UNCLASSIFIED

SSD-TR-61-21
VOLUME III

MAIN PROPELLANT TANK PRESSURIZATION SYSTEM STUDY AND TEST PROGRAM

VOLUME III
DESIGN HANDBOOK

LOCKHEED-GEORGIA COMPANY
A DIVISION OF LOCKHEED AIRCRAFT CORPORATION
MARIETTA, GEORGIA

ER 5296

FINAL REPORT

CONTRACT AF 04(611)-6087
CONTRACT AF 04(611)-7032

DECEMBER 1961

6593RD TEST GROUP
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
EDWARDS, CALIFORNIA

If this document is supplied under the requirements of a United States Government contract, the following legend shall apply unless the letter U appears in the coding box:

This data is furnished under a United States Government Contract and only those portions hereof which are marked (for example, by circling, underscoring or otherwise) and indicated as being subject to this legend shall not be released outside the Government (except to foreign governments, subject to these same limitations), nor be disclosed, used, or duplicated, for procurement or manufacturing purposes, except as otherwise authorized by contract, without the permission of Lockheed-Georgia Company, Marietta, Georgia. This legend shall be marked on any reproduction hereof in whole or in part.

The "otherwise marking" and "indicated portions" as used above shall mean this statement and includes all details or manufacture contained herein respectively.

Code U Contract AF 04(611)-6087
Contract AF 04(611)-7032

SSD-TR-61-21
VOLUME III

MAIN PROPELLANT TANK PRESSURIZATION SYSTEM STUDY AND TEST PROGRAM

VOLUME III

DESIGN HANDBOOK

LOCKHEED-GEORGIA COMPANY
A DIVISION OF LOCKHEED AIRCRAFT CORPORATION
MARIETTA, GEORGIA
ER 5296

FINAL REPORT
CONTRACT AF 04(611)-6087
CONTRACT AF 04(611)-7032
PROJECT NO. 6753
TASK NO. 675302

DECEMBER 1961

6593RD TEST GROUP
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
EDWARDS, CALIFORNIA

FOREWORD

This report, consisting of four volumes, is the final report of work done by Lockheed-Georgia Company, Marietta, Georgia, under contracts AF 04(611) -6087 "R & D of an Evaporated Propellant and Main Tank Injection Pressurization for Missile Propellant Tanks" and AF 04(611)-7032, "Thermodynamics Data for Design of Rocket Vehicle Tanks and Pressurization Systems" with the Air Force Flight Test Center, Edwards AFB, California. Work described herein was accomplished during the period 1 July 1960 through 31 October 1961 under contract AF 04(611)-6087 and 1 April 1961 through 17 October 1961 under contract AF 04(611)-7032.

Because the work done under contract AF 04(611)-7032 was directly related to the liquid hydrogen work done under contract AF 04(611)-6087 and the contract completion dates were compatible, approval was given by the Air Force to combine the final reports on these contracts.

The four volumes of the report are entitled as follows:

Volume I	-	Main Propellant Tank Pressurization System Study and Test Program - Liquid Hydrogen and Liquid Oxygen (Confidential)
Volume II	-	Main Propellant Tank Pressurization System Study and Test Program - Storable Propellants (Confidential)
Volume III	-	Main Propellant Tank Pressurization System Study and Test Program - Design Handbook (Unclassified
Volume IV	-	Main Propellant Tank Pressurization System Study and Test Program - Computer Program (Unclassified)

Volumes I and II have been classified Confidential because the system analysis of these volumes contain information on classified weapon systems.

ABSTRACT

Design information on liquid propellant tank pressurization systems is presented in handbook form. The areas covered are: pressurization gas requirements, including hand calculation procedures and nomographs; tankage, including material properties and volume and wall area curves; and components, including stored helium system weight curves and a simple but accurate heat exchanger design method.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

ILLUSTRATIONS (cont'd)

LIST OF TABLES

INTRODUCTION

During the expulsion of liquid from a container, the gas above the liquid expands and the pressure decreases unless supplemented from an external source. Three methods of maintaining pressure are by evaporated propellant (EP), main tank injection (MTI), and from a stored gas supply. The problem of determining missile tank pressurization system requirements for these three systems has been studied by analysis and tests. The purpose of this handbook is to present the results of the program to the missile design engineer for application to the design of pressurization systems. Since one of the major problems in the design of a pressurization system is that of accurately determining the amount of pressurizing gas required for expulsion of the various propellants, emphasis has been placed on that phase in the handbook.

An evaporated propellant pressurization system is one in which a portion of the propellant is vaporized, heated, and fed back into the top of its tank, where it is used to expel the propellant and maintain a given pressure in the tank. The handbook presents data for the design of evaporated propellant pressurization systems for liquid hydrogen and liquid oxygen.

A main tank injection system provides tank pressurization by controlled combustion of a hypergolic reagent injected into a propellant tank. This pressurization technique is applied herein to the storable propellants nitrogen tetroxide (N_2O_4), unsymmetrical dimethylhydrazine (UDMH), and a 50-50 mixture by weight of unsymmetrical dimethylhydrazine and anhydrous hydrazine (50-50 UDMH/N_2H_4).

Three methods have been presented for determining the amount of pressurizing gas required. These are nomograph, hand calculation, and computer program.

To expedite preliminary design calculations, one section has been devoted to curves for quickly determining tank volumes and areas for most of the common tank configurations. Also included is information on the physical properties of metals applicable to missile propellant tanks.

Since the component hardware is an essential part of a pressurization system, gas storage systems and heat exchangers are treated in some detail. System weight curves are presented for the former, but heat exchangers must be designed individually to meet specific requirements. A rapid but accurate heat exchanger design method is therefore presented.

PRESSURIZATION GAS REQUIREMENTS

EP Nomographs

Discussion

Five four-quadrant or two-quadrant curves, referred to herein as nomographs, have been prepared to allow evaporated propellant pressurizing gas requirements to be determined rapidly for the most important cases. The curves, Figures III-1 through III-5, are entered through the inlet gas temperature scale on the lower right. The equation of state, $W = PV/RT$, may then be used to calculate the final gas weight.

The nomographs cover evaporated propellant pressurization of liquid hydrogen and liquid oxygen in insulated stainless steel and aluminum tanks. The variables considered are inlet gas temperature, tank wall thermal capacitance (including ends and baffles, and expressed in terms of wall weight, since the material is specified), tank volume (including initial ullage), tank pressure, initial ullage, expulsion time, wall area, and heat input rate.

The nomographs are based on an extensive series of runs on the IBM pressurization program which is described in detail in Volume IV of this report. The runs used in the final plots are shown in Tables III-A-1 through III-A-4 of Appendix III-A. Many other runs were made in exploring the limits of applicability of the nomograph approach. These runs have not been tabulated.

The methods of dimensional analysis were used in establishing the proper groupings of variables in the nomographs. The resulting dimensionless groups were: the ratio of wall heat capacity to gas heat capacity; the ratio of total gas-to-wall heat transfer to gas heat capacity; the ratio of operating pressure to pre-launch saturation pressure; and the ratio of initial ullage volume to total tank volume.

It can be seen that the groupings used in the nomographs are based on the above dimensionless groups. They have been modified, however, by the incorporation of specific values wherever possible. This has made them dimensional instead of dimensionless and has required the preparation of five nomographs instead of one, but the utility of the nomographs to the pressurization system designer has been greatly enhanced.

One of the factors which makes the nomographs possible is the fact that the use of insulation on a propellant tank wall reduces the heat input rate and also, more important for the nomograph, reduces the dependence of total heat input on trajectory characteristics. It has been shown by pressurization program runs that any reasonable thickness of insulation (ground heat flux less than 0.05 Btu/sec - ft^2) causes all but a small fraction of the aerodynamic heating potential to be reradiated to space or absorbed by the insulation, leaving only a minor increase in average flight heat flux over the pre-launch value. Figure III-6 illustrates this effect. It is therefore considered valid to eliminate aerodynamic heating as a variable in the determination of final gas temperature in insulated tanks, and the nomographs are based on this assumption. The slight error involved is in the conservative direction.

The most significant of the other assumptions used in the preparation of the nomographs is that condensation is negligible, whether with slosh or without slosh. The test data have shown significant condensation, of the order of 30 percent of the incoming gas, in the 12-gallon test tank, but 10 percent condensation or less in the 75-gallon and 500-gallon tanks, and the effect in flight-size tanks is expected to be even less. This result is attributed to the rapid build-up of a stratified layer of saturated liquid just below the liquid-vapor interface. The use of the helium blanket also significantly reduced condensation in liquid oxygen tanks and the small liquid hydrogen tank, although it was found to be superfluous in the larger liquid hydrogen tanks because of the strong natural stratification tendency of liquid hydrogen.

Further assumptions are:

1. Ninety-nine percent of the heat entering the tank below the liquid level goes into sensible heating of the liquid, while the remaining one percent goes into vaporization. This assumption is based both on theoretical analysis of the transition from natural convection to boiling and on the results of the present test program, and is in line with the conclusions of other investigators.

2. The internal gas film heat transfer coefficient is 9 Btu/hr-ft^2-R. This is based on the test results shown in Volume I, and has been shown by natural convection theory to be a legitimate value for all the cases considered. Deviations from this value have been found to have only a small effect.

3. The pre-launch saturation pressure is one atmosphere.

A determined effort was made to develop a nomograph for uninsulated liquid oxygen tanks, but without success. Aerodynamic heating was found to have too great an effect on the final gas temperature to allow simple curves to be developed that would cover a useful range of trajectories. The use of the computer program in this case is recommended.

Sample Problem

Conditions

Liquid hydrogen tank pressurized by gaseous hydrogen. Cylindrical tank with hemispherical ends. Wall material stainless steel. External insulation. Liquid is saturated at one atmosphere before launch.

Diameter	40 ft
Length	60 ft
Wall thickness	0.12 in

Initial ullage	5%
Operating pressure, P	40 psia
Inlet gas temperature	300 R
Expulsion time, θ	120 sec

Calculated Values

Total tank volume, V	58,500 ft^3
Initial ullage volume, V_u	2,920 ft^3
Wall area, A	7,550 ft^2
Wall weight, W_w	37,300 lb
$\frac{W_w}{V}$	0.638 lb/ft^3
$\frac{A\theta}{V}$	15.5 sec/ft

From Figure III-1, the final gas temperature, T_2, is 245 R. Now all the necessary gas properties can be obtained:

Saturation pressure of propellant prior to launch, P_1	14.7 psia
Propellant temperature, T_1	37.0 R
Initial compressibility factor, Z_1	0.90
Final compressibility factor, Z_2	1.0

The gas weights can now be calculated:

Initial ullage gas weight, W_u

$$W_u = \frac{P_1 V_u}{Z_1 RT_1} = \frac{14.7 \times 144 \times 2920}{0.90 \times 767 \times 37} = 242 \text{ lb}$$

Final gas weight, W_t

$$W_t = \frac{P V}{Z_2 RT_2} = \frac{40 \times 144 \times 58500}{1.0 \times 767 \times 245} = 1790 \text{ lb}$$

Pressurizing gas weight, W_p

$$W_p = W_t - W_u = 1790 - 242 \doteq 1548 \text{ lb}$$

Nomenclature

The following symbols and units have been used in the nomographs and the nomograph sample calculation:

Symbol	Quantity and Units
A	Wall area, ft^2
P	Tank operating pressure, psia
P_1	Saturation pressure of propellant prior to launch, psia
R	Gas constant, ft-lb/lb-R (= 1544/molecular weight)
T_1	Propellant temperature, R
T_2	Final gas temperature, R
V	Total tank volume, ft^3
V_u	Initial ullage volume, ft^3
W_p	Pressurizing gas weight, lb
W_t	Final total gas weight, lb
W_u	Initial ullage gas weight, lb
W_w	Wall weight, lb
Z_1	Comnressibility factor at pressure P_1 and temperature T_1, dimensionless
Z_2	Compressibility factor at pressure P and temperature T_2, dimensionless
θ	Expulsion time, sec

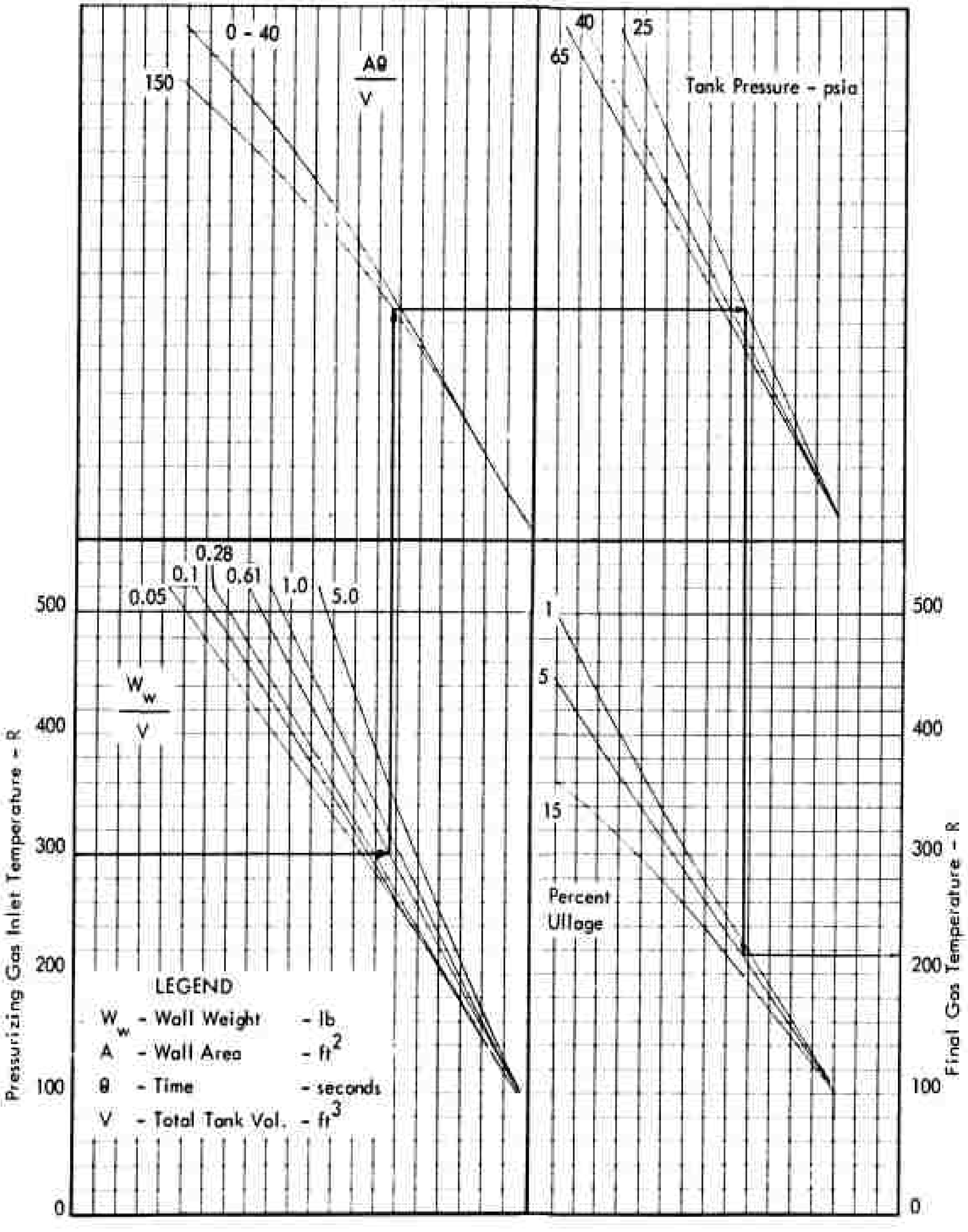

FIGURE III-1
NOMOGRAPH -
HYDROGEN EP WITH EXTERNALLY INSULATED STAINLESS STEEL WALLS

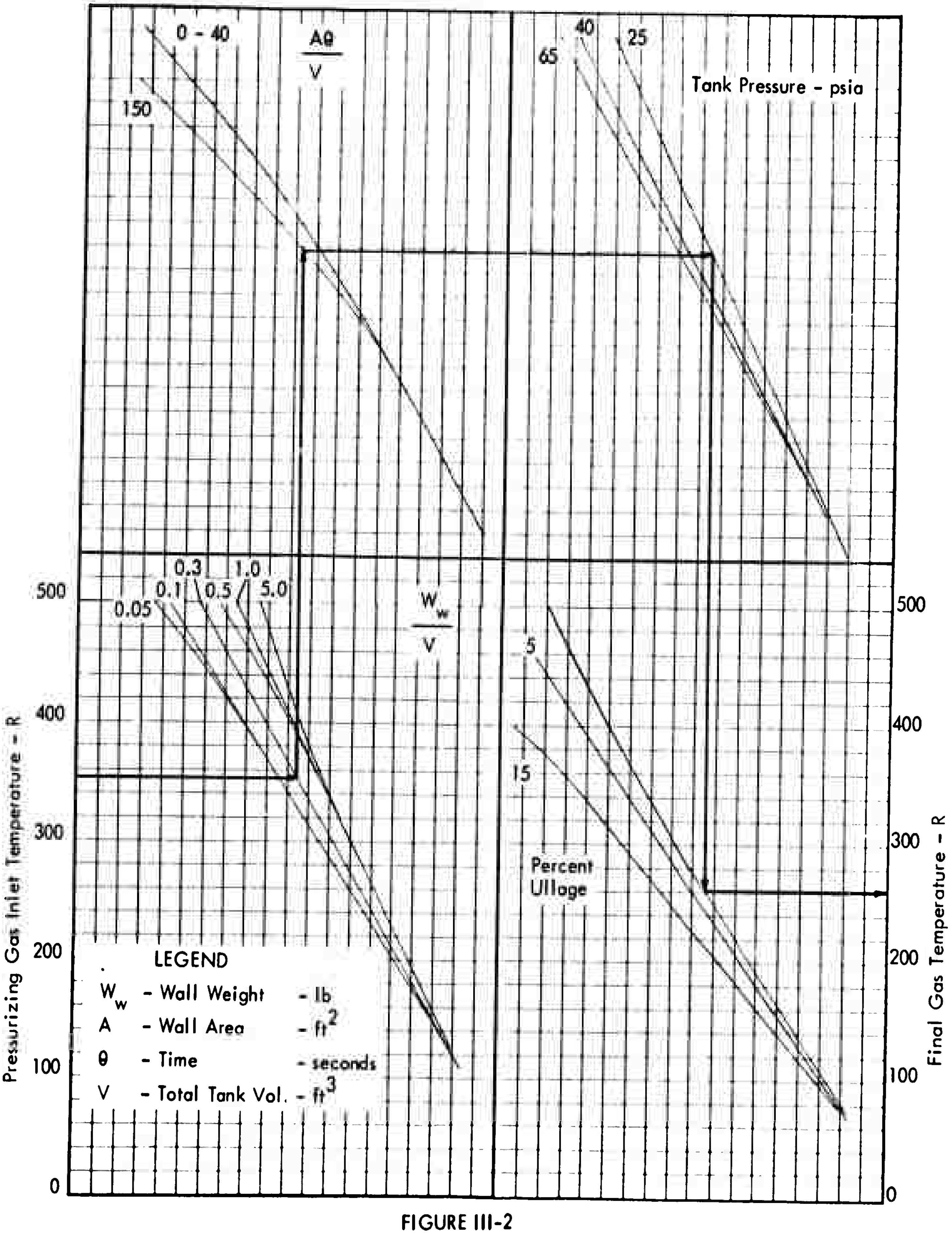

FIGURE III-2
NOMOGRAPH -
HYDROGEN EP WITH EXTERNALLY INSULATED ALUMINUM WALLS

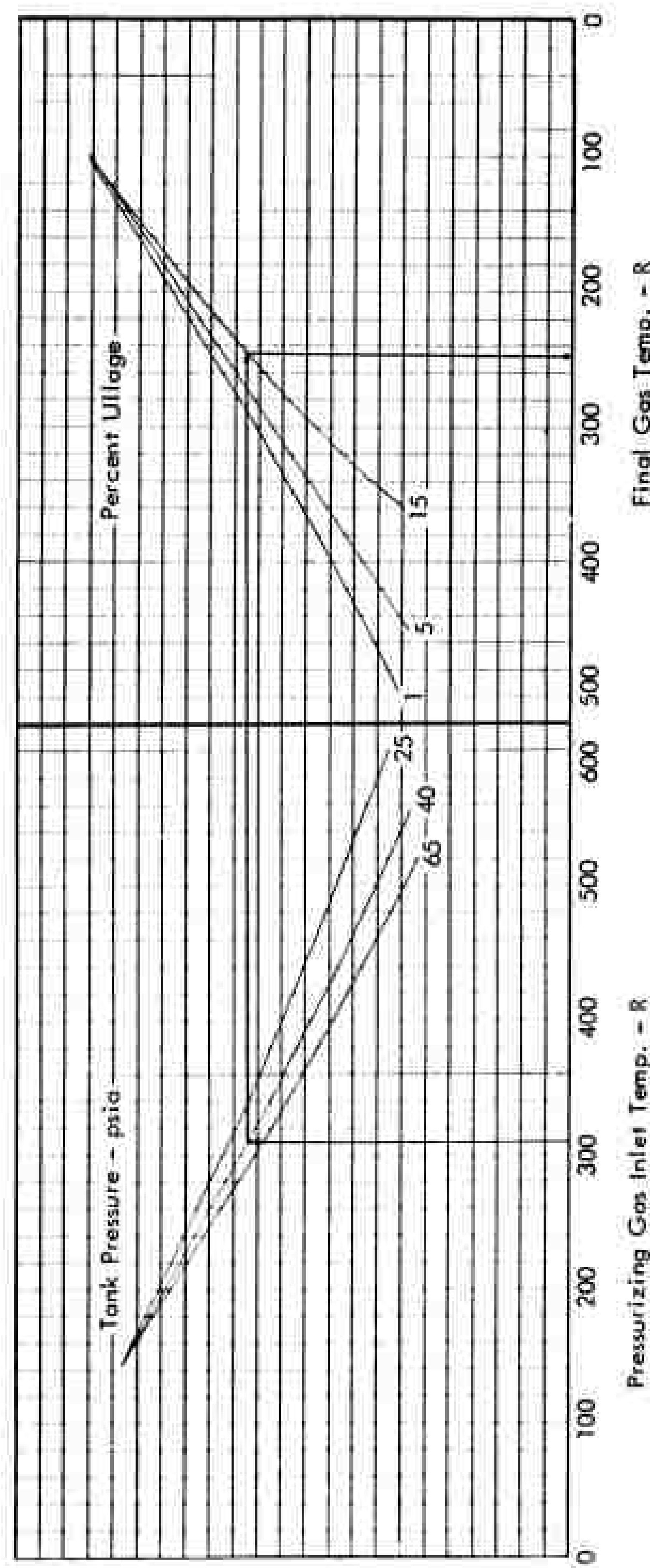

FIGURE III-3
NOMOGRAPH -
HYDROGEN EP WITH INTERNALLY INSULATED WALLS

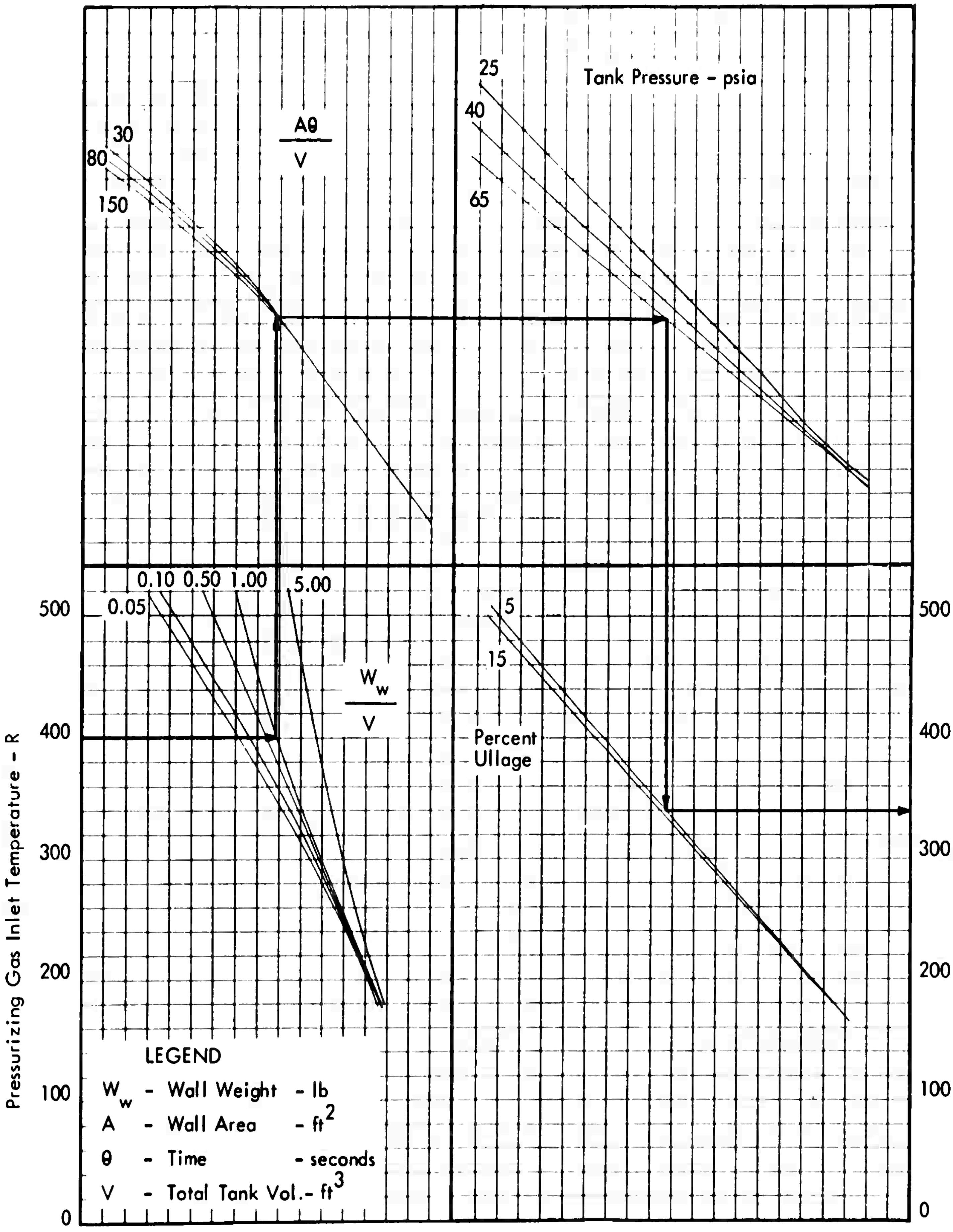

FIGURE III-4
NOMOGRAPH -
OXYGEN EP WITH EXTERNALLY INSULATED STAINLESS STEEL WALLS

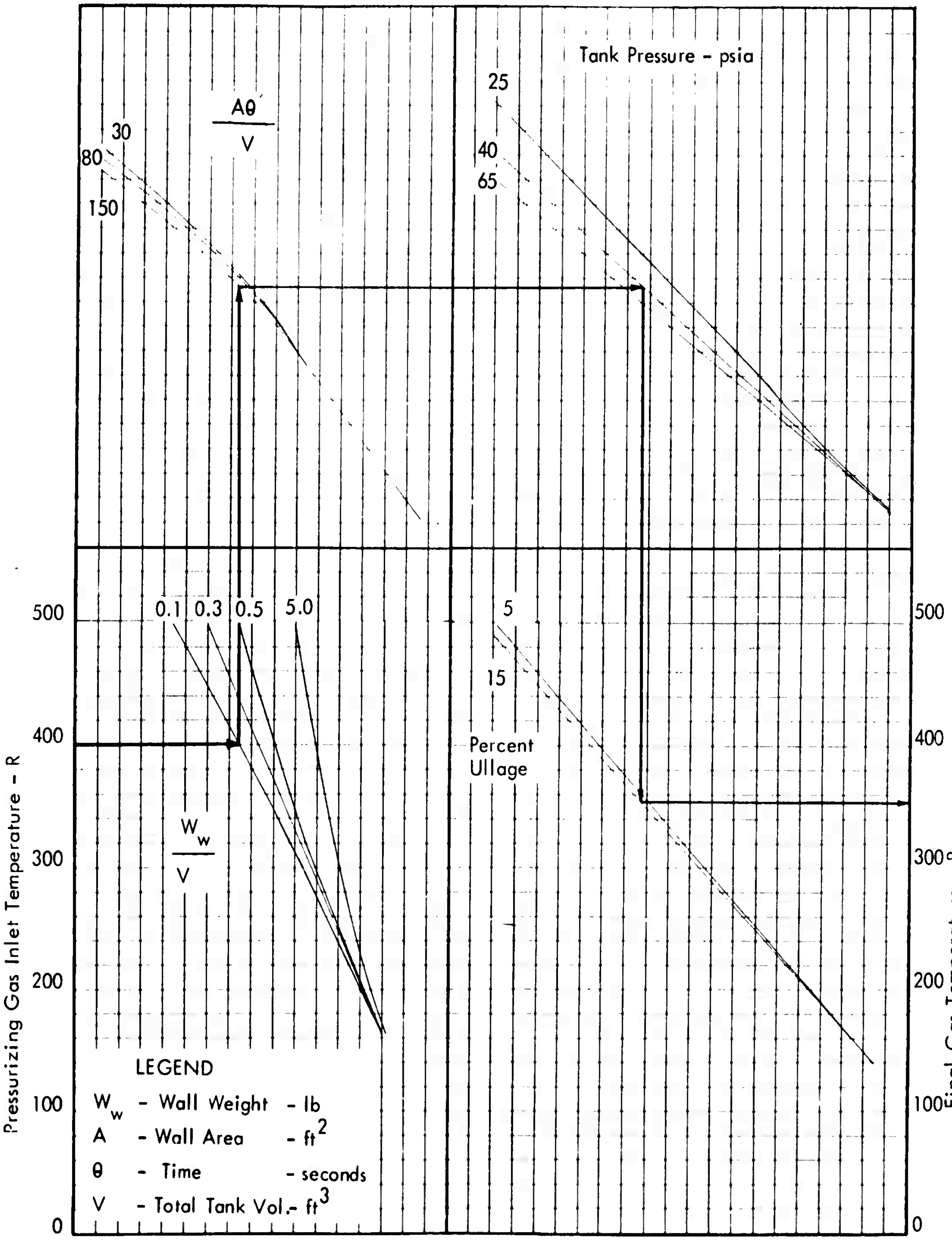

FIGURE III-5
NOMOGRAPH -

OXYGEN EP WITH EXTERNALLY INSULATED ALUMINUM WALLS

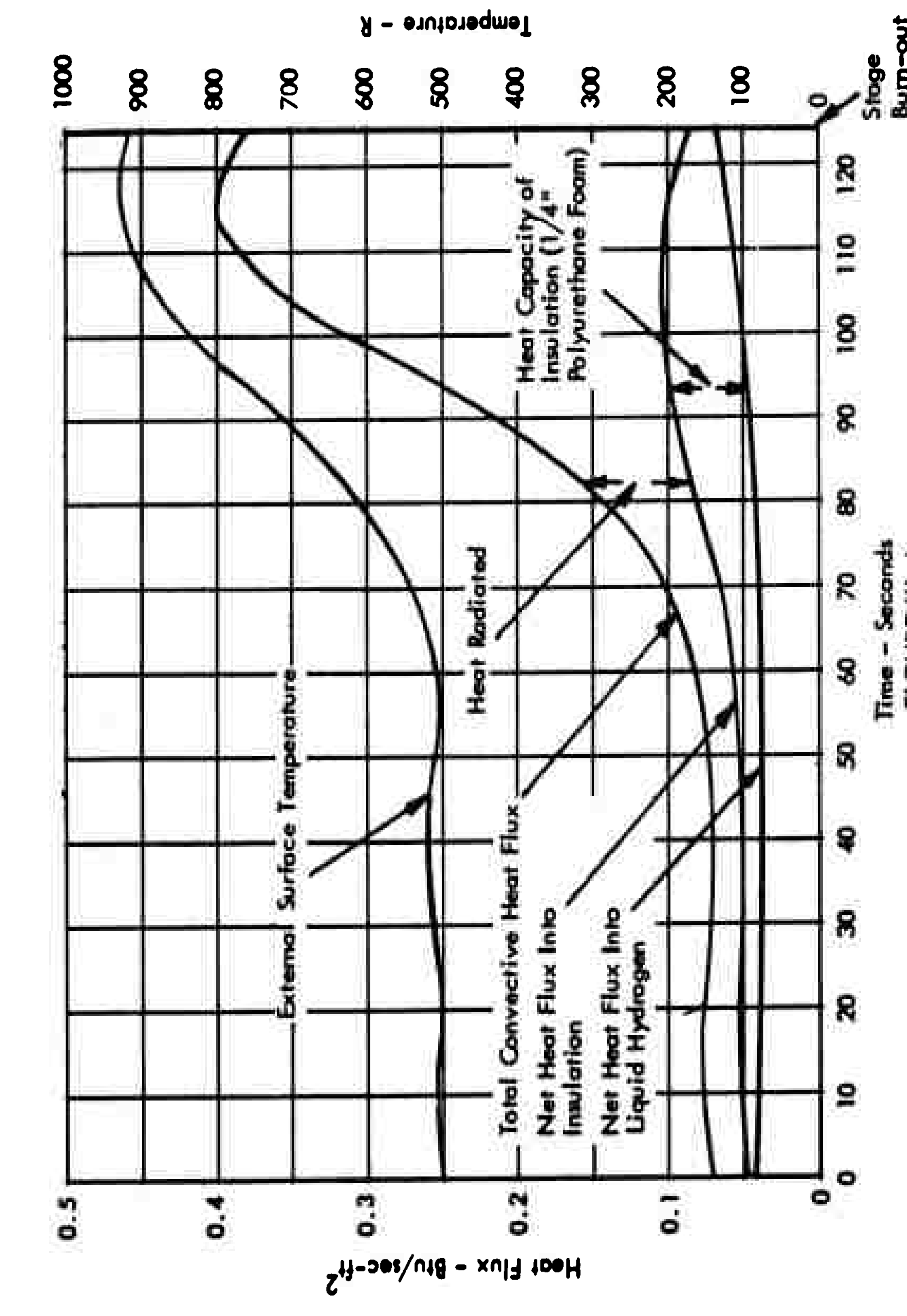

FIGURE III-6

TYPICAL MISSION PROFILE SHOWING LOW LIQUID HEATING WITH INSULATED TANK

EP Hand Calculation

Discussion

The calculation method presented herein has been developed to expedite the calculation of final pressurizing gas temperature for cases for which no nomograph is available. It is also somewhat more accurate than the nomographs. The nomographs have been found to agree within seven percent, on the average, with the test results obtained in the present program, while the hand calculation is within 3.8 percent. Alternatively, the computer program can be used to obtain 3.5 percent accuracy.

