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INTERNAL PRESSURES OF A SPACECRAFT OR OTHER SYSTEM OF COMPARTMENTS, CONNECTED IN VARIOUS WAYS AND INCLUDING OUTGASSING MATERIALS, IN A TIME-VARYING PRESSURE ENVIRONMENT

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PROJECT STATUS

This report describes a method for calculating the pressure versus time inside each of a system of volumes containing outgassing materials.

Authorization

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SUMMARY

A method of calculating the pressure profile for each compartment of a multi-compartment system such as a spacecraft is presented. The method is applicable to volumes connected in series or in parallel or both by passages of various sizes and geometries, where each volume may include several materials outgassing according to known or assumed characteristics. The entire system is exposed to a time-varying pressure environment.

An appropriate set of differential equations with variable coefficients is derived, which may be solved by computer to provide pressure profiles for each compartment. The profiles obtained are the result of viscous, intermediate, and molecular flow regimes experienced under appropriate conditions in the system of volumes and passages. Several computations which have been made are presented and compared to experimental results. Pressure profiles for volumes with various outgassing materials and various orifice sizes have been calculated and are grouped according to the molecular flow regime time constants and the outgassing characteristics of the material. From these parametric plots, the quasi-steady pressure in a volume containing outgassing materials can be estimated.

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SYMBOLS

A_i	- Surface area in volume i or passage area	(cm^2)
A_G	- Surface area of outgassing material	(cm^2)
C_{ij}	- Conductance through passage from chamber i to chamber j	$(1 \cdot sec^{-1})$
D	- Diameter	(cm)
E	- Total internal energy	(cal)
$G_i = \sum_n Q_{Gni}$	- Outgassing flow rate in volume i (From all materials n contained in Volume i)	$(torr \cdot 1 \cdot sec^{-1})$
H	- Total enthalpy	(cal)
J	- Tabular value for intermediate flow	
K	- Tabular value of molecular flow in annular section	
K_n	- Knudsen's number $\left(\frac{\lambda}{D}\right)$	(dimensionless)
L	- Length	(cm)
L_{ij}	- Leakage conductance between chambers i and j	$(1 \cdot sec^{-1})$
M	- Molecular weight of gas	(grm)
P_0	- External pressure	(torr)
P_i	- Absolute pressure in volume $i = 1, 2, 3, \ldots n$	(torr)
P_L	- Quasi-static pressure	(torr)
$\bar{P}$	- Average pressure	(torr)

Q_{ij}	- Flow rate through passage from chamber i to chamber j	$(\text{torr} \cdot 1 \cdot \text{sec}^{-1})$
Q_{Lij}	- Leakage flow rate into chamber i from chamber j	$(\text{torr} \cdot 1 \cdot \text{sec}^{-1})$
Q_G	- Outgassing rate of surface material after 1 hour vacuum exposure	$(\text{torr} \cdot 1 \cdot \text{sec}^{-1}\ \text{cm}^{-2})$
R	- Gas constant	$(62.36\ \text{torr} \cdot 1 \cdot \text{gram}^{-1}\ \text{mole}\ {}^{\circ}\text{K}^{-1})$
R_e	- Reynold's number $\left(\frac{U\rho D}{\mu}\right)$	(dimensionless)
S	- Pumping Speed	$(1 \cdot \text{sec}^{-1})$
T	- Temperature	(°K)
U	- Velocity of gas	$(\text{cm} \cdot \text{sec}^{-1})$
V_i	- Volume of chamber i	(1)
Y	- Tabular value for viscous flow in rectangular ducts	
a	- Passage dimension	(cm)
b	- Passage dimension	(cm)
h	- Heat transport coefficient	$(\text{cal sec}^{-1}\ \text{cm}^{-2}\ {}^{\circ}\text{K}^{-1})$
k	- Thermal conductivity	$(\text{cal cm sec}^{-1}\ \text{cm}^{-2}\ {}^{\circ}\text{K}^{-1})$
m_{ij}	- Mass flow rate through passage from chamber i to chamber j	(grm sec^{-1})
q_{nio}	- Initial outgassing rate per unit area from surface material n in chamber i	$(\text{torr} \cdot 1 \cdot \text{cm}^{-2} \cdot \text{sec}^{-1})$
q_{nif}	- Final outgassing rate per unit area from surface material n in volume i	$(\text{torr} \cdot 1 \cdot \text{cm}^{-2} \cdot \text{sec}^{-1})$

t	- Time	(sec)
$u = \frac{p_j}{p_i} \le 1$	- Pressure ratio across an aperture	
α	- Tabular value for molecular flow in rectangular ducts	
$\gamma = \frac{C_p}{C_v}$	- Specific heat ratio	(dimensionless)
η	- Ratio of viscosity of air @ 15°C to that of a given gas at the same temperature	
λ	- Mean free path	(cm)
μ	- Viscosity of gas	(grm sec^{-1} cm^{-2})
ρ	- Density of gas	(grm cm^{-3})
τ	- Time constant	(sec)
τ_{in}	- Time constant for surface material n in volume i	(sec)

INTERNAL PRESSURES OF A SPACECRAFT OR OTHER SYSTEM OF COMPARTMENTS, CONNECTED IN VARIOUS WAYS AND INCLUDING OUTGASSING MATERIALS, IN A TIME-VARYING PRESSURE ENVIRONMENT

INTRODUCTION

Many spacecraft failures have been attributed by inference, to improper pressure conditions (Refs. 1 and 2). For example, electrical voltage breakdown has occurred many times during spacecraft testing or during flight. In some cases it has occurred only during flight with systems which under testing appeared to be free of this type of problem (Refs. 2 and 3). This breakdown occurs when the ambient gas attains its critical pressure, which is a function of the nature of the gas species, the type of electrodes used and the distance between them, number of charged particles present, and the magnitude of the electric fields. In addition to this difficult problem, some of the other malfunctions and problems dependent on pressure conditions are:

- Loss of pressure in sealed components.
- Loss of lubrication due to evaporation or sublimation.
- Deterioration of adhesives such as loss of plasticizer due to evaporation or sublimation.
- Loss of convective heat transfer with resultant development of hot spots or cold spots.
- Loss of dielectric resistance followed by corona discharge or arcing.
- Fouling of terminals following condensation of outgassed material.
- Loss of system calibration resulting from unavailability of convective heat transfer at the existing pressure.
- Humidity, aerodynamic performance, radiation and ionization effects, electronic bombardment, etc.
- Pressure difference across surfaces sufficient to cause mechanical failure.

