(NASA-TM-78249) RADIATIVE AND FREE CONVECTIVE HEAT TRANSFER FROM A CONTAINERLESS SPHERE (NASA) 29 p HC A03/MF A01 CSCL 20D G3/34

N80-11377

Unclas 46057

NASA TECHNICAL MEMORANDUM

NASA TM-78249

RADIATIVE AND FREE CONVECTIVE HEAT TRANSFER FROM A CONTAINERLESS SPHERE

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September 1979

NASA

George C. Marshall Space Flight Center
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MSFC - Form 3190 (Rev June 1971)

TABLE OF CONTENTS

	Page
INTRODUCTION	1
DETERMINATION OF HEAT TRANSFER FORMULA	1
PROPERTIES OF COOLANT GASES	3
THE COMPUTER PROGRAM	7
RESULTS AND CONCLUSIONS	7
REFERENCES	16
APPENDIX A	17
APPENDIX B	21

LIST OF ILLUSTRATIONS

Figure	Title	Page
1.	Sample temperature as a function of total pressure for different initial argon pressures	10
2.	Sample temperature as a function of percentage helium for different initial argon pressures	11
3.	Sample temperature as a function of percentage helium for various emissivities	12
4.	Sample temperature as a function of percentage helium for various power inputs	13
5.	Sample temperature as a function of percentage helium for various sphere diameters	14
6.	Thermal conductivity and Grashof numbers as functions of percentage helium	15

TECHNICAL MEMORANDUM

RADIATIVE AND FREE CONVECTIVE HEAT TRANSFER FROM A CONTAINERLESS SPHERE

INTRODUCTION

Containerless processing of copper in an electromagnetic levitation device uses the natural heating of the sample (generated by the induced eddy currents) and cooling by a helium-argon gas mixture. Such a system has been in operation in the Space Sciences Laboratory, Marshall Space Flight Center, and significant undercooling during solidification has been noted. Temperatures on the order of 2000 K were known to be reached when approximately 20 torr of argon were present in the levitation chamber, and small amounts of helium (approximately 100 torr pressure) were known to reduce the copper sphere's temperature by more than 1000 K. As the coolant gases were admitted to the evacuated chamber through a valve at a large relative distance to the sphere, heat transfer could be considered to be accomplished by radiation and free convection.

In support of this experimentation, a relatively simple mathematical model for the prediction of heat transfer from the sphere was derived. Primary conditions to be considered were the nature of heat loss, the high temperatures and low pressures involved, and the restrictions on direct experimental measurements of various parameters (sphere diameter, emissivity and temperature, and gas temperature and pressure were the only measurable quantities). Parameters to be varied in the calculation of temperature were power input to the levitation coil, emissivity and diameter of the sphere, and gas pressures.

DETERMINATION OF HEAT TRANSFER FORMULA

Power input (PI) to the sphere is equal to total heat loss through radiation and free convection:

$$PI = Q_{rad} + Q_{conv} \quad .$$

The heat transfer due to radiation (Q_{rad}) is

$$Q_{rad} = \sigma\varepsilon A(T_1^4 - T_o^4)$$

where

σ = Stefan-Boltzman constant = 0.56697×10^{-8} W/m^2-K^4

ε = emissivity of sphere

A = surface area of sphere, cm^2

T_1 = sphere temperature, K

T_o = ambient gas temperature, K .

The heat transfer due to free convection (Q_{conv}) is

$$Q_{conv} = h_c A(T_1 - T_o)$$

where h_c = heat transfer ratio for free convection [1] or, putting h_c in terms of the Nusselt number, Nu,

$$Q_c = A(T_1 - T_o)\frac{k}{D}\,Nu$$

where k = thermal conductivity of coolant gas and D = sphere diameter.

Yuge [2] empirically determined the Nusselt number for a sphere in air with heat loss due to free convection to be

$$Nu = 2 + 0.39\,Gr^{1/4} \quad \text{for} \quad 1 < Gr < 10^5$$

where Gr = Grashof number. For Grashof numbers much less than one, Yuge recommended Mahony's equation:

$$Nu = 2 + O\,(Gr^{1/2})$$

where O = order of magnitude. By fitting a line to the lower portion of Yuge's data, O was found to equal 0.25. In his work, Mahony dealt mainly with Grashof numbers between 10^{-3} and 10^{-9} [3]. Because the Grashof numbers encountered fell between 10^{-3} and one, both formulas were tried. No significant differences in results were found. Yuge's equation was used because of the greater documentation and certainty in the Grashof coefficient.

The Grashof number was calculated in the same manner as Yuge:

$$Gr = \frac{gD^3 \Delta T}{T_o \nu_f^2}$$

where

g = acceleration due to gravity

D = sphere diameter

ΔT = sphere temperature T_1 - gas temperature T_o

T_o = gas temperature; $1/T_o$ = heat transfer coefficient (β)

ν_f = kinematic viscosity at film temperature $\dfrac{T_1 + T_o}{2}$

$$= \frac{\rho_f}{\mu_f}$$

where

ρ_f = gas density at film temperature

μ_f = dynamic viscosity at film temperature.

PROPERTIES OF COOLANT GASES

Because no direct measurement of gas properties (with the exceptions of pressure and temperature) was possible, methods for estimating the thermal conductivity, dynamic viscosity, and density were either derived or adapted. All properties were found to be highly temperature dependent, and the temperature difference $T_1 - T_o$ between the sphere and the surrounding gas was very large. Therefore, all properties were evaluated at the film temperature $T_f = (T_1 - T_o)/2$, as recommended by Yuge.

In the low pressure range found in the experiments, thermal conductivity k is not pressure dependent [4]. A temperature dependency of $T_f^{3/4}$ was determined empirically from data given in McAdams [1]:

$$k = k_o \, (0.0173) \left(\frac{T_f}{273} \right)^{0.75} \quad \text{W/cm K}$$

where

k_o = thermal conductivity of specific gas at 273 K in Btu/hr·ft-°F

0.0173 = conversion factor from Btu/hr-ft-°F to W/cm K.

This formula was weighted to provide more precise correlation with McAdams' data for higher temperatures and helium, the major component gas.