The hand calculation method, unlike the computer program, does not attempt to determine the continuously changing heat balance of each successive wall element as the tank empties. Instead, it considers only conditions at the beginning and end of the process. The gas to wall heat transfer is calculated using the average temperature during expulsion and the average weight of wall in contact with the gas, the wall also being assumed to remain at its average temperature throughout expulsion. These assumptions appear to represent severe simplifications of a very much more complex actual process. They are justified by the fact that they have consistently led to answers which are in good agreement with the results of computer runs.

The procedure is applicable to tanks of any shape, and can account for aerodynamic heating. It accounts for condensation but not for evaporation. However, evaporation and condensation are shown elsewhere in this report to have small effects on pressurization gas requirements.

The specific heat constants, k_1 through k_5, account for the variation of specific heat with temperature and (for gases) with pressure. These effects are marked in the cryogenic range. Saturated vapor temperature is used as the zero-enthalpy base point in the calculations, so in most cases the constants depend on the propellant used. The constants are derived from the curves in the tankage section of this volume.

Procedure

The equations used in the hand calculation are given below. Their derivation is too lengthy to include in a handbook such as this.

1. Assume final gas temperature and final wall temperature.
2. Look up specific heat constants k_1 through k_5 in Tables III-1 and III-2.
3. Calculate constants K_1 through K_4 as follows:

$$K_1 = \frac{P\,V\,k_1\,T_{in}}{Z_2\,R\,k_4\,W_w} \tag{1}$$

$$K_2 = \frac{1}{k_4\,W_w}\left[\frac{P\,V\,k_1}{Z_2\,R} + \left(\frac{P_1\,V_u}{Z_1\,RT_1} - W_c\right)\left(k_1\,T_{in} + k_2 + k_3\right) + k_5\,W_w - q_o\,\theta\right] \tag{2}$$

$$K_3 = \frac{P\,V\,k_1\,T_{in}}{Z_2\,RA\,\theta} \tag{3}$$

$$K_4 = \frac{1}{A\,\theta}\left[\frac{P\,V\,k_1}{Z_2\,R} + \left(\frac{P_1\,V_u}{Z_1\,RT_1} - W_c\right)\left(k_1\,T_{in} + k_2 + k_3\right)\right] \tag{4}$$

4. Calculate final gas temperature and check against assumption:

$$T_2 = \frac{1}{2}\left[\sqrt{K_2^2 + \frac{2K_2K_4}{h} + \left(\frac{K_4}{h}\right)^2 + 4\left(\frac{K_3}{h} + K_1\right)} - K_2 - \frac{K_4}{h}\right] \tag{5}$$

5. Calculate final wall temperature and check against assumption:

$$T_w = \frac{K_1}{T_2} - K_2 \tag{6}$$

6. Calculate final gas weight:

$$W_t = \frac{P V}{Z_2 R T_2} \tag{7}$$

7. Calculate initial ullage gas weight:

$$W_u = \frac{P_1 V_u}{Z_1 R T_1} \tag{8}$$

8. Calculate required weight of pressurizing gas:

$$W_p = W_t - W_u - W_c \tag{9}$$

<u>Sample Problem</u>

Conditions

Liquid hydrogen tank pressured by gaseous hydrogen. Cylindrical tank with hemispherical ends. Wall material stainless steel. External insulation. Negligible condensation and aerodynamic heating. Liquid is saturated at one atmosphere before launch.

Diameter	40 ft
Length	60 ft
Wall thickness	0.12 in
Initial ullage	5 %
Operating pressure, P	5760 psfa
Inlet gas temperature, T_{in}	300 R
Inside gas film heat transfer coefficient, h	10 Btu/hr-ft^2-R
Expulsion time, θ	0.0333 hr

Calculated values

Total tank volume, V	58,500 ft^3
Initial ullage volume, V_u	2,920 ft^3
Wall weight, W_w	37,300 lb

Wall area of initial ullage	913 ft^2
Total wall area	7,550 ft^2
Average gas-to-wall heat transfer area, A	4,232 ft^2

Assumptions

Final gas temperature, T_2	245 R
Final wall temperature, T_w	165 R

Gas Properties

Saturation pressure of propellant prior to launch, P_1	2116 psfa
Propellant temperature, T_1	37.0 R
Initial compressibility factor, Z_1	0.90
Final compressibility factor, Z_2	1.0

Specific heat constants

$$k_1 = 2.85\,,\; k_2 = -146\,,\; k_3 = 19,\; k_4 = 0.053\,,\; k_5 = -6.0$$

K_1 through K_4

$$K_1 = \frac{5760 \times 58500 \times 2.85 \times 300}{1.0 \times 767 \times 0.053 \times 37300} = 189{,}900$$

$$K_2 = \frac{1}{0.053 \times 37300}\left[\frac{5760 \times 58500 \times 2.85}{1.0 \times 767} + \left(\frac{2116 \times 2920}{0.90 \times 767 \times 37} - 0\right)\left(2.85 \times 300 - 146 + 19\right) - 6.0 \times 37300 - 0\right] = 0.000506\left(1{,}252{,}000 + 242 \times 728 - 223{,}700\right) = 610$$

$$K_3 = \frac{5760 \times 58500 \times 2.85 \times 300}{1.0 \times 767 \times 4232 \times 0.0333} = 2{,}664{,}000$$

$$K_4 = \frac{1}{4232 \times 0.0333}\left[\frac{5760 \times 58500 \times 2.85}{1.0 \times 767} + \left(\frac{2116 \times 2920}{0.90 \times 767 \times 37} - 0\right)\right.$$

$$\left.\left(2.85 \times 300 - 146 + 19\right)\right] = 0.00709\ \left(1,252,000 + 242 \times 728\right) = 10,120$$

Final gas temperature

$$T_2 = \frac{1}{2}\left[\sqrt{610^2 + \frac{2 \times 610 \times 10120}{10} + \left(\frac{10120}{10}\right)^2 + 4\left(\frac{2.664 \times 10^6}{10} + 189,900\right)}\right.$$

$$\left.- 610 - \frac{10120}{10}\right] = \frac{1}{2}\left[\sqrt{372,000 + 1,234,000 + 1,025,000 + 1,824,000}\right.$$

$$\left.- 610 - 1012\right] = \frac{1}{2}\left(2110 - 610 - 1012\right) = 244\ R$$

Final wall temperature

$$T_w = \frac{189,900}{244} - 610 - 169\ R$$

Nomenclature

The following symbols and units have been used in the hand calculation:

Symbol	Quantity and Units
A	Average gas-to-wall heat transfer area, ft^2
h	Inside gas film heat transfer coefficient, $Btu/hr\text{-}ft^2\text{-}R$
k_1 through k_5	Gas and wall specific heat constants in Equations (1) through (4)
K_1 through K_4	Constants in Equations (1) through (6)

P	Tank operating pressure, psfa
P_1	Saturation pressure of propellant prior to launch, psfa
q_o	Average aerodynamic heat flux to gas, Btu/hr-ft^2
R	Gas Constant, ft-lb/lb-R (= 1544/molecular weight)
T_1	Propellant temperature, R
T_2	Final gas temperature, R
T_{in}	Pressurizing gas inlet temperature, R
T_w	Final wall temperature, R
V	Total tank volume, ft^3
V_u	Initial ullage volume, ft^3
W_c	Weight of gas condensed, lb
W_p	Pressurizing gas weight, lb
W_t	Final weight of gas in tank, lb
W_u	Initial ullage gas weight, lb
W_w	Wall weight, lb
Z_1	Compressibility factor at pressure P_1 and temperature T_1, dimensionless
Z_2	Compressibility factor at pressure P and temperature T_2, dimensionless
θ	Expulsion time, hr

TABLE III-1

GAS SPECIFIC HEAT CONSTANTS

For Use In Hand Calculation Of
Pressurizing Gas Requirements

For pressurizing liquid oxygen

GO_2 on LO_2- $k_1 = 0.2155$ $k_2 = -35.5$ $k_3 = 0$

He on LO_2- $k_1 = 1.26$ $k_2 = -205$ $k_3 = 0$

For pressurizing liquid hydrogen

	k_1		k_2	
T_2, R	GH_2 on LH_2	He on LH_2	GH_2 on LH_2	He on LH_2
50-100	2.56	1.27	- 91	-46
100-150	2.52	1.26	- 87	-45
150-200	2.66	1.26	-108	-45
200-250	2.85	1.26	-146	-45
250-300	2.98	1.26	-180	-45
300-350	3.16	1.26	-233	-45
350-400	3.26	1.26	-268	-45
400-450	3.34	1.26	-300	-45
450-500	3.38	1.26	-318	-45
500-550	3.40	1.26	-328	-45

	k_3	
P, psia	GH_2 on LH_2	He on LH_2
15	0	0
30	12	5.9
45	22	10.4
60	29	-
75	34	-
90	39	-
100	42	-

TABLE III-2

WALL SPECIFIC HEAT CONSTANTS

For Use In Hand Calculation Of
Pressurizing Gas Requirements

	k_4			k_5(with LH_2)			k_5(with LO_2)		
T_w, R	Al	Ti	SS	Al	Ti	SS	Al	Ti	SS
70-100	0.033	0.014	0.014	- 0.8	- 0.4	- 0.5	--	--	--
100-130	0.069	0.040	0.028	- 4.8	- 3.6	- 2.5	--	--	--
130-160	0.096	0.060	0.040	- 8.3	- 6.5	- 4.2	--	--	--
160-190	0.117	0.080	0.053	-12.1	- 9.5	- 6.0	-18.7	- 13.4	- 8.3
190-220	0.133	0.094	0.064	-15.5	- 12.1	- 7.6	-22.1	- 16.0	- 9.9
220-250	0.147	0.106	0.072	-19.2	- 14.8	- 9.4	-25.8	- 18.7	-11.7
250-280	0.159	0.112	0.077	-21.9	- 16.1	-10.9	-28.5	- 20.0	-13.2
280-310	0.172	0.115	0.082	-24.7	- 16.4	-12.6	-31.3	- 20.3	-14.9
310-340	0.181	0.117	0.086	-27.2	- 16.6	-14.0	-33.8	- 20.5	-16.3
340-370	0.192	0.120	0.091	-29.7	- 17.0	-15.5	-36.3	- 20.9	-17.8
370-400	0.199	0.133	0.094	-31.8	- 22.6	-16.7	-38.4	- 26.5	-19.0
400-430	0.206	0.250	0.098	-34.1	- 72.0	-18.0	-40.7	- 75.9	-20.3
430-460	0.213	0.384	0.101	-36.0	-129.8	-19.0	-42.6	-133.7	-21.3

EP Computer Program

The IBM 7090 tank pressurization program has been found to provide the most accurate method of calculating pressurizing gas requirements. It is completely described in Volume IV of this report and need not be discussed here.

MTI Data And Calculations

General

A main tank injection (MTI) system is one in which a hypergolic reagent is injected into the main propellant tank and the resulting combustion gases are used to pressurize the tank. MTI systems may be divided into two types; separate feed and cross feed, as described in Volume II. The cross feed system is simpler and more reliable than the separate feed system, and its use is recommended wherever possible. The cross feed system is most applicable to vehicles using pump-fed engines. On vehicles using pressure-fed engines a separate feed system must be used on one propellant tank and may be required for both tanks.

In an MTI system, the pressurizing gas temperature increases with tank pressure, and because of this the use of MTI is generally not practical at high pressures.

The data presented in this section can be used in calculating pressurizing gas requirements and fuel and oxidizer weights in propulsion systems employing main tank injection pressurizing techniques. Empirical data were derived from the results of a test program of limited scope, no attempt being made to evaluate all of the variables inherent in an MTI pressurizing system. The data permit an approximate analysis of the requirements for an MTI system, but until more comprehensive tests are made, their use should be restricted to those applications where a high degree of accuracy is not required.

MTI Screening Tests

Table III-3 summarizes the results of a series of open-container tests in which the reactions of various fuel-oxidizer combinations were observed. These tests demonstrated the feasibility of combining N_2O_4 with N_2H_4, UDMH, or a 50-50 mixture of N_2H_4 and UDMH in an MTI system.

TABLE III-3

FUEL-OXIDIZER REACTIONS

Test Fluid	Injected Fluid	Observed Reaction
UDMH	N_2O_4	Smooth Combustion
50-50 UDMH/N_2H_4	N_2O_4	Smooth Combustion
N_2H_4	N_2O_4	Smooth Combustion
B_5H_9	ClF_3	Smooth, Intense Combustion
B_5H_9	BrF_5	Mild Detonation
RP-1	ClF_3	Smooth Combustion, Smoky
N_2H_4	ClF_3	Violent Reaction
RP-1	N_2O_4	No Reaction

N_2O_4 and UDMH or 50-50 UDMH-N_2H_4

The tables and graphs on the following pages are applicable to both the N_2O_4-UDMH and N_2O_4 - 50-50 UDMH-N_2H_4 oxidizer-fuel combinations. Data from this section were used in the calculations of oxidizer and fuel weight requirements shown in graphic form in Figures III-11 and III-12.

Bomb Calorimeter Heat Release Data - The results plotted in Figure III-7 were obtained from bomb calorimeter tests in which N_2O_4 introduced in varying amounts was used as the oxidizer. The heat release approaches the value for the heat of combustion of UDMH as excess oxidizer is provided for the reaction.

Combustion Temperature - Figure III-8 plots reaction temperature as a function of oxidizer-fuel ratio. Both computed and observed (bomb calorimeter) values are plotted.

Molecular Weight vs Mixture Ratio - Figure III-9 plots calculated and observed values for gas molecular weight as a function of oxidizer-fuel mixture ratios. Since mixture ratios can neither be controlled nor directly measured in an MTI system, molecular weight relationships offer a convenient method of indirectly determining the effective oxidizer-fuel ratio resulting from the actual combustion.

Combustion Products of UDMH-N_2O_4 - Table III-4 lists the results of an IBM computer program for the determination of the products of combustion of a range of oxidizer-fuel ratios.

Ullage Gas Temperature vs Pressure - Figure III-10 shows the results of an evaluation of test data in which ullage gas temperature is related to ullage pressure in an MTI system using N_2O_4 and 50-50 UDMH-N_2H_4. The temperature values plotted were obtained from a single temperature probe. The range of temperatures resulted from slight variations in test procedures. Temperature distribution and tank size effects have not been determined.

MTI Propellant Weights - Fuel Tank - Figure III-11 provides a graphic method for determining pressurizing gas weight and fuel and oxidizer weight requirements when the required ullage pressure has been specified. Three curves are presented:

1. Total pressurizing gas weight per unit volume.
2. Total fuel weight per unit volume of pressurizing gas.
3. Total oxidizer weight per unit volume of pressurizing gas.

The curve for total pressurizing gas weight is a solution of the equation:

$$W_{pg} = \frac{PVM}{RT}$$

where, W_{pg} = Total weight of pressurizing gas, lb

P = Ullage pressure, psia

V = Final ullage volume, cu ft

M = Gas molecular weight - empirically determined to be 24

R = Universal gas constant - 1544 ft-lb/lb-R

T = Temperature, °R - Values taken from plot of temperature vs pressure in Figure III-10.

TABLE III-4

COMBUSTION PRODUCTS OF UDMH AND N_2O_4

Mixture Ratio W_o/W_f	0.1	0.5	1.0	2.61	4.0	10.0
Chamber Pressure, psia	500	500	500	500	100	500
Combustion Temp., R	1157	2173	2797	5876	5385	3726
Molecular Wt. of Products	10.83	14.61	15.73	23.78	26.17	29.24
Density, lb/ft^3	0.6184	0.3405	0.2620	0.1885	0.0429	0.3657
Ratio of Specific Heats	1.213	1.252	1.310	1.222	1.224	1.250
c_p, Btu/lb - R	0.636	0.602	0.534	0.458	0.417	0.308
Products *						
H_2O	0.0429	0.0494	0.0682	0.3580	0.3071	0.1762
H_2	0.4078	0.4109	0.4534	0.0576	0.0159	
H				0.0137	0.0074	
OH				0.0321	0.0437	0.0016
O_2				0.0127	0.1111	0.3962
O				0.0053	0.0149	0.0001
NO				0.0098	0.0218	0.0085
N_2	0.1291	0.2146	0.2163	0.2915	0.3038	0.3289
CO		0.1394	0.2483	0.1219	0.0481	0.0001
CO_2		0.0115	0.0127	0.0973	0.1262	0.0884
NH_3	0.0917	0.0008	0.0002			
CH_4	0.0343	0.0935				
C	0.2942	0.0799				

* Products of combustion given as mole fractions.

Fuel and oxidizer weight requirements are calculated from oxidizer-fuel ratios taken from the graph of molecular weight vs mixture ratio, Figure III-9.

MTI Propellant Weights - Oxidizer Tank - Figure III-12 provides a graphic method for determining pressurizing gas weight and fuel and oxidizer weight requirements when the required ullage pressure has been specified. Three curves are presented:

1. Total pressurizing gas weight per unit volume.
2. Total fuel weight per unit volume of pressurizing gas.
3. Total oxidizer weight per unit volume of pressurizing gas.

The curve for total pressurizing gas weight is a solution of the following equation:

$$W_{pg} = \frac{PVM}{RT}$$

where, W_{pg} = Total weight of pressurizing gas

P = Ullage pressure, psia

V = Final ullage volume, cu ft

M = Gas molecular weight - empirically determined to be 14.5

R = Universal gas constant - 1544 ft-lb/lb-R

T = Temperature, °R - Values taken from plot of temperature vs pressure in Figure III-10.

Fuel and oxidizer weight requirements are calculated from oxidizer-fuel ratios taken from the graph of molecular weight vs mixture ratio, Figure III-9.

