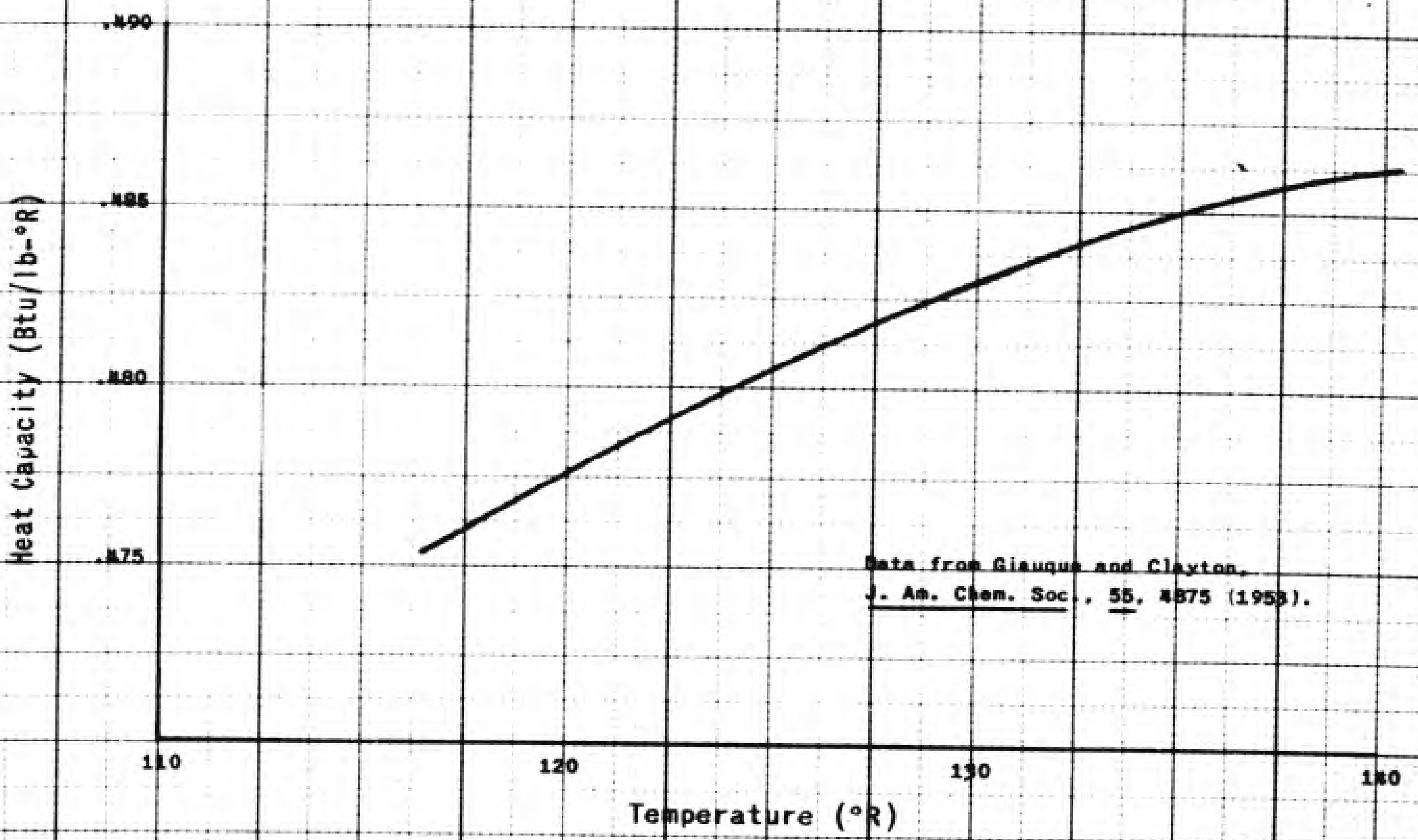
Temperature (°R)	Heat Capacity, C_p (Btu/lb - °F)
113.7	melting point
117.0	0.476
123.0	0.480
126.3	0.480
131.0	0.483
134.2	0.484
138.0	0.486
140.0	0.486

See Figure 70.

Reference: Giauque, W. F., and J. O. Clayton, J. Am. Chem. Soc., 55, 4875 (1933).

3. Heat Capacity of Gaseous Nitrogen

Temperature		Heat Capacity (Btu/lb - °F)				
(°K)	(°R)	1 atm	10 atm	40 atm	70 atm	100 atm
100	180	.256				
110	198	.253				
120	216	.252				
130	234	.251				
140	252	.251	.281			
150	270	.250	.272			
160	288	.250	.268			
170	306	.249	.264			
180	324	.249	.262	.321		
190	342	.249	.260	.306	.370	
200	360	.249	.259	.296	.345	.400
210	378	.249	.257	.289	.328	.368
220	396	.249	.256	.284	.314	.346
230	414	.249	.255	.280	.306	.332
240	432	.249	.254	.276	.299	.320
250	450	.249	.254	.273	.293	.311
260	468	.249	.253	.270	.288	.304
270	486	.249	.253	.268	.284	.298
280	504	.249	.253	.266	.280	.293
290	522	.249	.252	.265	.277	.289
300	540	.249	.252	.264	.276	.285



Data from Giauque and Clayton, *J. Am. Chem. Soc.*, 55, 4875 (1953).

Figure 70

HEAT CAPACITY OF LIQUID NITROGEN

See Figure 71.

Reference: Hilsenrath, J., *et al.*, National Bureau of Standards Circular 564, November 1, 1955.

4. Ratio of Specific Heats of Nitrogen Gas

See Figure 72.

Reference: Hilsenrath, J., *et al.*, National Bureau of Standards Circular 564, November 1, 1955.

F. THERMODYNAMIC PROPERTIES

1. Heat of Transition and Fusion of Solid Nitrogen

Transition	54.7 cal/g-mole	or 3.52 Btu/lb
Fusion	172.3 cal/g-mole	or 11.08 Btu/lb

Reference: Giauque, W. F. and J. O. Clayton, *J. Am. Chem. Soc.*, *55*, 4875 (1933).

2. Enthalpy of Liquid Nitrogen at One Atmosphere

Temperature (°R)	Enthalpy (Btu/lb)
113.7	-12.08
115	-11.48
120	- 9.40
125	7.00
130	- 4.60
135	- 2.18
139.5	0.00

Reference: Calculated from Specific Heat Data of Giauque, W. F., and J. O. Clayton, *J. Am. Chem. Soc.*, *55*, 4875 (1933)

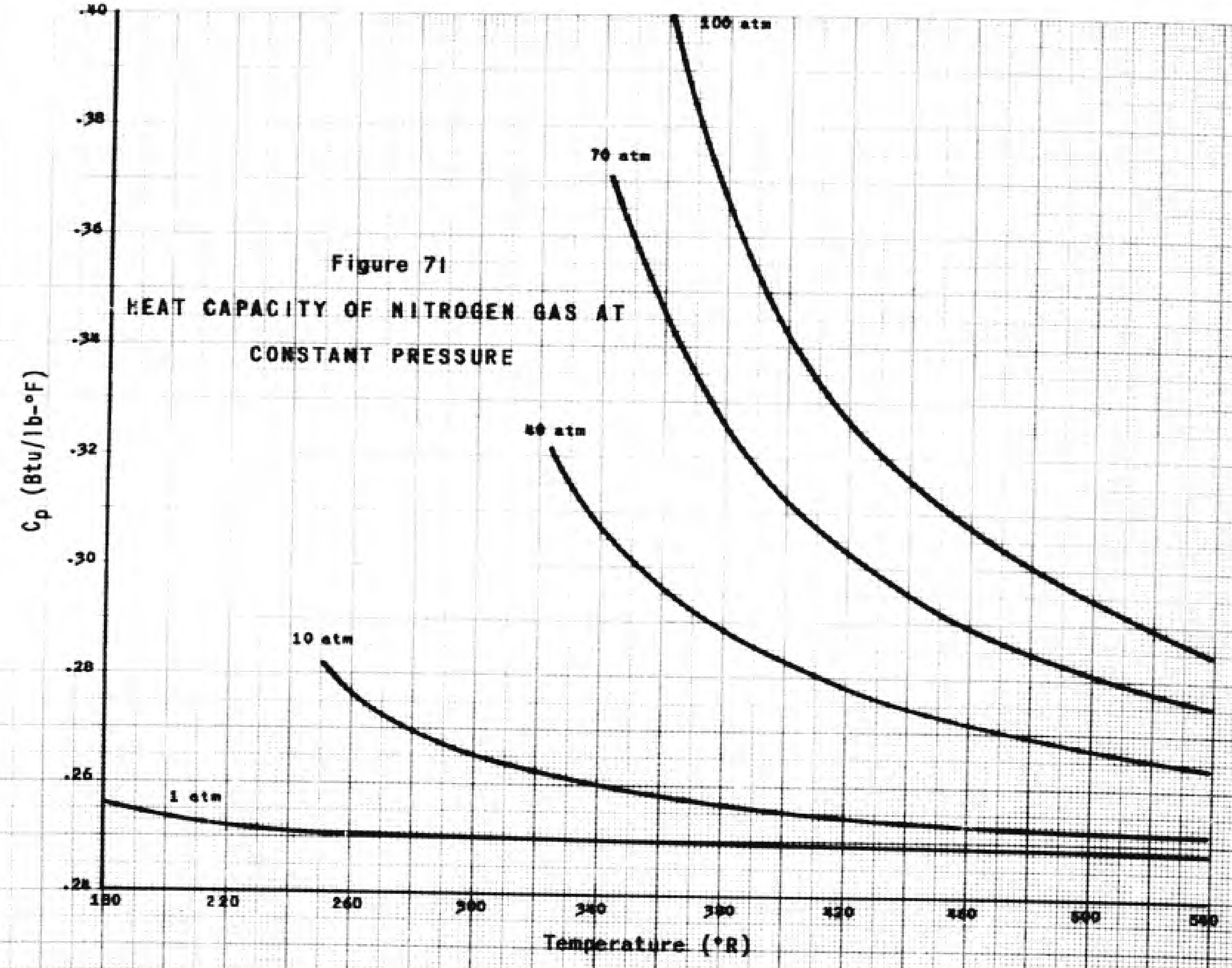


Figure 71

HEAT CAPACITY OF NITROGEN GAS AT CONSTANT PRESSURE

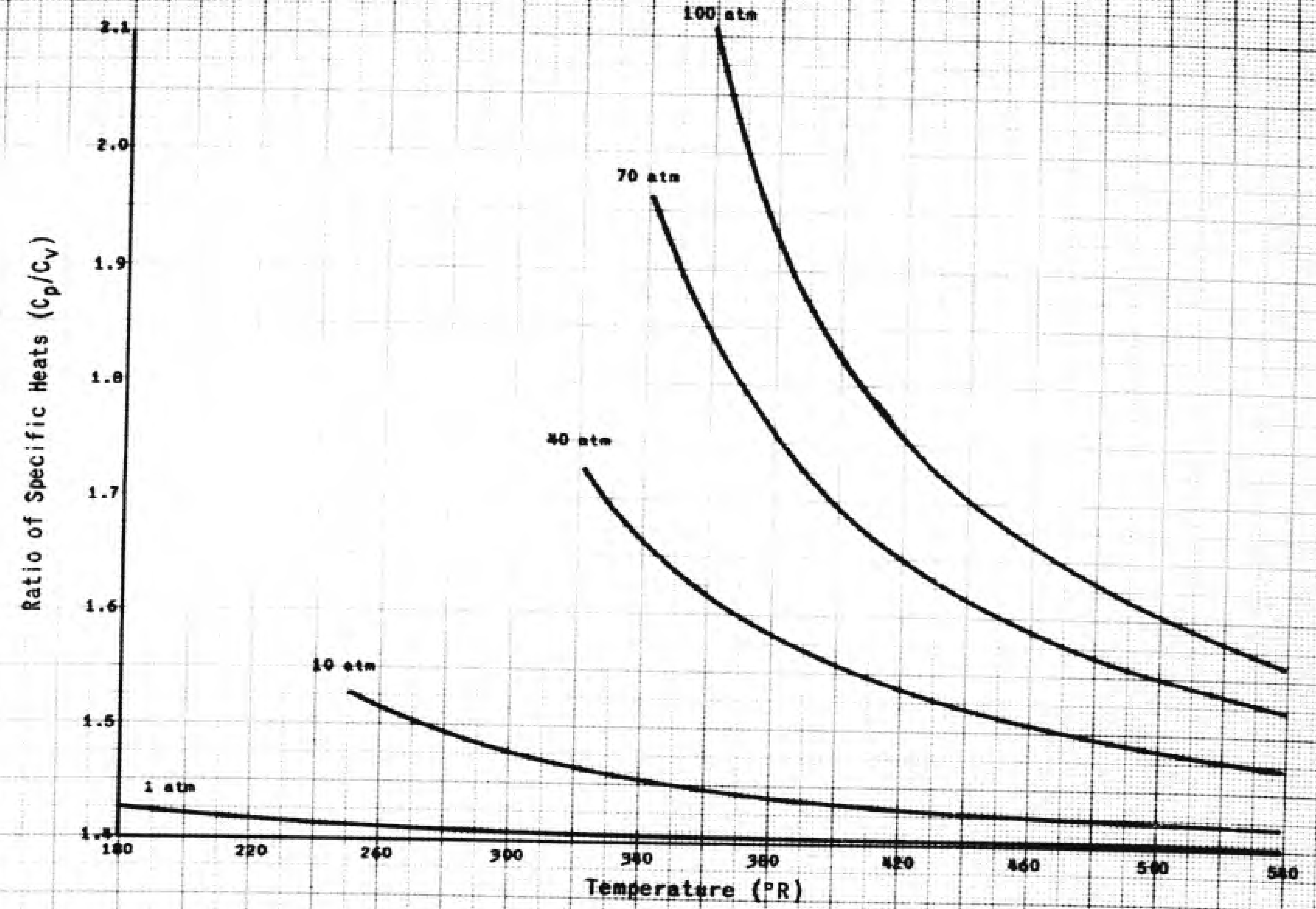


Figure 72

RATIO OF HEAT CAPACITIES OF NITROGEN GAS

3. Properties of Saturated Nitrogen

Temp. (°R)	Specific Volume (ft^3/lb)		Enthalpy (Btu/lb)			Entropy (Btu/lb-°F)		
	V_L	V_G	H_L	ΔH_{VAP}	H_V	S_L	ΔS_{VAP}	S_V
139.5	0.01985	3.473	0.000	85.64	85.64	0.000	0.6152	0.6152
145	0.02018	2.514	2.57	84.02	86.59	0.0183	0.5809	0.5992
150	0.02053	1.931	5.08	82.32	87.40	0.0350	0.5502	0.5851
155	0.02090	1.502	7.61	80.51	88.13	0.0514	0.5207	0.5721
160	0.02120	1.188	10.18	78.59	88.77	0.0673	0.4923	0.5596
165	0.02171	0.9418	12.78	76.54	89.32	0.0830	0.4649	0.5479
170	0.02215	0.7560	15.41	74.36	89.77	0.0985	0.4384	0.5369
175	0.02263	0.6183	18.07	72.02	90.09	0.1137	0.4124	0.5261
180	0.02316	0.5077	20.80	69.45	90.25	0.1287	0.3863	0.5150
185	0.02376	0.4179	23.63	66.58	90.21	0.1438	0.3606	0.5044
190	0.02444	0.3470	26.56	63.37	89.93	0.1589	0.3341	0.4930
195	0.02520	0.2888	29.59	59.85	89.44	0.1739	0.3173	0.4812
200	0.02604	0.2398	32.75	56.01	88.76	0.1889	0.2806	0.4695
205	0.02700	0.2000	36.14	51.68	87.82	0.2041	0.2523	0.4566
210	0.02820	0.1652	39.80	46.82	86.62	0.2198	0.2229	0.4427
215	0.02997	0.1348	43.81	40.96	84.77	0.2362	0.1914	0.4276
220	0.03238	0.1080	48.09	33.75	81.84	0.2543	0.1537	0.4080
225	0.03623	0.0834	53.87	23.78	77.65	0.2812	0.1058	0.3870
227	0.05092	0.05092	66.19	0.00	66.19	0.3357	0.0000	0.3357

See Figures 73 and 74.

Reference: Bloomer, O. T., and K. N. Rao, Thermodynamic Properties of Nitrogen, Institute of Gas Technology Research Bulletin 18, October 1952.

4. Properties of Superheated Nitrogen (See Table XX.)

See Figures 75-80.

5. Surface Tension of Liquid Nitrogen Against Its Own Vapor

Temperature (°K)	Surface Tension (dynes/cm)
68	11.00
69	10.76
70	10.53
71	10.30
72	10.07
73	9.84
74	9.62
75	9.39
76	9.16
77	8.94
78	8.72
79	8.50
80	8.27
81	8.06
82	7.84
83	7.63
84	7.42
85	7.20
86	6.99
87	6.78
88	6.57
89	6.37
90	6.16

See Figure 81.

Reference: Baly, E. C. C., and F. G. Donnon, Journal of the Chemical Society (London), Transactions, 81, 907 (1902).

TABLE XX

PROPERTIES OF SUPERHEATED NITROGEN

	P=10 psia (133.5°R)			P=15 psia (139.5°R)			P=40 psia (156.1°R)			P=60 psia (165°R)			P=10
Temp (°R)	V (ft^3/lb)	H (Btu/lb)	S (Btu/lb-°F)	V (ft^3/lb)	H (Btu/lb)	S (Btu/lb-°F)	V (ft^3/lb)	H (Btu/lb)	S (Btu/lb-°F)	V (ft^3/lb)	H (Btu/lb)	S (Btu/lb-°F)	V (ft^3/lb)
140	5.196	86.28	0.6459	3.410	85.73	0.6149	-	-	-				
150	5.595	89.00	0.6644	3.681	88.55	0.6338	-	-	-				
160	6.000	91.62	0.6815	3.947	91.25	0.6508	1.396	89.34	0.5725				
170	6.389	94.20	0.6927	4.220	93.88	0.6667	1.505	92.23	0.5905	0.9619	90.78	0.5562	-
180	6.779	96.77	0.7118	4.492	96.49	0.6824	1.619	94.99	0.6066	1.0415	93.77	0.5729	0.5781
190	7.171	99.32	0.7256	4.761	99.06	0.6962	1.731	97.70	0.6216	1.1200	96.64	0.5887	0.6328
200	7.572	101.84	0.7386	5.023	101.60	0.7092	1.839	100.40	0.6359	1.1956	99.46	0.6039	0.6846
210	7.960	104.36	0.7510	5.285	104.14	0.7215	1.948	103.07	0.6493	1.2677	102.22	0.6178	0.7309
220	8.348	106.88	0.7627	5.548	106.68	0.7334	2.053	105.73	0.6612	1.339	104.95	0.6305	0.7742
230	8.737	109.40	0.7740	5.818	109.22	0.7447	2.156	108.37	0.6730	1.4077	107.67	0.6424	0.8200
240	9.126	111.92	0.7848	6.078	111.75	0.7555	2.254	110.98	0.6840	1.4782	110.35	0.6536	0.8649
260	9.908	116.93	0.8050	6.598	116.79	0.7758	2.449	116.12	0.7045	1.615	115.61	0.6745	0.9510
280	10.682	121.92	0.8234	7.114	121.80	0.7944	2.644	121.23	0.7234	1.750	120.80	0.6935	1.0349
300	11.446	126.91	0.8406	7.630	126.81	0.8117	2.838	126.32	0.7409	1.883	125.94	0.7112	1.1159
320	12.222	131.90	0.8567	8.140	131.81	0.8279	3.034	131.38	0.7571	2.015	131.02	0.7276	1.1977
340	12.987	136.88	0.8718	8.658	136.80	0.8431	3.230	136.42	0.7724	2.145	136.10	0.7430	1.2776
360	13.765	141.86	0.8859	9.167	141.79	0.8572	3.424	141.45	0.7868	2.276	141.17	0.7576	1.3586
380	14.531	146.83	0.8992	9.687	146.77	0.8704	3.618	146.46	0.8004	2.405	146.21	0.7711	1.4371
400	15.296	151.81	0.9119	10.200	151.75	0.8831	3.813	151.47	0.8132	2.534	151.25	0.7838	1.516
420	16.062	156.79	0.9240	10.708	156.73	0.8952	4.003	156.47	0.8253	2.662	156.27	0.7960	1.595
440	16.827	161.76	0.9356	11.218	161.70	0.9068	4.198	161.47	0.8370	2.796	161.29	0.8077	1.674
460	17.593	166.73	0.9467	11.729	166.68	0.9178	4.394	166.45	0.8480	2.926	166.28	0.8189	1.752
480	18.377	171.70	0.9574	12.239	171.66	0.9284	4.590	171.45	0.8586	3.057	171.28	0.8296	1.832
500	19.143	176.66	0.9772	12.762	176.63	0.9386	4.781	176.41	0.8688	3.187	176.27	0.8398	1.911

1

TABLE XX

PROPERTIES OF SUPERHEATED NITROGEN

	139.5°R)	P=40 psia (156.1°R)			P=60 psia (165°R)			P=100 psia (177°R)			P=150 psia (188°R)		
	S	V	H	S	V	H	S	V	H	S	V	H	S
)	(Btu/lb-°F)	(ft^3/lb)	(Btu/lb)	(Btu/lb-°F)	(ft^3/lb)	(Btu/lb)	(Btu/lb-°F)	(ft^3/lb)	(Btu/lb)	(Btu/lb-°F)	(ft^3/lb)	(Btu/lb)	(Btu/lb-°F)
3	0.6149	-	-	-									
5	0.6338	-	-	-									
5	0.6508	1.396	89.34	0.5725									
8	0.6667	1.505	92.23	0.5905	0.9619	90.78	0.5562	-	-	-	-	-	-
9	0.6824	1.619	94.99	0.6066	1.0415	93.77	0.5729	0.5781	91.04	0.5257	-	-	-
6	0.6962	1.731	97.70	0.6216	1.1200	96.64	0.5887	0.6328	94.38	0.5445	0.3820	90.88	0.5021
0	0.7092	1.839	100.40	0.6359	1.1956	99.46	0.6039	0.6846	97.51	0.5607	0.4227	94.73	0.5215
4	0.7215	1.948	103.07	0.6493	1.2677	102.22	0.6178	0.7309	100.57	0.5753	0.4583	98.11	0.5384
8	0.7334	2.053	105.73	0.6612	1.339	104.95	0.6305	0.7742	103.40	0.5885	0.4926	101.25	0.5527
2	0.7447	2.156	108.37	0.6730	1.4077	107.67	0.6424	0.8200	106.27	0.6013	0.5232	104.35	0.5665
5	0.7555	2.254	110.98	0.6840	1.4782	110.35	0.6536	0.8649	109.08	0.6132	0.5582	107.35	0.5794
9	0.7758	2.449	116.12	0.7045	1.615	115.61	0.6745	0.9510	114.54	0.6352	0.6180	113.15	0.6027
0	0.7944	2.644	121.23	0.7234	1.750	120.80	0.6935	1.0349	119.89	0.6549	0.6771	118.69	0.6232
1	0.8117	2.838	126.32	0.7409	1.883	125.94	0.7112	1.1159	125.12	0.6730	0.7332	124.08	0.6418
1	0.8279	3.034	131.38	0.7571	2.015	131.02	0.7276	1.1977	130.32	0.6898	0.7887	129.26	0.6591
0	0.8431	3.230	136.42	0.7724	2.145	136.10	0.7430	1.2776	135.47	0.7056	0.8441	134.45	0.6750
9	0.8572	3.424	141.45	0.7868	2.276	141.17	0.7576	1.3586	140.60	0.7202	0.8984	139.70	0.6900
7	0.8704	3.618	146.46	0.8004	2.405	146.21	0.7711	1.4371	145.70	0.7338	0.9522	144.93	0.7040
5	0.8831	3.813	151.47	0.8132	2.534	151.25	0.7838	1.516	150.79	0.7468	1.0065	150.17	0.7170
3	0.8952	4.003	156.47	0.8253	2.662	156.27	0.7960	1.595	155.85	0.7590	1.0601	155.31	0.7294
0	0.9068	4.198	161.47	0.8370	2.796	161.29	0.8077	1.674	160.88	0.7707	1.1128	160.42	0.7411
8	0.9178	4.394	166.45	0.8480	2.926	166.28	0.8189	1.752	165.90	0.7821	1.1658	165.50	0.7542
6	0.9284	4.590	171.45	0.8586	3.057	171.28	0.8296	1.832	170.92	0.7928	1.2178	170.56	0.7631
3	0.9386	4.781	176.41	0.8688	3.187	176.27	0.8398	1.911	175.94	0.8030	1.2711	175.61	0.7734