Since mixtures of helium and argon do not involve rotational and vibrational degrees of freedom, Brokaw's simple empirical method for calculation of thermal conductivity [5] could be used. Brokaw utilized the fact that thermal conductivities for mixtures fall between the values found by simple mixing of the component conductivities and inverse mixing of the components:

$$\chi_1 k_1 + \chi_2 k_2 > k_m > \frac{1}{\dfrac{\chi_1}{k_1} + \dfrac{\chi_2}{k_2}}$$

where χ_1, χ_2 = mole fractions of component gases. Brokaw represented the mixture conductivity as a combination of simple and inverse mixing:

$$k_m = q k_{SM} + (1 - q) k_{RM}$$

where

$$k_{SM} = \chi_1 k_1 + \chi_2 k_2$$

and

$$\frac{1}{k_{RM}} = \frac{X_1}{k_1} + \frac{X_2}{k_2} \quad .$$

Brokaw then fit this curve to experimental data of numerous binary gas mixtures, including helium-argon, for various molar fractions to determine the value of q. The value of q was found to vary with the ratios of the gases [5]:

mole fraction	0	.1	.2	.3	.4	.5	.6	.7	.8	.9	.95	1.0
q	.32	.34	.37	.39	.42	.46	.50	.55	.61	.69	.74	.8

Brokaw's method was found to have approximately the same accuracy as other methods studied and to be much simpler in form. Therefore, Brokaw's method for gas mixtures was used in combination with the author's formula for individual gases to estimate thermal conductivities of the coolant gases.

Because the dynamic viscosities and the densities of the gases were needed in the calculation of the Grashof number, methods to calculate these properties were also needed. For the component gases, dynamic viscosity μ was taken to be

$$\mu = \mu_o \sqrt{\frac{T_f}{373}} \text{ Poise}$$

where μ_o = dynamic viscosity of specific gas at 373 K (P), again by fitting a curve to McAdams' data [1]. A pressure dependency was not incorporated due to the high temperature and low pressure values to be used.

Brokaw's method for calculation of viscosity of gas mixtures was used, as recommended by Reid, Prausnitz, and Sherwood. Brokaw's method is based on Sutherland's approximation

$$\mu_m = \sum_{i=1}^{n} \frac{X_i \mu_i}{\sum_{j=1}^{n} X_j \phi_{ij}} \quad ,$$

using

$$\phi_{ij} = \left(\frac{\mu_i}{\mu_j}\right)^{1/2} S_{ij}A_{ij}$$

where

S_{ij} = Sutherland constant

A_{ij} = a complicated function of molecular weights of the component gases.

A_{ij} can be taken from a chart [6] or a graph [4] and, for mixtures of nonpolar gases, S_{ij} can be set equal to one. Thus, for mixtures containing nonpolar gases,

$$\mu_m = \sum_{i=1}^{n} \frac{X_i \sqrt{\mu_i}}{\frac{X_i}{\sqrt{\mu_i}} \sum_{\substack{j=1 \\ j\neq 1}}^{n} \frac{A_{ij}}{\sqrt{\mu_i}} X_j} \quad .$$

This mixture formula has its best results for mixtures of inert gases; overall errors for nonpolar gas mixtures ranged from 0.6 percent to 2.5 percent error [6]. Brokaw's method can also be applied at any temperature, a vital feature for this project.

The densities of the gases were calculated by the formula

$$\rho = \left(\frac{M}{22.4 \times 10^3}\right)\left(\frac{273}{T_f}\right)\left(\frac{P}{760}\right) \text{ g/cm}^3$$

where T_f is in K, P is in torr, and M = molecular weight of gas. The method of simple mixing was used to calculate the mixture density:

$$\rho_m = X_1\rho_1 + X_2\rho_2 \quad .$$

THE COMPUTER PROGRAM

A FORTRAN program was designed to simplify calculations and extend the range of applicability to experimentation. Appendix A presents the program nomenclature, including a cross-reference to the nomenclature used in the text of this report; Appendix B presents a program listing.

In the program, nested DO loops are used to allow for variances of sphere emissivity EP, sphere diameter D, and power input PIN (*Set Experimental Parameters* section) in addition to argon pressure P1. Two separate DO loops are provided to change gas pressure (*Increase Pressure* and *Decrease Pressure* sections), simulating the experimental input and pump down of gas. The *Increase Pressure* loop uses the incremented mole fraction to calculate helium pressure P2 for constant P1 while the *Decrease Pressure* loop steadily decreases the total pressure PRTTL, holding the molar ratio of the gas mixture constant. Each pressure loop includes an implied loop within which the gas properties and sphere temperature are calculated (*Iterate to Satisfy Temperature Equation* sections). The gas properties are determined by solving the equations presented earlier in this report; the temperature is found using an iterative technique wherein the basic heat transfer is solved for sphere temperature T by using an estimated sphere temperature T_1. T_1 is initialized at RADT, the sphere temperature should only radiative heat transfer be present. The T_1's are revised as the implied loop is repeated until the difference $|T - T_1|$ is less than an input tolerance (in this case, 10 K). An iteration check (FLAG, FLAGM) is also provided to check for bad convergence.

RESULTS AND CONCLUSIONS

As pressure is increased, convection takes on an increasingly important role in cooling the sphere. Once the helium enters, convection becomes dominant. Varying the amount of argon initially present does not significantly change the sphere temperature (Figs. 1 and 2). The percentage of helium present in the mixture, and not the total amount of helium, determines the sphere temperature: 90 torr of helium added to 10 torr of argon changes the sphere temperature from 1577 K to 637 K, while 360 torr helium added to 40 torr argon effects a change from 1519 K to 618 K. This phenomenon is due to the fact that the Grashof number is the only pressure-dependent term in the heat transfer equation. As expected, emissivity produced the majority of its effect at low pressure, where Rad T is proportional to emissivity (Fig. 3). Sphere temperature is directly proportional to power input (Fig. 4) and inversely proportional to sphere diameter (Fig. 5). Once convective cooling dominates, an increase of 1.5 W in power is comparable to a decrease of 0.135 cm in diameter. During radiation's dominance, the power input change will not be as effective as the change in diameter.

Small fluctuations in the value of k_{mix} will effect great changes in the values of Comb T, while Rad T will remain constant. It is believed that the major source of error in this program is in the value of k_{mix}. As temperatures increase, the estimation for individual thermal conductivities will tend to be high. This deviation will decrease the apparent pressure effect on sphere temperature Comb T.

Correlation for the *Increase Pressure* portion of the program with experimental results was found to be good: the variance between sphere temperature at 20 torr argon and 200 torr total was 2.7 percent. The actual temperature values were approximately 5 percent higher than expected; however, the error in calculation of thermal conductivity would predict a higher power input (and thus temperature) for the same cooling effect on the sphere.