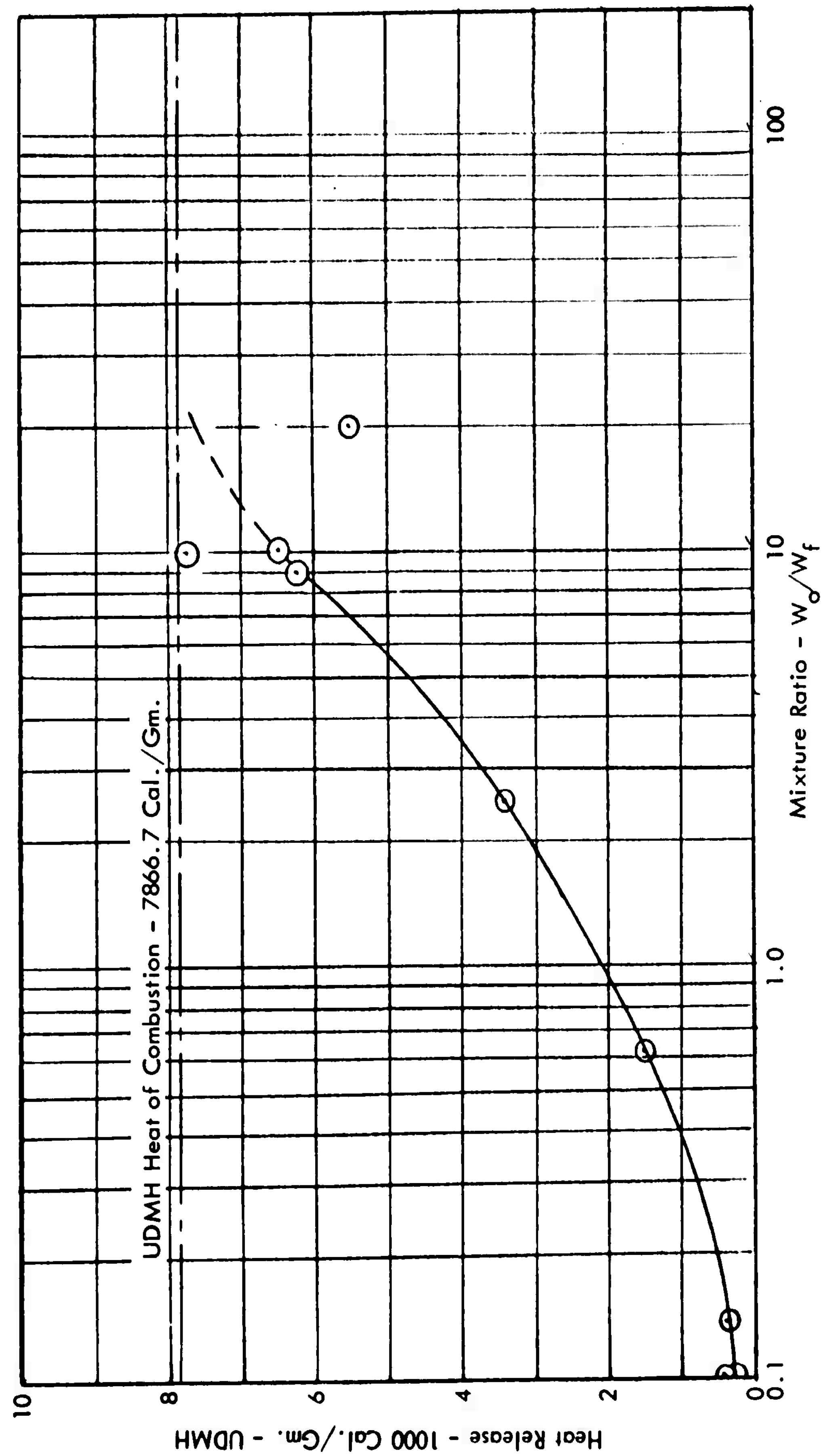

FIGURE III-7

BOMB CALORIMETER HEAT RELEASE DATA UDMH - N_2O_4

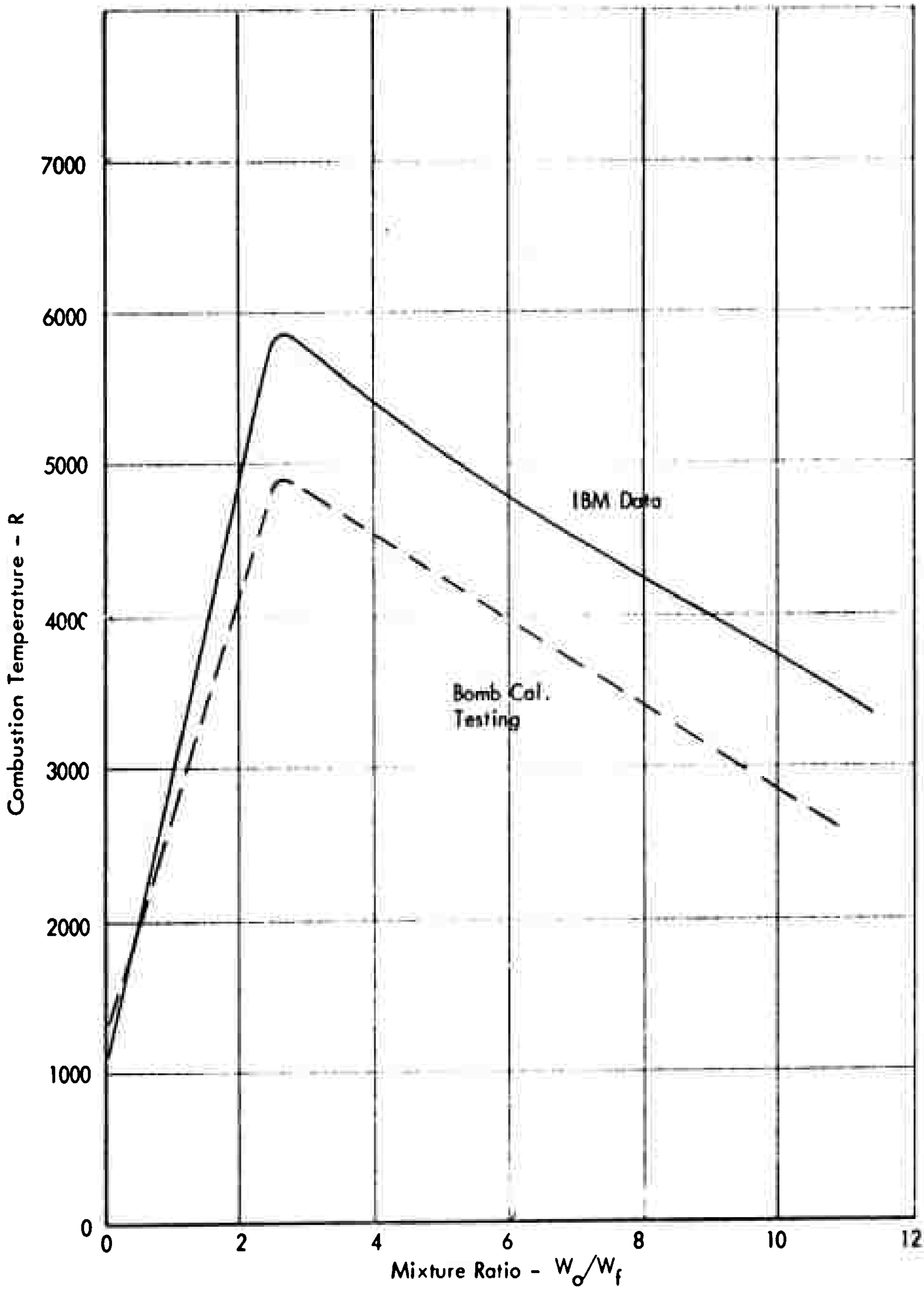

FIGURE III-8

UDMH-N_2O_4 COMBUSTION TEMPERATURE VS MIXTURE RATIO

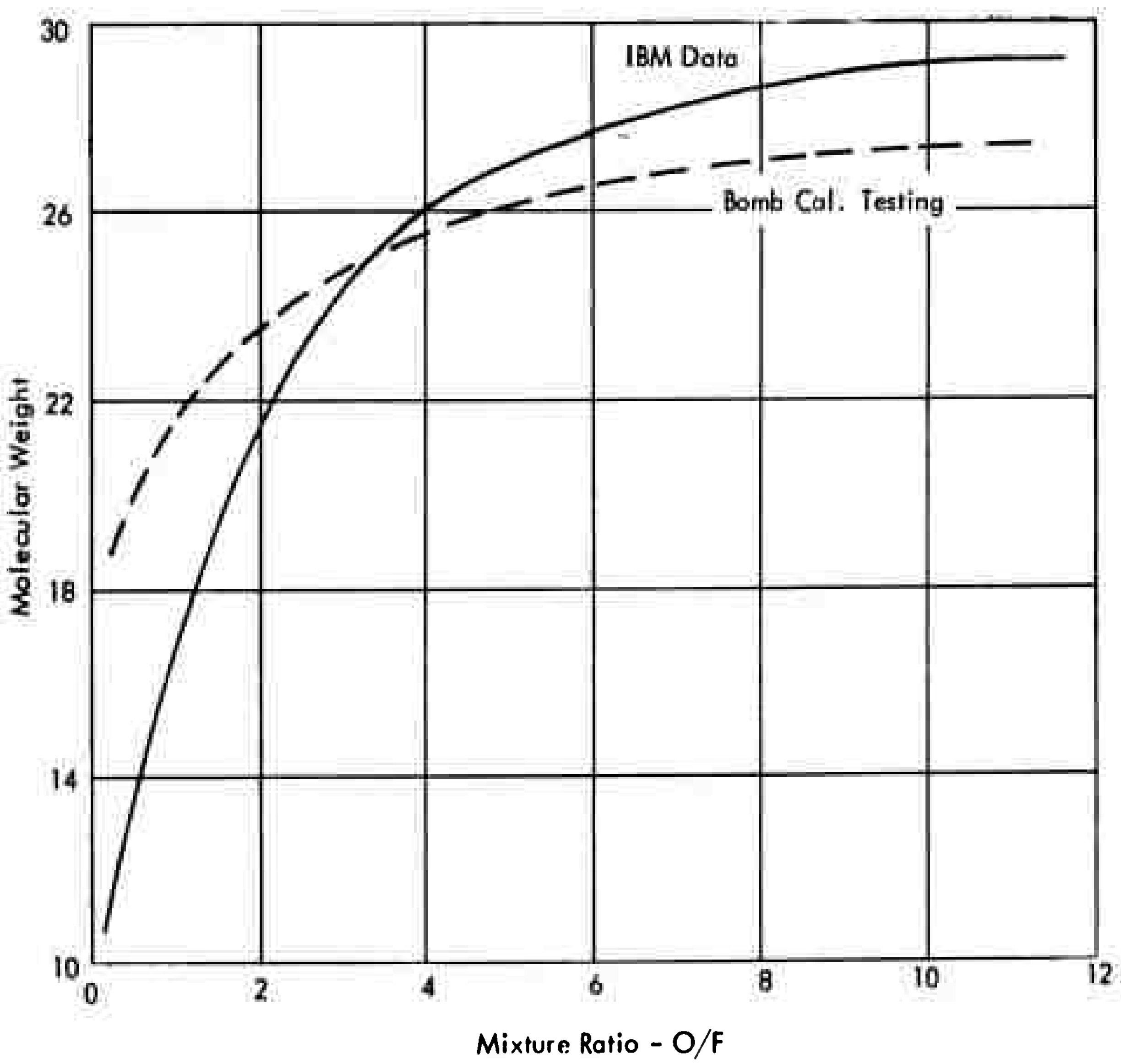

FIGURE III-9

UDMH-N_2O_4MOLECULAR WEIGHT VS MIXTURE RATIO

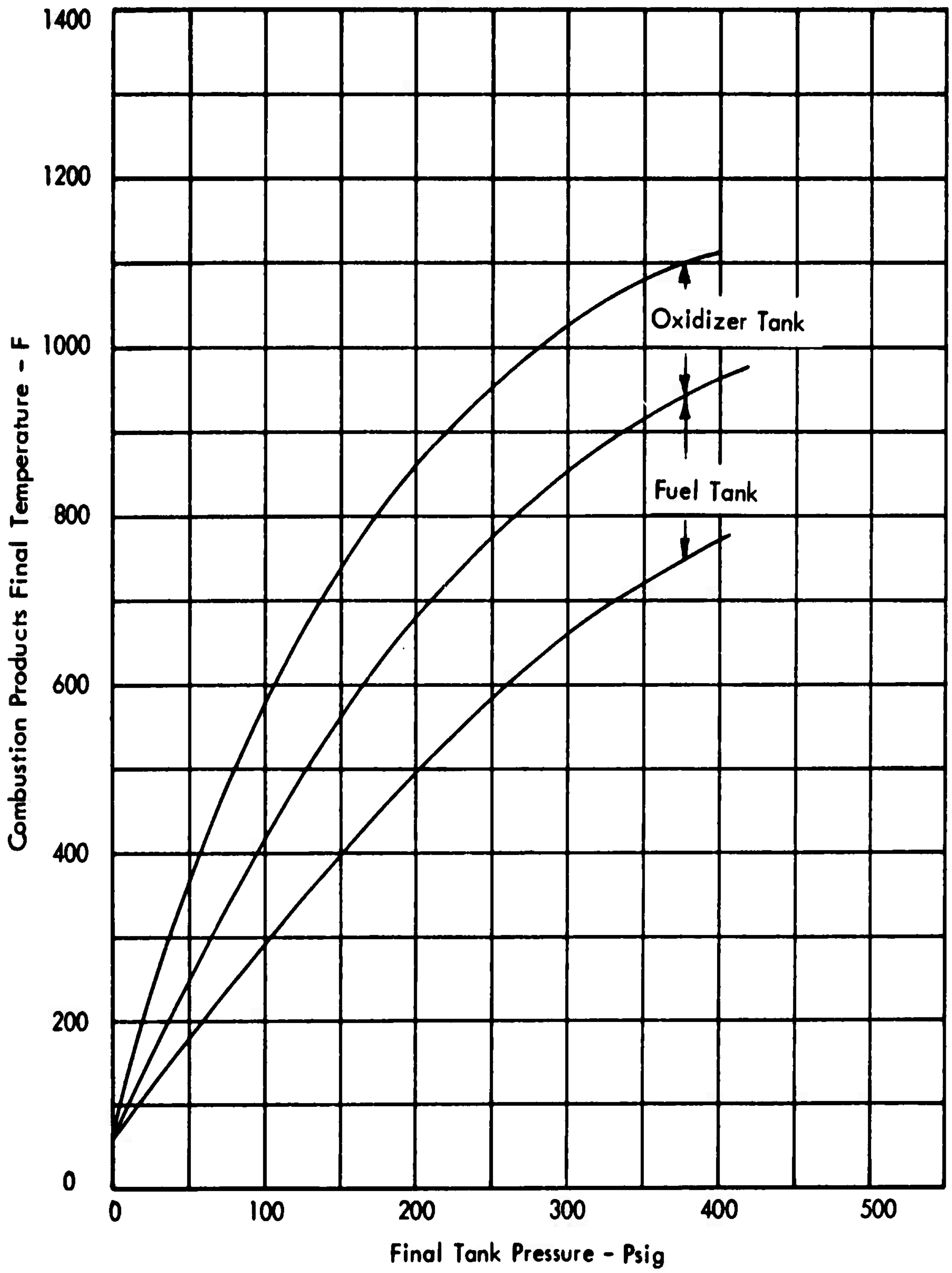

FIGURE III-10

MTI SYSTEM GAS TEMPERATURE VS PRESSURE
FOR N_2O_4, UDMH, 50-50 UDMH/N_2H_4

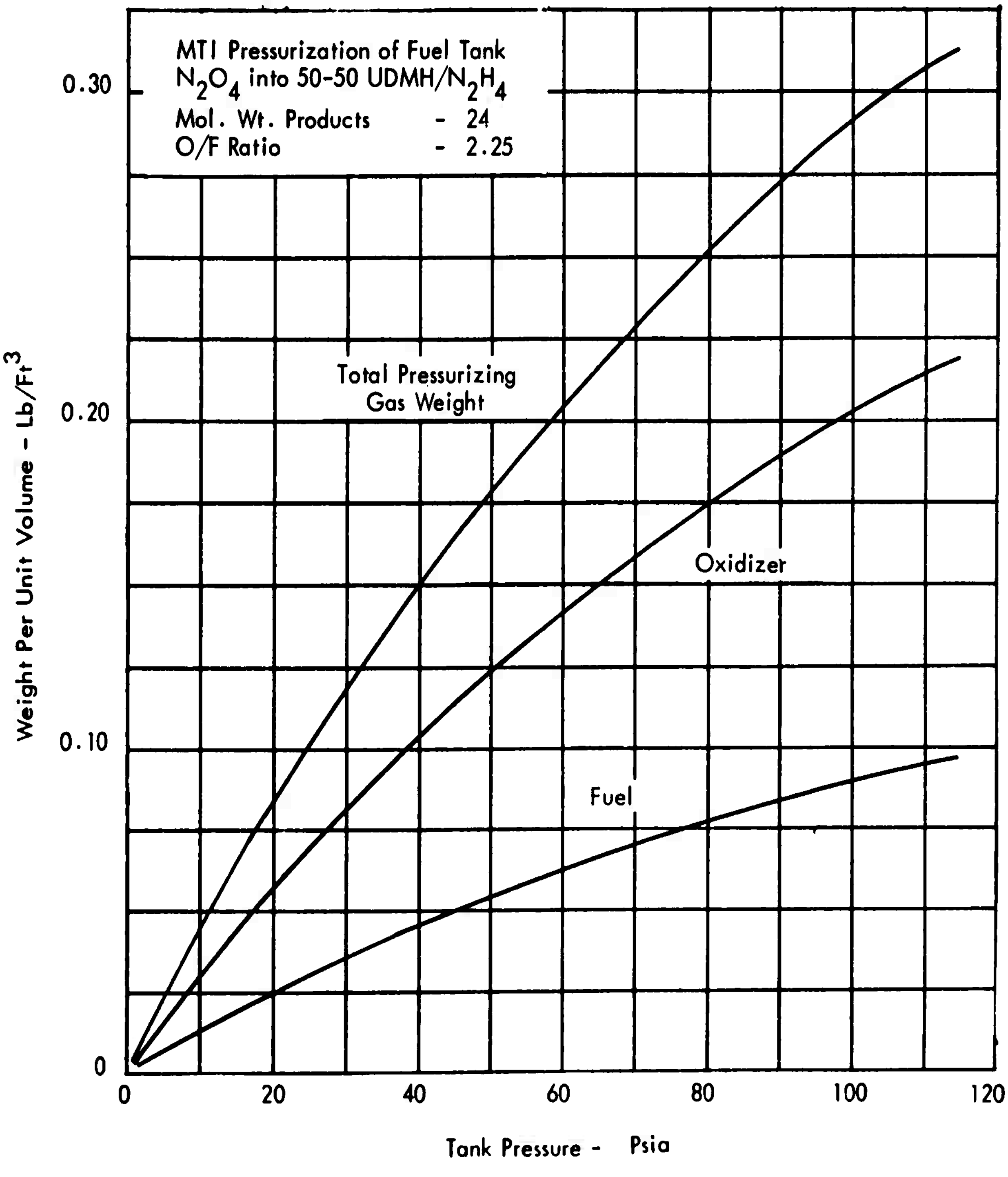

FIGURE III-11

MTI PROPELLANT WEIGHTS - FUEL TANK

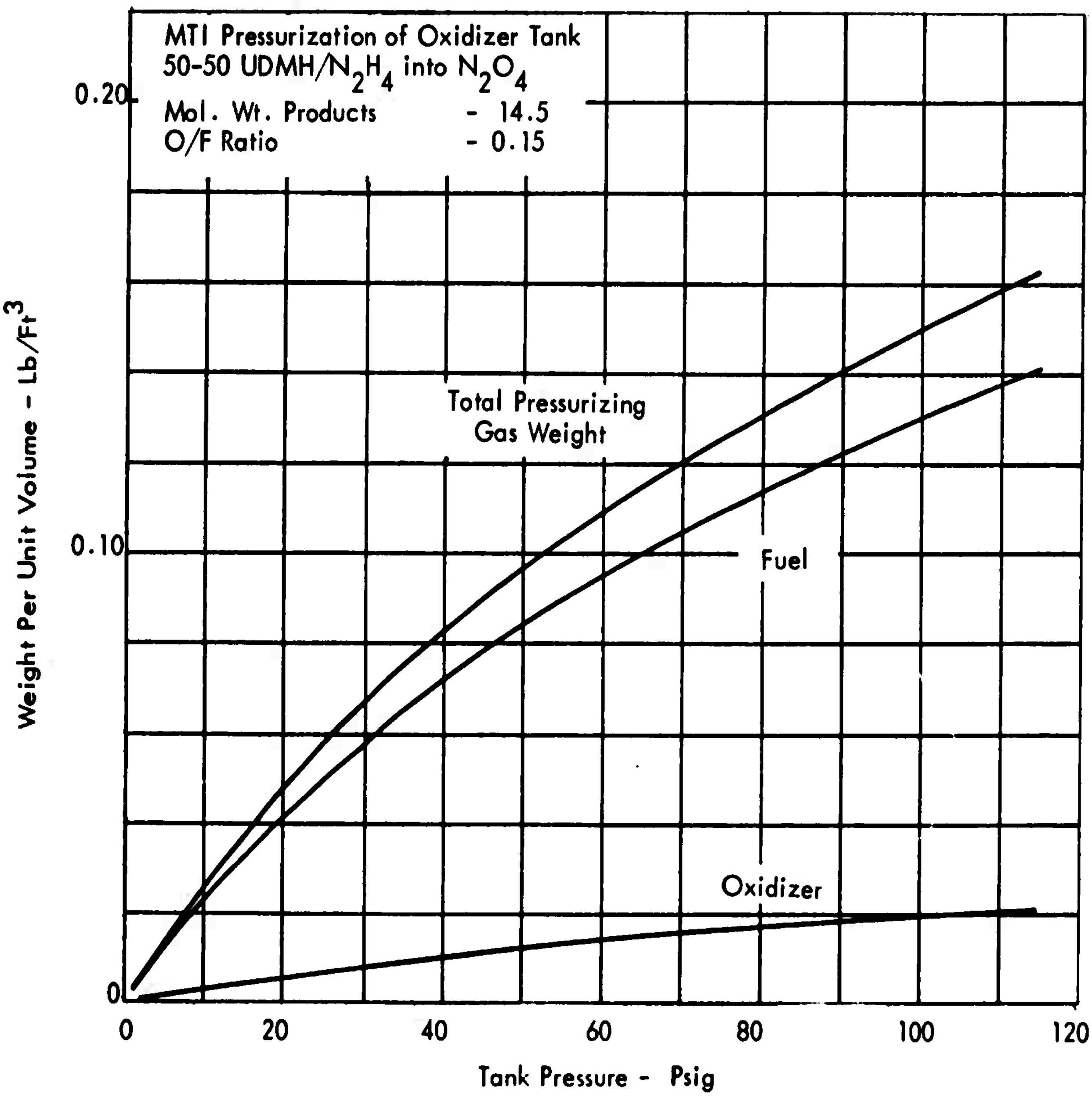

FIGURE III-12

MTI PROPELLANT WEIGHTS - OXIDIZER TANK

TANKAGE

As is discussed in Volume I, the pressurization system interacts with the vehicle structure in a number of ways, depending on pressure stabilization requirements, pump NPSH requirements, maximum allowable wall temperature, gas cooling by heat transfer to the walls, etc. In order to provide a convenient single source for the information required in the optimization of the pressurization system, data on the required tank physical and geometrical properties are provided in this section.

Physical Properties

Figures III-13 through III-24 show four of the most important physical properties for aluminum alloys, titanium alloys, and stainless steels. The curves are discussed below by property rather than by material.

The very-low-temperature properties shown herein are believed to be the best values available at this time. However, they are not as well established as the properties at room temperature and above, and should be used with caution if their effects are critical.

Design Tensile Strength

It will be recognized by the designer that the strength information of Figures III-13 III-17, and III-21 is by no means sufficient for the complete design of the vehicle. The effects of fatigue, welding, anisotropy, minimum gage, and many other factors must be taken into account in the final design. Tanks are largely designed by hoop tension however, so valid comparisons can often be obtained from simple tensile data.

For simplicity, the data are presented as either the tensile strength or the yield strength, whichever is lower after the application of appropriate margins. The usual criterion of 0.2 percent yield was used in defining the yield strength.

Specific Heat

Specific heat is usually affected only slightly by alloying constituents, so in most cases only one curve is given for each basic material. The strength curves include a notation of material density, which is required in the calculation of total thermal capacitance.

Thermal Conductivity

Conductivity actually rarely enters into the calculation of pressurizing gas requirements. It is required in the calculation of heat leaks and other thermodynamic problems, however, so its inclusion appears warranted.

As can be seen, thermal conductivity is materially affected by the addition of alloying elements. Curves of conductivity against temperature are given when available, but, in many cases, only individual points at specific temperatures have been found.

Linear Thermal Expansion

Like conductivity, thermal expansion is not needed for pressurizing gas calculations but is of general thermodynamic utility. It should be noted that the curves present not the usual parameter of expansion coefficient but rather total expansion; that is, the total percent length change caused by the total change in temperature. By using total expansion, the variation of expansion coefficient with temperature is automatically accounted for.

Emissivity

External surface emissivity is needed in the accurate calculation of the effect of aerodynamic heating on pressurizing gas requirements, but emissivity data are not given herein for several reasons:

1. A value of 0.9 can usually be assumed for aerodynamic heating calculations, since dull, highly emissive surface treatments can be applied to most materials. It is desirable to keep the emissivity as high as possible in order to minimize net aerodynamic heat input to the body.

2. The effect of aerodynamic heating on pressurizing gas requirements is small for an insulated tank, so emissivity need not be determined accurately.

3. Emissivity is very sensitive to surface conditions and sometimes to angle of emission and other factors. In other thermodynamic problems, in which radiation may be an important mode of heat transfer, data obtained under well-defined conditions should be used.

Propellant Properties

Table III-5 presents a convenient summary of the properties of a number of liquid propellants of interest.

Geometry

Figures III-25 through III-30 show the volumes and wall areas of spherical, cylindrical, and oblate spheroidal tanks as functions of their dimensions. These curves may be used for ready reference in investigating the effects of changes in vehicle and tank shape on pressurization system weight.

TABLE III-5

PROPELLANT PROPERTIES

(References III-1 and III-2)

	He	H_2	N_2	O_2	N_2O_4	UDMH	N_2H_4	B_5H_9	50-50 UDMH/ N_2H_4
Boiling Point at 1 Atm, F	-452.0	-423.0	-320.4	-297.4	70.1	145.4	235.4	137.1	158.2
Melting Point at 1 Atm, F	-458.0 (26 atm)	-434.6	-345.8	-361.1	11.8	-61.6	34.5	-59.8	18.8
Vapor Density at B.P., Lb/Ft^3	0.999	0.0830	0.288	0.296					
Liquid Density at B.P., Lb/Ft^3	7.803	4.37	50.19	71.29	90.5				56.1 (77.0 F)
Heat of Vaporization at B.P., Btu/lb	10.3	194.4	85.7	91.6	178.0	250.7 (77.0 F)	601.9 (77.0 F)	219.0 (-72.4 F)	425.8
Heat of Fusion at M.P., Btu/lb	1.8	25.2	11.0	5.9	137.0	72.0 (-72.0 F)	170.1 (77.0 F)		
Critical Temperature, F	-450.2	-399.8	-232.8	-181.1	316.4	480.2	716.0	435.2	634.0
Critical Pressure, Psia	33.2	188.1	492.3	730.3	1470.0	880.0	2135.0		

