Reacting Fluids Laboratory
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STATUS REPORT

ON

SOLUTION OF THE FROZEN FLOW MOMENTUM EQUATION

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Evaluation of the Energy Transfer
in the Char Zone During Ablation

by

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Summary

The solution of the momentum equation, including an inertial as well as the viscous term, for frozen flow in the char zone of a charring ablator is presented. This study is supplemental in nature to NASA-RFL-2 report (July 1, 1966) and represents the completion of work with the frozen flow model. The results are presented as pressure profile and/or pressure drops across the char layer.

In general, the pressure drop varied from 0.41 (2.12 lb/ft^2) to 3.51 (17.91 lb/ft^2) inches of water over a range of conditions bounded by the following:

a. mass flux, W: 0.01 to 0.09 lb/ft^2-sec

b. porosity, ϵ: 0.5 to 0.8

c. surface temperature, T_L: 2000 to 3000°F

The value of the heat flux at the char surface varied from 7.4 to 67.7 BTU/ft^2-sec over the same range of parameter values.

Also included are results indicating the effect of each of the parameters on the temperature profile.

Introduction

The objective of this study is to more precisely define the characteristics in the char zone under frozen flow considerations. The solution of the general energy equation in NASA-RFL-2 report (1) developed the heat transfer characteristics within this zone. Results were presented for three stages of development leading to the most general case and were shown as temperature profiles within the char zone. Supplementary results indicating the effect of parameter changes on the temperature profile are presented in this report.

Furthermore, to more closely define the char, the solution of the momentum equation written to include inertial as well as viscous effects is also analyzed. Results are shown as the pressure profile within the char zone and, in some cases, the pressure drop for comparative purposes.

In addition, the value of the heat flux at the char surface is also presented.

The solution to the momentum equation which contains two integral terms is achieved on the LSU-IBM 7040 digital computer using a modified version of the Fortran program written for the solution to the general energy equation (1). Simpson's Rule is applied to evaluate the integrals which contain values of the temperature and, in one case, the value of the gas viscosity which is a function of temperature. Therefore, the pressure profile calculation is made only after a successful temperature profile has been obtained. In this way the pressure profile and heat flux calculations are straight forward and do not require use of an iterative scheme.

This report completes work on the frozen flow model and future efforts will be directed to the adaptation of the general Fortran program for frozen flow to the evaluation of the equilibrium flow model (2) and the non-equilibrium flow model.

Nomenclature

A, B	Coefficients in momentum equation
a, b, c, d	Component values in generalized heat capacity equation
a', b', c', d'	Defined on page 9
$\overline{C_p}$	Heat capacity of gas mixture at constant pressure
F_w	Molecular weight of gas component
j	Defined on page 9
j'	Defined on page 9
K	Total number of gas components in system
k_e	Effective or overall thermal conductivity
L	Char thickness
P	Pressure
P_L	Pressure at char surface
q	Heat flux
R	Perfect gas constant
T	Temperature
T_o	Initial temperature
T_L	Final temperature
u	Gas velocity
W	Gas mass flux
Y	Mole fraction of gas components in system
z	Char distance
α	Viscous coefficient in momentum equation, $(\frac{\epsilon}{\gamma})$
β	Inertial coefficient in momentum equation
γ	Char permeability
Δ	Finite change operator
ϵ	Char porosity
μ	Viscosity of pure gas
$\overline{\mu}$	Viscosity of gas mixture
ρ	Gas density

σ	Collision diameter (gas viscosity calculation)
φ	Weighting factor (gas viscosity calculation) defined on page 7
Ω	Collision integral (gas viscosity calculation)

Discussion of the Momentum Equation

In order to more closely define the characteristics within the char zone of a charring ablator, the solution of the momentum equation, in addition to the energy equation (1), is desired. Because of the relatively high mass flux values ($W = 0.05\ lb/ft^2$-sec) inertial as well as viscous effects are included in the momentum equation. The equation with these terms is given below for one dimensional flow in a porous media.

$$\frac{dP}{dz} = Au + B\rho u^2 \tag{1}$$

where (Au) represents the viscous term and ($B\rho u^2$) the inertial term (3).

To obtain a result applicable across a finite char thickness, the following manipulations are performed. First, multiplication of equation (1) by the gas density, ρ, followed by substitution of the mass flux, $W = \rho u$, results in the following:

$$\left(\frac{dP}{dz}\right) = AW + BW^2 \tag{2}$$

Use of the ideal gas law equation as the equation of state written as $\rho = \frac{P(F_w)}{RT}$ followed by substitution into equation (2) for ρ and rearrangement gives equation (3):

$$PdP = \frac{RT}{F_w}(AW + BW^2)dz \tag{3}$$

Defining $A = \bar{\mu}\alpha$ and $B = \beta$ with substitution into equation (3) results in the following:

$$PdP = \frac{RT}{F_w}(\bar{\mu}\alpha w + \beta W^2)dz \tag{3a}$$

Separation of terms followed by integration results in the solution of equation (3a) for P, the pressure at any distance, z, in the char zone.

$$P = \left\{P_L^2 + \left(\frac{2R}{F_w}\right)\left[W\alpha \int_{z=z}^{z=L} \mu T dz + W^2\beta \int_{z=z}^{z=L} T dz\right]\right\}^{1/2} \tag{4}$$

Evaluation of α and β in Equation (4) from Experimental Data

In order to solve equation (4) for the pressure profile within a char zone, α and β, the viscous and inertial coefficients, must be specified. Alpha (α) can be redefined as the ratio of the char porosity (ϵ) to the permeability (γ), however, data on γ and β for char materials are very scarce.

One source of data recently obtained under a NASA contract by Southern Research Institute was used for this study (4). The results presented for a char material at constant temperature (70°F) was analyzed by applying equation (3a) for the isothermal case (8). Rearranging (3a) and taking the definite integral results in equation (5):

$$\left(\frac{(F_w)\ \Delta(P^2)}{2w\bar{\mu}\,RTL}\right) = \alpha + \beta\left(\frac{W}{\bar{\mu}}\right) \qquad (5)$$

Closer inspection shows that a plot of $\left(\frac{(F_W)\Delta(P^2)}{2W\bar{\mu}\,RTL}\right)$ vs $\left(\frac{W}{\bar{\mu}}\right)$ on rectangular coordinate paper results in a straight line curve with α as the y-intercept and β, the slope.

Figure IX is a plot of equation (5) for the data shown in Table V of Appendix A. The computer program for determining the x-y coordinates and a least squares fit of the resulting data is shown in Appendix B.

Evaluation of the Viscosity of the Gas Mixture

In order to determine the pressure profile, the value of the gas viscosity as a function of temperature must be known. The viscosity of a pure gas can be calculated from the empirical equation:

$$\mu_g = 2.6693 \times 10^{-3}[F_w T]^{1/2}/\sigma^2\Omega \qquad (6)$$

Values of σ for various pure gases are shown in Table III of Appendix A. The method of Wilke and Johnson is used to calculate the viscosity of gas mixtures. Although somewhat more complex than the method of Hirschfelder, et. al., the results are more accurate for a greater variety of gas systems. [5] The equations of Wilke and Johnson are:

$$\bar{\mu} = \frac{\mu_{g_1}}{1 + (y_2/y_1)\Phi_{12} + (y_3/y_1)\Phi_{13} + \ldots + (y_n/y_1)\Phi_{1n}} + \frac{\mu_{g_2}}{1 + (y_1/y_2)\Phi_{21} + (y_3/y_2)\Phi_{23} + \ldots + (y_n/y_2)\Phi_{2n}} + \cdots + \frac{\mu_{gm}}{1 + (y_1/y_m)\Phi_{m1} + (y_2/y_m)\Phi_{m2} + \ldots + (y_n/y_m)\Phi_{mn}} \qquad (6a)$$

where

$$\Phi_{mn} = \frac{\left[1 + (\mu_{gm}/\mu_{gn})^{1/2} (F_{wn}/F_{wm})^{1/4}\right]^2}{2\sqrt{2}\,[1 + (F_{w_m}/F_{w_n})]^{1/2}} \qquad (6b)$$

for n and m equal to 1, 2, 3, ..., K.

Effect of System Variables on the Pressure Profile

Although the overall pressure drop across the char zone for the frozen flow model is very small, the importance of knowing the effect of system variables on the pressure profile is essential in describing the char zone characteristics by a model. There are three variables which influence the pressure profile in the char zone. These are the mass flux (W), char porosity (ϵ), and surface temperature (T_L). Qualitatively, the effects can be analyzed by inspection of equation (3a) or (4). However, the extent to which each affects the pressure distribution in the char can be determined only by varying the parameter values. As illustrated in Figures I through IV and Table I, the pressure drop varied from 0.41 inches (2.12 lb/ft^2) of water to 3.51 inches (17.91 lb/ft^2) of water. These results are based on changes in the parameters over the following ranges: mass flux (0.01 - 0.09 lb/ft^2-sec), char porosity (0.5-0.8) and surface temperature (2000-3000°F).

Determination of the Heat Flux at the Surface of the Char

One additional quantity which can be calculated and which defines the characteristics in the char zone more precisely is the heat flux at the char surface. This quantity is a measure of the heat transfer by conduction into the surface and is calculated as: $q = k_e(dT/dz)_{z=L}$.[6] From the general energy equation for frozen flow,[1] it is seen that

$$W\bar{C}_p\epsilon\frac{dT}{dz} = \frac{d}{dz}(k_e\frac{dT}{dz}) \qquad (7)$$

Substitution for q into equation (7) results in equation (8):

$$\left.\frac{dq}{dz}\right|_{z=L} = \left.W\bar{C}_p\epsilon\frac{dT}{dz}\right|_{z=L} \qquad (8)$$

or, rearranging:

$$dq = W\bar{C}_p\epsilon dT \qquad (8a)$$

Integration of equation (8a) between T_o and T_L results in equation (9):

$$q = W\epsilon\int_{T_o}^{T_L}\bar{C}_p dT \qquad (9)$$

Substitution of the usual polynomial expression for $\bar{C}_p$ gives:[7]

$$q = W\epsilon\int_{T_o}^{T_L}(a + bT + cT^2 + dT^3)dT \qquad (10)$$

where a, b, c, and d are the pure gas coefficients.

For a system containing a gas mixture of K components equation (10) can be written as:

$$q = W\epsilon\int_{T_o}^{T_L}(a' + b'T + c'T^2 + d'T^3)dT \qquad (10a)$$

where

$$j' = \sum_{i=1}^{K} j_i y_i \qquad \text{for } j = a, b, c, d, \text{ and } j = a', b', c', d'$$

Integration of equation (10a) gives:

$$q = W\epsilon\left\{a'(T_L - T_o) + \frac{b'}{2}(T_L^2 - T_o^2) + \frac{c'}{3}(T_L^3 - T_o^3) + \frac{d'}{4}(T_L^4 - T_o^4)\right\} \quad (11)$$

As illustrated in Table I, the heat flux varied from 4.7 to 67.7 BTU/ft^2-sec for ranges in parameters of: mass flux (0.01-0.09 lb/ft^2-sec), char porosity (0.5-0.8) and surface temperature (2000-3000^{o}F).

Discussion of the Program for Determining the Pressure Profile and Heat Flux

The general Fortran program for the solution of the energy equation for the frozen flow model was extended to include calculation of the pressure profile and heat flux. These latter calculations are made after definition of the temperature profile to avoid lengthening the iterative scheme used for solving the general energy equation. The block diagram shown on page 10 illustrates the general program before (solid lines) and after (dashed lines) the inclusion of statements for determining the pressure profile and heat flux (see Diagram I). The specific function of each added portion will be discussed separately in the following paragraphs.

Program PRESS: The PRESS program calculates the pressure profile using a Simpson's Rule scheme for the two integrals shown in equation (4). Temperature and viscosity data required in the calculation are called from memory by an interpolation method, subprogram OMEGA. The data necessary for calculating the viscosity is obtained from values read into the program as input, whereas, the temperature data is stored from MAIN after the determination of the temperature profile.

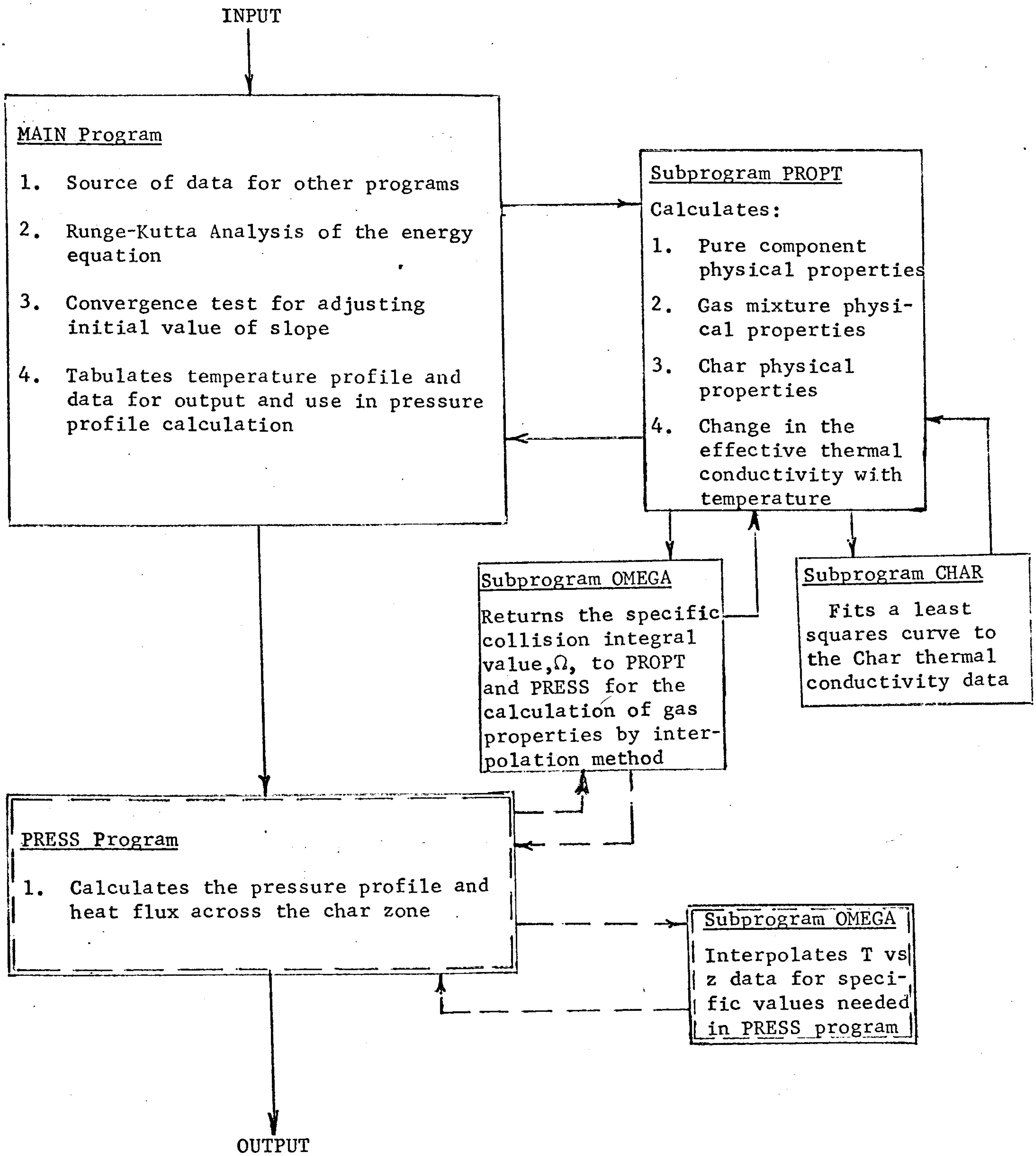
Simpson's Rule: The standard Simpson's Rule equation is used to evaluate the two integrals in equation (4). Written in general terms the equation is:

$$V = \left(\frac{h}{3}\right)\left(x_o + 4(x_{o+h}) + 2(x_{o+2h}) + \ldots + 2(x_{L-2n}) + 4(x_{L-h}) + x_L\right)$$

where V is the value of the integral and x is the term under the integral sign. corresponding to $T\bar{u}$ and T in equation (4). The interval size is designated by h.