Results for the *Decrease Pressure* portion of the program were discouraging. The increase in temperature is only approximately one-third that found experimentally. This is believed to be due to the dominance of the conductivity term, which depends upon the ratio of the gases rather than the total amount of gas present (Fig. 6). The small temperature change shown illustrates the temperature dependence on the Grashof number.

NOTE TO FIGURES:

Because total heat loss did not vary significantly with the total amounts of gas present but rather with the percentage of helium present (Figs. 1,2), Figures 2 through 5 are plotted as temperature versus percentage helium. All data (except where noted) were taken from runs with 20 torr argon initial pressure. The following is an approximation of results for runs beginning with 10 or 40 torr argon:

	Total Pressure		
He, Percent	10 torr Ar	20 torr Ar	40 torr Ar
0	10.0	20.0	40.0
10	11.1	22.2	44.4
20	12.5	25.0	50.0
30	14.3	28.6	57.1
40	16.7	33.3	66.7
50	20.0	40.0	80.0
60	25.0	50.0	100.0
70	33.3	66.7	133.3
80	50.0	100.0	200.0
90	100.0	200.0	400.0

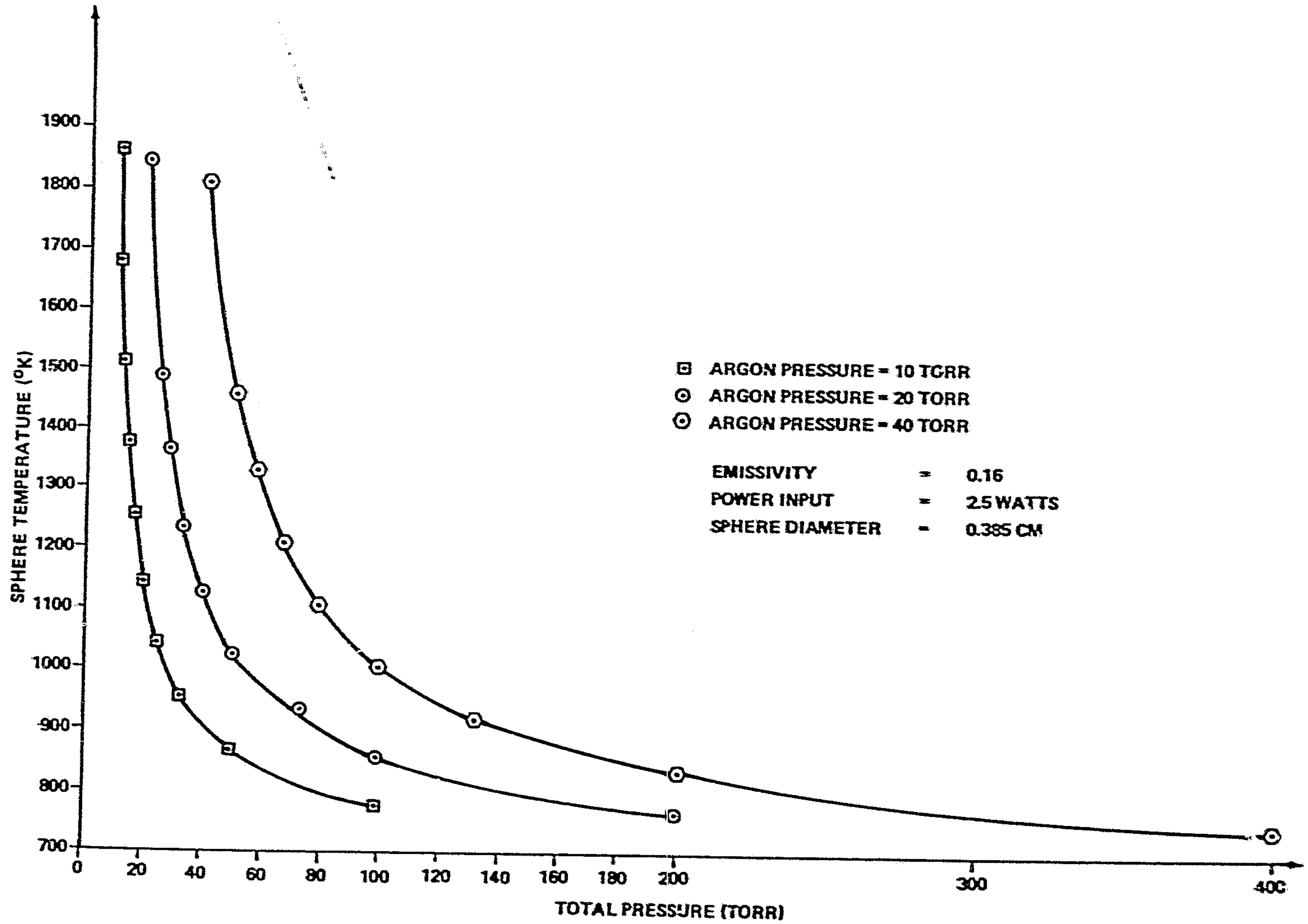

Figure 1. Sample temperature as a function of total pressure for different initial argon pressures.