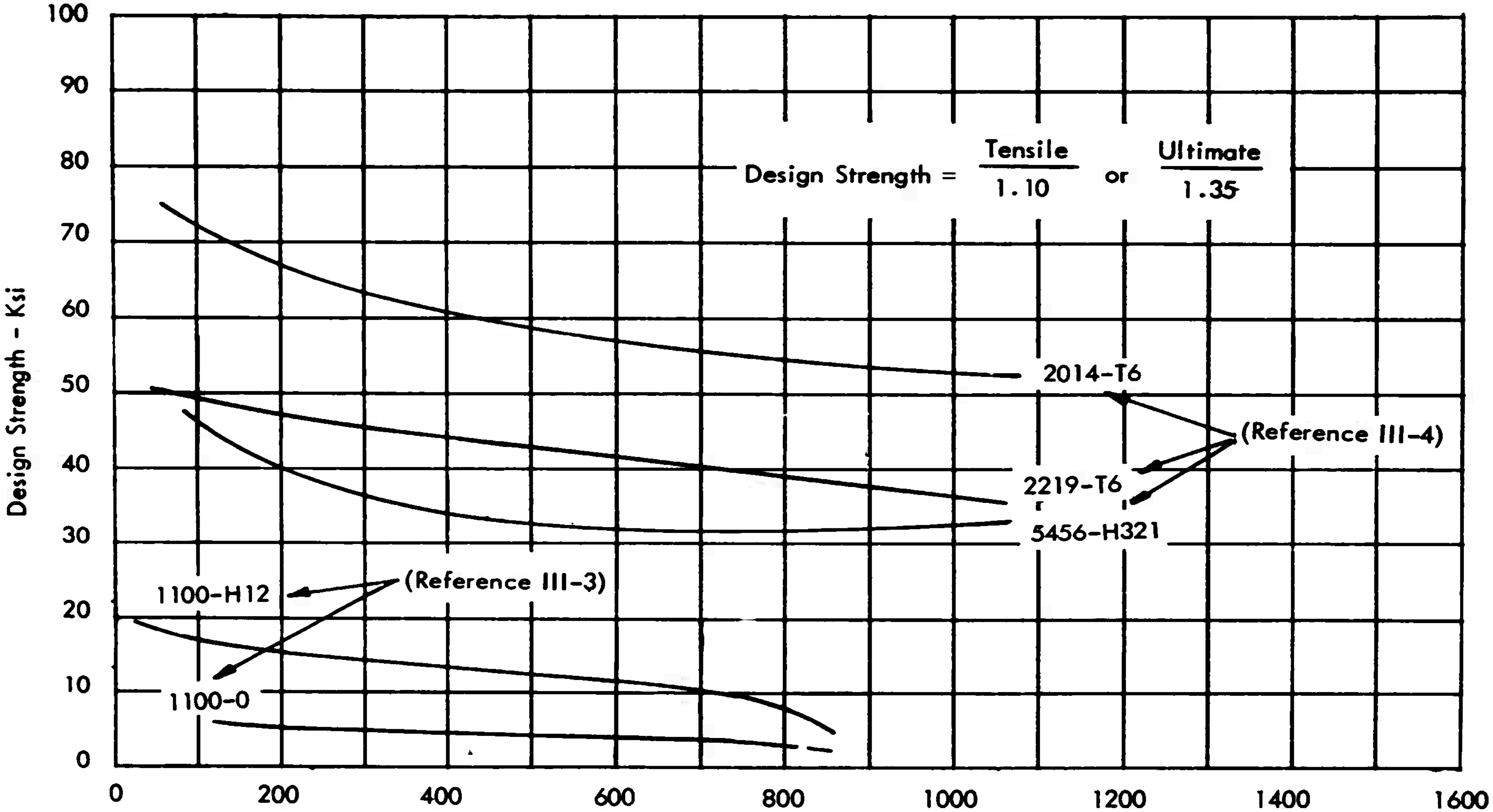

FIGURE III-13a

DESIGN TENSILE STRENGTH OF ALUMINUM ALLOYS

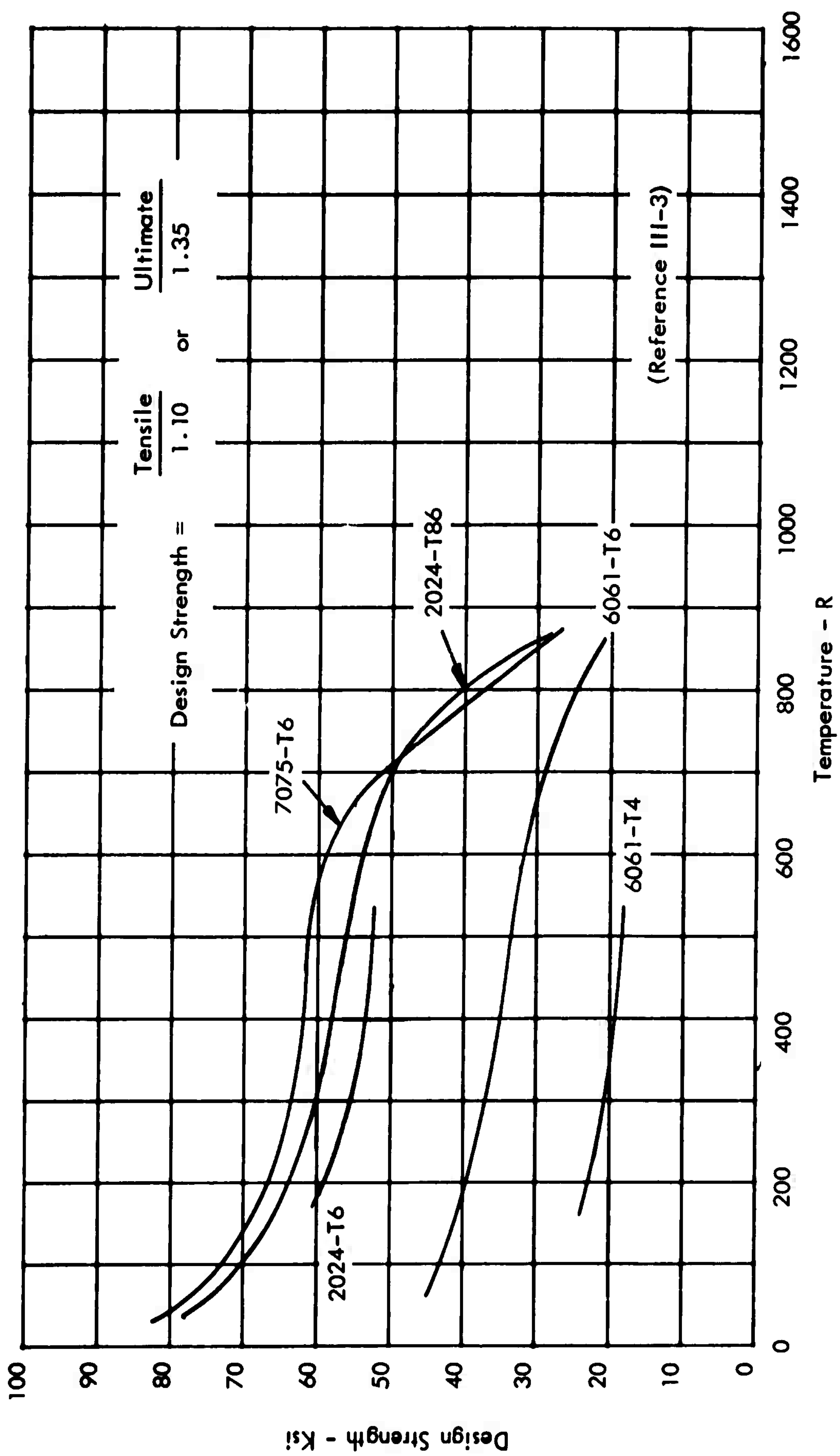

FIGURE III-13b

DESIGN TENSILE STRENGTH OF ALUMINUM ALLOYS

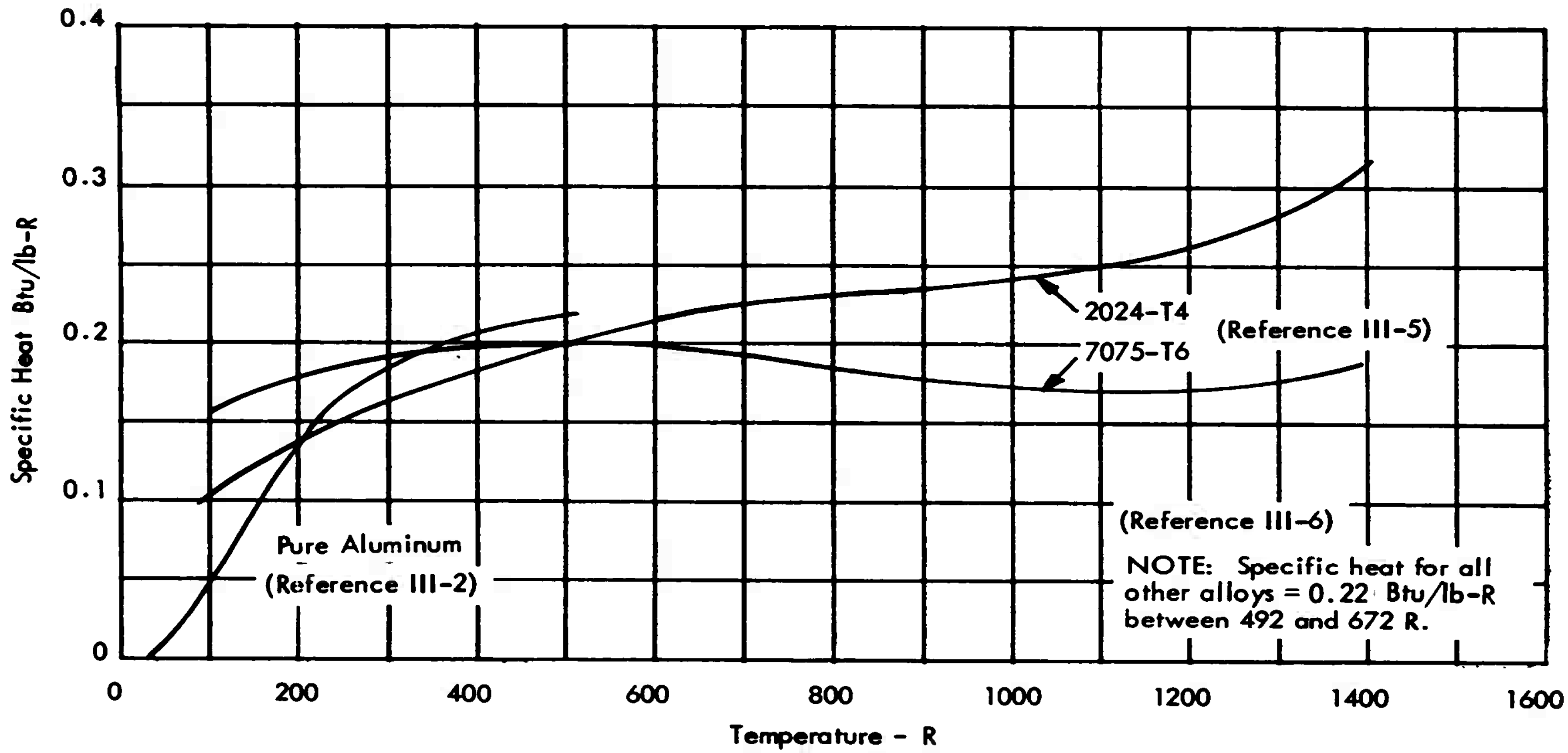

FIGURE III-14

SPECIFIC HEAT OF ALUMINUM ALLOYS

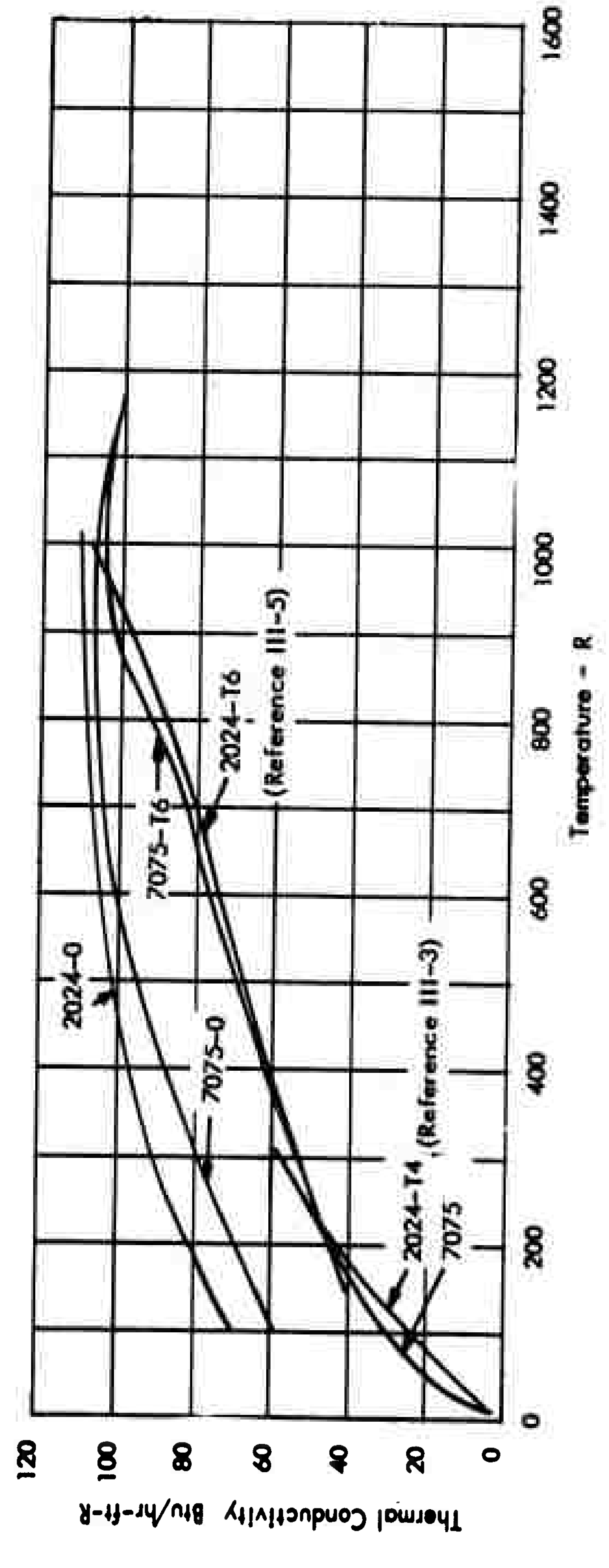

FIGURE III-15

THERMAL CONDUCTIVITY OF ALUMINUM ALLOYS

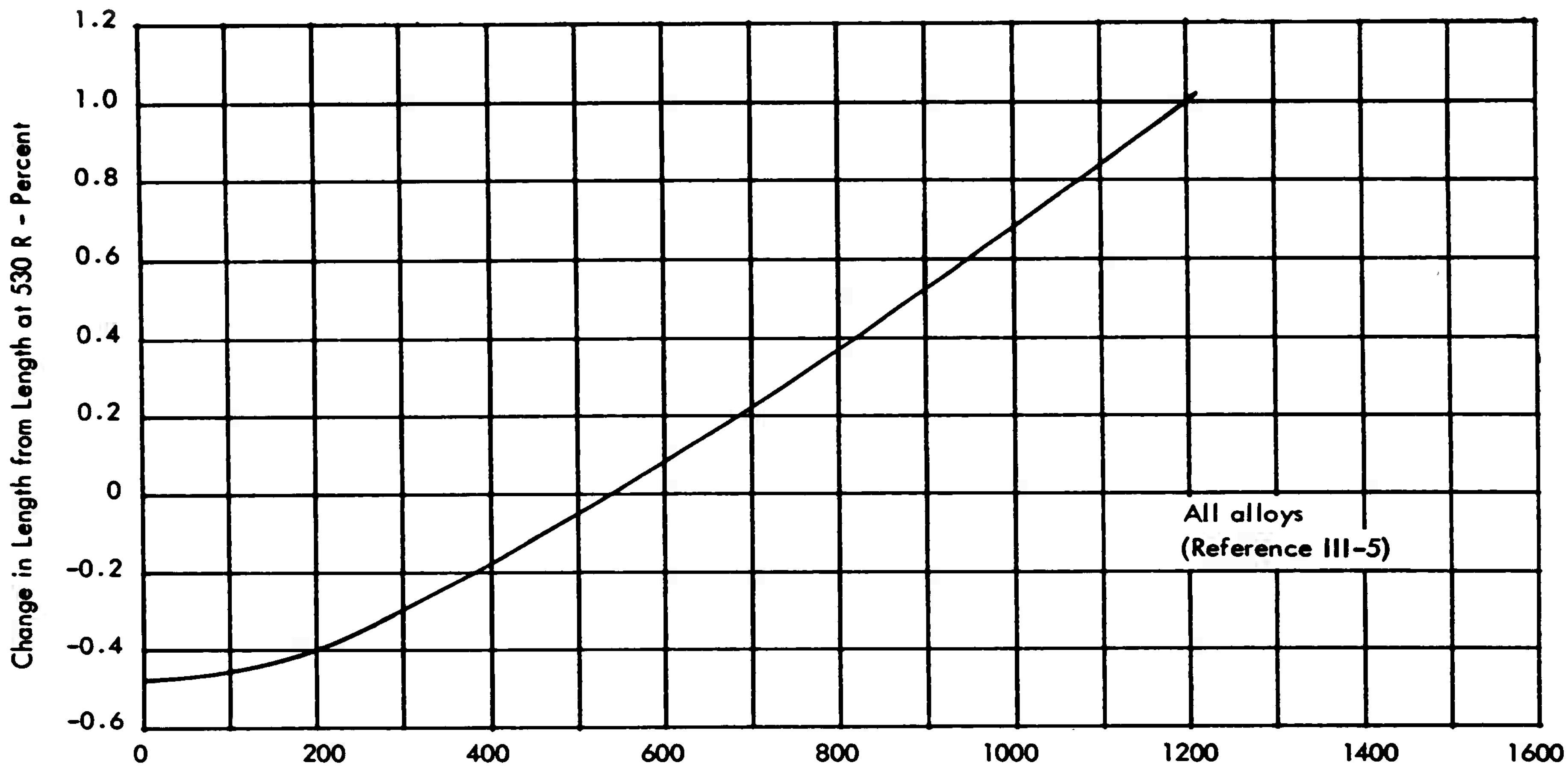

FIGURE III-16

LINEAR THERMAL EXPANSION OF ALUMINUM ALLOYS

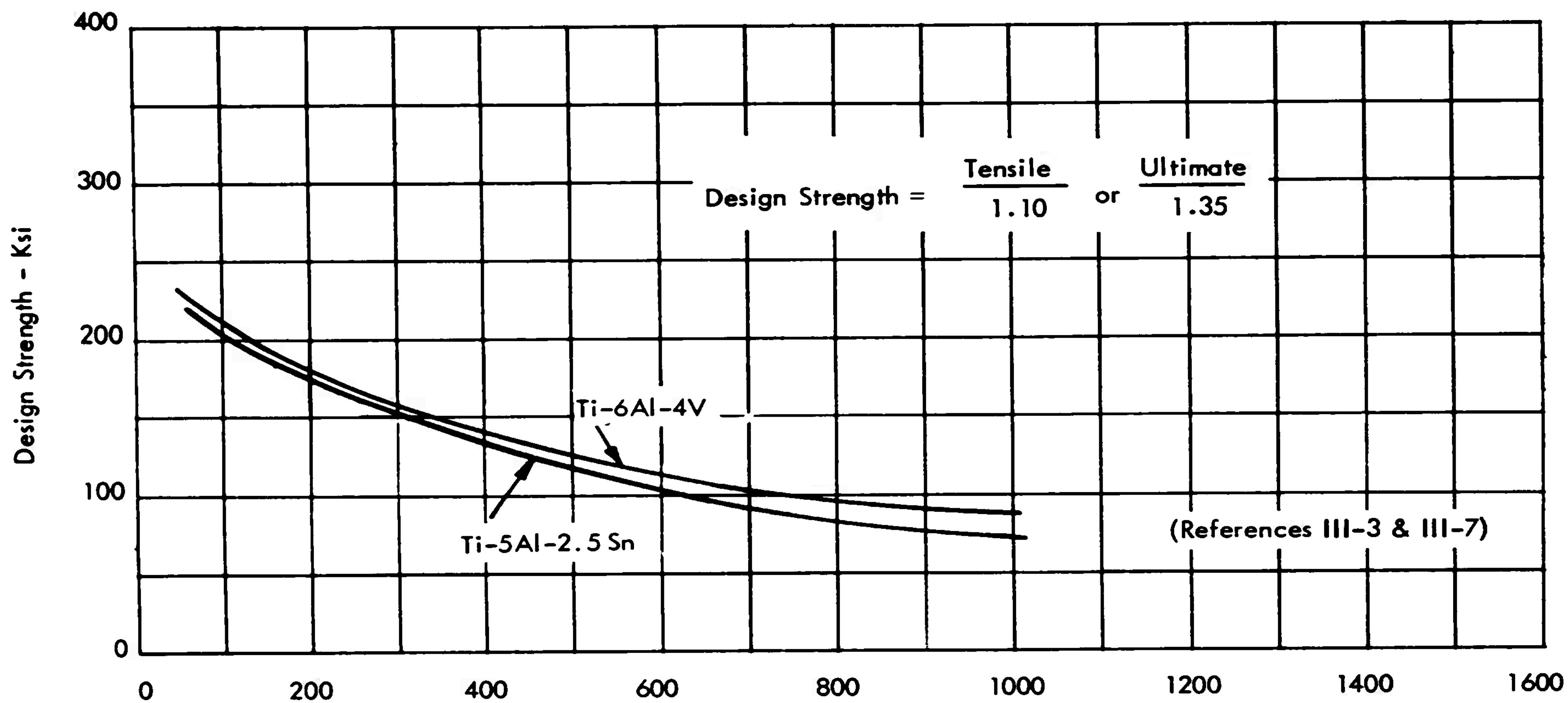

FIGURE III-17

DESIGN TENSILE STRENGTH OF TITANIUM ALLOYS

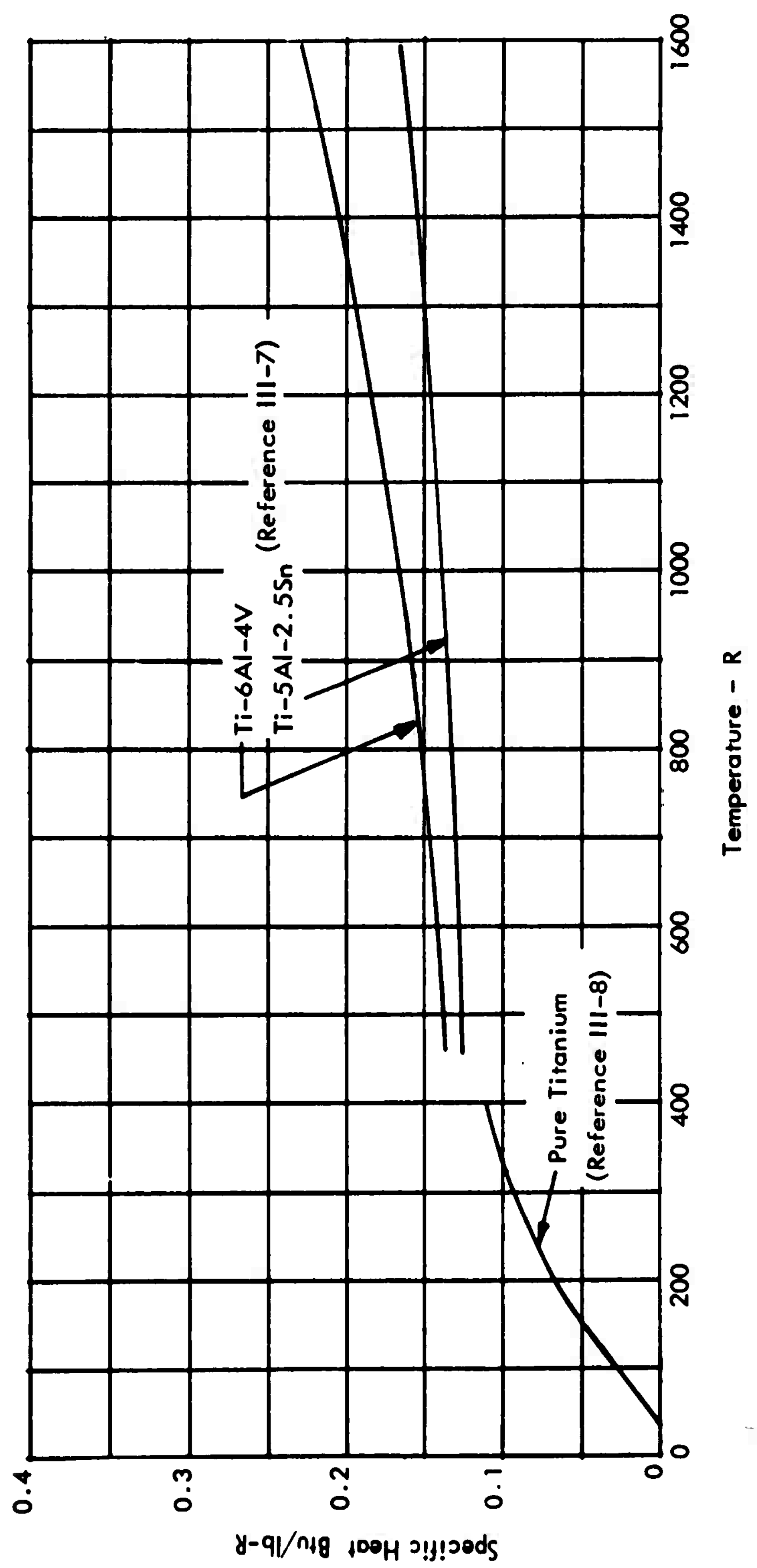

FIGURE III-18

SPECIFIC HEAT OF TITANIUM ALLOYS

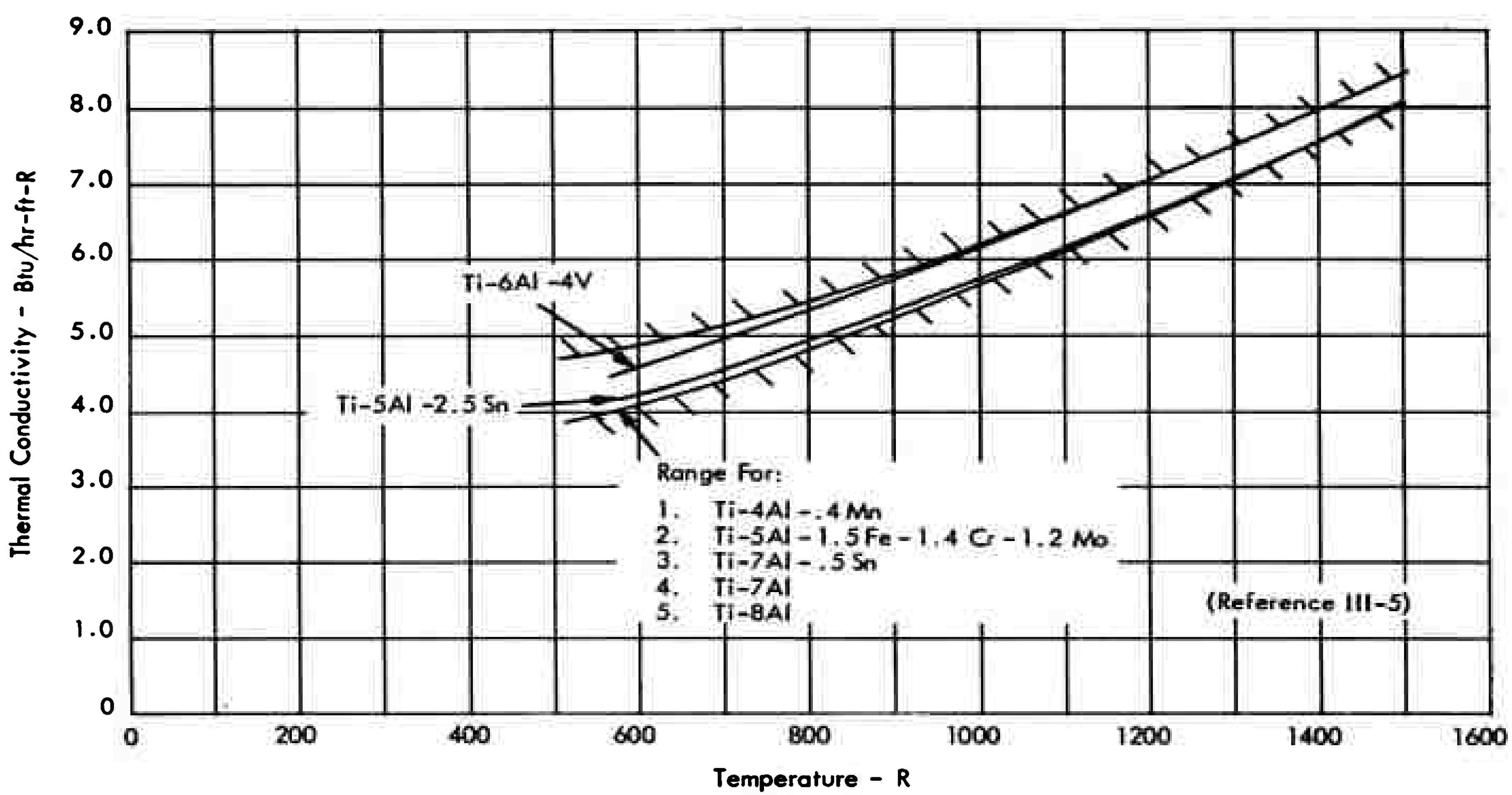

FIGURE III-19

THERMAL CONDUCTIVITY OF TITANIUM ALLOYS

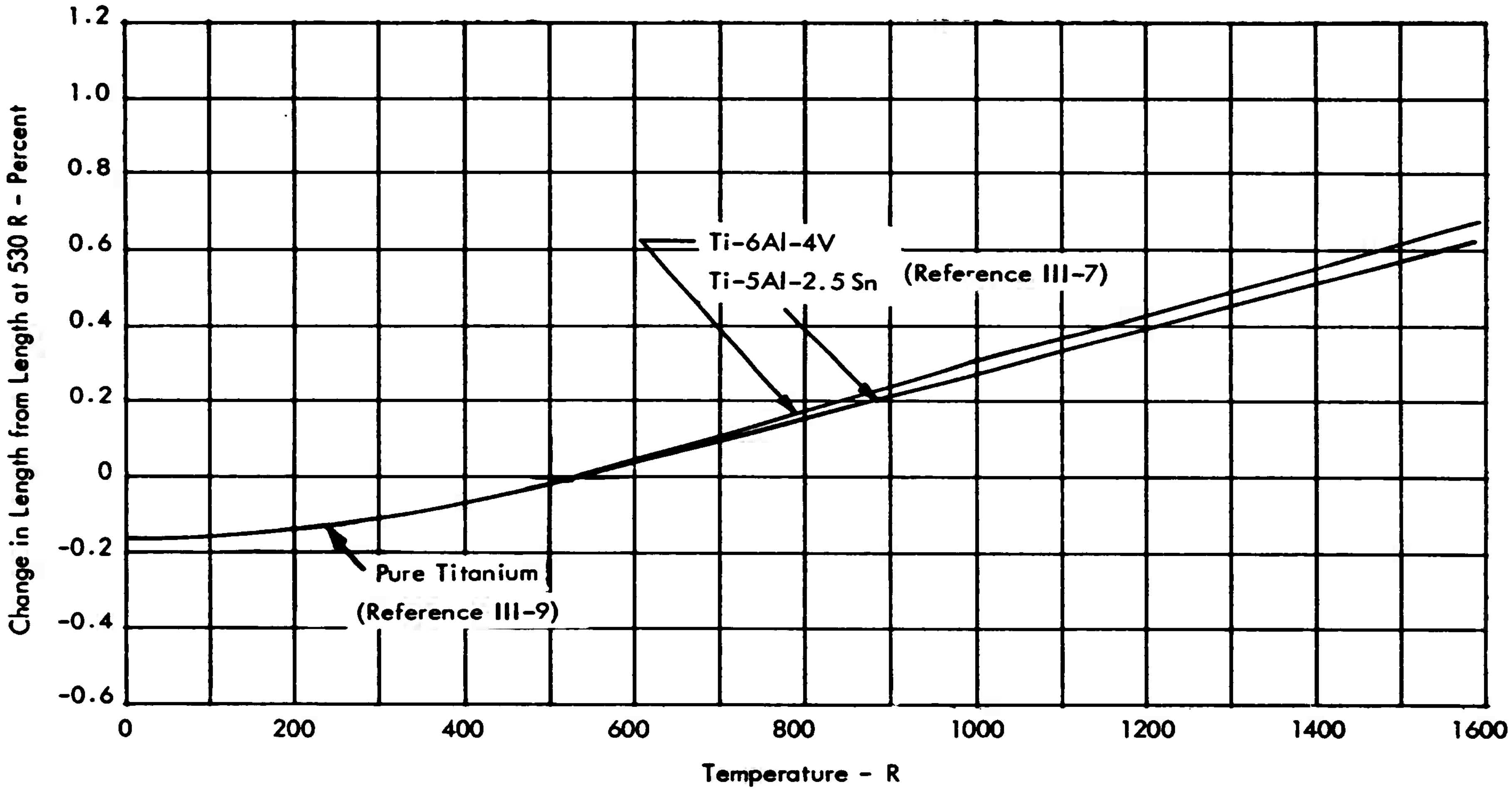

FIGURE III-20

LINEAR THERMAL EXPANSION OF TITANIUM ALLOYS

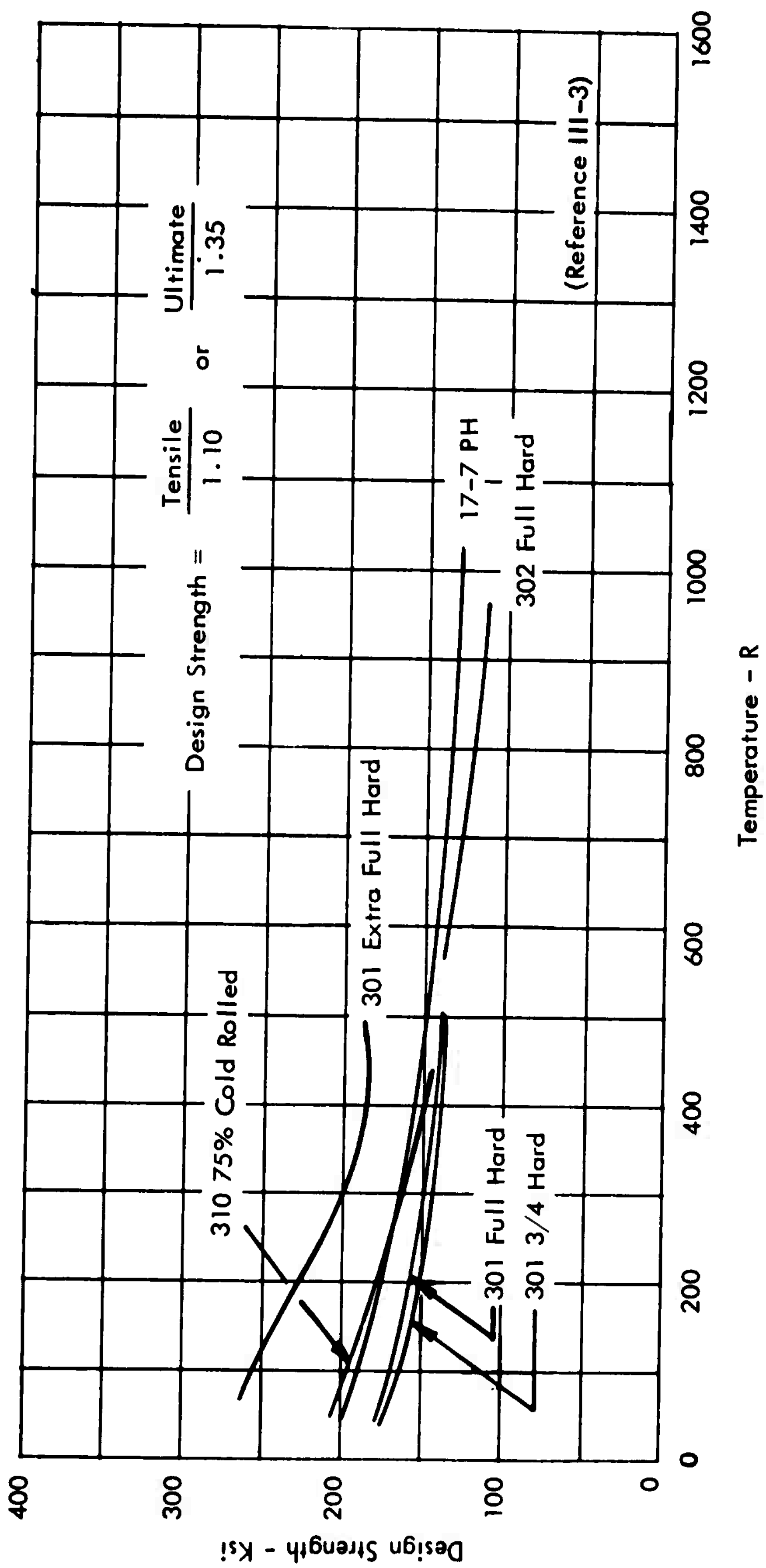

FIGURE III-21

DESIGN TENSILE STRENGTH OF STAINLESS STEELS

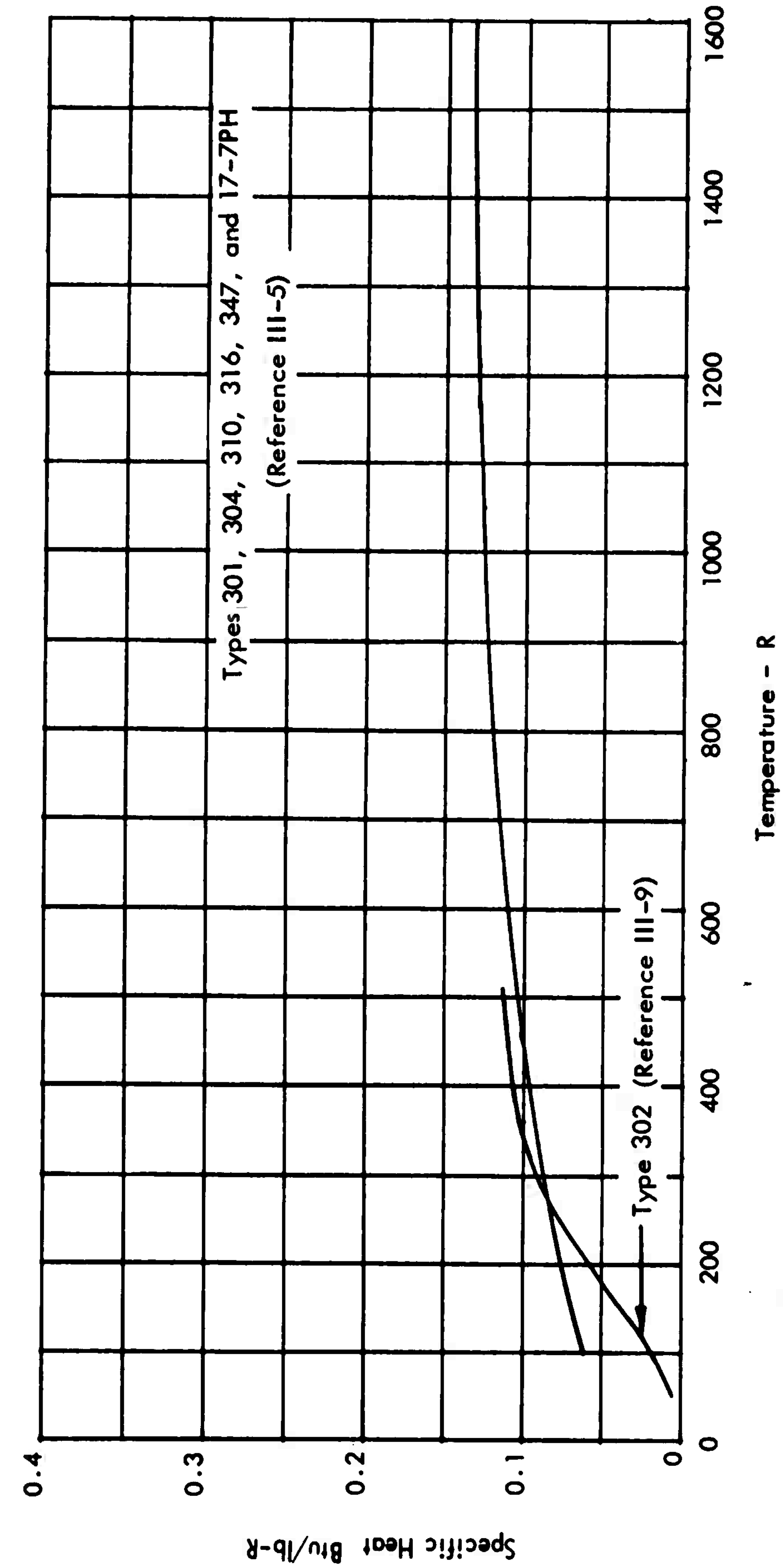

FIGURE III-22
SPECIFIC HEAT OF STAINLESS STEELS

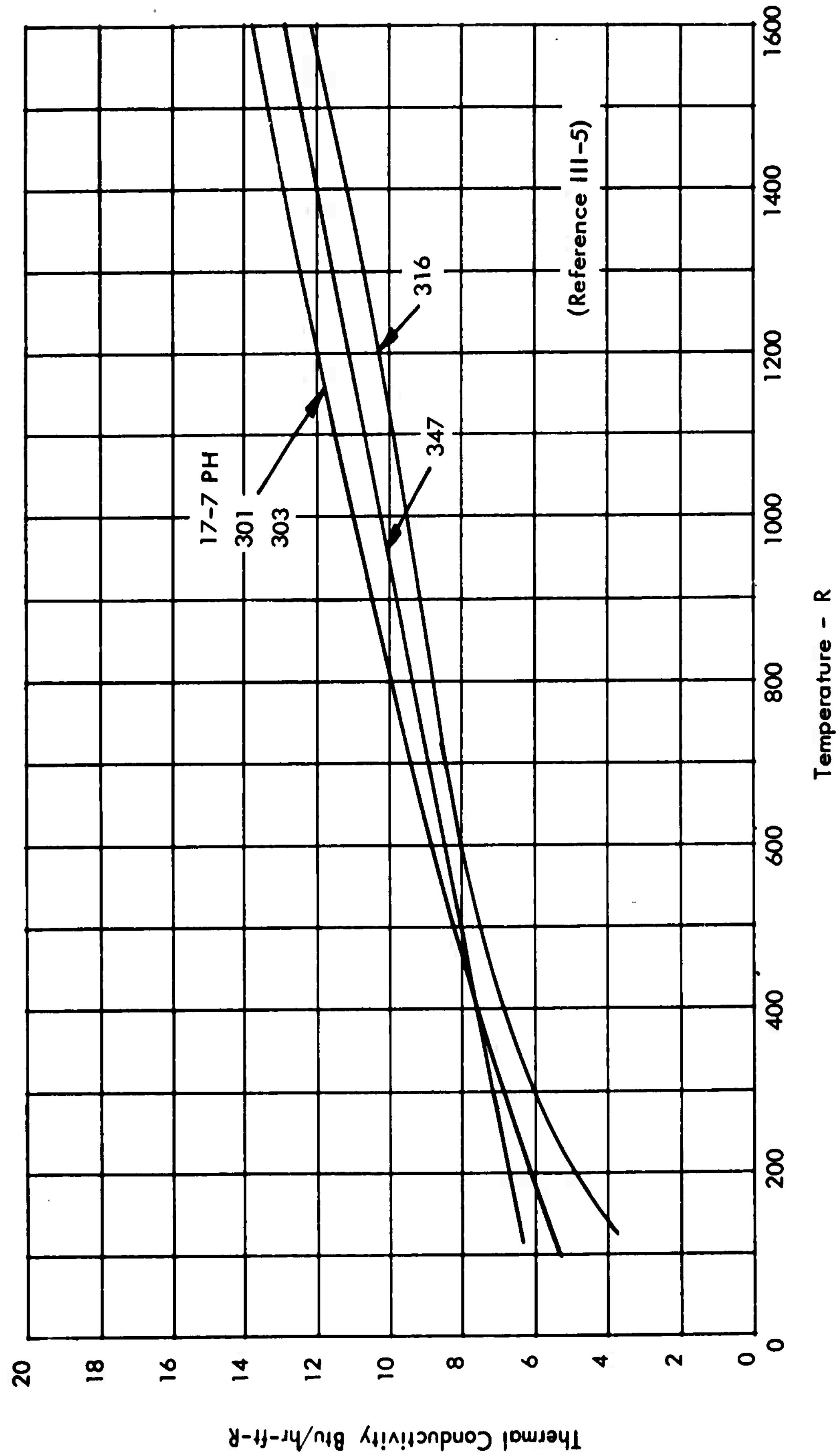

FIGURE III-23

THERMAL CONDUCTIVITY OF STAINLESS STEELS

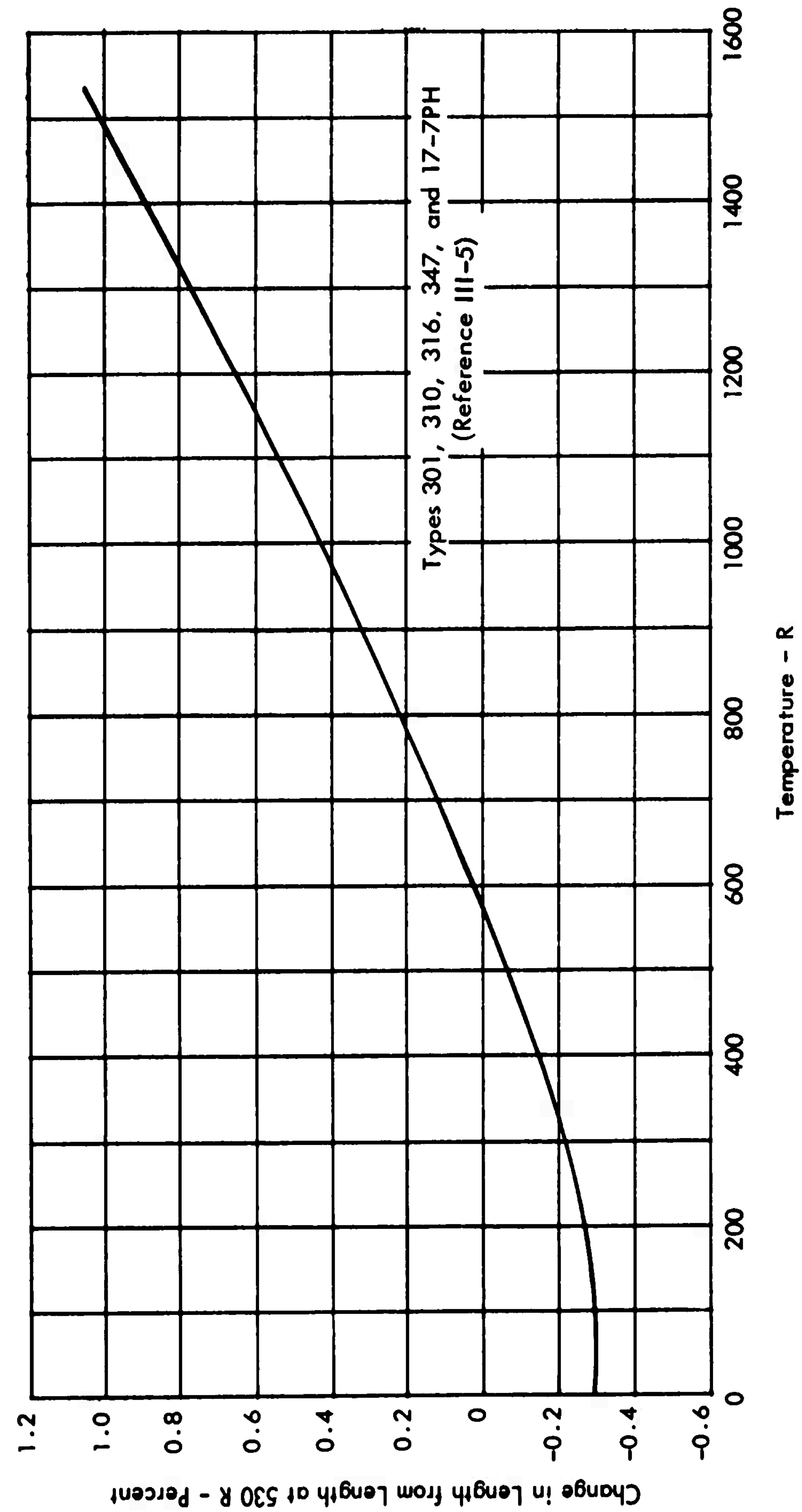

FIGURE III-24

LINEAR THERMAL EXPANSION OF STAINLESS STEELS

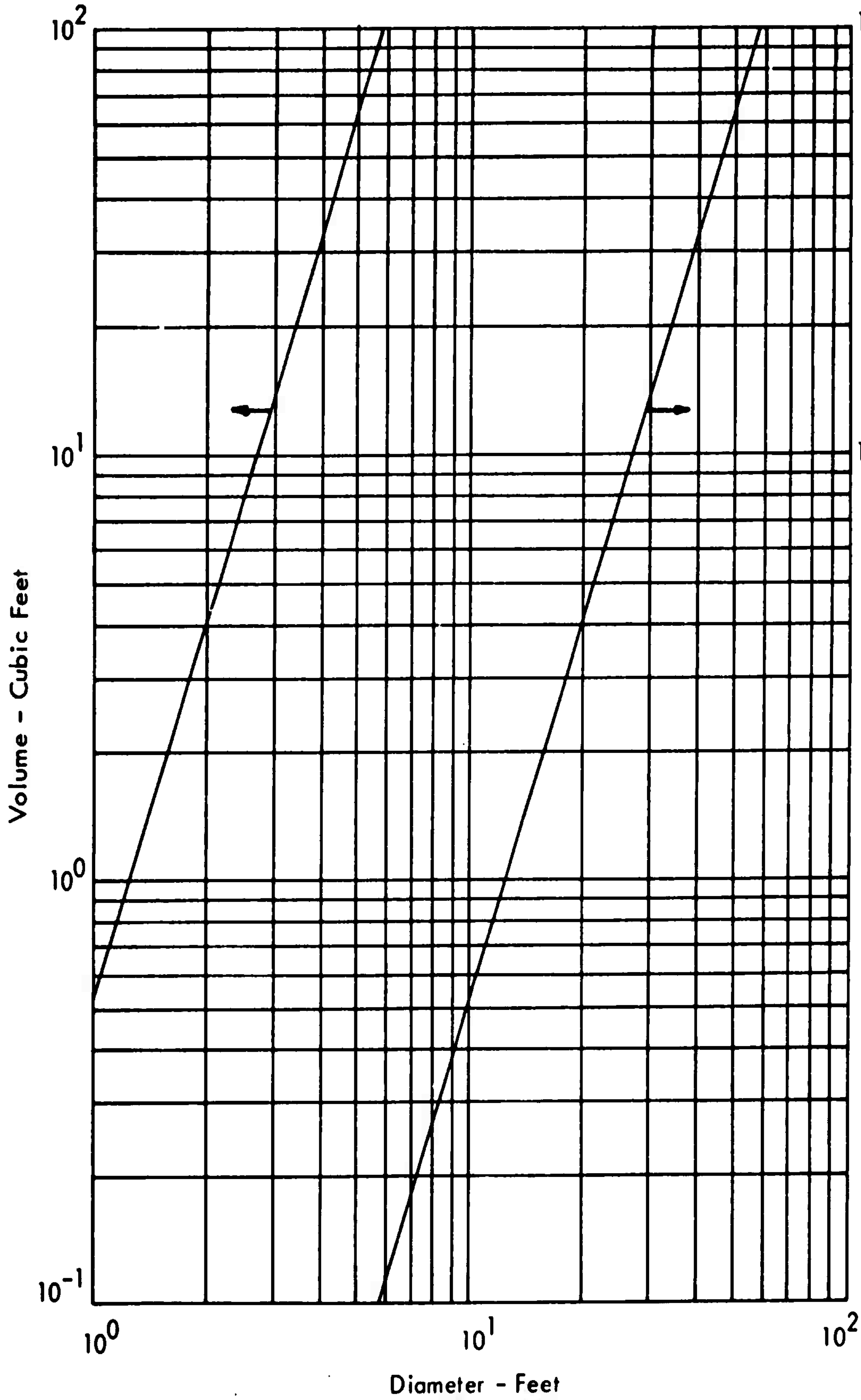

FIGURE III-25

SPHERICAL TANK VOLUME VS DIAMETER

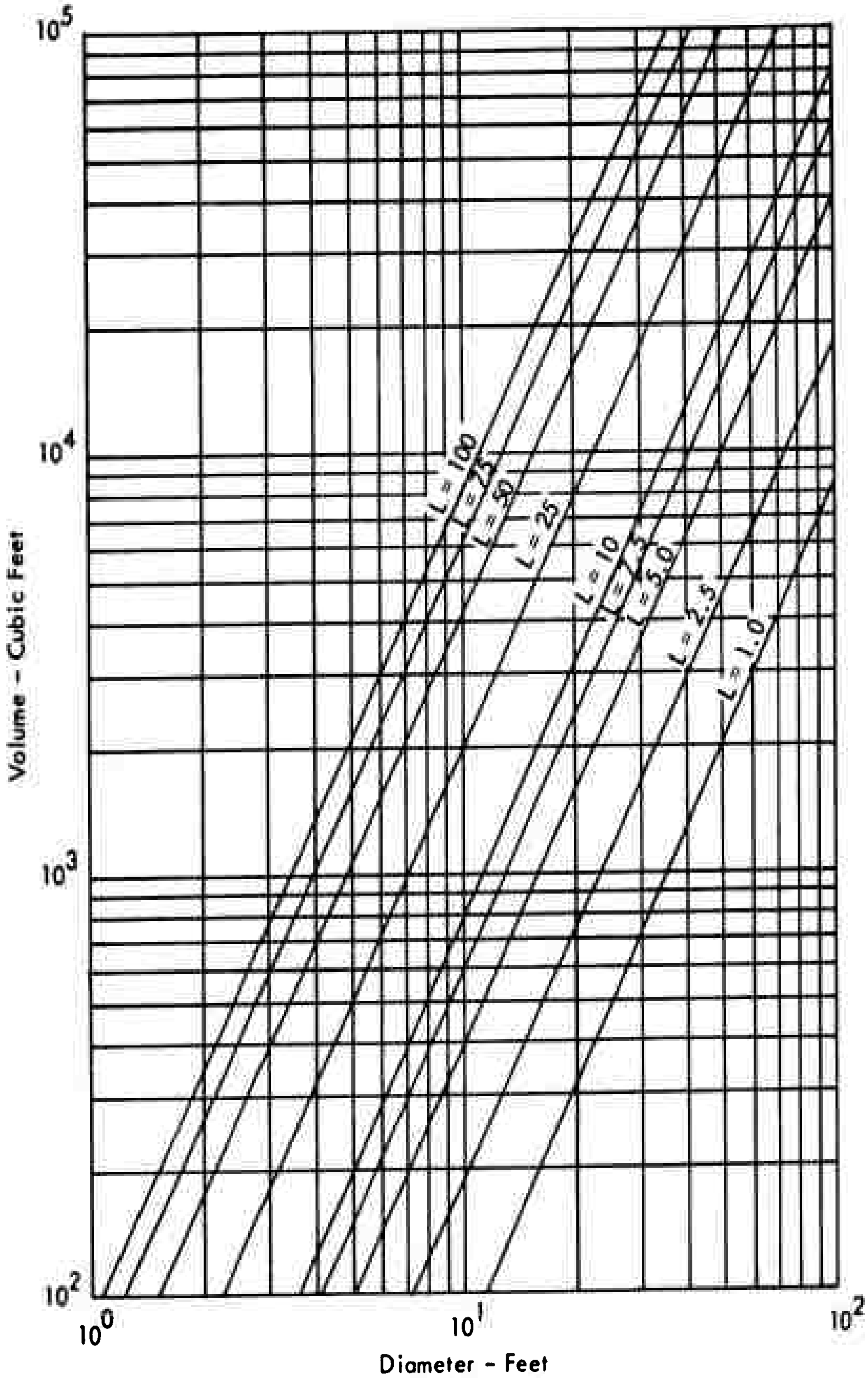

FIGURE III-26

CYLINDER VOLUME VS DIAMETER

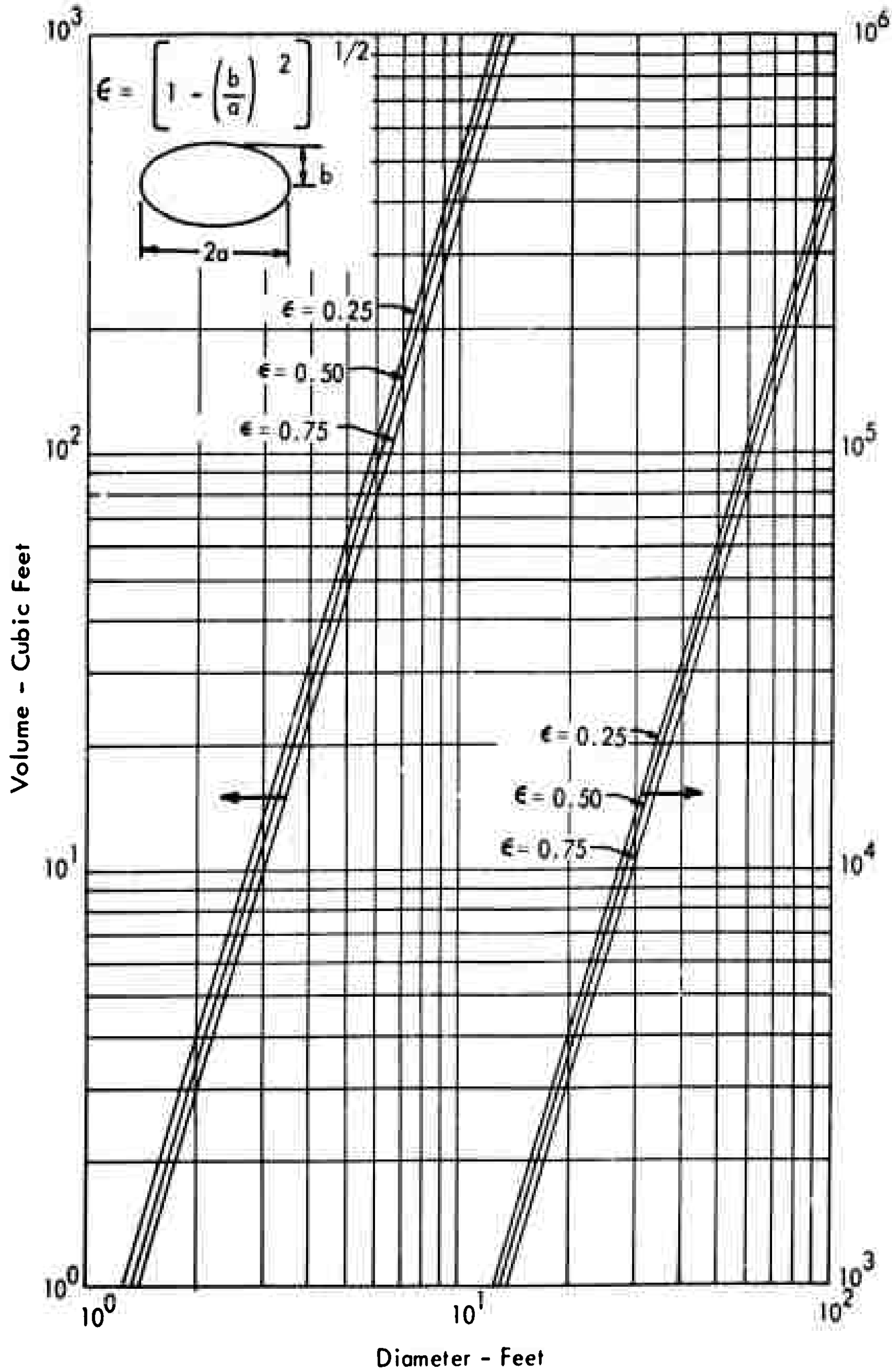

FIGURE III-27

OBLATE SPHEROID VOLUME VS DIAMETER

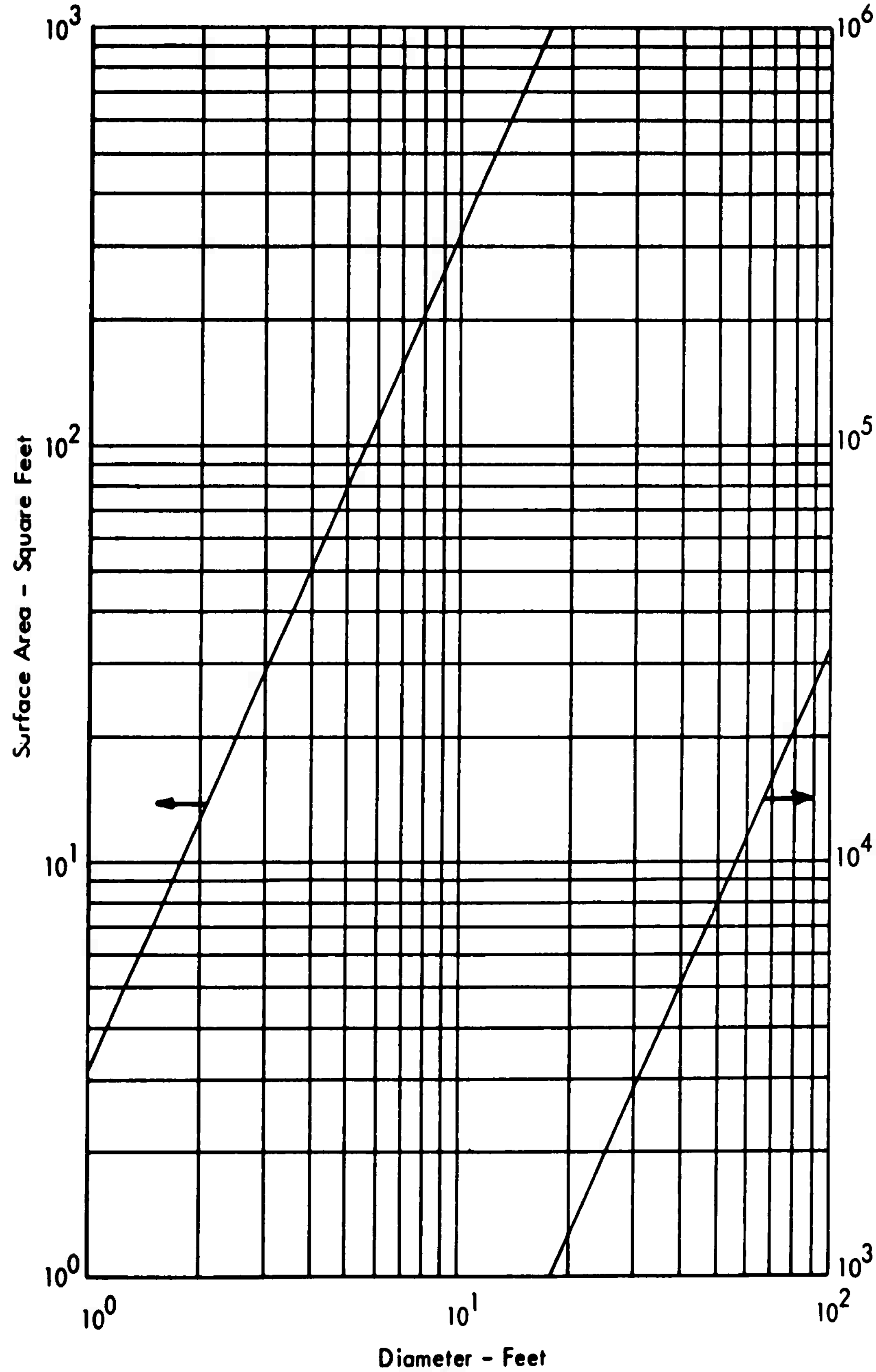

FIGURE III-28
SPHERICAL TANK SURFACE AREA VS DIAMETER

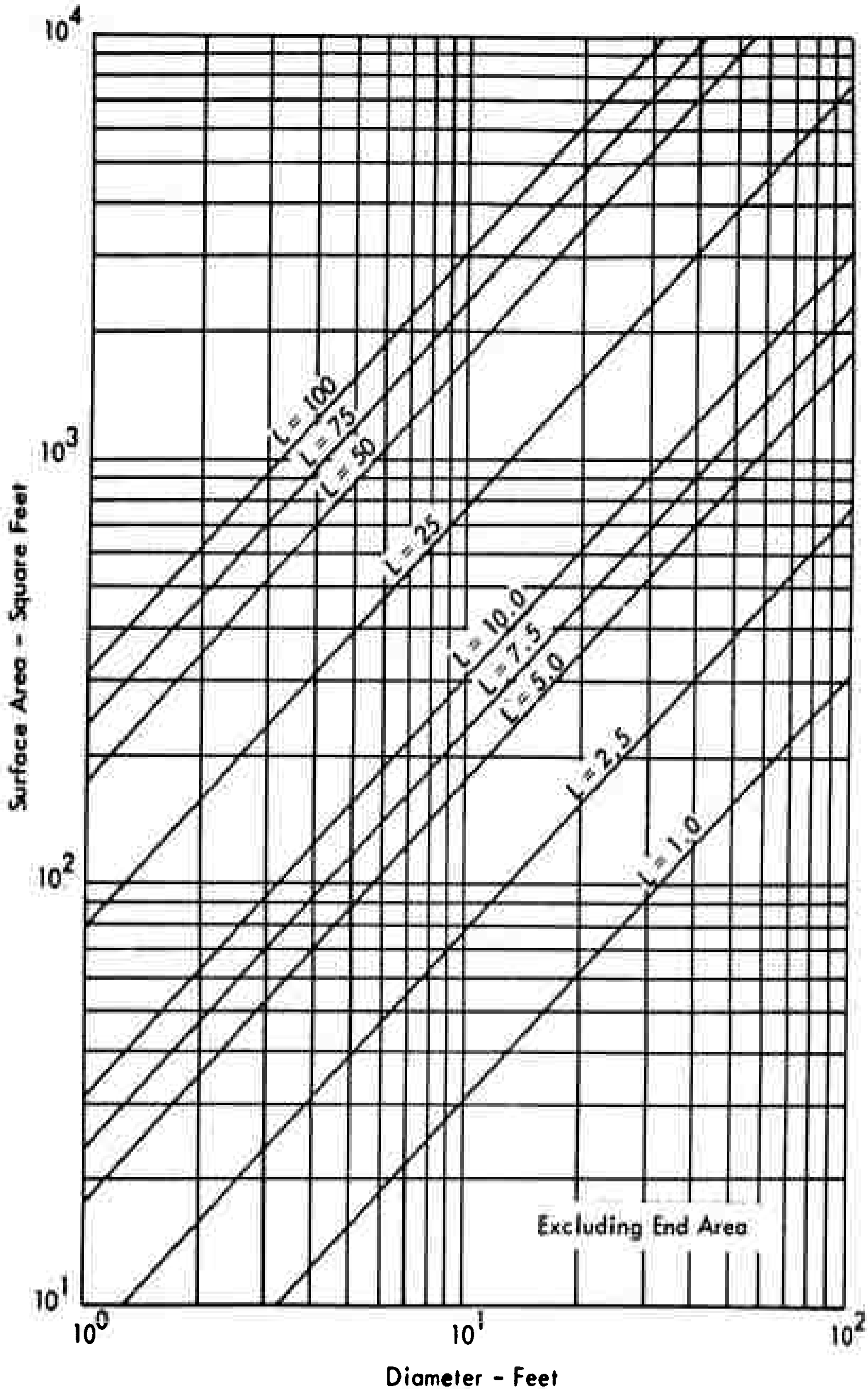

FIGURE III-29

CYLINDRICAL TANK SURFACE AREA VS DIAMETER

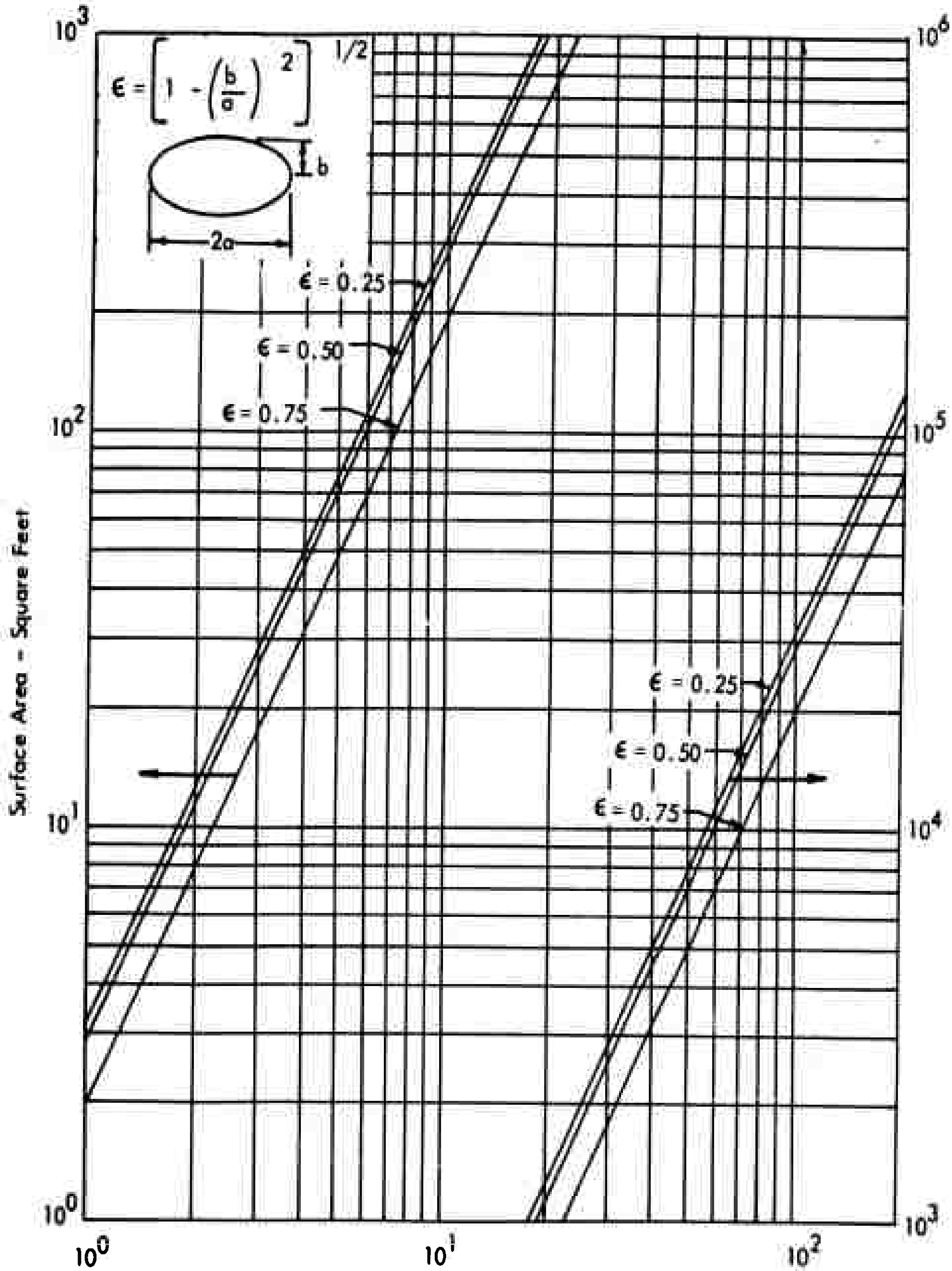

FIGURE III-30

SURFACE AREA OF OBLATE SPHEROID VS DIAMETER

COMPONENTS