TABLE XX (Continued)

Temp.	P=250 psia (203.2°R)			P=400 psia (219.4°R)			P=600 psia			P=800 psia			P=10	
(°R)	V (ft^3/lb)	H (Btu/lb)	S (Btu/lb-°F)	V (ft^3/lb)	H (Btu/lb)	S (Btu/lb-°F)	V (ft^3/lb)	H (Btu/lb)	S (Btu/lb-°F)	V (ft^3/lb)	H (Btu/lb)	S (Btu/lb-°F)	V (ft^3/lb)	(Bt
210	0.2349	92.23	0.4800	-	-	-	-	-	-					
220	0.2592	96.32	0.4998	0.1113	82.10	0.4175	-	-	-					
230	0.2851	100.00	0.5166	0.1426	90.55	0.4540	0.03563	55.88	0.2866	0.03134	51.51	0.2621	0.02930	49
240	0.3077	103.56	0.5317	0.1648	96.70	0.4769	0.07238	80.85	0.3928	0.03753	61.75	0.3057	0.03259	56
260	0.3513	110.12	0.5582	0.1989	105.06	0.5106	0.1112	96.56	0.4564	0.06789	86.13	0.4037	0.04725	76
280	0.3908	116.20	0.5810	0.2282	112.51	0.5368	0.1368	106.01	0.4915	0.09147	99.11	0.4519	0.06600	92
300	0.4266	121.93	0.6004	0.2539	118.57	0.5589	0.1577	113.72	0.5181	0.1101	108.55	0.4846	0.08220	103
320	0.4624	127.49	0.6183	0.2736	124.65	0.5786	0.1768	120.65	0.5405	0.1263	116.51	0.5104	0.09613	112
340	0.4971	132.99	0.6352	0.3019	130.49	0.5965	0.1939	127.02	0.5599	0.1404	123.58	0.5316	0.10879	120
360	0.5313	138.39	0.6508	0.3248	136.16	0.6126	0.2106	133.10	0.5773	0.1542	130.19	0.5507	0.12043	127
380	0.5649	143.74	0.6651	0.3473	141.70	0.6275	0.2264	138.98	0.5931	0.1666	136.43	0.5676	0.13091	133
400	0.5984	149.03	0.6785	0.3690	147.16	0.6416	0.2420	144.71	0.6074	0.1789	142.41	0.5829	0.14147	140
420	0.6315	154.26	0.6913	0.3907	152.55	0.6540	0.2570	150.33	0.6211	0.1909	148.24	0.5973	0.1515	146
440	0.6650	159.44	0.7034	0.4118	157.90	0.6669	0.2720	155.87	0.6343	0.2025	153.98	0.6106	0.1609	152
460	0.6974	164.59	0.7149	0.4332	163.20	0.6788	0.2868	161.33	0.6466	0.2140	159.64	0.6229	0.1706	157
480	0.7299	169.73	0.7258	0.4539	168.46	0.6900	0.3011	166.74	0.6582	0.2253	165.22	0.6345	0.1797	163
500	0.7619	174.86	0.7362	0.4747	173.70	0.7007	0.3155	172.12	0.6693	0.2362	170.76	0.6457	0.1669	169

Reference. Bloomer, O. T., and K. N. Rao, Institute of Gas Technology Research Bulletin 18, October 1952

TABLE XX (Continued)

.4°R)	P=600 psia			P=800 psia			P=1000 psia			P=1500 psia		
S	V	H	S	V	H	S	V	H	S	V	H	S
Btu/lb-°F)	(ft^3/lb)	(Btu/lb)	(Btu/lb-°F)	(ft^3/lb)	(Btu/lb)	(Btu/lb-°F)	(ft^3/lb)	(Btu/lb)	(Btu/lb-°F)	(ft^3/lb)	(Btu/lb)	(Btu/lb-°F)
-	-	-	-									
0 4175	-	-	-									
0 4540	0 03563	55 88	0 2866	0 03134	51 51	0.2621	0 02930	49 15	0.2466	0 02639	45 92	0.2235
0.4769	0 07238	80 85	0 3928	0 03753	61 75	0 3057	0 03259	56 98	0 2807	0 02876	53.40	0 2540
0 5106	0 1112	96 56	0 4564	0 06789	86 13	0 4037	0 04725	76.54	0 3588	0 03375	66.37	0 3061
0 5368	0 1368	106 01	0 4915	0 09147	99 11	0 4519	0 06600	92.08	0 4164	0 04178	80 20	0 3571
0.5589	0.1577	113 72	0 5181	0 1101	108 55	0 4846	0 08220	103.21	0 4550	0 04082	92 07	0 3987
0 5786	0 1768	120 65	0 5405	0 1263	116 51	0 5104	0 09613	112 25	0 4842	0 05992	102 64	0 4312
0.5965	0 1939	127 02	0 5599	0.1404	123 58	0 5316	0 10879	120 03	0 5079	0 06896	111 36	0 4589
0 6126	0 2106	133 10	0 5773	0 1542	130 19	0 5507	0 12043	127 19	0 5283	0 07734	120 21	0 4839
0 6275	0 2264	138 98	0 5931	0 1666	136 43	0 5676	0 13091	133 75	0 5461	0 08523	127 83	0 5050
0.6416	0 2420	144 71	0 6074	0 1789	142 41	0 5829	0 14147	140 06	0 5623	0.09248	134.90	0.5233
0.6540	0 2570	150.33	0 6211	0 1909	148 24	0 5973	0 1515	146 17	0 5773	0.09958	141 60	0.5398
0.6669	0.2720	155 87	0.6343	0 2025	153 98	0 6106	0 1609	152 13	0 5912	0 10645	147.99	0 5548
0 6788	0 2868	161.33	0 6466	0 2140	159.64	0 6229	0 1706	157 97	0 6039	0.11317	154.23	0.5684
0 6900	0.3011	166 74	0.6582	0.2253	165.22	0 6345	0.1797	163.71	0 6158	0.11969	160.34	0.5811
0.7007	0.3155	172.12	0.6693	0 2362	170.76	0.6457	0.1869	169.37	0 6272	0 12596	166.33	0 5932

es Technology Research Bulletin 18, October 1952

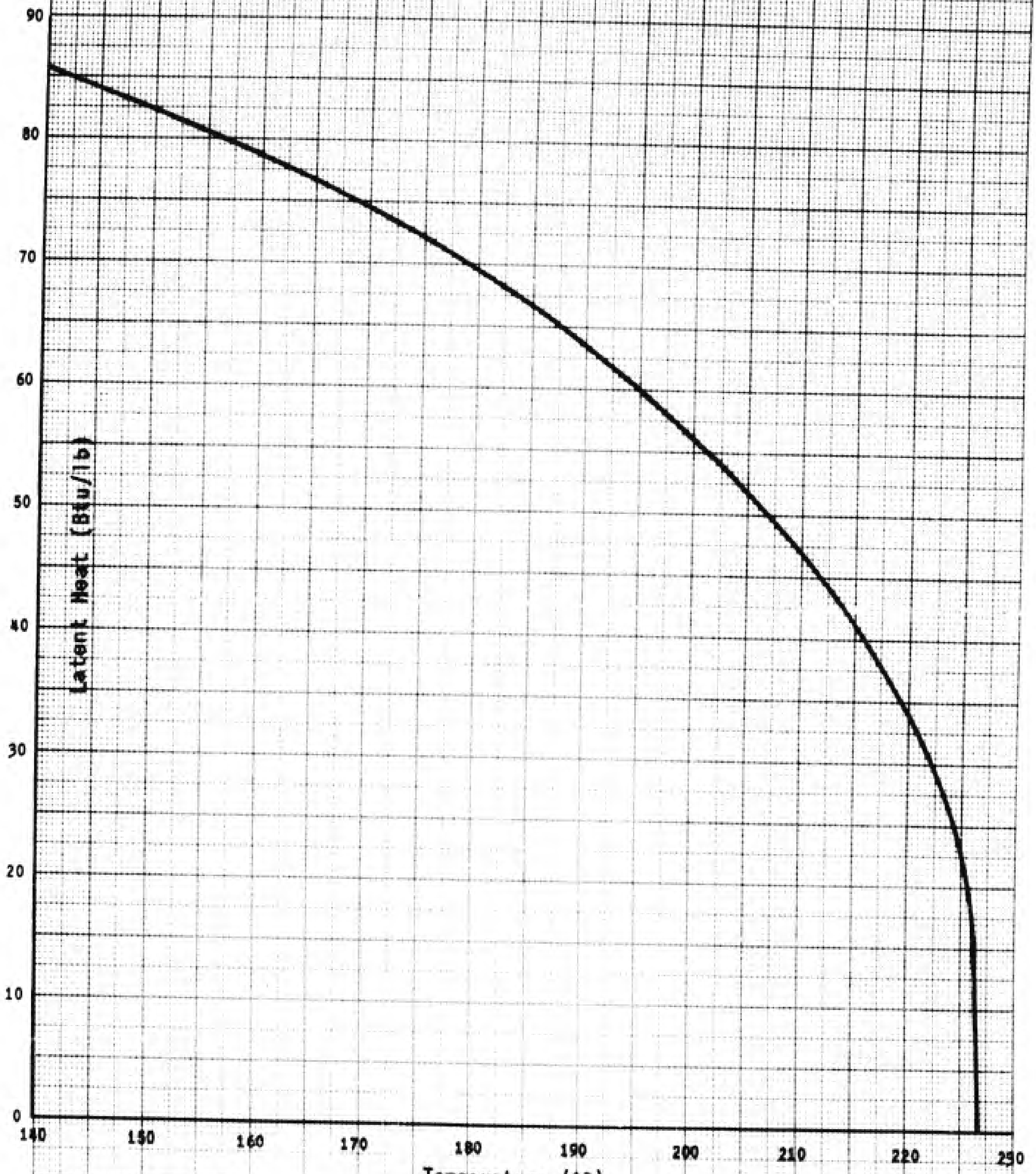
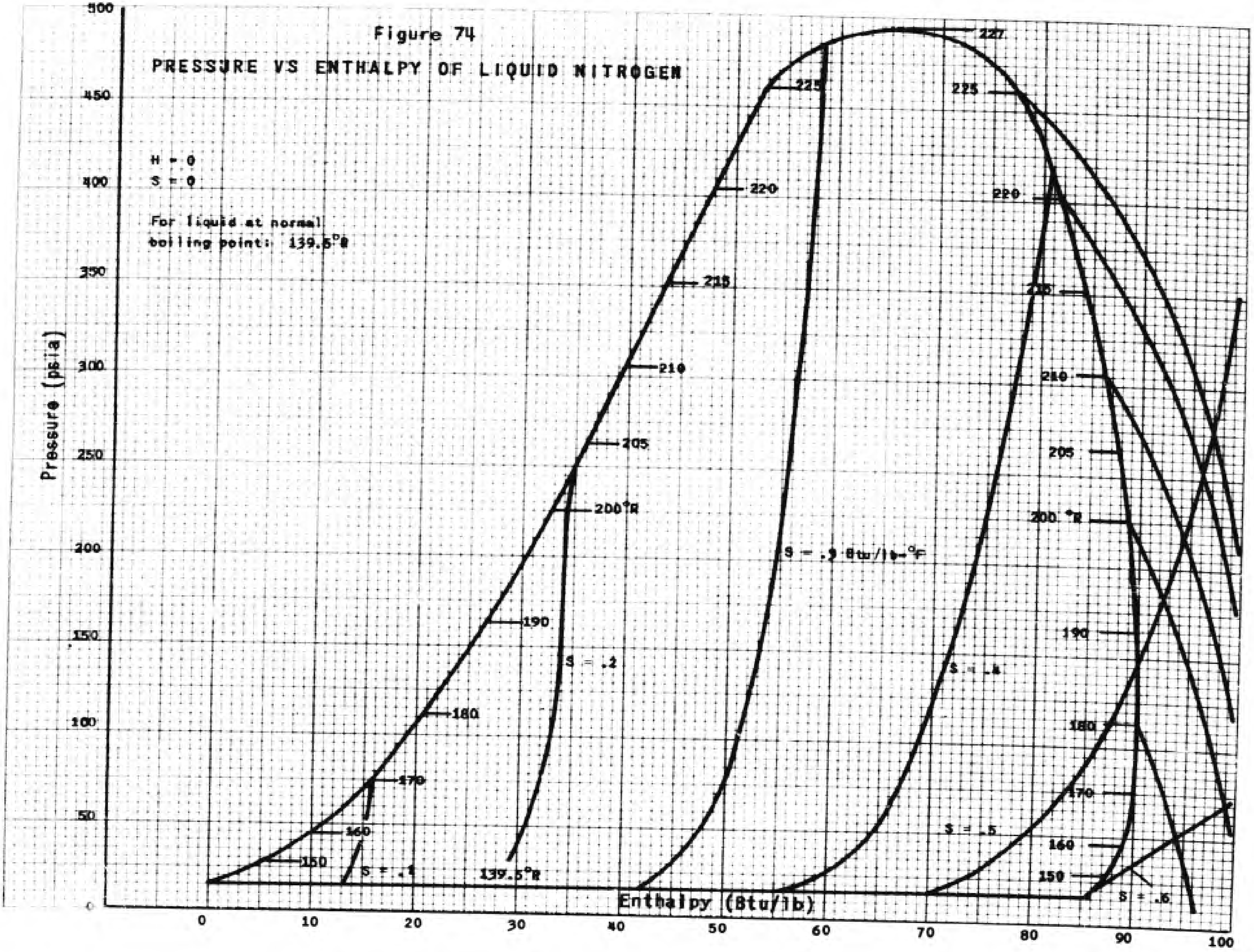