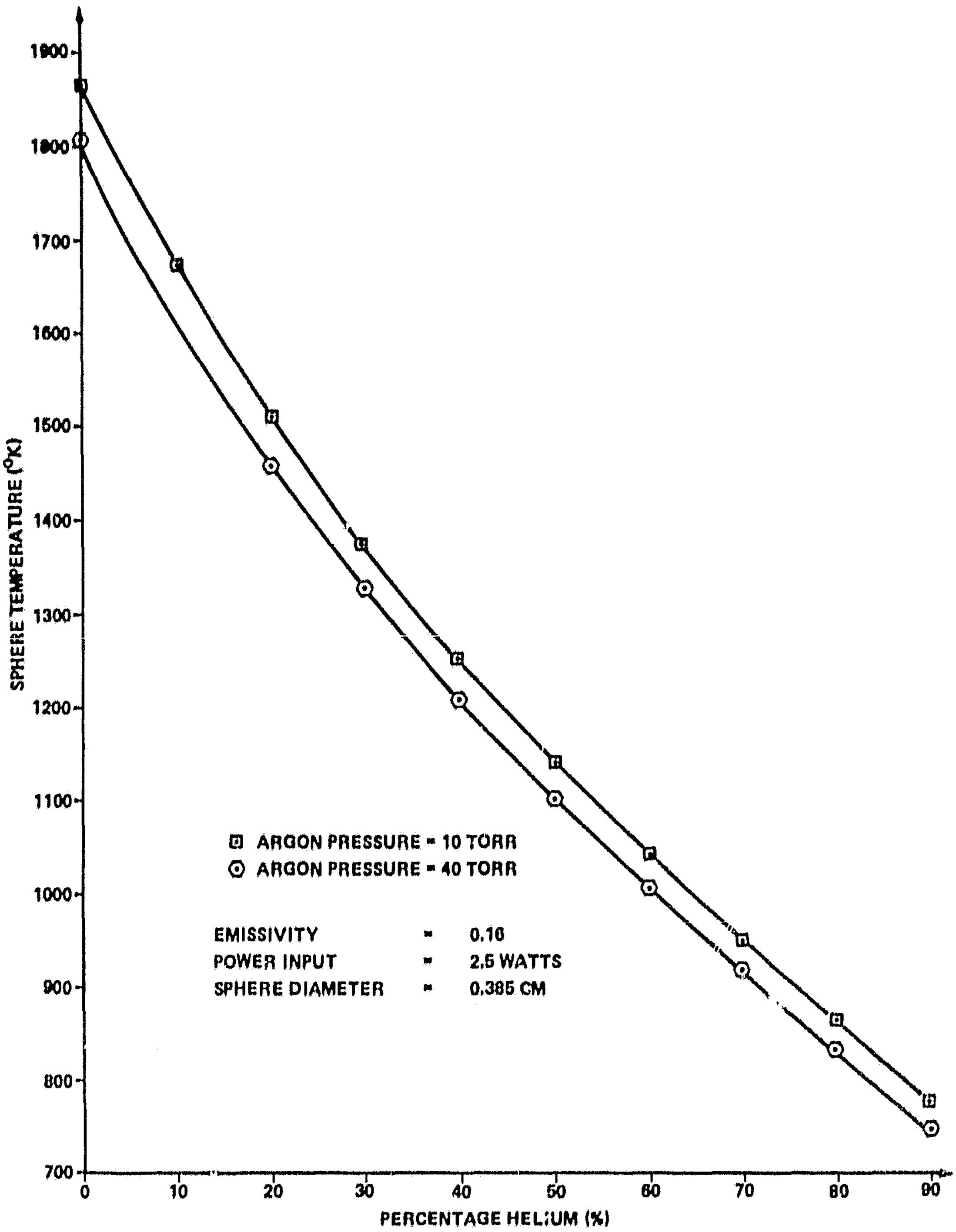

Figure 2. Sample temperature as a function of percentage helium for different initial argon pressures.

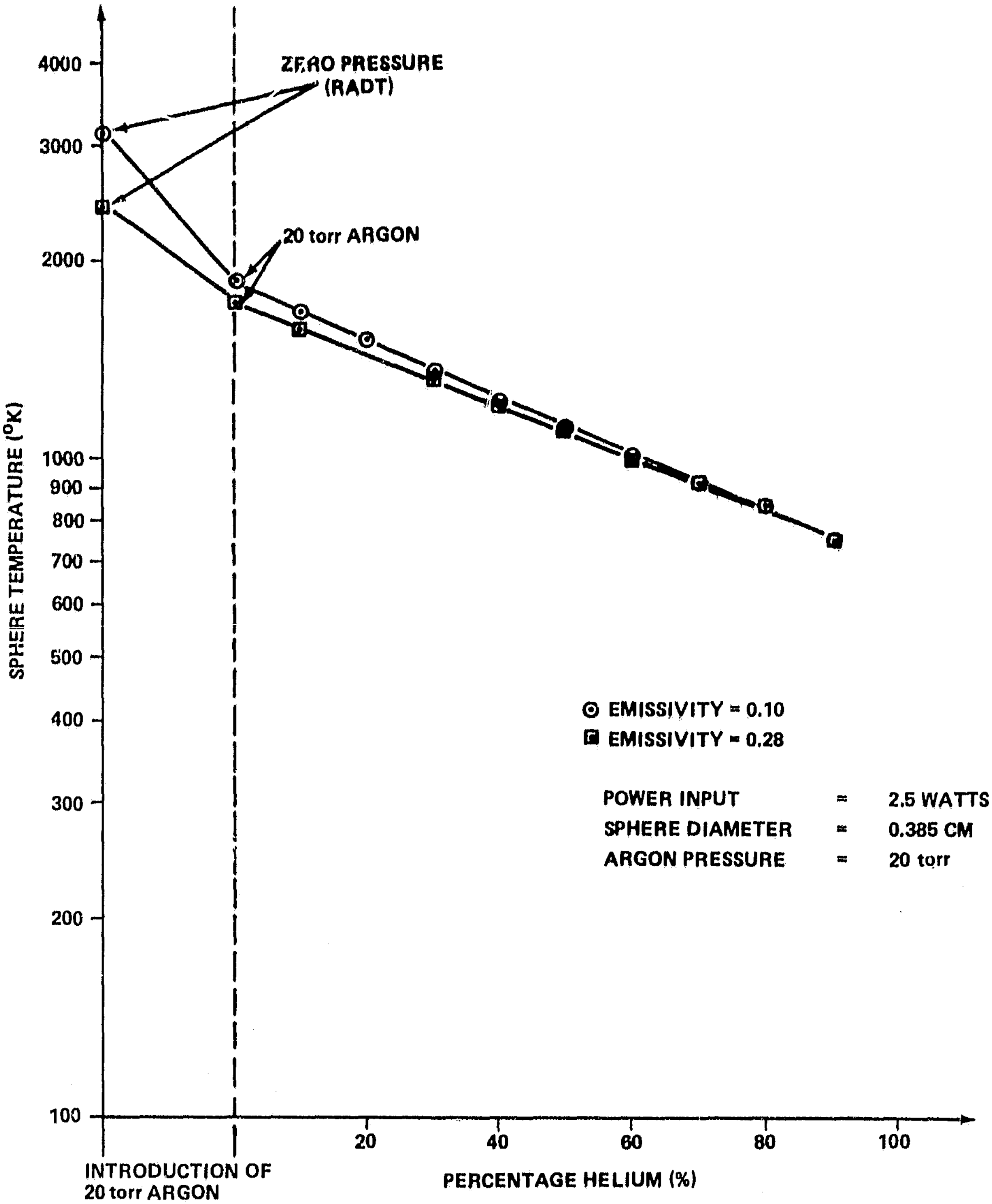

Figure 3. Sample temperature as a function of percentage helium for various emissivities.