Subprogram OMEGA: This is a subprogram used to interpolate between data points stored in the memory of the computer. In the original program for

DIAGRAM I


INPUT
MAIN Program
1. Source of data for other programs
2. Runge-Kutta Analysis of the energy equation
3. Convergence test for adjusting initial value of slope
4. Tabulates temperature profile and data for output and use in pressure profile calculation
Subprogram PROPT
Calculates:
1. Pure component physical properties
2. Gas mixture physical properties
3. Char physical properties
4. Change in the effective thermal conductivity with temperature
Subprogram OMEGA
Returns the specific collision integral value, Ω, to PROPT and PRESS for the calculation of gas properties by interpolation method
Subprogram CHAR
Fits a least squares curve to the Char thermal conductivity data
PRESS Program
1. Calculates the pressure profile and heat flux across the char zone
Subprogram OMEGA
Interpolates T vs z data for specific values needed in PRESS program
OUTPUT

the solution of the general energy equation, OMEGA was used to select the proper collision integral, Ω, corresponding to a specific temperature and gas component; hence, the name OMEGA. However, in the revised program, OMEGA is also used to call the proper temperature corresponding to a value of the char distance, z, from tabulated data representing the temperature profile calculated prior to pressure and heat flux calculations.

Results and Conclusions

The solution of the momentum equation under frozen flow conditions increases the knowledge about the char zone characteristics. The following conclusions result from this study:

1. Increasing the mass flux results in an increase in the pressure drop and heat flux across the char zone in a direct proportion to the percentage change affected.
2. Increasing the char porosity increases the heat flux in the same manner as described in (1); however, the values of the pressure drop decrease. This decrease is caused from the cooling effect noted in Figure V1, as a decrease in the localized temperature which has a greater influence on the pressure profile than does the char porosity.
3. Raising the surface temperature, likewise, results in an increase to both heat flux and pressure drop values proportional to the percentage change made.
4. Varying the gas composition affects the pressure drop and heat flux according to the overall change in the physical properties of the mixture. Increasing values of the heat capacity and gas viscosity would cause a corresponding increase in the values of the heat flux and pressure profile (Reference: Figure I).
5. The general Fortran program is now written to include the calculation of the temperature and pressure profiles and the heat flux at the char surface for a variety of input conditions. This essentially

concludes the analytical study of the frozen flow case, except as specific information is required for comparison with other models under study (i. e. equilibrium flow model and the non-equilibrium flow model).

Effect of Changes in the System Variables on the Frozen Flow Temperature Profile

As supplemental information to the NASA-RFL-2 report, an investigation into the effects of changes in system variables on the frozen flow temperature profile was recently completed. The variables studied were, as in the pressure profile study, the mass flux, char porosity, gas composition, and surface temperature with ranges of conditions identical to those for the solution of the momentum equation. Figures V through VIII illustrate the effect of each variable and the following section indicates the results obtained from the study.

Results and Conclusions

The following conclusions can be drawn from the results presented as temperature profiles in Figures V through VIII:

1. Changing the gas composition results in a slight shift of the temperature profile. The direction is entirely dependent on the relative value of the heat capacity for the mixture in question, $\overline{C_p}$. If the heat capacity increases a downward shift results representative of a cooling effect. The opposite is apparent if the heat capacity value decreases.
2. Increasing the mass flux and char porosity causes downward shifts in the temperature profile curve. This is a result of (a) increasing the coolant gas flow in the first case, and, (b) increasing the effect surface area for cooling in the latter.
3. Raising the surface temperature increases the heat load requirement on the system which results in increased localized temperatures throughout the char.

Future Research

The immediate plan is to combine the general program for frozen flow with a program that will generate mole fraction values of flowing gases as a function of temperature. This will be the first step in the development of a general program to study the equilibrium flow case.

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Table I. Summary
Effect of System Variables on the
Pressure Profile in the Char Zone
of a Charring Ablator

Composition (Mol %):

$CO = 23.8$, $CO_2 = 4.5$, $N_2 = 7.0$, $CH_4 = 57.4$, $C_6H_6 = 6.7$
$T_o = 500^oF$, $Z_L = 0.25$ in.

Figure	Surface Temp, T_L ^oF	Mass Flux, W lb/ft^2-sec	Char Porosity, ϵ	Heat Flux, Q BTU/ft^2-sec	Pressure Drop lb/ft^2
IV	2000	0.05	0.8	37.13	10.30
	2500	0.05	0.8	52.22	12.97
	3000	0.05	0.8	67.72	15.98
II	2000	0.05	0.8	37.13	10.30
	2000	0.05	0.7	32.49	10.68
	2000	0.05	0.5	23.21	11.48
III	2000	0.01	0.8	7.43	2.12
	2000	0.05	0.8	37.13	10.30
	2000	0.09	0.8	66.83	17.91
I	2000*	0.05	0.8	40.56	16.38

* Composition (Mol %):