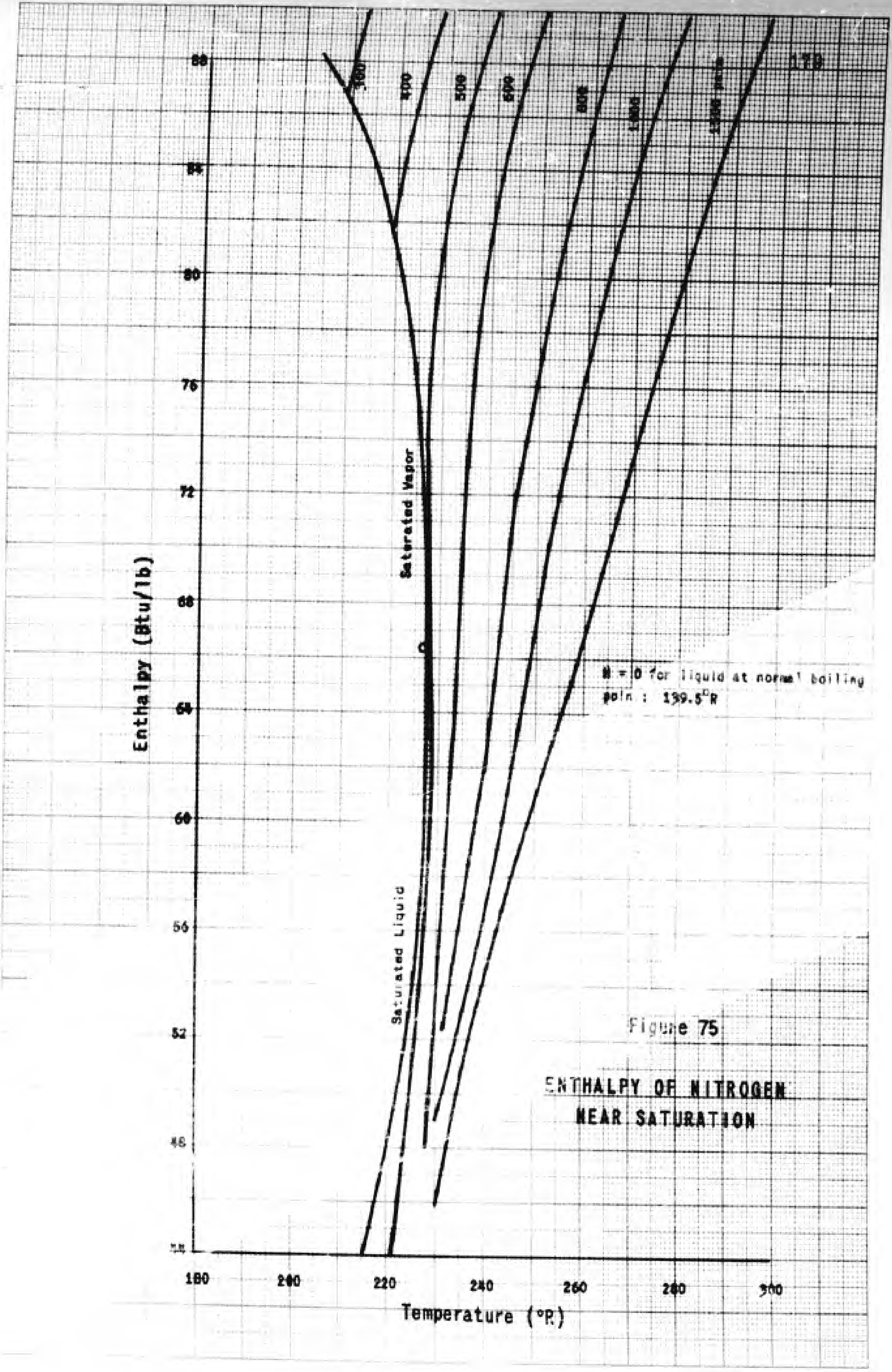
Figure 73

LATENT HEAT OF NITROGEN

Figure 74

PRESSURE VS ENTHALPY OF LIQUID NITROGEN





H = 0 for liquid at normal boiling point : 139.5°R

Figure 75

ENTHALPY OF NITROGEN NEAR SATURATION

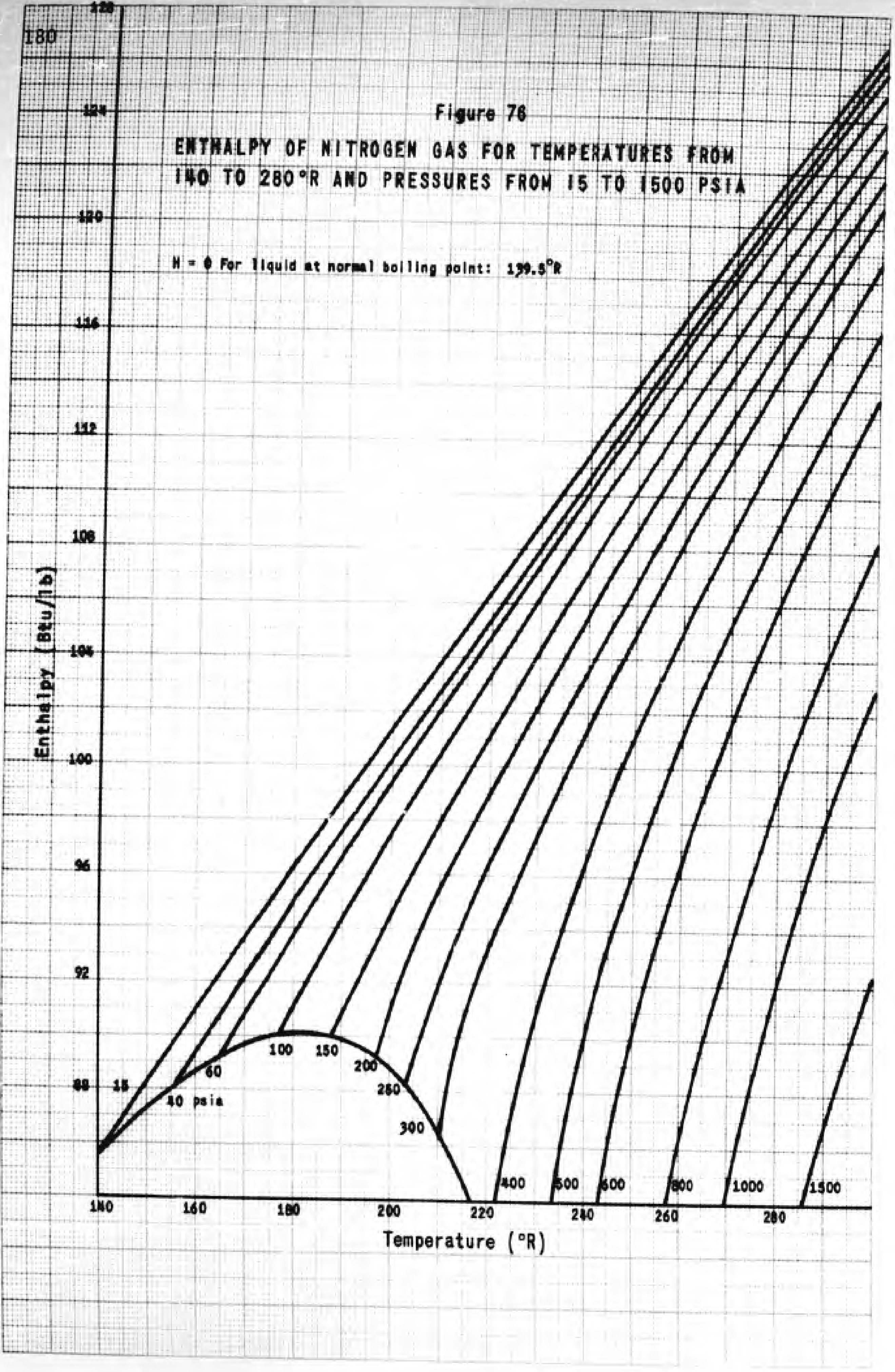


Figure 76

ENTHALPY OF NITROGEN GAS FOR TEMPERATURES FROM 140 TO 280°R AND PRESSURES FROM 15 TO 1500 PSIA

H = 0 For liquid at normal boiling point: 139.5°R

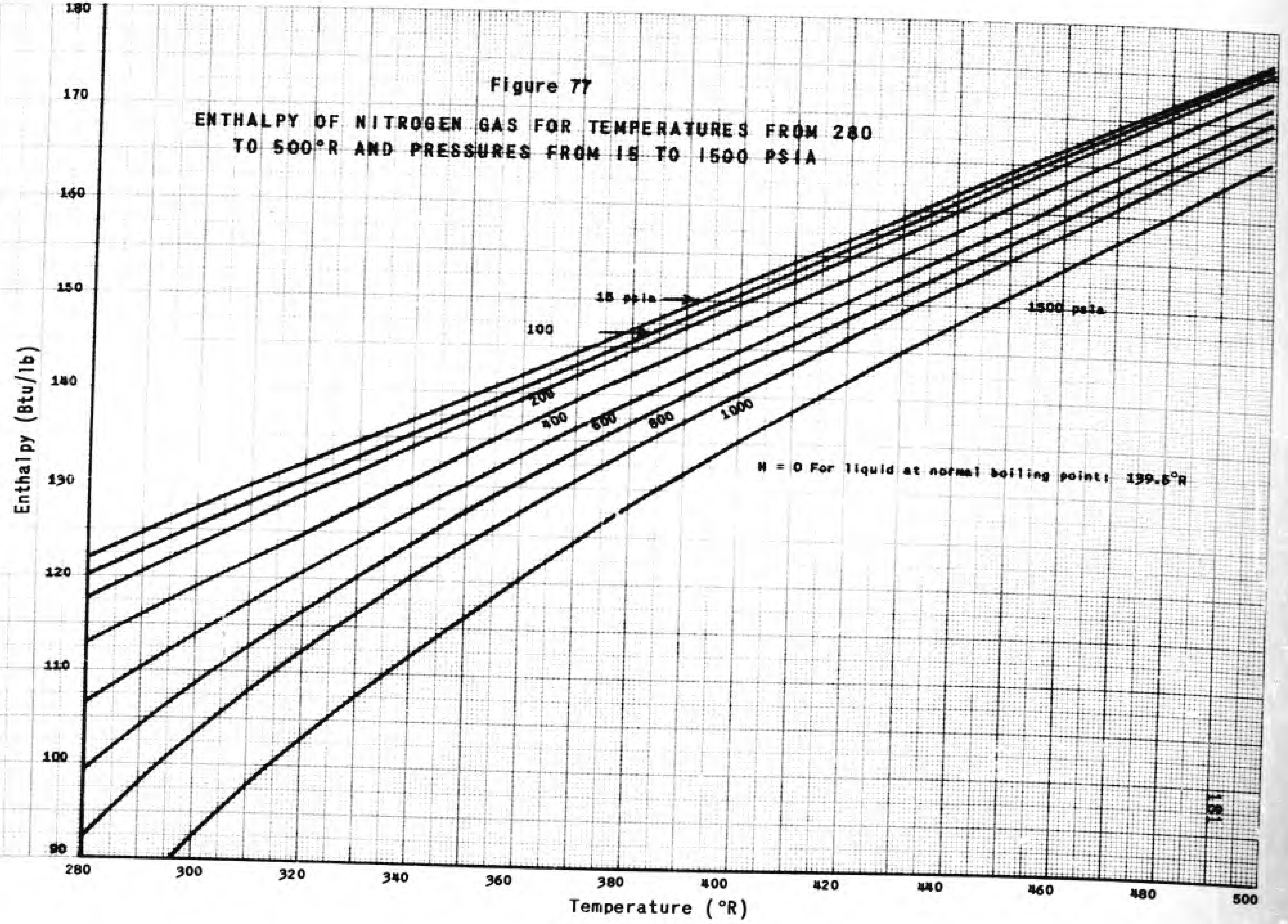


Figure 77

ENTHALPY OF NITROGEN GAS FOR TEMPERATURES FROM 280 TO 500°R AND PRESSURES FROM 15 TO 1500 PSIA

H = 0 For liquid at normal boiling point: 139.6°R

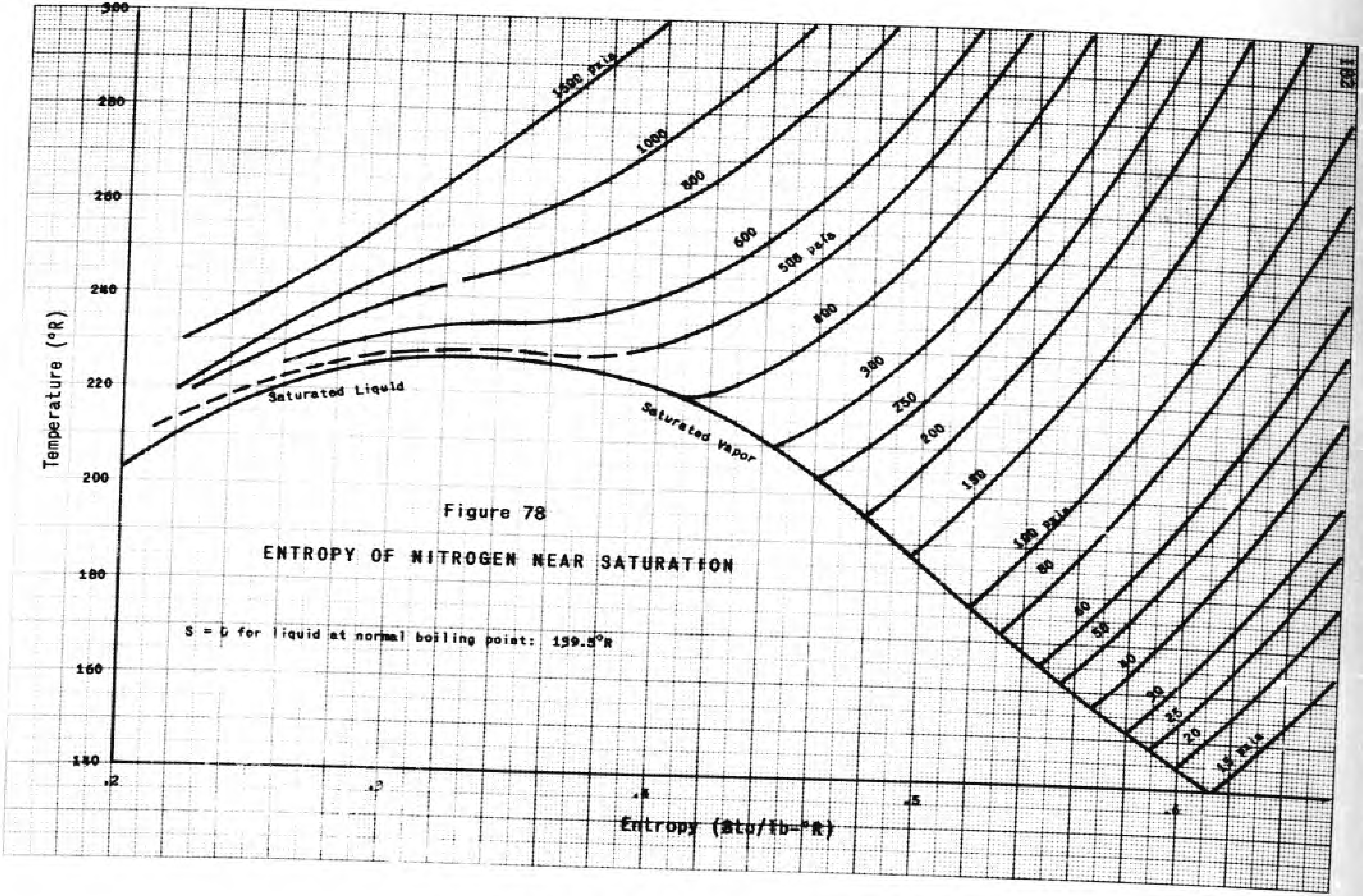


Figure 78

ENTROPY OF NITROGEN NEAR SATURATION

S = 0 for liquid at normal boiling point: 139.5°R

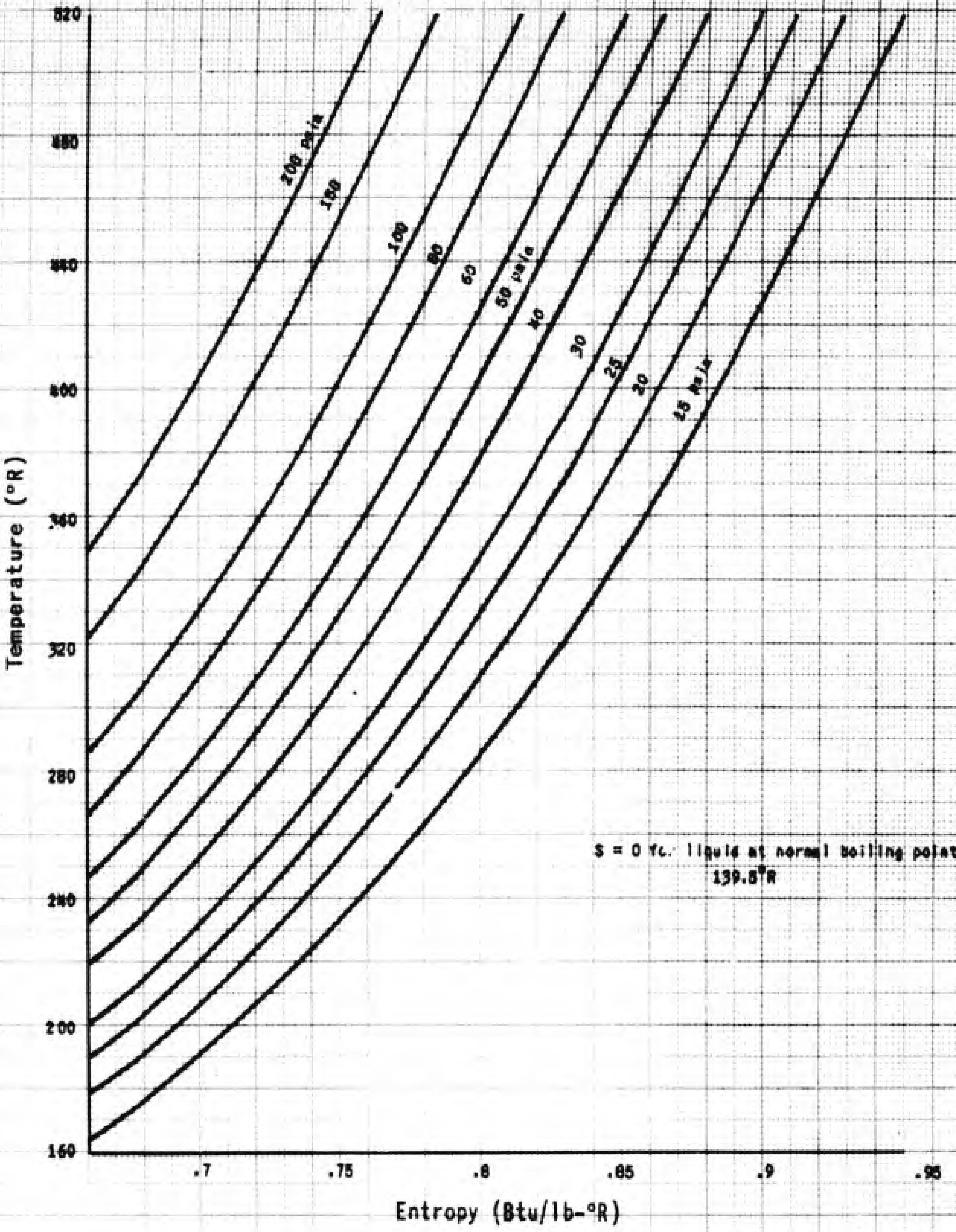


Figure 79

ENTROPY OF NITROGEN GAS FOR TEMPERATURES FROM 170 TO 520°R AND PRESSURES FROM 15 TO 200 PSIA

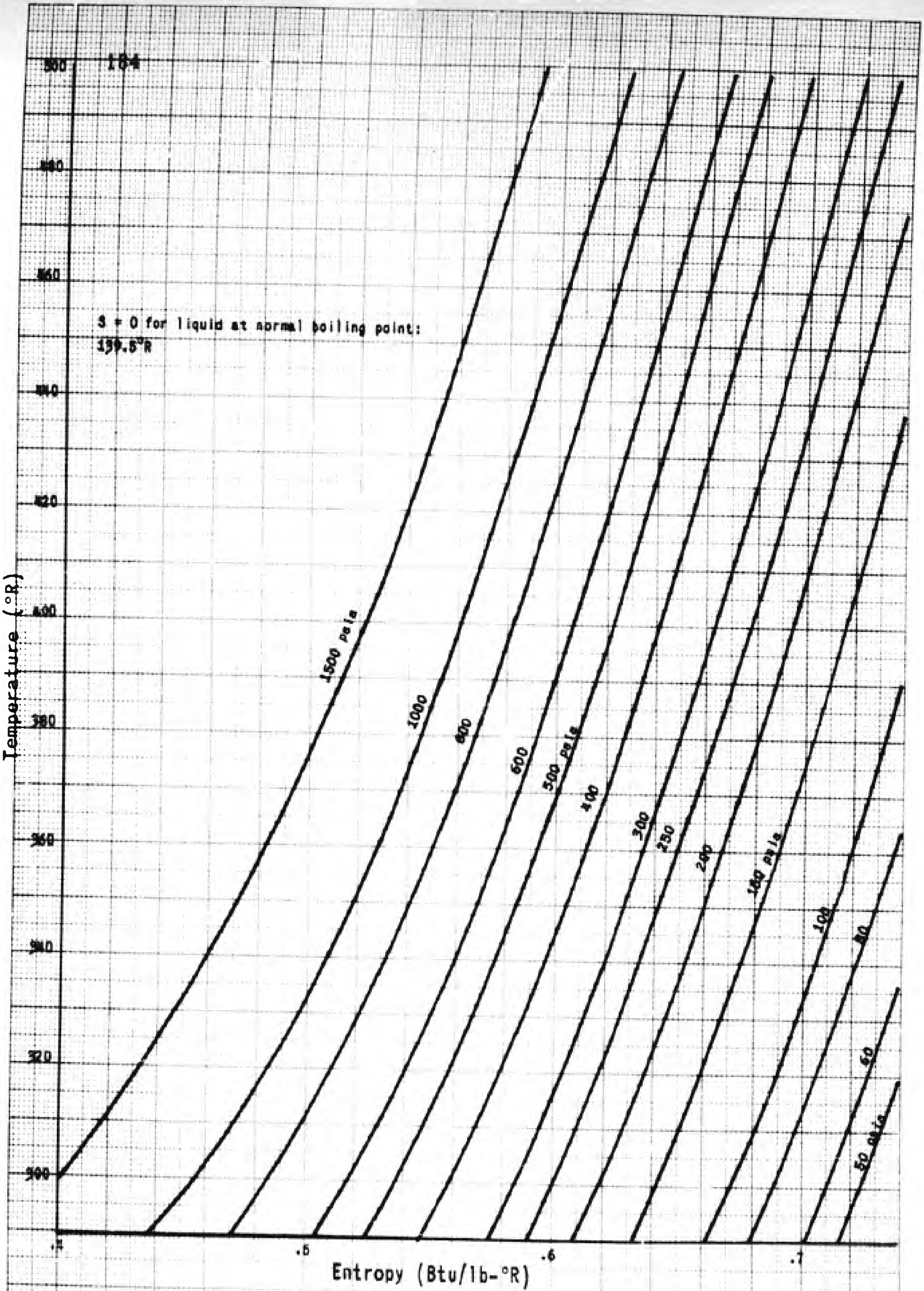


Figure 80

ENTROPY OF NITROGEN GAS FOR TEMPERATURES FROM 290 TO 500°R AND PRESSURES FROM 50 TO 1500 PSIA

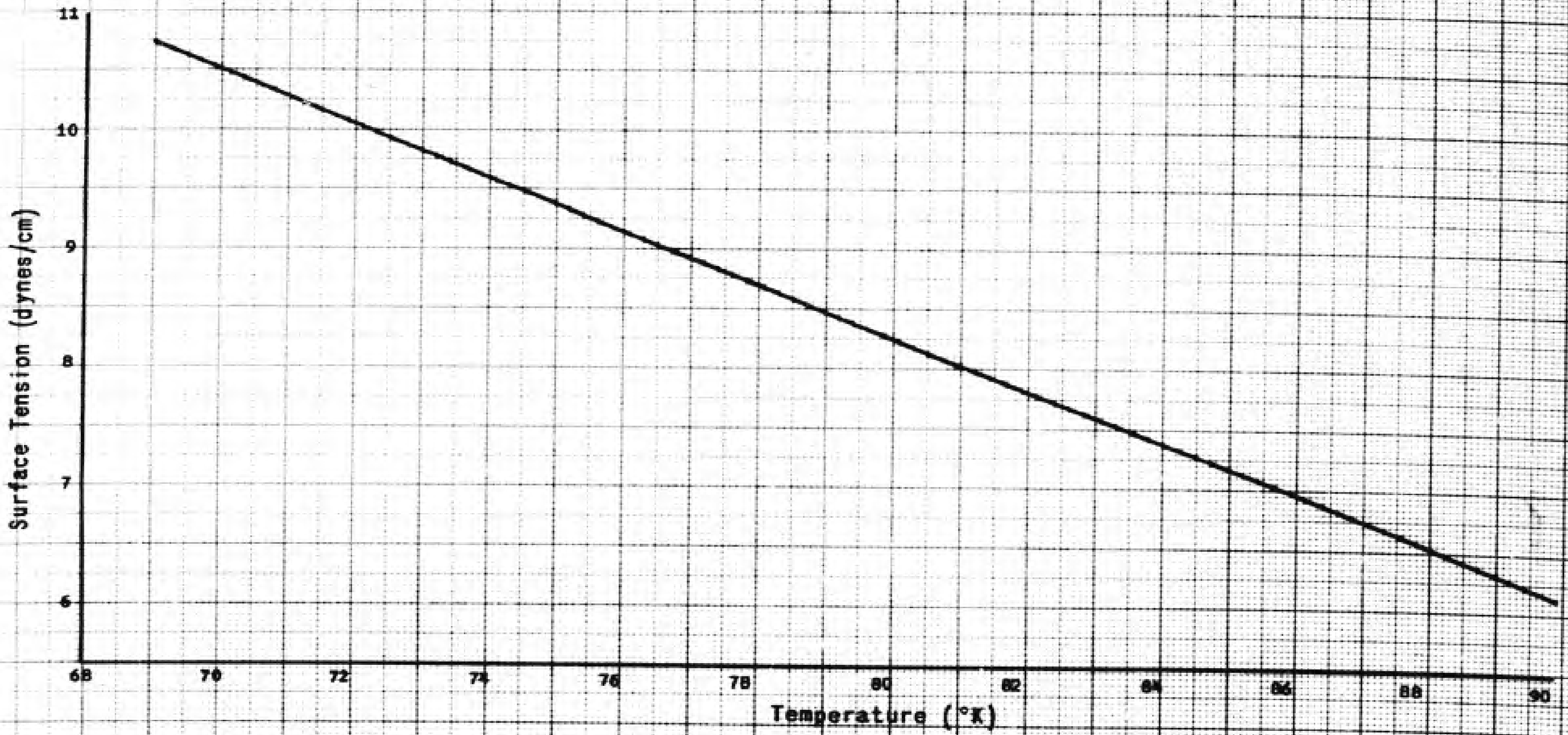


Figure 81

SURFACE TENSION OF LIQUID NITROGEN IN CONTACT WITH SATURATED VAPOR

G. TRANSPORT PROPERTIES

1. Viscosity of Liquid Nitrogen

Temperature (°K)	1/T (°K)	Viscosity (C_p)	Viscosity (lb/ft-hr)
77.3	.01292	.158	.383
76.1	.01312	.165	.400
71.4	.01401	.209	.506
69.2	.01444	.228	.552
69.1	.01447	.231	.560
64.8	.01542	.284	.688
64.3	.01558	.290	.703
63.9	.01567	.291	.705

See Figure 82

Reference: Rudenko, N. S., and L. W. Schisborikow, Phys. Z Sowjetunion, 6, 470 (1934).

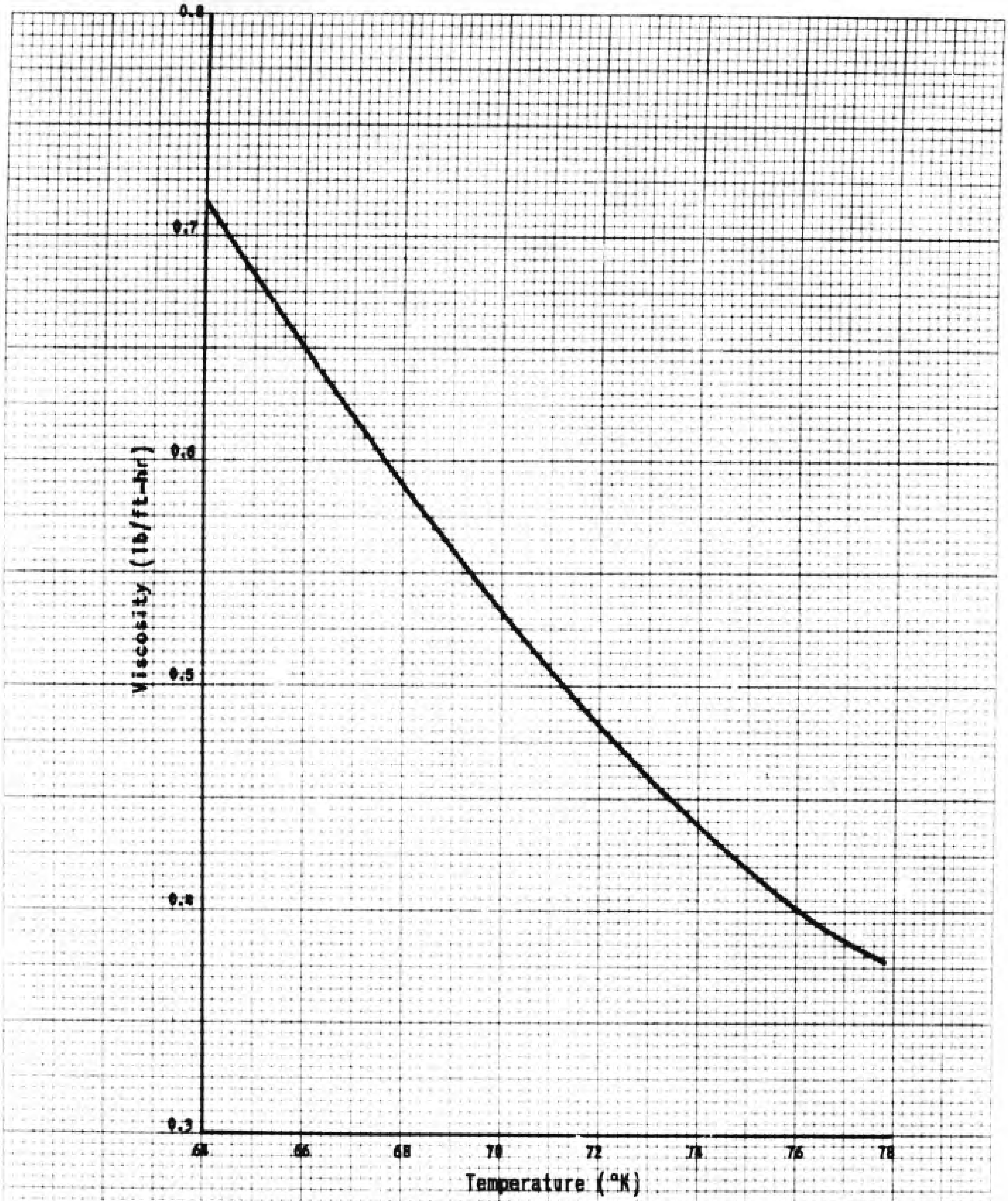


Figure 82
VISCOSITY OF LIQUID NITROGEN

2. Viscosity of Gaseous Nitrogen

Temperature	Viscosity at 14.7 psia		Viscosity at 1000 psia		Viscosity at 2000 psia		Viscosity at 6000 psia	
(°R)	(C_p)	($\frac{lb}{ft\text{-}hr}$)	(C_p)	($\frac{lb}{ft\text{-}hr}$)	(C_p)	($\frac{lb}{ft\text{-}hr}$)	(C_p)	($\frac{lb}{ft\text{-}hr}$)
160	.0060	.0145						
210	.0080	.0193						
260	.0097	.0235					.0495	.1199
285	.0106	.0256					.0430	.1040
310	.0113	.0274	.0141	.0341			.0381	.0922
335	.0122	.0296	.0157	.0380			.0348	.0842
360	.0129	.0312	.0163	.0394	.0183	.0443	.0324	.0785
385	.0136	.0329	.0168	.0406	.0188	.0455	.0307	.0743
410	.0144	.0349	.0173	.0419	.0194	.0470	.0295	.0715
435	.0150	.0363	.0179	.0433	.0199	.0482	.0288	.0696
460	.0156	.0378	.0184	.0445	.0205	.0496	.0285	.0690
485	.0163	.0394	.0190	.0460	.0210	.0509	.0285	.0690
510	.0170	.0411	.0195	.0471	.0215	.0521	.0288	.0686
535	.0176	.0426	.0200	.0484	.0220	.0532	.0293	.0710
560	.0183	.0443	.0205	.0496	.0225	.0545	.0299	.0724

See Figure 83.