Many of the problems listed above can be eliminated or minimized by the use of pressurized containers, coatings, selective insulation, encapsulation, shielding, etc. (Refs. 3 and 4). Also, in many cases possible difficulties can be avoided expediently by employing selective commands for the experiment; e.g., operation of the system at a limited voltage can be commanded for unfavorable pressure conditions, with full voltage operation at favorable pressure. Of course, it is hoped that those problems related to pressure conditions, as well as any other malfunction, will be discovered and eliminated during the thermal-vacuum testing of the spacecraft. These tests attempt to simulate the temperature and pressure encountered during launch and orbit flight. Chamber pressures below 10^{-6} torr are produced to establish the appropriate mode of heat transfer and hence provide simulation of the thermal environment. In testing, it is assumed that after long term vacuum exposure the pressure at any point in the spacecraft will be comparable to that produced and measured in the chamber itself. But this cannot generally be verified, due to the absence of pressure instrumentation at inaccessible internal locations and due to the fact that many materials in the pressure range 10^{-5} to 10^{-9} torr expel adsorbed and absorbed gases. The latter as well as other gases produced by evaporation, distillation and decomposition, affect the pressure considerably. These "outgassing" conditions are likely to exist for a long time and set up, at certain locations of the spacecraft, pressures higher than the chamber pressure (unbeknown to the experimenter). In addition, the transient pressures at the launch phase of the flight may produce pressure differentials depending on flow conductance, which cannot be reproduced during testing. Such differentials could establish conditions conducive to failures or temporary malfunctions.

In view of the above, it is the intent of this report to provide an analytical tool which can be used to estimate the variation with time of pressures in a spacecraft or other system of interconnected volumes. Knowledge of these pressures, which will permit undesirable pressure conditions to be identified, should be useful not only in connection with the qualification and reliability testing of the spacecraft, but also in determining the appropriate time for certain spacecraft operations. It is expected that the accuracy of the mathematical results will depend on the extent of knowledge of geometric leakage paths, container volumes, and material behavior. Many uses of this analytical tool will be indicated later.

In general, the analytical tool must provide a description of the internal pressure vs time for each compartment of a system of compartments arranged in a most general way, and connected by passages of different types. The following data must be given or assumed in order to carry out the calculation:

- External pressure vs time under flight conditions, or the chamber pressure during testing.

- Type of ambient gas contained in the system.

- Temperatures of ambient gas and of internal surfaces.
- Volume of compartments.
- Surface areas of compartments and of components within the compartments.
- Characteristics of the surface areas, i.e. the initial and final outgassing rates, and the outgassing time constant for each outgassing material.
- Areas, dimensions and types of passages and leakage paths between compartments.

ANALYTICAL MODEL

Figure 1 shows a model of volumes and connecting passages chosen so as to represent the general case of a system of interconnected compartments. The

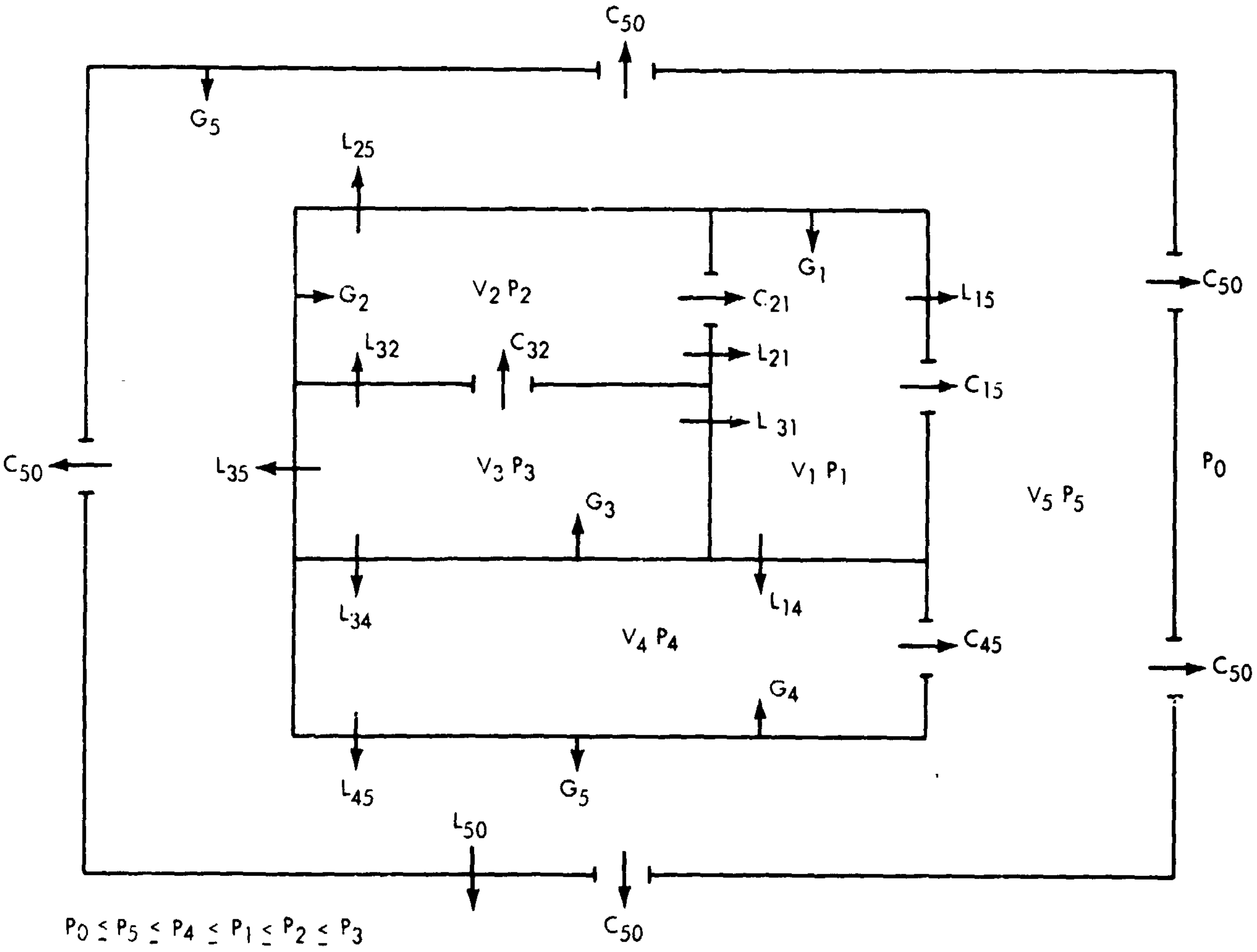


Figure 1–Arrangement of Volumes and Passages Used as a Model for the Derivation of Flow Equations

flow equations derived for the model are intended to provide a flow description for any system. The model is arranged so as to provide both series and parallel flow through main passages, leakages between chambers, and outgassing from different surfaces. The arrows in the figure show the reference flow directions, corresponding to the relative magnitudes assumed for the chamber pressures. The actual flow direction will be dictated by the actual pressure in each chamber, which will be a function of the system parameters. Outgassing from surfaces is shown by arrows originating at the separation walls.

