ORNL/TM-4931

Cy 51

OAK RIDGE NATIONAL LABORATORY LIBRARIES

3 4456 0550634 2

The Thermal Transport Properties of Helium, Helium-Air Mixtures, Water, and Tubing Steel Used in the CACHE Program to Compute HTGR Auxiliary Heat Exchanger Performance

J. R. Tallackson

OAK RIDGE NATIONAL LABORATORY
CENTRAL RESEARCH LIBRARY
DOCUMENT COLLECTION
LIBRARY LOAN COPY
DO NOT TRANSFER TO ANOTHER PERSON
If you wish someone else to see this document, send in name with document and the library will arrange a loan.

OAK RIDGE NATIONAL LABORATORY
OPERATED BY UNION CARBIDE CORPORATION FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy $6.50; Microfiche $2.25

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

ORNL/TM-4931

Contract No. W-7405-eng-26

Reactor Division

THE THERMAL TRANSPORT PROPERTIES OF HELIUM, HELIUM-AIR MIXTURES, WATER, AND TUBING STEEL USED IN THE CACHE PROGRAM TO COMPUTE HTGR AUXILIARY HEAT EXCHANGER PERFORMANCE

J. R. Tallackson

FEBRUARY 1976

NOTICE: This document contains information of a preliminary nature and was prepared primarily for internal use at the Oak Ridge National Laboratory. It is subject to revision or correction and therefore does not represent a final report.

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
U. S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

OAK RIDGE NATIONAL LABORATORY LIBRARIES

3 4456 0550634 2

CONTENTS

	Page
Abstract	1
INTRODUCTION	1
I. THE THERMAL TRANSPORT PROPERTIES OF PURE HELIUM	3
A. Thermal Conductivity	3
B. Viscosity	4
C. Specific Heat	4
II. THE THERMAL TRANSPORT PROPERTIES OF WATER	5
A. Thermal Conductivity of Water	5
B. Viscosity of Water	7
C. Specific Heat of Liquid Water	7
III. THE THERMAL CONDUCTIVITY OF STEEL TUBING	9
IV. THE THERMAL TRANSPORT PROPERTIES OF HELIUM DILUTED WITH OXYGEN, NITROGEN AND CARBON MONOXIDE	12
A. The Thermal Conductivity of Helium Diluted with Nitrogen, Oxygen, and Carbon Monoxide	17
B. The Viscosity of Helium Diluted with Nitrogen, Oxygen, and Carbon Monoxide	21
C. The Specific Heat of Helium-Air Gas Mixtures	27
APPENDIX A. EQUATIONS AND TABULATIONS FOR THE THERMAL CONDUCTIVITY OF PURE HELIUM	30
Summary of Equations Developed for Evaluating the Thermal Conductivity of Helium	83
APPENDIX B. THERMAL CONDUCTIVITY OF HELIUM-NITROGEN MIXTURES	88
APPENDIX C. THE VISCOSITY OF HELIUM	93
The Viscosity of Pure Helium	93
APPENDIX D. THE SPECIFIC HEAT OF HELIUM-AIR MIXTURES	100
REFERENCES	106

THE THERMAL TRANSPORT PROPERTIES OF HELIUM, HELIUM-AIR MIXTURES, WATER, AND TUBING STEEL USED IN THE CACHE PROGRAM TO COMPUTE HTGR AUXILIARY HEAT EXCHANGER PERFORMANCE

J. R. Tallackson

Abstract

This report presents, quantitatively, the thermal transport properties of the materials involved in digital computer calculations of heat transfer rates by the Core Auxiliary Heat Exchangers in large HTGR nuclear steam supply systems. These materials are pure helium, mixtures of helium with common gases having molecular weights in the range of 28 to 32, alloy steel tubing, and water.

For use in programmed computations the viscosity, thermal conductivity, and specific heat, are represented primarily by equations augmented by curves and tabulations. Materials supporting the development and selection of the property equations is included.

Keywords: Helium, carbon monoxide, nitrogen, heat transfer, thermal conductivity, oxygen, chrome – molybdenum steels, air, heat capacity, viscosity, gases.

INTRODUCTION

ORNL has been producing independent calculations of the afterheat removal capability of HTGR emergency cooling systems undergoing licensing review. Afterheat is transferred from the reactor core by auxiliary loops which circulate core coolant gas to Core Auxiliary Heat Exchangers (CAHEs). Heat removed by a CAHE is dumped, externally, by a water-to-air heat exchanger.

Adequate performance by the CAHE is vital to HTGR safety; therefore, it is essential that all computations of CAHE heat transfer rates be conducted with more than ordinary care.

CAHE performance is strongly influenced by the transport properties of the core coolant gases, and to a much lesser extent, by the properties of the tubing steel and water. In normal circumstances HTGR afterheat is removed from the core by circulating pressurized helium through the steam generators. During refueling or under emergency conditions the coolant gas is circulated through the auxiliary loops. The transport properties of concern; thermal conductivity, viscosity, and specific heat, of helium, steel, and water are well documented and readily available. Uncertainties in performance computations associated with these materials are small.

The limiting situation arises during a Design Basis Depressurization Accident (DBDA) followed by a Loss of Main Loop Cooling (LOMLC). In the remote event that an HTGR experiences a DBDA plus LOMLC, the helium remaining in the reactor vessel will become diluted by the ingress of air from the containment building. The oxygen in the air will react with the graphite in the core and carbon monoxide will be produced. The core coolant gas is, then, a mixture consisting principally of helium, nitrogen, and carbon monoxide. Mixture composition varies with elapsed time after the accident and the properties of the mixture, dependent on composition, strongly influence the performance of the CAHEs.

The thermal transport properties of gas mixtures are, in general, not well established by experiment. Theoretical calculations often leave much to be desired. Fortunately, a small amount of data on the thermal conductivity and viscosity of mixtures of helium with oxygen and nitrogen is available. This report describes how these data were used to develop equations to describe the properties of the core coolant gas following a DBDA. The experimental data and supporting information are included.

Because digital computer calculations are facilitated by using equations rather than tabulations to describe variable parameters, all property data are specified with equations for use in the Core Auxiliary Cooling Heat Exchanger (CACHE) program used to determine CAHE performance.

During the course of developing the gas property data used for the computations a large amount of related supportive information was produced. These data, while not used directly for the HTGR computations, are included with the thought that they may be convenient and useful for further related study.

*Acronym for Core Auxiliary Cooling Heat Exchanger

I. THE THERMAL TRANSPORT PROPERTIES OF PURE HELIUM

The thermal transport properties of helium have been thoroughly investigated and well documented. References 1 through 10 have been reviewed for the purpose of selecting suitable methods to evaluate these properties in programs used to calculate heat transfer to or from helium. The formulas reported by Petersen[1] were selected for use in the CACHE program. They were chosen chiefly because they are simple in format; not necessarily because it was assumed they were the most precise. It is shown in Appendix A that if the helium property data derived from different sources are compared within the applicable temperature range, the differences, reflected by CAHE heat transfer computations, are insignificant.

A. Thermal Conductivity

In Ref. 1, the thermal conductivity, k, is given by this equation:

$$k = (2.682 \times 10^{-3})(1.0 + 1.123 \times 10^{-3} P)T^{0.71(1-0.0002P)} \qquad \text{(I.A1)}$$

$k = w/(m^2\ K/m)$

T = absolute temperature, K

P = bar; (bar = $10^5 N/m^2$ = 0.9869 phys. atm)

Petersen[1] states: "The standard deviation, σ, is about 1% at 273 K and 6% at 1800 K, i.e.; $\sigma = 0.0035\ T\%$."

Within the pressure range from 15 psia to 750 psia the effect of pressure on the conductivity is less than 1.0%. For example:

k at 1 atm (~15 psia), 1000°F = 0.1802 (Btu/hr)/(ft^2-°F/ft),

k at 51 atm (~750 psia), 1000°F = 0.1815 (Btu/hr)/(ft^2-°F/ft).

For this reason the effect of pressure was ignored for use in the CACHE program and Eq. I.A1 above was simplified, thus:

$$k = 2.685\ T^{0.71}\ w/(m^2\ K/m) \qquad \text{(I.A2)}$$

and in English units

$$k = (1.0221 \times 10^{-3})T^{0.710} \qquad \text{(I.A3)}$$

at P = 1 atm = 14.7 psia

$$k = (1.0849 \times 10^{-3})T^{0.703} \qquad \text{(I.A4)}$$

at P = 51 atm = 750 psia

k = (Btu/hr)/(ft^2-°F/ft); T = °Rankine

Equation I.A3 was chosen to evaluate helium thermal conductivity because, compared with several other equations in recent or current use, it is the simplest in format and easily programmed.

In Appendix A five other equations for thermal conductivity are listed and helium conductivity computed with Eq. I.A1 and also with these five additional equations is tabulated in Tables A.1 and A.7. These tables are for pressures of 1 atm, 100 psia, 500 psia, 750 psia, 1000 psia, 1500 psia and 2000 psia and for temperatures from 50°F to 2000°F. Typical calculations of heat exchange rates with pressurized helium in HTGR Core Auxiliary Heat Exchangers involve helium film temperatures in the range 300°F to 1000°F. Within this range all tabulated conductivities agree within 3.0%.

B. Viscosity

As with thermal conductivity, there is no dearth of data sources for the viscosity of helium. The equation for viscosity which is incorporated in the CACHE program is from Ref. 1 and is a version of

$$\mu = (3.674 \times 10^{-7})\ T^{0.70},\ \text{kg/(m sec)}. \qquad \text{(I.B1)}$$

$$T = K$$

For the CACHE programs this equation was recast, thus:

$$\mu = (5.89 \times 10^{-4})\ T^{0.70},\ \text{lb}_m\text{/(ft-hr)} \qquad \text{(I.B2)}$$

$$T = {}^\circ\text{Rankine}$$

The author, Petersen,[1] states, "The standard deviation, σ, is about 0.4% at 273 K and 2.7% at 1800 K, i.e., $\sigma = 0.0015\ T\%$."

Appendix B contains other equations in recent or current use for computing helium viscosity. Figure 11 in section IV shows a curve of helium viscosity calculated with Eq. I.B2.

C. Specific Heat

All the authorities reviewed agree that within the ranges of temperature and pressure in typical HTGR systems that the specific heat of helium is essentially constant and cite values from 1.240 to 1.242 Btu/lb$_m$-°F. The higher value is used in the CACHE programs.

II. THE THERMAL TRANSPORT PROPERTIES OF WATER

A. Thermal Conductivity of Water

Within the CACHE program the thermal conductivity of water is evaluated by the equation

$$k = 0.3104 + (6.910 \times 10^{-4})T - (1.482 \times 10^{-6})T^2 + (5.255 \times 10^{-10})T^3 \qquad \text{(II.A1)}$$

$$k = (\text{Btu/hr})/(\text{ft}^2\text{-}^\circ\text{F/ft})$$

$$T = {}^\circ\text{F};\ 32^\circ\text{F} \le T \le 450^\circ\text{F}$$

This equation is a least squares fit[11] to data obtained by interpolation at 670 psia from tabulated data.[12] The equation for thermal conductivity in this reference is unnecessarily complex for use in CACHE. A second data source, Touloukian[10] et al. was reviewed for purposes of comparison but was not used to develop Eq. II.A1 above. Table 1 provides a comparison of tabulated and computed thermal conductivities of water; these data are plotted on Fig. 1.

The effect of pressure on thermal conductivity was ignored. If the pressure of liquid water at 300°F is increased from 75 psia to 1000 psia, the conductivity is increased by 0.6%.

Table 1. The thermal conductivity, k, of liquid water

Temperature (°F)	Thermal conductivity, k, (Btu/hr)/(ft²-°F/ft)		Error	Per cent error
	k from Ref. 12	k from Eq. II.A1		
32	0.3308	0.3310	+0.0002	+0.06
50	0.3414	0.3413	-0.0001	-0.03
100	0.3655	0.3652	-0.0003	-0.08
150	0.3826	0.3825	-0.0001	+0.03
200	0.3935	0.3935	0.000	0.00
250	0.3985	0.3988	+0.0003	+0.08
300	0.3980	0.3985	+0.0005	+0.13
350	0.3938	0.3933	-0.0005	-0.13
400	0.3836	0.3833	-0.0003	-0.08
450	0.3689	0.3692	+0.0003	+0.08

ORNL-DWG 76-2158

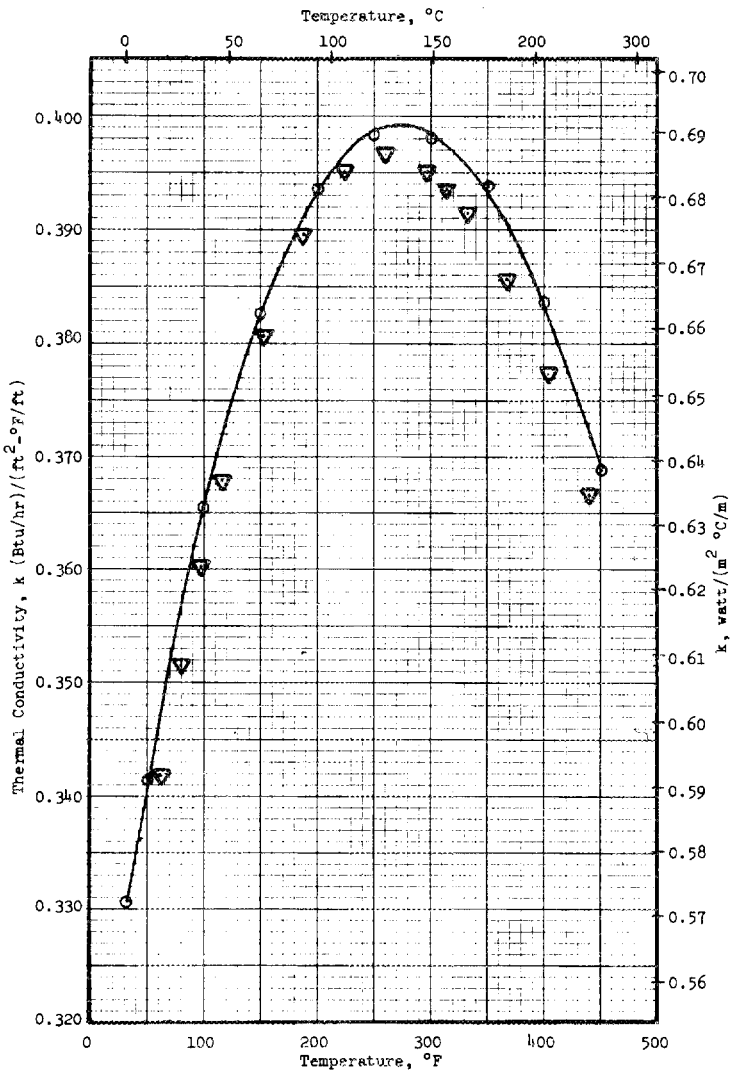

Fig. 1. The thermal conductivity of liquid water
⊙ Data from Ref. 12; ▽ Data from Ref. 10.

B. Viscosity of Water

Water viscosity in the CACHE program is evaluated with the equation

$$\mu = 378.4\ T^{-1.181},\ lb_m/ft\text{-}hr \qquad \text{(II.B1)}$$

$$T = {}^\circ F;\ 100^\circ F \leqq T \leqq 500^\circ F$$

This equation is a least squares fit[11] to tabulated[12] viscosity data for liquid water at 1000 psia. Table 2 and Fig. 2 show viscosity as a function of temperature from the tabulation and from Eq. II.B1. For the purposes of heat transfer computations, the effect of pressure on viscosity may be ignored. For example, at 300°F, increasing the pressure from 75 psia to 1000 psia increases the viscosity by 1.1%.

Table 2. The viscosity of liquid water at 1000 psia

Temp (°F)	Viscosity, $lb_m/(ft\text{-}hr)$ From Ref. 12	Viscosity, $lb_m/(ft\text{-}hr)$ From Eq. II.B1	Error	Per cent error
100	1.65	1.64	-0.010	-0.6
150	1.03	1.02	-0.010	-1.0
200	0.729	0.725	-0.004	-0.5
250	0.554	0.557	+0.003	+0.5
300	0.445	0.449	+0.004	+0.9
350	0.372	0.375	+0.003	+0.8
400	0.320	0.320	0.000	0.0
450	0.280	0.278	-0.002	-0.7
500	0.250	0.246	-0.004	-1.6

C. Specific Heat of Liquid Water

The equation in CACHE for the specific heat of pressurized water is:

$$C_p = 1.035 - (4.55 \times 10^{-4})\ T + (1.38 \times 10^{-6})\ T^2, \qquad \text{(II.C1)}$$

$$C_p = Btu/(lb_m\text{-}{}^\circ F);\ T = {}^\circ F,\ 100^\circ F \leqq T \leqq 400^\circ F.$$

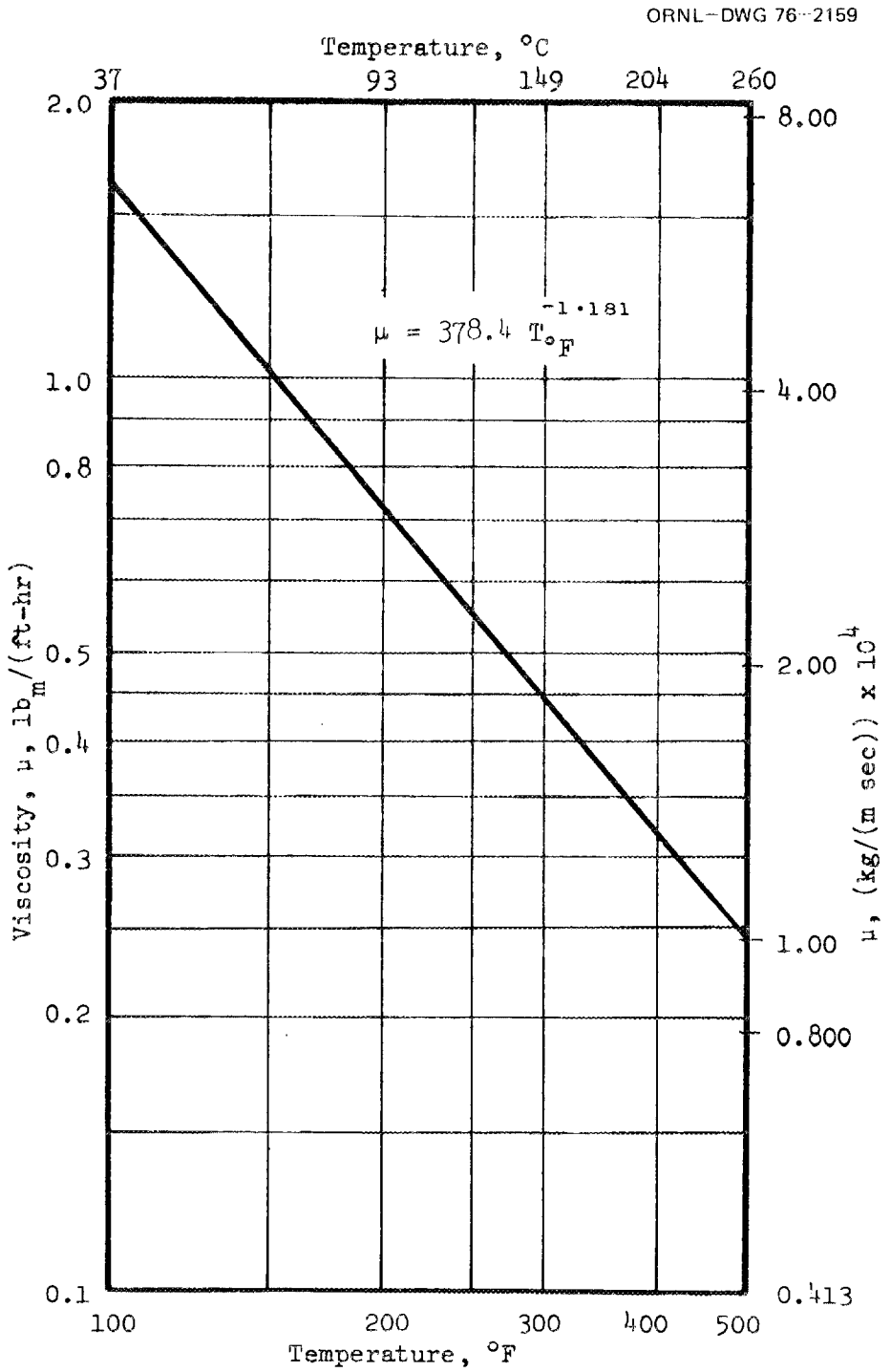

Fig. 2. The viscosity of liquid water. Based on data from Ref. 12.

Equation II.C1 is a least squares fit[11] to data obtained, by inspection, from a curve of $1/C_p$ versus T at 1000 psia in Fig. 6, page 293 in Ref. 12. It is obvious from this curve, that within the pressure range 0 to 1000 psia, the effect of pressure on specific heat is negligible. Table 3 and Fig. 3 show values of C_p from Ref. 12 and those calculated from Eq. II.C1.

Table 3. Specific heat of liquid water at 1000 psia

Temperature (°F)	Specific heat, C_p Btu/(lb-°F) Ref. 12.	Eq. II.C1	Difference	Per cent error
100	0.996	1.004	+0.008	+0.80
150	0.996	0.997	+0.001	+0.10
200	1.000	0.999	-0.001	-0.10
250	1.010	1.007	-0.003	-0.30
300	1.020	1.022	+0.002	+0.20
350	1.042	1.094	+0.002	+0.19
400	1.075	1.073	+0.002	+0.19

III. THE THERMAL CONDUCTIVITY OF STEEL TUBING

The tubing material currently specified for the cooler 75% of the core auxiliary heat exchangers is a low alloy, 1/2% Cr-1/2% Mo, steel. Data for the thermal conductivity of this steel were obtained from Refs. 13 and 14 and, for the CACHE program, tube wall conductivity is described by a first degree, least squares fit.[11] The equation is:

$$k = 22.2 - 0.00276T \qquad \text{(III.A1)}$$

$$k = (\text{Btu/hr})/(\text{ft}^2\text{-°F/ft});\ T = \text{°F}$$

in metric units

$$k = 38.28 - 0.008597T \qquad \text{(III.A2)}$$

$$k = \text{watts}/(\text{m}^2\ \text{°C/m});\quad T = \text{°C}$$

The data and Eq. III.A1 are shown in Fig. 4.

The tubing in the hot end, the lower 25%, is specified to be $2\frac{1}{4}$ Cr - 1% Mo steel. Steels of this type with chromium and molybdenum as the principal alloying agents and having a total alloy content, Cr + Mo, from 2% to 5% will have almost constant thermal conductivity

ORNL-DWG 76-2160

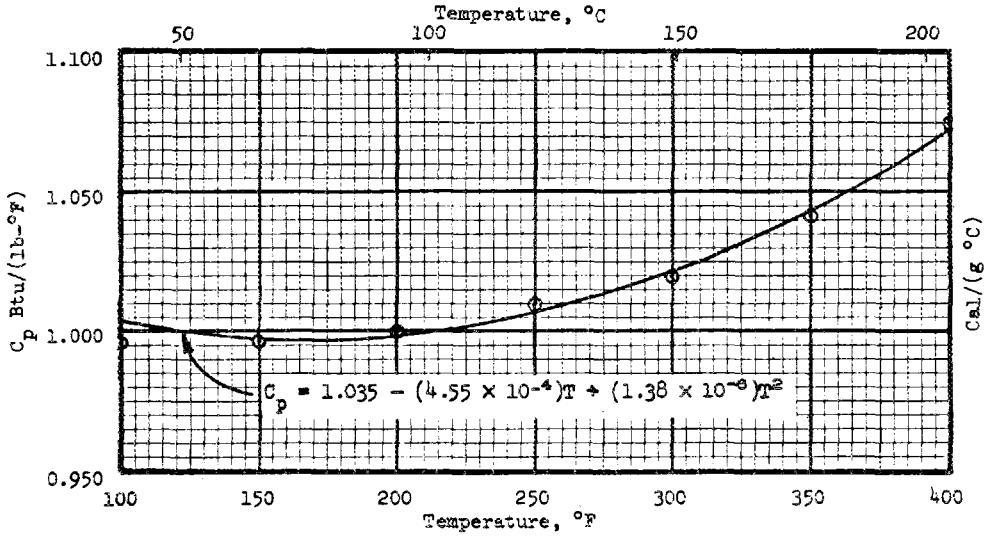

Fig. 3. The specific heat, C_p, of liquid water. Data based on Figure 6 in Ref. 12.

ORNL-DWG 76-2161

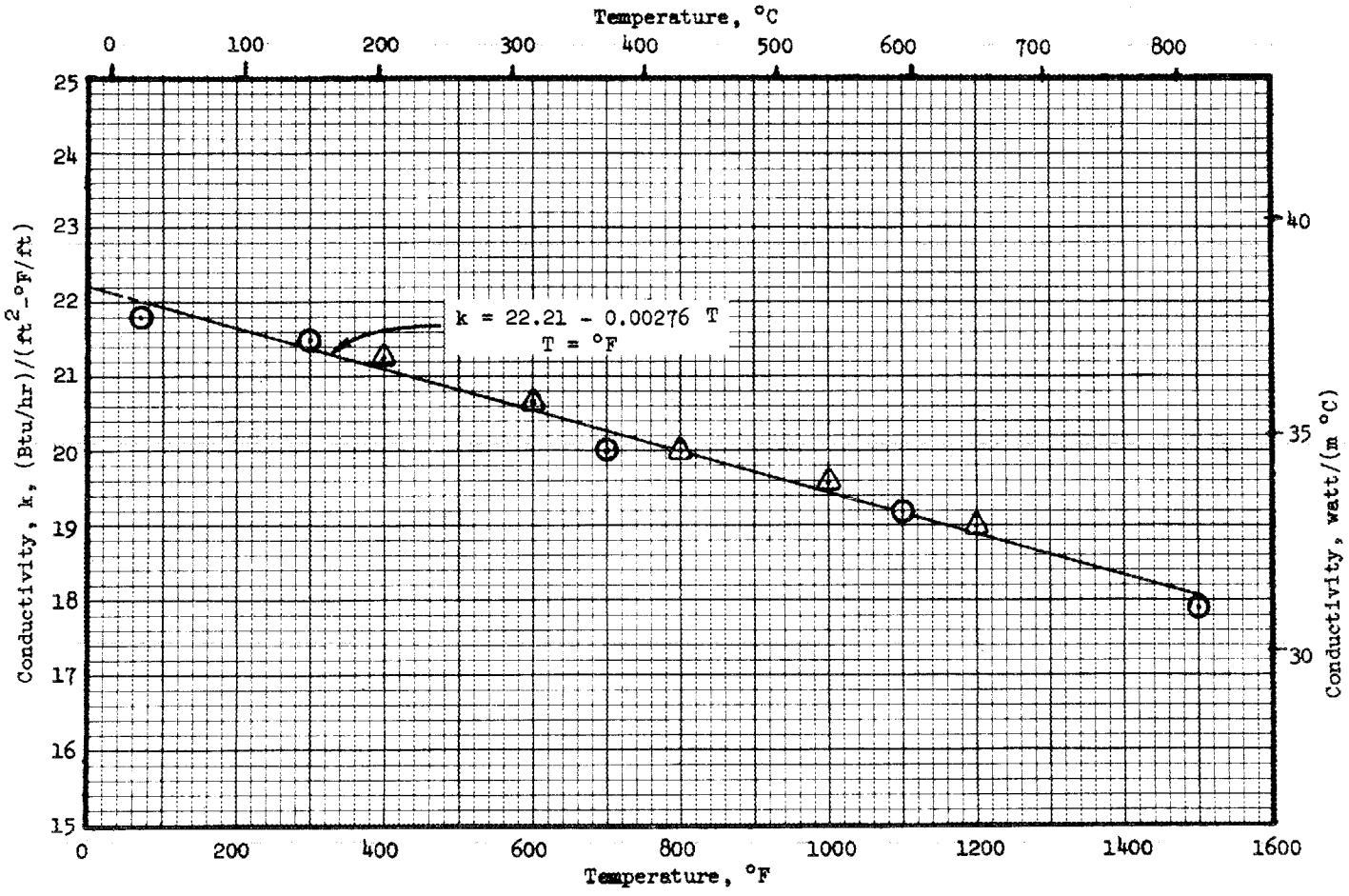

Fig. 4. Thermal conductivity of 1/2% Cr-1/2% Mo steel.
⊙ Data from Ref. 13; ▽ Data from Ref. 14.

from room temperature to 1500°F. From the curves, Fig. 5, and by interpolation of the tabulated data in Ref. 14, the thermal conductivity of this alloy was established to be constant at 16.7 (Btu/hr)/(ft^2-°F/ft).