At the critical point the viscosity is 0.0261 C_p or 0.0631 lb/ft-hr.

Reference: M. W. Kellog Co., Technical Data Book, G-60280, March 1942.

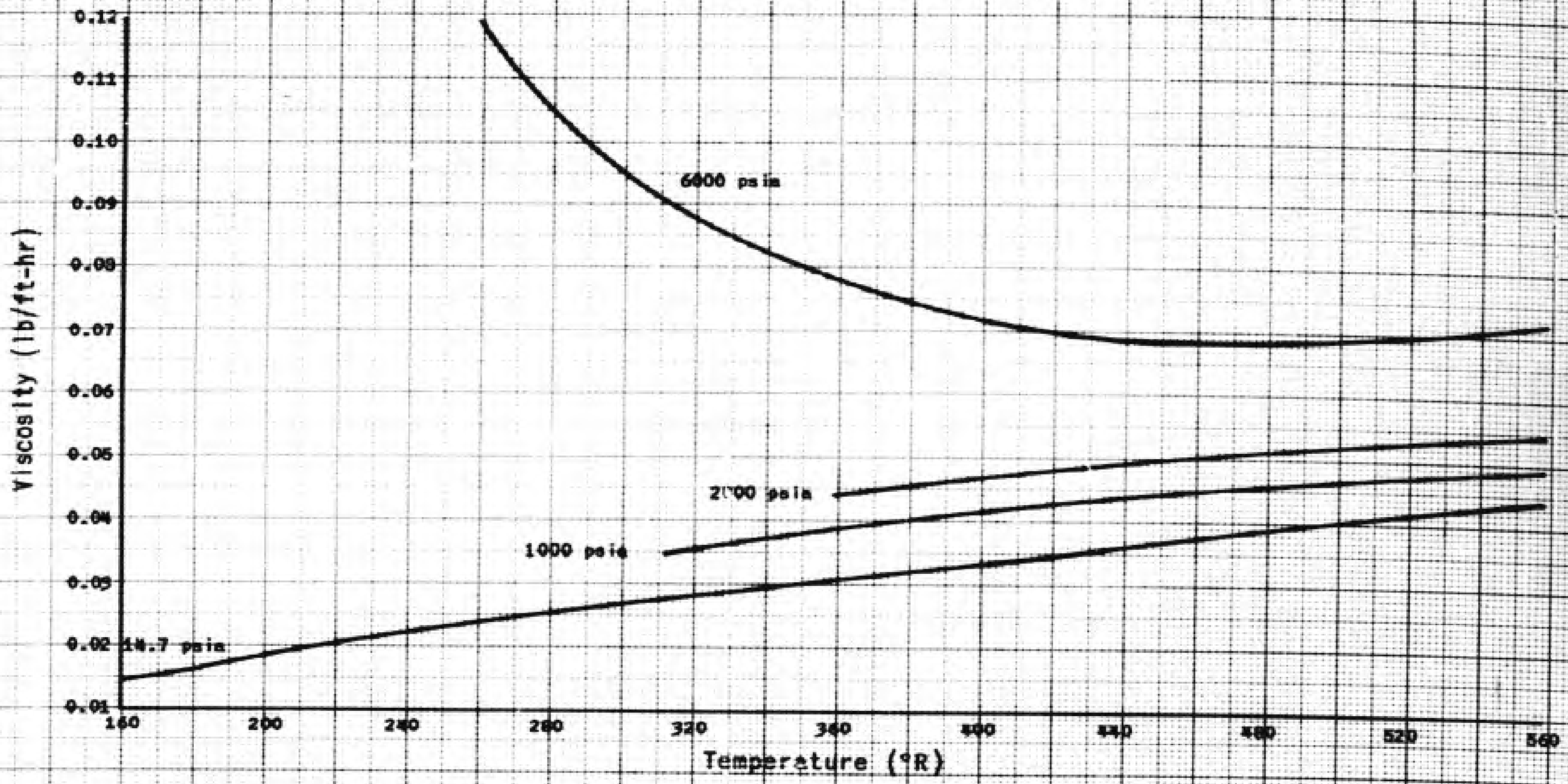


Figure 83

VISCOSITY OF GASEOUS NITROGEN

3. Thermal Conductivity of Solid Nitrogen

From calculations of the rate of formation of solid nitrogen from condensation from the gas phase Karamcheti estimates the thermal conductivity of solid nitrogen to be about 0.06 Btu/ft-hr-°F.

Reference: Karamcheti K, *A Note on the Thermal Conductivity of Solid Nitrogen and the Direct Condensation of Nitrogen Gas into a Solid* AFOSR TN 59 183 AD211 323 Engineering Center University of Southern California, Los Angeles 7 California USCEC Rept. 56-206 January 31 1959.

4. Thermal Conductivity of Liquid Nitrogen

$$K = 5.838 \times 10^{-4} - 3.236 \times 10^{-6} T$$

K = thermal conductivity cal/cm-sec-°K

T = temperature °K

$$K = 0.1410 - 0.000783T$$

K = thermal conductivity Btu/ft-hr-°F

T = temperature °K

See Figures 84 and 85.

References Powers R. W. R. W. Mattax and H. L. Johnston *J. Am. Chem. Soc* 76 5968 (1954).

Uhler A. *Journal Chem. Phys.* 20 463 (1952).

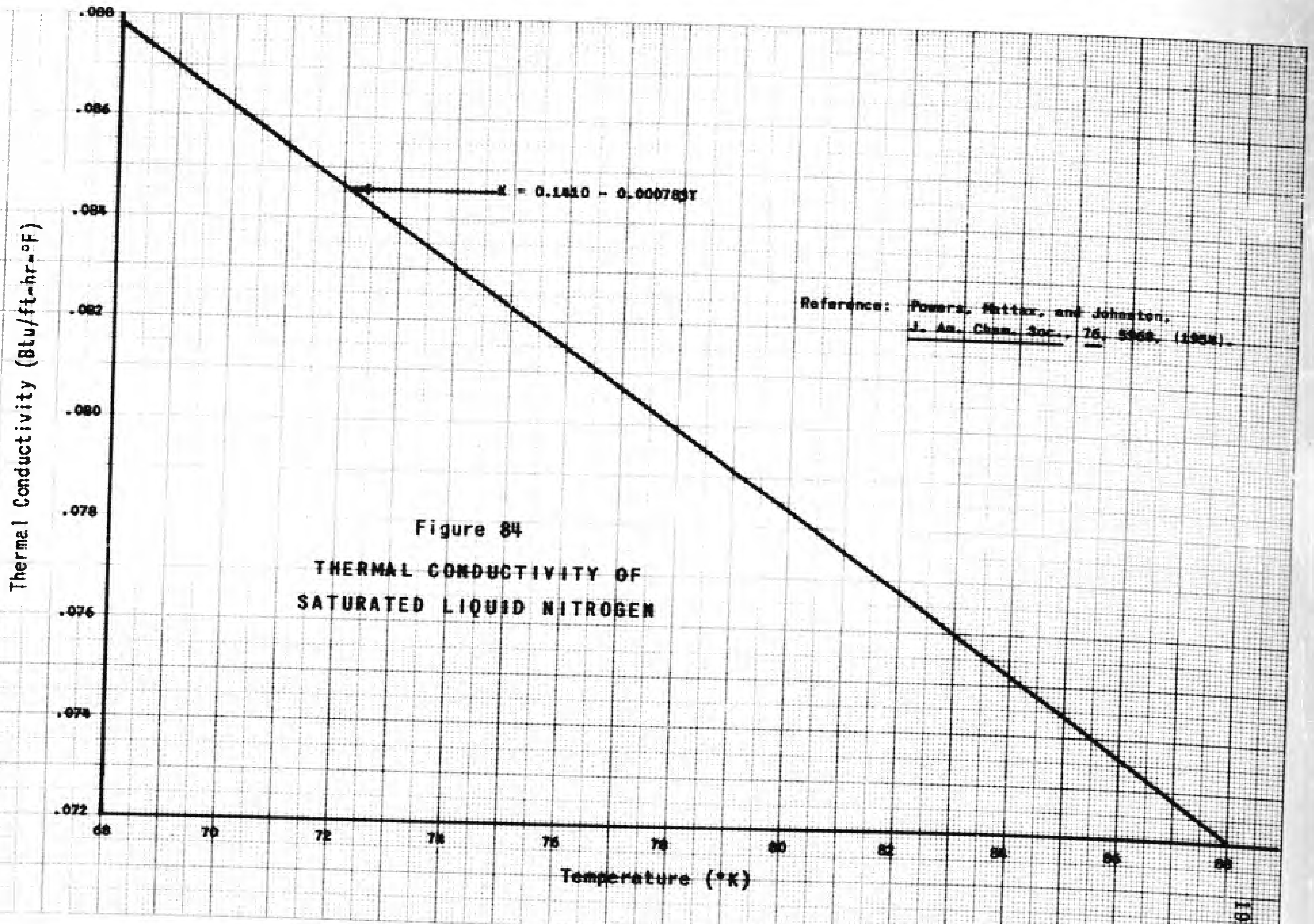
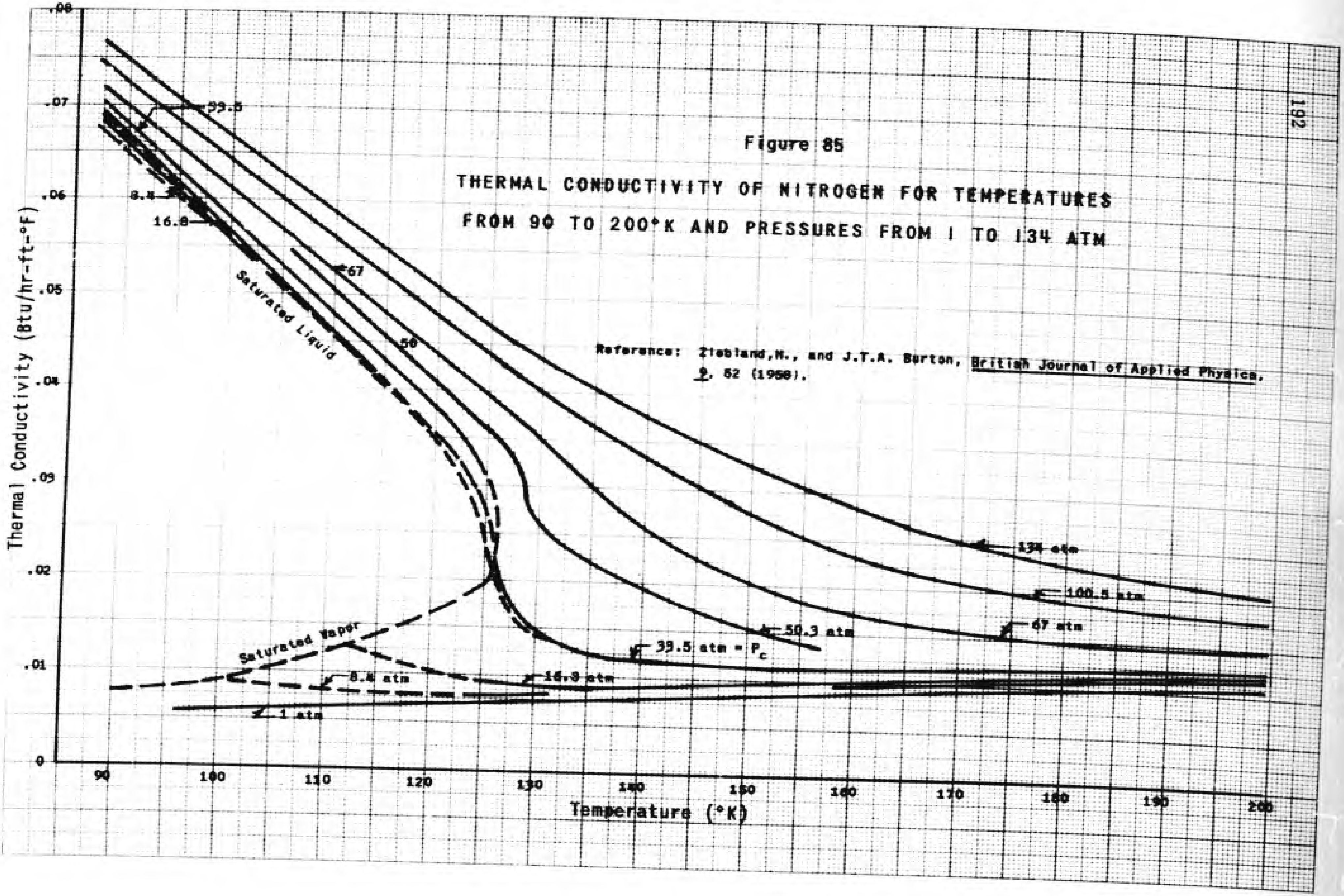


Figure 84

THERMAL CONDUCTIVITY OF
SATURATED LIQUID NITROGEN

Figure 85

THERMAL CONDUCTIVITY OF NITROGEN FOR TEMPERATURES FROM 90 TO 200°K AND PRESSURES FROM 1 TO 134 ATM



Reference: Ziebland, H., and J.T.A. Burton, British Journal of Applied Physics, 9, 52 (1958).

5. Thermal Conductivity of Gaseous Nitrogen

Temperature		Thermal Conductivity
(°K)	(°R)	(Btu/ft-hr-°F)
100	180	.00546
110	198	.00597
120	216	.00651
130	234	.00704
140	252	.00754
150	270	.00806
160	288	.00867
170	306	.00907
180	324	.00946
190	342	.01002
200	360	.01050
210	378	.01100
220	396	.01149
230	414	.01198
240	432	.01244
250	450	.01290
260	468	.01338
270	486	.01381
280	504	.01427
290	522	.01469
300	540	.01510

See Figure 86.

Reference: Hilsenrath, J., et al., National Bureau of Standards Circular 564, November 1, 1955.

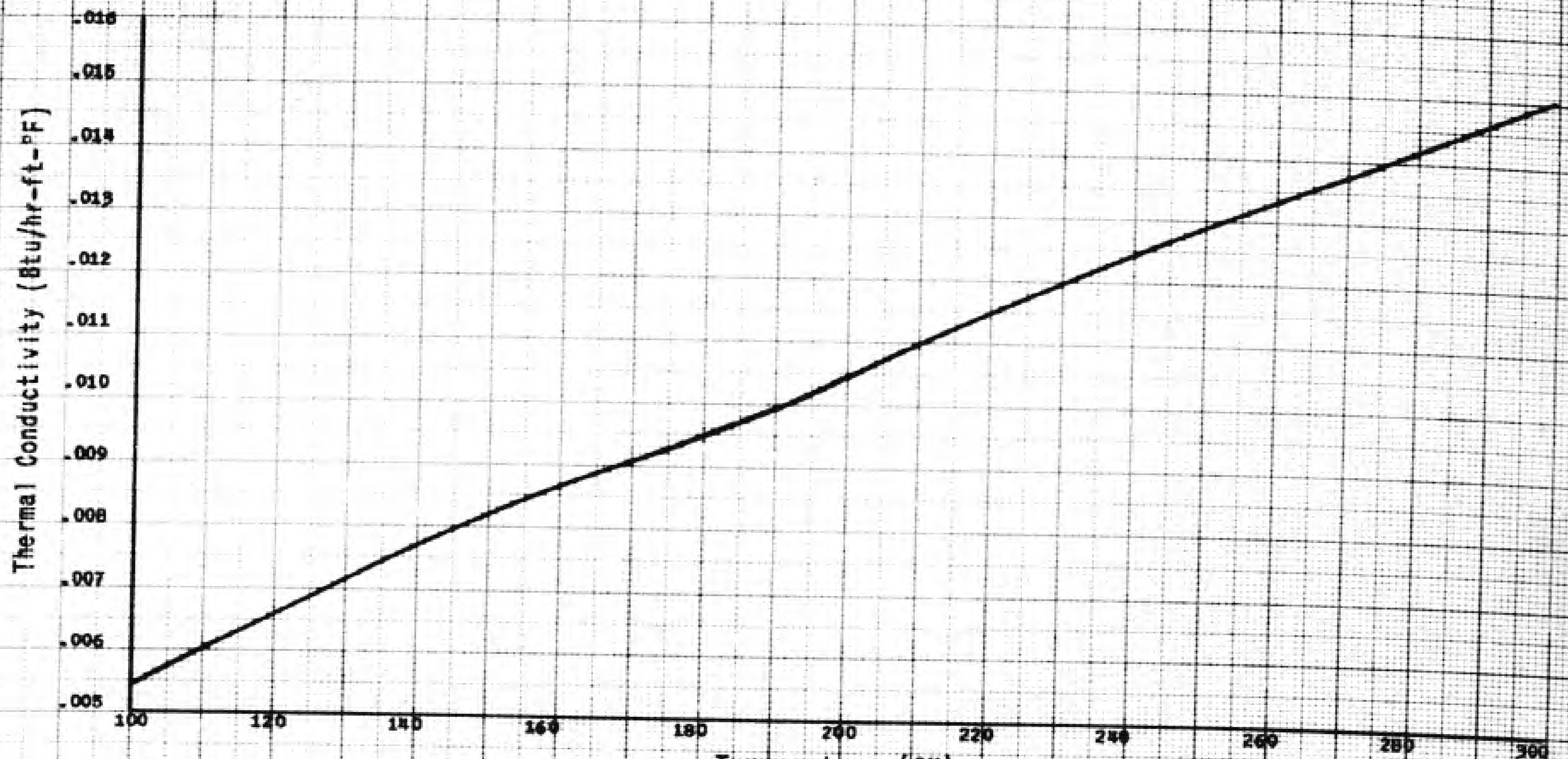


Figure 86
THERMAL CONDUCTIVITY OF GASEOUS NITROGEN AT 1 ATM FOR TEMPERATURES FROM 100 TO 300°K

6. Prandtl Number of Nitrogen Gas at One Atmosphere

Temperature (°K)	Temperature (°R)	Prandtl Number
100	180	.786
120	216	.778
140	252	.770
160	288	.762
180	324	.754
200	360	.747
220	396	.740
240	432	.733
260	468	.725
280	504	.719
300	540	.713

See Figure 87.

Reference: Hilsenrath, J., *et al.*, National Bureau of Standards Circular 564, November 1, 1955.

7. Self-Diffusion Coefficient of Nitrogen at One Atmosphere

T (°K)	D (ft^2/hr)
298	.821
273	.716
195	.402
78	.065

See Figure 88.

Reference: Winn, E. B., *Phys. Rev.*, *80*, 1024 (1950).