$CO = 19.4$, $N_2 = 1.9$, $H_2 = 51.8$, $CH_4 = 0.5$, $C_2H_4 = 0.1$, $C_2H_2 = 21.6$, $HCN = 4.7$

FIGURE I. EFFECT OF GAS COMPOSITION ON THE PRESSURE PROFILE IN THE CHAR ZONE OF A CHARRING ABLATOR

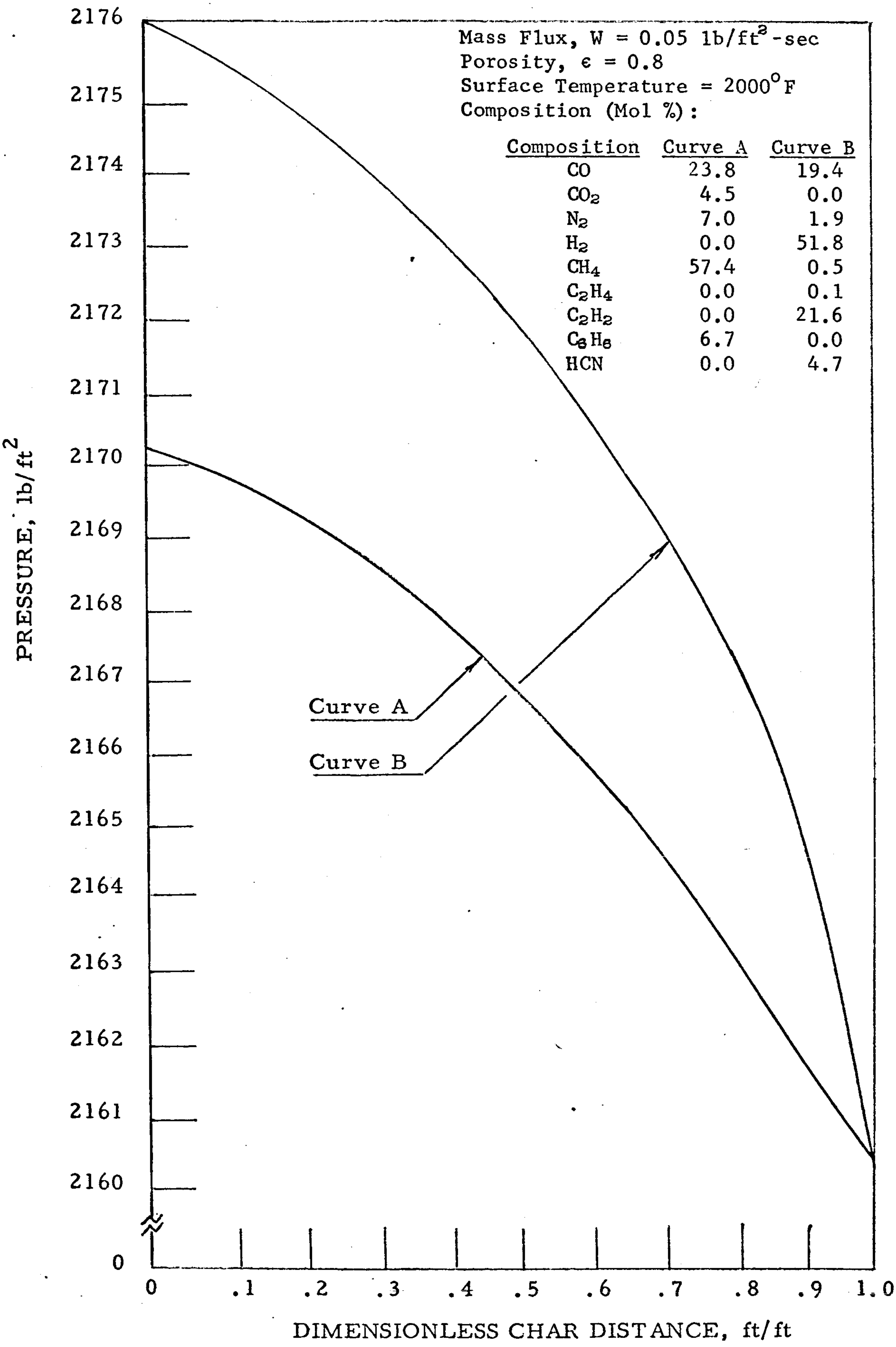


FIGURE II EFFECT OF CHAR POROSITY ON THE PRESSURE PROFILE IN THE CHAR ZONE OF A CHARRING ABLATOR

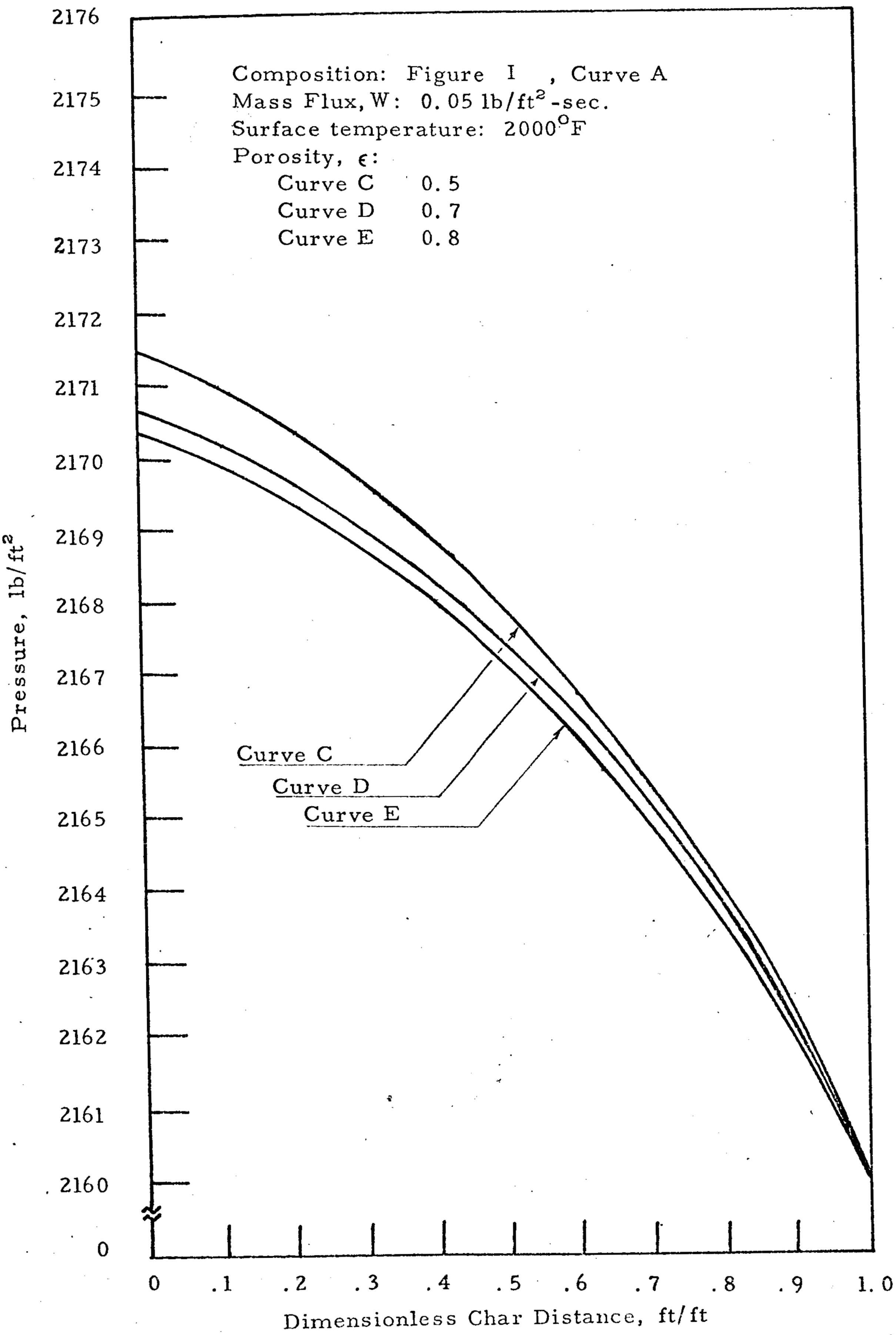


FIGURE III EFFECT OF MASS FLUX ON THE PRESSURE PROFILE IN THE CHAR ZONE OF A CHARRING ABLATOR

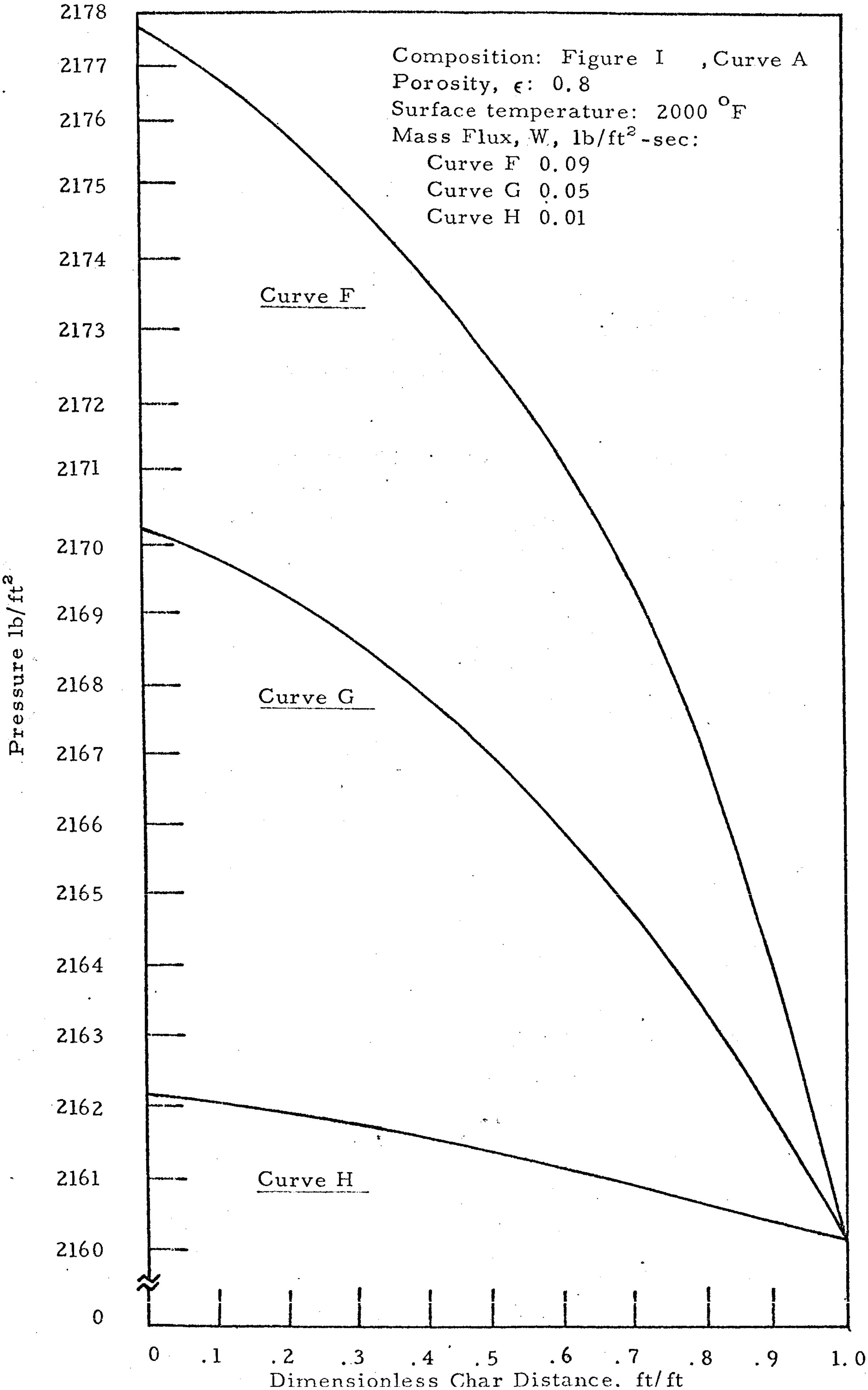


FIGURE IV EFFECT OF CHAR SURFACE TEMPERATURE, T_L, ON THE PRESSURE PROFILE IN THE CHAR ZONE OF A CHARRING ABLATOR

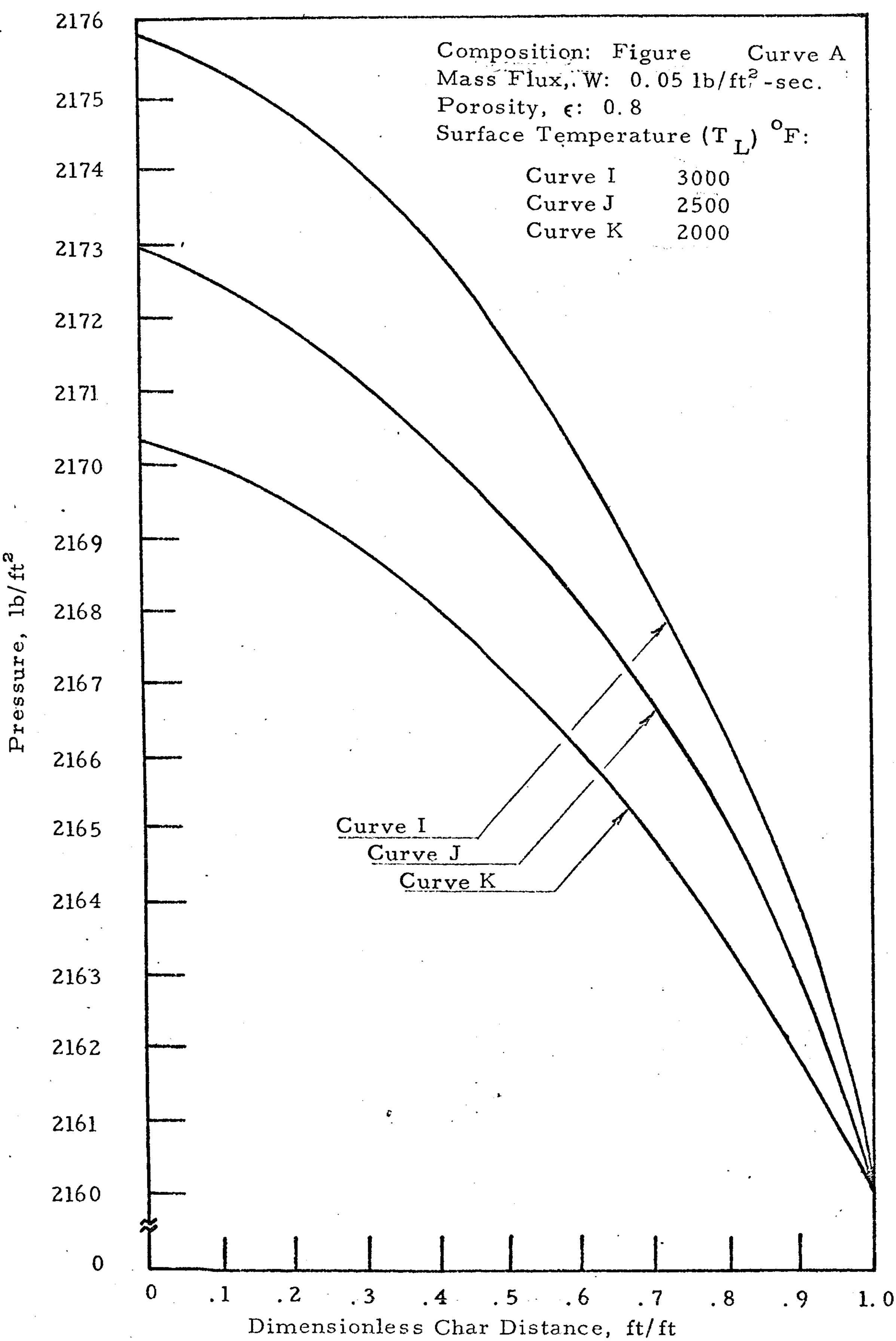


FIGURE V. EFFECT OF GAS COMPOSITION ON THE TEMPERATURE PROFILE IN THE CHAR ZONE OF A CHARRING ABLATOR

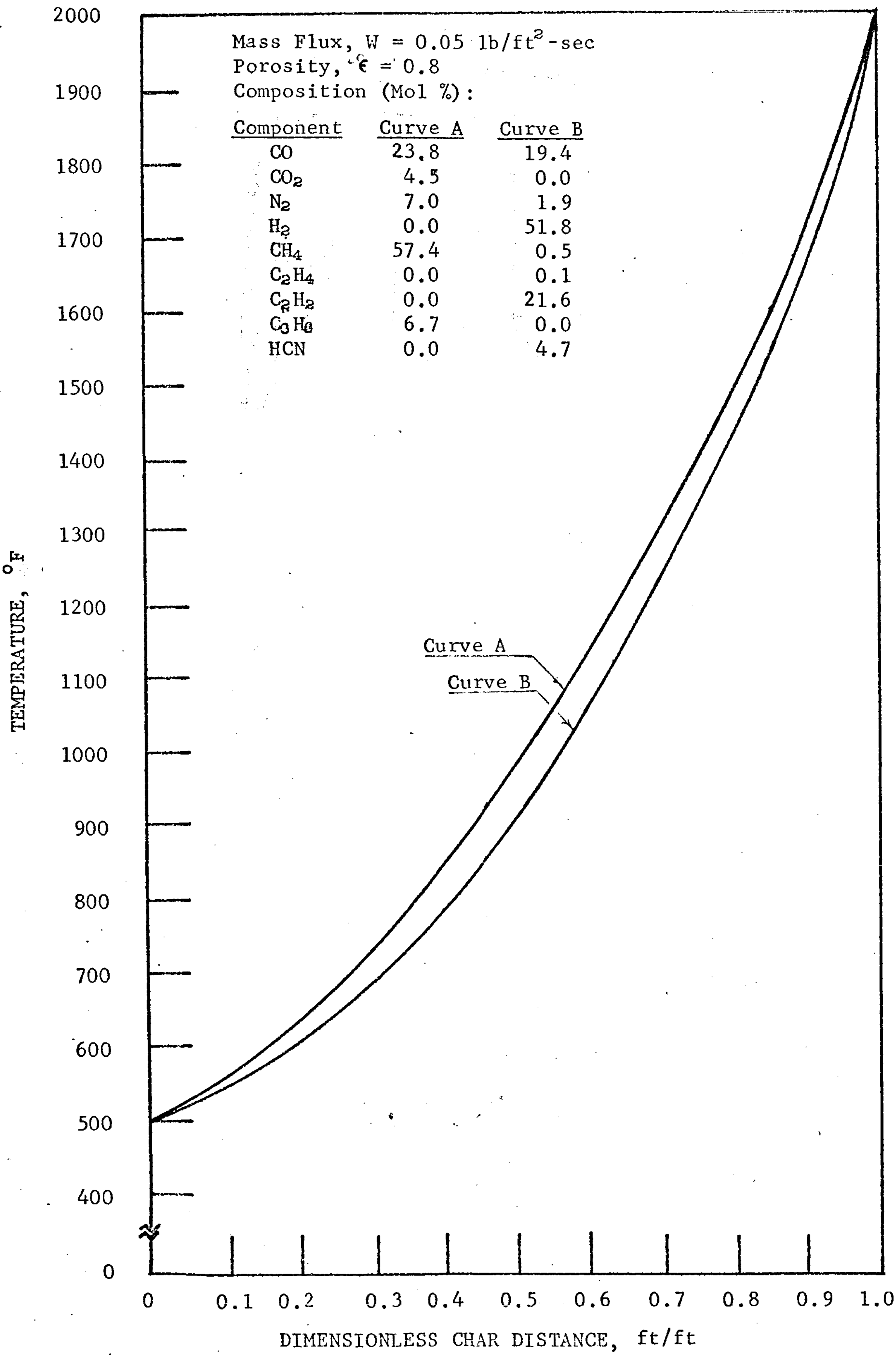


FIGURE VI. EFFECT OF CHAR POROSITY ON THE TEMPERATURE PROFILE IN THE CHAR ZONE OF A CHARRING ABLATOR

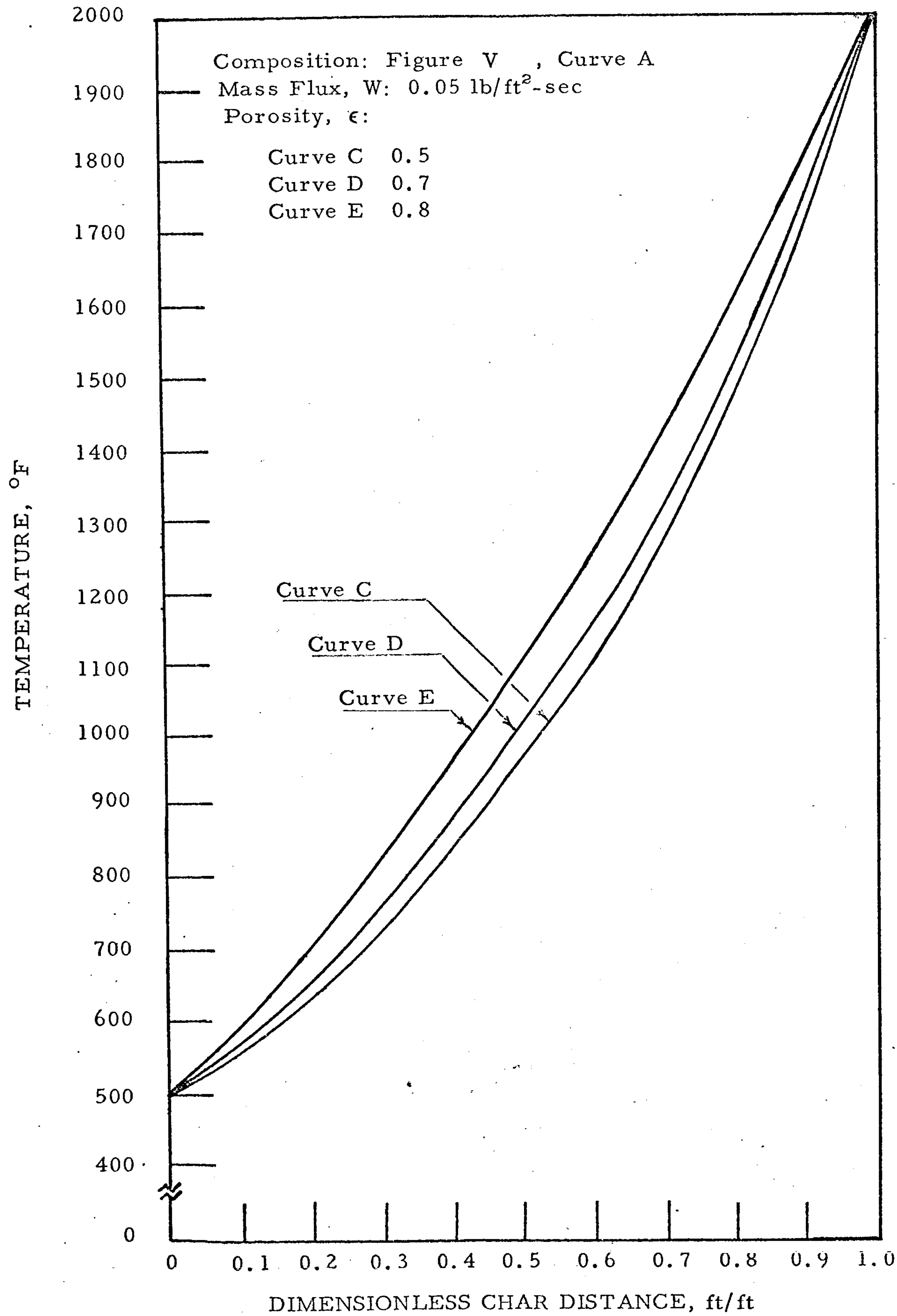


FIGURE VII. EFFECT OF MASS FLUX ON THE TEMPERATURE PROFILE IN THE CHAR ZONE OF A CHARRING ABLATOR

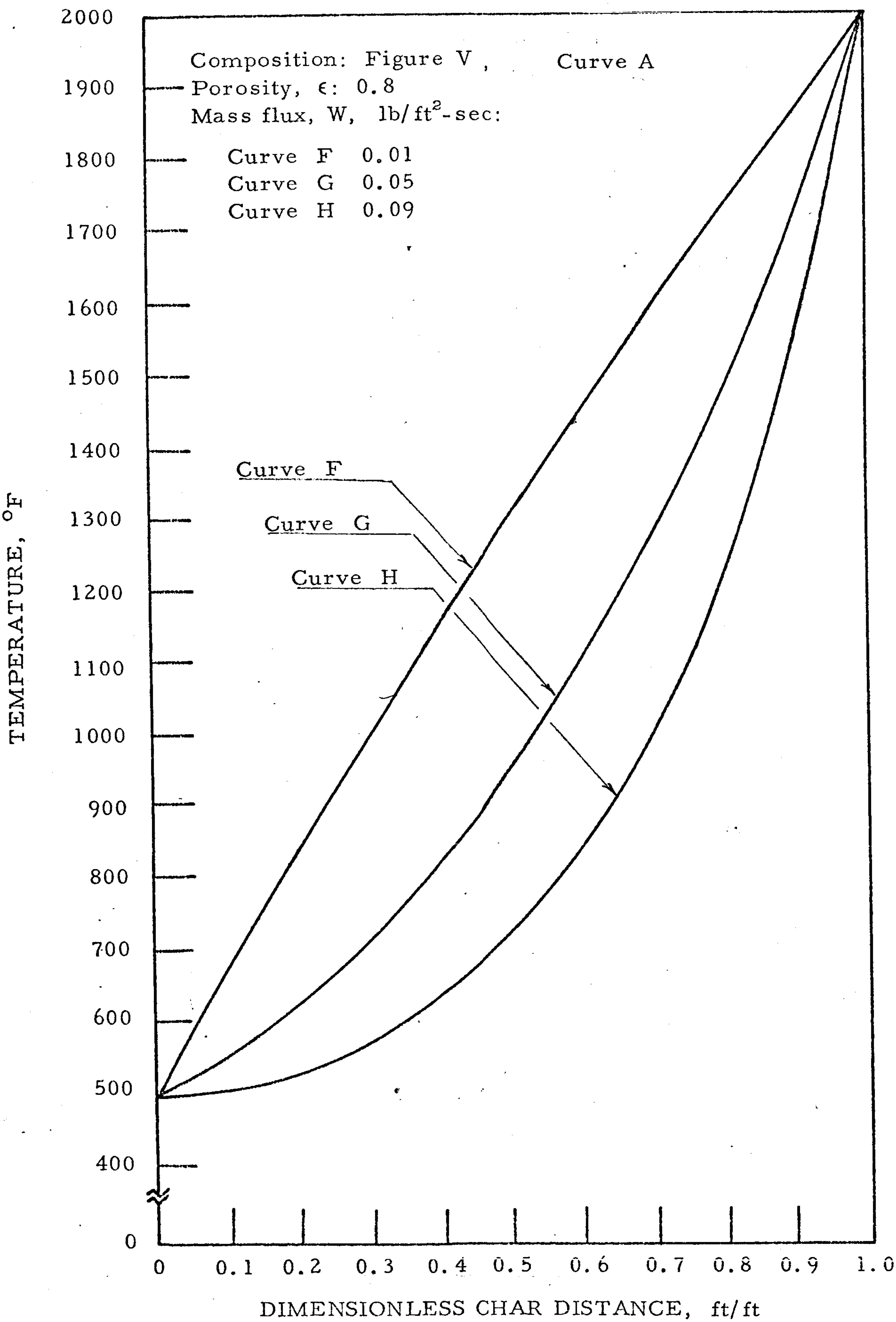
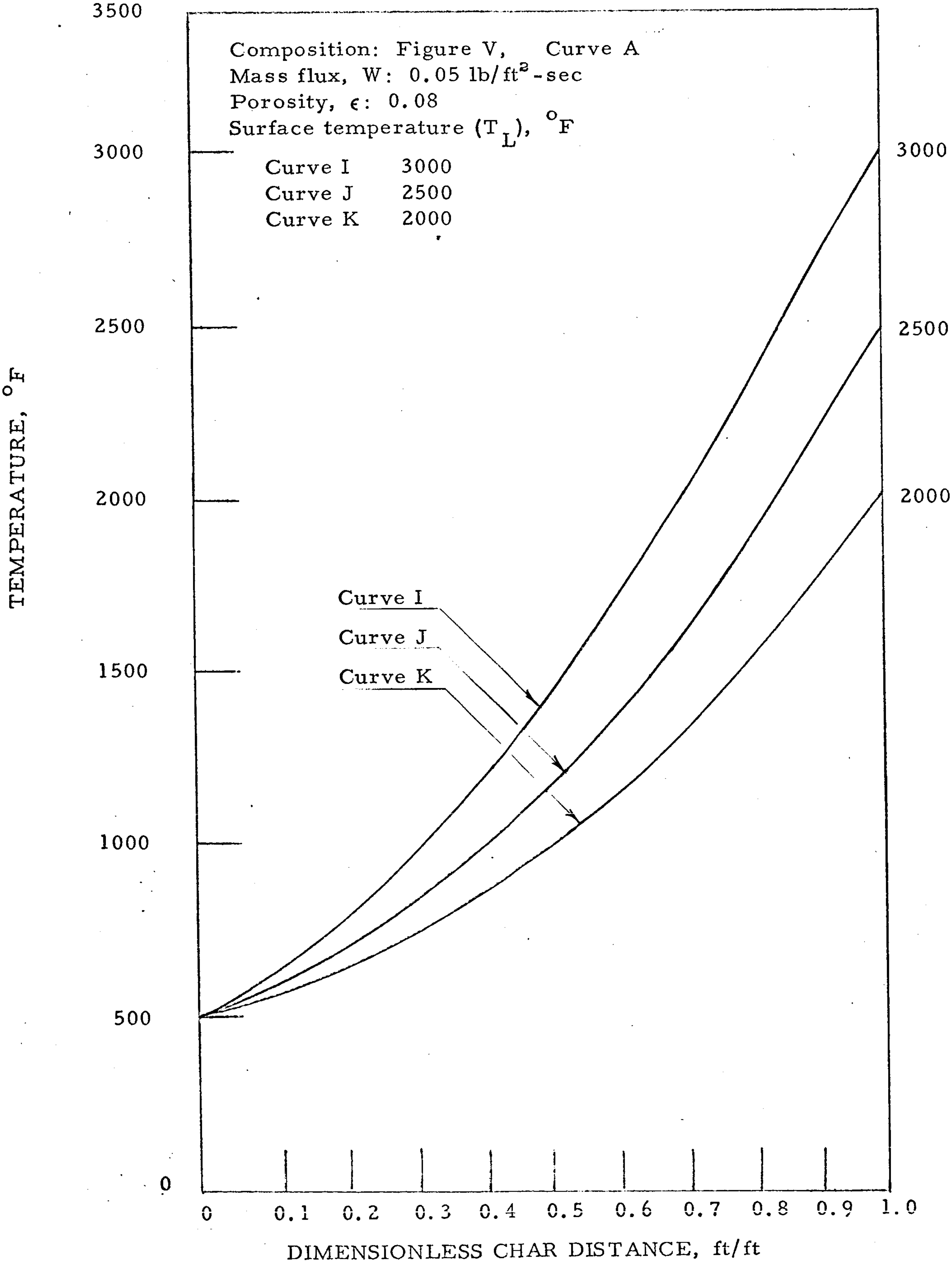


FIGURE VIII. EFFECT OF SURFACE TEMPERATURE (T_L) ON THE TEMPERATURE PROFILE IN THE CHAR ZONE OF A CHARRING ABLATOR



APPENDIX A

INTRODUCTION TO APPENDIX A

Appendix A contains the various physical property and other pertinent data necessary in the determination of the pressure profile and heat flux across the char zone. The following table summarizes the information presented:

Table II	Heat Capacity Coeffieients for Various Pure Components
Table III	Collision Integral and Lennard-Jones Potentials, etc. for Various Pure Components
Table IV	Degradation Gas Composition (Mass Fraction) vs. Temperature
Table IV-1	Degradation Gas Composition (Mole Fraction) vs. Temperature
Table V	Experimental Data for the Determination of Char Permeability at Constant Temperature.
Figure VI	Plot of Experimental Data and Least Squares Curve - Evaluation of α and β for use in Equation (4)

TABLE II
HEAT CAPACITY PARAMETERS FOR PURE GASES
AS A FUNCTION OF TEMPERATURE (7)

$$C_p^o = a + bT + cT^2 + dT^3 \quad (T = {}^oK)$$

Temperature Range ^oK >300^{o}K; <1500^{o}K
(C_p units - g-cal/g-mole-^{o}K)

Component	a	b x 10^2	c x 10^5	d x 10^9	Temp. Range, ^{o}K	Error Max.	Error Avg.
CO	6.726	0.04001	0.1283	-0.5307	273 - 1800	0.89	0.37
CO_2	5.316	1.4285	-0.8362	1.784	273 - 1800	0.67	0.22
N_2	6.903	-0.03753	0.1930	-0.6861	273 - 1800	0.59	0.34
H_2	6.952	-0.04576	0.09563	-0.2079	273 - 1800	1.01	0.26
HCN	6.34	0.8375	-0.2611	--	273 - 1500	1.42	0.76
CH_4	4.750	1.200	0.3030	-2.630	273 - 1500	1.33	0.57
C_2H_6	1.648	4.124	-1.530	1.740	273 - 1500	0.83	0.28
C_2H_4	0.944	3.735	-1.993	4.220	273 - 1500	0.54	0.13
C_2H_2	5.21	2.2008	-1.559	4.349	273 - 1500	1.46	0.59
C_6H_6	-8.650	11.578	-7.540	18.54	273 - 1500	0.34	0.20
C_3H_4 (1)	2.43	4.693	-2.781	6.484	273 - 1500	0.37	0.19