Pressure-Time History Equations

Equating the change of mass of a gas stored in a volume V to the difference of the masses of gas entering and leaving that volume in time dt gives

$$V\, d\rho = (m_{in} - m_{out})\, dt \;.$$

Since the change in density, according to the equation of state, is

$$d\rho = \frac{dP}{RT} ,$$

substitution yields

$$V \frac{dP}{dt} = RT\,(m_{in} - m_{out}) \;.$$

The flow rate, Q, may be defined in terms of a conductance, C, and the pressure differential, ΔP, as

$$Q = C\Delta P = RTm ,$$

so that the above isothermal equation of mass balance becomes:

$$V \frac{dP}{dt} = C_{in} \Delta P - C_0 \Delta P .$$

One can add to the right side of this equation the sources G_i, representing the outgassing from the surfaces within volume i. This outgassing, as will be discussed later, is independent of pressure but depends on temperature and on the nature of the outgassing materials in the chamber. The basic equation for the pressure history in a volume then becomes

$$V \frac{dP}{dt} = C_{in} \Delta P - C_0 \Delta P + G_i . \tag{1}$$

Applying this equation to each of the volume of Figure 1 in turn, for an assumed monotonic sequence of pressures

$$P_0 \leq P_5 \leq P_4 \leq P_1 \leq P_2 \leq P_3 ,$$

one obtains:

$$\dot{P}_1 = \frac{1}{V_1} [(C_{21} + L_{21}) (P_2 - P_1) + L_{31} (P_3 - P_1)$$

$$- (C_{15} + L_{15}) (P_1 - P_5) - L_{14} (P_1 - P_4) + G_1] ,$$

$$\dot{P}_2 = \frac{1}{V_2} [(C_{32} + L_{32}) (P_3 - P_2) - (C_{21} + L_{21}) (P_2 - P_1) - L_{25} (P_2 - P_5) + G_2] ,$$

$$\dot{P}_3 = \frac{1}{V_3} [- (C_{32} + L_{32}) (P_3 - P_2) - L_{31} (P_3 - P_1)$$

$$- L_{34} (P_3 - P_4) - L_{35} (P_3 - P_5) + G_3] ,$$

$$\dot{P}_4 = \frac{1}{V_4} [L_{34} (P_3 - P_4) + L_{14} (P_1 - P_4)$$

$$- (C_{45} + L_{45}) (P_4 - P_5) + G_4] ,$$

$$\dot{P}_5 = \frac{1}{V_5} [(C_{15} + L_{15}) (P_1 - P_5) + L_{25} (P_2 - P_5)$$

$$+ L_{35} (P_3 - P_5) + (L_{45} + C_{45}) (P_4 - P_5)$$

$$- (C_{50} + L_{50}) (P_5 - P_0) + G_5] .$$

For a given P_i (t), the above equations can be generalized as follows to describe the rate of pressure change in the i^{th} chamber of an N chamber arrangement:

$$\dot{P}_i = \frac{1}{V_i} \left[G_i + \sum_{j=0}^{N} (C_{ij} + L_{ij}) (P_j - P_i) \right] , \tag{2}$$

where

$$i = 1, 2, 3, \ldots, N; \; G_i = \sum_n Q_{Gni}; \; C_{ij} = C_{ji} \text{ and } L_{ij} = L_{ji} \cdot$$

(The sum in

$$\sum_n Q_{Gni}$$

is over all the different outgassing materials n contained in volume i.) The symmetry conditions for the conductances are valid in the molecular flow regime but not always in the viscous flow regime (Refs. 5 and 6).

The sign of ($P_j - P_i$) determines the direction of flow between chamber i and chamber j. For the fictitious chamber arrangement shown in Figure 1, matrices could be used to provide the passage and leakage conductances. Any other chamber arrangement could also be described by equations (2) and the appropriate conductance matrices.

A solution of equations (2), given the initial chamber pressures, the conductances, the environment pressure as a function of time, and the outgassing data, will provide the pressure-time history in each chamber of such an arrangement. The functional forms of the conductances, outgassing functions, and external pressure forcing functions will be described next.

Conductances

The conductance of a passage is defined as the rate of flow of gas through the passage per unit of pressure difference producing the flow:

$$C_{ij} = \frac{Q_{ij}}{P_i - P_j} . \tag{3}$$

The conductance is a function of the geometry of the passages, the temperature, and the molecular weight of the gas flowing. It is also a function of the pressure and viscosity of the gas depending on the flow regime.

The characteristics that govern the flow regime of the fluid are the Reynolds number, $R_e = U\rho D/\mu$, which relates the inertial force to the viscous force, and the Knudsen number, $K_n = \lambda/D$, which relates the mean free path of the gas to a characteristic dimension of the container (Refs. 5-7).

For $R_e > 2300$, the inertial force prevails over the viscous force, except for a narrow region adjacent to the walls, and the flow is turbulent. During evacuation, turbulent flow can occur near atmospheric pressure for a very short period. It is experienced when high capacity displacement pumps evacuate the system through improperly sized, long, small diameter passages (Refs. 6-9). This type of flow will not be included here because of its short duration, and (mainly) because of the difficulties it entails.

For $R_e < 2300$, the viscous force prevails and the flow is viscous or laminar.

The conductances employed here are appropriate for the three types of flow which occur at low pressure: viscous, slip-intermediate, and free molecular flow. The parameter which differentiates these regimes is the Knudsen number. This number, which can be also expressed as the ratio of the Mach number to the Reynold's number (Ref. 10), compares the mean free path of the molecules to a characteristic dimension of the container. It indicates whether the molecules are colliding with each other or with the wall of the container. The following criteria can be used to distinguish the flow regimes (Ref. 11):

- For $K_n < 10^{-2}$, the flow is governed by collisions of the molecules with each other and is viscous.
- For $10^{-2} < K_n < 10$, the flow is an intermediate type characterized by collisions of the molecules with each other and also with the container wall.
- For $K_n > 10$, the molecules are colliding with the confining wall and the flow is of the free molecular type.

From the formulae for the conductances given below, it will be seen that the molecular conductances are independent of pressure. This is because the flow is a random motion of the molecules. The intermediate flow is a combination of the viscous and the molecular types of flow. The flow changes from completely viscous at high pressure, where a zero relative velocity between fluid and wall exists, to a transition flow with a relative velocity at the wall. At lower pressures, the flow becomes a free molecular flow. Conductances for free molecular flow are modified by an experimental coefficient to account for the transition flow region.

Formulae for conductance of several geometrical arrangements are found in the literature (Refs. 5-9, 11-13). The list which follows includes the most common conductances, taken, for convenience of presentation, from Ref. 8. These conductances, which are normally given for air at ambient temperature, have been modified to make them applicable to other gases and temperatures. For geometric passages not listed, one can make use of the analogy between vacuum circuits and electrical circuits to obtain effective total conductances by combining simple conductances in series or parallel, as follows:

- Series combination arrangement: $\frac{1}{C_e} = \sum \frac{1}{C_{ij}}$. (4)

- Parallel combination arrangement: $C_e = \sum C_{ij}$. (5)

1. Thin small aperture (Orifice)

a. Viscous flow i.e. $K_n < 10^{-2}$

For $1 \geq u \geq .52$,

$$C_{ij} = 23.97\left(\frac{T}{M}\right)^{1/2} (1 - u)^{-1} u^{.712} (1 - u^{.288})^{1/2} A. \tag{6}$$