Design information is presented herein for stored gas pressurization subsystems and for heat exchangers. Each of these components is amenable to handbook presentation, since (a) they contribute substantially to system weight and (b) the calculations involved can be laborious if full information is not available.

The other components of a pressurization system are primarily lines and valves. Initial line sizing can be based on low pressure drops by simply maintaining a flow Mach number of approximately 0.25, although a much more sophisticated optimization is required for a final design. Valve weights vary so much with size and functional requirements that little purpose would be served by presenting valve weight data. Manufacturers should be contacted for valve weight information.

Gas Storage

Figures III-31 and III-32 present gas storage system weight as a function of initial temperature. The curve for isentropic expansion, Figure III-31, gives higher weights than the isothermal expansion curve, Figure III-32, since isentropic expansion assumes no heat transfer from the bottle to the gas during blowdown. The gas therefore cools due to its expansion, and the residual gas weight is greater. The actual process is between the two, being nearly isentropic for fiberglass bottles, which give up heat slowly, and for large bottles, which have less heat transfer area per unit volume of gas. If it is desired to heat the gas in the bottles to maintain isothermal conditions during expansion, Figure III-33 shows the heat input rates that would be required.

The hooks in the curves of Figure III-31 at low storage temperatures are caused by deviations of the compressibility factor, Z, from unity as the gas approaches saturation.

Figures III-34 and III-35, which again are for isentropic and isothermal expansion respectively, may be used if it is desired to determine not only the total system weight, which is given by Figures III-31 and III-32, but also the weight contribution of the residual gas as opposed to the bottles.