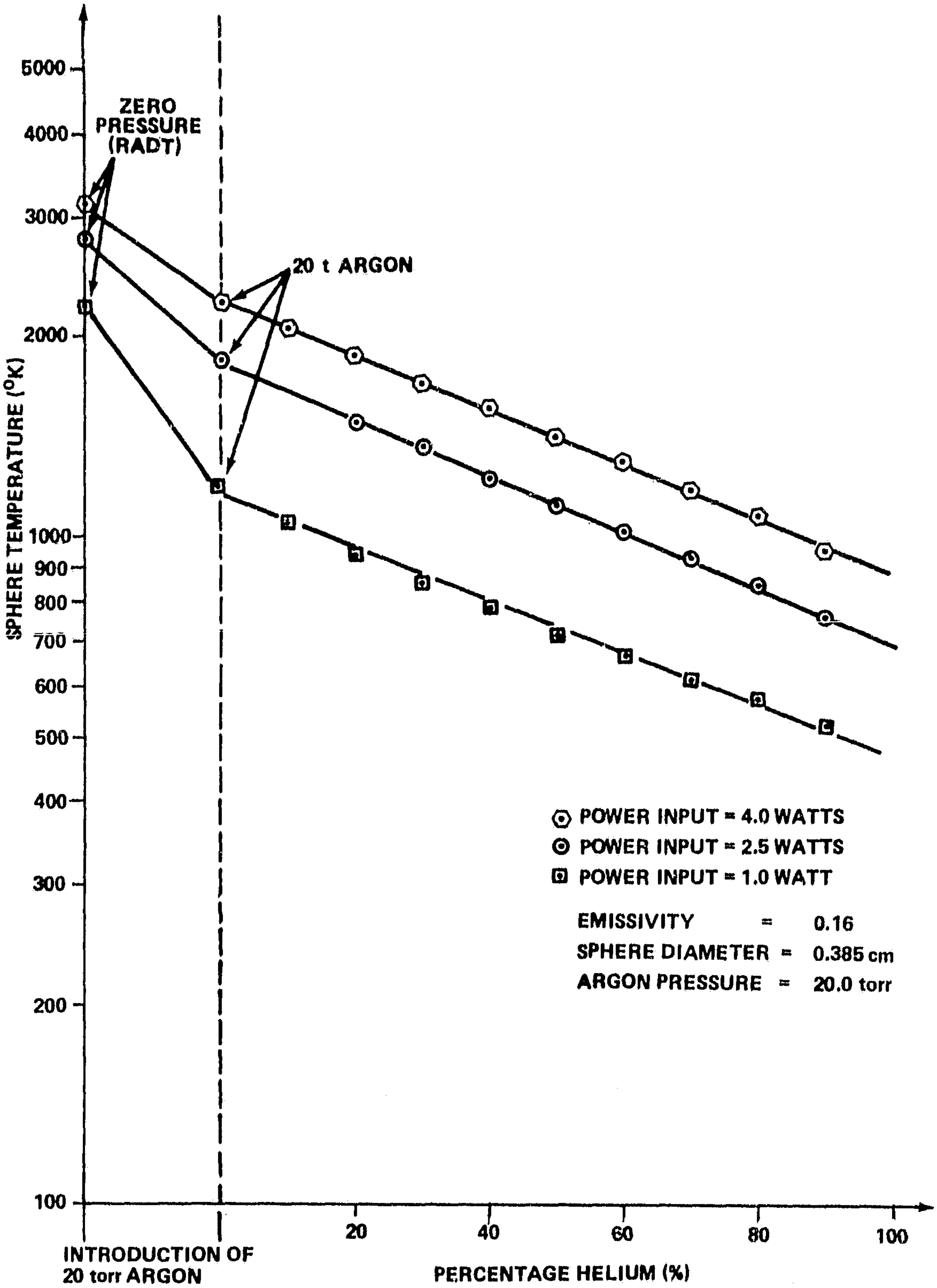

Figure 4. Sample temperature as a function of percentage helium for various power inputs.