For $.52 \geq u \geq .1$,

$$C_{ij} = 6.27\left(\frac{T}{M}\right)^{1/2} (1 - u)^{-1} A. \tag{7}$$

For $.1 \geq u \geq 0$,

$$C_{ij} = 6.27\left(\frac{T}{M}\right)^{1/2} A. \tag{8}$$

b. Molecular flow i.e. $K_n > 10$

$$C_{ij} = 3.62\left(\frac{T}{M}\right)^{1/2} A. \tag{9}$$

c. Intermediate Flow i.e. $10^{-2} < K_n < 10$

$$C_{ij} = \frac{(C_{ij})\,\mathrm{mol} + (C_{ij})\,\mathrm{visc}}{2} . \tag{10}$$

2. Long pipe

a. Viscous flow

The conductance is inversely proportional to the viscosity, which in turn varies directly with the square root of the temperature (Refs. 11 and 14). The conductance of the air at 20°C has been modified by multiplying its coefficient by the ratio of the viscosities and by a temperature function, so that

$$C_{ij} = 3120\,\eta\,(T)^{-1/2}\,\frac{(P_j + P_i)}{2}\,\frac{D^4}{L}, \tag{11}$$

where η, the ratio of the viscosities, is given in Table 1.

b. Molecular flow

$$C_{ij} = 3.81\left(\frac{T}{M}\right)^{1/2}\frac{D^3}{L}. \tag{12}$$

c. Intermediate flow

$$C_{ij} = 3.81\left(\frac{T}{M}\right)^{1/2}(J)\,\frac{D^3}{L}, \tag{13}$$

where the intermediate flow coefficient J is shown in Table 1.

3. Short tubes

a. Viscous flow

One can use the series combination of orifice and pipe, i.e.,

$$\left(C_{ij}\right) = \frac{1}{\dfrac{1}{(C_{ij})_{orifice}} + \dfrac{1}{(C_{ij})_{pipe}}}. \tag{14}$$

Table 1
Coefficients for Conductances (from Reference 8)

Gas	Mol. Wgt (grm)	$\eta = \frac{\text{Visc. Air}}{\text{Visc. Gas}}$ @ 15°C
H_2	2.02	2.1
H_e	4.0	.93
NH_3	17.0	1.86
H_2O	18.0	1.90
N_2	28.0	1.04
Air	28.7	1.0
O_2	32.0	.90
A	39.9	.82
CO_2	44.0	1.24

Intermediate Flow Factor J		Rectangular Duct Flow Coefficients Y, α		
DP (torr-cm)	J	a/b	Y	α
2×10^{-2}	1.1	1.0	1.0	1.108
4×10^{-2}	1.4	.9	.99	
6×10^{-2}	1.7	.8	.98	
8×10^{-2}	2.0	.7	.95	
1×10^{-1}	2.3	.6	.90	1.126
2×10^{-1}	3.8	.5	.82	1.151
4×10^{-1}	6.9	.4	.71	
6×10^{-1}	9.9	.3	.58	1.198
8×10^{-1}	13.0	.2	.42	1.297
1.0	16.0	.1	.23	1.444
2.0	31.0			
4.0	62.0			
10.0	153.0			

Coaxial Tube Factor K						
D_2/D_1	0	.259	.50	.707	.866	.966
K	1	1.072	1.154	1.254	1.430	1.675

b. Molecular flow

$$C_{ij} = 3.81 \left(\frac{T}{M}\right)^{1/2} \frac{D^3}{L + 4/3D} \quad . \tag{15}$$

c. Intermediate flow

$$C_{ij} = (C_{ij})_{mol} \, (J) \tag{16}$$

4. Rectangular Duct

a. Viscous flow

The conductance of air at 20°C, modified in the same manner as for the long pipe, yields the following:

$$C_{ij} = 4455 \, \eta \, (T)^{-1/2} \, (Y) \, \frac{a^2 b^2}{L} \left(\frac{P_i + P_j}{2}\right), \tag{17}$$

where the values of η and Y, a flow coefficient, are listed in Table 1.

b. Molecular flow

$$C_{ij} = 9.68 \, (\alpha) \left(\frac{T}{M}\right)^{1/2} \frac{a^2 b^2}{L(a + b)} \quad , \tag{18}$$

where the value of coefficient α is listed in Table 1.

c. Intermediate flow

$$C_{ij} = (C_{ij})_{mol} \, (J) \; .$$

5. Long annular tube

a. Viscous flow

$$C_{ij} = 3050\ \eta \frac{T^{-1/2}}{L} \left[D_1^4 - D_2^4 - \frac{(D_1^2 - D_2^2)}{\ln_e D_1/D_2} \right] \frac{(P_i + P_j)}{2} \quad . \tag{19}$$

b. Molecular flow

$$C_{ij} = 3.81 \left(\frac{T}{M} \right)^{1/2} (K) \frac{(D_1 - D_2)^2 (D_1 + D_2)}{L} \quad , \tag{20}$$

where the value of the coefficient K is indicated as a function of the ratio of the diameters in Table 1.

c. Intermediate flow

$$C_{ij} = (C_{ij})_{mol}\ (J)\ .$$

Initial Conditions – Boundary Conditions

In addition to the geometric description of the system, one must specify the type of gas and the pressure and temperature conditions which exist at the start of evacuation of the system. It is also necessary to establish the pressures at which the different types of flow regimes exist (namely the viscous, intermediate, and molecular flow regimes). At these pressures, which are established by the passage dimensions and the mean free paths of the molecules, the conductances appropriate for each flow must be used for the integration of the flow equation. As indicated previously, the Knudsen number provides a criteria for the change-over (Ref. 11): For $K_n < 10^{-2}$ the flow is viscous; For $K_n > 1.0$ the flow is molecular.

The Knudsen number, with the substitution of the expression for the mean free path of the gas in terms of the pressure, temperature, and size of the molecule, becomes

$$K_n = \frac{\lambda}{D} = \frac{1}{D\sqrt{2}\,\pi n \sigma^2} = \frac{BT}{D\sqrt{2}\,\pi \sigma^2 P} = \frac{2.331 \times 10^{-20} T}{DP\sigma^2}, \qquad (21)$$

where σ is the molecular diameter of the gas ($\sigma = 3.74 \times 10^{-8}$ cm for air), n is the number of molecules per unit volume, and B is the Boltzmann Constant.

The flow regimes can now be established in terms of the pressure P and a dimension D as follows:

- Molecular flow: $K_n > 1.0,$

$$DP < \frac{2.331 \times 10^{-20} T}{\sigma^2}, \qquad (22)$$

which for air at 25°C becomes

$$DP < 5 \times 10^{-3} \text{ (torr - cm)}. \qquad (23)$$

- Viscous flow: $K_n < 10^{-2},$

$$DP > 2.331 \times \frac{10^{-18} T}{\sigma^2}. \qquad (24)$$

which for air at 25°C is

$$DP \geq .5 \text{ (torr - cm)}. \qquad (25)$$

In the above, P is an average pressure and D a characteristic dimension of the container. This dimension is, for example, the internal diameter of a pipe. In general, it can be taken as being the smallest dimension in a passage or as an equivalent diameter for a passage of area A, i.e.,

$$D = \left(\frac{4A}{\pi}\right)^{1/2}. \qquad (26)$$

The pressure of the pipe flow P, is taken to be the average of the inlet and exit pressures.