IV. THE THERMAL TRANSPORT PROPERTIES OF HELIUM DILUTED WITH OXYGEN, NITROGEN AND CARBON MONOXIDE

In an HTGR, the Design Basis Depressurization Accident (DBDA) coupled with a Loss of Main Loop Cooling (LOMLC) involves heat transfer by the CAHE from mixtures of helium with air and the reaction products formed by air in contact with high temperature graphite. It is, therefore, necessary to have good information as to the thermal transport properties of these gas mixtures if reliable computations of afterheat removal rates are required. If the mixture composition is established and if the specific heats of the components therein are known, it is a simple matter to evaluate the specific heat, C_p, of the mixture. A similar statement does not apply to thermal conductivity and viscosity. There are, apparently, no simple theoretical expressions which describe the conductivity and viscosity of gas mixtures in terms of mole fractions, molecular weights, or weight fractions of the components of the mixture and the transport properties of the pure components. This is particularly true when the mixture consists of a monatomic gas and multi-component gas molecules of widely disparate weights; helium and air, for example.

This unfortunate situation is illustrated by quotations from Refs. 15 and 16.

From Reid and Sherwood[15] pages 199 and 201:

6-8. Estimation of the Viscosity of A Gas Mixture

"The extension of the modern molecular theory to describe the viscosity of a nonpolar gas mixture at low pressure has been summarized by Hirschfelder et al. (32,177). The relations obtained are quite complicated, and less complex, though less accurate, relations are given by Wilke (472) and Johnson.

With regard to the problem of estimating viscosities of gas mixtures at elevated pressures, only a small amount of experimental data is available, and proposed estimation methods have not been fully tested."

ORNL-DWG 76-2162

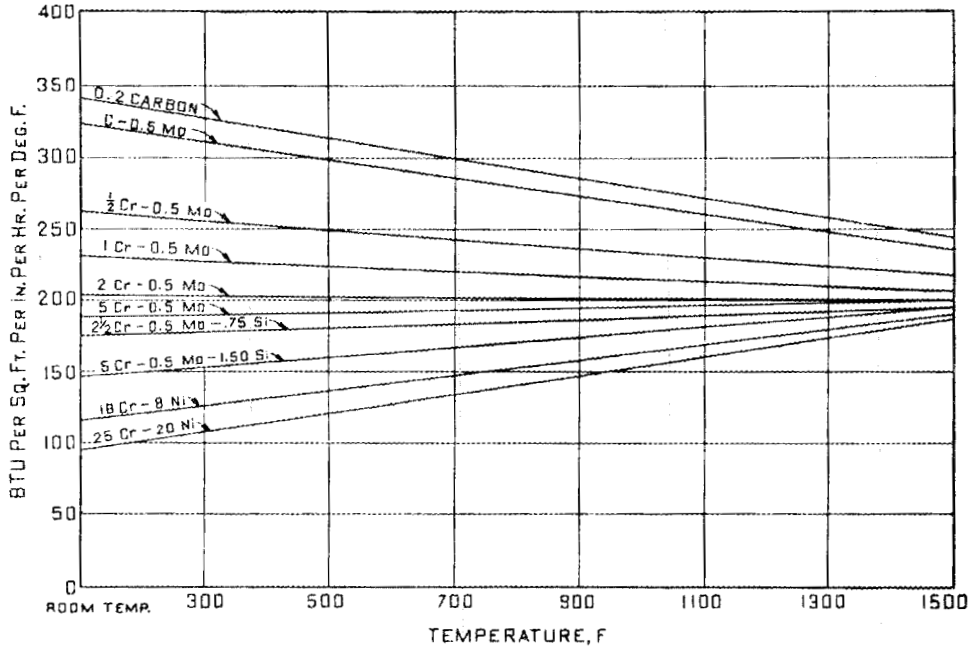

Fig. 5. The thermal conductivity* of chrome-molybdenum alloy steels.

*United States Steel Co. data. This figure is a reproduced copy of data in Ref. 14.

and from page 240:

7-7. Thermal Conductivity of Gas Mixtures

"The thermal conductivity of a gas mixture is not generally a linear function of the composition of the mixture and may be greater or less than that for any of the pure constituents.

Application of the modern kinetic theory to the problem of predicting the thermal conductivities of nonreacting mixtures is quite complicated and gives only fair predictions even for monatomic-gas mixtures. Various semiempirical relations have been developed, however, the best of these being due to Lindsay and Bromley (235) and to Brokaw (40)."

Brokaw[16] states:

"When the experimental thermal conductivities of binary mixtures of hydrogen or helium with heavier gases (mixtures in which thermal conductivity varies over a wide range) are examined the experimental conductivity is lower than that predicted by simple molar mixing, that is:

$$\lambda_m < \lambda_{SM} = x_1 \lambda_1 + x_2 \lambda_2 \qquad \text{(IV.A1)}$$

But measured values are larger than those calculated from a reciprocal mixing rule:"

$$\lambda_m > \lambda_{RM}; \quad \frac{1}{\lambda_{RM}} = \frac{x_1}{\lambda_1} + \frac{x_2}{\lambda_2} \qquad \text{(IV.A2)}$$

x_1, x_2 . . . . . mole fraction

λ_1 λ_2 . . . . . thermal conductivities

SM . . . . . simple mixing

RM . . . . . reciprocal mixing

m . . . . . mixture

It is even more unfortunate that published experimental data on mixture properties are relatively scarce and do not span the range of compositions and temperatures involved in CAHE performance computations.

In summary: There exist small amounts of published experimental data on the viscosity and thermal conductivity of mixtures. Theoretical methods to estimate these properties are available but, as indicated above, they are of uncertain accuracy. In addition, the user will require a more than passing familiarity with statistical and quantum mechanics if these theoretical estimates are to be used with confidence.

It was decided to use such experimental data as are available to develop the temperature and composition dependent relations used to compute viscosity and thermal conductivity of mixtures in the CACHE programs.

Two publications served as sources for the thermal conductivity and viscosity of mixtures of helium diluted with nitrogen and oxygen. The monumental work of Touloukian, Liley and Saxena[10] contains thermal conductivity data-curves and tabulations. A report by Johnson[17] presents experimentally determined viscosities. Neither publication contains ranges required to evaluate, properly and completely, the afterheat removal capability of an HTGR after a DBDA and LOMLC.

It is not possible to determine to a high degree of precision the conditions expected to exist in an HTGR reactor vessel after the extremely unlikely occurrence of a sudden depressurization. The atmosphere in the reactor vessel will be a time varying mixture consisting principally of helium diluted by nitrogen, oxygen and carbon monoxide.

Estimates of conditions in an HTGR after a DBDA + LOMLC have been made.[18] Figure 6 shows the results of a typical set of calculated post-DBDA conditions which have been used as the basis for CAHE heat transfer computations. Note that the constituents of the gas mixture are not explicitly stated; the variation of mixture composition is stated only in terms of molecular weight. This is reasonable since the diluent gases, nitrogen, oxygen and carbon monoxide, are all non-polar and all have similar (28 to 32) molecular weights.

ORNL DWG 76-2163

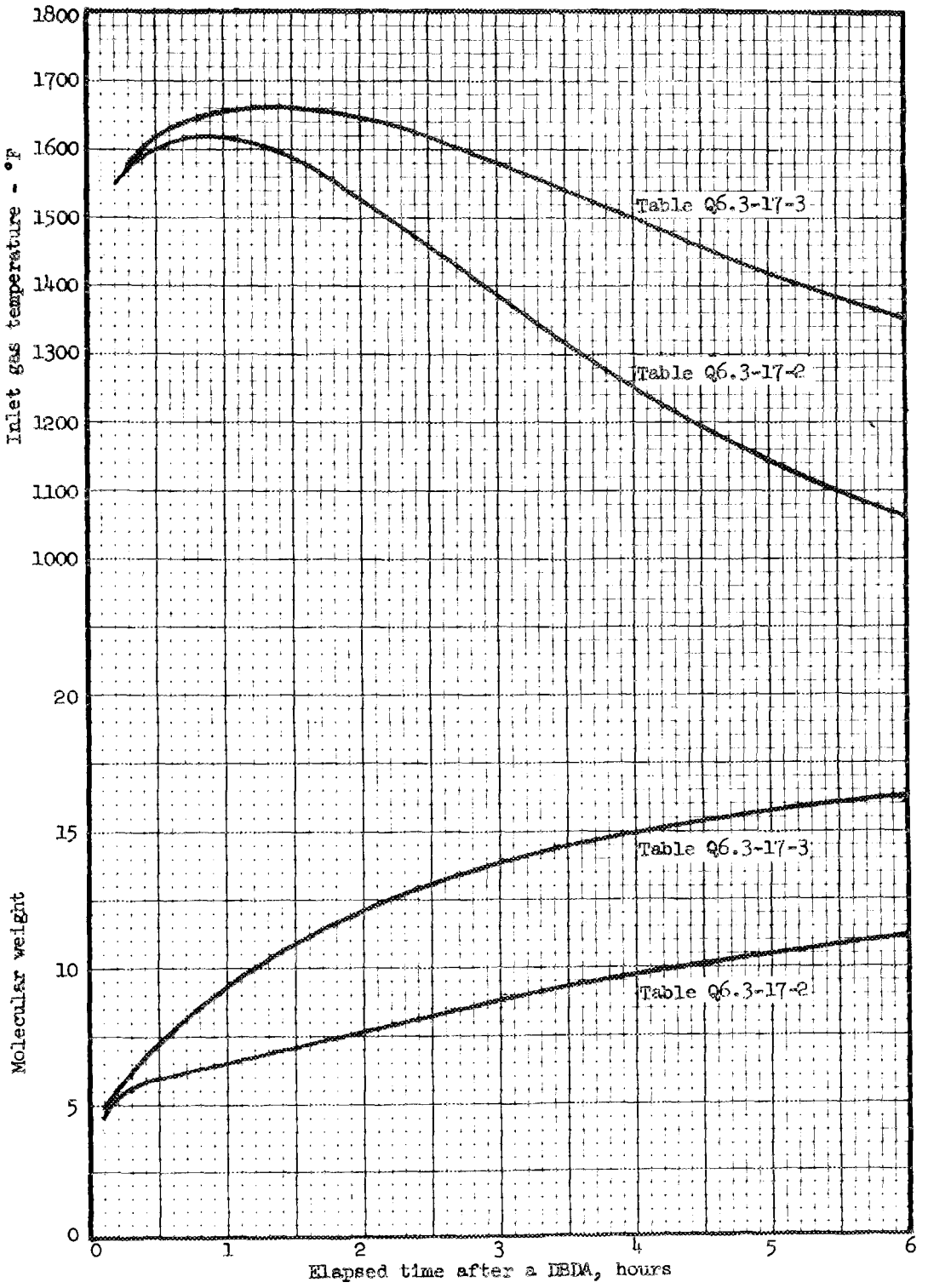

Fig. 6. "Expected" and "conservative" CAHE inlet gas conditions used to analyze the performance of the CAHE after a Design Basis Depressurization Accident (DBDA).

These data from Tables Q.6.3-17.2 and Q6.3-17.3, ch. 23, Feb. 1975, in the Fulton Generating Station PSAR.[18] "Expected" conditions are in Table Q6.3-17.2.

A. The Thermal Conductivity of Helium Diluted with Nitrogen, Oxygen, and Carbon Monoxide

The thermal conductivities of the pure diluent gases and of air are not dissimilar. This is evident from Fig. 7. These curves are based on conductivity tabulations in Ref. 10. In Fig. 8 the thermal conductivities of helium-nitrogen mixtures are shown. The solid line curves represent graphically smoothed experimental data from Table 85b in Ref. 10. The dashed lines are calculated conductivities developed by an equation, IV.A3, shown in the next paragraph.

Experimental data[10] for the helium-nitrogen system and the helium-oxygen system at 113°F, Fig. 9, are nearly identical and tend to support the assumption that the conductivities of helium with any air-like gas with a molecular weight of 28 to 32 are quite similar. The tabulations for the helium-nitrogen system, spanning a wider temperature range, were used to develop the equations used to evaluate the thermal conductivity of the HTGR core coolant gas after a DBDA. The graphical smoothing procedure used to develop these tables[10] produced a recognizable asymptotic error in the 601°F data; i.e., when the mole fraction of nitrogen is zero the tabulated thermal conductivity of pure helium is 0.135 (Btu/hr)/(ft^2-°F/ft). A more correct value, Eq. I.A1, is 0.144. The tabulation of helium-nitrogen system thermal conductivity at 601°F (589K) with the substitution of the higher and correct value of conductivity, when the mole fraction of nitrogen is zero, was used as baseline data to develop the mixture conductivity equation used in HTGR Core Auxiliary Heat Exchanger heat transfer computations after a depressurization accident. The equation arrived at is:

$$k = \left[\frac{.03991}{.27716+F} - .003196 + .07014F - .15767F^2 + .08612F^3\right](T/1061)^{.66} \qquad \text{(IV.A3)}$$

k = mixture thermal conductivity (Btu/hr)/(ft^2-°F/ft)

F = mole fraction of nitrogen (or oxygen or carbon monoxide)

T = absolute temperature, °R

The bracketed polynomial is an equation developed to fit the helium-nitrogen data at 601°F (1061°R). The term in parentheses approximates the variation of conductivity with temperature.

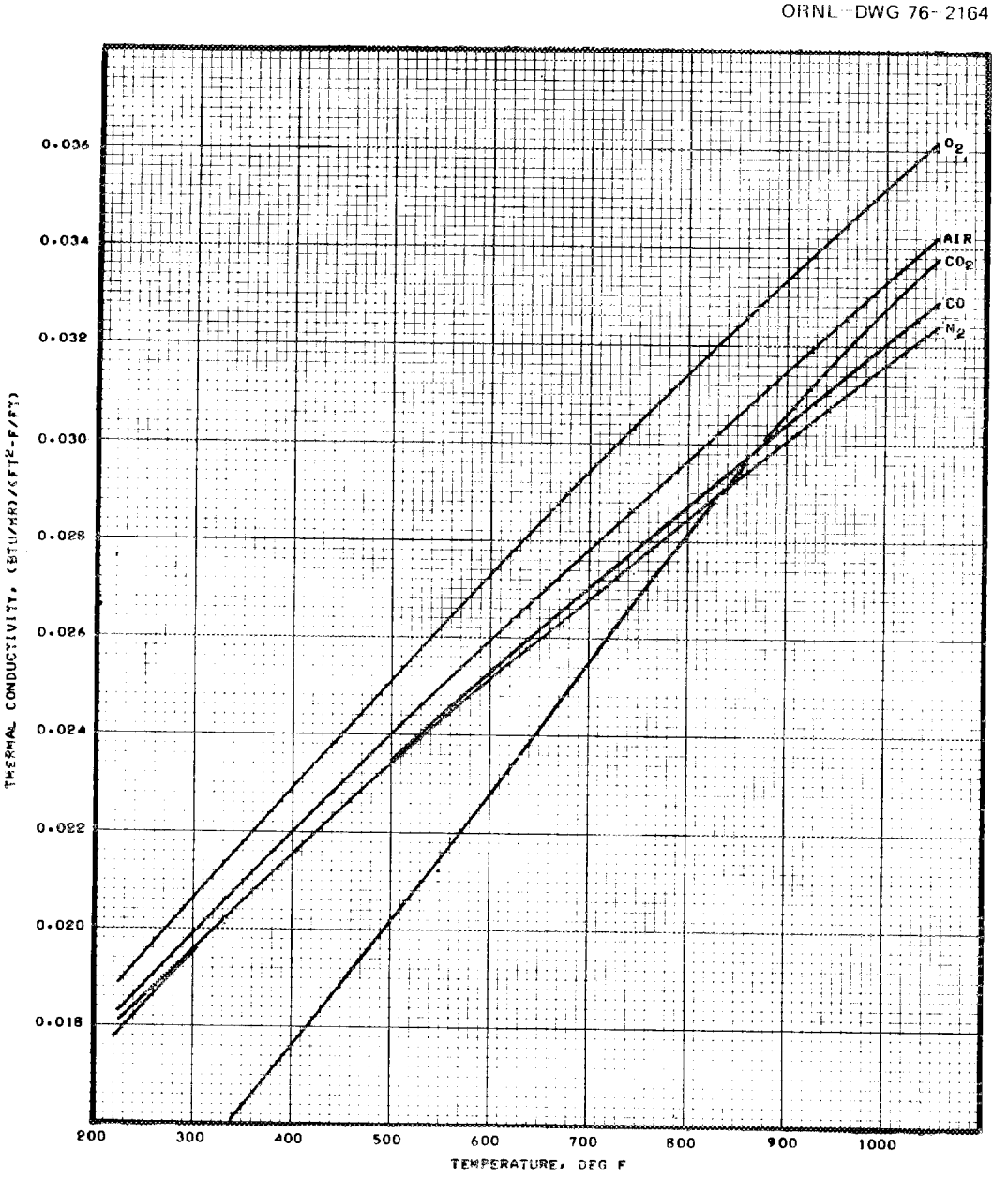

Fig. 7. The thermal conductivities of common gases having molecular weights from 28 to 44.

ORNL-DWG 76-2165

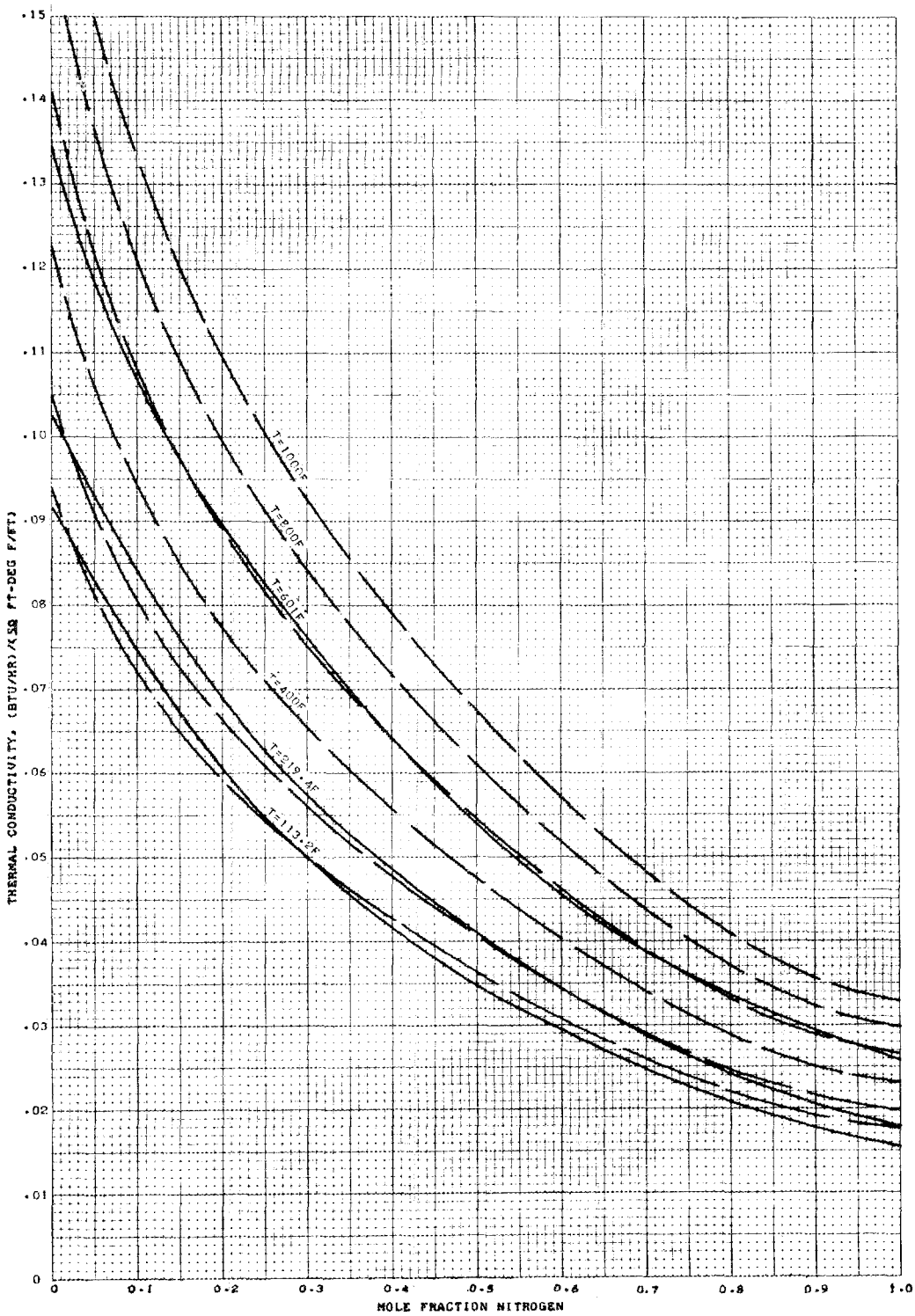

Fig. 8. Thermal conductivity of helium-nitrogen mixtures.

[a]Solid line curves at 601°F, 219.4°F, and 113.2°F are experimentally based data from Ref. 10.

[b]Dashed line curves are calculated with Eq.(IV.A3).

ORNL-DWG 76-2166

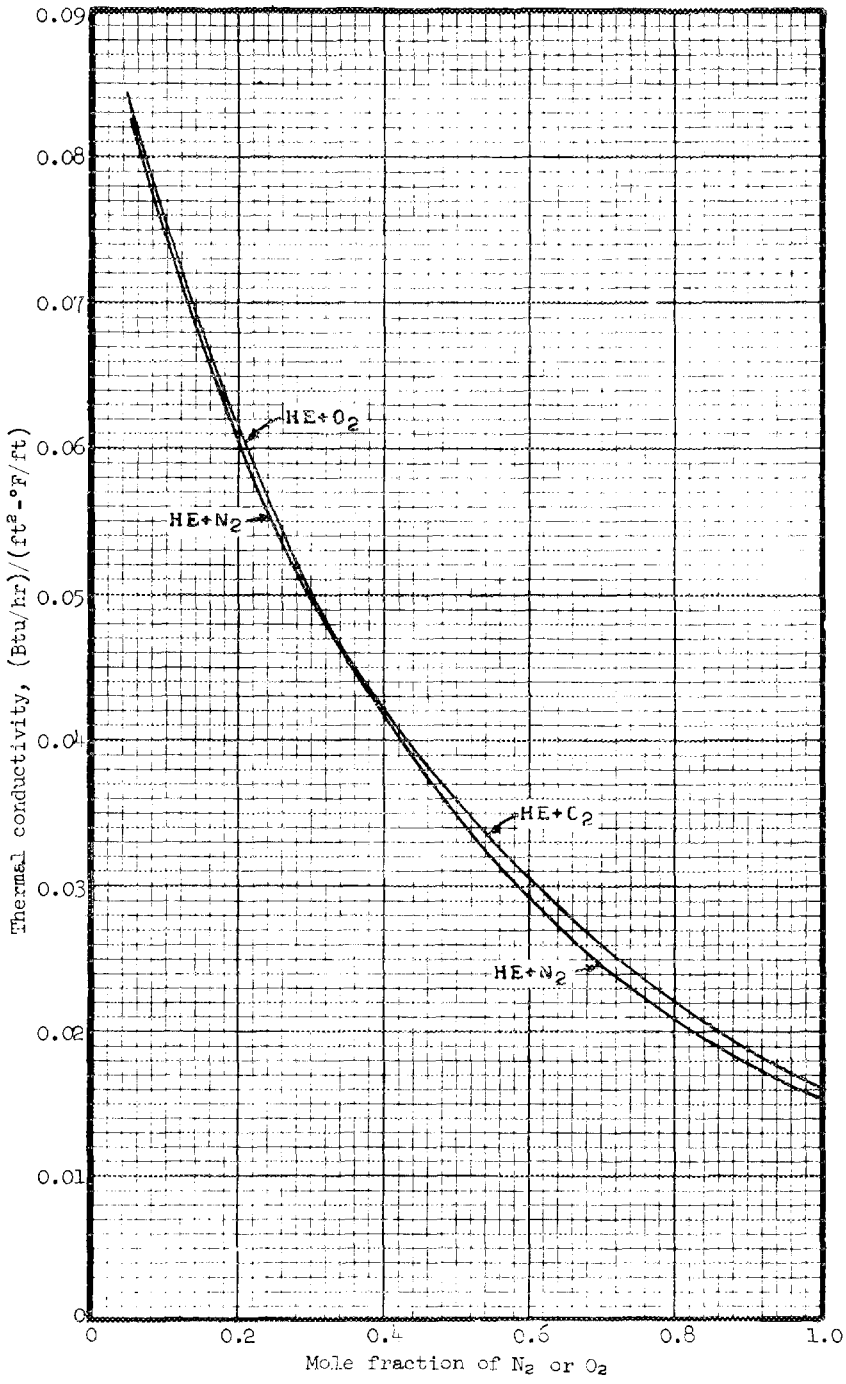

Fig. 9. Thermal conductivity of helium-nitrogem and helium-oxygen mixtures. (Data from Ref. 10).

Figure 10 shows additional curves of thermal conductivity as a function of molecular weight evaluated with Eq. IV.A3. For comparison, the conductivities of pure helium and pure nitrogen are included. The applicable temperature range for typical HTGR computations, based on mean gas film temperatures, is from 300°F to 1000°F. The anticipated mixture molecular weights are not expected to exceed 20. Additional data and discussion of the procedure used to develop Eq. IV.A3 is in Appendix B.