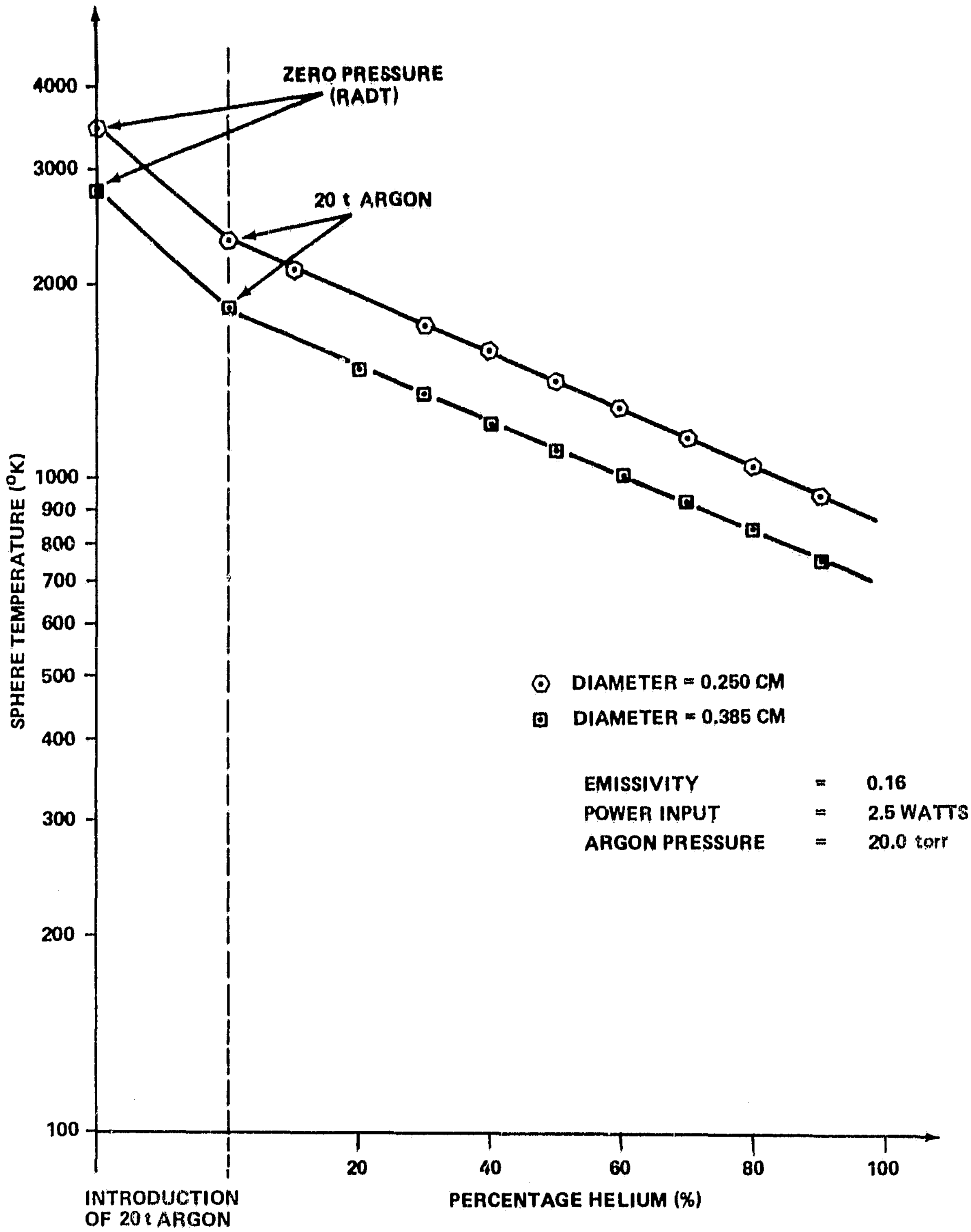

Figure 5. Sample temperature as a function of percentage helium for various sphere diameters.

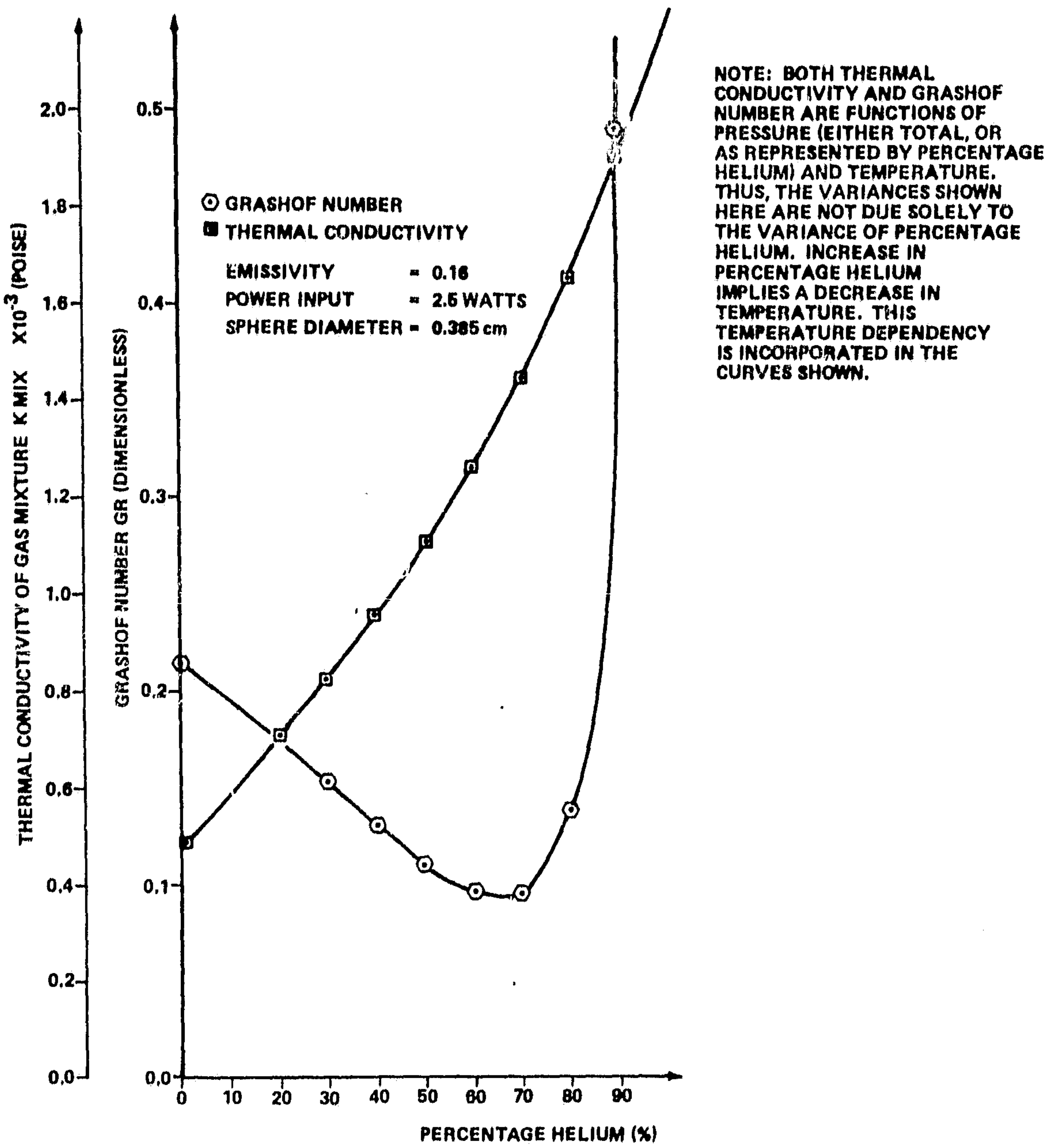

Figure 6. Thermal conductivity and Grashof numbers as functions of percentage helium.

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APPENDIX A

NOMENCLATURE

Report	Program	Definition
A_{12}, A_{21}	A12,A21	Dimensionless parameter used in calculation of gas mixture viscosities, function of the molecular weight ratios $\left(\frac{M_1}{M_2}, \frac{M_2}{M_1}\right)$
–	ARGT	The argument of T used in calculation of intermediate values of sphere temperatures $T = ARGT^{1/4}$ (K^4)
–	AVDT	Absolute value of intermediate sphere temperature value difference $\lvert T - T_1 \rvert$ (K)
Comb T	COMBT	Sphere temperature due to combined radiative and free convective heat transfer (K)
D	D	Diameter of sphere (cm)
ε	EP	Emissivity of sphere
FLAG	FLAG	Iteration counter for temperature calculation
FLAGM	FLAGM	Maximum number of iterations allowed in calculation of sphere temperature
Gr	GR	Grashof number for gas mixture, dimensionless ratio of buoyant to inertial forces
k_o	K10,K20	Thermal conductivity of gas (1,2) at 273 K (Btu-hr-ft-°F), used in calculation of thermal conductivity of gas (W/cm-K) at film temperature
k_1, k_2	K1,K2	Thermal conductivity of gas (1,2) (W/cm-K)
k_m	KMIX	Thermal conductivity of gas mixture (W/cm-K)
M	M1,M2	Molecular weight of gas (1,2)
μ_o	MU10,MU20	Dynamic viscosity of gas (1,2) at 373 K (P) used in calculation of dynamic viscosity of gas (1,2) at film temperature (P)