Outgassing Functions

Also affecting the ambient gas in the container, are gases which evolve from the container surfaces and the equipment inside the container under vacuum conditions. These gases are those which were physically and chemically sorbed by the surfaces, those which were in solution in the material, and those arising from evaporation and decomposition products. The exact mechanism of outgassing is still a matter of controversy, but theoretical and experimental determinations of outgassing rates have been reported in the literature (Refs. 15 and 16).

It is found from experience that the outgassing of materials may be characterized, in general, by the following statements:

- The outgassing depends on the nature of the materials; for a given material it is a function of the material's surface treatment and of the atmospheric composition to which the material was exposed prior to exposure to vacuum.
- The outgassing is proportional to the surface area and increases rapidly with the temperature. It decreases slowly with time and apparently never becomes zero at ambient temperature.
- At pressures lower than 10^{-3} torr, the outgassing rate is independent of the pressure; i.e., the number of molecules expelled by the surface per unit time does not depend on the pressure above the outgassing surface. This behavior has not been established with complete certainty, but is valid as a first approximation.

Outgassing rates of various materials at ambient temperature have been plotted as a function of time. Figure 2 shows degassing rates for some materials. These outgassing fluxes have been obtained by exposing the materials to vacuum and comparing the rates with those provided by known conductances, or by reading the rates of pressure increase.

Tabulation of outgassing properties of many materials is indicated in Tables 2 and 3. These tables, reproduced from Ref. 1[illegible] for metallic, elastomeric, plastics, and ceramic materials at 25°C, list the outgassing rates and their slopes at 1, 4, and 10 hours of exposure to vacuum. A knowledge of the outgassing rates of the materials at each instant is required for the solution of the pressure

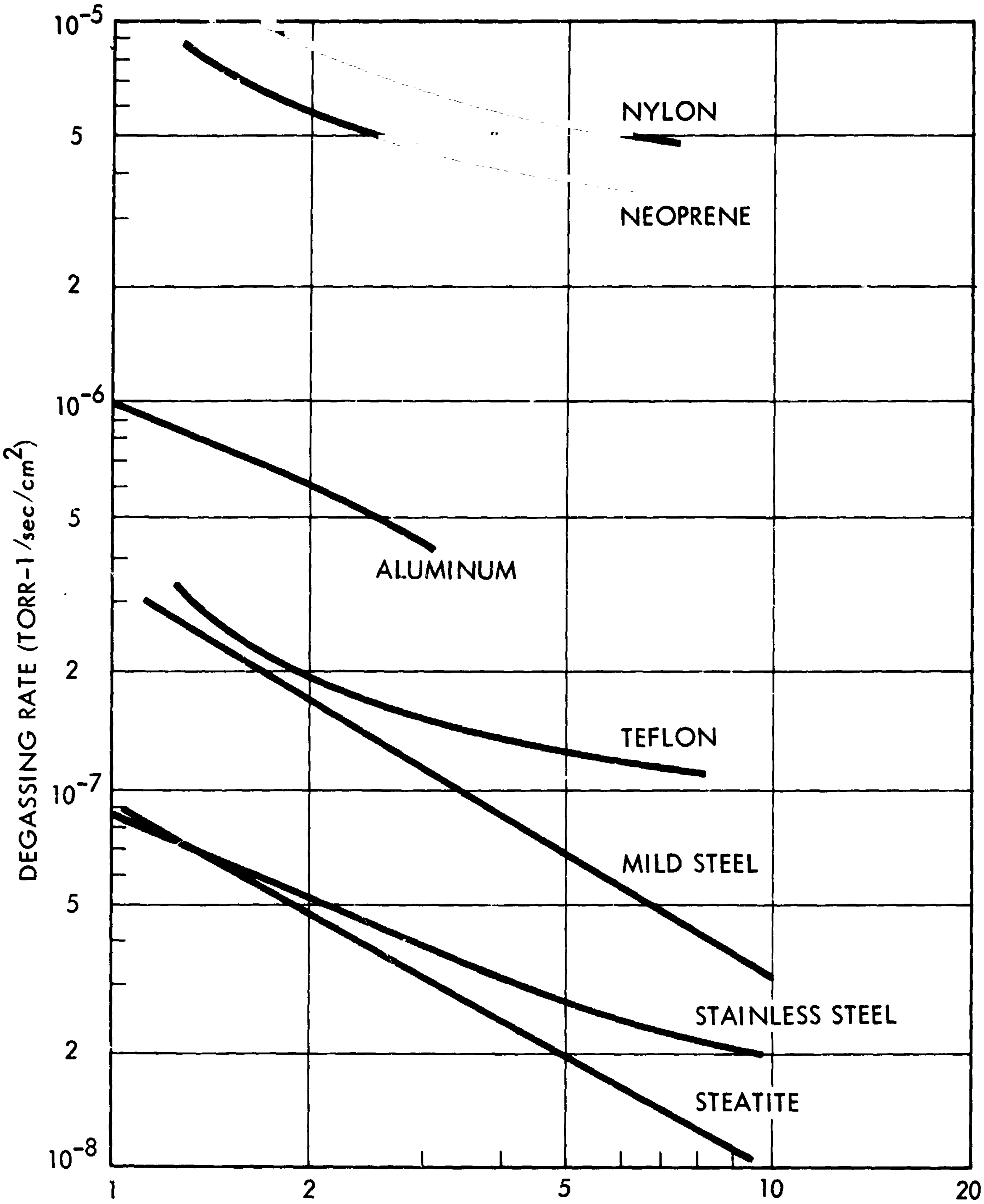


Figure 2–Degassing Rate Per Unit Surface Area Versus Time for Some Materials

Table 2
Outgassing Rate Constants for Metallic Materials
(From Reference 15)

A_m = area of sample (cm^2);
S_a = pumping speed for air at 25 °C (l/sec);
K_h = air equivalent outgassing rate after *h* hr of pumping ($\text{Torr-l-sec}^{-1}\text{-cm}^{-2}$);
α_h = absolute value of slope of log–log graph of outgassing rate vs. time after *h* hr of pumping.