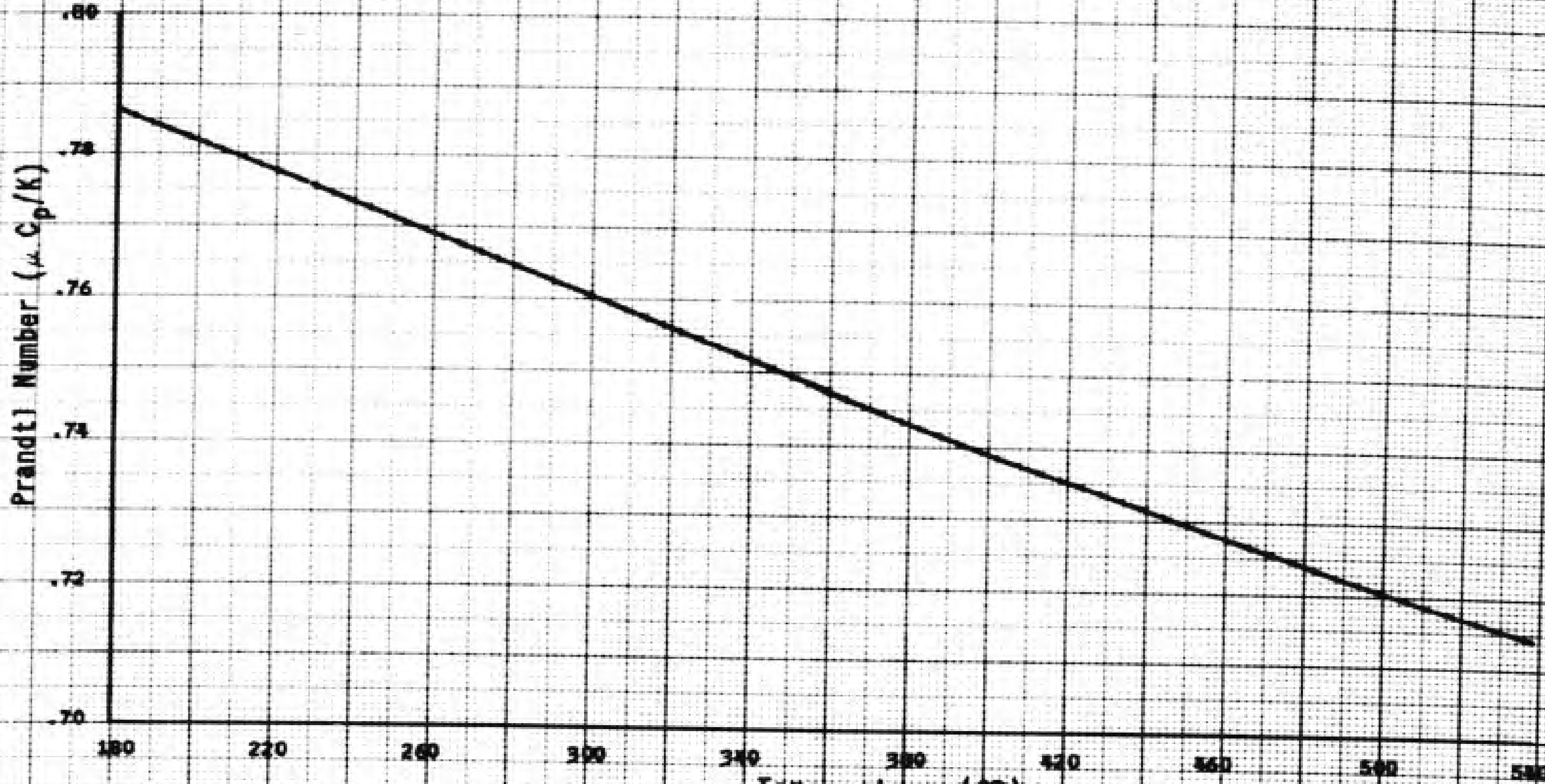


Figure 87

PRANDTL NUMBER OF GASEOUS NITROGEN

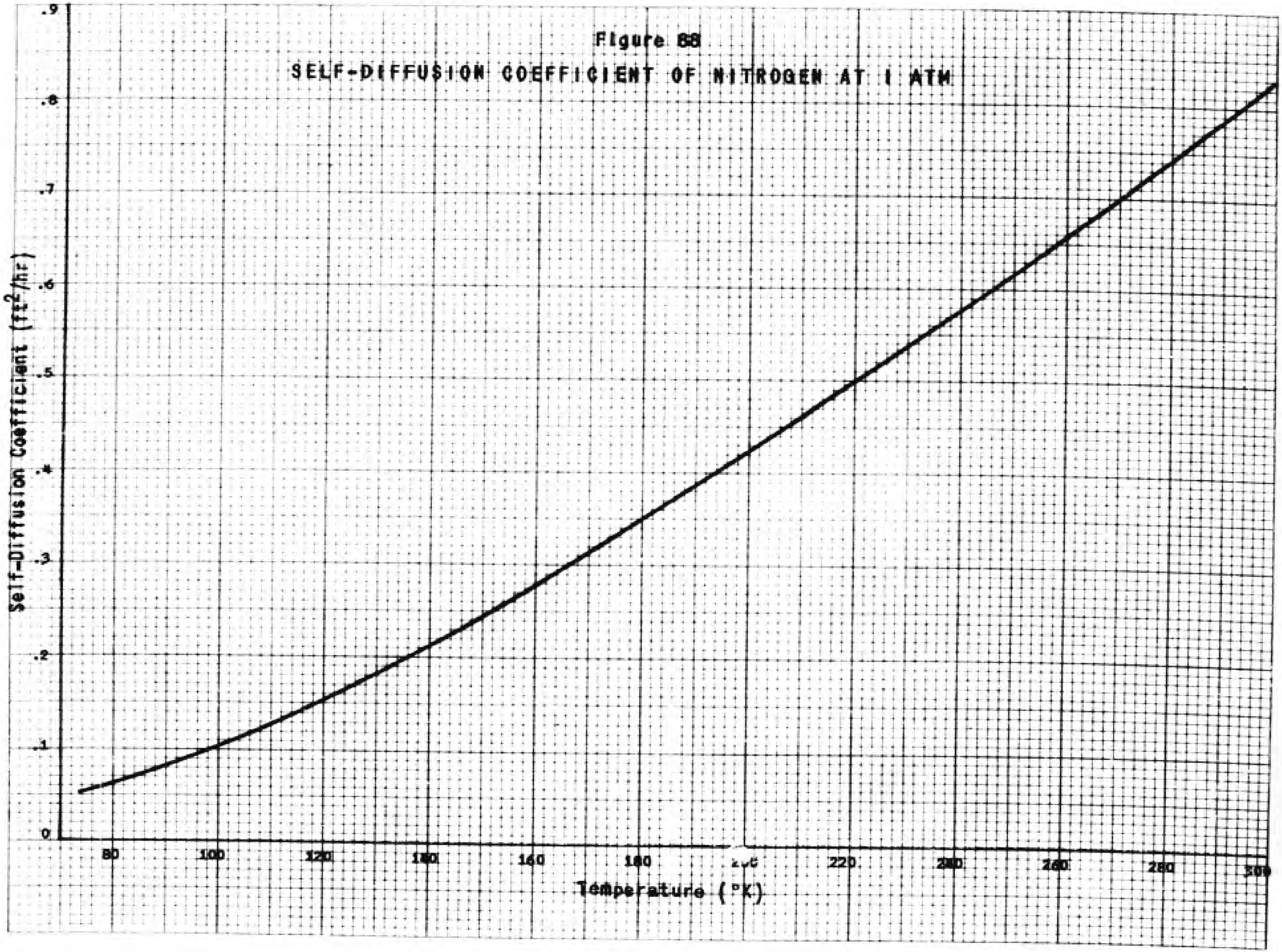


Figure 88

SELF-DIFFUSION COEFFICIENT OF NITROGEN AT 1 ATM

H. ELECTROMAGNETIC PROPERTIES

1. Dielectric Constant of Liquid Nitrogen at One Atmosphere

$$e = 1.680 - .0029\ T$$

e = dielectric constant

T = temperature, °K

The equation is valid for the temperature interval of 63 - 78°K.

Reference: Maryott, A. A., and E. R. Smith, National Bureau of Standards Circular 514, 1951.

2. Refractive Index of Saturated Liquid Nitrogen

Temperature (°K)	Refractive Index		
	4358A°	5461A°	6939A°
77.3	1.2019	1.990	
77.2	1.2021	1.1993	1.1980
75.1			1.999
74.1	1.2053	1.2026	
73.[illegible]			1.2015
72.4	1.2074	1.2042	
70.9			1.2045
69.3	1.2104		
69.2		1.2080	
68.4			1.2068
68.3		1.2092	
68.2	1.2121		
66.3	1.2140	1.2111	
65.5	1.2150	1.2121	1.2101
63.5	1.2171	1.2144	1.2121

See Figure 89.

Reference: Johns, H. E., and J. O. Wilhelm, Canadian Journal of Research, 15, 101 (July 1937).

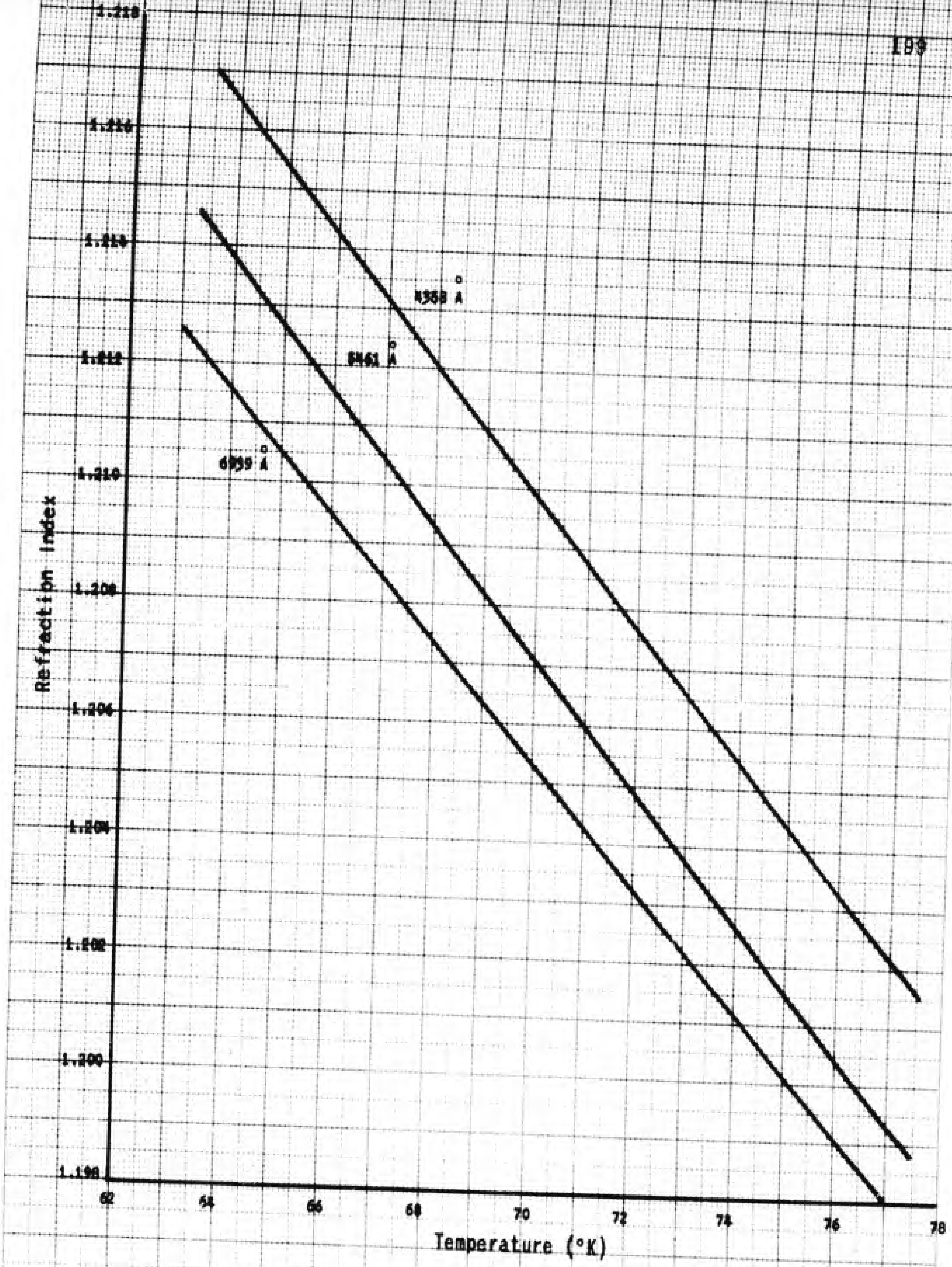


Figure 89

REFRACTION INDEX OF SATURATED LIQUID NITROGEN

APPENDIX A

LIQUID HYDROGEN DEWARS

TABLE A-I

SUPPLIERS OF LIQUID HYDROGEN AND LIQUID HELIUM CONTAINERS

Supplier	Dewar Capacity Range
Superior Air Products Co.[1] 132 Malvern Street Newark 5, New Jersey	8 Sizes--5 to 100 Liters
Hoffman Laboratories 5 Evans Terminal Hillside, New Jersey	15, 25, and 50 Liters (other sizes may also be available)
Standard Air Company, Inc. 80 Gardner Avenue Brooklyn 37, New York	10 Sizes--5 to 100 Liters

1. Delivery of Dewars in three to four weeks can be expected, on the basis of ADL's previous purchases from Superior Air Products Co.

TABLE A-II

LIQUID LOSSES FROM DEWARS MANUFACTURED BY SUPERIOR AIR PRODUCTS[1]

Dewar Size (liters)	Liquid Helium Loss as Gas (cm^3/24 hr, STP)	Liquid Nitrogen Loss (liters/24 hr)
10	100	1.5
15	175	2.0
25	225	2.75
30	250	2.75
50	500	3.00

---

1. Personal communication.

TABLE A-III

PRICE LIST OF SUPAIRCO[1] LIQUID HELIUM OR LIQUID HYDROGEN CONTAINERS[2]

Helium or Hydrogen Capacity (liters)	Nitrogen Capacity (liters)	Price[3] With Stainless Steel Casing 7/10/59	Standard Repair (Replacement Parts Extra)
5	6	$ 475.00	$135.00
10	12	570.00	160.00
15	18	650.00	180.00
25	30	745.00	210.00
30	35	825.00	240.00
50	60	970.00	260.00
75	60	1225.00	320.00
100	65	1370.00	390.00

[1] Superior Air Products Co.

[2] All sizes equipped with caster-mounted removable dolly.

[3] All prices f.o.b., Newark, N. J., as of July 10, 1959.

TABLE A-IV

SPECIFICATIONS OF SUPAIRCO LIQUID HELIUM OR LIQUID HYDROGEN CONTAINERS

Capacity Liquid Hydrogen/Helium	Approximate (Max.) Outside Diameter	Approximate (Max.) Over-all Height
5 liters	14"	30"
10 liters	16-1/4"	33-7/8"
15 liters	16-1/4"	38-1/2"
25 liters	20-1/4"	41"
30 liters	20-1/4"	43-3/4"
50 liters	25-1/8"	49-1/2"
75 liters	25-1/8"	54-1/8"
100 liters	26-1/4"	60-5/8"

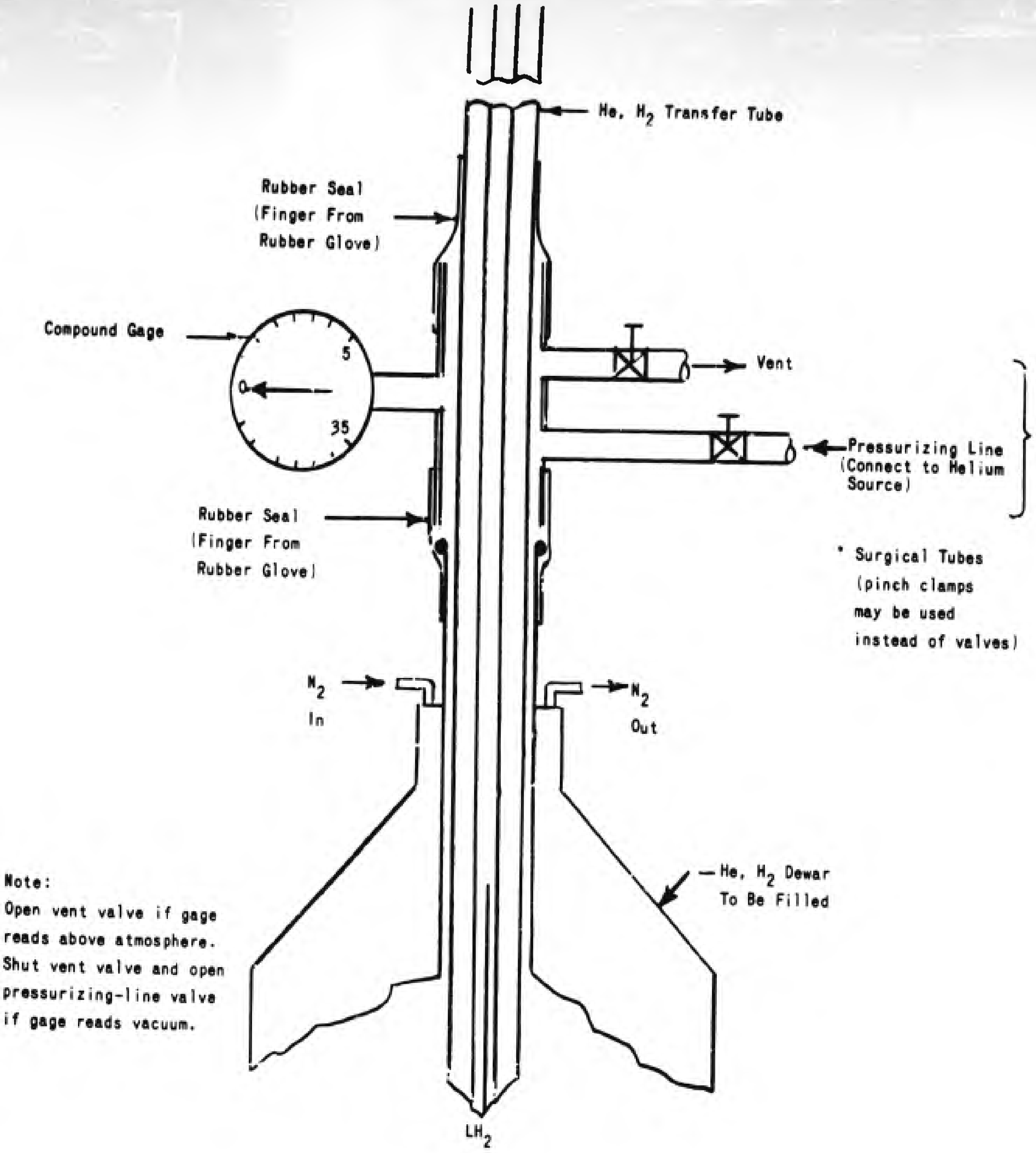
TABLE A-V

HOFFMAN LIQUID HYDROGEN AND LIQUID HELIUM CONTAINERS

Dewar Size (liters)	Liquid Helium Loss (cm^3/24 hr)	Capacity of Liquid Nitrogen Jacket (liters)	Approximate Prices,[1] 2/10/59
15	150	22	$625
25	150	34	685
50	200	42	785

---

1. Personal communication.



* Surgical Tubes (pinch clamps may be used instead of valves)

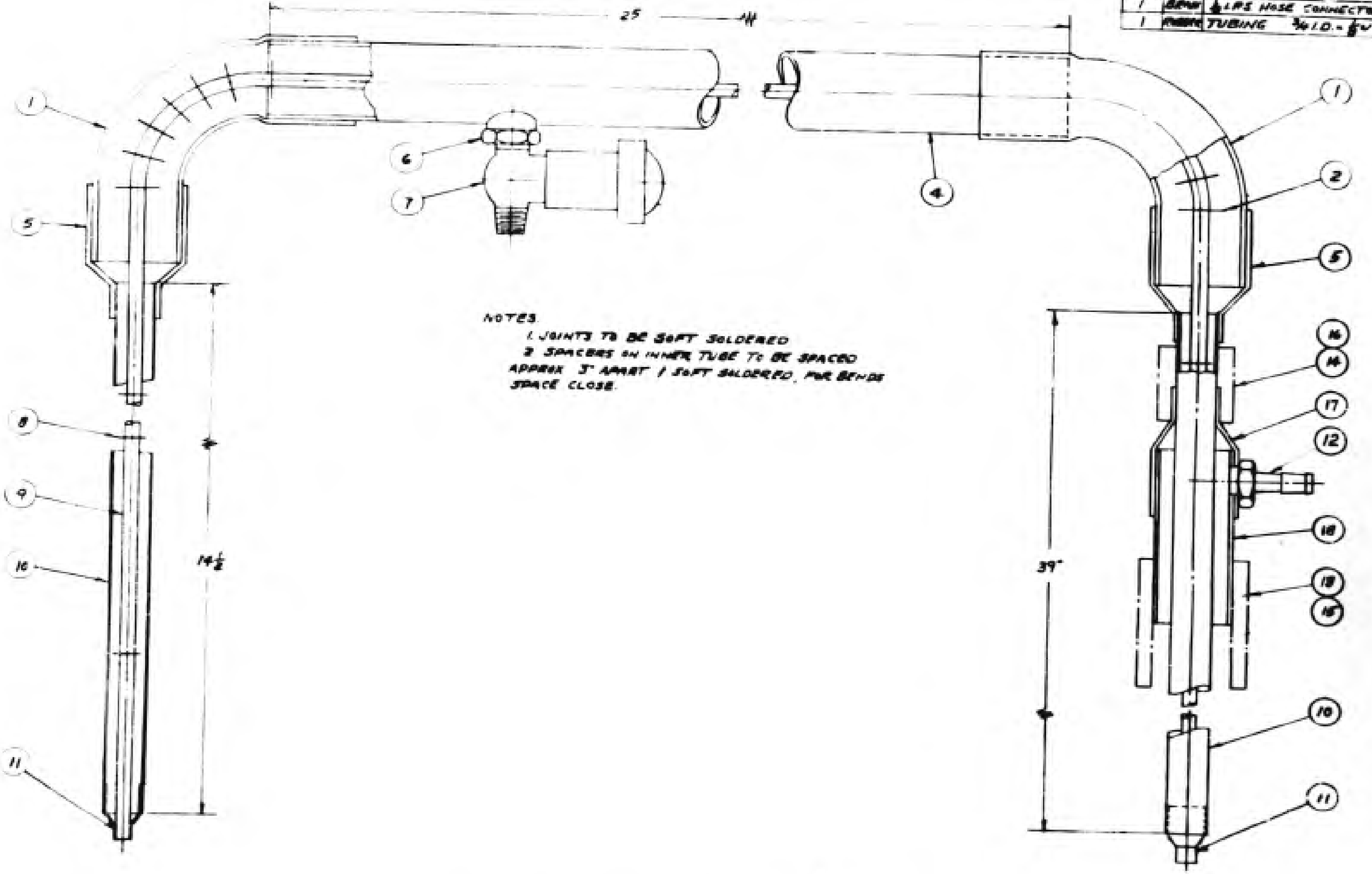
Note:
Open vent valve if gage reads above atmosphere. Shut vent valve and open pressurizing-line valve if gage reads vacuum.

Figure A-1

ADAPTER FOR FILLING WARM LIQUID HYDROGEN DEWAR

QUAN	MAT'L	NAME	DWG. NO.	PART NO.
1	RUBBER	TUBING 3/8 I.D. × 1/8 W.T. × 2' LG		14
1		HOSE CLAMP		15
1		HOSE CLAMP		16
1	WROT COPPER	REDUCING COUPLING 1/2 × 3/4 NOM.		17
1	COPPER	TUBE 1/4 NOM. × 2 1/2 LG.		18
				19

QUAN	MAT'L	NAME	ITEM NO.	DWG. NO.	PART NO.
2	WROT CU	3/4 NOM 90° STREET ELBOW 1/4 SHEET			1
	ST.STL	SPACER .005 MK		A1607-B	2
					3
25"	COPPER	TUBE 3/4 NOM.			4
2	WROT CU	REDUCING COUPLING 3/4 × 1/2 NOM.			5
1	BRASS	ADAPTER 1/8 NOM. × 1/4 NAT.			6
1	BRASS	VACUUM VALVE			7
	ST.STL	SPACER .005 THK 1.340 O.D.		A1607-B	8
84"	MONEL	TUBE 3/16 O.D. × .008 W.T.			9
49"	ST.STL	TUBE 1/2 O.D. × .010 W.T.			10
2	ST.STL	ADAPTER 1/2 DIA. × 1/2 LG		AR655Y2	11
1	BRASS	1/4 I.P.S HOSE CONNECTOR			12
1	RUBBER	TUBING 3/4 I.D. × 1/8 W.T. × 3' LG			15



NOTES.
1. JOINTS TO BE SOFT SOLDERED
2. SPACERS ON INNER TUBE TO BE SPACED APPROX 3" APART / SOFT SOLDERED. FOR BENDS SPACE CLOSE.

Figure A-2
HELIUM TRANSFER TUBE FOR 25-LITER DEWAR

QUAN	MATL	DESCRIPTION	PART NO	DWG NO
1	BRASS	VALVE ADAPTER	1	A3116-F
1	BRASS	VALVE COUPLING	2	A3116-G
1	BRASS	SHEATH ADAPTER	3	A3116-A
1	ST STL	PIN 1/8 OD x 1" LG	4	
2	NEOP.	"O" RING AN6227B-7	5	
1	NYLON	WASHER 1" OD x 1/2 ID x 1/16 THK	6	
1	BRASS	PLUG	7	A3116-C
1	ST STL	SEAT #304	8	A3116-B
1	STL	SPRING 1/2 OD x 1/2 FL x .047 W.D.	9	
1	ST STL	TUBE #304 3/8 OD x .015 WT	10	
1	ST STL	TUBE #304 5/16 OD x .010 WT	11	
1	MONEL	TUBE 3/16 OD x .006 WT	12	
	ST STL	SPACERS	13	

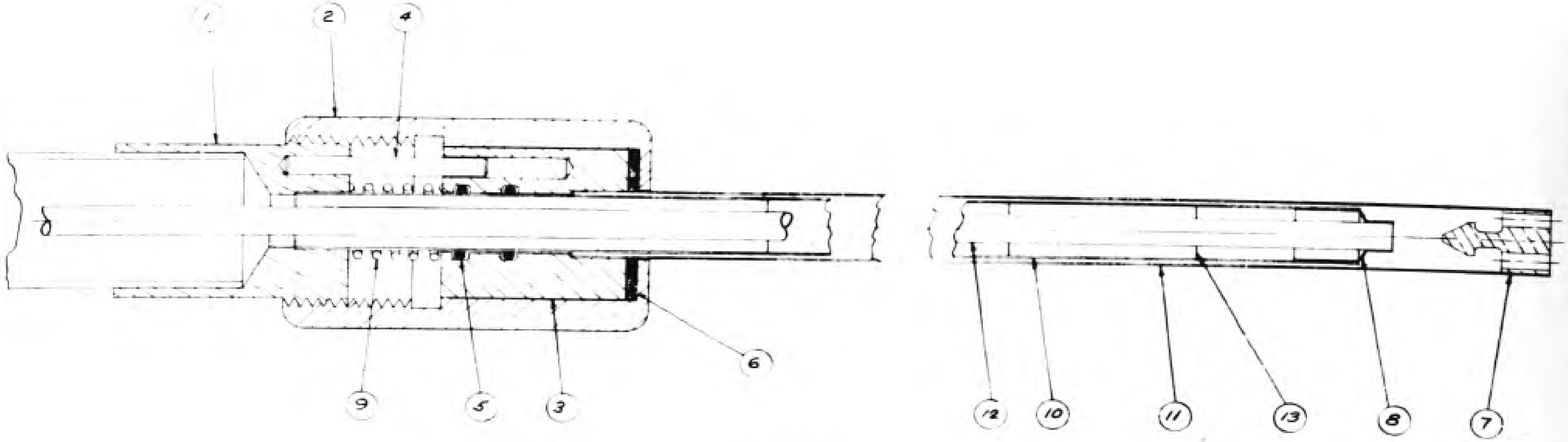


Figure A-3
CRYOSTAT DRAWOFF VALVE

SUPERIOR AIR PRODUCTS CO.
132 Malvern Street
Newark 5, New Jersey

General Instructions
H/H Containers

INDEX.