B. The Viscosity of Helium Diluted with Nitrogen, Oxygen, and Carbon Monoxide

The viscosity of helium mixed with oxygen, nitrogen, and carbon monoxide has been estimated by using experimental data published by Johnson.[17] This report contains experimental curves of viscosity versus temperature for three mixtures of oxygen and helium. The oxygen mole fractions in the mixtures were 0.28, 0.53, and 0.72 corresponding to mixture molecular weights of 11.8, 18.8, and 24.2. Garber* developed three equations to fit Johnson's data. These are:

A. Mole fraction O_2 = 0.28

$$\mu = (5.942 \times 10^{-4})T^{.71} \qquad \text{(IV.B1)}$$

B. Mole fraction O_2 = 0.53

$$\mu = (7.216 \times 10^{-4})T^{.685} \qquad \text{(IV.B2)}$$

C. Mole fraction O_2 = 0.72

$$\mu = (10.50 \times 10^{-4})T^{.629} \qquad \text{(IV.B3)}$$

μ = viscosity, lbm/ft-hr

T = absolute temperature, °Rankine

Figure 11 shows the experimental viscosity data from Johnson's report, a gas mixture viscosity curve calculated with Eq. IV.B1, and the viscosity of pure helium calculated with Eq. I.B2. Unlike the thermal conductivity of similar gas mixtures, the addition of oxygen to helium

*S. P. Garber, ORNL summer participant (student) sponsored and funded by Oak Ridge Associated Universities.

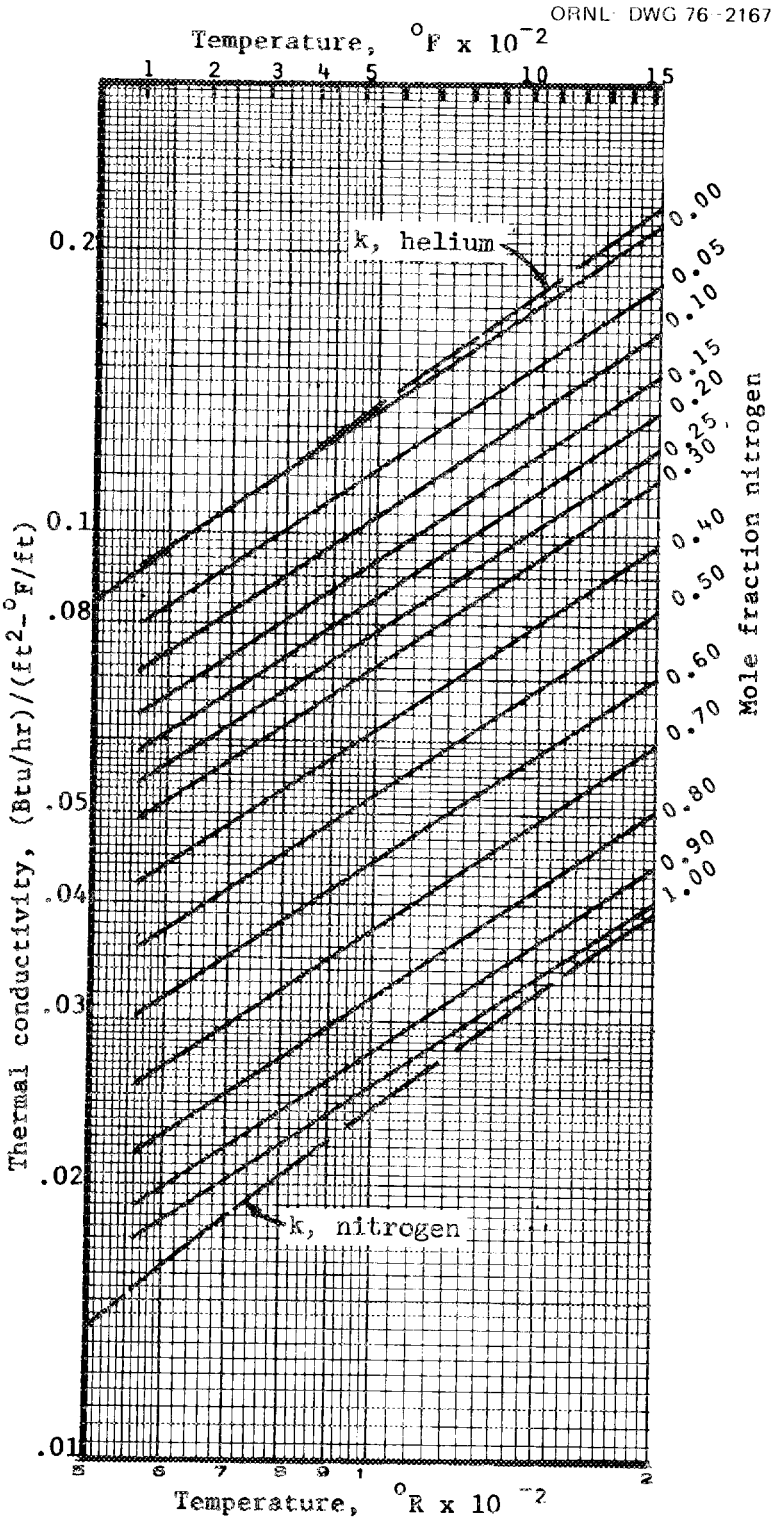

Fig. 10. The thermal conductivity of helium–nitrogen gas mixtures from Eq. IV. A3 and the thermal conductivities of pure helium[1] and pure nitrogen.[10]

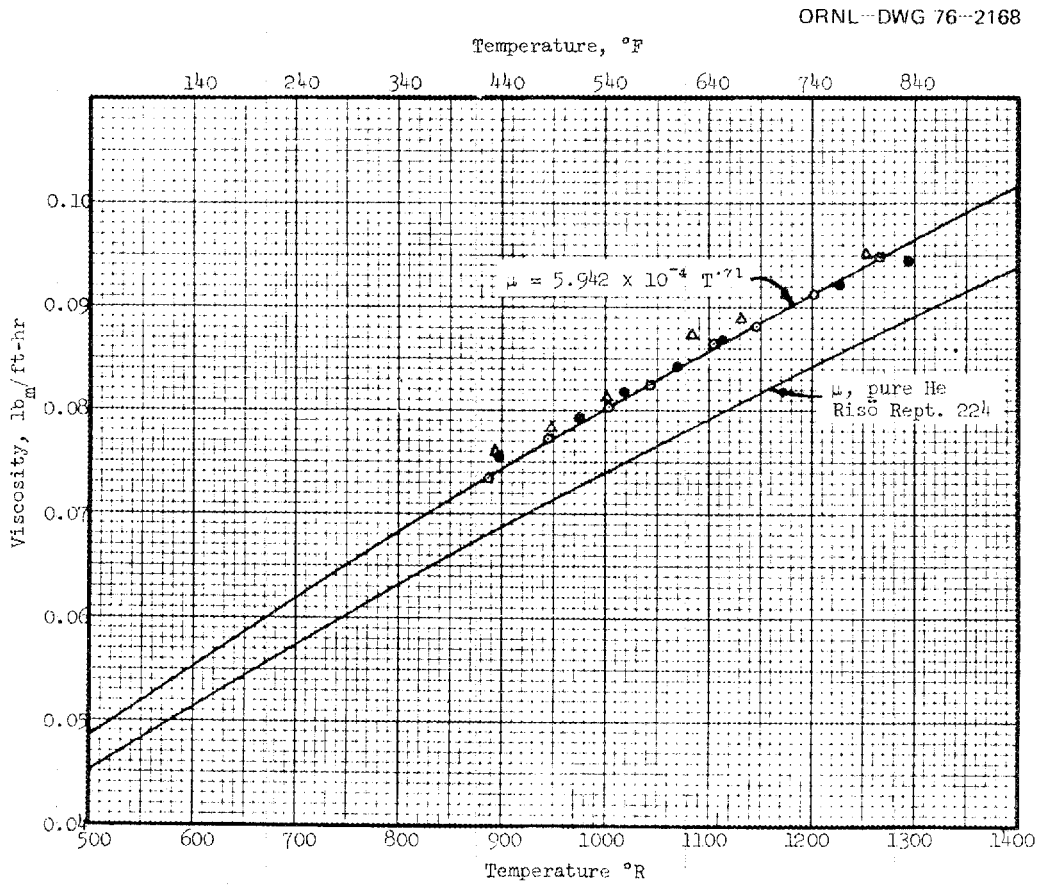

Fig. 11. The viscosity of helium and helium-oxygen mixtures.

*Experimental data

○ 28 mole% O_2

● 53 mole% O_2

▽ 72 mole% O_2

*C. A. Johnson; SURI Rept. Che. E. 273-566 F3, 1956.

does not produce drastic changes in the viscosity of the resulting mixture if compared with the viscosity of pure helium. The data also show that when the mole fraction of oxygen in the mixture exceeds 0.28 that oxygen additions to the mixture have little or no effect on viscosity. This aspect of mixture behavior is well illustrated by Fig. 12 also derived from Johnson's work. The continuous curves are theoretical calculations by Johnson[17] of viscosity as a function of composition. The results of two theoretical methods are shown. The three discrete points are experimental values. The agreement of theory and these experiments is adequate from the standpoint of use in heat transfer computations and tends to contradict the general statements by Reid and Sherwood and by Brokaw cited earlier in this report. Additional experimental evidence is a prerequisite to firm conclusions regarding such agreement.

By inspection of Fig. 11 it is apparent that Eq. IV.B1 is a sufficiently good fit to the data for mixtures containing oxygen mole fractions of 0.28, and 0.53. This equation currently is used to specify mixture viscosity in CAHE heat transfer calculations when the gas mixture molecular weight is above 11.0.

When the molecular weight of the gas mixture is less than 11.0, equivalent to an air mole fraction of 0.28, mixture viscosity is specified by a simple linear interpolation between the viscosity of gas mixture with oxygen mole fraction of 0.28 and the viscosity of pure helium. The interpolating equation used in the CACHE heat exchange program is:

$$\mu_m = (F_d/.28)\ (\mu_{.28}) + [(0.28 - F_d)/.28]\mu_h$$

F_d = mole fraction of diluent gas or gases (nitrogen, oxygen, carbon monoxide); $0.0 \leq F_d < 0.28$

$\mu_{.28}$ = viscosity of helium-air mixture containing 0.28 mole fraction of oxygen, evaluated with Eq. IV.B1; lb_m/ft-hr

μ_h = viscosity of pure helium evaluated with Eq. I.B2, lb_m/ft-hr

μ_m = gas mixture viscosity, lb_m/ft-hr.

Figure 13 shows viscosity versus mixture composition for the temperature range applicable to post-DBDA calculations of CAHE performance.

ORNL-DWG 76-2169

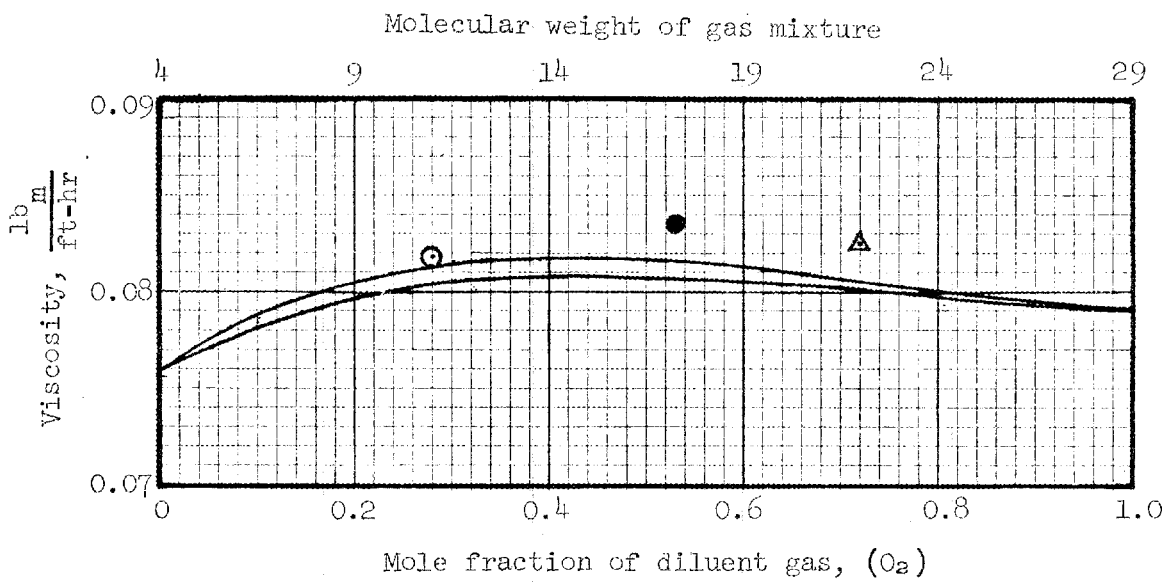

Fig. 12. Viscosity of helium-oxygen gas mixtures at 571°F (1031°R) based on data in Ref. 17.

NOTE: (1) The continuous curves are theoretical values.
(2) The molecular weight scale is based on the assumption that oxygen and air are equivalent.

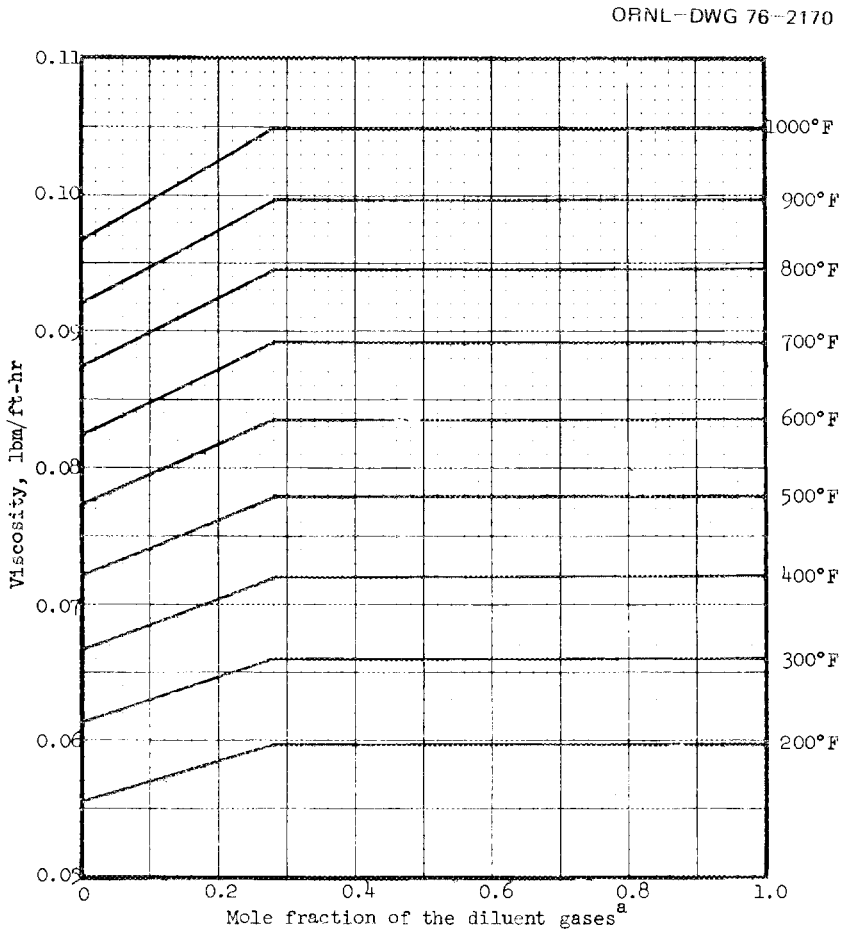

Fig. 13. Viscosity of the gas mixtures[a] used to calculate Core Auxiliary Heat Exchanger (CAHE) performance after a Design Basis Depressurization Accident (DBDA).

[a]The gas mixture is assumed to consist of helium diluted with nitrogen, carbon monoxide, and oxygen.

Use of this method of specifying viscosity contains these implicit assumptions:

(1) The viscosity of mixtures of helium with carbon monoxide and/or nitrogen behave similarly to helium-oxygen viscosities and are numerically similar. In this connection it is noted that the molecular weights of these diluent gases are equal or nearly equal and that the viscosities of the pure diluent gases are not far apart. Appendix C contains viscosity data for pure nitrogen, oxygen, carbon monoxide and air to illustrate this similarity.

(2) That Eq. IV.B1 is a good approximation to mixture viscosities at gas temperatures not included in Johnson's experiments. This is not unreasonable since, very generally, gas viscosity tends to vary with absolute temperature raised to a fractional exponent at temperatures encompassing CAHE computational requirements.

It is, perhaps, fortunate that small percentage changes or errors in specifying gas viscosity are reflected as considerably smaller changes in the gas film heat transfer coefficient.[19] In a typical CAHE heat exchange computation involving gas mixtures, a 10% error in specifying mixture viscosity will alter the computed gas film coefficient by approximately 3%. From Fig. 11 it is seen that, from temperatures of 430°F to 930°F, the viscosity increases produced by adding oxygen to helium are about 10%; i.e., if helium viscosity were specified, regardless of the gas composition, the calculated CAHE performance would be increased approximately 3%.

C. The Specific Heat of Helium-Air Gas Mixtures

The specific heat of a gas mixture is obtained by summing the products of the specific heats of the component gases and their weight fractions in the mixture. In a mixture of N different gases the mixture specific heat is

$$(C_p)_{mixt} = Y_1(C_p)_1 + Y_2(C_p)_2 + \cdots + Y_N(C_p)_N \qquad \text{(IV.C1)}$$

$(C_p)_{mixt}$ = mixture specific heat, Btu/lb-°F

$(C_p)_1$, $(C_p)_2$ ··· $(C_p)_N$ = specific heats of the component gases in the mixture

Y_1, Y_2 ·· Y_N = weight fractions of the component gases in the mixture

For HTGR computations it has been assumed that the specific heat of air is representative of the specific heats of the gases that dilute the helium after a DBDA. The specific heat of air has been well established; therefore, it is considered to be a single component gas of molecular weight 29 for purposes of determining post-DBDA gas mixture specific heat. For helium-air mixtures IV.C1 becomes

$$(C_p)_{mixt} = Y_h(C_p)_h + (1-Y_h)(C_p)_a, \text{ Btu/lb-°F} \qquad \text{(IV.C2)}$$

Y_h = weight fraction of helium in the mixture

$(C_p)_h$ = specific heat of helium

$(C_p)_h = 1.242$ Btu/lb-°F

$(C_p)_a$ = specific heat of air, Btu/lb-°F

$$(C_p)_a = 0.2304 + (3.7672 \times 10^{-5})\,T - (4.860 \times 10^{-9})T^2 \qquad \text{(IV.C3)}$$

T = °F

Figure 14 shows the specific heats of air-helium mixtures at 300°F and 1000°F as a function of the molecular weight of the mixture. Weight and mole fractions of the air in the mixture are included in Fig. 14.

Appendix D contains equations for computing weight fractions and mole fractions from the molecular weight of the mixture. This appendix also contains tabulations, and on Fig. D.2 ,curves of the specific heats of air, oxygen, nitrogen, and carbon monoxide. These are the gases which are predicted to exist in the primary containment in the unlikely event of a DBDA. It can be noted from Fig. D.2 that, as should be expected from the similarity of their molecular weights, the specific heats of nitrogen, carbon monoxide and oxygen are not far apart. The data for air is compared with calculated values from Eq. IV.C3, the least squares fit to the data.

ORNL-DWG 76-2171

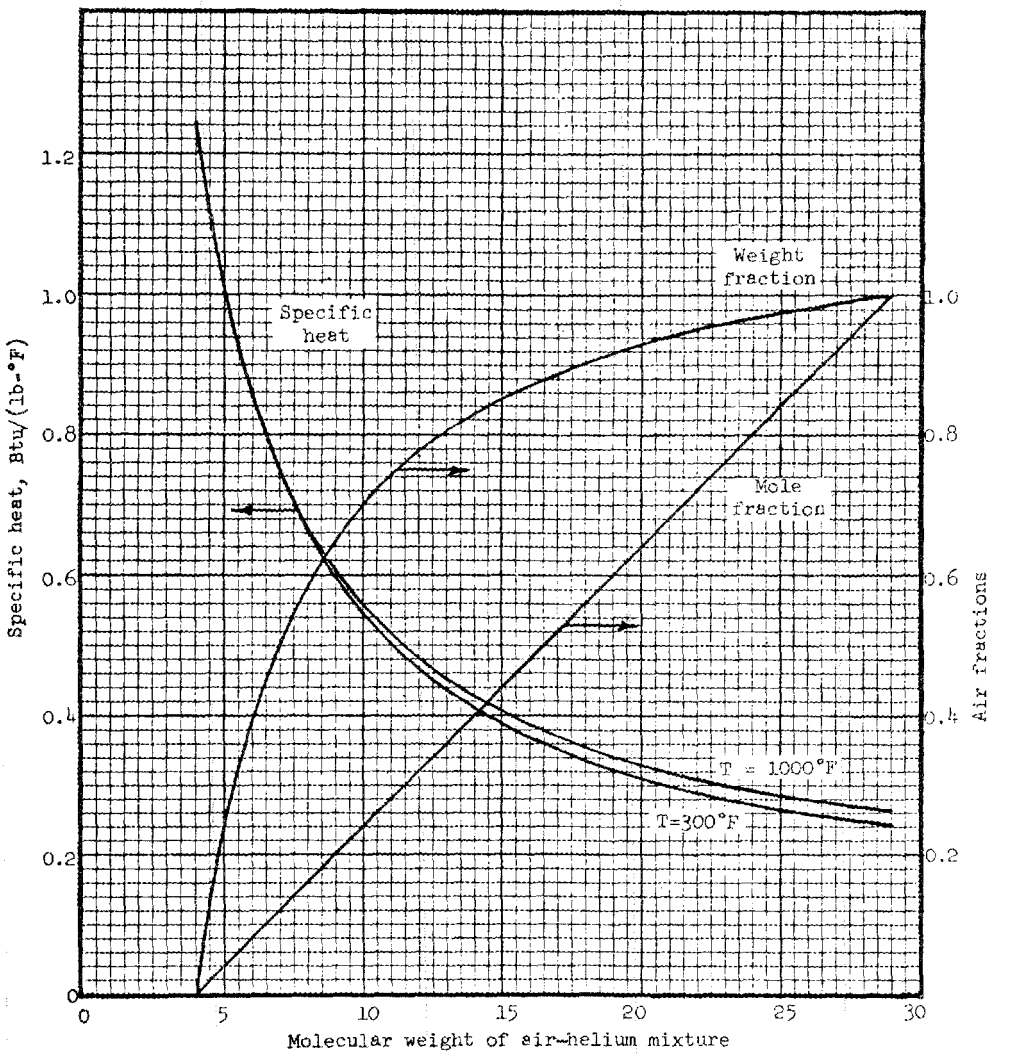

Fig. 14. The specific heat and fractional composition of air-helium mixtures.

Appendix A

Equations and Tabulations for the Thermal Conductivity of Pure Helium

During and after establishing the programs to calculate HTGR heat exchanger performance, it became evident that persons currently investigating heat transfer by helium are not using the same equations to evaluate the viscosity and thermal conductivity of helium. Because the results of the computations are likely to receive careful scrutiny, it was deemed appropriate to investigate the variations in computed properties obtained by choices of the thermal conductivity equation used in the heat transfer programs. The effect on computed heat transfer rates was then estimated.

Since the information has been gathered and is available, it is incorporated in this appendix with the thought that others may find the data useful.

Six equations for thermal conductivity are listed.* No attempt to evaluate them on a comparative basis was made and none should be inferred. Figures A1 and A2 show maximum and minimum curves of conductivity at two pressures. These curves are envelopes and, between them, enclose all values of conductivity computed from the six equations listed. Typical calculations of Core Auxiliary Heat Exchanger (CAHE) performance involve helium film temperatures from 300°F to 1000°F with average film temperatures in the 600°F – 700°F region. At 750 psia and 650°F the maximum and minimum values of calculated conductivity are 0.151 and 0.146 (Btu/hr)/(ft^2-°F/ft). In CAHE performance calculations the gas side film coefficient of heat transfer is evaluated with equations having the general form:

$$N_{Nu} = \frac{h}{Dk} = C_o \, N_{Re}^{\;x} \, N_{Pr}^{\;y} \tag{A.1A}$$

or

$$h = C_o \, Dk \left[\frac{DG}{\mu}\right]^x \left[\frac{C_p \mu}{k}\right]^y \tag{A.1B}$$

*(Refs. 1, 2, 8, 20, 21, 22, 23, 24)

ORNL-DWG 75-9953

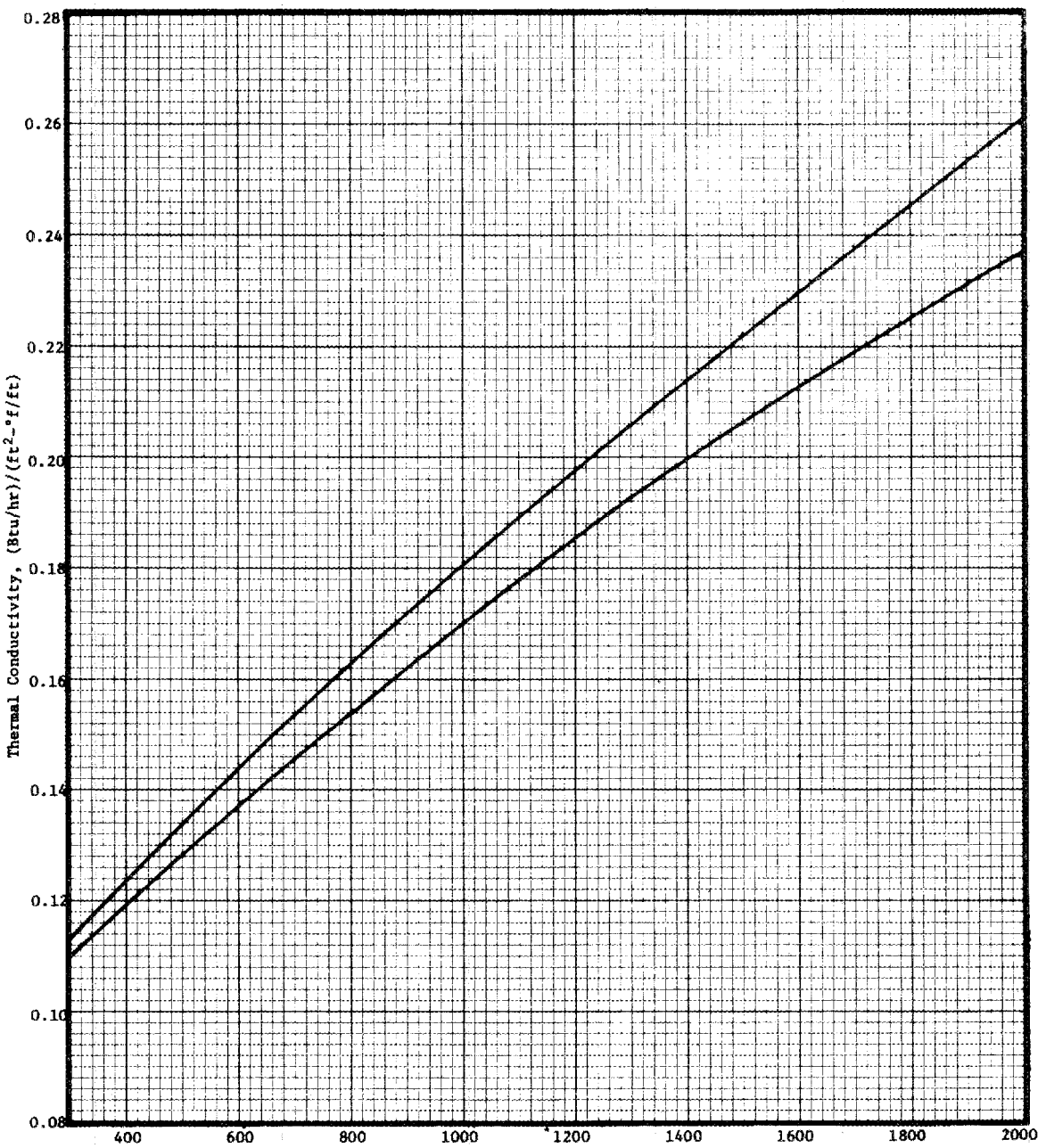

Fig. A.1. The range, maximum and minimum values, of helium thermal conductivity at 14.7 psia from the computed values in Table A.1.