Material	A_m	S_a	10^7K_1	α_1	10^7K_4	α_4	10^7K_{10}	α_{10}
1. Stainless steel EN 58B (polished, vapor degreased)	—	1	—	—	0.049	1.6	0.014	—
2. Stainless steel	65	3.5	1.75	1.1	0.44	0.84	0.21	0.75
3. Stainless steel	—	0.7	0.9	0.75	0.3	0.75	0.2	0.75
4. Mild steel	65	3.5	5.4	1	1.4	1	0.5	1
5. Mild steel (slightly rusty)	—	1	6.0	3.1	0.28	1.5	0.13	1
6. Steel, rusty	65	3.5	44	1.4	5.5	1.4	1.6	1.3
7. Iron	12	—	4	1	1	1	—	—
8. Nickel plated mild steel (polished, vapor degreased)	—	1	5	2	0.036	1.4	0.01	—
9. Nickel plated steel	65	3.5	2.8	2	—	—	—	—
10. Chrome plated mild steel (polished, vapor degreased)	—	1	0.1	1	0.023	0.93	0.009	—
11. Aluminum, anodized	65	3.5	—	—	3.6	0.8	1.1	2.3
12. Aluminum, bright rolled (cleaned in Stergene)	65	3.5	—	—	0.22	1	0.075	1
13. Aluminum	12	—	15	1	3.7	—	—	—
14. Duraluminum	—	0.7	1.7	0.75	0.6	0.75	0.35	0.75
15. Aluminum spray coated mild steel	65	0.4	0.6	0.75	0.2	0.75	0.1	0.75
16. Aluminum spray coated mild steel (rusted)	65	0.4	1.8	0.65	0.8	0.75	0.4	0.75
17. Copper (24 hr at 95 per cent humidity)	100	0.32	0.2	2	—	—	—	—
18. Copper	12	—	23	1	—	—	—	—
19. Brass (24 hr at 95 per cent humidity)	43	0.32	0.15	2.5	—	—	—	—
20. Brass, cast	650	3.5	10	1	2.5	1	1.1	0.75
21. Brass, wave-guide section	50	0.3	4	2	0.3	1.4	0.1	1.2
22. Nickel	12	—	6	1	1.5	1	—	—
23. Nickel	12	—	10	1	2.5	1	—	—
24. Molybdenum	12	—	7	1	1.7	1	—	—
25. Tantalum	12	—	9	1	—	—	—	—
26. Zirconium	12	—	13	1	—	—	—	—
27. Tungsten	12	—	2	1	—	—	—	—
28. Silver	12	—	6	1	—	—	—	—

history equation. Equations for the outgassing as a function of time, G(t), have therefore been fitted to the data in the tables. Techniques described below were used to calculate the parameters of these equations for several materials.

For outgassing rates at temperatures other than 25°C, an estimate of the increase of the outgassing rates with the temperature can be obtained from the empirical relation proposed by Arrhenius for the increase of the rate of chemical reaction with the temperature:

$$Q = Q_0 \exp\left(-\frac{\Delta H}{RT}\right),$$

where Q is the rate at temperature T, Q_0 a constant (determined from Q at 25°C), ΔH a constant representing the energy of the activation of the material, R the gas

Table 3
Outgassing Rate Constants for Non-Metallic Materials
(From reference 15)

A_m = area of sample (cm^2);
S_a = pumping speed for air at 25 °C (l/sec);
K_1 = air equivalent outgassing rate after 1 hr of pumping (Torr-l-sec^{-1}-cm^{-2});
K_4 = outgassing rate after 4 hr of pumping;
α_1 = absolute value of slope of log–log graph of outgassing rate vs. time after 1 hr of pumping;
α_4 = absolute value of slope of log–log graph after 4 hr;
t_m = time at which α begins to increase rapidly above α_1 for given sample (hr);
w_m^2 = square of sample thickness, w_m (mm).

Material	A_m	S_a	10^7K_1	α_1	10^7K_4	α_4	t_m	w_m^2
A. Elastomers								
1. Natural gum rubber (32 Durometer)	75	0.5	12	0.5	6.0	0.5	12	9
Natural gum rubber (32 Durometer)	1	0.5	13	0.5	6.5	0.5	10	9
2. Natural white rubber J.1260 total outgassing	100	0.35	11.5	0.40	6.6	0.42	5	2.6
3. Natural white rubber J.1260 non-condensable in liquid air	100	0.35	2	0.5	0.2	1.6	—	2.6
4. Natural crepe rubber (vulcanized with S 20 min)	22.2	0.7	73	0.7	31	0.65	—	•
5. Natural crepe rubber (vulcanized with Te 20 min)	22.2	0.7	61	0.5	28	0.60	—	•
6. Neoprene F-905	65	0.3	50	0.49	25	0.55	>30	16
7. Neoprene 60° Shore	—	1	80	0.45	43	0.49	> 7	—
8. Neoprene	65	3.5	300	0.4	180	0.4	15	—
9. Neoprene (24 hr at 95 per cent humidity)	7.6	0.32	1400	0.75	480	0.96	> 5	—
10. Neoprene (outgassed + 24 hr dry N_2)	7.6	0.32	120	0.5	—	—	—	—
11. Neoprene GNA (V-4-2) (½ hr 50 per cent rel. humidity)	30	2	--	—	30	—	—	—
12. Neoprene (bell jar gasket, 50 Durometer)	68	0.4	30	0.5	14.5	0.5	—	•
13. Neoprene 1157 (sulfur free)	65	1.5	54	0.45	30	0.45	>20	10
14. Red vacuum hose (24 hr at 95 per cent humidity)	141	0.32	88	0.6	30	0.8	3	•
15. Red vacuum hose (outgassed + 24 hr dry N_2)	141	0.32	11	0.5	—	—	—	•
16. Perbunan	65	3.5	35	0.3	22	0.5	5	—
17. Perbunan PD 651 (vulcanized 30 min)	22.2	0.7	56	0.4	31	0.5	4	•
18. Perbunan DR-39 (low acrylonitrile)	22.2	0.7	94	0.65	41	0.56	20	•
19. Perbunan (Bayer)	12	0.1	20	0.5	10	0.5	—	—
20. Perbunan (Bayer) (tempered)	12	0.39	4	0.59	1.2	1.1	—	—
21. Butyl GRI (V-3) (½ hr 50 per cent relative humidity)	30	2	—	—	20	—	—	—
22. Butyl (DR-41) (40% C black; vulcanized 12 min)	22.2	0.7	15	0.68	4.	0.64	—	•
23. Butyl (BU. 12000)	100	0.35	20	0.64	6	0.42	—	2.6
24. Butyl (BU. 12000) (non-condensable liquid air)	100	0.35	1	0.42	0.55	0.51	—	2.6
25. Convaseal	65	3.5	14	0.2	9	0.39	—	—
26. Convaseal (extruded ⅜ in. square)	39	0.4	10	0.5	4.9	0.6	>50	91•
27. Convaseal	100	0.4	5.0	0.46	2.6	0.4	>30	10
28. Polyisocyanate rubber D-43	22.2	0.7	280	0.45	127	0.57	10	•
29. Nygon	65	3.5	130	0.5	65	0.6	5	—
30. Hycar H-50 (ASTM spec. SB-510)	6.5	1.5	120	0.42	70	0.45	>50	10
31. Hycar H-50 (ASTM spec. SB-510)	65	1.5	140	0.48	74	0.5	>96	10
32. Silicone rubber (Wacker R 60)	12	0.39	70	1.07	17	1.1	—	—
33. Silicone rubber (Wacker R 80)	12	0.39	180	1.0	44	1.2	—	—
34. Silicone rubber (24 hr 95 per cent humidity)	100	0.32	230	0.65	46	1.3	—	—
35. Silicone rubber (outgassed + 24 hr dry N_2)	100	0.32	13	0.5	—	—	—	—
36. Silastic	—	1	25	0.55	6	1.8	—	—
37. Silicone rubber	22.2	0.7	94	0.75	31	0.8	20	•
38. Silastic X-6145-C	65	1.5	25	1.0	5.6	1.07	>96	10
39. Silastic 8-164 (red, 62 Durometer)	65	1.3	12	0.9	3.7	0.9	>70	10
40. Silastic 50 (white, cured 24 hr at 480 °F, 74 Durometer)	65	1.3	28	1.0	6.0	1.0	>50	10
41. Silastic 50 (white, 55 Durometer)	65	1.3	30	1.0	6.4	1.0	>50	10
42. Silastic 67-163 (red, 61 Durometer)	65	1.3	19	0.93	5.4	1.0	>50	10