A. DESCRIPTION

GENERAL

1. General - These containers are designed for the efficient storage of liquid helium or liquid hydrogen. They utilize high vacuum insulation together with a liquid nitrogen shield to obtain extremely low evaporation losses. The design used results in a minimum loss rate not only of the helium or hydrogen, but also of the liquid nitrogen used in the shield. The general configuration is shown on Supairco Drawing A-2927 in a simplified cross-section.

   The container consists of an inner vessel, an inner vessel vacuum jacket, and an outer protective casing. The entire assembly is neck supported insofar as is possible. Soft solder and/or silver solder joints are used throughout the container, with substantial strength joints designed to withstand normal laboratory handling. Materials are used which have desirable properties for use at the low temperatures encountered. All references in the following text will be to liquid helium; however, the vessel can store liquid hydrogen with nitrogen shielding, or liquid argon with liquid oxygen shielding.

INNER ASSEMBLY

2. Inner Assembly - The inner vessel assembly is permanently evacuated before insertion into the liquid nitrogen shield, and the entire assembly is free to contract or expand with temperature changes at the bellows joint of the upper neck ring. The space between the innermost vessel wall and its vacuum jacket is permanently evacuated to approximately .01 microns and radiation in this space is kept at a minimum by the highly polished walls which face each other. A charcoal absorbent is also utilized in this space to minimize the effects of "outgassing" over a long period of time.

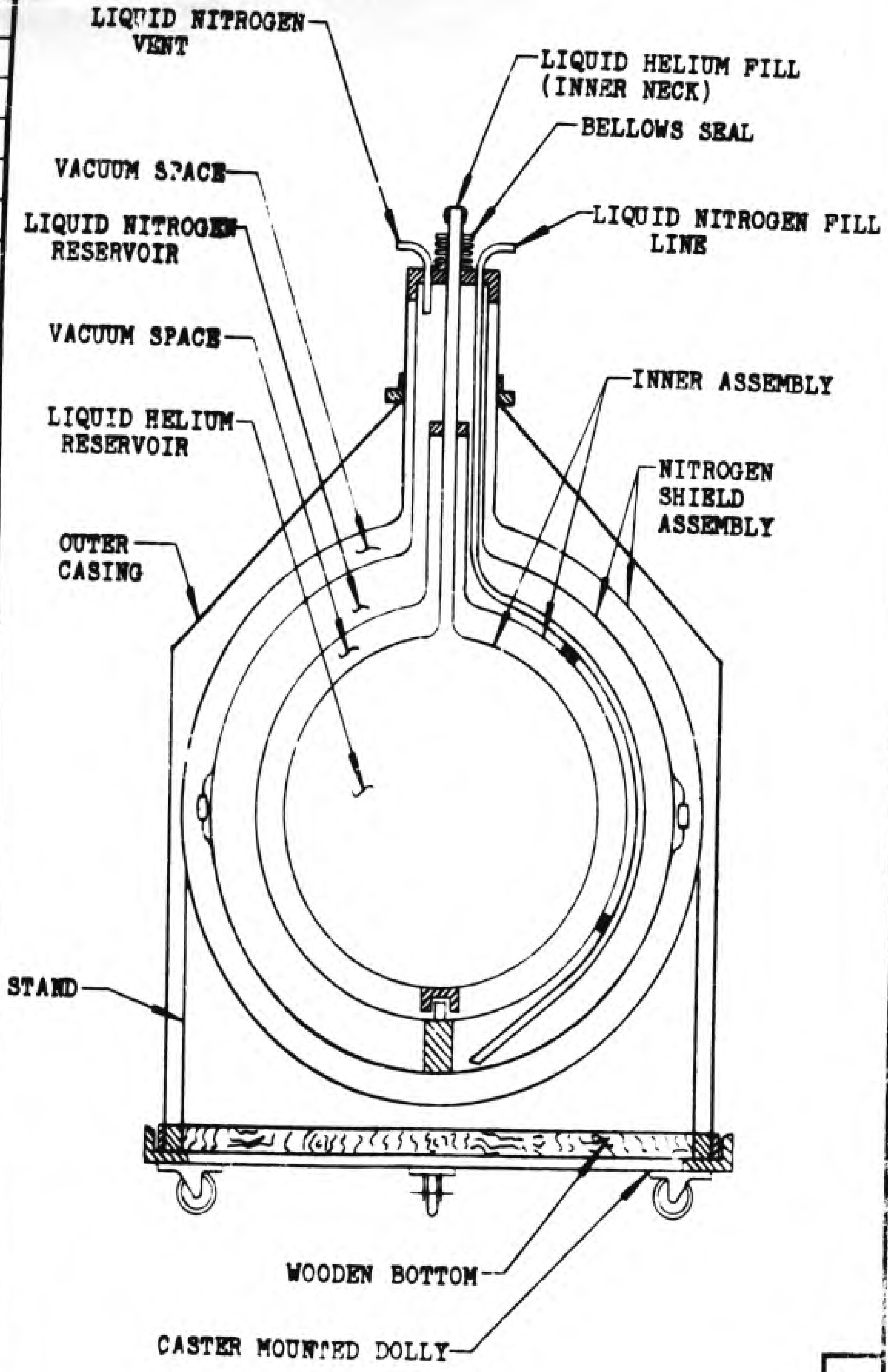
NITROGEN SHIELD

3. Nitrogen Shield - The liquid nitrogen shield is actually a liquid nitrogen container with a high vacuum insulation

jacket, within which the liquid helium/hydrogen inner assembly is mounted. The liquid nitrogen FILL fitting leads to a long dip tube extending to the bottom of the nitrogen shield space. This tube is installed to allow the nitrogen shield to be emptied without turning the container from a vertical upright position. The liquid nitrogen VENT fitting terminates just inside the upper neck ring, and serves as an escape point for evaporated nitrogen. The vacuum jacket of the nitrogen shield is also permanently evacuated to .01 microns and sealed off, with a charcoal adsorbent inside to overcome "outgassing" over a long period of time.

OUTER CASING

4. Outer Casing - The combined inner assembly and nitrogen shield are supported by a thin metal stand which in turn rests on the wooden bottom of the outer casing. The casing is made of painted carbon steel or of stainless steel. The latter is mandatory where the container is used in the vicinity of a strong magnetic field and is also recommended whenever possible to avoid corrosion from condensed moisture which collects during fill and discharge of the vessel and shield.



A-2927

REVISIONS			
LTR.	E. C. NO.	DATE	BY

UNLESS OTHERWISE SPECIFIED THESE NOTES APPLY.

1. FRACTIONS ± .010" DECIMALS ± .005"
2. TOLERANCE ON ANGLES ± 1°
3. ALL MALE THREADS MUST BE NATIONAL FORM CLASS 3 FIT.
4. ALL FEMALE THREADS MUST BE NATIONAL FORM CLASS 3 FIT.
5. ALL PIPE THREADS MUST BE AMER. NAT'L FORM TAPER THD.
6. RADIUS OR CHAMFER C ORNERS OR EDGES .005"

MATERIAL

MATERIAL SPEC. NO.

WEIGHT LBS.

ASSEMBLY DWG.

ORIGINALLY DESIGNED FOR

SUPERIOR AIR PRODUCTS CO.
NEWARK, N. J., U. S. A.

TITLE HELIUM-HYDROGEN CONTAINER
SIMPLIFIED CROSS SECTION

SCALE NONE

DRAWN A. FAPO

DATE 5-2-50

CKD /

APP.

A-2927

B. OPERATING INSTRUCTIONS

GENERAL

1. **General** - With normal precautions and proper care, the service life of these containers is comparable to that for liquid nitrogen dewars. Experience factors and field reports indicate that many helium dewars are in service after 5 years of continuous or intermittent use.

DRYING OUT

2. **Drying Out** - Before the container is placed in service, or if any possibility exists that moisture has entered into the container, it should be purged with warm (not over 212° F) dry, oil-free nitrogen gas to remove all traces of moisture. Temperatures over 212° F might damage or weaken a soft-solder joint. If the container is heated to 212° F, cool to room temperature with dry nitrogen to minimize the temperature change when liquid nitrogen is added. Both the inner vessel and the liquid nitrogen shield should be dried out in the same manner.

PRESSURE

3. **Pressure** - The helium/hydrogen vessel proper and the nitrogen shield should not be exposed to pressures normally above 3 psig and NEVER above 5 psig. Minimum wall thickness materials have been used to reduce cooling down losses, and even though these materials show higher tensile strength at low temperatures than at room temperature, the above pressures are the maximum we recommend. If higher working pressures are required special vessels can be furnished.

COOLING DOWN

4. **Cooling Down** - The nitrogen shield is filled through the FILL fitting. Add the liquid nitrogen slowly to take advantage of the sensible heat in the nitrogen vapor, as well as the latent heat in the liquid. When the liquid nitrogen has completely filled the shield, droplets of liquid nitrogen will emerge from the nitrogen shield VENT fitting. The inner vessel may then be filled with liquid nitrogen. When the complete assembly is cooled down to liquid nitrogen temperature, whatever liquid nitrogen re-

mains in the inner vessel may be displaced with cold helium gas (if available) or warm helium gas.

5. Filling - Liquid helium can then be added from source, using a vacuum-jacketed transfer tube when transferring either from a cryostat or from one vessel to another. Liquid hydrogen can be transferred in the same manner, with the exception that the hydrogen gas which is evolved must be handled with the normal safety precautions for hydrogen.

FILLING

6. Emptying Shield - To empty the nitrogen shield space, apply pressure on the nitrogen vent fitting with dry nitrogen gas. This will force the liquid in the shield up through the fill dip tube and out the nitrogen fill fitting. This is convenient when it is necessary to remove the nitrogen from the container for warming up or other reasons.

EMPTYING SHIELD

7. Moisture Accumulation - Moisture will tend to diffuse inwardly into both the nitrogen shield and the inner vessel due to sudden barometric changes or thermal oscillations. To prevent moisture entry into the nitrogen shield where it might freeze and possibly obstruct the nitrogen vent, we recommend the use of a simple "bunsen" type valve. This consists of a short length of ordinary surgical or laboratory gum rubber tubing which has a longitudinal slit in it approximately 1" long. When one end of this tube is slipped over the nitrogen FILL fitting and one end over the nitrogen VENT fitting, the nitrogen evaporating within the nitrogen shield due to heat leak inward will build up sufficient pressure to periodically open the slit and escape. This maintains a slight positive pressure over the liquid nitrogen shield at all times. A sudden increase in barometric pressure due to a change in atmospheric conditions will not be able to cause wet atmospheric air to enter the liquid nitrogen shield which could happen if the vent were left open.

MOISTURE

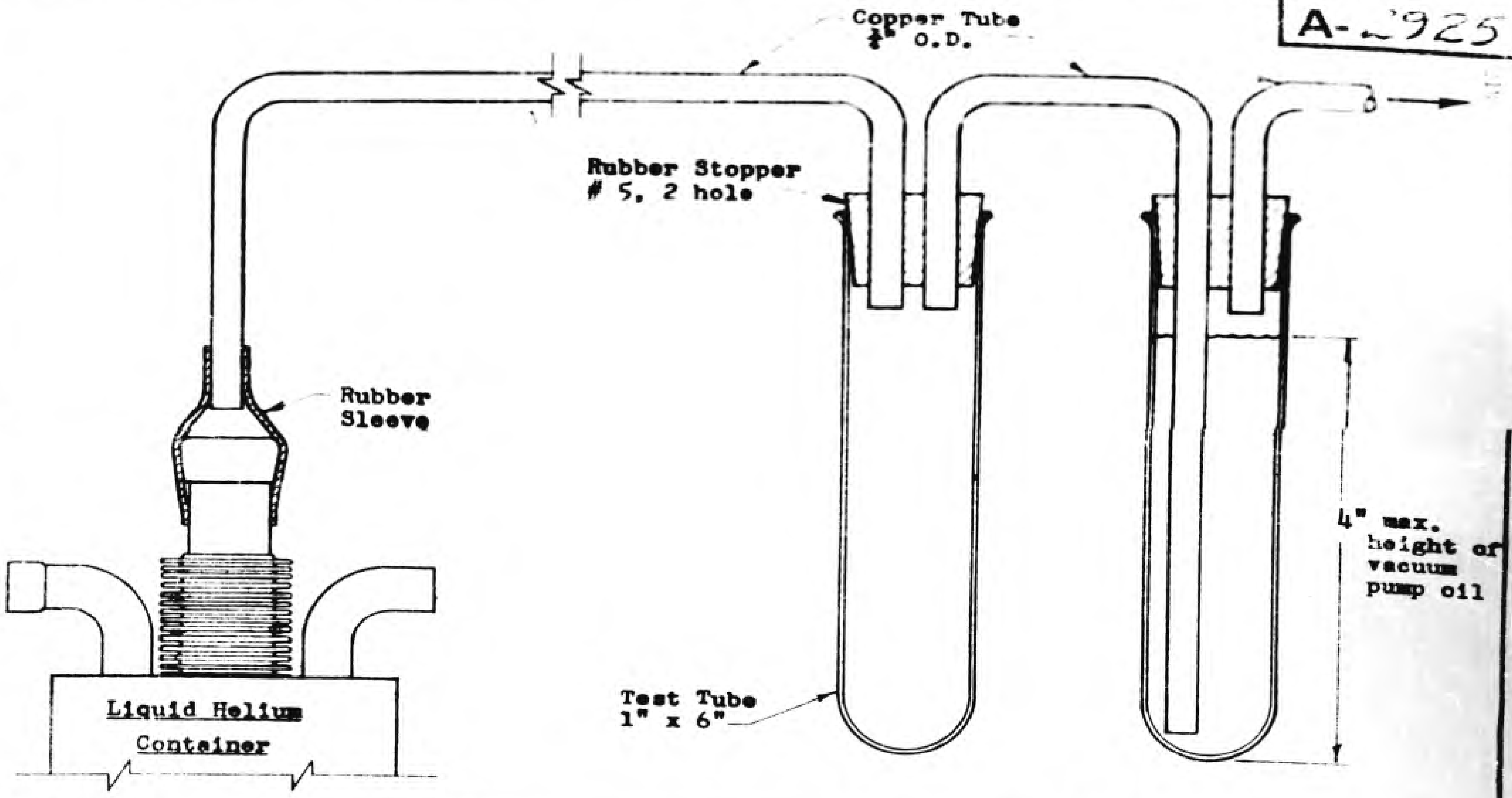
A similar "bunsen" valve can be used for the liquid helium space if liquid helium is stored. A rubber "bunsen" valve is NOT recommended when liquid hydrogen is stored since hydrogen will "age" the gum rubber rapidly and it will become so brittle that the valve will not operate. In such a case it is possible to use a commercial one-way valve or even a simple valve made from common laboratory equipment, such as shown on Supairco Drawing A-2925.

For earlier vessels which are not equipped with a bellows seal, the method shown in the reprint "Method for Prevention of Plugged Nitrogen Vents on Liquid Helium Storage Vessels" is very useful.

<u>CAUTION</u>

A more positive method of insuring that pressure is not building up in the container is to allow the evaporating helium and/or nitrogen to either bubble through a liquid for a visual spot inspection or to pass through a laboratory wet gasometer which can be read periodically. In either case precautions should be taken as shown on Supairco Drawing A-2925 to prevent back flow of liquid into container. Unless positive precautions, similar to those stated above, are taken moisture can freeze in the container blocking it. Pressure can build up under those conditions to dangerous levels.

A-2925



REVISIONS				
LTR.	E.C. NO.	DATE	BY	

MATERIAL

MATERIAL SPEC. NO.

WEIGHT LBS. | ASSEMBLY DWG.

ORIGINALLY DESIGNED FOR

SUPERIOR AIR PRODUCTS CO.
NEWARK, N. J., U. S. A.

TITLE HELIUM BACK-PRESSURE VALVE TO 3" WATER PRESSURE

SCALE None
DRAWN JES
DATE 5/5/58
CK.D ✓
APP [illegible]

A-2925

UNLESS OTHERWISE SPECIFIED THESE NOTES APPLY:
1. FRACTIONS ± .010" DECIMALS ± .005"
2. TOLERANCE ON ANGLES ± 1°
3. [illegible] THREADS MUST BE NATIONAL FORM CLASS 3 FIT.
4. ALL FEMALE THREADS MUST BE NATIONAL FORM CLASS 2 FIT.
5. ALL PIPE THREADS MUST BE AMER. NAT'L. FORM TAPER THD.
6. RADIUS OR CHAMFER ON CORNERS OR EDGES .015"

C. HANDLING

1. **General** - These containers are designed for laboratory use. It can be seen on Supairco Drawing A-2927 that though the inner container assembly is restrained from movement within the liquid nitrogen shield, the innermost shell of this assembly is free to move within its vacuum jacket. In addition, the innermost neck is made of extremely thin wall material. These precautions taken to minimize heat leak, with resultant lower evaporation rate also make the container vulnerable to rough handling, and in particular, sudden shock loads. GENERAL

2. **Precautions** - If the following rules are observed, the container life will be appreciably lengthened: PRECAUTIONS

   a) NEVER POUR liquid out of the container.
   b) DO NOT ROLL the container on a TILTED axis.
   c) Keep the container VERTICAL at all times.
   d) AVOID SUDDEN THERMAL SHOCKS.
   e) DO NOT DROP the container.
   f) Use the proper accessories for filling, discharging and movement within the laboratory.

3. **Transportation** - Although the containers have been designed for laboratory use, many have been put into transport service with success. As stated above, the container will not withstand sudden shock loads of any magnitude. Transportation by truck or by air is possible if such loads are avoided. Cushioning of the carrying crate and mounting the container in a spring loaded carrying frame are precautions which can be taken but careful handling by truckers and a knowledge of the limitations of the vessel are two important factors which affect the success of road or air transport of these containers. TRANSPORTATION

RECEIVING INSPECTION

4. Receiving Inspection - The container should be tested immediately after receipt to determine if it has been damaged in transit. Prior to shipment, every container is tested over a period of one to two weeks with liquid nitrogen to determine vacuum tightness. To duplicate this test after cooling down container fill the inner vessel with liquid nitrogen and measure the weight loss per 24 hours over a 3-day period. Then add liquid nitrogen to the nitrogen shield and repeat the weight loss measurements for 3 days more.

If the container is tested within a few days of the inspection test it receives in our own shops you will find that the losses are comparable to those shown on the enclosed test data sheet. However, if there is any lapse of time between our tests and those performed on receipt of the vessel you are liable to experience a considerable difference in the pounds lost per 24 hours. Outgassing occurring over a period of time accounts for this.

The pounds per 24 hours loss is not as important as the fact that the vessel reaches a point where you have a steady pound/day loss. An accelerated pound/day loss over a 72 hour period would indicate heat leak.

If the tests indicate a damaged container, a claim should be made immediately to the carrier by the consignee and our sales department should be notified so that instructions as to repair and/or replacement may be sent to the customer.

SHIPMENT EMPTY

5. Shipment Empty - The container is shipped from our plant with a heavy mandrel within the inner neck. This mandrel serves to strengthen the inner neck and should always be used whenever the container is shipped empty, even in case the container is being returned for repair.

D. REPAIR

REPAIR

Inasmuch as the assembly of the container involves several critical joints, we do not recommend repair in the field. The loss of vacuum for any period of time will tarnish the inner polished surfaces and repair of the leak alone will not restore the container to its original efficiency. Repair charges quoted are based on complete disassembly, repolishing, reevacuating, reassembly and test of the vessel. Should examination reveal any parts requiring replacement additional cost is involved. Containers which have been in use for extended periods of time may indicate a loss in efficiency which cannot be justifiably attributed to a gross vacuum leak. It may well be that some migration of the outgassed impurities has taken place and has caused a change in the emissivity of the polished surfaces. Bringing the container to room temperature and re-cooling to operating temperature may restore the original efficiency.

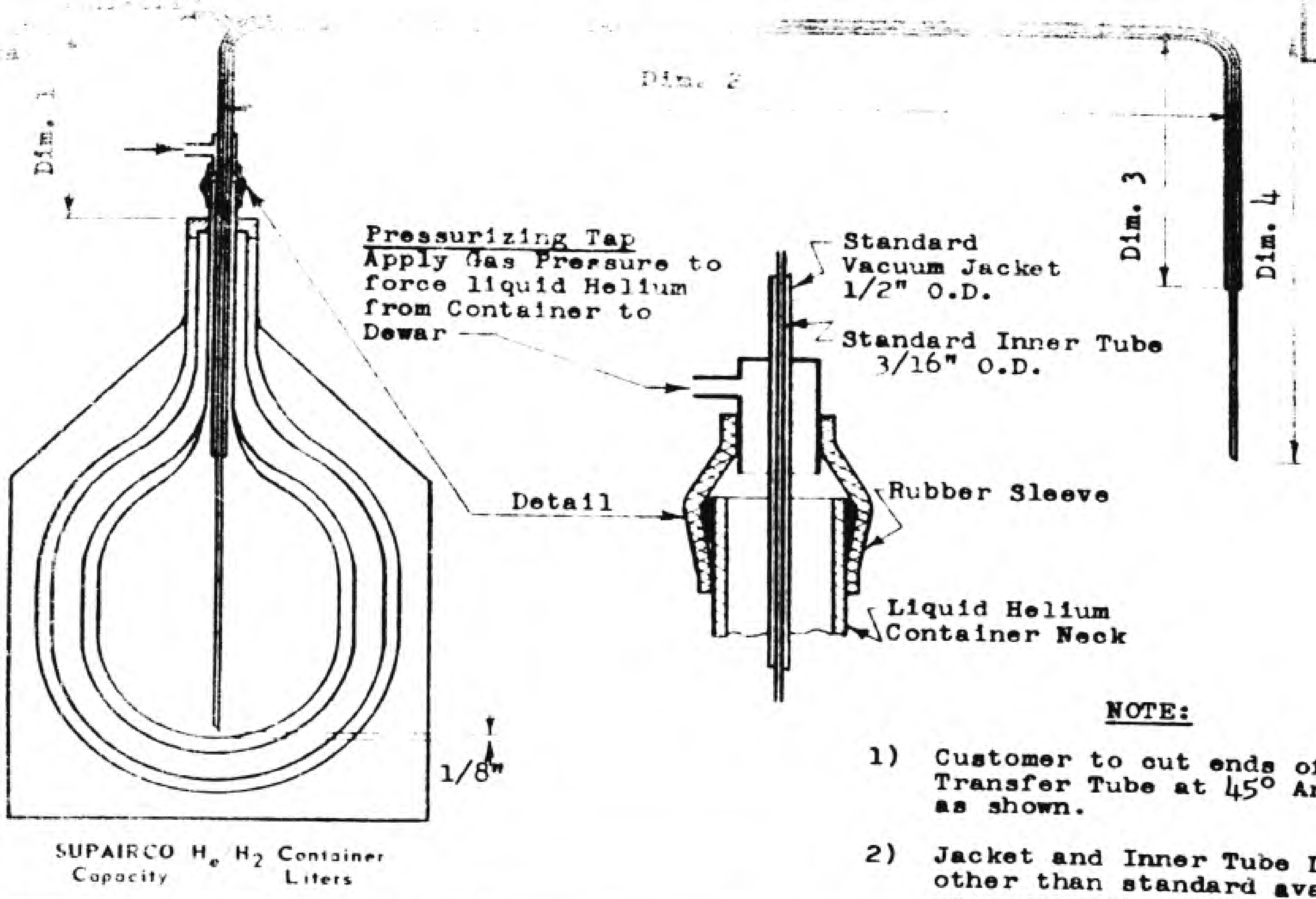
Any container returned for repair should be handled as carefully as if it were new. The shipping mandrel should be inserted and the container carefully crated for return in order that the nature of the failure may be more readily determined.