ORNL-DWG 75 9954

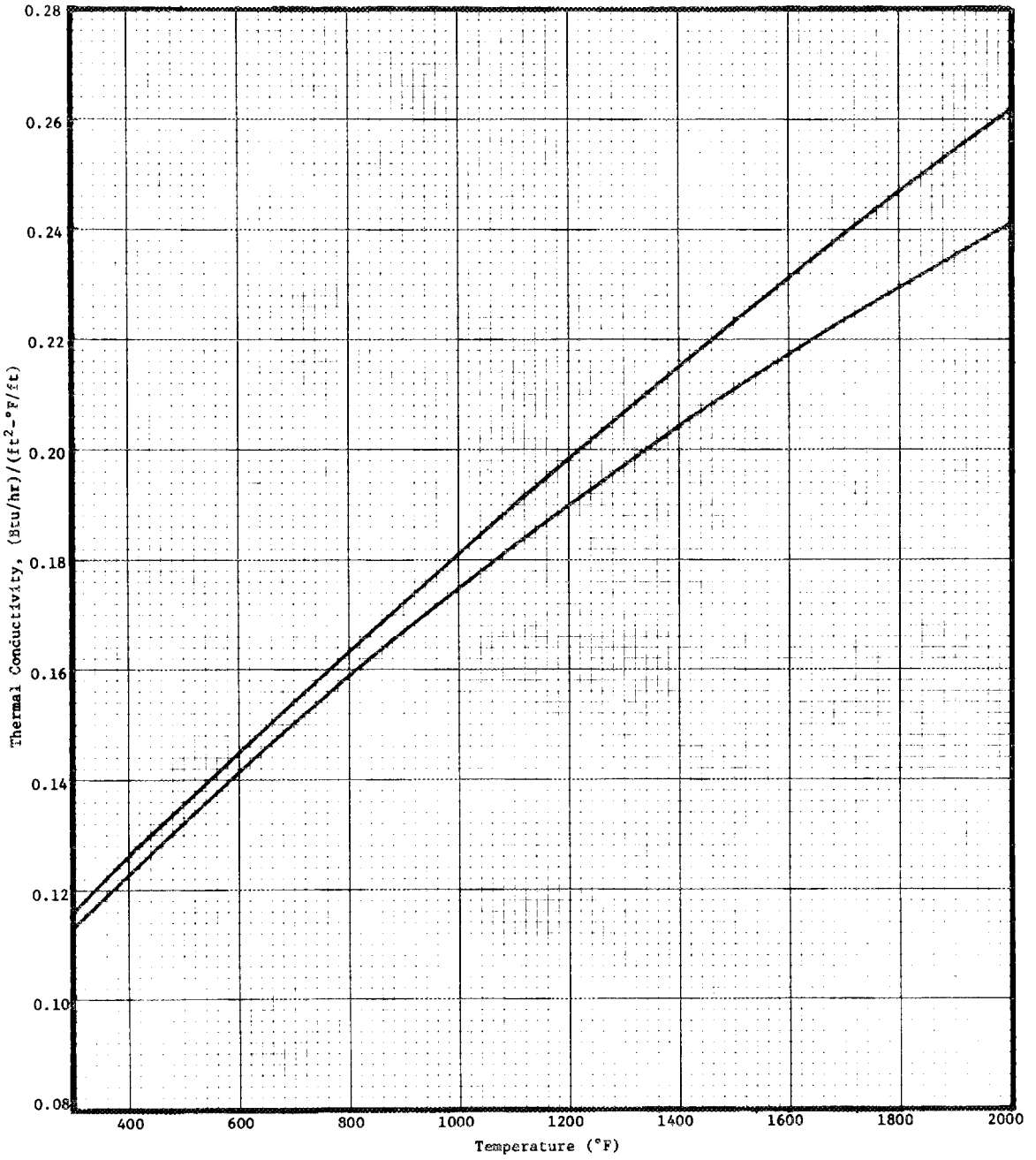

Fig. A.2. The range, maximum and minimum values, of helium thermal conductivity at 750 psia from the computed values in Table A.4.

in which

h = film coefficient of heat transfer, (Btu/hr)/(ft^2-°F)

k = thermal conductivity of the gas evaluated at the mean film temperature, (Btu/hr)/(ft^2-°F/ft)

μ = viscosity of the gas evaluated at the mean film temperature, lb/ft-hr

D = equivalent diameter (tube dia.), ft

G = mass flow rate of gas, lb/(ft^2-hr)

C_p = specific heat, at constant pressure, of the gas, Btu/(lb-°F)

C_o = constant

It is easy to show that the effect (the fractional change in the film coefficient, h) produced by incremental differences, Δk and $\Delta\mu$, in thermal conductivity and viscosity is given by:

$$\frac{\Delta h}{h} = (1 - y)\frac{\Delta k}{k} - (x - y)\frac{\Delta\mu}{\mu} \qquad \text{(A.2A)}$$

Typical values of the exponents x and y will be 0.60 and 0.33, respectively. The above equation then becomes

$$\frac{\Delta h}{h} = 0.67\frac{\Delta k}{k} - 0.27\frac{\Delta\mu}{\mu} \qquad \text{(A.2B)}$$

In Fig. A.2 the maximum and minimum values of k at 650°F are 0.151 and 0.146; using their difference as Δk in Eq. A.2B:

$$\frac{\Delta h}{h} = 0.67\frac{(0.151 - 0.146)}{0.151} = 0.022$$

It can be concluded that, for CAHE performance calculations, if helium conductivity is evaluated with any of the listed equations, the results will be uniform within about 2%.

Tables A.1 through A.7 are helium conductivities calculated using the equations A.3 through A.8 in the following section. Conductivities are in English and metric units. It should be mentioned that:
(1) Equation A.3 (Ref. 1), used in the CACHE programs* to compute CAHE performance during operation with pressurized helium gives values on or near the maximum curves on Figs. A.1 and A.2.

*J. R. Tallackson, CACHE—An Extended Basic Program which Computes the Performance of Shell and Tube Heat Exchangers, ORNL-TM-4952, 1975.

Table A.1

THERMAL CONDUCTIVITY OF HELIUM AT 14.696 PSIA

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

REFERENCE LIST:

K1; RISO REPT 224. K2; GA CO.
K3; J.P. SANDERS, ORNL. K4; D.L. MC ELROY, ORNL
K5; JULICH, REPT KFA-IRE-17/72.
K6; ASHRAE, THERMOPHYS. PROP., 1973.

PRESSURE = 14.696 PSIA = 1 ATM = 1.01327 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
50.00	509.70	0.0854	0.0862	0.0859
BTU/(HR-FT-F)		---	0.0845	0.0843
10.01	283.17	0.1478	0.1491	0.1486
WATT/(METER-K)		---	0.1463	0.1459
100.00	559.70	0.0912	0.0918	0.0908
BTU/(HR-FT-F)		---	0.0905	0.0901
37.78	310.94	0.1579	0.1588	0.1572
WATT/(METER-K)		---	0.1567	0.1559
150.00	609.70	0.0969	0.0972	0.0957
BTU/(HR-FT-F)		---	0.0963	0.0957
65.56	338.72	0.1678	0.1683	0.1656
WATT/(METER-K)		---	0.1668	0.1657
200.00	659.70	0.1025	0.1025	0.1005
BTU/(HR-FT-F)		---	0.1020	0.1013
93.34	366.50	0.1775	0.1774	0.1739
WATT/(METER-K)		---	0.1766	0.1754
250.00	709.70	0.1080	0.1077	0.1052
BTU/(HR-FT-F)		---	0.1076	0.1069
121.12	394.23	0.1869	0.1864	0.1821
WATT/(METER-K)		---	0.1862	0.1850

Table A.1 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 14.696 PSIA = 1 ATM = 1.01327 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
300.00	759.70	0.1133	0.1128	0.1099
BTU/(HR-FT-F)		---	0.1130	0.1123
148.90	422.06	0.1961	0.1952	0.1902
WATT/(METER-K)		---	0.1956	0.1944
350.00	809.70	0.1186	0.1177	0.1145
BTU/(HR-FT-F)		---	0.1184	0.1177
176.67	449.83	0.2052	0.2037	0.1983
WATT/(METER-K)		---	0.2049	0.2037
400.00	859.70	0.1237	0.1226	0.1191
BTU/(HR-FT-F)		---	0.1236	0.1230
204.45	477.61	0.2141	0.2121	0.2062
WATT/(METER-K)		---	0.2140	0.2129
450.00	909.70	0.1288	0.1273	0.1237
BTU/(HR-FT-F)		0.1308	0.1288	0.1282
232.23	505.39	0.2229	0.2204	0.2140
WATT/(METER-K)		0.2263	0.2229	0.2219
500.00	959.70	0.1338	0.1320	0.1281
BTU/(HR-FT-F)		0.1353	0.1339	0.1334
260.01	533.17	0.2315	0.2284	0.2218
WATT/(METER-K)		0.2342	0.2317	0.2308
550.00	1009.70	0.1387	0.1366	0.1326
BTU/(HR-FT-F)		0.1398	0.1389	0.1384
287.78	560.94	0.2400	0.2364	0.2294
WATT/(METER-K)		0.2420	0.2403	0.2396

Table A.1 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 14.696 PSIA = 1 ATM = 1.01327 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
600.00	1059.70	0.1435	0.1411	0.1369
BTU/(HR-FT-F)		0.1443	0.1438	0.1433
315.56	588.72	0.2484	0.2442	0.2370
WATT/(METER-K)		0.2498	0.2489	0.2481
650.00	1109.70	0.1483	0.1456	0.1412
BTU/(HR-FT-F)		0.1488	0.1486	0.1482
343.34	616.50	0.2567	0.2519	0.2444
WATT/(METER-K)		0.2575	0.2572	0.2564
700.00	1159.70	0.1530	0.1500	0.1455
BTU/(HR-FT-F)		0.1532	0.1534	0.1529
371.12	644.28	0.2648	0.2595	0.2518
WATT/(METER-K)		0.2651	0.2655	0.2646
750.00	1209.70	0.1577	0.1543	0.1497
BTU/(HR-FT-F)		0.1575	0.1581	0.1575
398.90	672.06	0.2729	0.2670	0.2591
WATT/(METER-K)		0.2726	0.2737	0.2726
800.00	1259.70	0.1623	0.1586	0.1538
BTU/(HR-FT-F)		0.1618	0.1627	0.1620
426.67	699.83	0.2809	0.2744	0.2662
WATT/(METER-K)		0.2801	0.2817	0.2804
850.00	1309.70	0.1668	0.1628	0.1579
BTU/(HR-FT-F)		0.1661	0.1673	0.1665
454.45	727.61	0.2887	0.2817	0.2733
WATT/(METER-K)		0.2875	0.2896	0.2881

Table A.1 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 14.696 PSIA = 1 ATM = 1.01327 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
900.00	1359.70	0.1713	0.1669	0.1619
BTU/(HR-FT-F)		0.1704	0.1718	0.1708
482.23	755.39	0.2965	0.2889	0.2803
WATT/(METER-K)		0.2949	0.2973	0.2956
950.00	1409.70	0.1758	0.1710	0.1659
BTU/(HR-FT-F)		0.1746	0.1762	0.1751
510.01	783.17	0.3042	0.2960	0.2372
WATT/(METER-K)		0.3022	0.3050	0.3030
1000.00	1459.70	0.1802	0.1751	0.1699
BTU/(HR-FT-F)		0.1788	0.1805	0.1793
537.78	810.94	0.3118	0.3031	0.2940
WATT/(METER-K)		0.3094	0.3125	0.3103
1050.00	1509.70	0.1845	0.1791	0.1737
BTU/(HR-FT-F)		0.1829	0.1848	0.1834
565.56	838.72	0.3194	0.3100	0.3007
WATT/(METER-K)		0.3165	0.3198	0.3174
1100.00	1559.70	0.1888	0.1831	0.1775
BTU/(HR-FT-F)		0.1870	0.1889	0.1875
593.34	866.50	0.3268	0.3169	0.3073
WATT/(METER-K)		0.3236	0.3270	0.3244
1150.00	1609.70	0.1931	0.1870	0.1813
BTU/(HR-FT-F)		0.1910	0.1930	0.1914
621.12	894.28	0.3343	0.3237	0.3138
WATT/(METER-K)		0.3306	0.3341	0.3313

Table A.1 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 14.696 PSIA = 1 ATM = 1.01327 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
1200.00	1659.70	0.1974	0.1909	0.1850
BTU/(HR-FT-F)		0.1951	0.1970	0.1954
648.90	922.06	0.3416	0.3305	0.3202
WATT/(METER-K)		0.3376	0.3410	0.3381
1250.00	1709.70	0.2016	0.1948	0.1886
BTU/(HR-FT-F)		0.1990	0.2009	0.1992
676.67	949.83	0.3489	0.3371	0.3265
WATT/(METER-K)		0.3445	0.3477	0.3448
1300.00	1759.70	0.2057	0.1986	0.1922
BTU/(HR-FT-F)		0.2030	0.2047	0.2030
704.45	977.61	0.3561	0.3438	0.3327
WATT/(METER-K)		0.3513	0.3543	0.3514
1350.00	1809.70	0.2099	0.2024	0.1958
BTU/(HR-FT-F)		0.2069	0.2085	0.2068
732.23	1005.39	0.3632	0.3503	0.3388
WATT/(METER-K)		0.3581	0.3608	0.3578
1400.00	1859.70	0.2140	0.2062	0.1993
BTU/(HR-FT-F)		0.2108	0.2122	0.2104
760.01	1033.17	0.3703	0.3568	0.3449
WATT/(METER-K)		0.3648	0.3672	0.3642
1450.00	1909.70	0.2180	0.2099	0.2027
BTU/(HR-FT-F)		0.2146	0.2158	0.2141
787.78	1060.94	0.3774	0.3632	0.3508
WATT/(METER-K)		0.3714	0.3734	0.3705

Table A.1 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 14.696 PSIA = 1 ATM = 1.01327 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
1500.00	1959.70	0.2221	0.2136	0.2061
BTU/(HR-FT-F)		0.2184	0.2193	0.2177
815.56	1088.72	0.3843	0.3696	0.3566
WATT/(METER-K)		0.3779	0.3796	0.3767
1550.00	2009.70	0.2261	0.2172	0.2094
BTU/(HR-FT-F)		0.2221	0.2228	0.2212
843.34	1116.50	0.3913	0.3760	0.3624
WATT/(METER-K)		0.3844	0.3856	0.3828
1600.00	2059.70	0.2301	0.2208	0.2126
BTU/(HR-FT-F)		0.2258	0.2263	0.2247
871.12	1144.28	0.3982	0.3822	0.3680
WATT/(METER-K)		0.3909	0.3916	0.3889
1650.00	2109.70	0.2340	0.2244	0.2159
BTU/(HR-FT-F)		0.2295	0.2297	0.2281
898.90	1172.06	0.4050	0.3885	0.3736
WATT/(METER-K)		0.3972	0.3975	0.3949
1700.00	2159.70	0.2379	0.2280	0.2190
BTU/(HR-FT-F)		0.2332	0.2331	0.2315
926.67	1199.83	0.4118	0.3946	0.3791
WATT/(METER-K)		0.4035	0.4034	0.4007
1750.00	2209.70	0.2418	0.2316	0.2221
BTU/(HR-FT-F)		0.2368	0.2364	0.2349
954.45	1227.61	0.4185	0.4008	0.3844
WATT/(METER-K)		0.4098	0.4092	0.4065

Table A.1 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 14.696 PSIA = 1 ATM = 1.01327 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
1800.00	2259.70	0.2457	0.2351	0.2252
BTU/(HR-FT-F)		0.2403	0.2398	0.2382
982.23	1255.39	0.4252	0.4069	0.3897
WATT/(METER-K)		0.4159	0.4150	0.4123
1850.00	2309.70	0.2495	0.2386	0.2281
BTU/(HR-FT-F)		0.2438	0.2431	0.2415
1010.01	1283.17	0.4319	0.4129	0.3949
WATT/(METER-K)		0.4220	0.4208	0.4180
1900.00	2359.70	0.2534	0.2420	0.2311
BTU/(HR-FT-F)		0.2473	0.2464	0.2447
1037.78	1310.94	0.4385	0.4189	0.3999
WATT/(METER-K)		0.4280	0.4265	0.4236
1950.00	2409.70	0.2572	0.2455	0.2340
BTU/(HR-FT-F)		0.2508	0.2497	0.2479
1065.56	1338.72	0.4451	0.4249	0.4049
WATT/(METER-K)		0.4340	0.4322	0.4291
2000.00	2459.70	0.2609	0.2489	0.2368
BTU/(HR-FT-F)		0.2542	0.2530	0.2511
1093.34	1366.50	0.4516	0.4308	0.4098
WATT/(METER-K)		0.4399	0.4379	0.4346

Table A.2
THERMAL CONDUCTIVITY OF HELIUM AT 100 PSIA

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

REFERENCE LIST:

K1; RISO REPT 224. K2; GA CO.
K3; J.P. SANDERS, ORNL. K4; D.L. MC ELROY, ORNL
K5; JULICH, REPT KFA-IRE-17/72.
K6; ASHRAE, THERMOPHYS. PROP., 1973.

PRESSURE = 100 PSIA = 6.80457 ATM = 6.8949 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
50.00	509.70	0.0855	0.0890	0.0885
BTU/(HR-FT-F)		---	0.0846	0.0843
10.01	283.17	0.1480	0.1540	0.1532
WATT/(METER-K)		---	0.1463	0.1459
100.00	559.70	0.0914	0.0946	0.0935
BTU/(HR-FT-F)		---	0.0905	0.0901
37.78	310.94	0.1582	0.1637	0.1618
WATT/(METER-K)		---	0.1567	0.1559
150.00	609.70	0.0971	0.1001	0.0984
BTU/(HR-FT-F)		---	0.0963	0.0957
65.56	338.72	0.1681	0.1732	0.1702
WATT/(METER-K)		---	0.1668	0.1657
200.00	659.70	0.1027	0.1054	0.1032
BTU/(HR-FT-F)		---	0.1020	0.1013
93.34	366.50	0.1777	0.1823	0.1786
WATT/(METER-K)		---	0.1766	0.1754
250.00	709.70	0.1082	0.1105	0.1080
BTU/(HR-FT-F)		---	0.1076	0.1069
121.12	394.28	0.1872	0.1913	0.1869
WATT/(METER-K)		---	0.1862	0.1850

Table A.2 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 100 PSIA = 6.80457 ATM = 6.8949 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
300.00	759.70	0.1135	0.1156	0.1127
BTU/(HR-FT-F)		---	0.1130	0.1123
148.90	422.06	0.1964	0.2001	0.1951
WATT/(METER-K)		---	0.1956	0.1944
350.00	809.70	0.1188	0.1205	0.1174
BTU/(HR-FT-F)		---	0.1184	0.1177
176.67	449.83	0.2055	0.2086	0.2032
WATT/(METER-K)		---	0.2049	0.2037
400.00	859.70	0.1239	0.1254	0.1220
BTU/(HR-FT-F)		---	0.1236	0.1230
204.45	477.61	0.2145	0.2170	0.2112
WATT/(METER-K)		---	0.2140	0.2129
450.00	909.70	0.1290	0.1301	0.1266
BTU/(HR-FT-F)		0.1303	0.1288	0.1282
232.23	505.39	0.2232	0.2253	0.2191
WATT/(METER-K)		0.2264	0.2229	0.2219
500.00	959.70	0.1340	0.1348	0.1311
BTU/(HR-FT-F)		0.1354	0.1339	0.1334
260.01	533.17	0.2319	0.2333	0.2269
WATT/(METER-K)		0.2343	0.2317	0.2308
550.00	1009.70	0.1389	0.1394	0.1355
BTU/(HR-FT-F)		0.1399	0.1389	0.1384
287.78	560.94	0.2404	0.2413	0.2346
WATT/(METER-K)		0.2421	0.2403	0.2396

Table A.2 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 100 PSIA = 6.80457 ATM = 6.8949 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
600.00	1059.70	0.1437	0.1439	0.1399
BTU/(HR-FT-F)		0.1444	0.1438	0.1433
315.56	588.72	0.2487	0.2491	0.2421
WATT/(METER-K)		0.2499	0.2489	0.2481
650.00	1109.70	0.1485	0.1484	0.1442
BTU/(HR-FT-F)		0.1488	0.1486	0.1482
343.34	616.50	0.2570	0.2568	0.2496
WATT/(METER-K)		0.2575	0.2572	0.2564
700.00	1159.70	0.1532	0.1528	0.1485
BTU/(HR-FT-F)		0.1532	0.1534	0.1529
371.12	644.28	0.2652	0.2644	0.2570
WATT/(METER-K)		0.2651	0.2655	0.2646
750.00	1209.70	0.1579	0.1571	0.1527
BTU/(HR-FT-F)		0.1576	0.1581	0.1575
398.90	672.06	0.2732	0.2719	0.2643
WATT/(METER-K)		0.2727	0.2737	0.2726
800.00	1259.70	0.1625	0.1614	0.1569
BTU/(HR-FT-F)		0.1619	0.1628	0.1620
426.67	699.83	0.2812	0.2793	0.2716
WATT/(METER-K)		0.2802	0.2817	0.2804
850.00	1309.70	0.1670	0.1656	0.1610
BTU/(HR-FT-F)		0.1662	0.1673	0.1665
454.45	727.61	0.2890	0.2866	0.2737
WATT/(METER-K)		0.2876	0.2896	0.2881

Table A.2 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 100 PSIA = 6.80457 ATM = 6.8949 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
900.00	1359.70	0.1715	0.1698	0.1651
BTU/(HR-FT-F)		0.1704	0.1718	0.1708
482.23	755.39	0.2968	0.2938	0.2857
WATT/(METER-K)		0.2949	0.2973	0.2956
950.00	1409.70	0.1759	0.1739	0.1690
BTU/(HR-FT-F)		0.1746	0.1762	0.1751
510.01	783.17	0.3045	0.3009	0.2926
WATT/(METER-K)		0.3022	0.3050	0.3030
1000.00	1459.70	0.1803	0.1779	0.1730
BTU/(HR-FT-F)		0.1783	0.1805	0.1793
537.78	810.94	0.3121	0.3080	0.2994
WATT/(METER-K)		0.3094	0.3125	0.3103
1050.00	1509.70	0.1847	0.1820	0.1769
BTU/(HR-FT-F)		0.1829	0.1848	0.1834
565.56	838.72	0.3197	0.3149	0.3061
WATT/(METER-K)		0.3166	0.3198	0.3174
1100.00	1559.70	0.1890	0.1859	0.1807
BTU/(HR-FT-F)		0.1870	0.1889	0.1875
593.34	866.50	0.3272	0.3213	0.3127
WATT/(METER-K)		0.3237	0.3270	0.3244
1150.00	1609.70	0.1933	0.1899	0.1844
BTU/(HR-FT-F)		0.1911	0.1930	0.1914
621.12	894.28	0.3346	0.3286	0.3192
WATT/(METER-K)		0.3307	0.3341	0.3313

Table A.2 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 100 PSIA = 6.80457 ATM = 6.8949 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
1200.00	1659.70	0.1975	0.1938	0.1881
BTU/(HR-FT-F)		0.1951	0.1970	0.1954
648.90	922.06	0.3419	0.3354	0.3256
WATT/(METER-K)		0.3377	0.3410	0.3381
1250.00	1709.70	0.2017	0.1976	0.1918
BTU/(HR-FT-F)		0.1991	0.2009	0.1992
676.67	949.83	0.3492	0.3420	0.3320
WATT/(METER-K)		0.3445	0.3477	0.3448
1300.00	1759.70	0.2059	0.2014	0.1954
BTU/(HR-FT-F)		0.2030	0.2047	0.2030
704.45	977.61	0.3564	0.3487	0.3382
WATT/(METER-K)		0.3514	0.3543	0.3514
1350.00	1809.70	0.2100	0.2052	0.1989
BTU/(HR-FT-F)		0.2069	0.2085	0.2068
732.23	1005.39	0.3635	0.3552	0.3443
WATT/(METER-K)		0.3581	0.3608	0.3578
1400.00	1859.70	0.2141	0.2090	0.2024
BTU/(HR-FT-F)		0.2108	0.2122	0.2104
760.01	1033.17	0.3706	0.3617	0.3503
WATT/(METER-K)		0.3648	0.3672	0.3642
1450.00	1909.70	0.2182	0.2127	0.2058
BTU/(HR-FT-F)		0.2146	0.2158	0.2141
787.78	1060.94	0.3776	0.3681	0.3562
WATT/(METER-K)		0.3714	0.3734	0.3705

Table A.2 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 100 PSIA = 6.80457 ATM = 6.8949 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
1500.00 BTU/(HR-FT-F)	1959.70	0.2222 0.2184	0.2164 0.2193	0.2092 0.2177
815.56 WATT/(METER-K)	1088.72	0.3846 0.3780	0.3745 0.3796	0.3621 0.3767
1550.00 BTU/(HR-FT-F)	2009.70	0.2262 0.2221	0.2201 0.2228	0.2125 0.2212
843.34 WATT/(METER-K)	1116.50	0.3916 0.3845	0.3808 0.3856	0.3678 0.3828
1600.00 BTU/(HR-FT-F)	2059.70	0.2302 0.2259	0.2237 0.2263	0.2158 0.2247
871.12 WATT/(METER-K)	1144.28	0.3984 0.3909	0.3871 0.3916	0.3734 0.3889
1650.00 BTU/(HR-FT-F)	2109.70	0.2342 0.2295	0.2273 0.2297	0.2190 0.2231
898.90 WATT/(METER-K)	1172.06	0.4053 0.3973	0.3934 0.3975	0.3790 0.3949
1700.00 BTU/(HR-FT-F)	2159.70	0.2381 0.2332	0.2308 0.2331	0.2221 0.2315
926.67 WATT/(METER-K)	1199.83	0.4121 0.4036	0.3995 0.4034	0.3844 0.4007
1750.00 BTU/(HR-FT-F)	2209.70	0.2420 0.2368	0.2344 0.2364	0.2252 0.2349
954.45 WATT/(METER-K)	1227.61	0.4188 0.4098	0.4057 0.4092	0.3897 0.4065

Table A.2 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 100 PSIA = 6.80457 ATM = 6.8949 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
1800.00	2259.70	0.2459	0.2379	0.2282
BTU/(HR-FT-F)		0.2403	0.2398	0.2382
982.23	1255.39	0.4255	0.4118	0.3950
WATT/(METER-K)		0.4160	0.4150	0.4123
1850.00	2309.70	0.2497	0.2414	0.2312
BTU/(HR-FT-F)		0.2439	0.2431	0.2415
1010.01	1283.17	0.4322	0.4178	0.4001
WATT/(METER-K)		0.4220	0.4208	0.4130
1900.00	2359.70	0.2535	0.2449	0.2341
BTU/(HR-FT-F)		0.2473	0.2464	0.2447
1037.78	1310.94	0.4388	0.4233	0.4051
WATT/(METER-K)		0.4281	0.4265	0.4236
1950.00	2409.70	0.2573	0.2483	0.2369
BTU/(HR-FT-F)		0.2508	0.2497	0.2479
1065.56	1338.72	0.4453	0.4298	0.4101
WATT/(METER-K)		0.4340	0.4322	0.4291
2000.00	2459.70	0.2611	0.2517	0.2397
BTU/(HR-FT-F)		0.2542	0.2530	0.2511
1093.34	1366.50	0.4519	0.4357	0.4149
WATT/(METER-K)		0.4399	0.4379	0.4346

Table A.3

THERMAL CONDUCTIVITY OF HELIUM AT 500 PSIA

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

REFERENCE LIST:

K1; RISO REPT 224. K2; GA CO.
K3; J.P. SANDERS, ORNL. K4; D.L. MC ELROY, ORNL
K5; JULICH, REPT KFA-IRE-17/72.
K6; ASHRAE, THERMOPHYS. PROP., 1973.