Table 3 (continued)

Material	A_m	S_e	10^7K_1	α_1	10^7K_6	α_6	t_m	$w_m^{\frac{1}{2}}$
B. Plastics								
1. Teflon, Dupont	12	0.23	4	0.7	1.6	0.7	—	—
2. Teflon, high temperature (24 hr at 95 per cent humidity)	27	0.32	42	0.93	6	—	—	—
3. Teflon, high temperature (outgassed + 24 hr dry N_2)	27	0.32	0.1	2	—	—	—	—
4. Teflon, Ceroc (24 hr at 95 per cent humidity)	42	0.32	35	0.46	19	—	—	—
5. Teflon, Dupont	65	1.5	5	0.68	1.2	1.2	3	2.6
6. PTFE	—	1	3	0.45	1.5	0.56	—	—
7. Kel-F (Oak Ridge National Laboratory)	65	1.5	0.4	0.57	0.17	0.53	—	10
8. Kel-F 270 (Resistoflex Corp.)	47	0.4	—	—	0.16	0.55	—	0.6
9. Araldite D	650	3.5	80	0.8	22	0.78	—	—
10. Araldite D	30	0.7	19	0.3	12.5	0.5	—	—
11. Araldite B	30	0.7	18	0.4	9.2	0.5	—	—
12. Araldite F	30	0.7	15	0.5	7.3	0.5	—	—
13. Araldite, Type 1 (Ciba, cured 15 hr 266 °F)	62	0.4	5.5	1.3	0.9	1.3	10	0.3
14. Epoxy resin 200 (24 hr 95 per cent humidity)	50	0.32	110	0.6	—	—	—	—
15. Epoxy resin 200 (outgassed + 24 hr dry N_2)	50	0.32	0.2	1.6	—	—	—	—
16. Eppon, Shell Oil Co.	41	0.4	40	1.2	8.5	1.2	50	40
17. Plexiglas (Alsthom)	30	0.7	31	0.4	18	0.4	—	—
18. Plexiglas M222 (Röhm and Haas)	12	0.10	19	0.43	10	0.57	—	—
19. Plexiglas (24 hr at 95 per cent humidity)	62	0.32	115	0.65	40	0.75	—	—
20. Plexiglas (outgassed + 24 hr dry N_2)	62	0.32	10	0.5	—	—	—	—
21. Mylar (24 hr at 95 per cent humidity)	289	0.32	0.1	4.3	—	—	—	—
22. Mylar V-200 (24 hr at 95 per cent humidity)	370	0.32	23	0.75	4	—	—	—
23. Mylar V-200 (outgassed + 24 hr dry N_2)	370	0.32	1.3	1.33	—	—	—	—
24. High temperature Thermalon (24 hr at 95 per cent humidity)	32	0.32	13	2.3	0.1	—	—	—
25. Polyvinylchloride (24 hr at 95 per cent humidity)	70	0.32	8.5	1.0	0.2	—	—	—
26. Polyvinylchloride (outgassed + 24 hr dry N_2)	70	0.32	0.08	3.2	—	—	—	—
27. Polyethylene (BASF)	12	0.10	2.3	0.5	1.15	0.5	—	—
28. Polyethylene (Dynamit-AG)	12	0.23	2.6	0.5	1.3	0.5	—	—
29. Polyamid (Bayer)	12	0.12	46	0.5	23	0.5	—	—
30. Ultramid (BASF)	12	0.1	17	0.5	8.5	0.5	—	—
31. Polyvinylcarbazol (BASF)	12	0.23	16	0.5	8	0.5	—	—
32. Polystyrol (BASF)	12	0.14	6	0.5	3	0.5	—	—
33. Polystyrol (Dynamit-AG)	12	0.14	15	0.5	7.5	0.5	—	—
34. Polyurethane (Bayer)	12	0.85	5	0.5	2.5	0.5	—	—
35. Textolite 11564 (24 hr at 95 per cent humidity)	61	0.32	55	0.7	18	1.1	—	—
36. Textolite 11564 (outgassed + 24 hr dry N_2)	61	0.32	0.1	3.3	—	—	—	—
37. Nylon	—	1	120	0.5	60	0.5	—	—
38. Peramfil (General Electric Co.)	57	0.4	400	1.8	40	1.2	50	23
39. Polyester (Zenith Plastic Co., fiber glass laminate)	52	0.4	23	0.84	7	0.84	50	16
40. Polyester (Plastone, fiber glass laminate)	59	0.4	25	0.84	8	0.81	50	40
41. Polyester (Perault)	30	0.4	34	0.72	13.5	0.67	40	40
42. Polyester, Norsodyne	430	0.7	16	0.36	10	0.36	100	—
43. Celluloid	12	0.39	86	0.5	43	0.5	—	—
44. Polythene	80	0.4	200	1.6	20	1.6	—	—
45. Methylmethacrylate	174	0.7	42	0.9	14	0.57	—	—
46. Epicote	82	0.7	25	0.5	12.5	0.5	—	—
C. Ceramics								
1. Porcelain, glazed	30	0.7	6.5	0.5	3.0	0.5	—	—
2. Steatite	30	0.7	0.9	1	0.24	1	—	—

constant, and T the absolute temperature. The rates of many organic reactions are doubled for each 10°K rise in temperature. A rule of thumb frequently suggested is that a 10% change in absolute temperature will cause a 10:1 change in outgassing rate (Ref. 7).

From the plots of Figure 2, the outgassing rates are seen to be representable by the following functions:

$$q = q_0 \, t^{-\alpha} \tag{27}$$

and

$$q = q_0 \, e^{-t/\tau} + q_f , \tag{28}$$

In these expressions q_0 is the initial outgassing rate, q_f is the final outgassing rate, α is the slope of the outgassing curve (27) and τ is a time constant which represents, for the curve (28), the time required for the outgassing rate to drop to a value

$$q = \frac{q_0}{e} + q_f \approx .368 \, q_0 + q_f .$$

It should be pointed out that an expression such as the above could be obtained experimentally for an entire package containing various materials. The equivalent outgassing so obtained could then be used in calculations involving the interaction of this package with others. The outgassing can be programmed as a mathematical function or provided in tabular or graphical form for the use to be made of it here.