E. ACCESSORIES

1. **Transfer Tubes** - For transferring liquid helium or hydrogen both rigid and flexible vacuum jacketed tubes are available. These are fabricated on an individual custom basis, with considerable variation in length and configuration available for a minimum charge. Our Drawing A-644 indicates the rigid type, and our Drawing A-2906 shows the flexible type. TRANSFER TUBES

2. **Dollies** - For inter-laboratory movement, caster-mounted dollies are supplied with all sizes of containers. DOLLIES

A- 44



NOTE:

1) Customer to cut ends of Transfer Tube at 45° Angle as shown.

2) Jacket and Inner Tube Diameters other than standard available upon request.

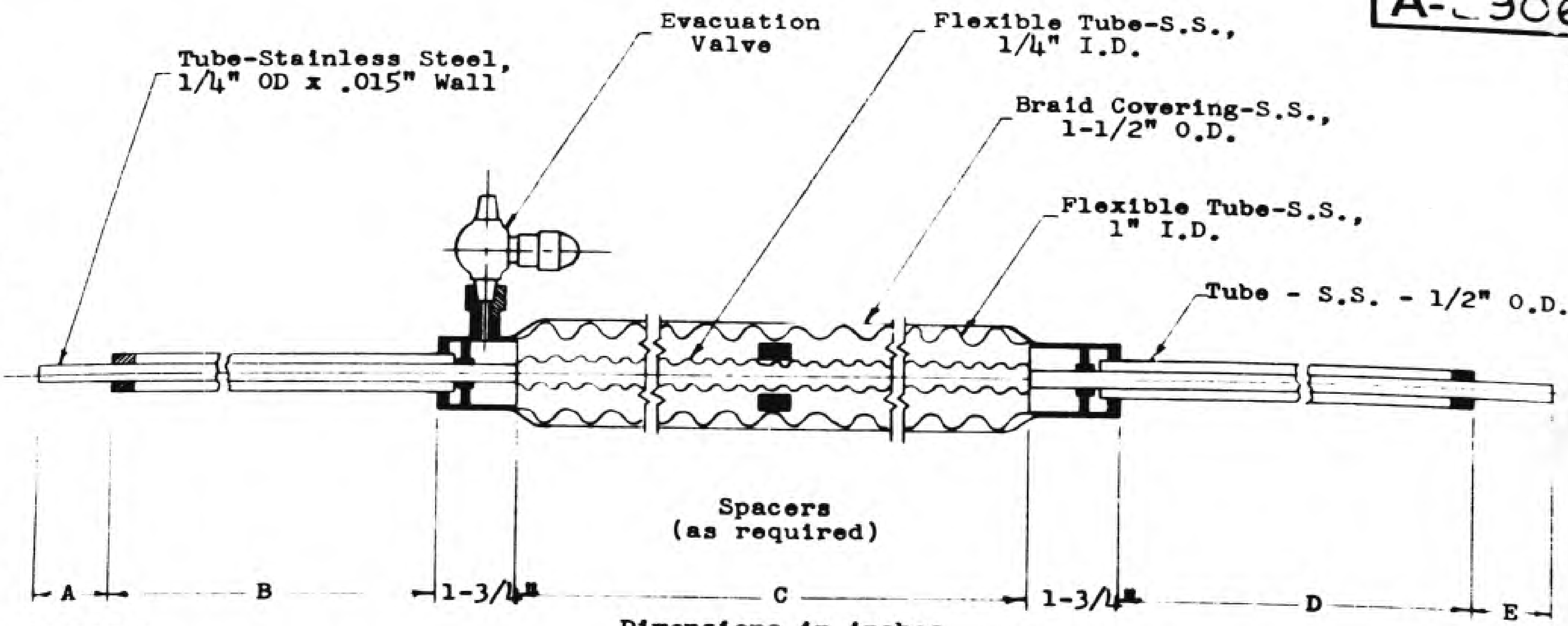
SUPERIOR AIR PRODUCTS CO
NEWARK, N. J., U. S. A.

TITLE TRANSFER TUBE
LIQUID HELIUM/HYDROGEN

MATERIAL			
MATERIAL SPEC. NO.			
WEIGHT LBS	ASSEMBLY DWG.		
ORIGINALLY DESIGNED FOR			
SCALE None	DRAWN L.T.	DATE 5/53	
CK'D ✓			
APP LEP	A-644		

UNLESS OTHERWISE SPECIFIED: 1. FRACTIONS ± .010 DECIMALS ± .005
2. TOLERANCE ON ANGLES ±
4. ALL FEMALE THREADS MUST BE NATIONAL FORM CLASS 2 FIT
5. ALL PIPE THREADS MUST BE AMER. NAT'L FORM TAPER THD.
6. [illegible] CHAMFER ON [illegible] CORNERS [illegible] EDGES [illegible]

A-‿306



Options:

1. Right angle bend in rigid portions of tube.
2. Pressurizing tap.

Dimensions in inches

A	B	C	D	E

Note:

The minimum turning radius of the flexible portion is 8" R @ center line of tube. (13" of length is required for each 90° turn)

REVISIONS			
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A	352	12-18-58	[illegible]

MATERIAL

MATERIAL SPEC. NO.

WEIGHT LBS.

ASSEMBLY DWG.

ORIGINALLY DESIGNED FOR

UNLESS OTHERWISE SPECIFIED THESE NOTES APPLY

1. FRACTIONS ± .010" DECIMALS ± .005"
2. TOLERANCE ON ANGLES ± 1°
3. [illegible] MALE THREADS MUST BE NATIONAL FORM CLASS 3 FIT.
4. ALL FEMALE THREADS MUST BE NATIONAL FORM CLASS 2 FIT.
5. ALL PIPE THREADS MUST BE AMER. NAT'L FORM TAPER THD.
6. RADIUS OR CHAMFER O[illegible] CORNERS OR EDGES .005"

SUPERIOR AIR PRODUCTS CO.
NEWARK, N. J., U. S. A.

TITLE TRANSPER TUBE - FLEXIBLE
Vacuum Insulated

SCALE --

DRAWN J. L.

DATE 4/4/58

C'K'D ✓

APP. [illegible]

A-?906

F. MODIFICATIONS

1. Lifting Lugs - Lifting lugs can be incorporated in the outer vessel jacket for a nominal extra charge. LIFTING LUGS

2. Other - The inner vessel can be provided for higher working pressures, for cylindrical configuration, for corrosive service, and with variable size neck openings. OTHER

APPENDIX B

LIQUID HYDROGEN SAFETY MANUAL

A. GENERAL PROPERTIES

1. Chemical Composition

Hydrogen, H_2. The hydrogen molecule exists in two forms (ortho and para), depending on the relative direction of spin of the two atoms. In the past, storage of the liquid was difficult because of the heat released as the ortho slowly and spontaneously changed to para hydrogen. With the current use of catalysts at production facilities, almost pure para hydrogen can be produced in the liquid form, and the problem caused by heat release is eliminated.

2. General Appearance

High-purity liquid hydrogen is a transparent, colorless, odorless liquid. At atmosphere pressure, it boils vigorously (because of its low boiling point) and creates a voluminous vapor cloud.

3. Chemical Nature

Liquid hydrogen is nontoxic and relatively inert except in the presence of oxidizers. When it is allowed to evaporate in air, it forms mixtures that are highly combustible over a relatively wide range of concentrations.

4. Physical Properties

Boiling Point	-423°F
Freezing Point	-435°F
Density at -423°F	4.4 lb/ft^3
Auto-Ignition	1076°F
Flammability Limits in Air (H_2 gas)	4.0 to 74.2% H_2
Viscosity at -423°F	140 micropoise

Vapor Pressure:

-433°F	1.94 psi
-423°F	14.7 psi
-420°F	23.7 psi
-402°F	162 psi

5. Solubility

With the exception of helium, all known substances are essentially insoluble in liquid hydrogen.

6. Stability

Liquid hydrogen is chemically stable. Because of its low boiling point it is physically stable only when stored under suitable conditions. When stored in properly designed containers, the 24-hour evaporation rate may be less than 1.5% for a 1000-gallon container.

7. Compatibility

Hydrogen in either liquid or gaseous form will react violently with strong oxidizers, such as oxygen and fluorine, and will ignite with a small amount of energy.

As with most cryogenic fluids the effect of low temperature on material properties is extremely important. Mild steels and most ferrous alloys lose ductility at liquid hydrogen temperatures and become brittle. Moreover, the severe temperature changes to which the equipment is subjected can cause stress concentrations that mustbe taken into account in equipment design.

B. HAZARDS

1. Health Hazards

Since hydrogen is nontoxic, the chief danger to health lies in the extreme cold of the liquid form and in the possibility of fire.

The main hazard of the liquid arises from its coldness. Serious "burns" can occur when the skin or other parts of the body are exposed to liquid hydrogen temperatures by contact with pipes, valves, etc., or with the liquid itself.

Since mixtures of the vapor and air are extremely flammable, a serious fire hazard always exists when hydrogen vapors are present in the atmosphere. Furthermore, mixtures having a high percentage of hydrogen will not support life.

Parts of the body that have come into contact with liquid hydrogen should be treated as for frostbite. Extensive and severe burns should be kept sterile and should receive medical attention as soon as possible.

2. Fire Hazards

When no impurities are present, hydrogen burns with a colorless invisible flame. Burning can be initiated with a small amount of energy and can take place with hydrogen-air mixtures that are as little as 4% or as high as 74% hydrogen.

Unconfined hydrogen-air mixtures burn rapidly, once burning is initiated by a spark or flame. In confined areas or when ignition is accomplished by a shock source such as a blasting cap or a small explosive charge, a detonation, or an explosion, of the mixture can occur.

One can control hydrogen fires more effectively by shutting off the supply. Equipment should be designed so that the supply of hydrogen can be shut off in the event of most pipeline failures. Small fires, as from minor gas leaks, can be controlled by the use of steam. If hydrogen flames are extinguished, the liquid will continue to vaporize and form a cloud of combustible gas; if this cloud should be ignited, it might cause more damage than the small fire would have caused. Where large spills occur, the area over a considerable distance (at least 400 feet from the source) should be vacated. Adjacent structures may be sprayed with water for their protection. It should be emphasized that the outer edges of the flame, or fire, generally cannot be seen.

3. Explosion Hazards

Normally, liquid hydrogen does not present an explosive hazard when it evaporates and mixes with air in an unconfined space. The explosive hazard exists when the mixture is confined or partially confined, or when it is ignited with a shock-source initiator such as TNT. Explosive hazards also exist when oxygen-enriched solid air or strong oxidizers, such as oxygen or fluorine, are present. Pressure rupture, with severe consequences, can occur when the liquid is held in a closed system with no refrigeration. Hydrogen cannot be maintained as a liquid if its temperature rises above -400°F, regardless of confining pressure. Liquid hydrogen trapped between valves can cause violent rupture of the pipe. Loss of refrigeration can cause a storage tank to rupture if the pressure is not relieved by suitable devices.

All sources of ignition should be kept away from areas where liquid hydrogen is stored or handled. There should be no smoking; explosion-proof electrical equipment and spark-proof tools should be used; and equipment should be grounded to remove static electricity.

Hydrogen vapors should be vented at a remote location, and storage tanks and other containers should be kept under positive pressure to ensure that air does not enter the system. Enclosures of any type that would allow trapping of hydrogen should be either eliminated or ventilated.

Pressure rupture of equipment can be avoided by the proper use of pressure-relief valves and blowout disks. Pressure gages should also be used.

C. SAFETY MEASURES

1. Education of Personnel

The following subjects should be explained to all personnel working with liquid hydrogen:

a. Nature and properties of hydrogen in both the liquid and gaseous phases.

b. Approved materials that are compatible with liquid hydrogen.

c. Proper equipment and its operation.

d. Use and care of protective equipment and clothing.

e. First-aid instructions.

Trained supervision of all potentially hazardous activities involving liquid hydrogen is essential.

2. Personal Protection

Gloves may be of leather or asbestos, depending upon the job requirements. They should be loose-fitting for quick removal but not of the gauntlet type. Sleeves should be rolled down over the gloves to reduce chances of liquid collecting inside the glove.

Footwear should be of leather and easily removable. It is preferable that they have high tops, to prevent liquid hydrogen from entering in the event of spillage. Pants legs should be worn outside and over the shoe tops. Shoes whose soles have been exposed to the liquid should be removed immediately; otherwise, heat transfer through the soles might reduce the temperature sufficiently to cause frostbite.

A face shield and cap should be worn by personnel handling liquid hydrogen. Because of the fire hazard, flame-resistant, light-colored coveralls should also be worn. Respiratory protection is not required.

D. TRANSFER AND STORAGE

1. General

Both fixed and mobile containers for liquid hydrogen should be of approved design, materials, and construction.

An adequate water supply or fire extinguishers must be available for fighting fires (of combustibles other than hydrogen). Approved, safety-type personnel showers and fire blankets must be properly located for immediate use in an emergency. Protected areas should be provided for personnel safety in the event that hydrogen spilling from large storage tanks or pipelines is ignited.

2. Materials

The ability of materials to maintain satisfactory physical properties and to withstand thermal stresses caused by large temperature changes during cooldown or warmup is of prime importance.

The ferrous alloys, except the austenitic nickel-chromium alloys (18-8 stainless steel series), lose their ductility when subjected to the low temperatures of liquid hydrogen and become too brittle for such service.

The following metals are generally acceptable for service with liquid hydrogen:

18-8 Stainless steel series

Copper

Bronze

Brass

Monel

Aluminum

Everdur

Lubricants are generally not practical in the presence of liquid hydrogen, since they solidify and become brittle at the temperature of the liquid. Where "O" rings are used in fittings, vacuum grease is satisfactory.

The following nonmetals are satisfactory for use with liquid hydrogen.

Teflon

Kel-F

Asbestos impregnated with Teflon

3. Equipment

Liquid hydrogen may be stored in either fixed or mobile tanks of proven design and materials. Storage and shipping containers designed for noncryogenic fluids should not be used in this service. Storage tanks should be tested in accordance with the provisions of applicable ASME, ASTM, or ICC specifications for unfired pressure vessels, so that material or fabrication defects will be avoided. Materials used for pressure vessels containing liquid hydrogen should be impact-tested in accordance with paragraph UG-84 of Section VII of the ASME Code for Unfired Pressure Vessels.

Containers for shipment, storage, and transfer of liquid hydrogen should be fabricated in accordance with the physical and structural requirements of the service they are expected to endure. The containers should be insulated and vacuum jacketed to prevent rapid vaporization of the contents. The inner storage tank should be of welded construction, equipped with an adequate pressure-relief valve for control of maximum pressure and a rupture disk to relieve unusually fast pressure buildup. Insulation material such as evacuated perlite or santocel is acceptable The insulation material should be compatible with liquid oxygen, for if the outer tank fails, air may be condensed and mixed with it. If liquid nitrogen is used as a coolant, proper relief valves, rupture disks, and venting should be incorporated into the design

Pipes and fittings should be of the approved materials and construction and should be hydrostatically tested at the prescribed pressures. Welded and flanged connections are recommended. Eutectic braze procedures are also satisfactory with stainless steel. Threaded connections, particularly where directly exposed to liquid hydrogen temperatures, should be avoided.

Only pumps and shaft seals specifically designed and qualified by test for liquid hydrogen should be used.

Gaskets may be made of the approved materials listed above, depending upon the particular application.

Globe, gate, plug, or ball valves may be utilized; they must conform to particular specifications to ensure they are suitable for use with liquid hydrogen. Valves must be capable of being purged efficiently and have an adequate packing design to provide good sealing and to prevent plugging or condensation of air.

4. Main Storage

Enclosures of any kind for large storage tanks should be avoided. All storage tanks for liquid hydrogen should be surrounded by a dike enclosing a volume at least 10% larger than the capacity of the storage vessels. The diked area should be covered to a depth of 6 inches with 1 to 1 and 1/2 inches of crushed rock.

All main storage tanks and containers should be located with due regard to the quantity-distance tables established by the service using the facility.

No smoking, sparks, or open flames should be permitted in storage areas. The area should be kept free of all other combustibles, and periodic inspection should be made to ensure good housekeeping practices.

5. Ready Storage

The provisions and regulations covering main storage should apply without exception to ready storage.

6. Transfer Procedures

Operational procedures will be defined by the cognizant authority or by the manufacturer of the hydrogen equipment. All operating personnel should have complete and thorough instruction prior to operating the equipment. All valves, pumps, switches, etc., should be identified and tagged.

Suppliers of liquid hydrogen will furnish loading and unloading instructions as part of their service. The users should be instructed by the supplier in the proper use of the equipment.

The necessary procedures for the transfer of liquid hydrogen to and from storage tanks should be based on specific tank designs and the requirements of both the user and the supplier.

Tanks should be cleaned; solid particles such as welding slag and dirt should be removed so that the plugging of strainers or valves will be avoided. If liquid cleaners are used, all traces of liquid must be removed before hydrogen is admitted.

Before liquid hydrogen is admitted, the system must be thoroughly purged. (The only substance (other than hydrogen) that can be left in the system is helium.) Purging requires the evacuation of the air, followed by the breaking of the vacuum with nitrogen gas. This procedure should be repeated until the concentration of oxygen in the tank is well below the combustible limit (4.0% O_2 by volume). The tank should then be re-evacuated and the vacuum broken with hydrogen gas.

Storage tanks should be vented at least 30 feet above the ground and at a remote location. Purges of steam or nitrogen should be available for extinguishing fires in stacks where venting rates are low. For continuous venting at rates in excess of 30 lb/min, provision should be made for burning the gas.

7. Spills, Leaks. and Decontamination

The principal danger from a spill or leak is fire. The danger of fire can be reduced if the storage area is not enclosed and if provisions are made for increasing the evaporation rate. There is no efficient means of decontamination other than rapid vaporization and dilution with the air.

E. SHIPPING

According to "Agent H.A. Campbell's Tariff No. 10, Interstate Commerce Commission Regulations for Transportation of Explosives and Other Dangerous Articles by Land and Water," liquid hydrogen is not to be offered or accepted for transportation. Special permits have been obtained by the Air Force, however.

Shipping containers are insulated and vacuum jacketed. As in storage tanks, proper pressure-relief valves and rupture disks are mandatory. Shipping over long distances may require that the container be vented before the destination is reached. Safe procedures that require hydrogen to be vented in remote areas should be followed.

The design of a semitrailer for transportation of liquid hydrogen is given in R & D Exhibit WCLEF-398A, dated 10 March 1958, Semitrailer, Tank, AF/M32U-1, Wright Air Development Center, Directorate of Development, Aeronautical Accessories Laboratory. Additional engineering information may be obtained from laboratories and producers experienced in cryogenic work.

Producers will supply loading and unloading instructions as part of their service.

F. RECOMMENDED SAFETY INSTRUCTION FORMAT
(to be posted at operations site)

1. Hazards

a. Skin contact causes severe frostbite and "burns."

b. Extremely flammable--part or all of the flame may be invisible.

c. Explosive hazards are present when

(1) Solid air collects in liquid hydrogen.

(2) Gaseous hydrogen is mixed with air in a confined space.

2. First Aid

When skin comes in contact with the liquid or cold pipes, valves, etc.

a. Remove clothing if saturated with the liquid.

b. Keep affected skin areas sterile.

c. Call for medical attention.

3. Safety Precautions

a. All personnel shall be familiar with

(1) Nature and characteristics of liquid hydrogen.

(2) Safety features of the equipment and facilities.

(3) Proper operating procedures.

(4) Fire regulations.

b. Approved clothing, including face shields and gloves, shall be worn where specified.

c. Always provide good ventilation and allow no ignition source of any type to be brought into the area.

APPENDIX C

A STUDY OF THE HAZARDS IN THE STORAGE AND HANDLING OF LIQUID HYDROGEN[1]

by

L. H. Cassutt,[2] F. E. Maddocks,[3] W. A. Sawyer[4]

A. INTRODUCTION

The need to improve propulsion systems for missiles and space vehicles has focused attention on many fuels and oxidants previously considered impractical for such applications. A factor in the earlier rejection of these propellants was the extreme hazard associated with their use--at least as revealed in laboratory programs. Although one of these propellants, liquid hydrogen, has been a laboratory curiosity for years, knowledge of its characteristics was insufficient to provide a sound basis for the design of equipment for its production and use. The low ignition-energy characteristic and the wide limits of flammability of mixtures of hydrogen and air and the effects of detonation of such mixtures under confined conditions made handling and storage hazards appear great. For these reasons, the Air Research and Development Command felt it desirable, before producing liquid hydrogen in large quantity, to initiate a research program to develop realistic safety criteria. Such criteria could bring about a substantial reduction in the cost of the capital equipment for the production and storage facilities and could point out safety devices that would prevent major losses.

B. POTENTIAL HAZARDS

As an initial step in devising a test program, an analysis was made of the probable causes of accidents that had occurred at liquid hydrogen facilities and of conditions that could conceivably cause others. From this analysis a number of hazardous situations were postulated for which more information was needed. The failure of a storage tank in

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1. This work was sponsored by the U. S. Air Force Air Research and Development Command under Contract No. AF 18(600)-1687.
2. Senior Engineer, Arthur D. Little, Inc.
3. Assistant Section Head, Arthur D. Little, Inc.
4. Section Head, Arthur D. Little, Inc.

which all its contents are released onto the ground is an example of these situations. Following such a failure the hydrogen vaporizes and mixes with the surrounding air to form a combustible--or possibly a detonable--mixture. Other such hazardous situations would be created by a pipeline rupture releasing a large vapor cloud that might be ignited, or by the accumulation of solid oxygen or solid air in valves, strainers, or other process equipment.

C. POSSIBILITY OF DETONATION IN FREE SPACE

Gross spillage would create one of the greatest problems--one that could produce the most disastrous consequences. The release of a large quantity of liquid, which would be vaporized by absorbing heat from the ground and the surrounding atmosphere, would produce a large volume of hydrogen and air. For example, the contents of a 60,000-pound storage tank would produce 2,100,000 pounds of detonable mixture if mixed with air in stoichiometric proportions. The fundamental question to be answered is--Will a hydrogen-air mixture in free space detonate when ignited?

It has been well established experimentally that a hydrogen/oxygen mixture confined in tubes will detonate over wide limits of mixture proportions. The addition of nitrogen inhibits detonation to some extent but does not completely suppress it. These data could not be readily extrapolated from the two-dimensional to the three-dimensional case, however, because the method of propagation of a plane detonation wave differs from that of a spherical detonation wave. Only in recent years have various investigators (References 1 - 5) demonstrated the existence of stable spherical detonation waves by experiments carried out with oxygen or enriched air and with shock-wave initiators. These investigations indicated, however, the difficulty of detonating unconfined fuel-air mixtures, because the limits of detonation were reduced from those in tubes and strong initiators were required.