PRESSURE = 500 PSIA = 34.0229 ATM = 34.4745 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
50.00	509.70	0.0862	0.0903	0.0898
BTU/(HR-FT-F)		---	0.0846	0.0843
10.01	283.17	0.1492	0.1571	0.1554
WATT/(METER-K)		---	0.1463	0.1459
100.00	559.70	0.0921	0.0964	0.0948
BTU/(HR-FT-F)		---	0.0905	0.0901
37.78	310.94	0.1594	0.1663	0.1640
WATT/(METER-K)		---	0.1567	0.1559
150.00	609.70	0.0976	0.1018	0.0997
BTU/(HR-FT-F)		---	0.0964	0.0957
65.56	338.72	0.1693	0.1762	0.1725
WATT/(METER-K)		---	0.1668	0.1657
200.00	659.70	0.1034	0.1071	0.1045
BTU/(HR-FT-F)		---	0.1020	0.1013
93.34	366.50	0.1790	0.1854	0.1809
WATT/(METER-K)		---	0.1766	0.1754
250.00	709.70	0.1089	0.1123	0.1093
BTU/(HR-FT-F)		---	0.1076	0.1069
121.12	394.28	0.1885	0.1944	0.1892
WATT/(METER-K)		---	0.1862	0.1850

Table A.3 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 500 PSIA = 34.0229 ATM = 34.4745 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
300.00	759.70	0.1143	0.1174	0.1141
BTU/(HR-FT-F)		---	0.1130	0.1123
148.90	422.06	0.1977	0.2031	0.1974
WATT/(METER-K)		---	0.1956	0.1944
350.00	809.70	0.1195	0.1223	0.1188
BTU/(HR-FT-F)		---	0.1184	0.1177
176.67	449.83	0.2068	0.2117	0.2055
WATT/(METER-K)		---	0.2049	0.2037
400.00	859.70	0.1247	0.1272	0.1234
BTU/(HR-FT-F)		---	0.1236	0.1230
204.45	477.61	0.2158	0.2201	0.2135
WATT/(METER-K)		---	0.2140	0.2129
450.00	909.70	0.1297	0.1319	0.1279
BTU/(HR-FT-F)		0.1312	0.1288	0.1282
232.23	505.39	0.2245	0.2283	0.2214
WATT/(METER-K)		0.2271	0.2229	0.2219
500.00	959.70	0.1347	0.1366	0.1325
BTU/(HR-FT-F)		0.1357	0.1339	0.1334
260.01	533.17	0.2332	0.2364	0.2292
WATT/(METER-K)		0.2349	0.2317	0.2308
550.00	1009.70	0.1396	0.1412	0.1369
BTU/(HR-FT-F)		0.1402	0.1389	0.1384
287.78	560.94	0.2417	0.2444	0.2369
WATT/(METER-K)		0.2427	0.2403	0.2396

Table A.3 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 500 PSIA = 34.0229 ATM = 34.4745 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
600.00	1059.70	0.1445	0.1457	0.1413
BTU/(HR-FT-F)		0.1447	0.1438	0.1433
315.56	588.72	0.2501	0.2522	0.2445
WATT/(METER-K)		0.2504	0.2489	0.2481
650.00	1109.70	0.1493	0.1502	0.1456
BTU/(HR-FT-F)		0.1491	0.1486	0.1482
343.34	616.50	0.2583	0.2599	0.2520
WATT/(METER-K)		0.2580	0.2573	0.2564
700.00	1159.70	0.1540	0.1546	0.1499
BTU/(HR-FT-F)		0.1535	0.1534	0.1529
371.12	644.28	0.2665	0.2675	0.2594
WATT/(METER-K)		0.2656	0.2655	0.2646
750.00	1209.70	0.1586	0.1589	0.1541
BTU/(HR-FT-F)		0.1578	0.1531	0.1575
398.90	672.06	0.2745	0.2750	0.2667
WATT/(METER-K)		0.2731	0.2737	0.2726
800.00	1259.70	0.1632	0.1632	0.1583
BTU/(HR-FT-F)		0.1621	0.1628	0.1620
426.67	699.33	0.2825	0.2824	0.2739
WATT/(METER-K)		0.2806	0.2817	0.2804
850.00	1309.70	0.1678	0.1674	0.1624
BTU/(HR-FT-F)		0.1664	0.1673	0.1665
454.45	727.61	0.2903	0.2897	0.2818
WATT/(METER-K)		0.2880	0.2896	0.2881

Table A.3 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 500 PSIA = 34.0229 ATM = 34.4745 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
900.00	1359.70	0.1722	0.1715	0.1664
BTU/(HR-FT-F)		0.1706	0.1718	0.1708
482.23	755.39	0.2981	0.2969	0.2880
WATT/(METER-K)		0.2953	0.2973	0.2956
950.00	1409.70	0.1767	0.1756	0.1704
BTU/(HR-FT-F)		0.1748	0.1762	0.1751
510.01	783.17	0.3058	0.3040	0.2949
WATT/(METER-K)		0.3026	0.3050	0.3030
1000.00	1459.70	0.1811	0.1797	0.1743
BTU/(HR-FT-F)		0.1790	0.1805	0.1793
537.78	810.94	0.3134	0.3110	0.3017
WATT/(METER-K)		0.3098	0.3125	0.3103
1050.00	1509.70	0.1854	0.1837	0.1782
BTU/(HR-FT-F)		0.1831	0.1848	0.1834
565.56	838.72	0.3209	0.3180	0.3084
WATT/(METER-K)		0.3169	0.3198	0.3174
1100.00	1559.70	0.1897	0.1877	0.1820
BTU/(HR-FT-F)		0.1872	0.1889	0.1875
593.34	866.50	0.3284	0.3249	0.3149
WATT/(METER-K)		0.3240	0.3270	0.3244
1150.00	1609.70	0.1940	0.1916	0.1857
BTU/(HR-FT-F)		0.1913	0.1930	0.1914
621.12	894.28	0.3358	0.3317	0.3214
WATT/(METER-K)		0.3318	0.3341	0.3313

Table A.3 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 500 PSIA = 34.0229 ATM = 34.4745 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
1200.00	1659.70	0.1982	0.1955	0.1894
BTU/(HR-FT-F)		0.1953	0.1970	0.1954
648.90	922.06	0.3431	0.3384	0.3278
WATT/(METER-K)		0.3380	0.3410	0.3381
1250.00	1709.70	0.2024	0.1994	0.1930
BTU/(HR-FT-F)		0.1992	0.2009	0.1992
676.67	949.83	0.3504	0.3451	0.3341
WATT/(METER-K)		0.3448	0.3477	0.3448
1300.00	1759.70	0.2066	0.2032	0.1966
BTU/(HR-FT-F)		0.2032	0.2047	0.2030
704.45	977.61	0.3575	0.3517	0.3403
WATT/(METER-K)		0.3516	0.3544	0.3514
1350.00	1809.70	0.2107	0.2070	0.2001
BTU/(HR-FT-F)		0.2071	0.2085	0.2063
732.23	1005.39	0.3647	0.3583	0.3464
WATT/(METER-K)		0.3584	0.3608	0.3578
1400.00	1859.70	0.2146	0.2108	0.2036
BTU/(HR-FT-F)		0.2109	0.2122	0.2104
760.01	1033.17	0.3718	0.3648	0.3523
WATT/(METER-K)		0.3651	0.3672	0.3642
1450.00	1909.70	0.2189	0.2145	0.2070
BTU/(HR-FT-F)		0.2148	0.2158	0.2141
787.78	1060.94	0.3788	0.3712	0.3580
WATT/(METER-K)		0.3717	0.3734	0.3705

Table A.3 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 500 PSIA = 34.0229 ATM = 34.4745 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
1500.00	1959.70	0.2229	0.2182	0.2103
BTU/(HR-FT-F)		0.2185	0.2193	0.2177
815.56	1088.72	0.3357	0.3776	0.3640
WATT/(METER-K)		0.3782	0.3796	0.3767
1550.00	2009.70	0.2269	0.2218	0.2136
BTU/(HR-FT-F)		0.2223	0.2223	0.2212
843.34	1116.50	0.3927	0.3839	0.3697
WATT/(METER-K)		0.3847	0.3856	0.3828
1600.00	2059.70	0.2308	0.2255	0.2168
BTU/(HR-FT-F)		0.2260	0.2263	0.2247
871.12	1144.28	0.3995	0.3902	0.3753
WATT/(METER-K)		0.3911	0.3916	0.3889
1650.00	2109.70	0.2348	0.2291	0.2200
BTU/(HR-FT-F)		0.2297	0.2297	0.2281
898.90	1172.06	0.4063	0.3964	0.3807
WATT/(METER-K)		0.3975	0.3975	0.3949
1700.00	2159.70	0.2387	0.2326	0.2231
BTU/(HR-FT-F)		0.2333	0.2331	0.2315
926.67	1199.33	0.4131	0.4026	0.3861
WATT/(METER-K)		0.4038	0.4034	0.4007
1750.00	2209.70	0.2426	0.2362	0.2261
BTU/(HR-FT-F)		0.2369	0.2364	0.2349
954.45	1227.61	0.4198	0.4087	0.3914
WATT/(METER-K)		0.4100	0.4092	0.4065

Table A.3 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 500 PSIA = 34.0229 ATM = 34.4745 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
1800.00	2259.70	0.2464	0.2397	0.2291
BTU/(HR-FT-F)		0.2405	0.2393	0.2382
982.23	1255.39	0.4265	0.4148	0.3965
WATT/(METER-K)		0.4162	0.4150	0.4123
1850.00	2309.70	0.2503	0.2432	0.2321
BTU/(HR-FT-F)		0.2440	0.2431	0.2415
1010.01	1283.17	0.4331	0.4209	0.4016
WATT/(METER-K)		0.4223	0.4203	0.4130
1900.00	2359.70	0.2541	0.2466	0.2349
BTU/(HR-FT-F)		0.2475	0.2464	0.2447
1037.78	1310.94	0.4397	0.4269	0.4066
WATT/(METER-K)		0.4283	0.4265	0.4236
1950.00	2409.70	0.2579	0.2501	0.2377
BTU/(HR-FT-F)		0.2509	0.2497	0.2479
1065.56	1338.72	0.4463	0.4328	0.4115
WATT/(METER-K)		0.4342	0.4322	0.4291
2000.00	2459.70	0.2616	0.2535	0.2405
BTU/(HR-FT-F)		0.2543	0.2530	0.2511
1093.34	1366.53	0.4523	0.4333	0.4162
WATT/(METER-K)		0.4421	0.4379	0.4346

Table A.4

THERMAL CONDUCTIVITY OF HELIUM AT 750 PSIA

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

REFERENCE LIST:

K1; RISO REPT 224. K2; GA CO.
K3; J.P. SANDERS, ORNL. K4; D.L. MC ELROY, ORNL
K5; JULICH, REPT KFA-IRE-17/72.
K6; ASHRAE, THERMOPHYS. PROP., 1973.

PRESSURE = 750 PSIA = 51.0343 ATM = 51.7117 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
50.00	509.70	0.0866	0.0913	0.0906
BTU/(HR-FT-F)		---	0.0846	0.0843
10.01	283.17	0.1499	0.1531	0.1568
WATT/(METER-K)		---	0.1463	0.1459
100.00	559.70	0.0925	0.0969	0.0956
BTU/(HR-FT-F)		---	0.0905	0.0901
37.73	310.94	0.1601	0.1675	0.1655
WATT/(METER-K)		---	0.1567	0.1559
150.00	609.70	0.0983	0.1024	0.1005
BTU/(HR-FT-F)		---	0.0964	0.0957
65.56	338.72	0.1701	0.1772	0.1740
WATT/(METER-K)		---	0.1668	0.1657
200.00	659.70	0.1039	0.1077	0.1054
BTU/(HR-FT-F)		---	0.1020	0.1013
93.34	366.50	0.1797	0.1864	0.1824
WATT/(METER-K)		---	0.1766	0.1754
250.00	709.70	0.1093	0.1129	0.1102
BTU/(HR-FT-F)		---	0.1076	0.1069
121.12	394.28	0.1892	0.1954	0.1907
WATT/(METER-K)		---	0.1862	0.1850

Table A.4 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 750 PSIA = 51.0343 ATM = 51.7117 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
300.00	759.70	0.1147	0.1179	0.1149
BTU/(HR-FT-F)		---	0.1130	0.1123
148.90	422.06	0.1935	0.2041	0.1989
WATT/(METER-K)		---	0.1957	0.1944
350.00	809.70	0.1199	0.1229	0.1196
BTU/(HR-FT-F)		---	0.1184	0.1177
176.67	449.83	0.2076	0.2127	0.2070
WATT/(METER-K)		---	0.2049	0.2037
400.00	859.70	0.1251	0.1277	0.1242
BTU/(HR-FT-F)		---	0.1236	0.1230
204.45	477.61	0.2165	0.2211	0.2150
WATT/(METER-K)		---	0.2140	0.2129
450.00	909.70	0.1302	0.1325	0.1288
BTU/(HR-FT-F)		0.1314	0.1288	0.1282
232.23	505.39	0.2253	0.2293	0.2229
WATT/(METER-K)		0.2275	0.2229	0.2219
500.00	959.70	0.1351	0.1372	0.1333
BTU/(HR-FT-F)		0.1360	0.1339	0.1334
260.01	533.17	0.2339	0.2374	0.2307
WATT/(METER-K)		0.2353	0.2317	0.2308
550.00	1009.70	0.1401	0.1413	0.1376
BTU/(HR-FT-F)		0.1404	0.1389	0.1384
287.78	560.94	0.2424	0.2454	0.2384
WATT/(METER-K)		0.2431	0.2403	0.2396

Table A.4 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 750 PSIA = 51.0343 ATM = 51.7117 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
600.00	1059.70	0.1449	0.1463	0.1422
BTU/(HR-FT-F)		0.1449	0.1433	0.1433
315.56	588.72	0.2508	0.2532	0.2460
WATT/(METER-K)		0.2508	0.2489	0.2481
650.00	1109.70	0.1497	0.1507	0.1465
BTU/(HR-FT-F)		0.1493	0.1486	0.1482
343.34	616.50	0.2590	0.2609	0.2535
WATT/(METER-K)		0.2584	0.2573	0.2564
700.00	1159.70	0.1544	0.1551	0.1507
BTU/(HR-FT-F)		0.1537	0.1534	0.1529
371.12	644.28	0.2672	0.2685	0.2609
WATT/(METER-K)		0.2660	0.2655	0.2646
750.00	1209.70	0.1590	0.1595	0.1550
BTU/(HR-FT-F)		0.1580	0.1581	0.1575
398.90	672.06	0.2752	0.2760	0.2682
WATT/(METER-K)		0.2735	0.2737	0.2726
300.00	1259.70	0.1636	0.1637	0.1591
BTU/(HR-FT-F)		0.1623	0.1623	0.1620
426.67	699.33	0.2832	0.2834	0.2754
WATT/(METER-K)		0.2809	0.2817	0.2804
850.00	1309.70	0.1681	0.1679	0.1632
BTU/(HR-FT-F)		0.1656	0.1673	0.1665
454.45	727.61	0.2910	0.2907	0.2825
WATT/(METER-K)		0.2883	0.2896	0.2851

Table A.4 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 750 PSIA = 51.0343 ATM = 51.7117 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F	DEG R	K1	K2	K3
UNITS OF@K		K4	K5	K6
DEG C	DEG K			
UNITS OF K				
900.00	1359.70	0.1726	0.1721	0.1672
BTU/(HR-FT-F)		0.1703	0.1713	0.1703
482.23	755.39	0.2988	0.2979	0.2394
WATT/(METER-K)		0.2956	0.2973	0.2956
950.00	1409.70	0.1771	0.1762	0.1712
BTU/(HR-FT-F)		0.1750	0.1762	0.1751
510.01	783.17	0.3065	0.3050	0.2963
WATT/(METER-K)		0.3029	0.3050	0.3030
1000.00	1459.70	0.1815	0.1803	0.1751
BTU/(HR-FT-F)		0.1791	0.1805	0.1793
537.78	810.94	0.3140	0.3120	0.3031
WATT/(METER-K)		0.3101	0.3125	0.3103
1050.00	1509.70	0.1858	0.1843	0.1790
BTU/(HR-FT-F)		0.1833	0.1848	0.1834
565.56	838.72	0.3216	0.3190	0.3098
WATT/(METER-K)		0.3172	0.3198	0.3174
1100.00	1559.70	0.1901	0.1883	0.1828
BTU/(HR-FT-F)		0.1873	0.1889	0.1875
593.34	866.50	0.3290	0.3259	0.3163
WATT/(METER-K)		0.3242	0.3270	0.3244
1150.00	1609.70	0.1944	0.1922	0.1865
BTU/(HR-FT-F)		0.1914	0.1930	0.1914
621.12	894.28	0.3364	0.3327	0.3228
WATT/(METER-K)		0.3312	0.3341	0.3313

Table A.4 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 750 PSIA = 51.0343 ATM = 51.7117 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
1200.00	1659.70	0.1986	0.1961	0.1902
BTU/(HR-FT-F)		0.1954	0.1970	0.1954
648.90	922.06	0.3437	0.3394	0.3292
WATT/(METER-K)		0.3382	0.3410	0.3381
1250.00	1709.70	0.2028	0.2000	0.1938
BTU/(HR-FT-F)		0.1994	0.2009	0.1992
676.67	949.83	0.3509	0.3461	0.3354
WATT/(METER-K)		0.3451	0.3477	0.3448
1300.00	1759.70	0.2069	0.2038	0.1974
BTU/(HR-FT-F)		0.2033	0.2047	0.2030
704.45	977.61	0.3581	0.3527	0.3416
WATT/(METER-K)		0.3519	0.3544	0.3514
1350.00	1809.70	0.2110	0.2076	0.2009
BTU/(HR-FT-F)		0.2072	0.2085	0.2068
732.23	1005.39	0.3652	0.3593	0.3476
WATT/(METER-K)		0.3586	0.3608	0.3573
1400.00	1859.70	0.2151	0.2113	0.2043
BTU/(HR-FT-F)		0.2110	0.2122	0.2104
760.01	1033.17	0.3723	0.3658	0.3536
WATT/(METER-K)		0.3653	0.3672	0.3642
1450.00	1909.70	0.2192	0.2150	0.2077
BTU/(HR-FT-F)		0.2149	0.2158	0.2141
787.78	1060.94	0.3793	0.3722	0.3595
WATT/(METER-K)		0.3719	0.3734	0.3705

Table A.4 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 750 PSIA = 51.0343 ATM = 51.7117 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
1500.00 BTU/(HR-FT-F)	1959.70	0.2232 0.2187	0.2187 0.2193	0.2110 0.2177
815.56 WATT/(METER-K)	1088.72	0.3863 0.3784	0.3786 0.3796	0.3652 0.3767
1550.00 BTU/(HR-FT-F)	2009.70	0.2272 0.2224	0.2224 0.2228	0.2143 0.2212
843.34 WATT/(METER-K)	1116.50	0.3932 0.3849	0.3849 0.3856	0.3708 0.3828
1600.00 BTU/(HR-FT-F)	2059.70	0.2311 0.2261	0.2260 0.2263	0.2175 0.2247
871.12 WATT/(METER-K)	1144.28	0.4000 0.3913	0.3912 0.3916	0.3764 0.3889
1650.00 BTU/(HR-FT-F)	2109.70	0.2351 0.2293	0.2296 0.2297	0.2206 0.2281
898.90 WATT/(METER-K)	1172.06	0.4068 0.3977	0.3974 0.3975	0.3818 0.3949
1700.00 BTU/(HR-FT-F)	2159.70	0.2390 0.2334	0.2332 0.2331	0.2237 0.2315
926.67 WATT/(METER-K)	1199.83	0.4136 0.4040	0.4036 0.4034	0.3872 0.4007
1750.00 BTU/(HR-FT-F)	2209.70	0.2428 0.2370	0.2367 0.2364	0.2267 0.2349
954.45 WATT/(METER-K)	1227.61	0.4203 0.4102	0.4097 0.4092	0.3924 0.4065

Table A.4 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 750 PSIA = 51.0343 ATM = 51.7117 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
1800.00	2259.70	0.2467	0.2403	0.2297
BTU/(HR-FT-F)		0.2405	0.2398	0.2382
982.23	1255.39	0.4269	0.4158	0.3975
WATT/(METER-K)		0.4163	0.4150	0.4123
1850.00	2309.70	0.2505	0.2437	0.2326
BTU/(HR-FT-F)		0.2441	0.2431	0.2415
1010.01	1283.17	0.4335	0.4219	0.4026
WATT/(METER-K)		0.4224	0.4208	0.4180
1900.00	2359.70	0.2543	0.2472	0.2354
BTU/(HR-FT-F)		0.2475	0.2464	0.2447
1037.78	1310.94	0.4401	0.4279	0.4075
WATT/(METER-K)		0.4284	0.4265	0.4236
1950.00	2409.70	0.2581	0.2507	0.2382
BTU/(HR-FT-F)		0.2510	0.2497	0.2479
1065.56	1338.72	0.4466	0.4333	0.4123
WATT/(METER-K)		0.4344	0.4322	0.4291
2000.00	2459.70	0.2618	0.2541	0.2410
BTU/(HR-FT-F)		0.2544	0.2530	0.2511
1093.34	1366.50	0.4531	0.4398	0.4171
WATT/(METER-K)		0.4403	0.4379	0.4346

Table A.5

THERMAL CONDUCTIVITY OF HELIUM AT 1000 PSIA

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

REFERENCE LIST:

K1; RISO REPT 224. K2; GA CO.
K3; J.P. SANDERS, ORNL. K4; D.L. MC ELROY, ORNL
K5; JULICH, REPT KFA-IRE-17/72.
K6; ASHRAE, THERMOPHYS. PROP., 1973.

PRESSURE = 1000 PSIA = 68.0457 ATM = 68.949 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
50.00	509.70	0.0870	0.0918	0.0914
BTU/(HR-FT-F)		---	0.0846	0.0843
10.01	283.17	0.1506	0.1588	0.1582
WATT/(METER-K)		---	0.1464	0.1459
100.00	559.70	0.0929	0.0974	0.0964
BTU/(HR-FT-F)		---	0.0905	0.0901
37.78	310.94	0.1608	0.1686	0.1669
WATT/(METER-K)		---	0.1567	0.1559
150.00	609.70	0.0986	0.1028	0.1013
BTU/(HR-FT-F)		---	0.0964	0.0957
65.56	338.72	0.1707	0.1780	0.1754
WATT/(METER-K)		---	0.1668	0.1657
200.00	659.70	0.1042	0.1081	0.1062
BTU/(HR-FT-F)		---	0.1020	0.1013
93.34	366.50	0.1804	0.1872	0.1838
WATT/(METER-K)		---	0.1766	0.1754
250.00	709.70	0.1097	0.1133	0.1110
BTU/(HR-FT-F)		---	0.1076	0.1069
121.12	394.28	0.1899	0.1961	0.1922
WATT/(METER-K)		---	0.1862	0.1850

Table A.5 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 1000 PSIA = 68.0457 ATM = 68.949 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
300.00	759.70	0.1151	0.1134	0.1158
BTU/(HR-FT-F)		---	0.1130	0.1123
148.90	422.06	0.1991	0.2049	0.2004
WATT/(METER-K)		---	0.1957	0.1944
350.00	809.70	0.1203	0.1233	0.1205
BTU/(HR-FT-F)		---	0.1184	0.1177
176.67	449.83	0.2082	0.2134	0.2035
WATT/(METER-K)		---	0.2049	0.2037
400.00	859.70	0.1255	0.1282	0.1251
BTU/(HR-FT-F)		---	0.1236	0.1230
204.45	477.61	0.2172	0.2218	0.2165
WATT/(METER-K)		---	0.2140	0.2129
450.00	909.70	0.1305	0.1329	0.1297
BTU/(HR-FT-F)		0.1317	0.1288	0.1282
232.23	505.39	0.2259	0.2301	0.2244
WATT/(METER-K)		0.2280	0.2229	0.2219
500.00	959.70	0.1355	0.1376	0.1342
BTU/(HR-FT-F)		0.1362	0.1339	0.1334
260.01	533.17	0.2345	0.2382	0.2322
WATT/(METER-K)		0.2358	0.2317	0.2308
550.00	1009.70	0.1404	0.1422	0.1336
BTU/(HR-FT-F)		0.1407	0.1389	0.1384
287.78	560.94	0.2430	0.2461	0.2399
WATT/(METER-K)		0.2435	0.2403	0.2396

Table A.5 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 1000 PSIA = 68.0457 ATM = 68.949 KG

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITSKØF K	DEG K K6	K1 K4	K2	K3
DEG C UNITS OF K	DEG K			
600.00	1059.70	0.1453	0.1467	0.1430
BTU/(HR-FT-F)		0.1451	0.1433	0.1433
315.56	588.72	0.2514	0.2539	0.2475
WATT/(METER-K)		0.2511	0.2439	0.2481
650.00	1109.70	0.1500	0.1512	0.1473
BTU/(HR-FT-F)		0.1495	0.1436	0.1432
343.34	616.50	0.2596	0.2617	0.2550
WATT/(METER-K)		0.2588	0.2573	0.2564
700.00	1159.70	0.1547	0.1556	0.1516
BTU/(HR-FT-F)		0.1539	0.1534	0.1529
371.12	644.28	0.2678	0.2692	0.2624
WATT/(METER-K)		0.2663	0.2655	0.2646
750.00	1209.70	0.1594	0.1599	0.1553
BTU/(HR-FT-F)		0.1532	0.1581	0.1575
398.90	672.06	0.2758	0.2767	0.2697
WATT/(METER-K)		0.2738	0.2737	0.2726
800.00	1259.70	0.1639	0.1642	0.1600
BTU/(HR-FT-F)		0.1625	0.1628	0.1623
426.67	699.33	0.2838	0.2841	0.2769
WATT/(METER-K)		0.2812	0.2817	0.2804
850.00	1309.70	0.1685	0.1684	0.1643
BTU/(HR-FT-F)		0.1667	0.1673	0.1665
454.45	727.61	0.2916	0.2914	0.2839
WATT/(METER-K)		0.2886	0.2895	0.2881