C_3H_4 (2)	4.21	4.073	-2.192	4.713	273 - 1500	0.36	0.13

(1) Propadiene, (2) Methyl Acetylene

TABLE III
COLLISION INTEGRAL AND LENNARD-JONES POTENTIALS, ETC. FOR PURE GASES (5)

Component Formula	ϵ/k °K	σ Å	T_c °K	T_b °K	P_c atm	V_c cc/g-mole
CO	110	3.590	133*	75#	34.5	93
CO_2	190	3.996	304.2*	192#	72.9	94
N_2	91.5	3.681	126.2*	80#	33.5	90
H_2	33.3	2.986	33.3*	19#	12.8	65
HCN	--	--	456.7*	259#	53.2	139
CH_4	136.5	3.822	191.0	111.8	45.8	99.5
C_2H_6	230	4.418	305.4*	193#	48.2	148
C_2H_4	205	4.232	282.4	169.4	50.0	124
C_2H_2	185	4.221	309.0	189.6	61.6	113
C_6H_6	440	5.270	562.6	352.8	48.6	261
C_3H_4	--	--	401	250	52.8	--

* Reference 7 - pp. 92-93, Table 7A-7B

\# Calculated, op. cit. page 89 from T_c data

Others from Reference 5, Table 8-2
Table 2-3, 2-10, 2-14

TABLE IV
DEGRADATION GAS COMPOSITION AS A
FUNCTION OF TEMPERATURE (9)

Component Formula	Formula Weight	Type of Molecule L - Linear NP - Non-Polar NL - Non-Linear	Mass Fraction 1000° R (540° F)	 2000° R (1540° F)	 3000° R (2540° F)
CO	28	Carbon Monoxide (L)	0.27	0.37	0.37
CO_2	44	Carbon Dioxide (L)	0.08	--	--
N_2	28	Nitrogen (L)	0.08	0.072	0.041
H_2	2	Hydrogen (L)	--	0.006	0.064
HCN	27	Hydrogen Cyanide (L)	--	0.014	0.071
CH_4	16	Methane (NP, NL)	0.36	0.30	0.02
C_2H_6	30	Ethane (NP, NL)	0.007	0.002	--
C_2H_4	28	Ethylene (NP, NL)	--	0.067	0.009
C_2H_2	26	Acetylene (L)	--	0.021	0.38
C_6H_6	78	Benzene (NP, NL)	0.21	0.091	--
C_3H_4	40		--	0.004	0.002
C_3H_5	41		--	0.040	0.01
C_4H_2	50		--	--	0.031
C_4H	49		--	--	0.0014
C_3H	37		--	--	0.0011

From Reference 9 Page 63, Figure 6, 1 atm

Note: Same Components (Different Compositions) at 0.1 and 10 atm

TABLE IV-1
DEGRADATION GAS COMPOSITION AS A FUNCTION OF TEMPERATURE (9)

Mass Fraction (Kratsch Report)

$T_{^oK}$	1 CO	2 CO_2	3 N_2	4 H_2	5 HCN	6 CH_4	7 C_2H_6	8 C_2H_4	9 C_2H_2	10 C_6H_6	11 C_3H_4
555	0.27	0.082	0.082	0	0	0.37	0.007	0	0	0.21	0
833	0.37	0	0.082	0	0	0.37	0.004	0.01	0	0.17	0
1111	0.37	0	0.072	0.0045	0.01	0.30	0.002	0.05	0.012	0.14	0.002
1389	0.37	0	0.055	0.027	0.046	0.17	0	0.07	0.15	0.004	0.009
1667	0.37	0	0.042	0.061	0.07	0.03	0	0.011	0.37	0	0.003
1945	0.37	0	0.037	0.070	0.085	0.004	0	0.002	0.38	0	0

Total Moles Calculation

$T_{^oK}$	1	2	3	4	5	6	7	8	9	10	11	Total
555	0.96	0.18	0.28	0	0	2.31	0.024	0	0	0.27	0	4.024
833	1.81	0	0.28	0	0	2.31	0.012	0.036	0	0.22	0	4.168
1111	1.31	0	0.26	0.23	0.04	1.88	0.006	0.18	0.046	0.18	0.005	4.137
1389	1.31	0	0.20	1.35	0.17	1.06	0	0.25	0.58	0.005	0.022	4.947
1667	1.31	0	0.15	3.05	0.26	0.19	0	0.038	1.42	0	0.008	6.426
1945	1.31	0	0.13	3.50	0.32	0.03	0	0.006	1.46	0	0	6.756

Mole Fraction

$T_{^oK}$	1	2	3	4	5	6	7	8	9	10	11
555	0.238	0.045	0.07	0	0	0.574	0.006	0	0	0.067	0
833	0.314	0	0.067	0	0	0.554	0.003	0.009	0	0.053	0
1111	0.316	0	0.063	0.056	0.01	0.454	0.001	0.044	0.011	0.044	0.001
1389	0.264	0	0.04	0.273	0.035	0.214	0	0.051	0.117	0.001	0.005
1667	0.204	0	0.023	0.474	0.041	0.030	0	0.006	0.221	0	0.001
1945	0.194	0	0.019	0.518	0.047	0.005	0	0.001	0.216	0	0