NOMENCLATURE (Concluded)

Report	Program	Definition
μ	MU1,MU2	Dynamic viscosity of gas (1,2) at film temperature (P)
μ_m	MUMIX	Dynamic viscosity of gas mixture at film temperature (P)
P_1, P_2	P1,P2	Amount of pressure of gas (1,2) (torr)
—	PCNT1,PCNT2	Percentage of gas (1,2) in mixture (percent)
PI	PIN	Power input to levitation coil (W)
P_{ttl}	PTTL	Total gas pressure during increase of pressure (torr)
PRTTL	PRTTL	Total gas pressure during pump down (torr)
q	Q(I)	Dimensionless parameter used in calculation of thermal conductivity of gas mixture, function of molar fraction of light gas
Rad T	RADT	Sphere temperature when only radiative cooling effects are considered (K)
ρ_1, ρ_2	RH01,RH02	Density of gas (1,2)
ρ_m	RHOMX	Density of gas mixture
T	T	Intermediate sphere temperature value used in determination of sphere temperature (K)
T_o	TO	Ambient gas temperature (K)
T_1	T1	Intermediate sphere temperature value used in determination of sphere temperature (K)
T_f	—	Film temperature $\frac{T_1 + T_o}{2}$
—	TOL	Tolerance between intermediate and final sphere temperature values (K)
X_1, X_2	X1,X2	Mole fraction of gas (1,2)

APPENDIX B

```
*FCONV *000003 IS ON CR00002 USING 00024 BLKS R 0000

      F NH4.L
            PROGRAM FCONV
      C***********************************************************************
      C*****                                                           ******
      C***** DATE:  AUGUST 9,1979                                      ******
      C*****                                                           ******
      C*****PROGRAMMER:  KAREN JOHNSON             PHONE: 453-4699     ******
      C*****ORGANIZATION:  ES-71                                       ******
      C*****PROJECT:  ELECTRO-MAGNETIC LEVITATOR  WORK FOR:  BILL ORAN ******
      C*****                                                           ******
      C*****PROGRAM DESCRIPTION:  CALCULATES THE SAMPLE TEMPERATURE DUE ******
      C*****   TO RADIATIVE AND FREE CONVECTIVE HEAT TRANSFER IN DEGREES******
      C*****   KELVIN WHICH A GIVEN POWER INPUT WILL PRODUCE FOR A     ******
      C*****   SPHERICAL MASS OF KNOWN DIAMETER AND EMISSIVITY WHEN    ******
      C*****   COOLED BY A BINARY GAS MIXTURE OF KNOWN COMPOSITION     ******
      C*****                                                           ******
      C*****INPUT:  DISC                                               ******
      C*****                                                           ******
      C*****OUTPUT:  LINE PRINTER                                      ******
      C*****                                                           ******
      C***********************************************************************
      C
      C INPUT DATA
      C
      C
            DIMENSION Q(10)
            REAL K10,K20,MU10,MU20,M1,M2
            DOUBLE PRECISION T1,RADT,T,ARGT,GR,RHO1,RHO2,RHOMX
            DOUBLE PRECISION K1,K2,KMIX,MU1,MU2,MUMIX
            DATA Q /.32,.34,.37,.39,.42,.46,.50,.55,.61,.69/
            DATA M1/40./,M2/4./,MU10/.00026/,MU20/.00022/,T0/300./
            DATA K10/.01/,K20/.082/,A12/.312/,A21/2.18/,TOL/10./,FLAGM/2000./
            DO 340 L=1,3
            EXP1 = FLOAT(L)-1
            P1 = 10.*2.**EXP1

      C WRITE INITIAL DATA
      C
            WRITE(6,20) FLAGM,TOL,T0,A12,A21
      20    FORMAT(" THE MAX NO OF ITERATIONS FLAGM = ",F5.0/" THE TOLERANCE T
           1OL",14X,"= ",F5.1/" THE AMBIENT GAS TEMPERATURE T0 =",F6.1//"  VIS
           1COSITY MIXTURE PARAMETERS"/" A12 =",F6.3,6X,"A21 =",F6.3//)
            WRITE(6,30) M1,M2,MU10,MU20,K10,K20
      30    FORMAT(37X,"1",16X,"2"/35X,"ARGON",12X,"HELIUM"/" MASS",31X,F3.0,
           114X,F3.0/" COEF OF VISCOSITY (MU0)",10X,F7.5,10X,F7.5/"COEF OF THE
           1RM COND (K0)",11X,F5.3,12X,F5.3///)
            WRITE (6,40)
      40    FORMAT(" EP     = EMISSIVITY OF SPHERE"/" PIN    = POWER INPUT TO LE
           1VITATION COIL (WATTS)"/" D      = DIAMETER OF SPHERE (CENTIMETERS)"
           1/" PTTL   = TOTAL GAS PRESSURE (TORRS)"/" PCNT1 = PERCENTAGE OF GAS
           1 1 IN MIXTURE"/" PCNT2 = PERCENTAGE OF GAS 2 IN MIXTURE"/" RADT  =
           1 SPHERE TEMP DUE TO RADIATIVE HEAT TRANSFER (P = 0, DEG KELVIN)"/"
           1 COMBT = SPHERE TEMP DUE TO COMBINED RADIATIVE AND CONVECTIVE HEAT
           1 TRANSFER (DEG KELVIN)"/" GR     = GRASHOF NUMBER FOR GAS MIXTURE"
           1///)
      C
      C
      C SET EXPERIMENTAL PARAMETERS
```