Table A.5 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 1000 PSIA = 68.0457 ATM = 68.949 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
900.00	1359.70	0.1730	0.1725	0.1681
BTU/(HR-FT-F)		0.1710	0.1718	0.1708
482.23	755.39	0.2993	0.2986	0.2909
WATT/(METER-K)		0.2959	0.2973	0.2956
950.00	1409.70	0.1774	0.1767	0.1720
BTU/(HR-FT-F)		0.1752	0.1762	0.1751
510.01	783.17	0.3070	0.3057	0.2978
WATT/(METER-K)		0.3031	0.3050	0.3030
1000.00	1459.70	0.1818	0.1807	0.1759
BTU/(HR-FT-F)		0.1793	0.1805	0.1793
537.78	810.94	0.3146	0.3128	0.3045
WATT/(METER-K)		0.3103	0.3125	0.3103
1050.00	1509.70	0.1861	0.1847	0.1798
BTU/(HR-FT-F)		0.1834	0.1848	0.1834
565.56	838.72	0.3221	0.3197	0.3112
WATT/(METER-K)		0.3174	0.3198	0.3174
1100.00	1559.70	0.1904	0.1887	0.1836
BTU/(HR-FT-F)		0.1875	0.1889	0.1875
593.34	866.52	0.3295	0.3266	0.3177
WATT/(METER-K)		0.3245	0.3270	0.3244
1150.00	1609.70	0.1947	0.1927	0.1873
BTU/(HR-FT-F)		0.1915	0.1930	0.1914
621.12	894.28	0.3369	0.3334	0.3242
WATT/(METER-K)		0.3315	0.3341	0.3313

Table A.5 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 1000 PSIA = 68.0457 ATM = 68.940 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG K	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
1200.00	1659.70	0.1939	0.1966	0.1910
BTU/(HR-FT-F)		0.1955	0.1970	0.1954
648.90	922.06	0.3442	0.3402	0.3305
WATT/(METER-K)		0.3384	0.3410	0.3381
1250.00	1709.70	0.2030	0.2004	0.1946
BTU/(HR-FT-F)		0.1995	0.2009	0.1992
676.67	949.83	0.3514	0.3469	0.3368
WATT/(METER-K)		0.3453	0.3477	0.3448
1300.00	1759.70	0.2072	0.2042	0.1981
BTU/(HR-FT-F)		0.2034	0.2047	0.2030
704.45	977.61	0.3586	0.3535	0.3429
WATT/(METER-K)		0.3521	0.3544	0.3514
1350.00	1809.70	0.2113	0.2080	0.2016
BTU/(HR-FT-F)		0.2073	0.2085	0.2068
732.23	1005.39	0.3657	0.3600	0.3489
WATT/(METER-K)		0.3588	0.3608	0.3573
1400.00	1859.70	0.2154	0.2118	0.2050
BTU/(HR-FT-F)		0.2112	0.2122	0.2104
760.01	1033.17	0.3727	0.3665	0.3549
WATT/(METER-K)		0.3655	0.3672	0.3642
1450.00	1909.70	0.2194	0.2155	0.2084
BTU/(HR-FT-F)		0.2150	0.2158	0.2141
787.78	1063.94	0.3797	0.3730	0.3607
WATT/(METER-K)		0.3721	0.3734	0.3705

Table A.5 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 1000 PSIA = 68.0457 ATM = 68.949 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
1500.00	1959.70	0.2234	0.2192	0.2117
BTU/(HR-FT-F)		0.2188	0.2193	0.2177
815.56	1088.72	0.3867	0.3793	0.3664
WATT/(METER-K)		0.3786	0.3796	0.3767
1550.00	2009.70	0.2274	0.2228	0.2149
BTU/(HR-FT-F)		0.2225	0.2228	0.2212
843.34	1116.50	0.3935	0.3857	0.3720
WATT/(METER-K)		0.3851	0.3856	0.3828
1600.00	2059.70	0.2313	0.2265	0.2181
BTU/(HR-FT-F)		0.2262	0.2263	0.2247
871.12	1144.28	0.4004	0.3919	0.3775
WATT/(METER-K)		0.3915	0.3916	0.3889
1650.00	2109.70	0.2352	0.2301	0.2213
BTU/(HR-FT-F)		0.2299	0.2297	0.2281
898.90	1172.06	0.4071	0.3982	0.3829
WATT/(METER-K)		0.3978	0.3975	0.3949
1700.00	2159.70	0.2391	0.2336	0.2243
BTU/(HR-FT-F)		0.2335	0.2331	0.2315
926.67	1199.33	0.4139	0.4044	0.3882
WATT/(METER-K)		0.4041	0.4034	0.4007
1750.00	2209.70	0.2432	0.2372	0.2273
BTU/(HR-FT-F)		0.2371	0.2364	0.2349
954.45	1227.61	0.4206	0.4106	0.3934
WATT/(METER-K)		0.4103	0.4092	0.4065

Table A.5 (Continued)

THERMAL CONDUCTIVITY OF [illegible] COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 1000 PSIA = 68.0457 ATM = 68.949 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
1800.00 BTU/(HR-FT-F)	2259.70	0.2468 0.2416	0.2407 0.2393	0.2333 0.2382
982.23 WATT/(METER-K)	1255.39	0.4272 0.4165	0.4166 0.4153	0.3935 0.4123
1850.00 BTU/(HR-FT-F)	2339.70	0.2506 0.2442	0.2442 0.2431	0.2332 0.2415
1010.01 WATT/(METER-K)	1283.17	0.4336 0.4226	0.4226 0.4203	0.4035 0.4180
1900.00 BTU/(HR-FT-F)	2359.70	0.2544 0.2476	0.2477 0.2464	0.2360 0.2447
1037.78 WATT/(METER-K)	1310.94	0.4404 0.4286	0.4286 0.4265	0.4034 0.4236
1950.00 BTU/(HR-FT-F)	2409.70	0.2582 0.2511	0.2511 0.2497	0.2387 0.2479
1065.56 WATT/(METER-K)	1338.72	0.4469 0.4345	0.4346 0.4322	0.4132 0.4291
2000.00 BTU/(HR-FT-F)	2459.70	0.2619 0.2545	0.2545 0.2537	0.2414 0.2511
1093.34 WATT/(METER-K)	1366.50	0.4533 0.4404	0.4405 0.4379	0.4179 0.4346

Table A.6

THERMAL CONDUCTIVITY OF HELIUM AT 1500 PSIA

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

REFERENCE LIST:

K1; RISO REPT 224. K2; GA CO.
K3; J.P. SANDERS, ORNL. K4; D.L. MC ELROY, ORNL
K5; JULICH, REPT KFA-IRE-17/72.
K6; ASHRAE, THERMOPHYS. PROP., 1973.

PRESSURE = 1500 PSIA = 102.069 ATM = 103.423 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
50.00	509.70	0.0877	0.0925	0.0917
BTU/(HR-FT-F)		---	0.0846	0.0843
10.01	283.17	0.1517	0.1600	0.1588
WATT/(METER-K)		---	0.1464	0.1459
100.00	559.70	0.0936	0.0981	0.0968
BTU/(HR-FT-F)		---	0.0905	0.0901
37.78	310.94	0.1619	0.1697	0.1675
WATT/(METER-K)		---	0.1567	0.1559
150.00	609.70	0.0993	0.1035	0.1017
BTU/(HR-FT-F)		---	0.0964	0.0957
65.56	338.72	0.1719	0.1792	0.1760
WATT/(METER-K)		---	0.1668	0.1657
200.00	659.70	0.1049	0.1083	0.1066
BTU/(HR-FT-F)		---	0.1020	0.1013
93.34	366.50	0.1816	0.1883	0.1845
WATT/(METER-K)		---	0.1766	0.1754
250.00	709.70	0.1104	0.1140	0.1115
BTU/(HR-FT-F)		---	0.1076	0.1069
121.12	394.28	0.1910	0.1973	0.1929
WATT/(METER-K)		---	0.1862	0.1850

Table A.6 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 1500 PSIA = 102.069 ATM = 103.423 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
300.00	759.70	0.1157	0.1191	0.1162
BTU/(HR-FT-F)		---	0.1131	0.1123
148.90	422.06	0.2003	0.2061	0.2012
WATT/(METER-K)		---	0.1957	0.1944
350.00	809.70	0.1210	0.1240	0.1209
BTU/(HR-FT-F)		---	0.1184	0.1177
176.67	449.83	0.2094	0.2146	0.2093
WATT/(METER-K)		---	0.2049	0.2037
400.00	859.70	0.1261	0.1289	0.1256
BTU/(HR-FT-F)		---	0.1236	0.1230
204.45	477.51	0.2183	0.2230	0.2174
WATT/(METER-K)		---	0.2140	0.2129
450.00	909.70	0.1312	0.1336	0.1302
BTU/(HR-FT-F)		0.1323	0.1288	0.1282
232.23	505.39	0.2270	0.2313	0.2253
WATT/(METER-K)		0.2290	0.2229	0.2219
500.00	959.70	0.1361	0.1383	0.1347
BTU/(HR-FT-F)		0.1368	0.1339	0.1334
260.01	533.17	0.2356	0.2393	0.2332
WATT/(METER-K)		0.2367	0.2317	0.2308
550.00	1009.70	0.1410	0.1429	0.1392
BTU/(HR-FT-F)		0.1412	0.1389	0.1384
287.78	560.94	0.2441	0.2473	0.2409
WATT/(METER-K)		0.2444	0.2404	0.2396

Table A.6 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 1500 PSIA = 102.069 ATM = 103.423 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
600.00	1059.70	0.1458	0.1474	0.1436
BTU/(HR-FT-F)		0.1456	0.1438	0.1433
315.56	588.72	0.2524	0.2551	0.2485
WATT/(METER-K)		0.2520	0.2489	0.2481
650.00	1109.70	0.1506	0.1519	0.1479
BTU/(HR-FT-F)		0.1500	0.1486	0.1482
343.34	616.50	0.2607	0.2628	0.2560
WATT/(METER-K)		0.2596	0.2573	0.2564
700.00	1159.70	0.1553	0.1563	0.1522
BTU/(HR-FT-F)		0.1543	0.1534	0.1529
371.12	644.28	0.2688	0.2704	0.2634
WATT/(METER-K)		0.2671	0.2655	0.2646
750.00	1209.70	0.1599	0.1606	0.1564
BTU/(HR-FT-F)		0.1586	0.1581	0.1575
398.90	672.06	0.2768	0.2779	0.2707
WATT/(METER-K)		0.2745	0.2737	0.2726
800.00	1259.70	0.1645	0.1649	0.1606
BTU/(HR-FT-F)		0.1629	0.1628	0.1620
426.67	699.83	0.2847	0.2853	0.2779
WATT/(METER-K)		0.2819	0.2817	0.2804
850.00	1309.70	0.1690	0.1691	0.1647
BTU/(HR-FT-F)		0.1671	0.1673	0.1665
454.45	727.61	0.2925	0.2926	0.2850
WATT/(METER-K)		0.2893	0.2896	0.2881

Table A.6 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 1500 PSIA = 102.069 ATM = 103.423 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
900.00	1359.70	0.1735	0.1732	0.1687
BTU/(HR-FT-F)		0.1713	0.1718	0.1708
482.23	755.39	0.3002	0.2998	0.2920
WATT/(METER-K)		0.2965	0.2973	0.2956
950.00	1409.70	0.1779	0.1773	0.1727
BTU/(HR-FT-F)		0.1755	0.1762	0.1751
510.01	783.17	0.3078	0.3069	0.2989
WATT/(METER-K)		0.3037	0.3050	0.3030
1000.00	1459.70	0.1822	0.1814	0.1766
BTU/(HR-FT-F)		0.1796	0.1805	0.1793
537.78	810.94	0.3154	0.3140	0.3056
WATT/(METER-K)		0.3109	0.3125	0.3103
1050.00	1509.70	0.1865	0.1854	0.1804
BTU/(HR-FT-F)		0.1837	0.1848	0.1834
565.56	838.72	0.3229	0.3209	0.3123
WATT/(METER-K)		0.3130	0.3198	0.3174
1100.00	1559.70	0.1908	0.1894	0.1842
BTU/(HR-FT-F)		0.1878	0.1889	0.1875
593.34	866.50	0.3303	0.3278	0.3188
WATT/(METER-K)		0.3256	0.3270	0.3244
1150.00	1609.70	0.1951	0.1933	0.1879
BTU/(HR-FT-F)		0.1918	0.1930	0.1914
621.12	894.23	0.3376	0.3346	0.3253
WATT/(METER-K)		0.3320	0.3341	0.3313

Table A.6 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 1500 PSIA = 102.069 ATM = 103.423 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
1200.00	1659.70	0.1992	0.1972	0.1916
BTU/(HR-FT-F)		0.1958	0.1970	0.1954
648.90	922.06	0.3448	0.3414	0.3316
WATT/(METER-K)		0.3389	0.3410	0.3381
1250.00	1709.70	0.2034	0.2011	0.1952
BTU/(HR-FT-F)		0.1998	0.2009	0.1992
676.67	949.83	0.3520	0.3480	0.3378
WATT/(METER-K)		0.3458	0.3477	0.3448
1300.00	1759.70	0.2075	0.2049	0.1987
BTU/(HR-FT-F)		0.2037	0.2047	0.2030
704.45	977.61	0.3592	0.3547	0.3439
WATT/(METER-K)		0.3525	0.3544	0.3514
1350.00	1809.70	0.2116	0.2087	0.2022
BTU/(HR-FT-F)		0.2076	0.2085	0.2068
732.23	1005.39	0.3662	0.3612	0.3500
WATT/(METER-K)		0.3593	0.3608	0.3578
1400.00	1859.70	0.2156	0.2125	0.2056
BTU/(HR-FT-F)		0.2114	0.2122	0.2104
760.01	1033.17	0.3732	0.3677	0.3559
WATT/(METER-K)		0.3659	0.3672	0.3642
1450.00	1909.70	0.2197	0.2162	0.2090
BTU/(HR-FT-F)		0.2152	0.2158	0.2141
787.78	1060.94	0.3802	0.3741	0.3617
WATT/(METER-K)		0.3725	0.3734	0.3705

Table A.6 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 1500 PSIA = 102.069 ATM = 103.423 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
1500.00	1959.70	0.2236	0.2199	0.2122
BTU/(HR-FT-F)		0.2190	0.2193	0.2177
815.56	1088.72	0.3871	0.3805	0.3673
WATT/(METER-K)		0.3790	0.3796	0.3767
1550.00	2009.70	0.2276	0.2235	0.2155
BTU/(HR-FT-F)		0.2227	0.2228	0.2212
843.34	1116.50	0.3939	0.3869	0.3729
WATT/(METER-K)		0.3855	0.3856	0.3828
1600.00	2059.70	0.2315	0.2271	0.2186
BTU/(HR-FT-F)		0.2264	0.2263	0.2247
871.12	1144.23	0.4007	0.3931	0.3784
WATT/(METER-K)		0.3919	0.3916	0.3889
1650.00	2109.70	0.2354	0.2307	0.2217
BTU/(HR-FT-F)		0.2301	0.2297	0.2281
898.90	1172.06	0.4074	0.3994	0.3838
WATT/(METER-K)		0.3982	0.3975	0.3949
1700.00	2159.70	0.2393	0.2343	0.2248
BTU/(HR-FT-F)		0.2337	0.2331	0.2315
926.67	1199.83	0.4141	0.4055	0.3890
WATT/(METER-K)		0.4045	0.4034	0.4007
1750.00	2209.70	0.2431	0.2379	0.2277
BTU/(HR-FT-F)		0.2373	0.2365	0.2349
954.45	1227.61	0.4203	0.4117	0.3942
WATT/(METER-K)		0.4107	0.4092	0.4065

Table A.6 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 1500 PSIA = 102.069 ATM = 103.423 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
1800.00 BTU/(HR-FT-F)	2259.70	0.2469 0.2408	0.2414 0.2398	0.2307 0.2382
982.23 WATT/(METER-K)	1255.39	0.4274 0.4168	0.4173 0.4150	0.3992 0.4123
1850.00 BTU/(HR-FT-F)	2309.70	0.2507 0.2444	0.2449 0.2431	0.2335 0.2415
1010.01 WATT/(METER-K)	1283.17	0.4339 0.4229	0.4233 0.4208	0.4042 0.4160
1900.00 BTU/(HR-FT-F)	2359.70	0.2545 0.2478	0.2483 0.2464	0.2363 0.2447
1037.78 WATT/(METER-K)	1310.94	0.4404 0.4289	0.4293 0.4265	0.4090 0.4236
1950.00 BTU/(HR-FT-F)	2409.70	0.2582 0.2513	0.2518 0.2497	0.2390 0.2479
1065.56 WATT/(METER-K)	1338.72	0.4469 0.4349	0.4358 0.4322	0.4137 0.4291
2000.00 BTU/(HR-FT-F)	2459.70	0.2619 0.2547	0.2552 0.2530	0.2417 0.2511
1093.34 WATT/(METER-K)	1366.50	0.4533 0.4407	0.4417 0.4379	0.4183 0.4346

Table A.7

THERMAL CONDUCTIVITY OF HELIUM AT 2000 PSIA

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

REFERENCE LIST:

K1; RISO REPT 224. K2; GA CO.
K3; J.P. SANDERS, ORNL. K4; D.L. MC ELROY, ORNL
K5; JULICH, REPT KFA-IRE-17/72.
K6; ASHRAE, THERMOPHYS. PROP., 1973.

PRESSURE = 2000 PSIA = 136.091 ATM = 137.898 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
50.00	509.70	0.0382	0.0930	0.0920
BTU/(HR-FT-F)		---	0.0846	0.0843
10.01	283.17	0.1527	0.1609	0.1593
WATT/(METER-K)		---	0.1464	0.1459
100.00	559.70	0.0941	0.0986	0.0971
BTU/(HR-FT-F)		---	0.0905	0.0901
37.78	310.94	0.1629	0.1707	0.1680
WATT/(METER-K)		---	0.1567	0.1559
150.00	609.70	0.0999	0.1041	0.1021
BTU/(HR-FT-F)		---	0.0964	0.0957
65.56	338.72	0.1728	0.1801	0.1767
WATT/(METER-K)		---	0.1668	0.1657
200.00	659.70	0.1054	0.1094	0.1070
BTU/(HR-FT-F)		---	0.1020	0.1013
93.34	366.50	0.1825	0.1893	0.1852
WATT/(METER-K)		---	0.1766	0.1754
250.00	709.70	0.1109	0.1145	0.1119
BTU/(HR-FT-F)		---	0.1076	0.1069
121.12	394.23	0.1919	0.1982	0.1936
WATT/(METER-K)		---	0.1862	0.1850

Table A.7 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 2000 PSIA = 136.091 ATM = 137.896 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
300.00	759.70	0.1162	0.1196	0.1167
BTU/(HR-FT-F)		---	0.1131	0.1123
148.90	422.06	0.2012	0.2070	0.2019
WATT/(METER-K)		---	0.1957	0.1944
350.00	809.70	0.1215	0.1245	0.1214
BTU/(HR-FT-F)		---	0.1184	0.1177
176.67	449.83	0.2102	0.2155	0.2102
WATT/(METER-K)		---	0.2049	0.2037
400.00	859.70	0.1266	0.1294	0.1261
BTU/(HR-FT-F)		---	0.1236	0.1230
204.45	477.61	0.2191	0.2239	0.2182
WATT/(METER-K)		---	0.2140	0.2129
450.00	909.70	0.1316	0.1341	0.1307
BTU/(HR-FT-F)		0.1329	0.1288	0.1232
232.23	505.39	0.2273	0.2322	0.2262
WATT/(METER-K)		0.2300	0.2229	0.2219
500.00	959.70	0.1366	0.1388	0.1353
BTU/(HR-FT-F)		0.1373	0.1339	0.1334
260.01	533.17	0.2364	0.2403	0.2341
WATT/(METER-K)		0.2377	0.2317	0.2303
550.00	1009.70	0.1415	0.1434	0.1397
BTU/(HR-FT-F)		0.1417	0.1389	0.1334
287.78	560.94	0.2448	0.2432	0.2419
WATT/(METER-K)		0.2453	0.2404	0.2396

Table A.7 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 2000 PSIA = 136.091 ATM = 137.898 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
600.00	1059.70	0.1463	0.1479	0.1442
BTU/(HR-FT-F)		0.1461	0.1438	0.1433
315.56	588.72	0.2532	0.2561	0.2495
WATT/(METER-K)		0.2529	0.2489	0.2481
650.00	1109.70	0.1510	0.1524	0.1485
BTU/(HR-FT-F)		0.1505	0.1486	0.1482
343.34	616.50	0.2613	0.2638	0.2570
WATT/(METER-K)		0.2604	0.2573	0.2564
700.00	1159.70	0.1557	0.1568	0.1528
BTU/(HR-FT-F)		0.1548	0.1534	0.1529
371.12	644.28	0.2694	0.2714	0.2645
WATT/(METER-K)		0.2679	0.2655	0.2646
750.00	1209.70	0.1603	0.1611	0.1570
BTU/(HR-FT-F)		0.1591	0.1581	0.1575
398.90	672.06	0.2774	0.2788	0.2718
WATT/(METER-K)		0.2753	0.2737	0.2726
800.00	1259.70	0.1648	0.1654	0.1612
BTU/(HR-FT-F)		0.1633	0.1628	0.1620
426.67	699.83	0.2852	0.2862	0.2790
WATT/(METER-K)		0.2826	0.2817	0.2804
850.00	1309.70	0.1693	0.1696	0.1653
BTU/(HR-FT-F)		0.1675	0.1673	0.1665
454.45	727.61	0.2930	0.2935	0.2861
WATT/(METER-K)		0.2899	0.2896	0.2881

Table A.7 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 2000 PSIA = 136.091 ATM = 137.895 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
900.00	1359.70	0.1737	0.1738	0.1693
BTU/(HR-FT-F)		0.1717	0.1718	0.1708
482.23	755.39	0.3007	0.3007	0.2931
WATT/(METER-K)		0.2972	0.2973	0.2956
950.00	1409.70	0.1781	0.1779	0.1733
BTU/(HR-FT-F)		0.1759	0.1762	0.1751
510.01	783.17	0.3083	0.3079	0.3000
WATT/(METER-K)		0.3044	0.3050	0.3030
1000.00	1459.70	0.1825	0.1819	0.1772
BTU/(HR-FT-F)		0.1800	0.1805	0.1793
537.78	810.94	0.3158	0.3149	0.3067
WATT/(METER-K)		0.3115	0.3125	0.3103
1050.00	1509.70	0.1868	0.1860	0.1811
BTU/(HR-FT-F)		0.1841	0.1848	0.1834
565.56	833.72	0.3232	0.3218	0.3134
WATT/(METER-K)		0.3186	0.3198	0.3174
1100.00	1559.70	0.1910	0.1899	0.1848
BTU/(HR-FT-F)		0.1881	0.1889	0.1875
593.34	866.50	0.3306	0.3287	0.3199
WATT/(METER-K)		0.3256	0.3270	0.3244
1150.00	1609.70	0.1952	0.1939	0.1886
BTU/(HR-FT-F)		0.1921	0.1930	0.1914
621.12	894.28	0.3379	0.3355	0.3263
WATT/(METER-K)		0.3326	0.3341	0.3313

Table A.7 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 2000 PSIA = 136.091 ATM = 137.898 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
1200.00	1659.70	0.1994	0.1978	0.1922
BTU/(HR-FT-F)		0.1961	0.1970	0.1954
648.90	922.06	0.3451	0.3423	0.3327
WATT/(METER-K)		0.3394	0.3410	0.3381
1250.00	1709.70	0.2035	0.2016	0.1958
BTU/(HR-FT-F)		0.2001	0.2009	0.1992
676.67	949.83	0.3522	0.3490	0.3389
WATT/(METER-K)		0.3463	0.3477	0.3448
1300.00	1759.70	0.2076	0.2054	0.1993
BTU/(HR-FT-F)		0.2040	0.2047	0.2030
704.45	977.61	0.3593	0.3556	0.3450
WATT/(METER-K)		0.3530	0.3544	0.3514
1350.00	1809.70	0.2117	0.2092	0.2028
BTU/(HR-FT-F)		0.2078	0.2085	0.2068
732.23	1005.39	0.3663	0.3621	0.3510
WATT/(METER-K)		0.3597	0.3608	0.3578
1400.00	1859.70	0.2157	0.2130	0.2062
BTU/(HR-FT-F)		0.2117	0.2122	0.2104
760.01	1033.17	0.3733	0.3686	0.3568
WATT/(METER-K)		0.3664	0.3672	0.3642
1450.00	1909.70	0.2197	0.2167	0.2095
BTU/(HR-FT-F)		0.2155	0.2158	0.2141
787.78	1060.94	0.3802	0.3751	0.3626
WATT/(METER-K)		0.3729	0.3734	0.3705

Table A.7 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 2000 PSIA = 136.091 ATM = 137.893 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
1500.00	1959.70	0.2236	0.2204	0.2128
BTU/(HR-FT-F)		0.2192	0.2193	0.2177
815.56	1088.72	0.3870	0.3814	0.3683
WATT/(METER-K)		0.3795	0.3796	0.3767
1550.00	2009.70	0.2275	0.2241	0.2160
BTU/(HR-FT-F)		0.2230	0.2228	0.2212
843.34	1116.50	0.3938	0.3878	0.3738
WATT/(METER-K)		0.3859	0.3856	0.3828
1600.00	2059.70	0.2314	0.2277	0.2191
BTU/(HR-FT-F)		0.2267	0.2263	0.2247
871.12	1144.28	0.4005	0.3941	0.3793
WATT/(METER-K)		0.3923	0.3916	0.3889
1650.00	2109.70	0.2353	0.2313	0.2222
BTU/(HR-FT-F)		0.2303	0.2297	0.2281
898.90	1172.06	0.4072	0.4003	0.3846
WATT/(METER-K)		0.3986	0.3975	0.3949
1700.00	2159.70	0.2391	0.2349	0.2252
BTU/(HR-FT-F)		0.2339	0.2331	0.2315
926.67	1199.83	0.4139	0.4065	0.3898
WATT/(METER-K)		0.4049	0.4034	0.4007
1750.00	2209.70	0.2429	0.2384	0.2282
BTU/(HR-FT-F)		0.2375	0.2365	0.2349
954.45	1227.61	0.4205	0.4126	0.3949
WATT/(METER-K)		0.4111	0.4092	0.4065

Table A.7 (Continued)

THERMAL CONDUCTIVITY OF HELIUM COMPUTED
WITH DIFFERENT EQUATIONS

PRESSURE = 2000 PSIA = 136.091 ATM = 137.895 BAR

TEMPERATURE		THERMAL CONDUCTIVITY		
DEG F UNITS OF K	DEG R	K1 K4	K2 K5	K3 K6
DEG C UNITS OF K	DEG K			
1800.00	2259.70	0.2467	0.2419	0.2311
BTU/(HR-FT-F)		0.2411	0.2398	0.2382
982.23	1255.39	0.4270	0.4157	0.3999
WATT/(METER-K)		0.4172	0.4150	0.4123
1850.00	2309.70	0.2505	0.2454	0.2339
BTU/(HR-FT-F)		0.2446	0.2431	0.2415
1010.01	1283.17	0.4335	0.4247	0.4048
WATT/(METER-K)		0.4233	0.4208	0.4180
1900.00	2359.70	0.2542	0.2489	0.2366
BTU/(HR-FT-F)		0.2480	0.2464	0.2447
1037.78	1310.94	0.4400	0.4307	0.4096
WATT/(METER-K)		0.4293	0.4265	0.4236
1950.00	2409.70	0.2579	0.2523	0.2393
BTU/(HR-FT-F)		0.2515	0.2497	0.2479
1065.56	1338.72	0.4464	0.4367	0.4142
WATT/(METER-K)		0.4352	0.4322	0.4291
2000.00	2459.70	0.2616	0.2557	0.2420
BTU/(HR-FT-F)		0.2548	0.2530	0.2511
1093.34	1366.50	0.4528	0.4426	0.4188
WATT/(METER-K)		0.4411	0.4379	0.4346

(2) Equation A.4 published by the General Atomic Co., (Ref. 20) also produces higher values of conductivity that are equal or very nearly equal to those calculated with Eq. A.3B.