Consequently, an experimental program was undertaken to determine under what conditions ideal hydrogen-air mixtures in free space could be detonated. A number of tests were carried out with 5-ft- and 8-ft-diameter latex balloons filled with mixtures of hydrogen and air (volumes of 100 ft^3 and 400 ft^3, respectively). Detonations were initiated at the center of the balloons with explosives, flame sources, hot wires and sparks. Blast pressures were measured with ceramic gages placed at ground level 15 to 35 ft from the center of the balloon. Initial tests with near-stoichiometric mixtures containing 32% hydrogen in a 5-ft-diameter balloon established that a three-dimensional shock wave would be propagated in free space if a sufficiently strong initiating source were available. For the hydrogen-air mixtures, however, a minimum initiating source of 2 gm of pentolite was required for full explosive yield. The use of a blasting cap having approximately 1/2 gm of explosive as the initiator reduced the yield 95%, with flame sources, sparks, and hot wires, combustion of the gases occurred with no measurable pressures.

Since the 2-gm charge supplied the minimum initiation energy for complete detonation of the near-stoichiometric hydrogen-air mixture and since this mixture is probably most easily detonated, the 2-gm charge as initiator was used in tests with other hydrogen-air mixtures. The results of the tests are presented in Figure C-1. The explosive yield for the mixtures was evaluated by a comparison of the measured overpressures with those obtained from standard C-4 charges under the same experimental conditions. The theoretical curve shown in Figure C-1 was determined on the assumption that hydrogen-air mixtures have explosive yields equivalent to those of conventional explosives with the same heat of explosion (Reference 6). Maximum yields were obtained with mixtures containing 30 to 40 mol-% hydrogen. The limits for partial detonation of the mixtures (approximately 20 to 50 mol-% hydrogen) agree quite well with the limits (18 to 59 mol-%) obtained by other experiments with mixtures in tubes.

A limited number of tests were also made with stoichiometric mixtures in 8-ft-diameter balloons in an effort to determine whether a greater path length would change the deflagration wave to a detonation wave. As in earlier tests with the 100-ft^3 balloon, spark-source initiation produced no detonation, but merely a rapid combustion of the mixture with no measurable pressure. Use of a blasting cap or 2-gm pentolite initiator gave yields that were directly related to the greater mass of gas, and there was no evidence of a transition to detonation. It was concluded, therefore, that the detonation of a hydrogen-air mixture in free space is possible only if a suitable mixture ratio is provided and if a strong enough shock-wave source is available. Since the probability that these idealized conditions would occur in practice is extremely remote, the chance of detonating a large mass of hydrogen gas released as a result of an accident is low.

D. DEFLAGRATION EFFECTS WITH LIQUID HYDROGEN

A program was also carried out to investigate deflagration effects of liquid hydrogen. A number of spills of liquid hydrogen in quantities from 1.25 gal to 5,000 gal were made. Ignition of the vaporized gases was by spark or flame sources. The ignition time was varied from prior to release to 8 sec after release, and the depth of the pools varied from 2 to 12 inches. Photographs were taken and radiation measurements of the flame were made. Instrumentation was provided to measure overpressures in the event of a detonation.

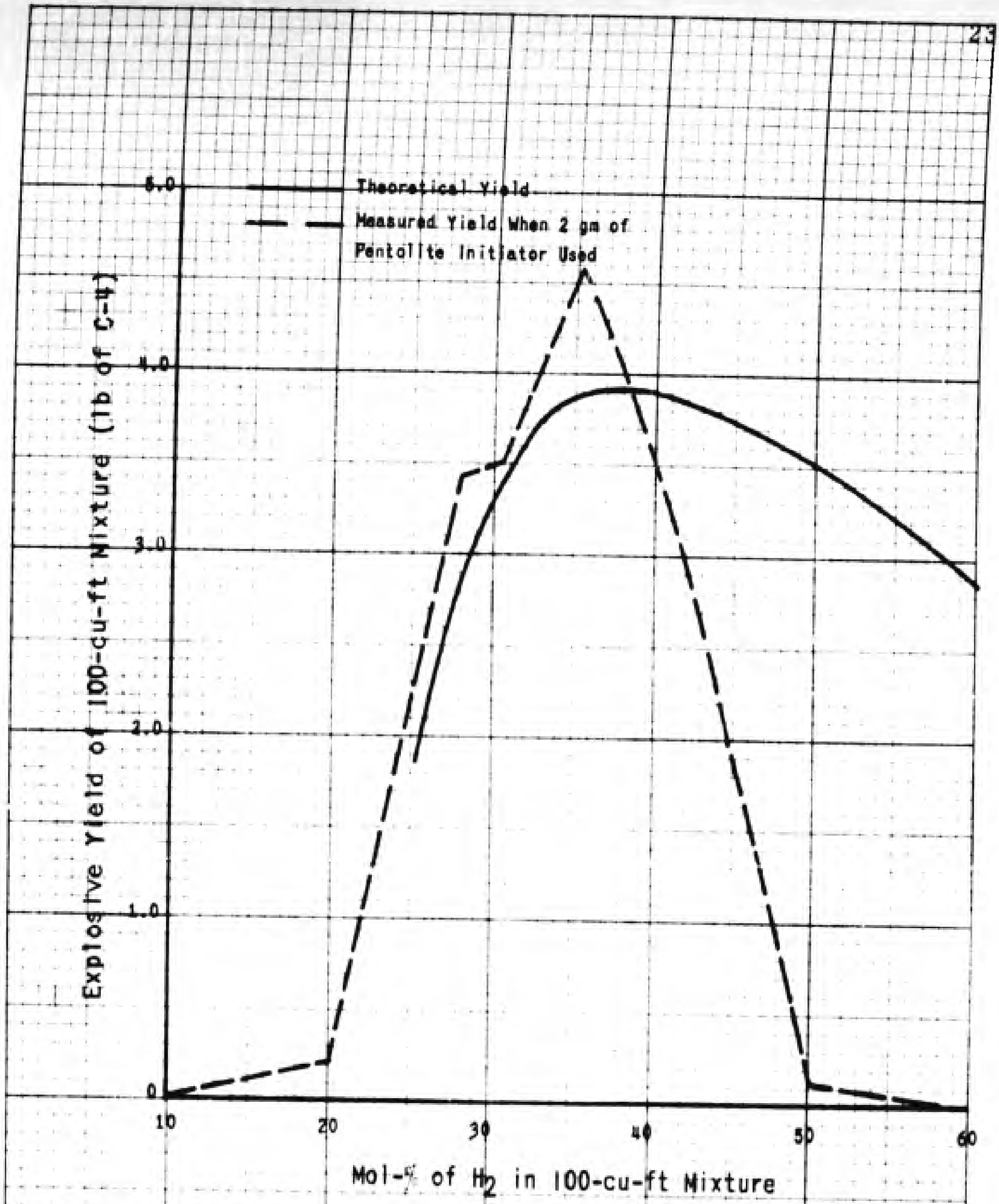

Figure C-1

EXPLOSIVE YIELD OF HYDROGEN-AIR MIXTURES IN FREE SPACE

In each case, no detonation or tendency toward detonation resulted. In the 1.25-gal tests, partial confinement was provided by the walls of the test bay, and it was observed that a stronger pressure pulse was obtained than when the liquid was spilled in the open. In fact, pressures obtained with the 1.25-gal quantities when confined were roughly equivalent to those obtained at the same distance in the 500-gal spills in the open. These results indicate that the barricading of storage vessels not only fails to provide protection, but may induce a pressure buildup that may be damaging.

The results were roughly similar in each test. They were characterized by initial vaporization of a large quantity of liquid and the formation of a cloud of water vapor mixed with the hydrogen and air. This cloud would remain close to the ground for some seconds and then rise slowly, drifting downwind and growing in size as more liquid was evaporated. The initial tendency to remain close to the ground is not unusual when the density of hydrogen gas at the boiling temperature is considered. Upon ignition, the fireball consumed almost all the material within the confines of the vapor cloud, and the remaining material in the pool burned in a few minutes. The results of radiation measurements taken with a thermopile are given in Figure C-2. The peak source brightness of approximately 12.6 Btu/sec-ft^2 corresponds to an emissivity of about 0.09 based on an assumed flame temperature of 3720°F.

For comparison, similar measurements made with propane are also shown in Figure C-2. The emissivity at the peak of this curve is approximately that of a black body, or 1. Another important point is that the peak thermal flux lasted for several minutes with propane but only for a few seconds with hydrogen. Other tests with hydrocarbons demonstrated that they behave in a manner similar to propane.

A number of spill tests were also made in which the vapor clouds were initiated by explosive igniters such as 2-gm and 4-gm pentolite charges. In no tests was there any tendency toward detonation or a significant increase in combustion pressures. Since detonation effects had been appreciable in the tests of ideal mixtures in the 5-ft balloons, it was concluded that the non-ideal mixing that occurs in actual spills considerably inhibits detonation.

In other tests to assess deflagration effects, liquid hydrogen issuing from pipelines was ignited, and the thermal radiation intensity and flame size were measured. In these tests the average measured thermal-flux level varied from 1.3 to 8.4 Btu/sec-ft^2, as compared with 12.6 Btu/sec-ft^2 for the spill tests, where contaminants were present. The wide variation in measured intensity was in part due to the difficulty in aiming

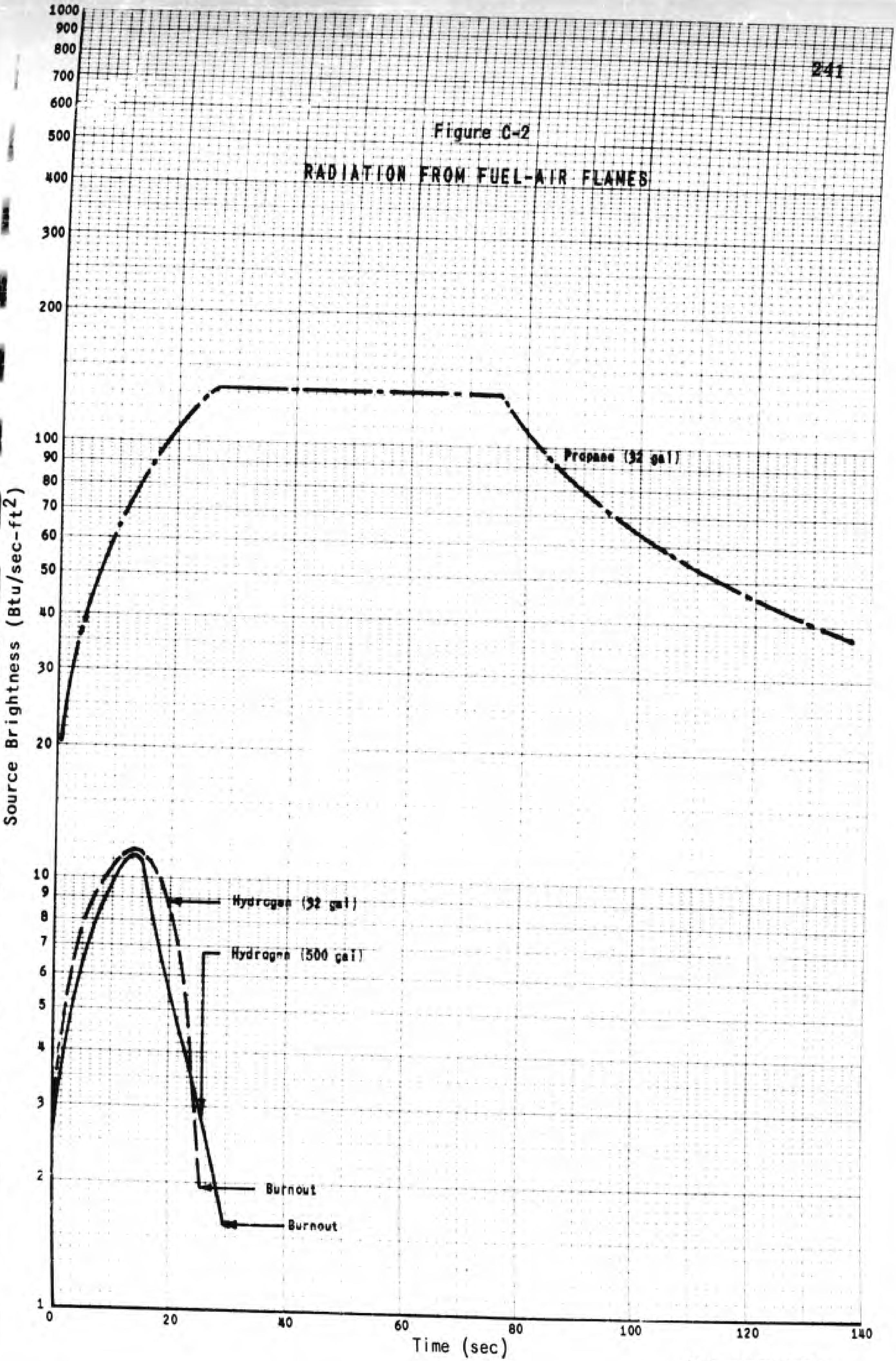

Figure C-2

RADIATION FROM FUEL-AIR FLAMES

the thermopile because of the lack of luminosity of the flame. Furthermore, as infrared films developed later proved, the flame was quite wind-sensitive; in the spill tests, strong convection effects induced by the flame tended to overcome wind effects.

These deflagration tests have demonstrated that the effects of hydrogen fires are less than those from fires with hydrocarbon fuels--in regard to both duration and radiation flux density. Spacing between liquid hydrogen tanks can be considerably reduced from that now required, provided the tanks are insulated for protection in a fire. The construction of dikes to confine the fire to the area directly involved is recommended.

E. RADIATION EFFECTS ON PERSONNEL

In addition to the effects of liquid hydrogen flame radiation on equipment, some work has been done to establish the minimum distance at which personnel can safely approach a liquid hydrogen flame without suffering second-degree burns (2+ median burns). AEC data on the thermal-radiation flux density necessary to produce such burns are based on short exposures (Reference 7). Work performed by Drs. F. C. Henriques and A. P. Moritz at the Harvard Medical School relates thermal injury and skin temperature. However, these data were obtained by a number of different tests in which various heat-transfer mechanisms were used (References 8 and 9). Additional work at the University of Rochester provides a simple equation relating the total flux and the exposure time required to cause 2+ median burns (Reference 10). This equation correlates well with the more general relations developed by Henriques and Moritz and has been used to calculate the thermal-radiation effects from liquid hydrogen/air flames. These data have been combined with information on flame sizes from large spills and pipeline breaks in calculating the distance within which personnel would suffer injury. In the determination of the recommended safe distance for unprotected personnel (Figure C-3) it was assumed that they would be exposed to the flame for 30 sec. It will be noted that for large spills a change in the size of the spill has little effect and that a distance of 180 ft is sufficient to prevent serious injury under all conditions. For a similar-sized fire with JP-4 fuel, the safe distance would be 675 ft. or almost four times that for hydrogen.

F. CLOUD FORMATION AND GROWTH

Another important hazard that is probably peculiar to liquid hydrogen is the possibility of ignition of the vapor cloud formed after large-scale accidental release. The spill tests carried out early in the program

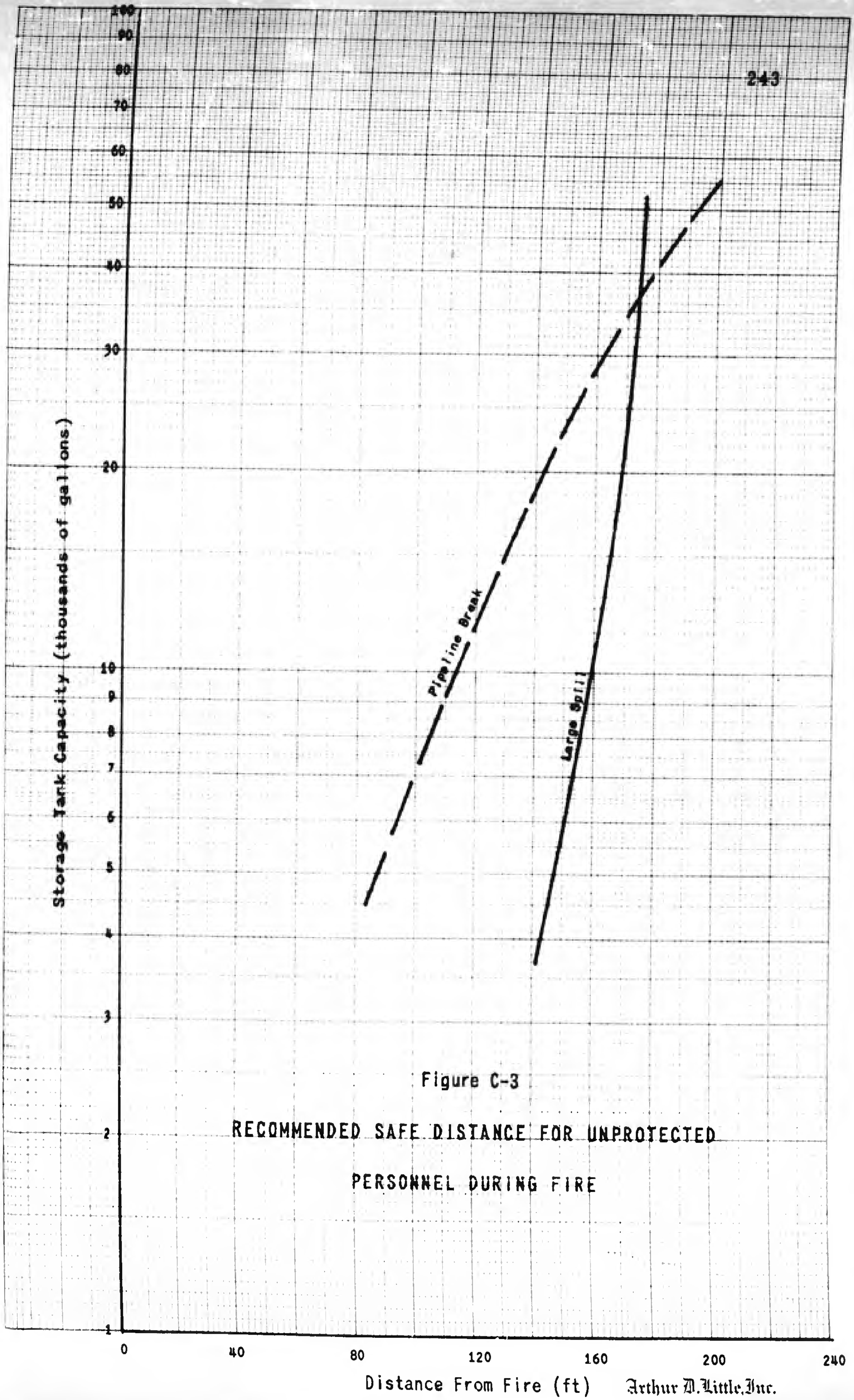

Figure C-3

RECOMMENDED SAFE DISTANCE FOR UNPROTECTED PERSONNEL DURING FIRE indicated that vapor-cloud ignition produces a hot fireball that will ignite combustible material within its confines. Two lines of investigation have been followed to determine the magnitude of this problem--one to provide data enabling the prediction of evaporation rates from the ground and the other to determine the distance downwind that a hazardous condition will exist.

The following are the types of tests and their results:

1. In measurements made of the liquid hydrogen evaporation rate, it has been determined that initially all heat supplied to the liquid comes from the ground. In later stages of evaporation (i.e., after approximately 3 min), some heat contribution is made by condensation of air into the hydrogen pool. The evaporation rate has an initial value of about 5 - 7 inches/min, decreasing rapidly to a steady-state value of about 1-1/2 inches/min. It was also found that ignition of the vapor does not affect the rate of evaporation significantly, but that a pebble bed of crushed rock would greatly increase the evaporation rate. It would seem desirable, therefore, to surround storage tanks with crushed rock in order to minimize the duration of the hazards of a spill.

2. In discharges of liquid hydrogen from a pipeline at rates varying from 30 to 300 gal/min, a vapor cloud is formed that persists near ground level for 500 - 700 ft downwind and at higher levels (but with greatly reduced density) for even further distances. Ignition of the cloud has been accomplished only within 100 ft of the vent; however, data is so preliminary that we cannot be sure that under certain conditions the vapor is not ignitable at greater distances. No significant concentration of hydrogen has been detected outside the limits of the visible cloud.

3. In spill tests, vapor clouds extending as far as 200 ft downwind have been formed. Upon ignition at the pool the flame traveled downwind for over 100 ft.

G. DETONABILITY OF MIXTURES OF LIQUID HYDROGEN AND SOLID AIR

In addition to the preceding test programs, the possibility of detonating liquid hydrogen with solid air present has been investigated. In the tests, liquid air was added to a container of hydrogen and attempts were then made to initiate detonation with a hot-wire source. Although considerable amounts of air were added (up to 300 gm in 1.25 gal of hydrogen) explosions were obtained only when considerable oxygen enrichment of the solid air occurred. It was concluded, therefore, that the detonation hazard due to contamination of liquid hydrogen with solid air is relatively slight. Additional evidence was supplied by laboratory tests in which the tendency of mixtures of liquid hydrogen and solid air to detonate was assessed by means of impact tests (Reference 11). Hydrogen-air mixtures failed to detonate even when the hammer was dropped from the full height of the impact tester. The impact sensitivity of liquid hydrogen and solid oxygen, on the other hand, was comparable to that of RDX.

H. CONCLUSIONS

It has been shown that liquid hydrogen is much safer to handle than many other missile propellants. When liquid hydrogen is accidentally mixed with air under unconfined conditions, the mixture does not detonate and the radiation effects from fires of such mixtures are less than those from fires of more conventional fuels. On the other hand, the low initiation-energy requirements and the wide flammability limits of such mixtures make ignition of a vapor cloud likely, and for that reason, extreme care should be taken to remove all potential sources of ignition from an area where liquid hydrogen is stored or handled.

I. REFERENCES

1. Jost, W., Explosions und Verbrennungsvorgange in Gasen, Berlin, 1939, pp. 185 - 186.

2. Taylor, G., Proc. Roy. Soc., A200, 235 (1950).

3. Zeldovich, Y. B., J. Exp. Theoret. Phys. (USSR), 112, 389 (1942).

4. Freiwald, H., and H. Ude, Comp. Rend., 236, 1741 (1953).

5. Manson, N., and F. Ferrie, Fourth Symposium on Combustion, Baltimore, Williams & Wilkins, 1953, p. 486.

6. Goodale, T. C., Theoretical Heats of Explosion of Perfect Liquid Oxygen-JP4 Fuel Mixtures and Their Probable Explosive Capabilities, Broadview Research Corporation, BRD-56-8A1, 1956 (C).

7. AEC, Effects of Atomic Weapons, 1950.

8. Henriques, F. C., and A. P. Moritz, "Studies of Thermal Injuries," Parts I-III, American Journal of Pathology, 23, July, September, and November 1947.

9. Henriques, F. C., and A. P. Moritz, "Studies of Thermal Injuries," Parts IV-V, Archives of Pathology, 43, May 1947.

10. Roth, R. E., and J. R. Henshaw, Flash Burn Studies: Limitations of a 2+ Median Effective Exposure Scaling Law, University of Rochester, U.R. 481, February 28, 1957.

11. Arthur D. Little, Inc., Study of Potential Hazards and Safety Precautions Required in Handling Large Quantities of Liquid Hydrogen, Contract AF 33(616)-5223, August 27, 1958 (S).