As is noted on the curves, the weight of the fiberglass bottles is based on a working stress of 65,000 psi. This is the value used in the standard equation for the required thickness of a sphere,

$$t = \frac{PR}{2s}$$

where

t = thickness, in

P = pressure, psi

R = radius, in

s = stress, psi

The stress in the fiberglass strands themselves is twice as great, or 130,000 psi, assuming that the strands run in all different tangential directions, which is the optimum lay. The difference between the two values (65,000 and 130,000) is caused by the fact that the stresses in a sphere are biaxial but the strength of the strands is monaxial.

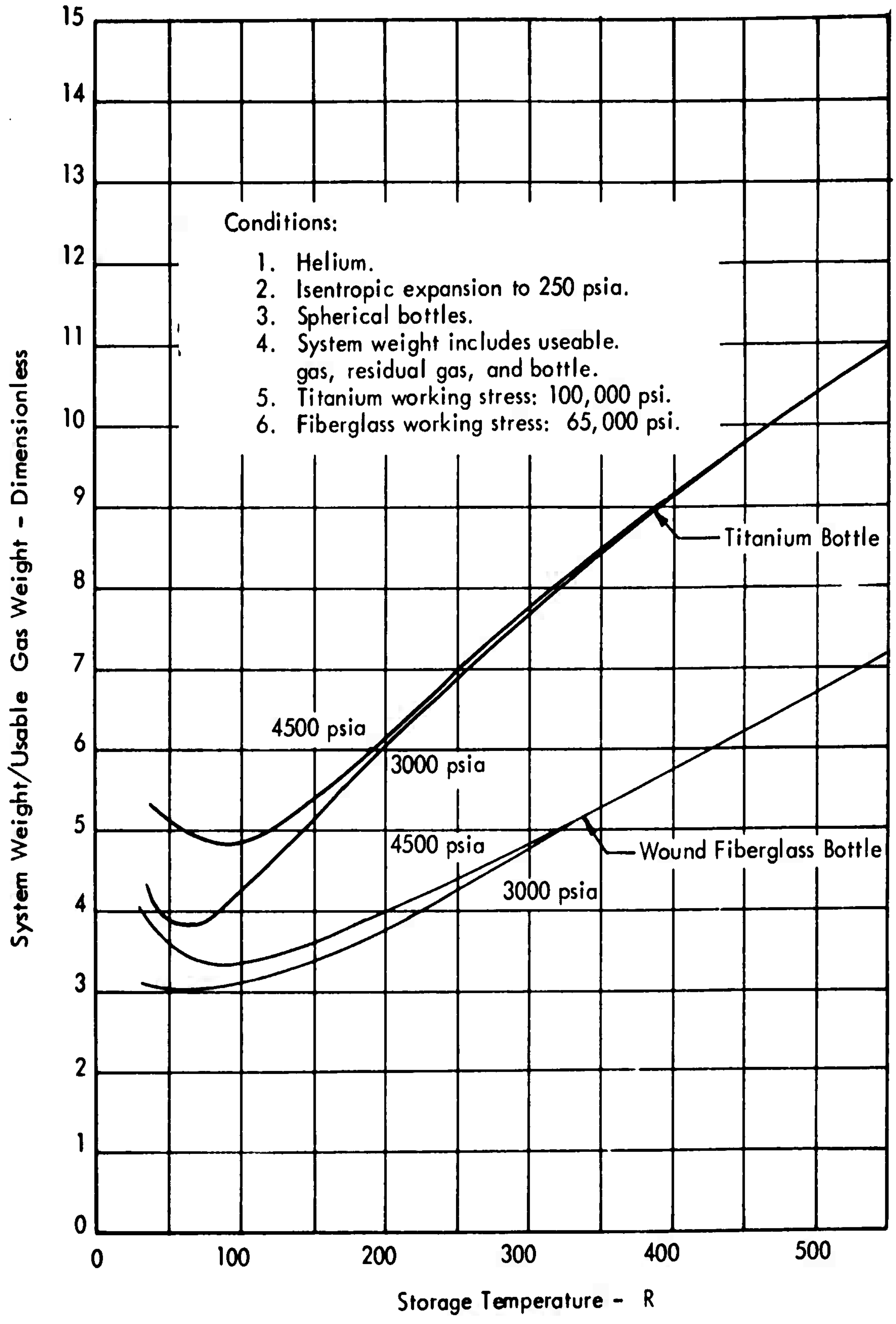

FIGURE III-31

SYSTEM WEIGHT - ISENTROPIC EXPANSION

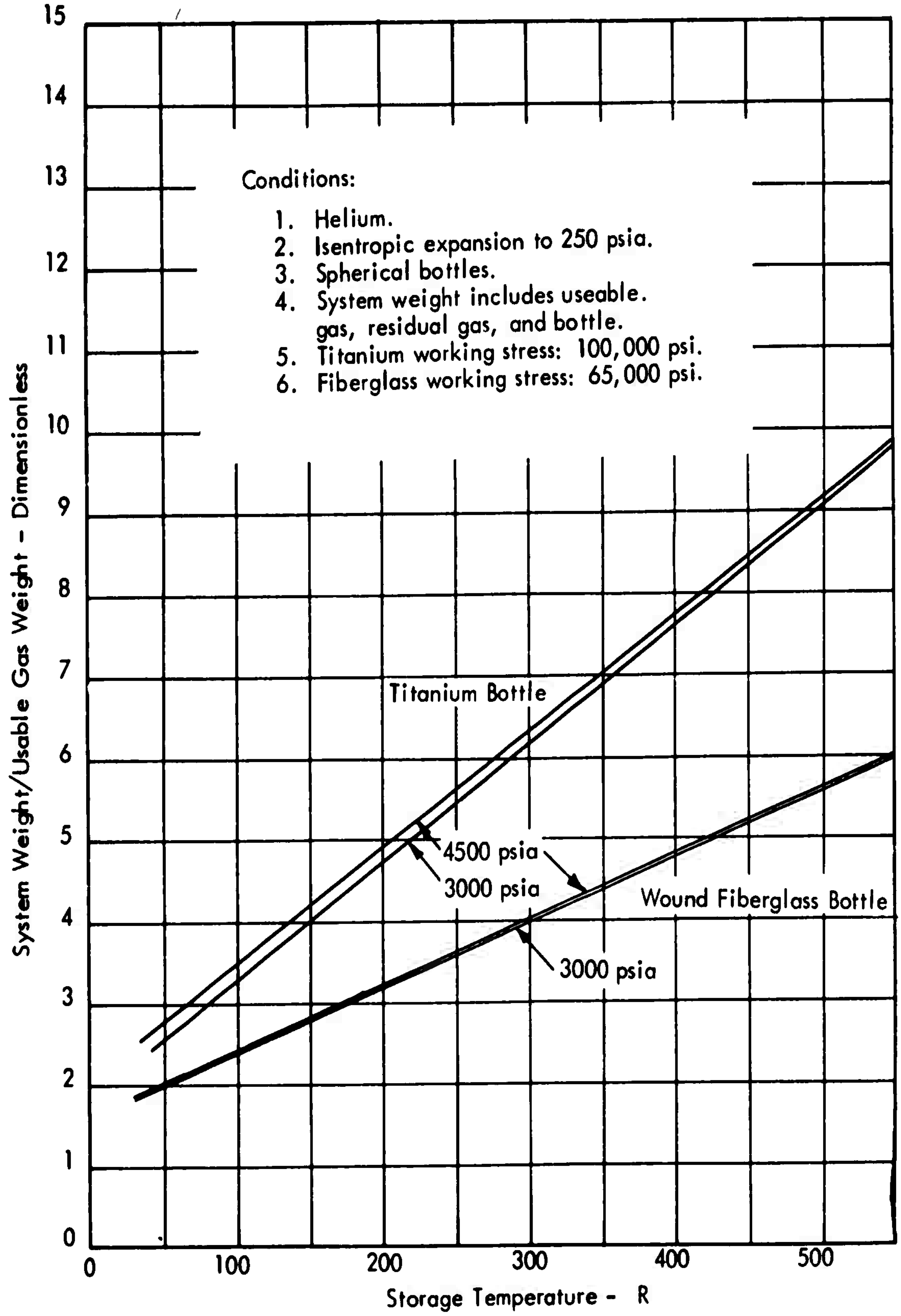

FIGURE III-32

SYSTEM WEIGHT - ISOTHERMAL EXPANSION

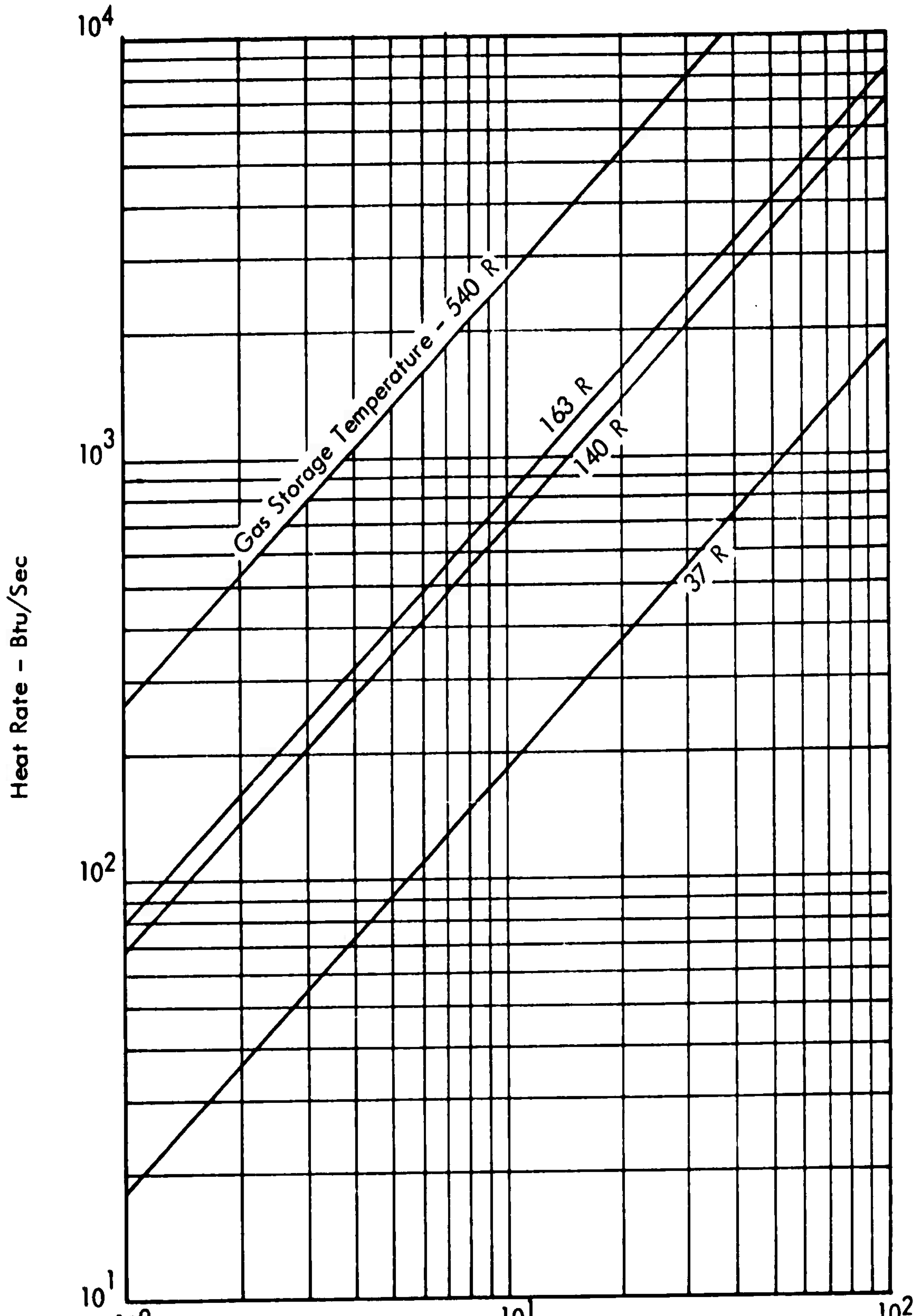

FIGURE III-33

HEAT RATE REQUIRED FOR ISOTHERMAL EXPANSION OF HELIUM

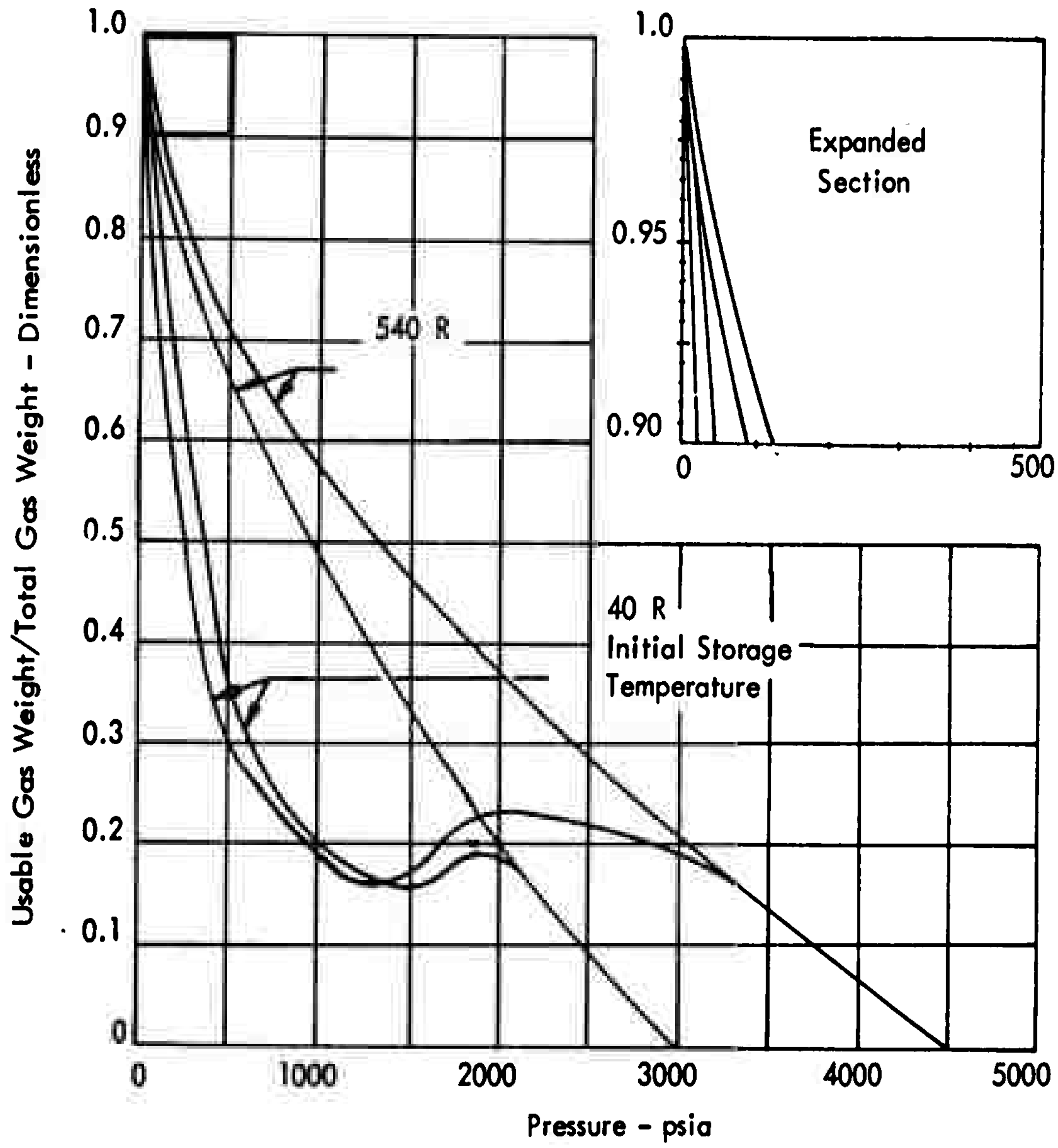

FIGURE III-34

HELIUM USABILITY - ISENTROPIC EXPANSION

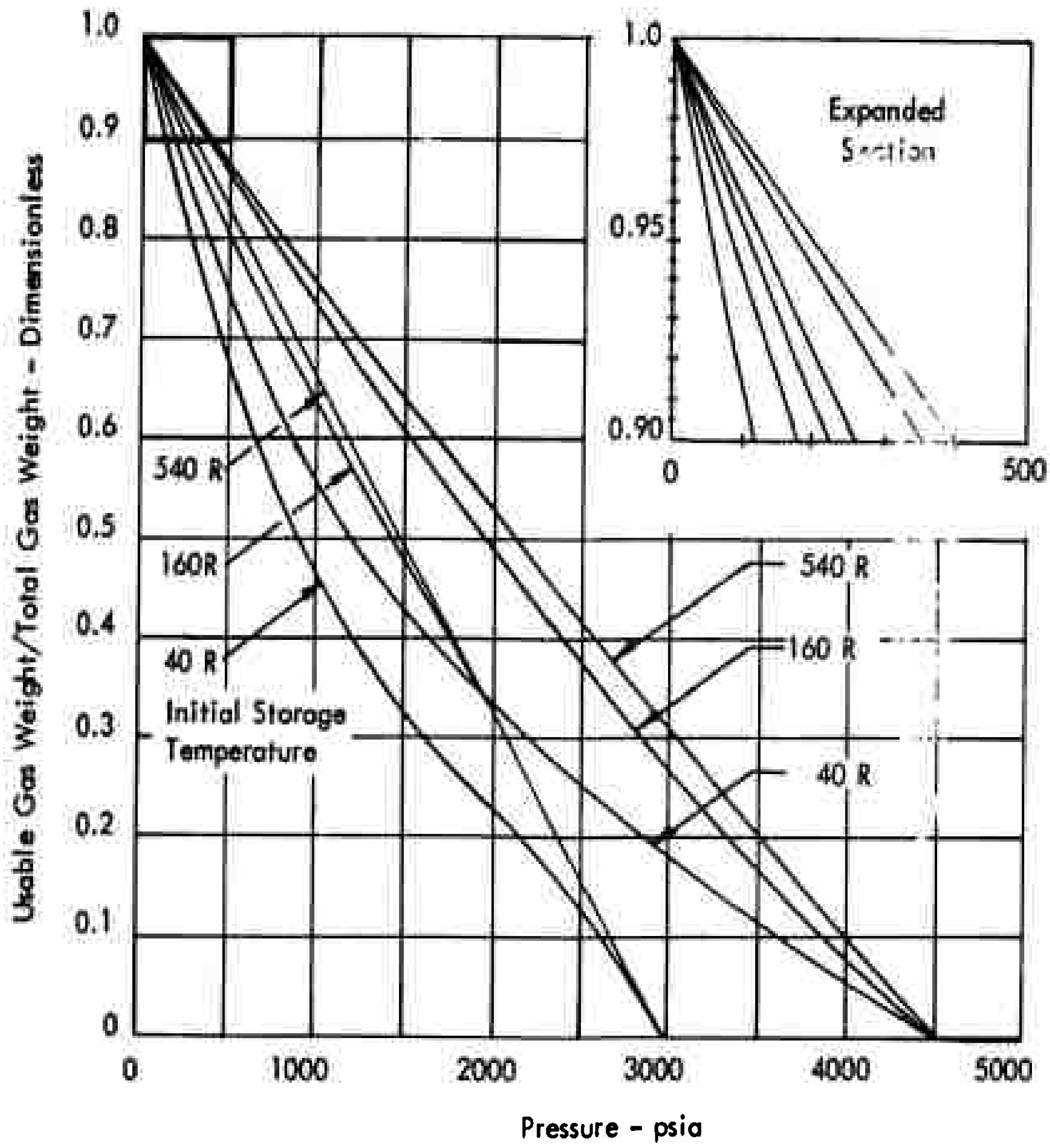

FIGURE III-35

HELIUM USABILITY - ISOTHERMAL EXPANSION

Heat Exchangers

General

The design of heat exchangers to meet a specified set of requirements is a tedious business, since there are so many variables which strongly influence the results. Simplifications such as the one presented herein are therefore of considerable value.

The approach used is an extension of that of Reference III-10. Curves of Stanton number and friction factor against Reynolds number, obtained from Reference III-11, are expressed mathematically and manipulated to obtain five core constants, which apply to a given type of surface with given fluids, regardless of the heat exchanger size and regardless of operating conditions, unless temperature has a substantial effect on fluid properties. The equations describing a specific heat exchanger in terms of its core constants and operating conditions are then solved to meet the specific requirements.

Maximum utility of this volume as a design handbook has been preserved by excluding the derivation of the heat exchanger equations, which runs to eight pages.

Applicability

The calculation method is applicable only to plate-fin heat exchangers, which are usually slightly smaller than the older tube-bundle types and of approximately the same weight.

The calculation method is applicable to any flow pass arrangement and to any fluids, as long as average fluid properties can be used in each of the two sides. It is not applicable, therefore, to heat exchangers involving change of phase of a fluid. In its present form it assumes that the type of heat transfer surface is the same in both the hot and cold sides, although the plate spacings and fin spacings may be different.

Approximations

Pressure losses in the core inlet, core exit, and headers have been neglected. Five percent of the core pressure drop should be allowed for such losses.

Fin effectivenesses of 90 percent for aluminum heat exchangers and 65 percent for steel heat exchangers can be assumed, especially if the fluids are gases. Actual values of both the non-core pressure losses and the fin effectivenesses should be checked after the heat exchanger is designed.

The core constant curves and the exponents a and i are based on average heat transfer and friction curves obtained from Reference III-11 for each of the three fin shapes — plain, louvered, and wavy. It is estimated that the error due to averaging is rarely more than ten percent of the heat exchanger weight.

The total heat exchanger weight, including headers and mounting provisions, is estimated to be approximately 50 percent more than the core weight.

Summary of Equations

The symbols used below are defined later, in the subsection on Nomenclature.

The following equations define the core constants:

C_1, hot-side heat transfer

$$C_1 = \frac{St_h \, Pr_h^{2/3}}{Re_h^{a}} \, 2^{1+a} \, 60^{a} \, \frac{c_{p_h}}{Pr_h^{2/3} \, \mu_h^{a}} \, \frac{(n_h b_h + 1)^{1-a} (b_h + b_c + 2d)^{a}}{b_h (1 - n_h \phi_h)} \qquad (1)$$

C_2, cold-side heat transfer

$$C_2 = \frac{St_c \; Pr_c^{2/3}}{Re_c^{\,a}} \; 2^{1+a} \; 60^a \; \frac{c_{p_c}}{Pr_c^{2/3} \mu_c^{\,a}} \; \frac{(n_c b_c + 1)^{1-a} (b_h + b_c + 2d)^a}{b_c (1 - n_c \phi_c)} \tag{2}$$

C_3, hot-side pressure drop

$$C_3 = \frac{f_h}{Re_h^{\,i}} \; \frac{120^i}{g} \; \frac{\mu_h^{-i} (n_h b_h + 1)^{1-i} (b_h + b_c + 2d)^{2+i}}{\left[b_n (1 - n_h \phi_h)\right]^3} \tag{3}$$

C_4, cold-side pressure drop

$$C_4 = \frac{f_c}{Re_c^{\,i}} \; \frac{120^i}{g} \; \frac{\mu_c^{-i} (n_c b_c + 1)^{1-i} (b_h + b_c + 2d)^{2+i}}{\left[b_c (1 - n_c \phi_c)\right]^3} \tag{4}$$

The above equations have already been solved and are plotted in Figures III-36 through III-41.

Exponents

Surface	Re	a	i
Plate-and-plain-fin	1500-10000	-0.20	-0.26
Plate-and-louvered-fin	1000-10000	-0.30	-0.25
Plate-and-wavy-fin	600-10000	-0.40	-0.43

C_5, weight

$$C_5 = \frac{\rho m}{b_h + b_c + 2d} (n_h \phi_h b_h + n_c \phi_c b_c + 2d) \tag{5}$$

The following equations and curves define the specific heat exchanger:

For any pass arrangement:

Effectiveness

$$\epsilon = \frac{C_h (t_{h_{in}} - t_{h_{out}})}{C_{min} (t_{h_{in}} - t_{c_{in}})} = \frac{C_c (t_{c_{out}} - t_{c_{in}})}{C_{min} (t_{h_{in}} - t_{c_{in}})} \tag{6}$$

NTU

$$NTU = \frac{UA}{C_{min}} \tag{7}$$

Effectiveness curves

Figures III-42, III-43, and III-44

Core weight

$$W = C_5 L_h L_c L_n \tag{8}$$

For multiple passes on hot side:

Length ratio

$$B = \left[\frac{\Delta P_c \, \rho_c}{\Delta P_h \, \rho_h} \left(\frac{N}{R} \right)^{2+i} \frac{C_3}{C_4} \; N \right]^{-\frac{1}{3+i}} \tag{9a}$$

UA

$$UA = \frac{C_1 C_2 (NRw_h)^{1+a} L_h^{1-a} L_n^{-a} \eta_h \, \eta_c}{C_1 N^{1+a} B \, \eta_n + C_2 R^{1+a} B^{-a} \eta_c} \tag{10a}$$

Hot-side Δ P

$$\Delta P_h = \frac{C_3 L_h N}{144 \rho_h} \left(\frac{w_h \quad N}{L_c \, L_n} \right)^{2+i} \tag{11a}$$

Cold-side ΔP

$$\Delta P_c = \frac{C_4 L_c}{144 \rho_c} \left(\frac{w_c}{L_h \, L_n} \right)^{2+i} \tag{12a}$$

For multiple passes on cold side:

Length ratio

$$B = \left[\frac{\Delta P_c \;\; \rho_c}{\Delta P_h \;\; \rho_h} \left(\frac{1}{N\,R} \right)^{2+i} \frac{C_3}{C_4} \;\; \frac{1}{N} \right]^{-\frac{1}{3+i}} \tag{9b}$$

UA

$$UA = \frac{C_1 C_2 \, (NRw_h)^{1+a} L_h^{\;1-a} L_n^{\;-a} \; \eta_h \; \eta_c}{C_1 \, B \, \eta_h + C_2 \, (RN)^{1+a} B^{-a} \, \eta_c} \tag{10b}$$

Hot-side ΔP

$$\Delta P_h = \frac{C_3 L_h}{144 \rho_h} \left(\frac{w_h}{L_c \, L_n} \right)^{2+i} \tag{11b}$$

Cold-side ΔP

$$\Delta P_c = \frac{C_4 L_c N}{144 \rho_c} \left(\frac{w_c N}{L_h L_n}\right)^{2+i} \tag{12b}$$

Selection Of Heat Transfer Surface

The problem statement is much more important than the type of surface in designing a heat exchanger. There are, however, significant differences between plain, louvered, and wavy fins. Both heat transfer coefficient and friction factor increase markedly from plain to louvered to wavy. Wavy is the most common in aerospace work, but one of the others might be more desirable in some cases, especially if pressure drop is more important than weight.

Reducing the fin spacing results in a more compact heat exchanger, although a relatively open spacing may be better if pressure drop is critical. Fin spacings of 20 or perhaps 25 per inch are as close as it is practical to manufacture.

Plate spacing usually has little effect on heat exchanger performance. Spacing of 0,25 to 0.50 inches are most common for gases, but liquids require closer spacing.

Sample Problem

Given:

Aluminum heat exchanger, wavy fins, air-to-air

Hot side:

3 passes (N = 3)

b_h = 3/8 in. = 0.0312 ft

n_h = 160 fins/ft

w_h = 60 lb/min

$t_{h_{in}}$ = 450F

$t_{h_{out}}$ = 72F

ΔP_h = 1.00 psi

P_{avg} = 32.5 psia

Cold side:

1 pass

b_c = 3/8 in. = 0.0312 ft

n_c = 120 fins/ft

w_c = 75 lb/min

$t_{c_{in}}$ = 4F

ΔP_c = 0.50 psi

P_{avg} = 2.69 psia

Fluid properties:

$$t_{h_{avg}} = \frac{450+72}{2} = 261F$$

$$t_{c_{out}} = t_{c_{in}} + \frac{w_h}{w_c}\left(t_{h_{in}} - t_{h_{out}}\right) = 306F$$

$$t_{c_{avg}} = \frac{4+306}{2} = 155F$$

$$\rho_h = 0.07651\ \frac{32.5}{14.7}\ \frac{460+60}{460+261} = 0.1220\ lb/ft^3$$

$$\rho_c = 0.07651\ \frac{2.69}{14.7}\ \frac{460+60}{460+155} = 0.01184\ lb/ft^3$$

μ_h = 0.0555 lb/hr-ft

$\mu_c = 0.0493$ lb/hr-ft

$Pr_h = 0.68$

$Pr_c = 0.69$

$c_{p_h} = 0.24$ Btu/lb-F

$c_{p_c} = 0.24$ Btu/lb-F

Exponential terms:

For wavy fins, a = -0.40, i = -0.43

$$\mu_h^{\,a} = 0.0555^{-0.40} = 3.180$$

$$\mu_c^{\,a} = 0.0493^{-0.40} = 3.340$$

$$\mu_h^{\,-i} = 0.0555^{0.43} = 0.2880$$

$$\mu_c^{\,-i} = 0.0493^{0.43} = 0.2740$$

$$Pr_h^{\,2/3} = 0.68^{2/3} = 0.773$$

$$Pr_c^{\,2/3} = 0.69^{2/3} = 0.781$$

Core constant curves:

From Figure III-38 at $n_h = 160$ fins/ft ,

$$C_1 \frac{Pr_h^{\,2/3} \; \mu_h^{\,a}}{c_{p_h}} = 83$$

At $n_c = 120$ fins/ft ,

$$C_2 \frac{Pr_c^{\,2/3} \; \mu_c^{\,a}}{c_{p_c}} = 58$$

From Figure III-41 at n_h = 160 fins/ft, b for side under consideration

= b_h = 0.0312 ft, b for other side = b_c = 0.0312 ft ,

$$\frac{C_3}{\mu_h^{-i}} = 0.0115$$

At n_c = 120 fins/ft , b for side under consideration = b_c = 0.0312 ft ,

b for other side = b_h = 0.0312 ft,

$$\frac{C_4}{\mu_c^{-i}} = 0.0075$$

Core constants:

$$C_1 = \frac{83 \times 0.24}{0.773 \times 3.180} = 8.10$$

$$C_2 = \frac{58 \times 0.24}{0.781 \times 3.340} = 5.34$$

$$C_3 = 0.0115 \times 0.2880 = 0.003314$$

$$C_4 = 0.0075 \times 0.2740 = 0.002055$$

Effectiveness, NTU, and UA:

$$\epsilon = \frac{C_h\,(t_{h_{in}} - t_{h_{out}})}{C_{min}\,(t_{h_{in}} - t_{c_{in}})} = 0.847$$

$$\frac{C_{min}}{C_{max}} = \frac{60 \times 0.24}{75 \times 0.24} = 0.800$$

From Figures III-43 and III-44, NTU = 4.3

$$UA = NTU \times C_{min} = 4.3 \times 60 \times 0.24 = 61.9 \text{ Btu/min-F}$$

Core size:

$$R = \frac{75}{60} = 1.25$$

$$B = \left[\frac{0.50 \times 0.01184}{1.00 \times 0.1220} \left(\frac{3}{1.25}\right)^{2-0.43} \frac{0.003314}{0.002055} \times 3\right]^{-\frac{1}{3-0.43}} \qquad (9a)$$

$$= (0.0485 \times 2.400^{1.57} \times 4.84)^{-0.3892}$$

$$= 1.0295$$

$\eta_h = 0.90$, $\eta_c = 0.90$

$$61.9 = \frac{8.10 \times 5.34 (3 \times 1.25 \times 60)^{1-0.40} L_h^{1+0.40} L_n^{0.40} \times 0.90 \times 0.90}{8.10 \times 3^{1-0.40} \times 1.0295 \times 0.90 + 5{,}34 \times 1.25 \times 1.25^{1-0.40} \times 1.0295^{0.40} \times 0.90} \qquad (9b)$$

$$= \frac{35.00 \times 225^{0.60} L_h^{1.40} L_n^{0.40}}{7.50 \times 3^{0.60} + 4.80 \times 1.25^{0.60} \times 1.0295^{0.40}}$$

$$L_h^{1.40} L_n^{0.40} = 1.378$$

The above equation defines a series of heat exchangers which meet the heat transfer requirements and have the prescribed ratio of hot-side to cold-side pressure drop. The final size is found by assuming L_h or L_n , calculating ΔP from Equation (11a) or (12a), and checking the calculated ΔP against the required ΔP.