(3) The conductivities computed with Eq. A.5 at pressures (psia) of 500, 750, and 1500 were obtained by linear interpolation between conductivities calculated at 100, 1000, and 2000 psia.

(4) In using Eq. A.7 the pressure (density) correction was computed with the assumption that helium is a perfect gas. This is a compromise; the expression for density in Ref. 8 is an implicit function of density and, computationally, very awkward. Because pressure effects on conductivity are small, this alteration is considered insignificant.

(5) The ASHRAE expression for conductivity, Eq. A.8 is apparently based on the recent work of Ho, Powell and Liley (Ref. 22).

SUMMARY OF EQUATIONS DEVELOPED FOR EVALUATING THE THERMAL CONDUCTIVITY OF HELIUM

A. From Ref. 1.

$$K1 = (2.682 \times 10^{-3})\ (1.0 + 1.123 \times 10^{-3}P)\ T^{.71(1-.0002P)} \qquad \text{(A.3A)}$$

$K1 = w/(m^2\ K/m)$

T = temperature, K

$273\ K \leqq T < 1800\ K$

P = bar; 1 bar = $10^5\ N/m^2$ = 0.9869 atm

in British units

$$K1 = (1.549 \times 10^{-3})(1.0 + 7.743\ 10^{-5}P)\left[\frac{T}{1.8}\right]^{.71(1.0-1.379\times10^{-5}P)} \qquad \text{(A.3B)}$$

$K1 = (Btu/hr)/(ft^2\text{-}F/ft)$

T = temperature, °R

$460°R \leqq T < 3240°R$

$0°F \leqq T < 2780°F$

P = absolute pressure, psia

The pressure effect is very small and can be neglected in most engineering computations.

B. From Ref. 20:

An equation for helium conductivity in recent use (1974), by the General Atomic Company is:

$$K2 = 1.29 \times 10^{-3}\ T^{0.674} + (8.15 \times 10^{-4})(P - 14.7)^{0.28} \qquad (A.4)$$

K2 = thermal conductivity, (Btu/hr)/(ft^2-°F/ft)

T = temperature, °Rankine

P = pressure, psia.

C. From Ref. 2:

Equations have been developed by Sanders[2] using data prepared by Wilson and published by the General Dynamics Corporation. Sanders developed polynomial fitting equations for computing the thermal conductivity of helium as a function of temperature at different pressures. These equations have the general form

$$K3 = A + BT + CT^2 \qquad (A.5)$$

K3 = (Btu/hr)/(ft^2-°F/ft)

T = temperature, °F

The constants, A, B, and C are slightly pressure dependent as shown in the following table.

Pressure (psia)	A	B	C
14.7	0.0809175	9.9936×10^{-5}	-1.10025×10^{-8}
100.0	0.0834957	10.0842×10^{-5}	-1.13598×10^{-8}
1000.0	0.0863791	10.1611×10^{-5}	-1.20405×10^{-8}
2000.0	0.0869068	10.3092×10^{-5}	-1.27824×10^{-8}

D. From Ref. 21:

McElroy, with data from Ref. 22, developed a second degree equation to describe the thermal conductivity of helium at 1.0 atm pressure. An additive density correction for other pressures from the experimental work of Tsederberg[23] is included. These equations, in metric units, are:

$$(K4)_o = 0.714046 \times 10^{-3} + 0.328159 \times 10^{-5}\ T - 0.42803 \times 10^{-9}\ T^2 \qquad (A.6A)$$

$$K4 = (K4)_o + (1.73 \times 10^{-4})\ (P/T)^{1.17}$$

$(K4)_o$ = thermal conductivity of helium at 1.0 atm pressure, w/(cm^2 K/cm)

K4 = thermal conductivity, of helium, w/(cm^2 K/cm)

T = temperature, K

500K < T < 1500K

P = pressure, atm

In British units:

$$(K4)_o = 0.04126 + (1.0534 \times 10^{-4})T - (7.6331 \times 10^{-9})T^2 \qquad (A.6B)$$

$$K4 = (K4)_o + (8.568 \times 10^{-4})\ (P/T)^{1.17}$$

K4 = thermal conductivity of helium, (Btu/hr)/(ft^2-°F/ft)

$(K4)_o$ = thermal conductivity of helium at 1 atm (= 14.696 psia) pressure

T = temperature, °Rankine

900°R (=440°F) < T < 2700°R (=2240°F)

P = pressure, psia

E. From Ref. 8:

$$(K5)_o = (2.97 \times 10^{-3})\ T^{.69} + \frac{(9.23 \times 10^9)\ (T - 273.16)}{(T - 273.16)^5 - 4.29 \times 10^{14}} \qquad (A.7A)$$

$$K5 = (K5)_o + 2.33 \times 10^{-4}\ \rho + 2.39 \times 10^{-6}\ \rho^2$$

$(K5)_o$ = thermal conductivity, w/m-K at P ≤ 1 bar

(Btu/hr)/(ft^2-°F/ft) = 0.5779 x (w/m K)

1 bar = 10^5 N/m^2 = 0.9869 atm

K5 = thermal conductivity, w/m k

P > 1 bar

ρ = density, kg/m^3

lb/ft^3 = 0.062428 x kg/m^3

T = temperature, °K .

In British units:

$$(K5)_o = (1.144 \times 10^{-3})\, T^{.69} + \frac{(2.96 \times 10^{9})(T - 491.7)}{(5.292\times10^{-2})(T-491.7)^5 + (4.29\times10^{14})} \tag{A.7B}$$

$$K5 = (K5)_o + (5.586 \times 10^{-6})(P/T) + (2.378 \times 10^{-9}(P/T)^2$$

$K5$ = thermal conductivity, $(Btu/hr)/(ft^2\text{-}^\circ F/ft)$

$P \leq 1$ bar $\cong$ 1 atm

$(K5)_o$ = thermal conductivity, $(Btu/hr)/(ft^2\text{-}^\circ F/ft)$

T = temperature, $^\circ R$

P = pressure, psia

F. From Ref. 24:

$$K6 = T^{0.5}/(A + B/T + C/T^2 + D/T^3) \tag{A.8A}$$

$K6 = mw/(cm^2\ K/cm)$

$T = K$

The constant terms and applicable temperature ranges are shown on the following table.

	5K to 45K 9°R to 81°R -451°F to -379°F	50K to 200K 90°R to 360°R -370°F to -100°F	200K to 500K 360°R to 900°R -100°F to 440°F	500K to 1000K 900°R to 1800°R 440°F to 1340°F
A	14.7978	9.97104	6.61227	7.48415
B	48.29403	590.260	2429.73	1429.50
C	-30.03851	-26632.5	-376539	-45815.2
D	0.0	522649	23473100	0.0
Avg. Deviation, %	0.5	0.2	0.0	0.1
Max. Deviation,%	1.9 at 45K	0.3 at 130K	0.1 at 240K	0.2 at 900K

For the temperature range 440°F to 1340°F the above formula in British units is:

$$K6 = 0.04307\ T^{0.5} / (7.48415 + 2573.1/T - 148441/T^2) \qquad \text{(A.8B)}$$

$$K6 = (\text{Btu/hr})/(\text{ft}^2\text{-°F/ft})$$

$$T = \text{°Rankine}$$

Appendix B

Thermal Conductivity of Helium-Nitrogen Mixtures

This appendix describes, in detail, the procedure and the supporting data used to develop Eq. IV.A3 used in the CACHE program to evaluate the thermal conductivity of mixtures of helium with air and air-like gases having molecular weights in the region 28 to 32.

Thermophysical data on the transport properties of these mixtures is scarce and does not cover the complete range of compositions and temperatures required for HTGR applications. The tabulations and curves of conductivity in Ref. 10 are the bases for Eq. IV.A3 in Section IV of this report. The data, Fig. 10, Section IV, of nitrogen-helium conductivity at 601°F versus the mole fraction of nitrogen was used to produce a fitting equation representing the variation of conductivity with composition. The effect of gas temperature was obtained from the data at 601°F and 219°F. In the unlikely event that a Design Basis Depressurization Accident (DBDA) occurs, followed by the ingress of air into the Prestressed Concrete Reactor Vessel (PCRV), it is expected that a portion of the core graphite will be partially oxidized producing carbon monoxide. The core coolant gas will consist principally of helium diluted with nitrogen and carbon monoxide. The composition will change with elapsed time after the DBDA. Because no data on the characteristics of such three component mixtures was located, and because the molecular weights, conductivities, and viscosities of air, carbon monoxide and nitrogen are similar (Fig. 7 in Section IV and Table C2 in Appendix C), it has been assumed that the helium-nitrogen data is applicable to the post-DBDA atmosphere in the PCRV.

Equation IV.A3 was developed in two parts. The first describes the variation of mixture conductivity with composition at 601°F; the second is a term supplying the temperature variation. The step-by-step procedure follows:

(1) It may be observed, Fig. 8 and Fig. 9, that the general shape of the curves of conductivity, k, versus F, the mole fraction of N_2 or O_2, for mixtures of helium with nitrogen or oxygen resembles a hyperbola. Therefore, an equation of the form

$$k_1 \cong \frac{A}{B+F} \tag{B.1A}$$

was used to obtain an approximate fit to the data. In this equation

k = thermal conductivity, (Btu/hr)/ft^2-°F/ft)

F = mole fraction of the diluent gas, N_2 or CO.

A,B = constants

The constants, A and B, were determined so that the "correct" value at 601°F for pure helium ($F = 0$) from Eq. I.A3 and the experimental value at $F = 0.6$ in Table 85b, Ref. 10, were satisfied. The resulting equation is

$$k_1 = \frac{0.03991}{0.27716+F} \tag{B.1B}$$

It was not anticipated that this simple equation would be adequate. Additional terms were added to reduce the errors, defined thus:

$$E(F) \doteq k_{exp} - k_1 \tag{B.2A}$$

$E(F)$ = error, the difference between the experimental values of k for $F > 0$ and k_1 defined by Eq. B.1B.

$k_{exp} = k_1$ at 601°F from Table 85b, Ref. 10, except at $F = 0$ as noted above.

The error, $E(F)$, was approximated by a least squares fitting polynomial in F and the final equation for mixture conductivity, k_o, at 601°F became

$$k_o \cong k_{exp} = k_1 + E(F), \text{ (Btu/hr)/(ft}^2\text{-°F/ft)} \tag{B.2B}$$

$$E(F) = -0.003196 + 0.07014F - 0.15767F^2 + 0.08612F^3 \tag{B.2C}$$

and

$$k_o = \frac{0.03991}{0.27716+F} - .003196 + 0.07014F - 0.15767F^2 + 0.08612F^3 \tag{B.3A}$$

This equation, B.3A, fits the data at 601°F within 3% over the entire range of nitrogen-helium composition. In the range of interest, when the mixture molecular weights are from 6.0 to seldom or ever more than 20 corresponding to mole fractions, F, of air (nitrogen) from 0.08

to 0.66, the maximum error is the order of 1.5%. Table B.1 lists the experimental and calculated values at 601°F, their differences, and their ratios.

The dependence of thermal conductivity with temperature was assumed to be of the form:

$$k(T) = k_o \, (T/T_o)^x \tag{B.4A}$$

k_o = k at 601°F (=1061°R), (from Eq. B.3A)
T_o = 1061°R
T = absolute temperature of mixture, °R

The exponent, x, is based on the data in Table 85b, Ref. 10, which shows values of k versus F at temperatures of 32°F, 86°F, 113°F, 219°F, and 601°F. Using the tabulated values of k at 219°F and 601°F, x was evaluated with the relation

$$x = \log (k/k_o)/\log (T/T_o) \tag{B.5A}$$

k, k_o - thermal conductivities, Table 85b, of a helium-nitrogen mixture both with the same mole fraction, F, of nitrogen at temperature T = 679°R and T_o = 1061°R.

after inserting temperatures

$$x = -2.24 \log (k/k_o) \tag{B.5B}$$

Figure B.1 shows the exponent, x, plotted as a function of F. The variation of x is, unfortunately, larger than desirable; from a minimum of 0.53 to a maximum of 0.82. Because this variation did not have a regular pattern, it was arbitrarily decided to establish x as a constant by using the arithmetic average, 0.66, of the values of x shown in Fig. B.1. The final equation for the thermal conductivity of these helium-nitrogen mixtures is

$$k = \left[\frac{.03991}{.27716+F} - .003196 + .07014F - .15767F^2 + .08612F^3\right]\left(\frac{T}{1061}\right)^{.66} \tag{B.6A}$$

(Also IV.A3)

Figure 10 in Section IV displays curves of k from Eq. B.6A as a function of temperature and composition. The data for pure helium and pure nitrogen are also shown for comparison. The agreement, when F = 0, with the

ORNL-DWG 76-2172

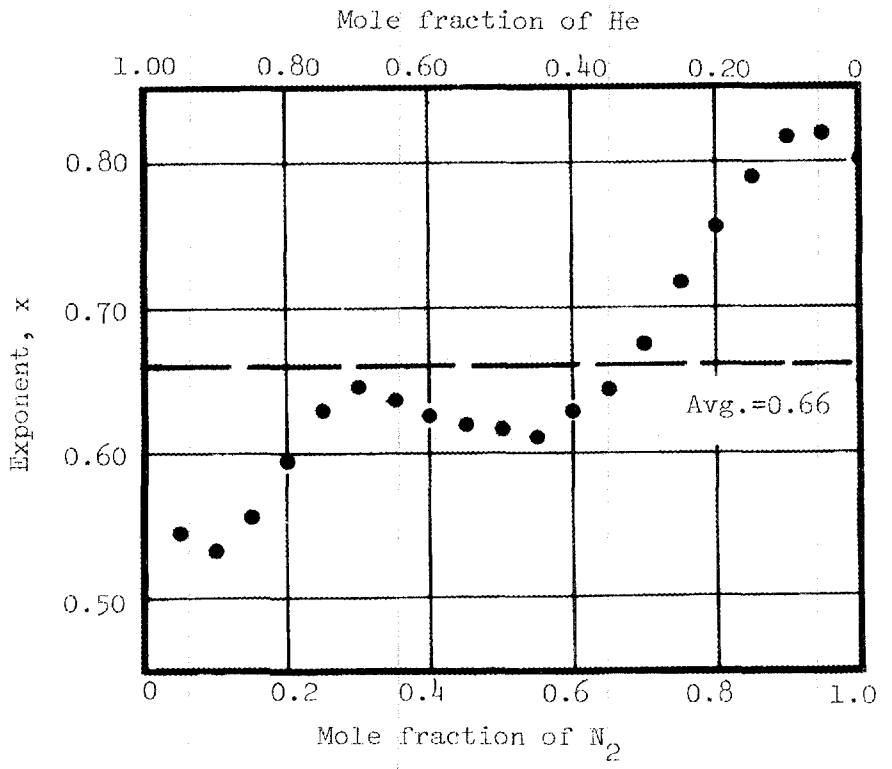

Fig. B.1. Variation of the exponent of temperature in an equation for thermal conductivity of helium-nitrogen mixtures assumed to have the form,

$k = k_o T^x$; T = absolute temperature

At F = 0; x ≐ 0.71 for pure helium, Ref. 1 or Eq. I.A3

At F > 0; x has been calculated from experimental values of thermal conductivity at temperatures of 377.2K and 589.2K, Table 85b, Ref. 10.

pure helium data is excellent. The agreement, when F = 1.0, with the nitrogen data is not as close, but no situations have been postulated in which F, the mole fraction of nitrogen in the mixture, is above 0.6. Furthermore, the exact composition of PCRV atmospheres after DBDAs cannot be forecast with extreme accuracy. The uncertainties in forecasting the post-DBDA gas compositions and their variation with elapsed time after reactor shutdown will, in all likelihood, be greater than errors in evaluating gas mixture thermal transport properties.

Table B.1. Comparison of experimental* and calculated** thermal conductivities of helium-nitrogen gas mixtures at 601°F

F, Mole fraction nitrogen,	Thermal conductivity, (Btu/hr)/(ft^2-°F/ft) Experimental, $k_{exp.}$	Calculated k_{calc}	Ratio, k_{calc}/k_{exp}
0	0.1434	0.140764	0.981618
0.05	0.1184	0.121886	1.02944
0.1	0.1069	0.108118	1.0114
0.15	0.0976	9.74761E-2	0.998731
0.2	0.0896	8.88345E-2	0.991457
0.25	0.0826	8.15197E-2	0.986922
0.3	0.0763	7.51137E-2	0.984452
0.35	6.99000E-2	6.93524E-2	0.992166
0.4	0.0641	6.40688E-2	0.999513
0.45	0.0589	5.91596E-2	1.00441
0.5	0.054	5.45646E-2	1.01046
0.55	0.0495	5.02541E-2	1.01523
0.6	0.0455	4.62194E-2	1.01581
0.65	0.0419	4.24681E-2	1.01356
0.7	3.88000E-2	3.90191E-2	1.00565
0.75	0.0362	3.59005E-2	0.991725
0.8	0.0337	3.31468E-2	0.983585
0.85	0.0315	3.07982E-2	0.977721
0.9	0.0295	2.88989E-2	0.979622
0.95	2.76000E-2	2.74963E-2	0.996243
1	2.58000E-2	2.66407E-2	1.03259

*Experimental data from Table 85b, Ref. 10.

$$^{**}k_{calc} = \frac{0.03991}{0.27716+F} - 0.003196 + 0.07014F - 0.15767F^2 + 0.08612F^3$$

Appendix C

The Viscosity of Helium

The Viscosity of Pure Helium

The information in this appendix was developed in the process of obtaining the equations in Sections I and IV describing the viscosity of pure helium and helium-air mixtures.

Before finally selecting Eq. I.B2 (Section I), several sources of viscosity data on pure helium were located and reviewed. In a subsequent paragraph six equations and their sources are listed. All give similar numerical results at 650°F. This is a representative value for the mean helium film temperature in the central region of an HTGR Core Auxiliary Heat Exchanger. The similarity is illustrated by Table C.1.

Table C.1. The viscosity of pure helium at 650°F evaluated with Equations C.1B through C.6B, inclusive.

Equation	Reference	Viscosity, $lb_m/(ft\text{-}hr)$
C.1B	Risö Report 224, Ref. 1	0.0798
C.2	GA Co., Ref. 20	0.0779
C.3	J. P. Sanders, Ref. 2	0.0789
C.4C	Bonka and Vogt, Ref. 8	0.0777
C.5B	J. M. Wright, Ref. 6	0.0778
C.6B	ASHRAE, Ref. 24	0.0788

Equation A.2B in Appendix A is a method of estimating the effect of small variations or differences in viscosity on the film coefficient of heat transfer. The film coefficient is less sensitive than for similar changes in conductivity and therefore no detailed comparative tabulations of viscosities based on these equations are provided. For example, in Table C.1 the maximum and minimum values, 0.0798 and 0.0777, differ by 0.0021. The effect of this incremental difference in a typical CAHE performance computation will be less than 1.0%.

It has been stated elsewhere in this report that the viscosities of air, nitrogen, carbon monoxide, and oxygen are generally similar and follow similar trends with temperature. Figure C.1 shows these viscosities based on equations in Ref. 24 and Ref. 25. Table C.2 provides calculated viscosity data in British and metric units.

Equations for Calculating the Viscosity of Helium:

A. From Ref. 1.:

$$\mu = (3.674 \times 10^{-7})T^{0.70} \qquad \text{(C.1A)}$$

μ = viscosity, kg/(m-sec)

T = temperature, K

$273\ K \leq T < 1800\ K$

in British units

$$\mu = (5.890 \times 10^{-4})T^{0.70} \qquad \text{(C.1B)}$$

(Identical to Eq. I.B2)

μ = viscosity, $lb_m/(ft\text{-}hr)$

T = temperature, °R

$460°R \leq T \leq 3240°R$

$0°F \leq T \leq 2780°F$

Petersen[1] states: "The standard deviation, σ, is about 0.4% at 273 K and 2.7% at 1800 K, i.e., $\sigma = 0.0015\ T\%$."

B. From Ref. 20 :

$$\mu = 6.9 \times 10^{-4}\ T^{0.674}\ lb_m/ft\text{-}hr \qquad \text{(C.2)}$$

T = °Rankine

C. From Ref. 2.:

Sanders, using Ref. 3 for source material, presents this empirical equation for helium viscosity:

$$\mu = (6.7 \times 10^{-4})T^{0.68}\ lb_m/(ft\text{-}hr) \qquad \text{(C.3)}$$

T = temperature, °R

Helium viscosity is stated to be independent of pressure from atmospheric to 2000 psia.

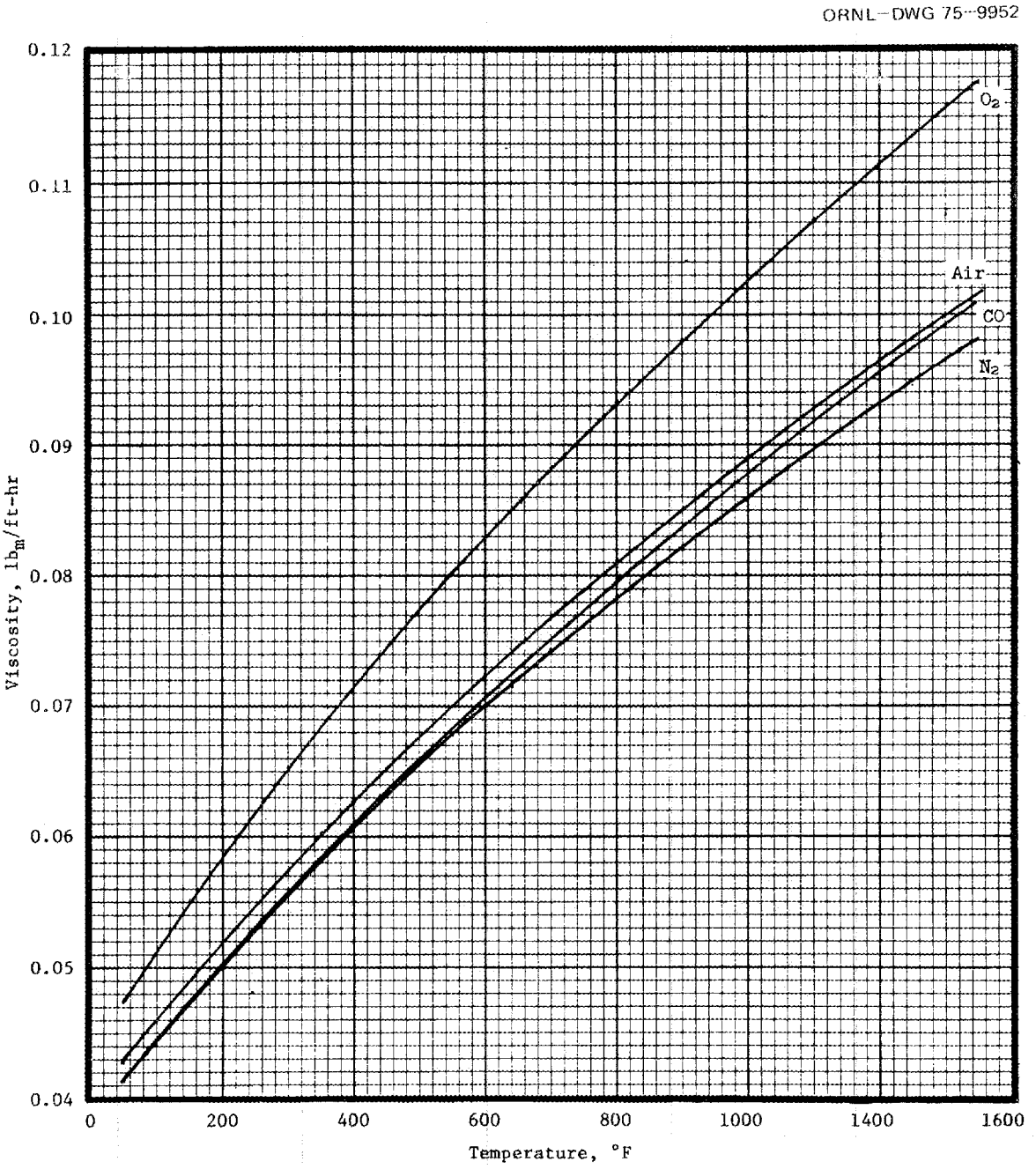

Fig. C.1. The viscosity of common gases with molecular weights from 28 to 32, computed with equations in Ref. 24 and 25.

TABLE C.2

----VISCØSITIES ØF NITRØGEN, ØXYGEN, AND AIR----

CØMPUTED FRØM EQUATIØNS IN THERMØPHYSICAL PRØPERTIES
ØF REFRIGERANTS. ASHRAE 1973.

TEMPERATURE		V,N2	V,Ø2	V,AIR
DEG F DEG C	DEG R DEG K	LB/FT-HR KG/M-S	LB/FT-HR KG/M-S	LB/FT-HR KG/M-S
50	509.7	4.12544E-2	4.77162E-2	4.28033E-2
10	283.167	1.70537E-5	1.97248E-5	1.76940E-5
100	559.7	4.43696E-2	5.14883E-2	4.59921E-2
37.7778	310.944	1.83414E-5	2.12842E-5	1.90121E-5
150	609.7	4.73615E-2	5.51149E-2	4.90520E-2
65.5556	338.722	1.95782E-5	2.27833E-5	2.02770E-5
200	659.7	5.02412E-2	5.86075E-2	5.19954E-2
93.3333	366.5	2.07686E-5	2.42271E-5	2.14938E-5
250	709.7	5.30184E-2	6.19770E-2	5.48331E-2
121.111	394.278	2.19167E-5	2.56200E-5	2.26668E-5
300	759.7	5.57015E-2	6.52331E-2	5.75743E-2
148.889	422.056	2.30258E-5	2.69660E-5	2.38000E-5
350	809.7	5.82983E-2	6.83847E-2	6.02270E-2
176.667	449.833	2.40993E-5	2.82688E-5	2.48966E-5
400	859.7	6.08154E-2	7.14395E-2	6.27983E-2
204.444	477.611	2.51398E-5	2.95316E-5	2.59595E-5
450	909.7	6.31159E-2	7.44626E-2	6.52945E-2
232.222	505.389	2.60908E-5	3.07812E-5	2.69913E-5
500	959.7	6.54510E-2	7.73523E-2	6.77210E-2
260	533.167	2.70560E-5	3.19758E-5	2.79944E-5
550	1009.7	6.77213E-2	8.01648E-2	7.00828E-2
287.778	560.944	2.79946E-5	3.31384E-5	2.89707E-5
600	1059.7	6.99317E-2	8.29052E-2	7.23843E-2
315.556	588.722	2.89083E-5	3.42712E-5	2.99221E-5
650	1109.7	7.20862E-2	8.55781E-2	7.46294E-2
343.333	616.5	2.97989E-5	3.53762E-5	3.08502E-5

TABLE C.2 (continued)

----VISCØSITIES ØF NITROGEN, ØXYGEN, AND AIR----

CØMPUTED FRØM EQUATIØNS IN THERMØPHYSICAL PRØPERTIES
ØF REFRIGERANTS. ASHRAE 1973.