TABLE V

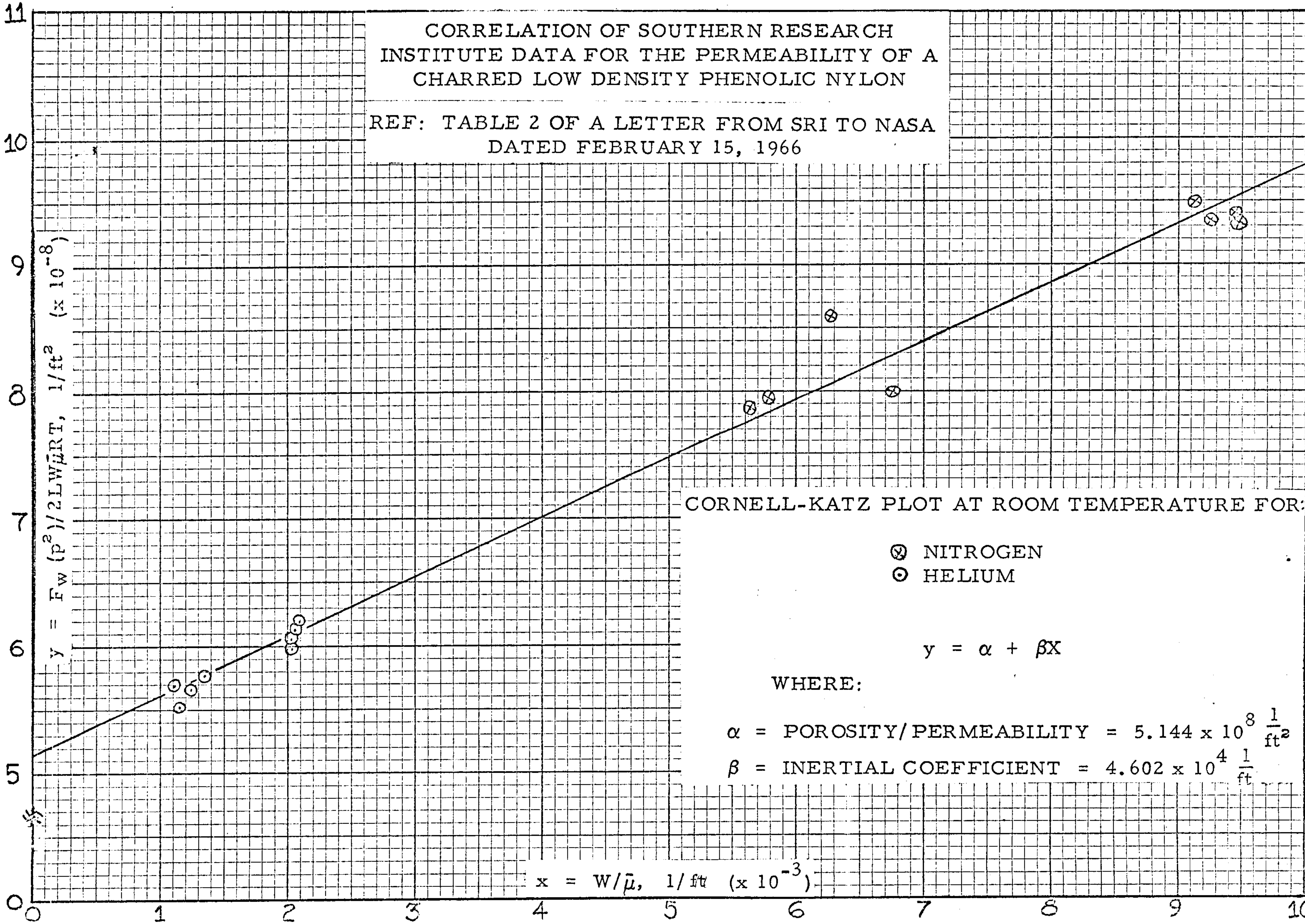
PERMEABILITY OF CHARRED LOW DENSITY PHENOLIC NYLON AT ROOM TEMPERATURE (4)(8)

Correlating Equation: $\frac{F_W \Delta(P^2)}{2W\bar{\mu}RTL} = \alpha + \beta(\frac{W}{\bar{\mu}})$

Specimen No. and Char Thickness	Purge Gas	Pressure Drop in. of H_2O	Mean Pressure in. of H_2O	Flow Rate of Gas cm^3/sec	$\frac{F_W \Delta(P^2)}{2W\bar{\mu}RTL}$ $1/ft^2(10^{-8})$	$\frac{W}{\bar{\mu}}$ 1/ft
Specimen No. 1 (0.273 in.)	Helium	1.35	407.48	109.91	5.6965	1103.5
		1.40	407.50	113.63	5.5102	1140.8
		2.60	408.10	202.26	5.9708	2030.6
		2.75	408.18	207.00	6.1719	2078.2
	Nitrogen	1.35	407.48	79.90	7.8340	5616.7
		1.40	407.50	82.13	7.9040	5773.4
		2.65	408.13	129.89	9.4746	9130.8
		2.70	408.15	133.82	9.3703	9407.0
Specimen No. 2 (0.272 in.)	Nitrogen	1.65	407.63	96.05	7.9679	6752.0
		1.65	407.63	89.16	8.5836	6267.6
		2.65	408.13	131.83	9.3352	9267.2
		2.70	408.15	134.84	9.2994	9478.7
	Helium	1.50	407.55	122.90	5.6614	1233.9
		1.65	407.53	132.82	5.7621	1333.5
		2.60	408.10	200.55	6.0217	2013.5
		2.70	408.15	205.20	6.1124	2060.2

KEUFFEL & ESSER CO.

FIGURE IX



APPENDIX B

Introduction to Appendix B

Appendix B contains the various program nomenclature, data and diagrams for calculating the pressure profile and heat flux across the char zone under frozen flow conditions (Section (1)). A complete program sheet for the general solution to the frozen flow problem including the temperature and pressure profile and the heat flux calculations is also presented.

Section (2) contains the program information used to evaluate α and β, the viscous and inertial coefficients in the momentum equation. Program sheets for the correlation of experimental data on char permeability and a least squares fit of the resulting values are likewise given.

Section (1)

General Program for the Calculation of the Temperature and Pressure Profiles in the Char Zone of a Charring Ablator

GENERAL PROGRAM FOR THE DETERMINATION OF THE TEMPERATURE AND PRESSURE PROFILES IN THE CHAR ZONE OF A CHARRING ABLATOR

Nomenclature

	INPUT DATA	UNITS
A(I), B(I), C(I), D(I)	Parameters in the heat capacity equation	---
ALPHA	Coefficient in the momentum equation	$1/ft^2$
BETA	Coefficient in the momentum equation	1/ft
DT(1)	Initial slope	$^oF/ft$
EK(I)	Potential parameter (E) divided by Boltzman Constant (K) for each component	---
EPS	Porosity	---
FW(I)	Molecular weight of each gas component	$\frac{lb}{lb\text{-}moles}$
HI	Initial interval size for temperature profile	ft
HS	Interval size for pressure profile	ft
HSiMPI	Interval size in Simpson's Rule evaluation	ft
K	No. of gas components	---
MDATA	No. of data points in the k_c vs temperature table	---
NDATA	No. of data points in the TK/E vs Omega table	---
PL	Pressure at the char surface	lb/ft^2
R	Gas constant	(cal/gmole-^oK)
SIG(I)	Collision diameter of each gas component	A^o
T(1)	Initial temperature	^oF
TL	Final Temperature	^oF
W	Mass flux	lb/ft^2-sec
XCOND(I)	Temperature data (for char conductivity)	^oK
YCOND(I)	Char conductivity data	cal/cm-sec-^oC
XTKE(I)	Temperature times ratio of the Boltzman Constant to the potential parameter data (for omega)	---
ZOMGA(I)	Collision integral data for each gas component	---
Y(I)	Mole fraction of each gas component	$\frac{\text{moles of (I)}}{\text{total moles}}$
ZL	Char thickness	ft

GENERAL PROGRAM FOR THE DETERMINATION OF THE TEMPERATURE AND PRESSURE PROFILES IN THE CHAR ZONE OF A CHARRING ABLATOR

Nomenclature

OUTPUT DATA

AVGFW	Average molecular weight of gas mixture	$\frac{lb}{lb\ mole}$
CDCHAR	Char Thermal Conductivity	Cal/car-sec^{o}C
CDMX	Thermal conductivity of gas mixture	Cal/sec-cm-^{o}C
CDO	Overall thermal conductivity	BTU/ ft-sec-^{o}F
CHARK	Char Thermal Conductivity	BTU/ft-sec-^{o}F
COND (I)	Thermal conductivity of the pure gas component	Cal/sec-cm-^{o}F
CP (I)	Heat capacity at constant pressure of the pure gas component	Cal/cmole-^{o}K
CPMX	Heat capacity of gas mixture	Cal/goide-^{o}K
CV(I)	Heat capacity at constant volume of the pure gas component	Cal/gmole-^{o}K
DCDO	Derivative of the overall thermal conductivity with respect to temperature	BTU/ft-sec-$(^{o}F)^2$
DELP	Pressure drop across char	lb/ft^2
DELTT	Temperature drop across char	^{o}F
DT(L)	Instantaneous slope $(\frac{dT}{dz})$ at a distance corresponding to L	^{o}F/ft
EPS	Char porosity	
GASCP	Heat capacity of gas mixture	BTU/lb-^{o}F
GASK	Thermal conductivity of gas mixture	BTU/ft-sec^{o}F
GROUP	$\left(\frac{W\epsilon C_{pmx}}{k_e} - (\frac{dk_e}{dT})(\frac{dT}{dz})/k_e\right)$	1/ft
L	Step counter corresponding to instaneous char distance	---
P(LS)	Instantaneous pressure at a distance corresponding to LS	lb/ft^2
Q	Heat flux at char surface	BTU/ft^2-sec
T(L)	Instantaneous temperature at a distance corresponding to L	^{o}F
TP(LS)	Instantaneous temperature at a distance corresponding to LS	^{o}F