Assume $L_n = 1.55$ ft

$$L_h = \left(\frac{1.378}{1.55^{0.40}}\right)^{\frac{1}{1.40}} = 1.1098 \text{ ft}$$

$$L_c = \frac{L_h}{B} = \frac{1.1098}{1.0295} = 1.078 \text{ ft}$$

$$\Delta P_h = \frac{0.003314 \times 1.1098 \times 3}{144 \times 0.1220} \left(\frac{60 \times 3}{1.078 \times 1.55}\right)^{2-0.43} \qquad (11a)$$

$$= 0.000627 \times 107.9^{1.57} = 0.977 \text{ psi}$$

This is close enough to the required value of 1.00 psi.

Typical fin and plate thicknesses for use in weight calculations are 0.006 and 0.012 inches respectively. Thus $\emptyset = 0.0005$ ft and d = 0.0010 ft. The density of aluminum, ρ_m, is 175 lb/ft^3.

$$C_5 = \frac{175(160 \times 0.0005 \times 0.0312 + 120 \times 0.0005 \times 0.0312 + 2 \times 0.0010)}{0.0312 + 0.0312 + 2 \times 0.0010} \qquad (5)$$

$$= 17.30 \text{ lb/ft}^3$$

$$W = 17.30 \times 1.1098 \times 1.078 \times 1.55 = 32.07 \text{ lb} \qquad (8)$$

Nomenclature

a	Slope of curve of St $Pr^{2/3}$ vs Re on log-log paper
B	L_h/L_c, dimensionless
b	Plate spacing, ft

C	Flow stream capacity rate, wc_p , Btu/min-F
C_{max}	C_h or C_c , whichever is greater
C_{min}	C_h or C_c , whichever is less
C_1 through C_5 - Core constants	
c_p	Specific heat of fluid, Btu/lb-F
d	Plate thickness, ft
f	Fanning friction factor, dimensionless
g	Acceleration due to gravity, ft/min^2 (= 115,800)
i	Slope of curve of Fanning friction factor vs Re on log-log paper
L	Length, ft (See Figure III-45 for application to multi-pass heat exchanger)
N	Number of passes
NTU	Number of heat transfer units, dimensionless
n	Number of fins per foot
ΔP	Pressure drop, psi
Pr	Prandtl number, dimensionless
R	w_c/w_h , dimensionless
Re	Reynolds number, dimensionless
St	Stanton number, dimensionless
t	Temperature, F
UA	Overall conductance, Btu/min-F
W	Weight, lb
w	Flow rate, lb/min
ϵ	Heat transfer effectiveness, dimensionless

η	Overall fin effectiveness, including plate area, dimensionless
μ	Viscosity, lb/hr-ft
ρ	Density, lb/ft^3
ϕ	Fin thickness, ft

Subscripts:

c	Cold-side
h	Hot-side
m	Metal
n	No-flow

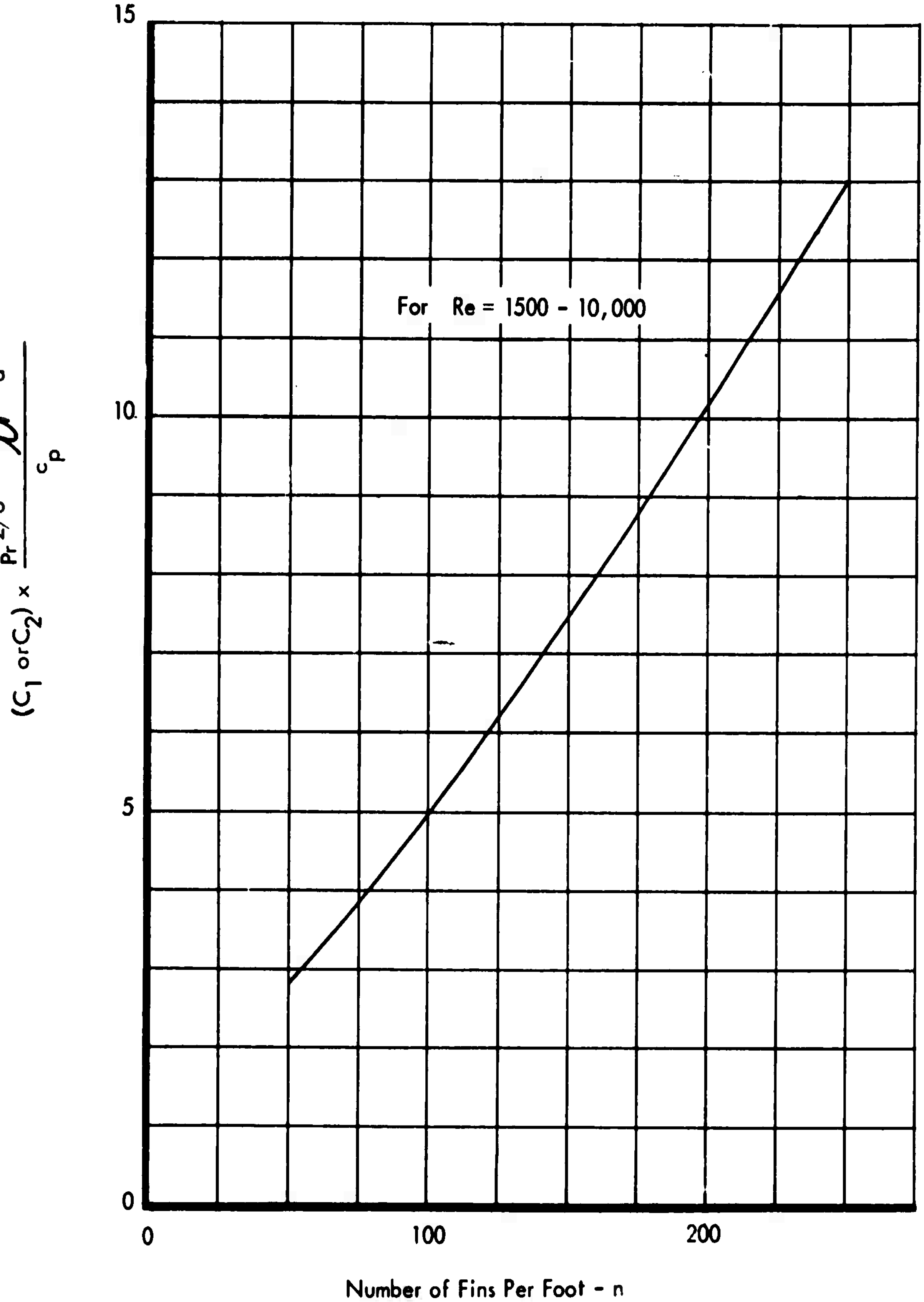

FIGURE III-36

CORE CONSTANTS C_1 AND C_2 -

PLATE-AND-PLAIN-FIN

HEAT TRANSFER SURFACES

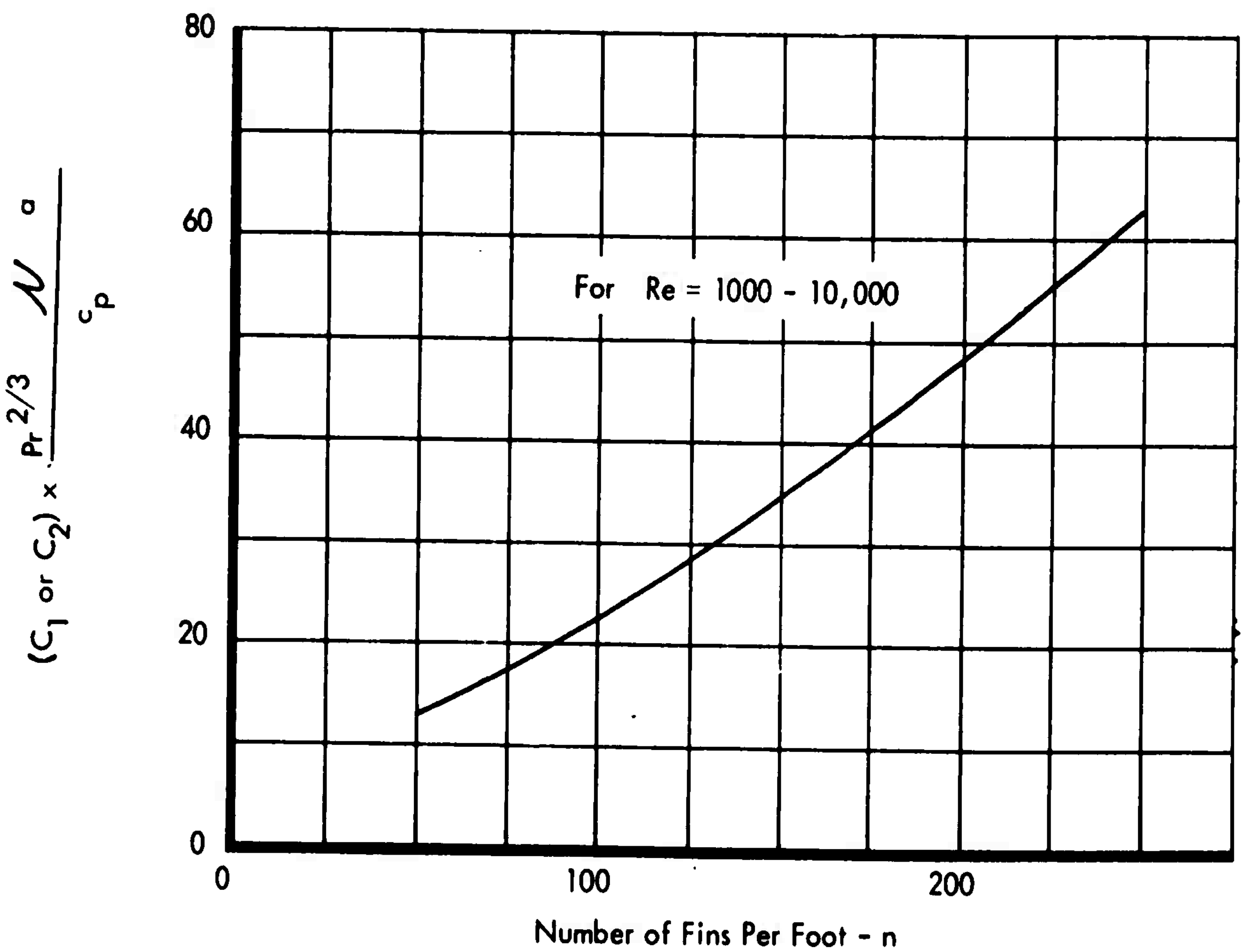

FIGURE III-37

CORE CONSTANTS C_i AND C_2 -

PLATE-AND-LOUVERED-FIN

HEAT TRANSFER SURFACES

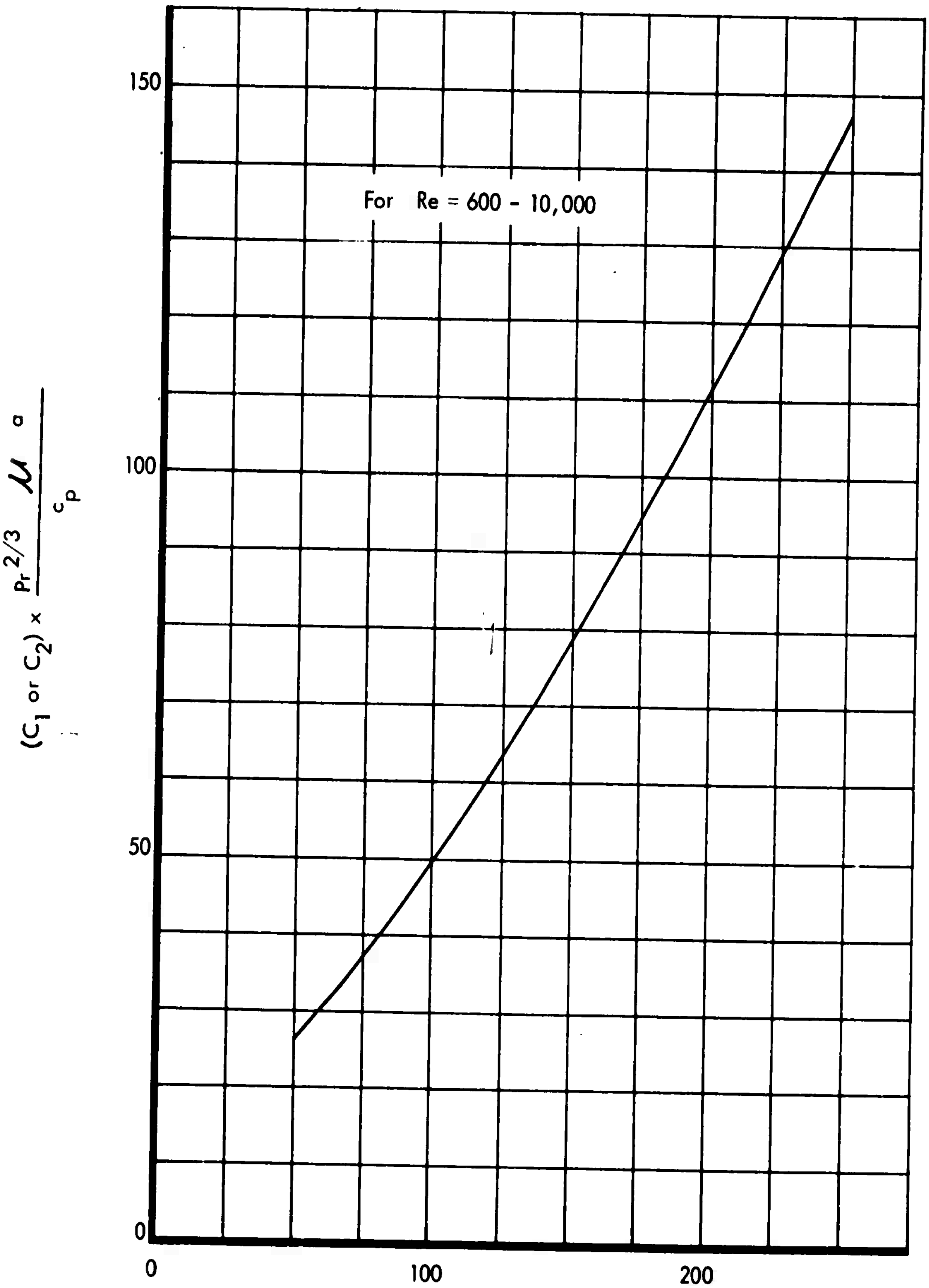

FIGURE III-38

CORE CONSTANTS C_1 AND C_2 -

PLATE-AND-WAVY-FIN

HEAT TRANSFER SURFACES

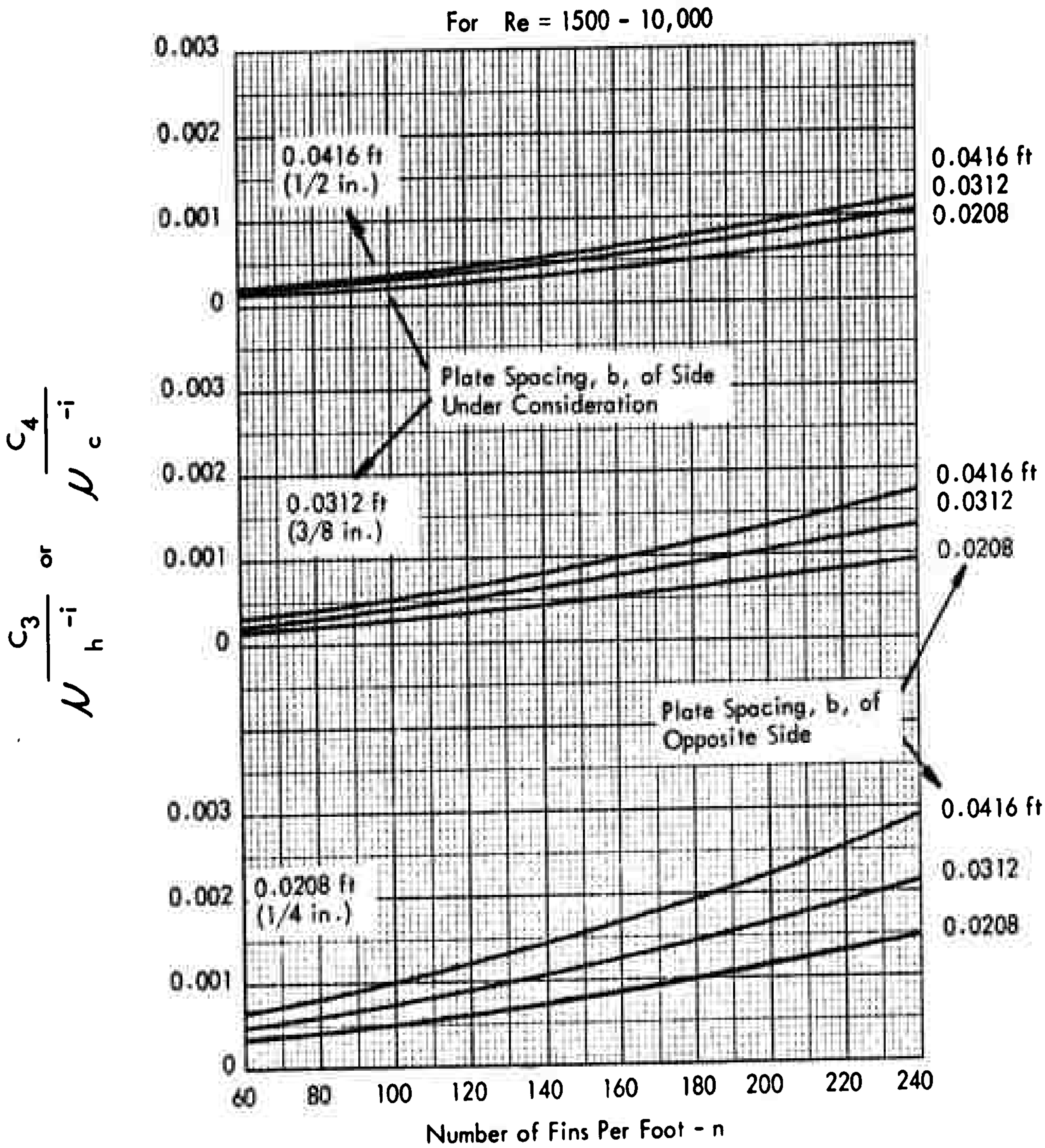

FIGURE III-39

CORE CONSTANTS C_3 AND C_4 -
PLATE-AND-PLAIN-FIN
HEAT TRANSFER SURFACES

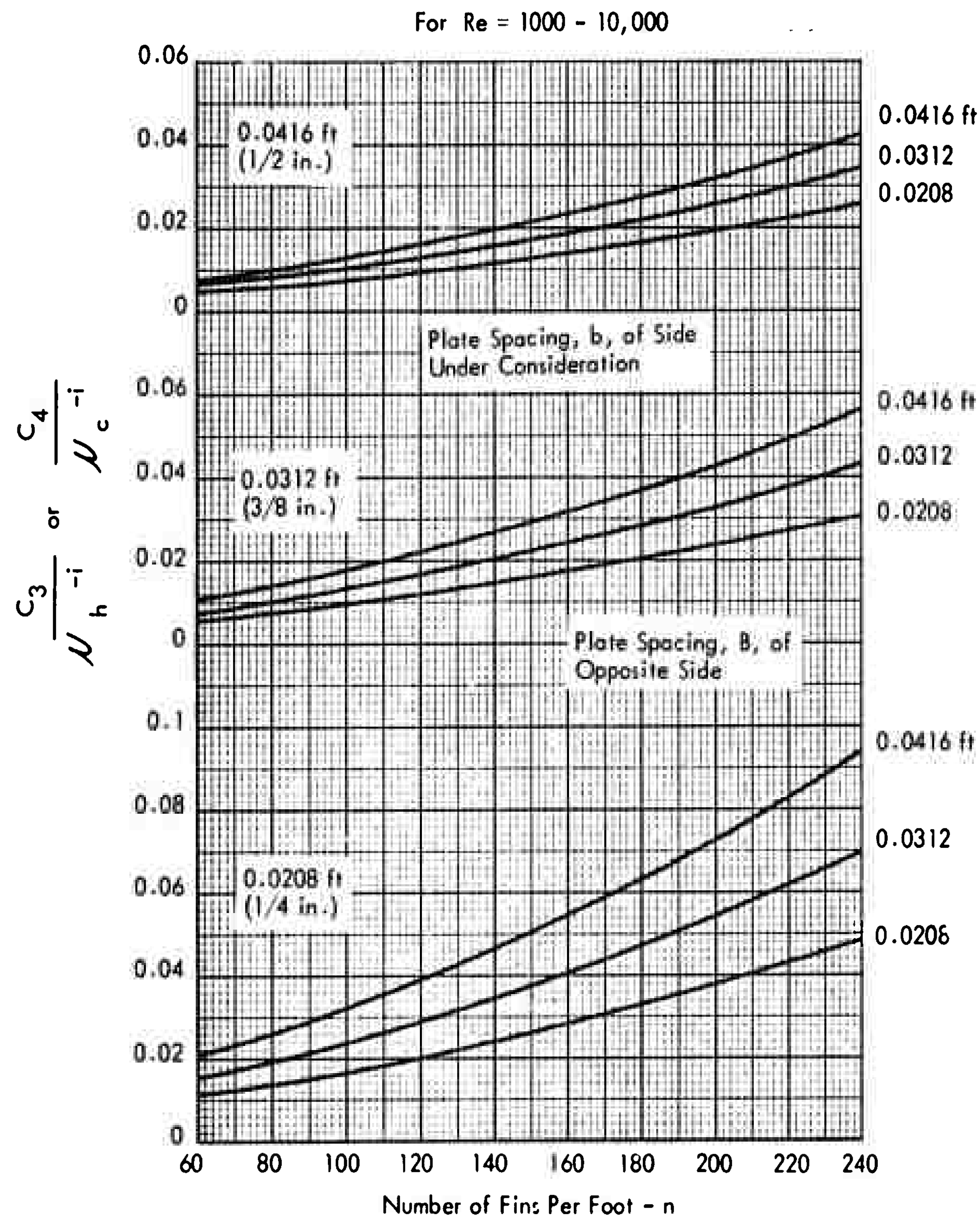

FIGURE III-40

CORE CONSTANTS C_3 AND C_4 -

PLATE-AND-LOUVERED-FIN

HEAT TRANSFER SURFACES

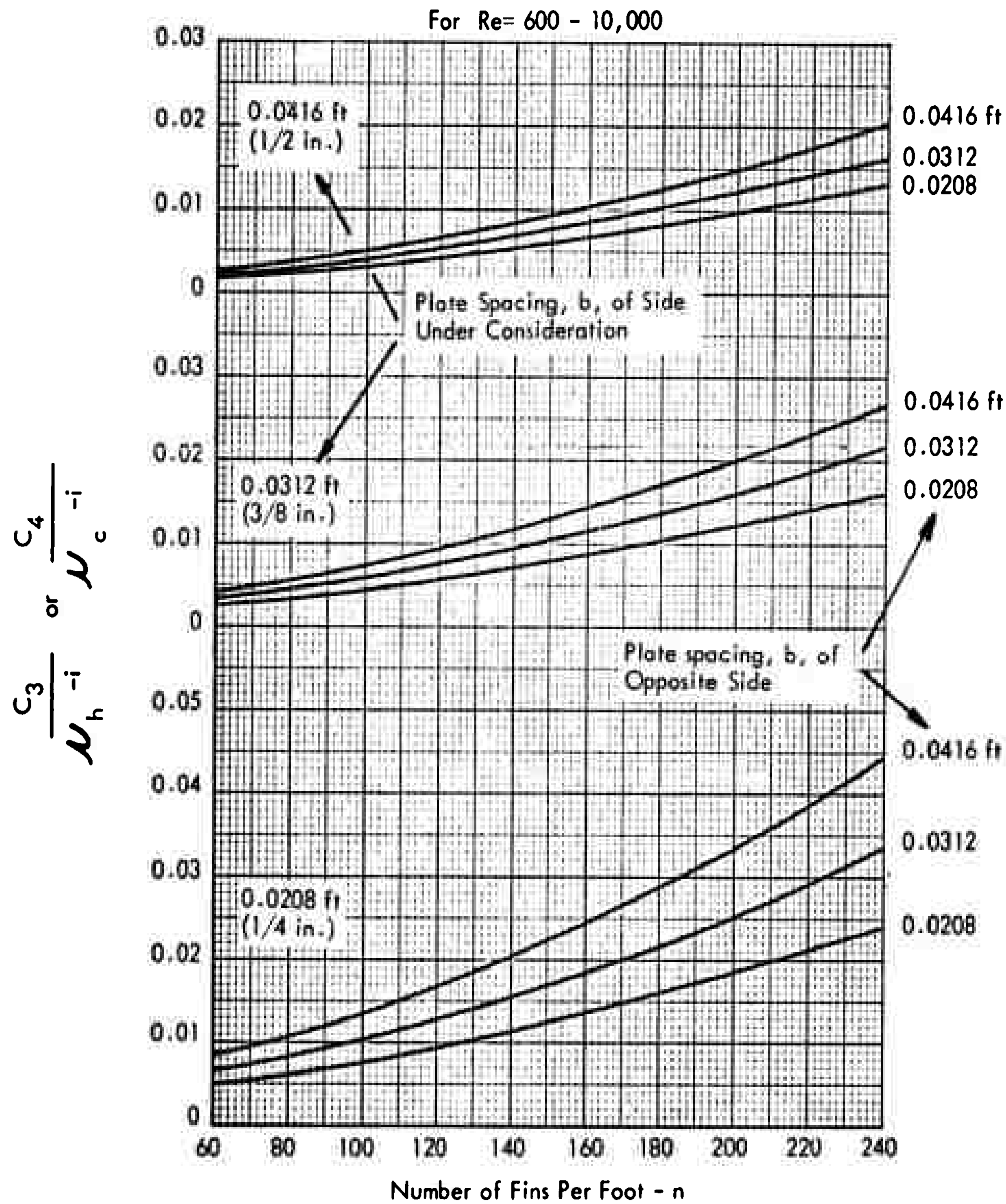

FIGURE III-41
CORE CONSTANTS C_3 AND C_4 -
PLATE-AND-WAVY-FIN
HEAT TRANSFER SURFACES

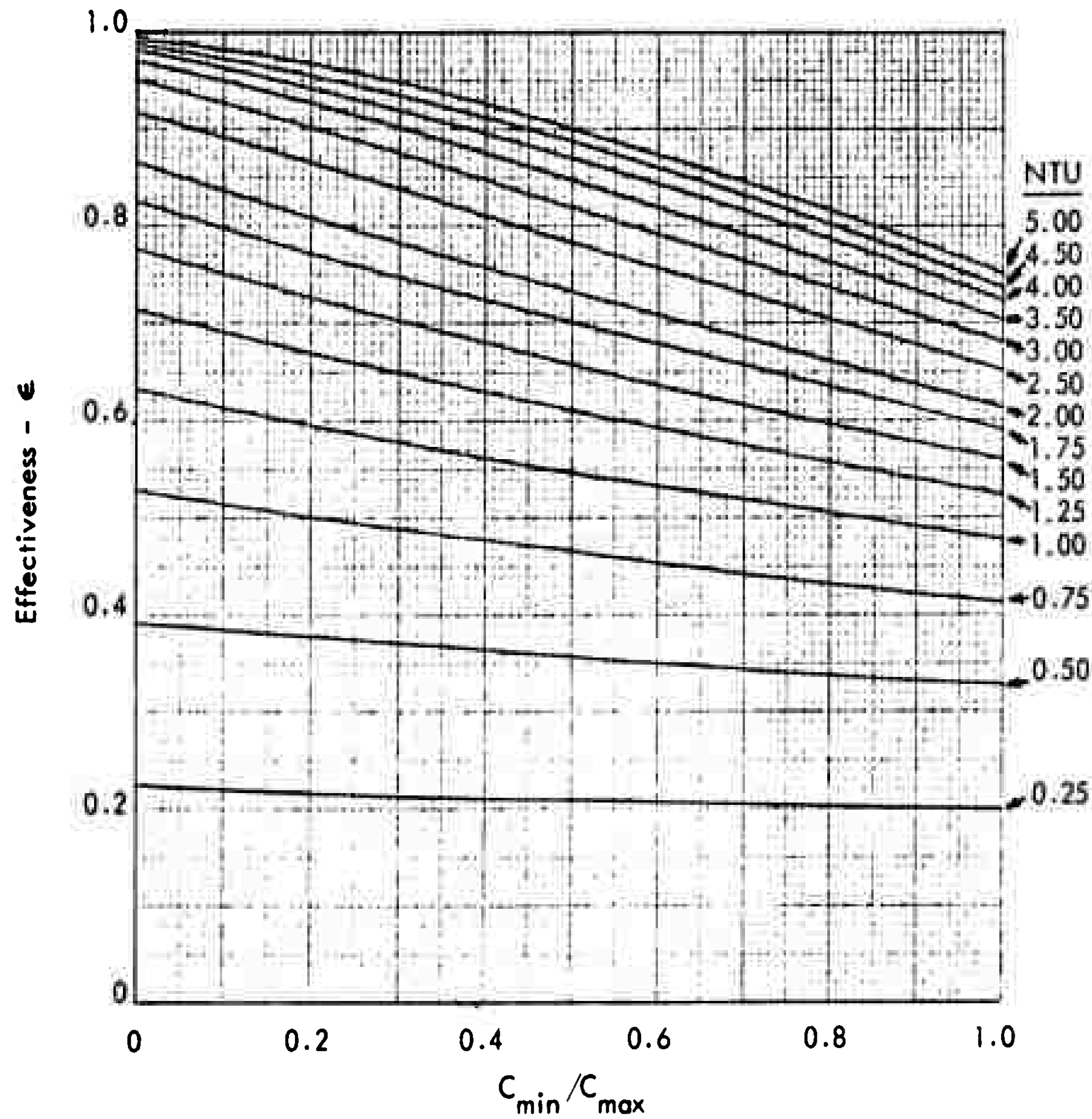

FIGURE III-42

EFFECTIVENESS - SINGLE-PASS CROSSFLOW HEAT EXCHANGER

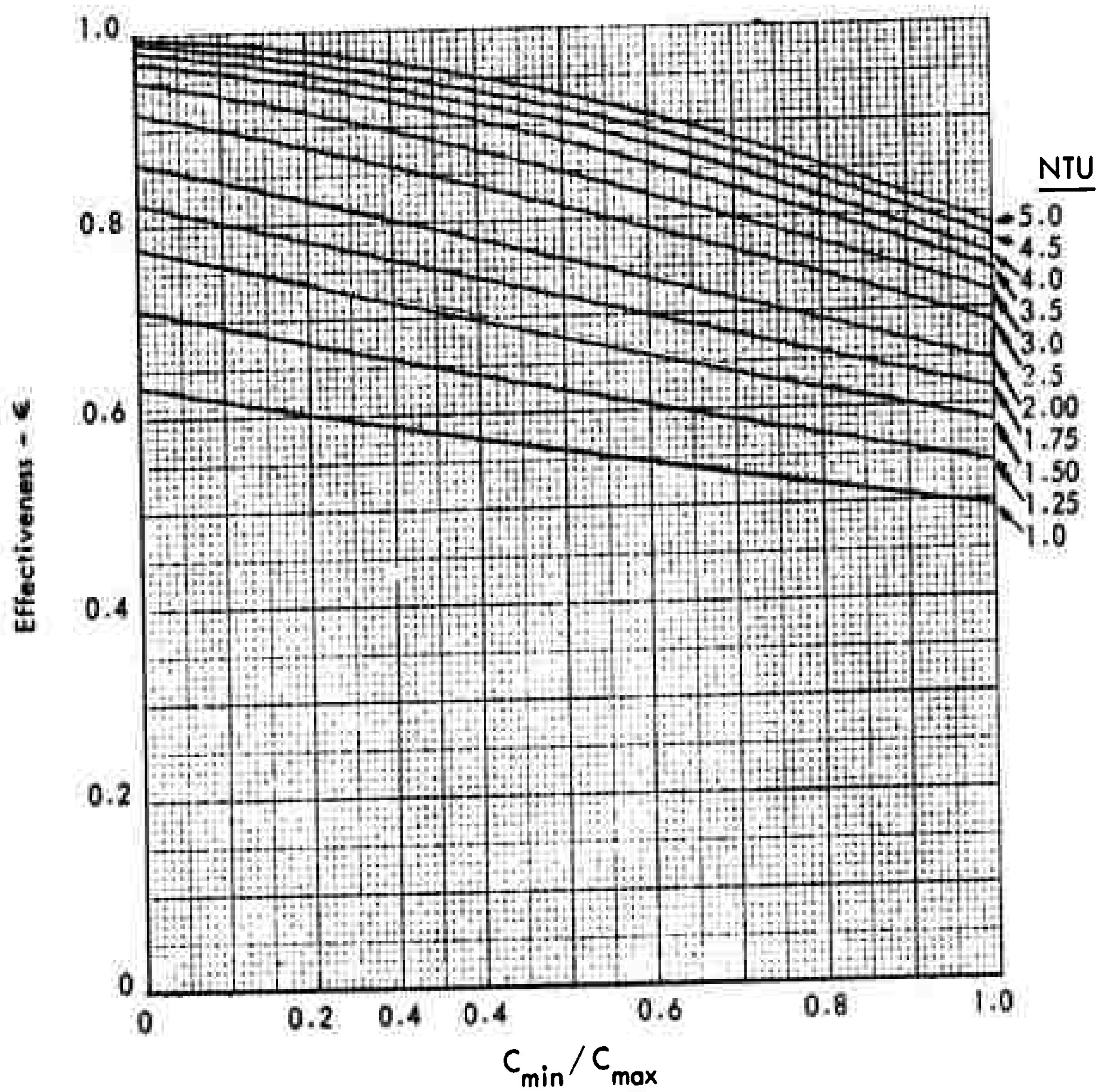

FIGURE III-43

EFFECTIVENESS - TWO-PASS CROSS-COUNTERFLOW HEAT EXCHANGER

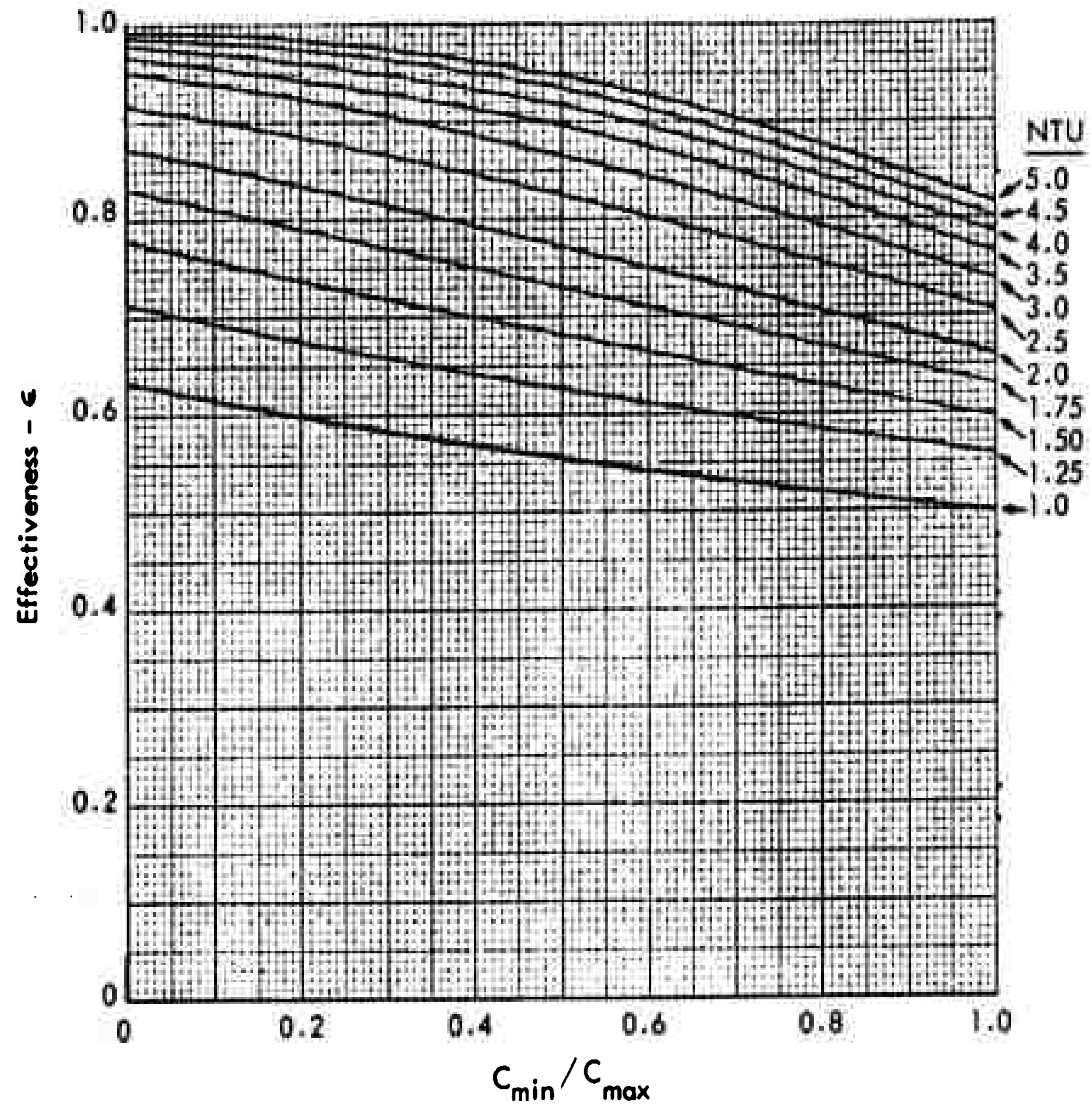

FIGURE III-44

EFFECTIVENESS - FOUR-PASS CROSS-COUNTERFLOW HEAT EXCHANGER

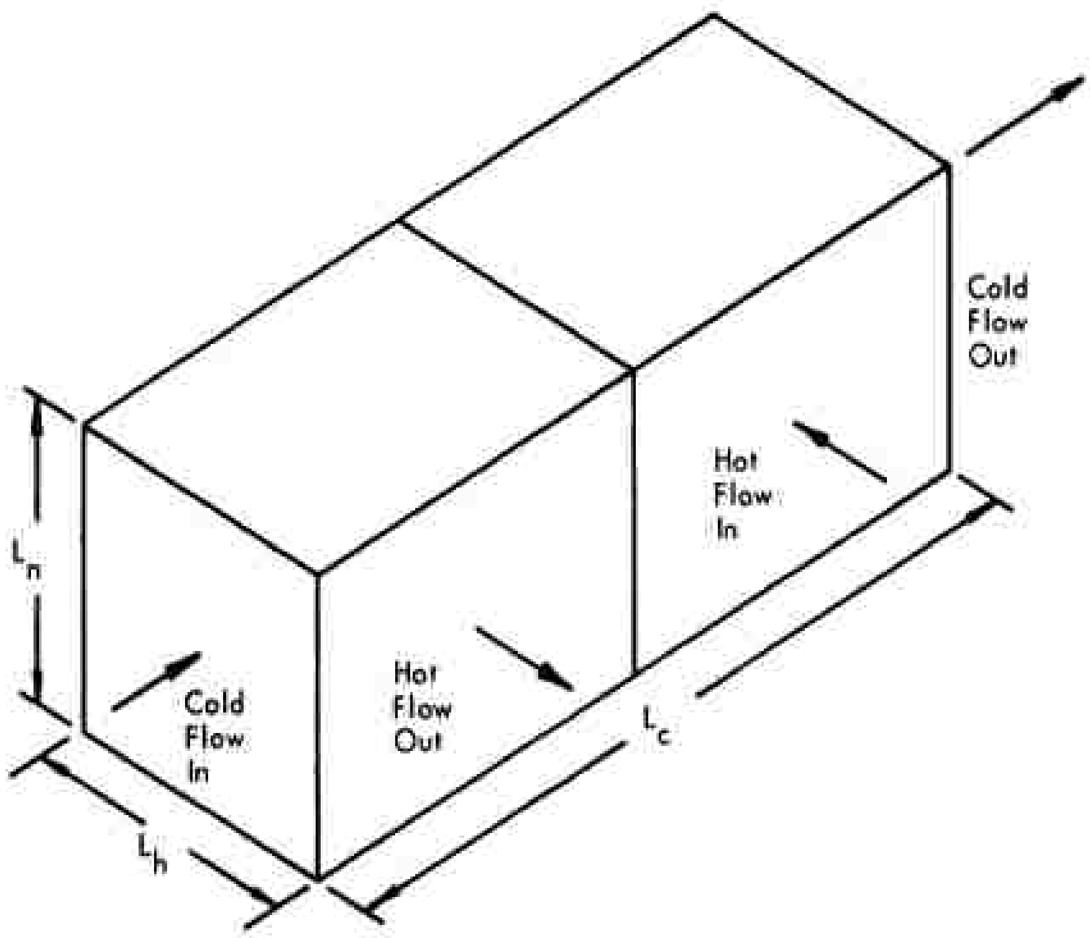

FIGURE III-45

DEFINITION OF LENGTHS L FOR MULTI-PASS HEAT EXCHANGER

SUMMARY

This volume of the report presents the results of the tank pressurization program in handbook form, for maximum utility to the designer of a pressurization system or of a complete vehicle. The information is organized into three areas: pressurization gas requirements, tankage, and components.

The two methods presented herein for determining pressurizing gas requirements for evaporated propellant pressurization systems are a hand calculation procedure, which is a simplification of the IBM program described in Volume IV, and a series of nomographs covering liquid hydrogen and liquid oxygen in insulated aluminum or stainless steel tanks. Another hand calculation method is presented for determining the injectant requirements and the resulting pressurizing gas weight in main tank injection pressurization systems.

The section on tankage provides curves of structural material properties and of tank volumes and wall areas as functions of size and shape.

The components for which design information is presented are heat exchangers and helium storage systems, since these items contribute significantly to system weight. The heat exchanger information is in the form of a simple but accurate hand calculation method, while the stored helium data are presented in curve form.

BIBLIOGRAPHY

III-1 "Rocket Propellant Handbook", B. Kit and D. S. Evered, The Macmillan Company, New York, 1960.

III-2 "Cryogenic Data Book", D. B. Chelton and D. B. Mann, Cryogenic Engineering Laboratory, National Bureau of Standards, Boulder, Colorado, 1959.

III-3 "Cryogenic Materials Data Handbook", T. F. Durham, R. M. McClintock, and R P. Reed, Cryogenic Engineering Laboratory, National Bureau of Standards, Boulder, Colorado.

III-4 "Review of Current Data on the Tensile Properties of Metals at Very Low Temperatures", J. E. Campbell, Defense Metals Information Center Report No. 148, February 14, 1961.

III-5 "Handbook of Thermophysical Properties of Solid Materials", Revised Edition, Volume II, A. Goldsmith, T. E. Waterman, H. J. Hirshhorn, Armour Research Foundation, The Macmillan Co., New York, 1961.

III-6 "Properties of Some Metals and Alloys", Development & Research Division, The International Nickel Co., Inc., New York, 1949.

III-7 "Metals Handbook", 8th Edition, Volume I, American Society for Metals, Novelty, Ohio, 1961.

III-8 "A Compendium of the Properties of Materials at Low Temperature; Phase I, Properties of Solids", V. J. Johnson, Cryogenic Engineering Laboratory, National Bureau of Standards. Boulder, Colorado, 1960.

III-9 "Cryogenic Engineering", Russell B. Scott, D. Von Nostrand Co., Princeton, New Jersey, 1959.

III-10 ASME Paper No. 58-HT-12, "Engineering Method for Determining a Design Envelope for Air-to-Air Crossflow Heat Exchangers", W. T. Shatzer, 1958.

III-11 "Compact Heat Exchangers", W. M. Kays and A. L. London, The National Press, Palo Alto, California, 1955.

APPENDIX III-A

The following computer runs were used in deriving and checking the nomographs for the EP pressurization systems. The variables were percent initial ullage, wall area, expulsion time, weight of tank walls, volume, inlet gas temperature, tank pressure, and tank wall material. Oxygen and hydrogen EP systems were considered with both stainless steel and aluminum tanks.

TABLE III-A-1

Computer Runs For Nomograph

Hydrogen EP With Externally-Insulated Stainless Steel Tank Walls

Initial Ullage, Percent	$\frac{A\theta}{V}$, Sec/Ft	$\frac{W_w}{V}$, Lb/Ft^3	Inlet Gas Temp., R	Press., Psia	Final Gas Temp., R Nom.	Comp.	Test
10.5	107	5.23	240	46	175	168	169
13.7	124	5.23	520	48	270	235	
8.2	144	5.23	280	47	200	159	171
21.1	104	5.23	245	47	160	159	161
12.1	133	5.23	290	45	200	188	171
18.0	111	5.23	270	48	172	159	158
8.3	116	5.23	280	46	195	181	128
11.3	126	5.23	225	46	170	165	164
10.6	124	5.23	270	45	185	169	171
5	23.5	0.613	500	48	355	354	
5	23.5	0.613	500	40	355	354	
5	23.5	0.613	300	40	244	243	
5	23.5	0.613	100	40	101	96	
5	18.75	0.050	100	40	101	99	
5	18.75	0.050	300	40	272	270	
5	18.75	0.050	500	40	410	414	
5	31.5	0.100	100	40	100	101	
5	37.5	0.100	300	40	264	267	

TABLE III-A-1 Continued

Initial Ullage, Percent	$\frac{A\theta}{V}$, Sec/Ft	$\frac{W_w}{V}$, Lb/Ft^3	Inlet Gas Temp.,R	Press., Psia	Final Gas Temp., R Nom.	Comp.	Test
5	37.5	0.100	400	40	392	401	
15	25.0	0.600	100	40	100	97	
15	25.0	0.600	300	40	222	223	
15	25.0	0.600	500	40	308	307	
5	23.5	0.613	500	40	355	355	
5	23.5	0.613	500	40	355	355	
5	23.5	0.613	300	40	244	245	
5	23.5	0.613	100	40	100	98	
5	23.5	0.100	500	40	392	400	
5	23.5	1.00	500	40	342	342	
5	23.5	5.00	500	40	310	307	
5	23.5	0.100	100	40	100	100	
5	23.5	0.100	300	40	266	266	
5	23.5	5.000	100	40	100	93	
5	23.5	5.000	300	40	218	215	
5	32.5	0.280	520	25	350	344	
5	32.5	0.280	300	25	238	239	
5	5.25	0.050	300	40	270	273	
5	5.25	0.050	300	25	250	257	

TABLE III-A-2

Computer Runs For Nomograph

Oxygen EP With Externally-Insulated Aluminum Tank Walls

Initial Ullage, Percent	$\frac{A\theta}{V}$, Sec/Ft	$\frac{W_w}{V}$, Lb/Ft^3	Inlet Gas Temp.,R	Press., Psia	Final Gas Temp.,R Nom.	Comp.
5	148	1.54	520	27	295	287
4.79	148	0.525	520	27	330	340
5	80	5.0	500	25	270	250
15	80	0.3	500	65	415	410
15	80	0.1	500	25	390	391
15	80	0.3	500	25	360	350
15	80	4.8	500	25	265	250
15	80	0.48	500	25	330	328
5	80	0.5	500	25	340	335
15	80	0.48	500	65	385	389
15	80	4.8	500	65	300	302
15	80	0.1	500	65	450	445
5	30	0.1	520	65	470	477
5	30	0.1	350	65	337	337
5	150	0.1	520	65	460	460
5	150	0.1	350	65	335	332
5	80	0.1	500	25	400	408
5	80	0.3	500	25	365	360
5	80	0.3	500	65	420	415

TABLE III-A-2 Continued

Initial Ullage, Percent	$\frac{A\theta}{V}$, Sec/Ft	$\frac{W_w}{V}$, Lb/Ft^3	Inlet Gas Temp.,R	Press., Psia	Final Gas Temp., R Nom.	Comp.
5	80	0.1	500	65	460	453
5	80	5.0	500	65	302	302
5	80	0.5	500	65	390	393
5	80	5.0	300	65	240	232
5	80	5.0	220	65	195	197
5	80	0.1	300	65	295	292
5	80	0.1	220	65	225	220
5	80	0.1	220	25	200	221
5	80	5.0	220	25	185	188
5	80	0.3	350	25	280	289
5	80	0.5	350	25	270	274

TABLE III-A-3

Computer Runs For Nomograph

Oxygen EP With Externally-Insulated Stainless Steel Tank Walls

Initial Ullage, Percent	$\frac{A\theta}{V}$, Sec/Ft	$\frac{W_w}{V}$, Lb/Ft^3	Inlet Gas Temp., R	Press., Psia	Final Gas Temp., R Nom.	Final Gas Temp., R Comp.
5	80	0.05	200	65	195	203
5	80	5.0	200	65	190	191
4.4	32.5	0.243	520	28.6	415	410
4.76	148	0.527	520	27	385	373
5	80	0.05	300	65	297	297
5	80	5.0	300	65	245	243
5	80	5.0	500	65	315	315
5	80	0.05	500	65	470	472
5	80	0.1	500	65	460	462
5	80	1.0	300	65	275	272
5	80	1.0	500	65	390	391
5	80	5.0	500	65	320	324
5	80	0.5	500	65	418	420

TABLE III-A-4

Computer Runs For Nomograph

Hydrogen EP With Externally-Insulated Aluminum Tank Walls

Initial Ullage, Percent	$\frac{A\theta}{V}$, Sec/Ft	$\frac{W_w}{V}$, Lb/Ft^3	Inlet Gas Temp., R	Pres., Psia	Final Gas Temp., R Nom.	Final Gas Temp., R Comp.
5	7.5	0.046	500	40	405	404
5	7.5	5.0	500	40	320	324
15	25	0.613	500	65	320	337
15	25	0.3	400	25	245	252
15	25	0.613	500	25	270	242
5	7.5	0.1	200	40	185	184
5	7.5	0.1	500	40	395	391
5	7.5	1.0	200	40	165	168
5	7.5	1.0	500	40	345	342
5	7.5	0.5	200	40	170	168
5	7.5	0.5	500	40	355	355
5	7.5	0.05	200	40	186	186
5	7.5	5.0	200	40	170	161
5	7.5	5.0	500	40	320	324
5	7.5	0.05	500	40	400	404

SSD-TR-61-21
Volume III

AD-

Lockheed-Georgia Company, Marietta Georgia
MAIN PROPELLANT TANK PRESSURIZATION SYSTEM STUDY AND TEST PROGRAM, VOLUME III OF IV, DESIGN HANDBOOK. December 1961. 95 p. incl. illus., tables, 11 refs. (Project 6753, Task 675302) (Final Report; Lockheed Report ER-5296; SSD-TR-61-21)
(Contract AF 04(611)-6087 and AF 04 (611)-7032)

Unclassified Volume

(over)

UNCLASSIFIED

1. Liquid Rocket Propellants - Combustion
2. Liquid Rocket Propellants - Vaporization
3. Pressure Tanks Control Sys.
4. Propellant Tanks - Pressure Distribution

UNCLASSIFIED

AD-

Lockheed-Georgia Company, Marietta Georgia
MAIN PROPELLANT TANK PRESSURIZATION SYSTEM STUDY AND TEST PROGRAM, VOLUM III OF IV, DESIGN HANDBOOK. December 1961. 95 p. incl. illus., tables, 11 refs. (Project 6753, Task 675302) (Final Report; Lockheed Report ER-5296; SSD-TR-61-21)
(Contract AF 04(611)-6087 and AF 04 (611)-7032)

Unclassified Volume

(over)

UNCLASSIFIED

1. Liquid Rocket Propellants - Combustion
2. Liquid Rocket Propellants - Vaporization
3. Pressure Tanks Control Sys.
4. Propellant Tanks - Pressure Distribution

UNCLASSIFIED

AD-

Lockheed-Georgia Company, Marietta Georgia
MAIN PROPELLANT TANK PRESSURIZATION SYSTEM STUDY AND TEST PROGRAM, VOLUME III OF IV, DESIGN HANDBOOK. December 1961. 95 p. incl. illus., tables, 11 refs. (Project 6753, Task 675302) (Final Report; Lockheed Report ER-5296; SSD-TR-61-21)
(Contract AF 04(611)-6087 and AF 04 (611)-7032)

Unclassified Volume

(over)

UNCLASSIFIED

1. Liquid Rocket Propellants - Combustion
2. Liquid Rocket Propellants - Vaporization
3. Pressure Tanks Control Sys.
4. Propellant Tanks - Pressure Distribution

UNCLASSIFIED

AD-

Lockheed-Georgia Company, Marietta Georgia
MAIN PROPELLANT TANK PRESSURIZATION SYSTEM STUDY AND TEST PROGRAM, VOLUME III OF IV, DESIGN HANDBOOK. December 1961. 95 p. incl. illus., tables, 11 refs. (Project 6753, Task 675302) (Final Report; Lockheed Report ER-5296; SSD-TR-61-21)
(Contract AF 04(611)-6087 and AF 04 (611)-7032)

Unclassified Volume

(over)

UNCLASSIFIED

1. Liquid Rocket Propellants - Combustion
2. Liquid Rocket Propellants - Vaporization
3. Pressure Tanks Control Sys.
4. Propellant Tanks - Pressure Distribution

UNCLASSIFIED

SSD-TR-61-21
Volume III

AD-

UNCLASSIFIED

Design information on liquid propellant tank pressurization systems is presented in handbook form. The areas covered are: pressurization gas requirements, including hand calculation procedures and nomographs; tankage, including material properties and volume and wall area curves; and components, including stored helium system weight curves and a simple but accurate heat exchanger design method.

I. 6593rd Test Group Air Force Systems Command

II. Contract AF 04(611)-6087

III. Contract AF 04(611)-7032

UNCLASSIFIED

AD-

UNCLASSIFIED

Design information on liquid propellant tank pressurization systems is presented in handbook form. The areas covered are: pressurization gas requirements, including hand calculation procedures and nomographs; tankage, including material properties and volume and wall area curves; and components, including stored helium system weight curves and a simple but accurate heat exchanger design method.

I. 6593rd Test Group Air Force Systems Command

II. Contract AF 04(611)-6087

III. Contract AF 04(611)-7032

UNCLASSIFIED

AD-

UNCLASSIFIED

Design information on liquid propellant tank pressurization systems is presented in handbook form. The areas covered are: pressurization gas requirements, including hand calculation procedures and nomographs; tankage, including material properties and volume and wall area curves; and components, including stored helium system weight curves and a simple but accurate heat exchanger design method.

I. 6593rd Test Group Air Force Systems Command

II. Contract AF 04(611)-6087

III. Contract AF 04(611)-7032

UNCLASSIFIED

AD-

UNCLASSIFIED

Design information on liquid propellant tank pressurization systems is presented in handbook form. The areas covered are: pressurization gas requirements, including hand calculation procedures and nomographs; tankage, including material properties and volume and wall area curves; and components, including stored helium system weight curves and a simple but accurate heat

I. 6593rd Test Group Air Force Systems Command

II. Contract AF 04(611)-6087

III. Contract AF 04(611)-7032

UNCLASSIFIED

SSD-TR-61-21
Volume III

AD-

UNCLASSIFIED

Lockheed-Georgia Company, Marietta Georgia
MAIN PROPELLANT TANK PRESSURIZATION SYSTEM STUDY AND TEST PROGRAM, VOLUME III OF IV, DESIGN HANDBOOK. December 1961. 95 p. incl. illus., tables, 11 refs. (Project 6753, Task 675302) (Final Report; Lockheed Report ER-5296; SSD-TR-61-21)
(Contract AF 04(611)-6087 and AF 04 (611)-7032)

1. Liquid Rocket Propellants - Combustion
2. Liquid Rocket Propellants - Vaporization
3. Pressure Tanks Control Sys.
4. Propellant Tanks - Pressure Distribution

Unclassified Volume

(over)

UNCLASSIFIED

AD-

UNCLASSIFIED

Lockheed-Georgia Company, Marietta Georgia
MAIN PROPELLANT TANK PRESSURIZATION SYSTEM STUDY AND TEST PROGRAM, VOLUM III OF IV, DESIGN HANDBOOK. December 1961. 95 p. incl. illus., tables, 11 refs. (Project 6753, Task 675302) (Final Report; Lockheed Report ER-5296; SSD-TR-61-21)
(Contract AF 04(611)-6087 and AF 04 (611)-7032)

1. Liquid Rocket Propellants - Combustion
2. Liquid Rocket Propellants - Vaporization
3. Pressure Tanks Control Sys.
4. Propellant Tanks - Pressure Distribution

Unclassified Volume

(over)

UNCLASSIFIED

AD-

UNCLASSIFIED

Lockheed-Georgia Company, Marietta Georgia
MAIN PROPELLANT TANK PRESSURIZATION SYSTEM STUDY AND TEST PROGRAM, VOLUME III OF IV, DESIGN HANDBOOK. December 1961. 95 p. incl. illus., tables, 11 refs. (Project 6753, Task 675302) (Final Report; Lockheed Report ER-5296; SSD-TR-61-21)
(Contract AF 04(611)-6087 and AF 04 (611)-7032)

1. Liquid Rocket Propellants Combustion
2. Liquid Rocket Propellants - Vaporization
3. Pressure Tanks Control Sys.
4. Propellant Tanks - Pressure Distribution

Unclassified Volume

(over)

UNCLASSIFIED

AD-

UNCLASSIFIED

Lockheed-Georgia Company, Marietta Georgia
MAIN PROPELLANT TANK PRESSURIZATION SYSTEM STUDY AND TEST PROGRAM, VOLUME III OF IV, DESIGN HANDBOOK. December 1961. 95 p. incl. illus., tables, 11 refs. (Project 6753, Task 675302) (Final Report; Lockheed Report ER-5296; SSD-TR-61-21)
(Contract AF 04(611)-6087 and AF 04 (611)-7032)

1. Liquid Rocket Propellants - Combustion
2. Liquid Rocket Propellants - Vaporization
3. Pressure Tanks Control Sys.
4. Propellant Tanks - Pressure Distribution

Unclassified Volume

(over)

UNCLASSIFIED

SSD-TR-61-21
Volume III

AD-

UNCLASSIFIED

Design information on liquid propellant tank pressurization systems is presented in handbook form. The areas covered are: pressurization gas requirements, including hand calculation procedures and nomographs; tankage, including material properties and volume and wall area curves; and components, including stored helium system weight curves and a simple but accurate heat exchanger design method.

I. 6593rd Test Group Air Force Systems Command

II. Contract AF 04(611)-6087

III. Contract AF 04(611)-7032

UNCLASSIFIED

AD-

UNCLASSIFIED

Design information on liquid propellant tank pressurization systems is presented in handbook form. The areas covered are: pressurization gas requirements, including hand calculation procedures and nomographs; tankage, including material properties and volume and wall area curves; and components, including stored helium system weight curves and a simple but accurate heat exchanger design method.

I. 6593rd Test Group Air Force Systems Command

II. Contract AF 04(611)-6087

III. Contract AF 04(611)-7032

UNCLASSIFIED

AD-

UNCLASSIFIED

Design information on liquid propellant tank pressurization systems is presented in handbook form. The areas covered are: pressurization gas requirements, including hand calculation procedures and nomographs; tankage, including material properties and volume and wall area curves; and components, including stored helium system weight curves and a simple but accurate heat exchanger design method.

I. 6593rd Test Group Air Force Systems Command

II. Contract AF 04(611)-6087

III. Contract AF 04(611)-7032

UNCLASSIFIED

AD-

UNCLASSIFIED

Design information on liquid propellant tank pressurization systems is presented in handbook form. The areas covered are: pressurization gas requirements, including hand calculation procedures and nomographs; tankage, including material properties and volume and wall area curves; and components, including stored helium system weight curves and a simple but accurate heat

I. 6593rd Test Group Air Force Systems Command

II. Contract AF 04(611)-6087

III. Contract AF 04(611)-7032

UNCLASSIFIED