TEMPERATURE		V,N2	V,Ø2	V,AIR
DEG F DEG C	DEG R DEG K	LB/FT-HR KG/M-S	LB/FT-HR KG/M-S	LB/FT-HR KG/M-S
700 371.111	1159.7 644.278	7.41887E-2 3.06680E-5	8.81878E-2 3.64550E-5	7.68217E-2 3.17565E-5
750 398.889	1209.7 672.056	7.62425E-2 3.15170E-5	9.07381E-2 3.75092E-5	7.89645E-2 3.26422E-5
800 426.667	1259.7 699.833	7.82507E-2 3.23472E-5	9.32325E-2 3.85403E-5	8.10606E-2 3.35087E-5
850 454.444	1309.7 727.611	8.02159E-2 3.31595E-5	9.56741E-2 3.95496E-5	8.31128E-2 3.43570E-5
900 482.222	1359.7 755.389	8.21407E-2 3.39552E-5	9.80659E-2 4.05384E-5	8.51234E-2 3.51882E-5
950 510	1409.7 783.167	8.40273E-2 3.47351E-5	0.100411 4.15076E-5	8.70947E-2 3.60031E-5
1000 537.778	1459.7 810.944	8.58778E-2 3.55001E-5	0.10271 4.24583E-5	8.90287E-2 3.68026E-5
1050 565.556	1509.7 838.722	8.76940E-2 3.62508E-5	0.104968 4.33915E-5	9.09273E-2 3.75874E-5
1100 593.333	1559.7 866.5	8.94777E-2 3.69882E-5	0.107185 4.43079E-5	9.27923E-2 3.83584E-5
1150 621.111	1609.7 894.278	9.12305E-2 3.77127E-5	0.109363 4.52085E-5	9.46253E-2 3.91161E-5
1200 648.889	1659.7 922.056	9.29538E-2 3.84251E-5	0.111505 4.60939E-5	9.64277E-2 3.98611E-5
1250 676.667	1709.7 949.833	9.46490E-2 3.91259E-5	0.113612 4.69648E-5	9.82009E-2 4.05942E-5
1300 704.444	1759.7 977.611	9.63173E-2 3.98155E-5	0.115685 4.78219E-5	9.99462E-2 4.13156E-5
1350 732.222	1809.7 1005.39	9.79600E-2 4.04946E-5	0.117727 4.86657E-5	0.101665 4.20261E-5

D. From Ref. 8.:

Bonka and Vogt give these equations for helium viscosity:

$$\mu_o = (3.78 \times 10^{-7})T^{0.69} + (5 \times 10^{-7})/(0.52 + T/569.6) \qquad (C.4A)$$

$$\mu = \mu_o + (2.67 \times 10^{-10})\rho^2 \qquad (C.4B)$$

μ_o = viscosity, N s/m^2

$P \leq 1$ bar

μ = viscosity, N s/m^2

$P > 1$ bar

T = temperature, K

ρ = density, kg/m^3

The density correction is negligible, 1 part in 10^9, and can be ignored in HTGR computations.

In British units the equation for viscosity is:

$$\mu_o = (6.095 \times 10^{-4})\ T^{0.69} + 1.2095 \times 10^{-3}/(.52 + 9.7534 \times 10^{-4}T) \qquad (C.4C)$$

μ_o = viscosity lb_m/ft-hr

T = temperature, °R

E. From Ref. 6.:

J. M. Wright proposes this equation for helium viscosity:

$$\mu = (2.79 \times 10^{-6})\ T\ [(T/5.3)^{0.75} + (T/5.3)^{-0.75}]^{-0.47} \qquad (C.5A)$$

μ = viscosity, poises = g/(cm-sec)

T = temperature, K

$15K \leq T \leq 1090K$

After rearranging and converting to British units, the equation is written:

$$\mu = (3.75 \times 10^{-4})\ T\ (0.1842\ T^{0.75} + 1/0.1842T^{0.75})^{-0.47} \qquad (C.5B)$$

μ = viscosity, lb_m/(ft-hr)

T = temperature, °R

$27°R \leq T \leq 1960°R$

$-433°F \leq T \leq 1500°F$

Wright states that the average error in this equation is 0.8%.

F. From Ref. 24.:

This ASHRAE publication contains an equation having the general form:

$$\mu = T^{0.5}/(A + B/T + C/T^2 + D/T^3) \qquad (C.6A)$$

μ = viscosity, $(N\ s/m^2) \times 10^{-6}$

$N\ s/m^2$ = kg/m-sec

T = temperature, K

The constants and the accuracy of the fit are tabulated for three temperature ranges.

	Temperature range		
	1.25 K to 20.0 K 2.25°R to 36.0°R - 457.4°F to -423.7°F	20 K to 300 K 36.0°R to 540°F -424°F to 80°F	300 K to 1000 K 540°R to 1800°R 80°F to 1340°F
A	1.11871	0.83477	0.55797
B	3.30741	2.44262	180.017
C	-0.18070	-592.753	-40566.2
D	-1.13103	5650.18	4431360
Avg. dev.	0.2%	1.4%	0.0%
Max. dev.	0.7% at 20 K	4.3% at 300 K	0.5% at 950 K

In British units this equation becomes

$$\mu = (1.8031 \times 10^{-3})\ T^{0.5}/Z$$

$$Z = 0.55797 + 324.031/T - 131434/T^2 + 25{,}843{,}700/T^3 \qquad (C.6B)$$

$\mu = lb_m/ft\text{-}hr$

T = temperature, °R

$540°R \le T \le 1800°R$

$80°F \le T \le 1340°F$

Appendix D

The Specific Heat of Helium-Air Mixtures

When the composition of a gas mixture is known or established, and the specific heats of the individual gases in the mixture are known, the specific heat of the mixture is easily determined. In strict terms a mixture of air and helium consists of three components; however, since the thermal transport properties of air are well established, it will be considered as a single component gas. Gas composition is usually expressed in terms of mole fractions of the components or the molecular weight of the mixture. Mixture specific heat is dependent on the weight fractions of the constituent gases. The equations that interrelate these modes of stating composition are simple and well known; they are included as a matter of convenience. For a two component gas, air and helium, the composition equations are outlined below.

1. Symbols:

Subscripts . . . . . a, h, and m refer to air, helium and mixtures of air with helium respectively.

A = molecular weight

$A_a = 28.97$

$A_h = 4.00$

F = mole fraction, moles/mole of mixture

W = weight/mole, lbs/mole of mixture

Y = weight fraction, lbs/lb of mixture

C_p = specific heat, Btu/lb-°F

2. Weight fractions when the molecular weight of the gas mixture is given:

$$Y_a = \frac{W_a}{A_m} = \frac{A_a(A_m - A_h)}{A_m(A_a - A_h)} = 1.1602 \left(\frac{A_m - 4.00}{A_m}\right) \tag{D.1A}$$

$$Y_h = \frac{W_h}{A_m} = \frac{A_h(A_m - A_a)}{A_m(A_h \quad A_a)} = -0.1602 \left(\frac{A_m - 28.97}{A_m}\right) \tag{D.2A}$$

3. Mole fractions when the weight fraction is given:

$$F_a = \frac{Y_a\ A_h}{Y_a A_h + (1 - Y_a)A_a} = \frac{4.00\ Y_a}{4.00\ Y_a + 28.97\ (1 - Y_a)} \tag{D.3A}$$

$$F_h = \frac{Y_h\ A_a}{Y_h\ A_a + (1 - Y_h)A_h} = \frac{28.97\ Y_h}{28.97\ Y_h + 4.00\ (1 - Y_h)} \tag{D.4A}$$

4. Mole fractions when the molecular weight is given:

$$F_a = \frac{A_m - A_h}{A_a - A_h} = \frac{A_m - 4.00}{24.97} \tag{D.5A}$$

$$F_h = \frac{A_m - A_a}{A_h - A_a} = \frac{A_m - 28.97}{24.97} \tag{D.6A}$$

5. Specific Heat:

$$(C_p)_m = Y_a(C_p)_a + Y_h(C_p)_h = Y_a(C_p)_a + 1.242\ (1 - Y_a) \tag{D.7A}$$

The specific heat at constant pressure, $(C_p)_a$ of air was obtained from a tabulation* of enthalpy versus temperature in Ref. 26, thus:

$$C_p = \frac{\Delta h}{\Delta T}$$

A least squares fit (Ref. 11) with a second degree polynomial was used to approximate the tabulated values of $(C_p)_a$ so obtained. The resulting equation is:

---

*This tabulation has been abstracted from Ref. 27.

$$(C_p)_a = 0.2304 + (3.7672 \times 10^{-5})T - (4.860 \times 10^{-9})T^2 \qquad \text{(D.8A)}$$

$$T = {}^\circ F \qquad \text{(Also Eq. IV.C3)}$$

Table D.1., the printout of the fitting program, contains the tabulated values of $\Delta h/\Delta T$ and $(C_p)_a$ computed with Eq. D.8A. A graphic comparison of $(C_p)_a$ from Eq. D.8A with the tabulated values in Ref. 27 is in Fig. D.1. Figure 14 in Section IV shows curves of the specific heat of air-helium mixtures at 500°F and 900°F, computed by substituting Eq. D.8A into Eq. D.7A.

Table D.1. The specific heat of air at constant pressure; a comparison of tabulated values[20] with a second degree polynomial fit[a]

Temperature (°F)	Specific heat [Btu/(lb-°F)] (Ref. 20)	(Eq. D.8A)	Difference	Percent Difference
300	.243	.241245	1.75505×10^{-3}	.727495
390	.245	.244334	6.66377×10^{-4}	.272732
450	.246	.246349	-3.48996×10^{-4}	-.141667
490	.247	.247673	-6.73137×10^{-4}	-.271785
590	.25	.250915	-9.15451×10^{-4}	-.364845
690	.253	.254061	-1.06057×10^{-3}	-.417446
790	.256	.257108	-1.10848×10^{-3}	-.431133
890	.26	.260059	-5.91907×10^{-5}	-2.27605×10^{-2}
990	.263	.262913	8.72971×10^{-5}	3.32038×10^{-2}
1050	.265	.264578	4.21846×10^{-4}	.159441
1090	.265	.265669	-6.69015×10^{-4}	-.251823
1150	.267	.267276	-2.76146×10^{-4}	-.103318
1190	.269	.268328	6.71874×10^{-4}	.250393
1290	.271	.27089	1.09963×10^{-4}	4.09533×10^{-2}
1390	.274	.273355	6.45252×10^{-4}	.236049
1490	.276	.275722	2.77742×10^{-4}	.100733
1550	.278	.277096	9.03893×10^{-4}	.326202
1590	.279	.277993	1.00743×10^{-3}	.362396
1650	.28	.279308	6.91903×10^{-4}	.24772
1690	.28	.280166	-1.65676×10^{-4}	-5.91351×10^{-2}
1720	.281	.280799	2.01345×10^{-4}	7.17046×10^{-2}
1750	.281	.281423	-4.22886×10^{-4}	-.150267
1790	.282	.282242	-2.41585×10^{-4}	-8.55951×10^{-2}
1850	.283	.28344	-4.40474×10^{-4}	-.155403
1900	.284	.284413	-4.12818×10^{-4}	-.145147
1950	.285	.285361	-3.60862×10^{-4}	-.126458
2000	.286	.286285	-2.84606×10^{-4}	-9.94137×10^{-2}

[a] $(C_p)_a = 0.2304 + (3.7672 \times 10^{-5})T - (4.86 \times 10^{-9})T^2$, Eq. D.8A

ORNL-DWG 76-2173

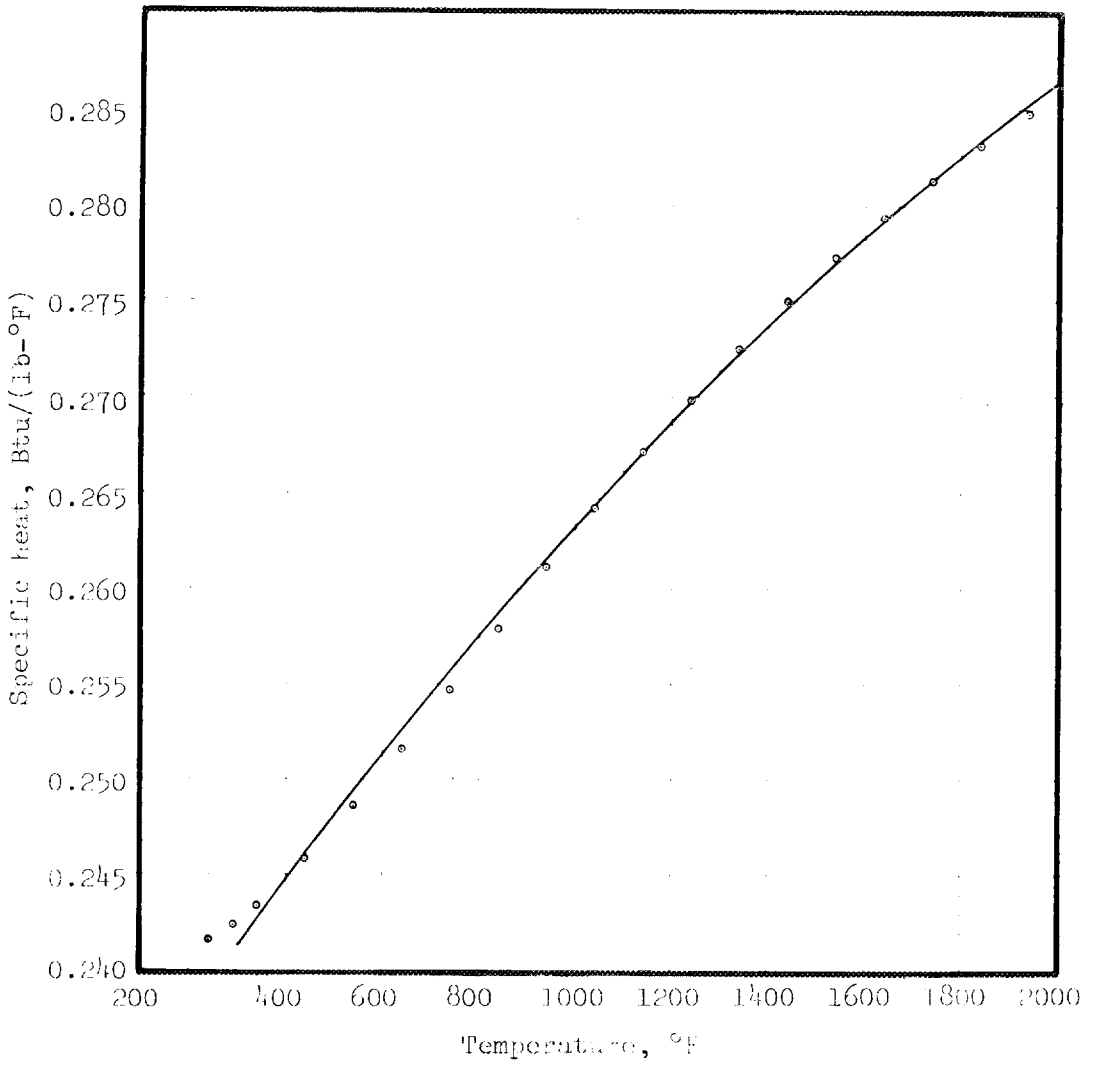

Fig. D.1. Calculated[a] and tabulated[b] values for the specific heat of air at constant pressure.

[a]The continuous curve represents the equation:

$$C_p = 0.2304 + (3.7672 \times 10^{-5})\ T - (4.86 \times 10^{-9})\ T^2;\ T = {}^\circ F$$

[b] ⊙, From Keenan and Kaye, "Gas Tables," Ref. 27.

ORNL-DWG 75-9956

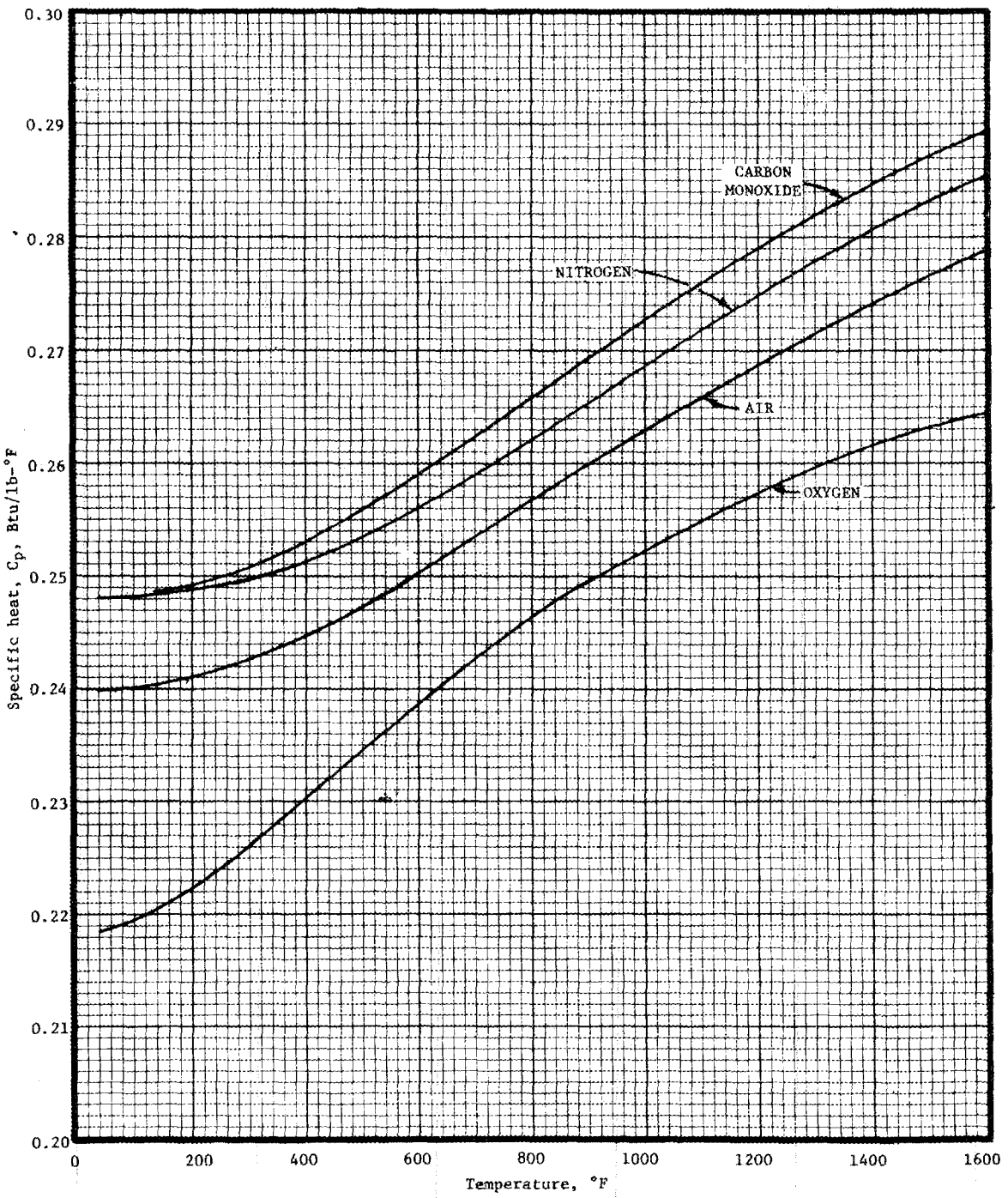

Fig. D.2. The specific heats at constant pressure of the gases that dilute the helium in the PCRV after a DBDA-LOMLC.

References

1. Helge Petersen, The Properties of Helium: Density, Specific Heats, Viscosity, and Thermal Conductivity at Pressures from 1 to 100 Bar and From Room Temperature to About 1800 K, Risö Report No. 224, (September 1970).

2. J. P. Sanders, Oak Ridge National Laboratory, private communication (Nov. 20, 1970).

3. M. P. Wilson, Jr., Thermodynamic and Transport Properties of Helium, GA-1355 (January 1960).

4. Jesse T. Simmons, The Physical and Thermodynamic Properties of Helium, Tech. Report D-9027, Wm. R. Whittaker Co., Ltd., Los Angeles, Calif. (July 1, 1957).

5. Roger A. Svehla, Estimated Viscosities and Thermal Conductivities of Gases at High Temperatures, NASA Technical Report R-132 (1962).

6. J. M. Wright, Calculated Thermal Conductivities of Pure Gases and Gaseous Mixtures at Elevated Temperatures, AECD-4197, General Electric Corp., Hanford Works (1951).

7. J. Phys. Chem. Ref. Data, 1, 279-421 (1972).

8. H. Bonka and G. Vogt, H-S-Diagramm fur Helium Nach den Daten von Cederburg, U. A., Internal Report KFA-IRE-17/72, Kern forschungsanlage Julich, Geselleschaft mit Beschrankter Hattung; Institut fur Reactorent wicklung.

9. J. P. Moore and D. L. McElroy, private communication.

10. Y. S. Touloukian, P. E. Liley and S. C. Saxena, Thermophysical Properties of Matter, vol 3, Thermal Conductivity of Nonmetallic Liquids and Gases, IFI/PLENUM, New York-Washington (1970).

11. "POLFIT, A Program to Fit Least Square Polynomials to Bivariate Data Using an Orthogonal Polynomial Method," Call-A-Computer Co.

12. C. A. Meyer, et al., ASME Steam Tables, The American Society of Mechanical Engineers, 1967.

13. Steels for Nuclear Applications — Mechanical and Physical Properties of Steels for Nuclear Applications, vol 3, United States Steel Corp. Pittsburgh, Pa., (1967).

14. Pipe and Tubes for Elevated Temperature Service, National Tube Division, United States Steel Corporation, Bulletin No. 26.

15. R. C. Reid and T. K. Sherwood, The Properties of Gases and Liquids, Their Estimation and Correlation, McGraw-Hill, New York, 1958.

16. R. S. Brokaw, "Estimating Thermal Conductivities for Nonpolar Gas Mixtures," Ind. Eng. Chem., 47, (11), 2398–2400 (November 1955).

17. C. A. Johnson, Viscosity of Gas Mixtures, Report Ch. E. 273–566F3, Syracuse University Research Institute (July 1, 1956).

18. Preliminary Safety Analysis Report, Fulton Generating Station, Philadelphia Electric Company.

19. J. P. Sanders, HTGR Safety Studies Progress Report for the Period Ending June 30, 1974, GCR-DL: 74-2 (Aug. 22, 1974).

20. J. Goodwin, General Atomic Company, private communication.

21. D. L. McElroy, Oak Ridge National Laboratory, private communication (1972).

22. C. Y. Ho, R. W. Powell and P. E. Liley, Thermal Conductivity of the Elements, NSRDS-NBS, Category 5, U. S. Government Printing Office, Washington, D. C.

23. N. V. Tsederberg, Thermal Conductivity of Gases and Liquids, The MIT Press, Cambridge, Mass., 1965.

24. Thermophysical Properties of Refrigerants, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 1973.

25. Joseph Hilsenrath and Y. S. Touloukian, "The Viscosity, Thermal Conductivity, and Prandtl Number for Air, O_2, N_2, NO, H_2, CO, CO_2, He, and A," ASME Trans. vol 76, 967–85 (August 1954).

26. W. C. Reynolds, Thermodynamics, McGraw-Hill, New York, 1965.

27. J. H. Keenan and J. Kaye, Gas Tables, Wiley, New York, 1948.

Internal Distribution

1. J. L. Anderson
2. S. J. Ball
3. A. L. Boch
4. J. P. Callahan
5. T. E. Cole
6. J. H. Coobs
7. W. B. Cottrell
8. F. L. Culler
9. W. P. Eatherly
10. G. G. Fee
11. M. H. Fontana
12. G. E. Giles, Jr.
13. M. J. Goglia
14. H. W. Hoffman
15. F. J. Homan
16. J. D. Jenkins
17-19. P. R. Kasten
20. T. B. Lindemer
21. A. L. Lotts
22. R. N. Lyon
23. R. E. Macpherson/ J. A. Conlin
24. A. P. Malinauskas
25. Walter J. McCarthy
26. L. C. Oakes
27. H. Postma
28. P. L. Rittenhouse
29. M. W. Rosenthal
30-32. J. P. Sanders
33. Myrtleen Sheldon
34. I. Spiewak
35-44. J. R. Tallackson
45. John J. Taylor
46. D. B. Trauger
47. W. D. Turner
48. G. D. Whitman
49. W. J. Wilcox
50. ORNL Patent Office
51-52. Central Research Library
53. Document Reference Section
54-58. Laboratory Records Department
59. Laboratory Records Department (RC)

External Distribution

60. Director, Division of Reactor Licensing, USNRC, Washington, D. C. 20555
61. Director, Division of Technical Review, USNRC, Washington, D. C. 20555
62. Assistant Director for Reactor Safety, Division of Technical Review, USNRC, Washington, D. C. 20555
63-82. Chief, Gas Cooled Reactors Branch, Division of Reactor Licensing, USNRC, Washington, D. C. 20555
83. Chief, Reactor Systems Branch, Division of Technical Review, USNRC, Washington, D. C. 20555
84. Chief, Core Performance Branch, Division of Technical Review, USNRC, Washington, D. C. 20555
85-86. Director, Office of Nuclear Regulatory Research, USNRC, Washington, D. C. 20555
87. Assistant Director, Advanced Reactor Safety Research, Division of Reactor Safety Research, USNRC, Washington, D. C. 20555
88. Chief, Experimental Gas Cooled Reactor Safety Research Branch, Division of Reactor Safety Research, USNRC, Washington, D. C. 20555
89. Director, Division of Reactor Research and Development, ERDA, Washington, D. C. 20545
90-92. Office of Reactor Safety Research Coordination, ERDA, Washington, D. C. 20545

93. Assistant Director, Gas Cooled Reactor Projects, Division of Reactor Research and Development, ERDA, Washington, D. C. 20545
94. Assistant Director, Reactor Safety, Division of Reactor Research and Development, ERDA, Washington, D. C. 20545
95. Chief, Gas Reactor Safety Branch, Division of Reactor Research and Development, ERDA, Washington, D. C. 20545
96. Director, Research and Technical Support Division, ERDA, OR
97. Director, Reactor Division, ERDA, OR
98-124. Technical Information Center, ERDA, OR
125. W. H. Beach, Gas Cooled Reactor Branch, Division of Reactor Safety Research, USNRC, Washington, D. C. 20555
126. A. Bournia, Gas Cooled Reactors Branch, Division of Reactor Licensing, USNRC, Washington, D. C. 20555
127. E. Lantz, Gas Cooled Reactors Branch, Division of Reactor Licensing, USNRC, Washington, D. C. 20555