W	Mass Flux	lb/ft^2-sec
XAXIS(L)	Dimensionless char distance term (Z/ZL)	ft/ft
YAXIX(L)	Dimensionless temperature term (T(L) - T(1)/(TL - T(1))	°F/°F
Z	Instantaneous char distance	ft
ZL	Char thickness	ft
Z(LS)	Instantaneous char distance at LS	ft

```
$CATE           C8/C2/66
$CLCSE          S.SPP1
$JCB            APRIL
$IBJCB          NCDECK
$IBFTC MAIN
C       GARY C. APRIL   NASA PRCJECT 135-30-8621
C       1 = CC, 2 = CC2, 3 = N2, 4 = CH4, 5 = C6H6
C       KT/E VS. OMEGA   REIC AND SHERWCCD, TABLE 6-1, PAGE 187
        CIMENSICN T(5CC),DT(5CC),XTKE(1CO),ZOMGA(1CO),EK(5C)
        CIMENSICN XN(5CO),FN(5CC),TT(500),TP(5CC)
        CIMENSICN SIG(5C),FW(50),A(50),B(50),C(50),D(5C),CP(50),CCND(50)
        CIMENSICN CV(5C),Y(50),VIS(50),XCOND(50),YCCND(50)
        CIMENSICN XAXIS(5CO),YAXIS(5CC),QT(50C),QDT(500),Z(5CO)
        CIMENSICN FROD(5CO),ZX(5CO),P(500),ZY(500)
  1C    READ1,T(1),CT(1),TL,HI,ZL,R,W,EPS,DELT
        READ2,NDATA,MDATA,K
        READ3,(XTKE(I),ZOMGA(I),I=1,NDATA)
        READ 4, (EK(I),SIG(I),FW(I),Y(I),I=1,K)
        READ 5, (A(I),B(I),C(I),D(I),I=1,K)
        READ 6, (XCCND(I),YCCND(I),I=1,MDATA)
        READ7,ALPHA,BETA,HSIMPI,HS,PL
  1     FCRMAT(9F8.C)
  2     FCRMAT(3I6)
  3     FCRMAT(2F15.0)
  4     FCRMAT(4F15.0)
  5     FCRMAT (4E15.5)
  6     FCRMAT (F15.0,E15.5)
  7     FCRMAT(2E15.5,3F1C.C)
        CCMMCN K,EK,A,B,C,D,R,FW,SIG,XTKE,ZOMGA,Y,XCOND,YCOND,DELT,NDATA
        CCMMCN MDATA,EPS
        PRINT 4CCC,W,EPS,TL,ZL,HI
 4CCO   FCRMAT(1X,2HW=,F15.6,4X,4HEPS=,F15.6,4X,3HTL=,F15.6,4X,3HZL=,
     1     F15.6,4X,3HHI=,F15.6)
        Z(1)=C.C
        JCHAR=1
        NC=1
  4C    N=1
        H=HI
        XAXIS(1)=C.0
        YAXIS(1)=C.C
  5C    Z=0.C
  55    IF(N-1)56,56,101
  56    T(N+1)=H*DT(N) + T(N)
        DT(N+1)=DT(N)
        GC TC 138
 1C1    TC=T(N)
        THETA=T(N)
 1C2    DTC=DT(N)
        DTHETA=DT(N)
        MX=1
        IF(DT(1))1109,11C9,1C3
 11C9   DT(1)=DT(1)/((1.C+0.5*((TL-TCHECK)/TL))*2.0)
        GC TC 4C
 1C3    ARK = H*DTC
        RANKIN=TC+460.C
```

```
      TVAR=RANKIN/1.8
  104 CALL PRCPT (TVAR,JCHAR,CPMX,CDO,DCDO,AVGFW)
      JCHAR=2
      GASCP=(CPMX*454.0)/(252.0*1.8*AVGFW)
      GRCUP=(W*EPS*GASCP/CDO)-(DCDO*DTC/CDO)
      DA=ARK*GRCUP
  105 GO TO (110,120,130,135),MX
  110 A1=ARK
      DA1=DA
      TC=THETA+0.5*A1
      DTC=DTHETA+0.5*DA1
      MX=2
      IF(TC)133,133,103
  120 A2=ARK
      DA2=DA
      TC=THETA+0.5*A2
      DTC=DTHETA+0.5*DA2
      MX=3
      IF(TC)133,133,103
  130 A3=ARK
      DA3=DA
      TC=THETA+A3
      DTC=DTHETA+DA3
      MX=4
      IF(TC)133,133,103
  133 PRINT 2222,TC
 2222 FORMAT(1H0,3HTC=,1X,F15.6,8X,8HNEGATIVE)
      DT(1)=DT(1)*0.5
      GO TO 40
  135 A4=ARK
      DA4=DA
      T(N+1)=T(N)+(1.0/6.0)*(A1+2.0*A2+2.0*A3+A4)
      DT(N+1)=DT(N)+(1.0/6.0)*(DA1+2.0*DA2+2.0*DA3+DA4)
      IF(T(N+1)-3500.0)5000,5000,6000
 5000 IF(T(N+1))136,136,138
  136 PRINT 137, T(N+1)
  137 FORMAT(1H0,7HT(N+1)=,1X,F15.6,8X,8HNEGATIVE)
      DT(1)=DT(1)*0.5
      GO TO 40
 6000 PRINT 8000,T(N+1)
 8000 FORMAT(1H0,7HT(N+1)=,1X,F15.6,4X,8HEXCEEDED,1X,4H3500,1X,3HMAX)
      TRATIO=(TL-T(N+1))/TL
      DT(1)=DT(1)*(1.0+0.5*TRATIO)
      TCHECK=T(N+1)
      IF(DT(N+1))300,300,40
  138 Z(N+1)=Z(N)+H
      XAXIS(N+1)=Z(N+1)/ZL
      YAXIS(N+1)=(T(N+1)-T(1))/(TL-T(1))
      IF(ABS(ZL-Z(N+1))-.00001)150,150,145
  145 N=N+1
      GO TO 101
  150 GT(NC)=T(N+1)
      GDT(NC)=DT(1)
      DIFF=ABS(TL-T(N+1))
 1110 PRINT1111,T(1),DT(1)
```

```
 1111 FCRMAT(1HC,5HT(1)=,1X,F15.6,4X,6HDT(1)=,1X,F15.6)
      STEP=(1C.C*(ZL/HI)+5.C)/1C.C
      LSTEP=STEP
      LCHAR=LSTEP + 1
      PRINT18C
 18C  FCRMAT(1HC,8X,4HT(L),8X,5HDT(L),9X,8HXAXIS(L),7X,8HYAXIS(L),
     1   4X,1HL)
      DC2CC L=1,LCHAR
      PRINT19C,T(L),DT(L),XAXIS(L),YAXIS(L),L
 19C  FCRMAT(1X,4F15.6,I5)
 2CC  CCNTINUE
      IF(DIFF-1.C)155,155,151
 151  IF(DIFF-1CC.C)153,153,152
 152  TRATIC=(TL-T(N+1))/TL
      DT(1)=DT(1)*(1.C+0.5*TRATIO)
      TCHECK=T(N+1)
      NC=NC+1
      GC TC 4C
 153  IF(NC-1)152,152,154
 154  RATIC=(TL-QT(NC))/(QT(NO-1)-QT(NC))
      RDASH=RATIC*(QDT(NC-1)-QDT(NO))
      DT(1)=DT(1)+RDASH
      NC=NC+1
      GC TC 4C
 155  PRINT 3333
 3333 FCRMAT(1HC,11HTEMPERATURE,1X,7HPROFILE,1X,7HDEFINED)
C     CALCULATICN OF PRESSURE PROFILE
      SIMP1=C.C
      SIMP2=0.C
      ZS=ZL/HS
      NS=(1C.C*ZS+5.C)/10.C
      LS=NS+1
      ZX(LS)=ZL
      TP(LS)=TL
      P(LS)=PL
      DC 26C N=1,NS
      NBAR=N-1
      HN=NBAR
      LC=LS-NBAR
      ZX(LC)=ZX(LS)-HN*HS
      ZSIMP=HS/HSIMPI
      MS=(10.C*ZSIMP+5.0)/1C.C
      MP=MS+1
      ZY(MP)=ZX(LC)
      DC 240 M=1,MP
      MBAR=M-1
      HM=MBAR
      MC=MP-MBAR
      ZY(MC)=ZY(MP)-HM*HSIMPI
      ZVAR=ZY(MC)
      ITEMP=LCHAR
      TVIS=C.C
      CALL CMEGA(ZVAR,Z,T,ITEMP,SCM)
 2C5  TVIS=SCM
      TK=(TVIS+46C.C)/1.8
```

```
 209  DO 216 I=1,K
      TKE=(1.0/EK(I))*TK
      OMGA=0.0
      IMAX=NDATA
 211  CALL OMEGA(TKE,XTKE,ZOMGA,IMAX,SOM)
      OMGA=SOM
      VIS(I)=2.6693*10.**(-3.)*(FW(I)*TK)**0.5/(SIG(I)**2.0)*OMGA
 216  CONTINUE
      VMIX=0.0
 222  DO 237 J=1,K
      TERM=1.0
 223  DO 230 L=1,K
      IF(L-J)226,225,226
 225  GO TO 230
 226  TOPV=(1.0+(VIS(J)/VIS(L))**0.5*(FW(L)/FW(J))**0.25)**2.0
 227  BOTV=2.0*SQRT(2.0)*(1.+FW(J)/FW(L))**0.5
 228  PHIV=TOPV/BOTV
      TERM=TERM+PHIV*(Y(L)/Y(J))
 230  CONTINUE
      VMIX=VMIX+(VIS(J)/TERM)
 237  CONTINUE
      VISCOS=VMIX*2.42/3600.0
      TT(MC)=TVIS
      PROD(MC)=TVIS*VISCOS
 240  CONTINUE
      ZX(LC-1)=ZX(LC)-HS
      TP(LC-1)=TT(1)
      SUM1=0.0
      SUM2=0.0
      SUM3=0.0
      SUM4=0.0
      MEVEN=MP-1
      DO255 KP=2,MEVEN,2
      SUM1=SUM1+4.0*PROD(KP)
      SUM3=SUM3+4.0*TT(KP)
 255  CONTINUE
      MODD=MP-2
      DO256 KP=3,MODD,2
      SUM2=SUM2+2.0*PROD(KP)
      SUM4=SUM4+2.0*TT(KP)
 256  CONTINUE
      SIMP1=(HSIMPI/3.0)*(PROD(1)+PROD(MP)+SUM1+SUM2)+SIMP1
      SIMP2=(HSIMPI/3.0)*(TT(1)+TT(MP)+SUM3+SUM4)+SIMP2
      P(LC-1)=SQRT(PL**2+(2.0*R/AVGFW)*(778.16/32.2)*(W*ALPHA*SIMP1+
     1   (W**2)*BETA*SIMP2))
 260  CONTINUE
 261  PRINT262
 262  FORMAT(1H0,3H(I),3X,5HZX(I),10X,5HTP(I),11X,4HP(I))
 265  DO268 I=1,LS
      PRINT266,I,ZX(I),TP(I),P(I)
 266  FORMAT(1H0,I5,3F15.6)
 268  CONTINUE
      PRINT 4444
 4444 FORMAT(1H0,37HTEMPERATURE-PRESSURE PROFILES DEFINED)
C     CALCULATION OF THE HEAT FLUX AT THE CHAR SURFACE
```

```
      SUMA=0.0
      SUMB=0.0
      SUMC=0.0
      SUMD=0.0
      DO 270 I=1,K
      AQ=A(I)*Y(I)
      BQ=B(I)*Y(I)
      CQ=C(I)*Y(I)
      DQ=D(I)*Y(I)
      SUMA=SUMA+AQ
      SUMB=SUMB+BQ
      SUMC=SUMC+CQ
      SUMD=SUMD+DQ
  270 CONTINUE
      TLK=(TL+460.0)/1.8
      T1K=(T(1)+460.0)/1.8
      DELT1=(TLK-T1K)
      DELT2=((TLK**2)-(T1K**2))
      DELT3=((TLK**3)-(T1K**3))
      DELT4=((TLK**4)-(T1K**4))
      DELTT=(TL-T(1))
      Q=(W*EPS*((SUMA*DELT1)+(0.5*SUMB*DELT2)+(0.33*SUMC*DELT3)
     1   +(0.25*SUMD*DELT4))*454.0)/(AVGFW*252.0)
      DELP=(P(1)-PL)
      PRINT 271
  271 FORMAT(1H0,3X,5HDELTT,6X,4HDELP,7X,1HQ)
      PRINT 272,DELTT,DELP,Q
  272 FORMAT(1H0,3F10.4)
      PRINT 8888
 8888 FORMAT(1H0,21HALL VARIABLES DEFINED)
  300 STOP
      END
$IBFTC PROPT
C     SUBROUTINE PROPT  (HEAT CAPACITY AND CONDUCTIVITY VS. TEMPERATURE)
      SUBROUTINE PROPT (TVAR,JCHAR,CPMX,CDO,DCDC,AVGFW)
      DIMENSION EK(50),A(50),B(50),C(50),D(50),FW(50),SIG(50),XTKE(100)
      DIMENSION ZOMGA(100),XCOND(50),YCOND(50),Y(50)
      DIMENSION CP(50),CV(50),COND(50),XN(500),FN(500)
      COMMON K,EK,A,B,C,D,R,FW,SIG,XTKE,ZOMGA,Y,XCOND,YCOND,DELT,NDATA
      COMMON MDATA,EPS
      RANKIN=1.8*TVAR
      FAREN=RANKIN-460.0
      T=TVAR
      TC=T+DELT
  500 DO516 I=1,K
      TKE=(1.0/EK(I))*TC
      OMGA=0.0
      IMAX=NDATA
      CALL OMEGA (TKE,XTKE,ZOMGA,IMAX,SOM)
      OMGA=SOM
          CP(I)=A(I)+B(I)*TC+C(I)*TC**2.0+D(I)*TC**3.0
      CV(I)=(CP(I)-R)
          TOP=2.6693*10.0**(-5.0)*(TC/FW(I))**0.5*(CV(I)+4.47)
          BOT=(SIG(I)**2.0*OMGA)
          COND(I)=TOP/BOT
```

```
 516   CONTINUE
            CPMX=0.0
            CDMX=0.0
            AVGFW=0.0
       DO537 J=1,K
            SUMCP=CP(J)*Y(J)
            CPMX=CPMX+SUMCP
            SUMCD=COND(J)*Y(J)
            CDMX=CDMX+SUMCD
            SUMFW=FW(J)*Y(J)
            AVGFW=AVGFW+SUMFW
 537   CONTINUE
       GO TO (538,539),JCHAR
 538   CALL CHAR (XCOND,YCOND,MDATA,SLOPE,YINTCP)
 539   SCHAR=SLOPE
       YCHAR=YINTCP
       CDCHAR=(SCHAR*TC)+YCHAR
       CHARK=(CDCHAR*30.48)/(252.0*1.8)
       GASK=(CDMX*30.48)/(252.0*1.8)
       CDC=CHARK
       IF(ABS(T-TC)-.00001)560,560,540
 540   IF(T-TC)541,550,550
 541   CDCP=CDC
       TC=T-DELT
       JCHAR=2
       GO TO 500
 550   CDCN=CDC
       DELTF=DELT*1.8
       DCDC=(CDCP-CDCN)/(DELTF*2.0)
       TC=T
       GO TO 500
 560   RETURN
       END
$IBFTC OMEGA
C      SUBROUTINE OMEGA  (LENNARD JONES NUMBERS FOR GASES VS. TEMPERATURE)
       SUBROUTINE OMEGA (VAR,X,F,IMAX,SOM)
       DIMENSION X(500),F(500),XN(500),FN(500)
       NPTS=3
 607   XUP=1.E30
       DO611 I=1,IMAX
       T=VAR-X(I)
       IF(T)608,609,609
 608   T=-T
 609   IF(T-XUP)610,611,611
 610   IP=I
       XUP=T
 611   CONTINUE
       IN=1
       NPP=NPTS+1
       DO618I=1,NPP
       FN(I)=F(IP)
       XN(I)=X(IP)
       IF(IN)612,612,613
 612   IC=IP-I
       GO TO 615
```

```
 613   IQ=IP+I
       IF(IMAX-IQ)614,615,615
 614   IP=IP-1
       GO TO 618
 615   IF(IQ)616,616,617
 616   IP=IP+1
       GO TO 618
 617   IP=IQ
       IN=-IN
 618   CONTINUE
       SOM=0.0
       FACT=1.0
       DO620 J=1,NPTS
       SOM=SOM+FACT*FN(1)
       DO619 I=J,NPTS
       IQ=I-J+1
 619   FN(IQ)=(FN(IQ+1)-FN(IQ))/(XN(I+1)-XN(IQ))
 620   FACT=FACT*(VAR-XN(J))
       RETURN
       END
$IBFTC CHAR
C      SUBROUTINE CHAR (CHAR CONDUCTIVITY VS. TEMPERATURE----SLOPE AND INTERCEPT)
       SUBROUTINE CHAR (XCOND,YCOND,MDATA,SLOPE,YINTCP)
       DIMENSION XCOND(50),YCOND(50)
            SUMX=0.0
            SUMY=0.0
            SUMXY=0.0
            SUMX2=0.0
            SUMY2=0.0
       TN=MDATA
       DO710 J=1,MDATA
            SUMX=SUMX+XCOND(J)
            SUMY=SUMY+YCOND(J)
            SUMXY=SUMXY+XCOND(J)*YCOND(J)
            SUMX2=SUMX2+XCOND(J)**2.0
            SUMY2=SUMY2+YCOND(J)**2.0
 710   CONTINUE
 720        SLOPE=(SUMXY-(SUMX*SUMY/TN))/(SUMX2-(SUMX**2.0/TN))
 730       YINTCP=(SUMY-(SLOPE*SUMX))/TN
       RETURN
       END
$ENTRY
```

INPUT DATA

T(1)	DT(1)	TL	HI	ZL	R	W	EPS	DELT
500.0	24170.8	2000.0	.000208	0.0208	1.987	0.05	0.8	50.0

NDATA	MDATA	K
34	9	5

XTKE(I)	ZOMGA(I)
0.30	2.785
0.35	2.628
0.40	2.492
0.45	2.368
0.50	2.257
0.55	2.156
0.60	2.065
0.65	1.982
0.70	1.908
0.75	[illegible]

0.80	1.780
0.85	1.725
0.90	1.675
0.95	1.629
1.00	1.587
1.10	1.514
1.20	1.452
1.30	1.399
1.50	1.314
1.70	1.248
1.90	1.197
2.2	1.138
2.6	1.081
3.2	1.022
4.0	0.9700
5.0	0.9269
7.0	0.8727
10.0	0.8242
20.0	0.7432
40.0	0.6718
70.0	0.6194
100.0	0.5882
200.0	0.5320
400.0	0.4811

EK(I)	SIG(I)	FW(I)	Y(I)
110.0	3.590	28.0	0.245
190.0	3.996	44.0	0.046
91.5	3.681	28.0	0.073
136.5	3.822	16.0	0.570
440.0	5.270	78.0	0.068