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

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```
C
C
      DO 320 IEP=10,26,6
      EP = FLOAT(IEP)/100
      DO 310 ID=250,385,135
      D = FLOAT(ID)/1000
      DO 300 IPIN=10,40,15
      PIN = FLOAT(IPIN)/10
C
C
C INCREASE PRESSURE
C
C
      WRITE(6,45)
45    FORMAT(" INCREASE PRESSURE"/)
      WRITE(6,50)
50    FORMAT(3X,"EP",8X,"PIN",9X,"D",10X,"PTTL",8X,"PRES1",7X,"PRES2",
     1       7X,"PCNT2",7X,"RADT",8X,"COMBT",10X,"GR",10X,"KMIX"/)
      T1 = (PIN/(1.78E-12*D**2*EP)+T0**4)**.25
      RADT = T1
      DO 180 IX2=1,10
      X2 = (FLOAT(IX2)-1.)/10.
      X1 = 1.-X2
      I = IX2
      P2 = X2*(P1/X1)
      FLAG = 0
C
C ITERATE TO SATISFY TEMPERATURE EQUATION
C
60    FLAG = FLAG + 1
      RHO1 = (3.21E-5*M1*P1)/(T1+T0)
      RHO2 = (3.21E-5*M2*P2)/(T1+T0)
      RHOMX = X1*RHO1+X2*RHO2
      MU1 = 3.66E-2*MU10*(T1+T0)**.5
      MU2 = 3.66E-2*MU20*(T1+T0)**.5
      MUMIX = ((X1*MU1)/(X1+A12*(MU1/MU2)**.5*X2))+((X2*MU2)/(X2+A21*
     1        (MU2/MU1)**.5*X1))
      K1 = 1.53E-4*K10*((T1+T0)**.75)
      K2 = 1.53E-4*K20*((T1+T0)**.75)
      KMIX = Q(I)*(X1*K1+X2*K2)+(1.-Q(I))*(1./((X1/K1)+(X2/K2)))
      IF (X2-.3) 65,65,93
65    ARGT=((PIN-(6.28*KMIX*D*(T1-T0))-((6.86*KMIX*D**1.75*RHOMX**.5*
     1      (T1-T0)**1.25)/(T0**.25*MUMIX**.5)))/(1.78E-12*EP*D**2))
     2       +T0**4
      IF(ARGT) 70,70,90
70    IF(FLAGM-FLAG) 140,140,80
80    T1 = T1 - 100
      GO TO 60
90    T = ARGT**.25
      GO TO 96
93    T=((PIN-(1.78E-12*EP*D**2*(T1**4-T0**4))-((6.86*KMIX*D**1.75*
     1  RHOMX**.5*(T1-T0)**1.25)/(T0**.25*MUMIX**.5)))/(6.28*KMIX*D))
     2  +T0
96    AVDT = DABS(T-T1)
      IF(TOL-AVDT) 100,160,160
100   IF(FLAGM-FLAG) 140,140,110
110   T1 = (T+T1)/2
      IF(T1-T0) 120,120,130
120   T1 = T0 + 100


130   GO TO 60
```

```
C
C CALCULATE AND WRITE FINAL DATA
C
 140    WRITE (6,150) T,T1,RADT
 150    FORMAT(/," BAD CONVERGENCE    THE LAST TWO VALUES OF T WERE ",F6.0,
       !      " AND ",F6.0," RADT = ",F6.0/)
        GO TO 180
 160    PTTL = P1 + P2
        PCNT2 = X2*100.
        GR = (980.*D**3*RHOMX**2*(T1-T0))/(T0*MUMIX**2)
        WRITE(6,170) EP,PIN,D,PTTL,P1,P2,PCNT2,RADT,T,GR,KMIX
 170    FORMAT(F5.2,F11.1,F11.3,F13.1,3F12.1,F13.0,F12.0,E15.3,E13.3)
 180    CONTINUE
C
C
C DECREASE PRESSURE
C
C
        WRITE (6,185)
 185    FORMAT(//25X,"*******************************************************
       !**************"//" DECREASE PRESSURE"//3X,"EP",8X,"PIN",9X,"D",10X,
       !"PTTL",9X,"PRES1",7X,"PRES2",7X,"PCNT2",7X,"RADT",8X,"COMBT",10X,
       !"GR",10X,"KMIX"/)
C
C SET CONSTANTS AND INITIALIZE VARIABLES
C
        X1 = .1
        X2 = .9
        PCNT2 = X2 * 100.
        PRTTL = PTTL
        T1 = RADT
        DO 280 N=1,13
        PRES1 = X1*PRTTL
        PRES2 = X2*PRTTL
        FLAG = 0
C
C ITERATE TO SATISFY TEMPERATURE EQUATION
C
 190    FLAG = FLAG + 1.
        RHO1 = (3.21E-5*M1*PRES1)/(T1+T0)
        RHO2 = (3.21E-5*M2*PRES2)/(T1+T0)
        RHOMX = X1*RHO1+X2*RHO2
        MU1 = 3.66E-2*MU10*(T1+T0)**.5
        MU2 = 3.66E-2*MU20*(T1+T0)**.5
        MUMIX = ((X1*MU1)/(X1+A12*(MU1/MU2)**.5*X2))+((X2*MU2)/(X2+A21*
       !           (MU2/MU1)**.5*X1))
        K1 = 1.53E-4*K10*((T1+T0)**.75)
        K2 = 1.53E-1*K20*((T1+T0)**.75)
        KMIX = Q(I)*(X1*K1+X2*K2)+(1.-Q(I))*(1./((X1/K1)+(X2/K2)))
        T = ((PIN-(1.78E-12*EP*D**2*(T1**4-T0**4))-((6.86*KMIX*D**1.75*
       !     RHOMX**.5*(T1-T0)**1.25)/(T0**.25*MUMIX**.5)))/(6.28*KMIX*D))
       !     +T0
        AVDT = DABS(T-T1)
        IF(TOL-AVDT) 200,260,260
 200    IF(FLAGM-FLAG) 240,240,210
 210    T1 = (T+T1)/2.
        IF(T1-T0) 220,220,230
 220    T1 = T0 + 100.
 230    GO TO 190
C
```

```
C CALCULATE AND WRITE FINAL DATA
C
240   WRITE(6,250) T,T1
250   FORMAT(/' BAD CONVERGENCE     T = ',F6.0,'  T1 = ',F6.0/)
      GO TO 260
260   GR = (980.*D**3*RHOMX**2*(T1-T0))/(T0*MUMIX**2)
      WRITE(6,270) EP,PIN,D,PRTTL,PRES1,PRES2,PCNT2,RADT,T,GR,KMIX
270   FORMAT(F5.2,F11.1,F11.3,F13.1,3F12.1,F13.0,F12.0,E15.3,E13.3)
C
C CHECK IF PUMP DOWN IS COMPLETED
C
      PRTTL = PRTTL-30.
      IF(PRTTL.LE.0.)  GO TO 285
280   CONTINUE
285   WRITE(6,290)
290   FORMAT(/25X,'*********************************************************
     1**************'//)
300   CONTINUE
310   CONTINUE
320   CONTINUE
      WRITE(6,330)
330   FORMAT(1H1)
340   CONTINUE
      STOP
      END
      END$
```

APPROVAL

RADIATIVE AND FREE CONVECTIVE HEAT TRANSFER FROM A CONTAINERLESS SPHERE

By Karen Johnson

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer This report, in its entirety, has been determined to be unclassified.

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