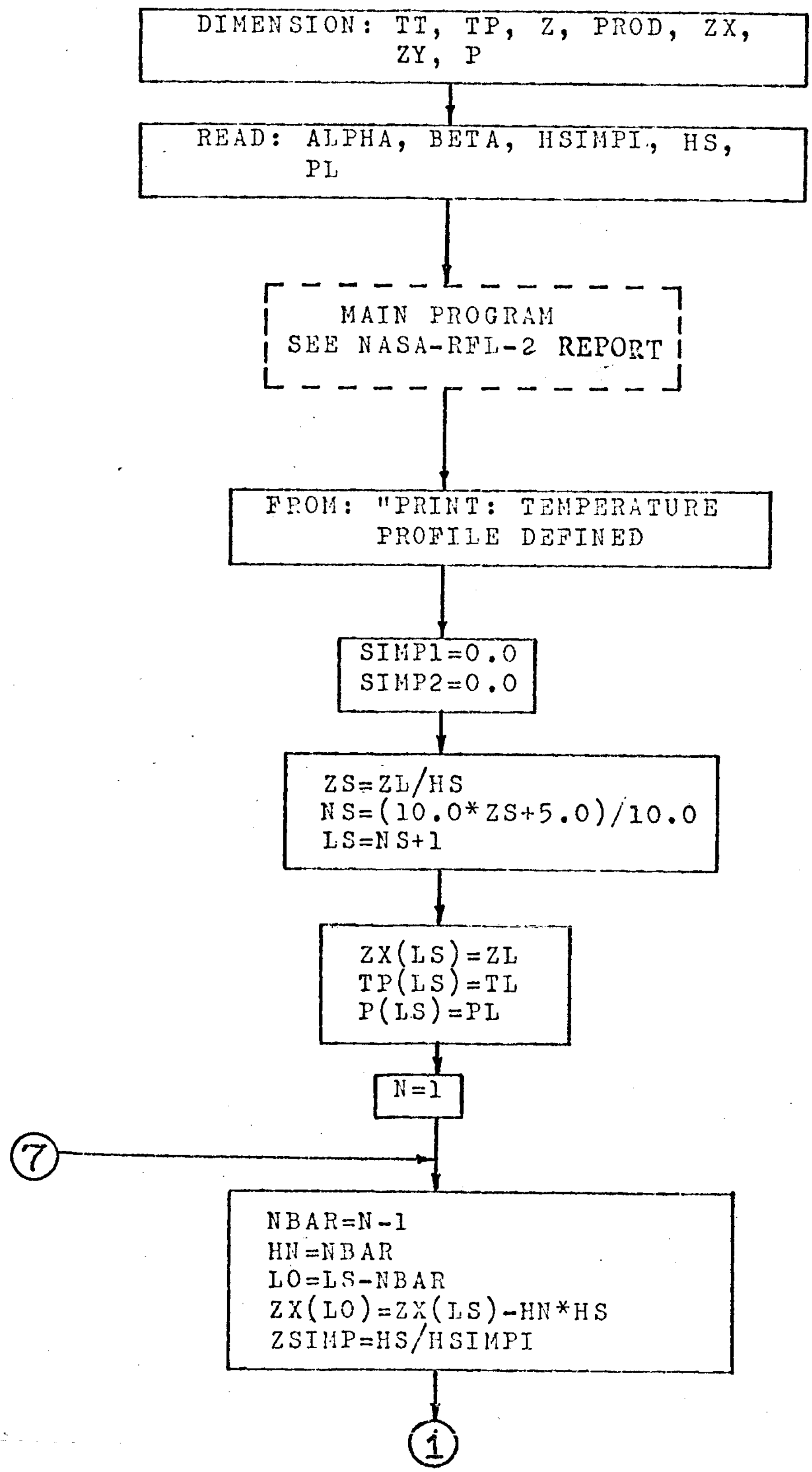
A(I)	B(I)	C(I)	D(I)
672600E+00	004001E-02	12830E-05	-53070E-09
531600E+00	142850E-02	-83620E-05	178400E-09
690300E+00	-03753E-02	19300E-05	-68610E-09
475000E+00	120000E-02	30300E-05	-263000E-09
-865000E+00	1157800E-02	-754000E-05	1854000E-09

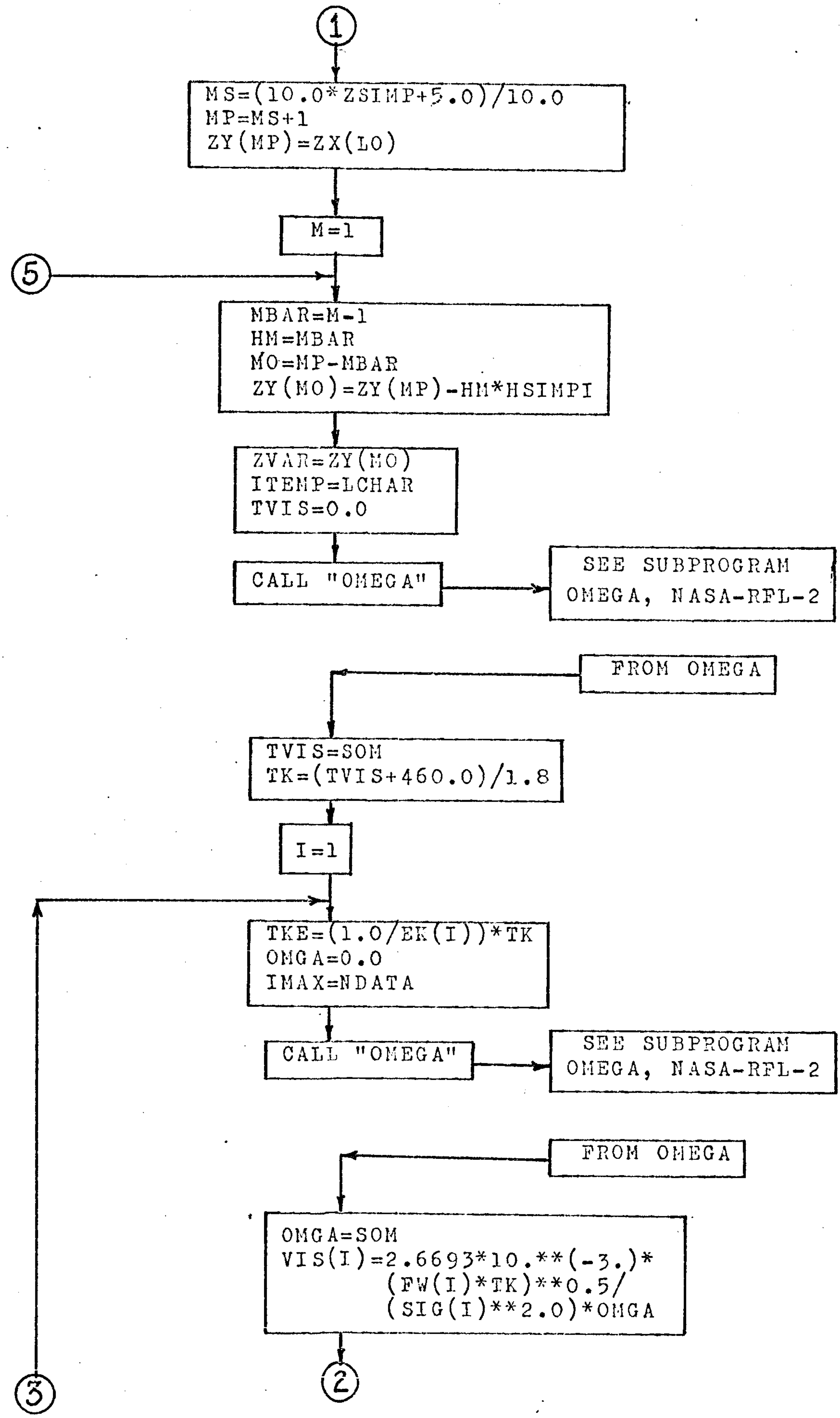
XCOND(I)	YCOND(I)
698.0	244000E-03
909.0	298000E-03
1001.0	356000E-03
1073.0	356000E-03
1346.0	451000E-03
1515.0	447000E-03
1709.0	575000E-03
1848.0	559000E-03
1998.0	616000E-03

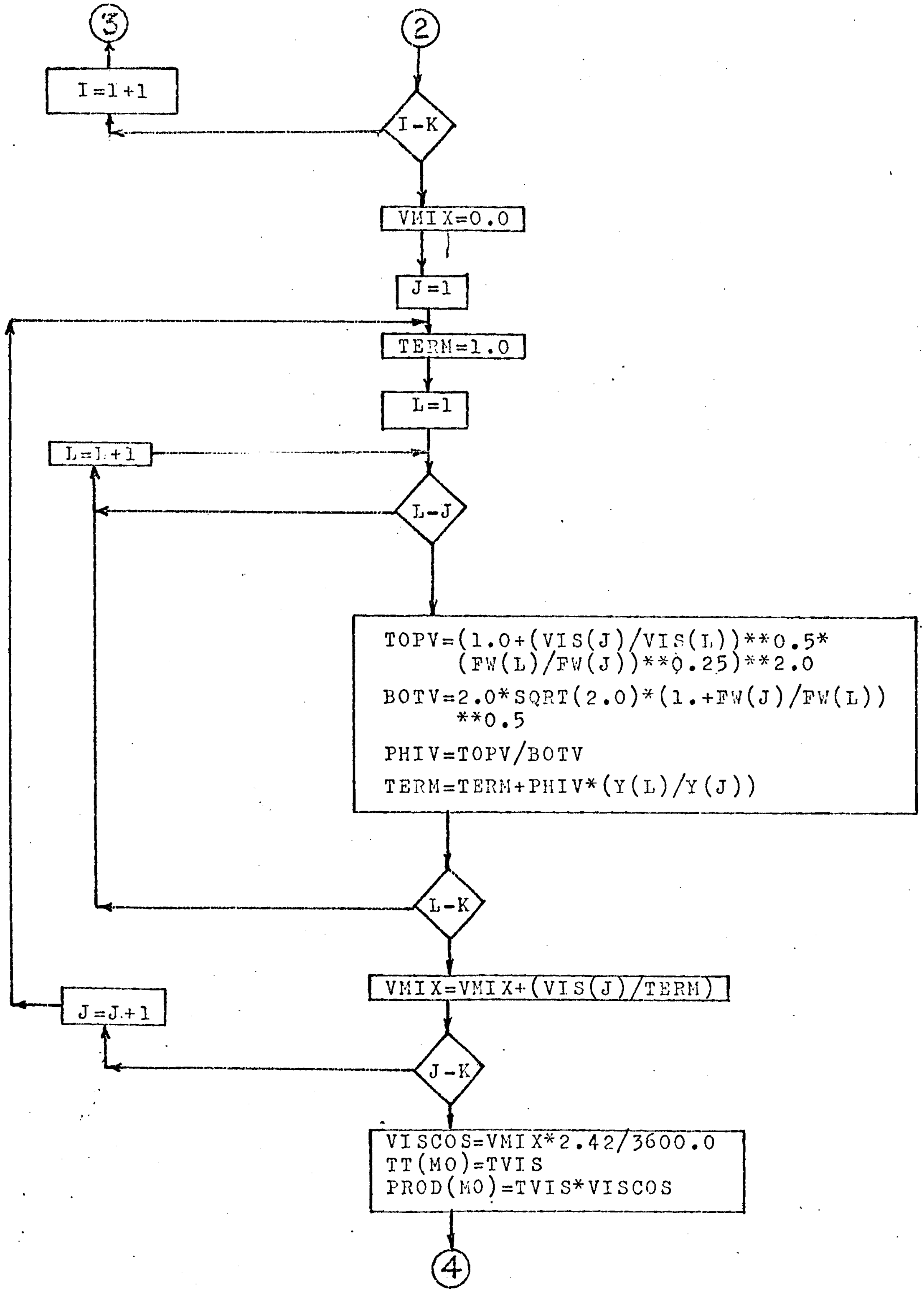
ALPHA	BETA	HSIMPI	HS	PL
050000E+09	050000E+05	0.0000208	0.00208	2160.0

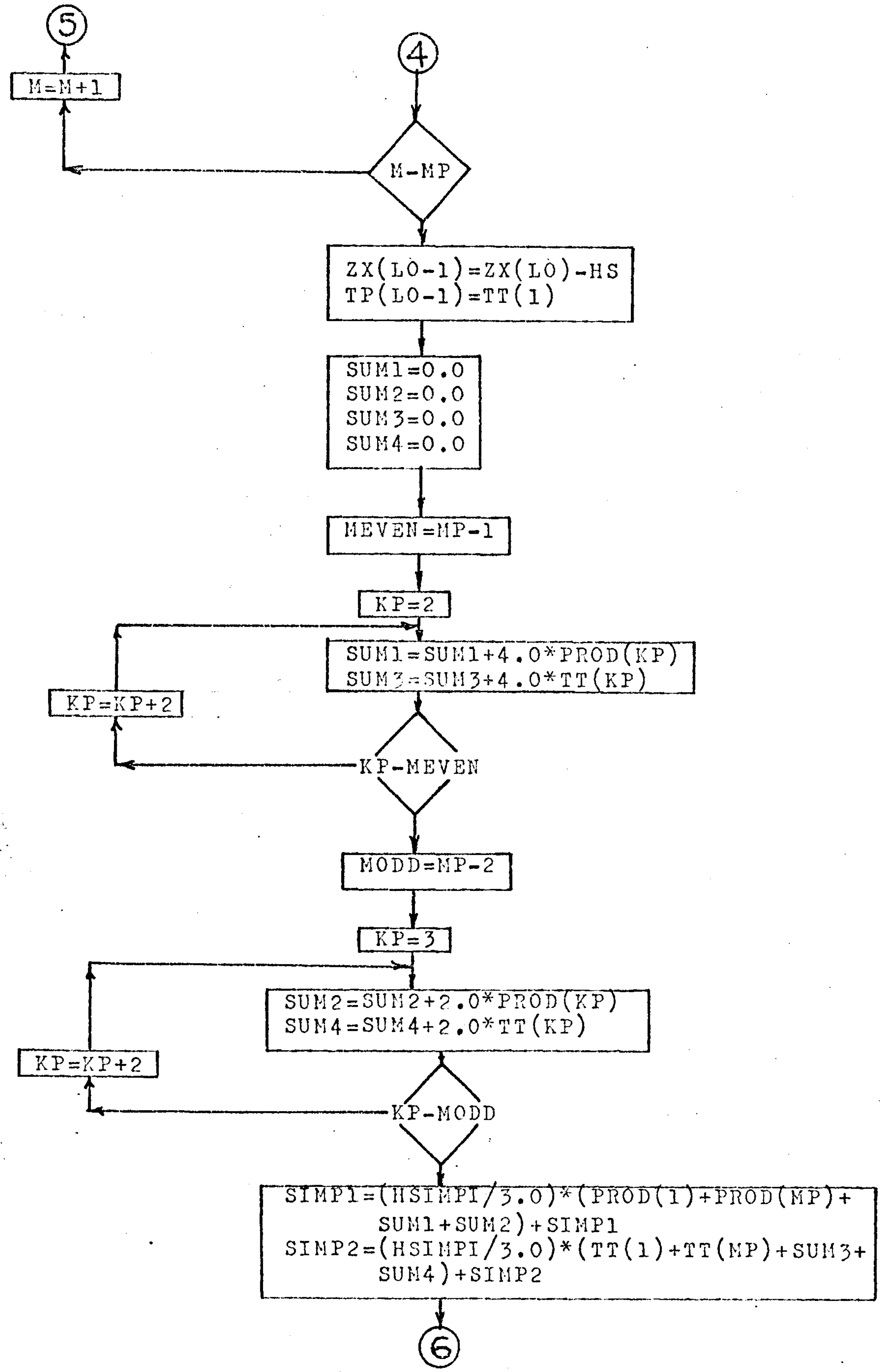
$STOP

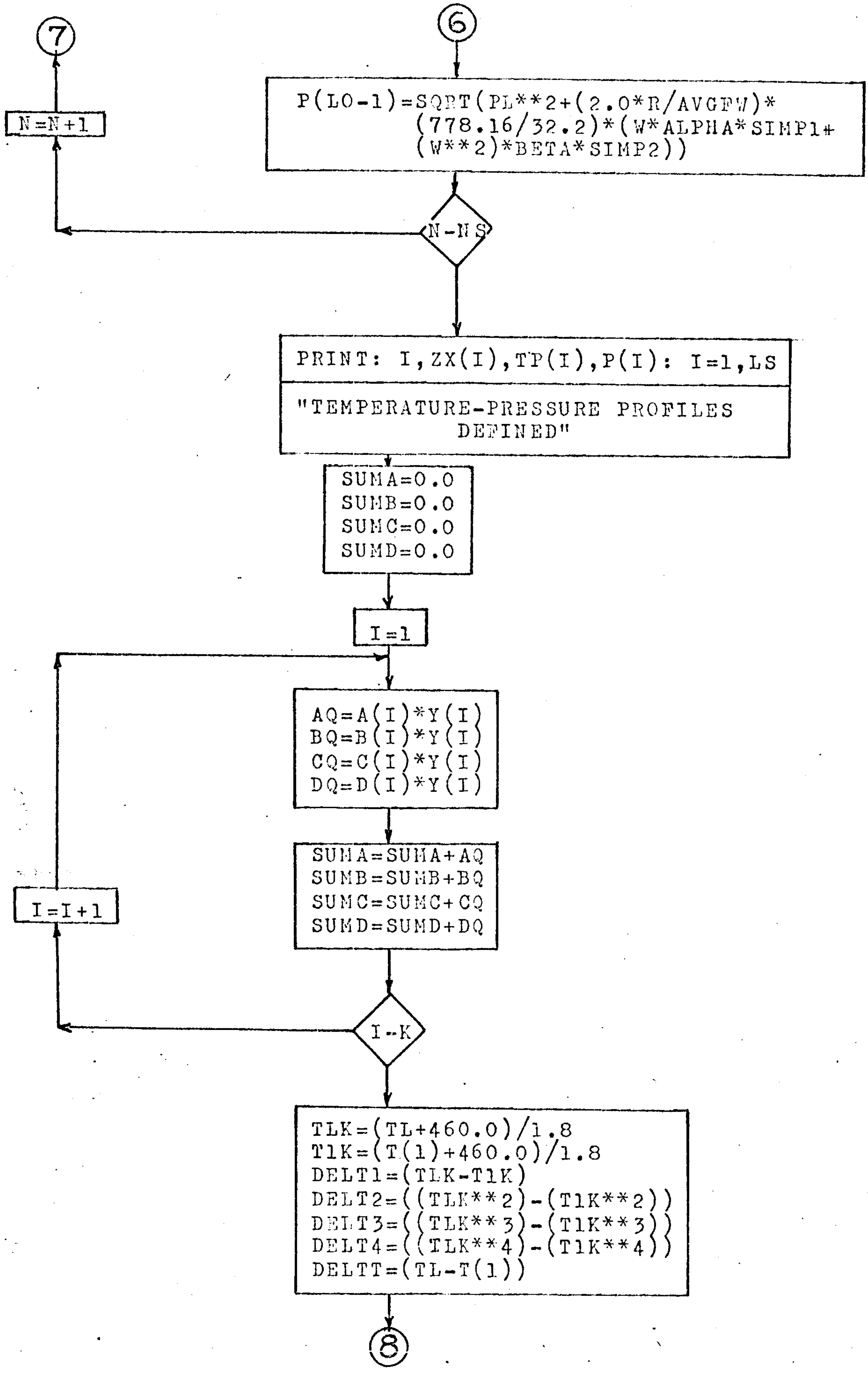
SUPPLEMENTARY FLOW DIAGRAM FOR
DETERMINING THE PRESSURE PROFILE
AND HEAT FLUX ACROSS THE
CHAR ZONE OF A CHARRING ABLATOR

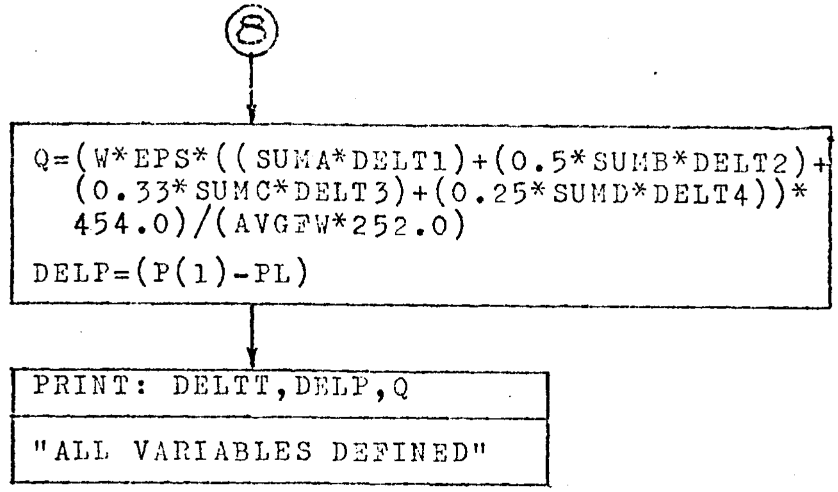



1
MS=(10.0*ZSIMP+5.0)/10.0
MP=MS+1
ZY(MP)=ZX(LO)
M=1
5
MBAR=M-1
HM=MBAR
MO=MP-MBAR
ZY(MO)=ZY(MP)-HM*HSIMPI
ZVAR=ZY(MO)
ITEMP=LCHAR
TVIS=0.0
CALL "OMEGA"
SEE SUBPROGRAM OMEGA, NASA-RFL-2
FROM OMEGA
TVIS=SOM
TK=(TVIS+460.0)/1.8
I=1
TKE=(1.0/EK(I))*TK
OMGA=0.0
IMAX=NDATA
CALL "OMEGA"
SEE SUBPROGRAM OMEGA, NASA-RFL-2
FROM OMEGA
OMGA=SOM
VIS(I)=2.6693*10.**(-3.)*
(FW(I)*TK)**0.5/
(SIG(I)**2.0)*OMGA
2
3


3
2
I=I+1
I-K
VMIX=0.0
J=1
TERM=1.0
L=1
L=L+1
L-J
TOPV=(1.0+(VIS(J)/VIS(L))**0.5*
(FW(L)/FW(J))**0.25)**2.0
BOTV=2.0*SQRT(2.0)*(1.+FW(J)/FW(L))
**0.5
PHIV=TOPV/BOTV
TERM=TERM+PHIV*(Y(L)/Y(J))
L-K
VMIX=VMIX+(VIS(J)/TERM)
J=J+1
J-K
VISCOS=VMIX*2.42/3600.0
TT(MO)=TVIS
PROD(MO)=TVIS*VISCOS
4


5
M=M+1
4
M-MP
ZX(LO-1)=ZX(LO)-HS
TP(LO-1)=TT(1)
SUM1=0.0
SUM2=0.0
SUM3=0.0
SUM4=0.0
MEVEN=MP-1
KP=2
SUM1=SUM1+4.0*PROD(KP)
SUM3=SUM3+4.0*TT(KP)
KP=KP+2
KP-MEVEN
MODD=MP-2
KP=3
SUM2=SUM2+2.0*PROD(KP)
SUM4=SUM4+2.0*TT(KP)
KP=KP+2
KP-MODD
SIMP1=(HSIMPI/3.0)*(PROD(1)+PROD(MP)+
SUM1+SUM2)+SIMP1
SIMP2=(HSIMPI/3.0)*(TT(1)+TT(MP)+SUM3+
SUM4)+SIMP2
6


6
7
N=N+1
P(LO-1)=SQRT(PL**2+(2.0*R/AVGFW)*
(778.16/32.2)*(W*ALPHA*SIMP1+
(W**2)*BETA*SIMP2))
N-NS
PRINT: I,ZX(I),TP(I),P(I): I=1,LS
"TEMPERATURE-PRESSURE PROFILES DEFINED"
SUMA=0.0
SUMB=0.0
SUMC=0.0
SUMD=0.0
I=1
AQ=A(I)*Y(I)
BQ=B(I)*Y(I)
CQ=C(I)*Y(I)
DQ=D(I)*Y(I)
SUMA=SUMA+AQ
SUMB=SUMB+BQ
SUMC=SUMC+CQ
SUMD=SUMD+DQ
I=I+1
I-K
TLK=(TL+460.0)/1.8
T1K=(T(1)+460.0)/1.8
DELT1=(TLK-T1K)
DELT2=((TLK**2)-(T1K**2))
DELT3=((TLK**3)-(T1K**3))
DELT4=((TLK**4)-(T1K**4))
DELTT=(TL-T(1))
8


8
Q=(W*EPS*((SUMA*DELT1)+(0.5*SUMB*DELT2)+(0.33*SUMC*DELT3)+(0.25*SUMD*DELT4))*454.0)/(AVGFW*252.0)
DELP=(P(1)-PL)
PRINT: DELTT,DELP,Q
"ALL VARIABLES DEFINED"

Section (2)

Programs for the Evaluation of α and β from Experimental Data

(a) Determination of x-y coordinates of Equation (5)

(b) Least Squares Fit of the Experimental Data for the Determination of α and β

DETERMINATION OF X-Y COORDINATES OF EQUATION (5)

Nomenclature

	Input Data	Units
NO	Number of Test gases used	--
MO	Number of tests per gas component	--
MT	Total number of tests	--
DIA	Char diameter	inches
R	Perfect gas constant	ft^3-lb_F/ft^2-lbmole-^oR
T	Temperature	^oR
ZL	Char thickness	inches
RHO	Gas density	lb/ft^3
VIS	Gas viscosity	cp
FW	Gas molecular weight	lb/lbmoles
DELTP	Pressure drop across char	in. of H_2O
PMEAN	Mean pressure of the system	in. of H_2O
VEL	Gas velocity	cm^3/sec

	Output Data	
XAXIS	$(W/\bar{\mu})$ term in equation (5)	1/ft
YAXIS	$(F_w \Delta (P^2))/2W\bar{\mu}RTL$ term in Equation (5)	$1/ft^2$

```
$CATE           C7/1C/66
$CLCSE          S.SPP1
$JCB            APRIL
$IBJCB          NCDECK
$RELCAD         UC4,SRCH,NAME=WATFOR
C       GARY C. APRIL    NASA 135-30-8621
C       PRCGRAM TC CETERMINE PERMEABILITY AND INERTIAL CCEFFICIENTS
        CIMENSICN RHC(3C),VIS(3C),FW(30),DELTP(300),PMEAN(3CO),VEL(300),
      1   XAXIS(1C,30C),YAXIS(1C,300)
        REAC5,NC,MC,MT
        REAC 10,CIA,R,T
        REAC 2C,ZL
        REAC3C,(RHC(I),VIS(I),FW(I),I=1,NC)
        REAC4C,(CELTP(I),PMEAN(I),VEL(I),I=1,MT)
   5    FCRMAT (3I1C)
  1C    FCRMAT(3F1C.0)
  2C    FCRMAT(F1C.0)
  3C    FCRMAT(3F1C.0)
  4C    FCRMAT(3F1C.0)
        MI=1
        CC1C1 N=1,NC
        GC TC (6C,65),N
  6C    PRINT 61
  61    FCRMAT(1HC,6HHELIUM)
        GC TC 8C
  65    PRINT 66
  66    FCRMAT (1HC,8HNITROGEN)
  8C    CC1CC M=MI,MO
        AREA=3.1416*(DIA*2.54)**2.C/4.C
        W=VEL(M)*RHC(N)/(AREA*3C.48)
        P1=PMEAN(M)-0.5*CELTP(M)
        P2=CELTP(M)+P1
        P1SC=P1**2
        P2SC=P2**2
        PCCNV=(144.C/(12.C*2.311))**2.C
        CELP2=(P2SC-P1SQ)*PCCNV
        YCCNV=36CC.0*32.2*12.C/2.42
        YAXIS(N,M)=(FW(N)*CELP2/(ZL*W*VIS(N)*R*T*2.0))*YCCNV
        XCCNV=36CC.0/2.42
        XAXIS(N,M)=(W/VIS(N))*XCCNV
        PRINT 5C,XAXIS(N,M),YAXIS(N,M)
  5C    FCRMAT(1HC,11HXAXIS(N,M)=,E15.5,8X,11HYAXIS(N,M)=,E15.5)
  1CC   CCNTINUE
        MI=MC+1
        MC=MT
  1C1   CCNTINUE
        STCP
        ENC
$ENTRY
```

NC	MC	MT
2	8	16

DIA	R	T
0.75	1545.12	530.0

ZL
0.273

RHO	VIS	FW
0.01114	0.019	4.0
0.0780	0.019	28.0

DELTP	PMEAN	VEL
1.35	407.48	109.91
1.35	407.50	113.63
2.60	408.10	202.26
2.75	408.18	207.00
1.50	407.55	122.90
1.65	407.53	132.82
2.60	408.10	200.55
2.70	408.15	205.20
1.35	407.48	79.90
1.40	407.50	82.13
2.65	408.13	129.89
2.70	408.15	133.82
1.65	407.63	96.05
1.65	407.63	89.16
2.65	408.13	131.83
2.70	408.15	134.84

$STOP

LEAST SQUARES FIT OF THE EXPERIMENTAL DATA FOR THE DETERMINATION OF α AND β

Nomenclature

	Input Data	Units
N	Number of data points	--
X	$(W/\bar{\mu})$ term of Equation (5)	1/ft
Y	$(F_w \Delta(P^2))/2W\bar{\mu}RTL$ term of Equation (5)	$1/ft^2$
	Output Data	
A	Value of β, slope of Equation (5)	1/ft
B	Value of α, y-intercept of Equation (5)	$1/ft^2$
R2	Correlation coefficient	--
SYEST	Standard deviation of Y estimated from the regression equation	$1/ft^2$

```
C       GARY C. APRIL
C       NASA PROJECT NO. 135-30-8621
C       LEAST SQUARES FIT - REGRESSION CORRELATION OF DATA - TWO VARIABLES
        DIMENSIONX(500),Y(500)
        READ2,N
  2     FORMAT (I2)
        READ4,(X(J),Y(J),J=1,N)
  4     FORMAT (F15.0, E15.5)
        SUMX=0.0
        SUMY=0.0
        SUMXY=0.0
        SUMX2=0.0
        SUMY2=0.0
        TN=N
C       REGRESSION EQUATION (Y=AX+B)
  5     DO10 J=1,N
        SUMX=SUMX+X(J)
        SUMY=SUMY+Y(J)
        SUMXY=SUMXY+X(J)*Y(J)
        SUMX2=SUMX2+X(J)**2.0
        SUMY2=SUMY2+Y(J)**2.0
  10    CONTINUE
        PRINT 70, SUMX,SUMY,SUMXY,SUMX2,SUMY2
  70    FORMAT (1X,5E15.8)
  20    A=(SUMXY-(SUMX*SUMY/TN))/(SUMX2-(SUMX**2.0/TN))
  30    B=(SUMY-(A*SUMX))/TN
C       CORRELATION COEFFICIENT(R2)
  40    R2=(SUMXY-(SUMX*SUMY/TN))*A/(SUMY2-(SUMY**2.0/TN))
C       STANDARD DEVIATION OF Y ESTIMATED FROM REGRESSION EQUATION (SYEST)
  50    SYEST=SQRT((SUMX2-(SUMX**2.0/TN))*(1.0-R2)/(TN-2.0))
        PRINT60,A,B,R2,SYEST
  60    FORMAT (1X,4E15.8)
        STOP
        END
$ENTRY
```

N

16

X	Y
1103.5	0.56965E+09
1140.8	0.55102E+09
2030.6	0.59708E+09
2078.2	0.61719E+09
1233.9	0.56614E+09
1333.5	0.57621E+09
2013.5	0.60217E+09
2060.2	0.61124E+09
5616.7	0.78340E+09
5773.4	0.79040E+09
9130.8	0.94746E+09
9407.0	0.93703E+09
6752.0	0.79679E+09
6267.6	0.85836E+09
9267.2	0.93352E+09
9478.7	0.92994E+09

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