With the outgassing rates at 1 hour, 4 hours and 10 hours provided by the tables, the parameters of the exponential equation (28) representing the outgassing can be obtained as follows. Using the system of equations

$$Q_1 = Ae^{-1/c} + B,$$

$$Q_4 = Ae^{-4/c} + B,$$

$$Q_{10} = Ae^{-10/c} + B,$$

where the Q_i are the known rates, and A, B, C are the parameters to be found, the following ratio is obtained:

$$\frac{1}{R} = \frac{Q_4 - Q_{10}}{Q_1 - Q_4} = \frac{e^{-4/c}}{e^{-1/c}} \frac{(1 - e^{-6/c})}{(1 - e^{-3/c})} = \frac{1 + e^{-3c}}{e^{3/c}} = e^{-3/c} + e^{-6/c} \qquad (29)$$

Letting $x^{-1} = e^{-3/c}$ and $x^{-2} = e^{-6/c}$, this may be rewritten

$$\frac{1}{R} = \frac{x+1}{x^2}, \quad \text{or} \quad x^2 - Rx - R = 0,$$

which when solved for the positive root yields

$$x = e^{3/c} = \frac{R + \sqrt{R^2 + 4R}}{2},$$

from which the parameter 1/C is found:

$$\frac{1}{C} = \frac{\ln x}{3} = \frac{1}{3} \ln \left[\frac{R + \sqrt{R^2 + 4R}}{2} \right]. \qquad (30)$$

With C known, the parameter A can then be obtained as

$$A = \frac{Q_1 - Q_4}{(e^{-4/c} - e^{-1/c})}, \tag{31}$$

and finally

$$B = Q_{10} - A\, e^{-10/c}. \tag{32}$$

The tables provide outgassing rates at only two different times for some materials. However, the slopes of the outgassing, α, are provided at these points. In these cases, to fit the data to the exponential equation, one can use the average of the slopes to establish

$$1/C = \frac{\alpha_1 + \alpha_2}{2}, \tag{33}$$

The parameters A and B are then obtained as above, by using equations like (31) and (32).

Table 4 presents the values of A, B, and C calculated for some of the materials listed in Tables 2 and 3.

If the tables provide only one rate of outgassing and a corresponding slope, the outgassing equation to be used is $Q = At^{-\alpha}$. The coefficient A can be obtained directly by substitution of the given values, i.e.,

$$A = Q_n\, t_n^{\alpha}.$$

In general then

$$Q = (Q_n\, t_n^{\alpha})\, t^{-\alpha} \tag{34}$$

Table 4
Coefficients for the Outgassing Equations

```
A =  2.89358704E-07     B =  2.04534053E-08     C =  1.59446027E 00          STAINLESS
        CHECK        1.75000000E-07     1,75000000E-07
        CHECK        4.40000000E-08     4,40000000E-08
        CHECK        2.10000000E-08     2,10000000E-08

A =  1.33501518E-07     B =  1.97837272E-08     C =  1.55634089E 00          STAINLESS
        CHECK        9.00000000E-08     9,00000000E-08
        CHECK        3.00000000E-08     3,00000000E-08
        CHECK        2.00000000E-08     2,00000000E-08

A =  8.59353759E-07     B =  4.66586056E-08     C =  1.80186918E 00          MILDSTEEL
        CHECK        5.40000000E-07     5,40000000E-07
        CHECK        1.40000000E-07     1,40000000E-07
        CHECK        5.00000000E-08     5,00000000E-08

A =  4.42083779E 03     B =  1.30385160E-08     C =  1.51461795E-01          MILDSTEEL
        CHECK        6.00000000E 00     6,00000000E 00
        CHECK        2.80000000E-08     2,80385160E-08
        CHECK        1.30000000E-08     1,30385160E-08

A =  9.37587115E-06     B =  1.56619232E-07     C =  1.26138528E 00          STEELRUSTY
        CHECK        4.40000000E-06     4,40000000E-06
        CHECK        5.50000000E-07     5,50000000E-07
        CHECK        1.60000000E-07     1,60000000E-07

A =  2.00829151E-06     B =  9.99990889E-08     C =  5.25967783E-01          IRON
        CHECK        4.00000000E-07     4,00000000E-07
        CHECK        1.01000000E-07     1,01000000E-07
        CHECK        1.00000000E-07     1,00000000E-07

A =  2.87832014E-06     B =  9.99929417E-10     C =  5.70660338E-01          NICKELPOL
        CHECK        5.00000000E-07     5,00000000E-07
        CHECK        3.60000000E-09     3,60000001E-09
        CHECK        1.00000000E-09     1,00000001E-09

A =  1.69295054E-08     B =  8.64559783E-10     C =  1.62101720E 00          CHROMEPLATESTEEL
        CHECK        1.00000000E-08     1,00000000E-08
        CHECK        2.30000000E-09     2,30000000E-09
        CHECK        9.00000000E-10     9,00000000E-10

A =  2.36120169E-07     B =  3.40549934E-08     C =  1.81129749E 00          DURALUM
        CHECK        1.70000000E-07     1,70000000E-07
        CHECK        6.00000000E-08     6,00000000E-08
        CHECK        3.50000000E-08     3,50000000E-08

A =  8.52669080E-05     B =  9.55184500E-09     C =  1.90534165E 00          ALUMCOATSTEEL
        CHECK        6.00000000E-08     6,00000000E-08
        CHECK        2.00000000E-08     2,00000000E-08
        CHECK        1.00000000E-08     1,00000000E-08

A =  1.64347917E-06     B =  1.06283627E-07     C =  1.64154488E 00          BRASS
        CHECK        1.00000000E-06     1,00000000E-06
        CHECK        2.50000000E-07     2,50000000E-07
        CHECK        1.10000000E-07     1,10000000E-07


A =  4.56447441E-06     B =  2.67376208E-07     C =  1.69765586E 00     SILASTIC 50
     CHECK       2.80000000E-06     2.80000000E-06
     CHECK       7.00000000E-07     7,00000000E-07
     CHECK       2.80000000E-07     2,80000000E-07
A =  4.41243965E-08     B =  4.89773118E-10     C =  1.22537899E 00     EPOXY 200
     CHECK       2.00000000E-08     2.00000000E-08
     CHECK       2.17637641E-09     2,17637641E-09
     CHECK       5.02377286E-10     5,02377287E-10
A =  5.31418681E-07     B =  1.49938401E-07     C =  2.39554783E 00     POLYURETHANE (RA
     CHECK       5.00000000E-07     5.00000000E-07
     CHECK       2.50000000E-07     2.50000000E-07
     CHECK       1.58113883E-07     1.58113883E-07
A =  7.28652981E-06     B =  2.42698515E-07     C =  1.50982959E 00           EPON S
     CHECK       4.00000000E-06     4.00000000E-06
     CHECK       7.57858283E-07     7,57858283E-07
     CHECK       2.52382938E-07     2.52382938E-07
A =  3.18851208E-07     B =  8.99630405E-08     C =  2.39554783E 00             PTFE
     CHECK       3.00000000E-07     3.00000000E-07
     CHECK       1.50000000E-07     1,50000000E-07
     CHECK       9.48683298E-08     9.48683298E-08
A =  1.20198978E-05     B =  5.45001053E-07     C =  1.60847067E 00           RTV SI
     CHECK       7.00000000E-06     7.00000000E-06
     CHECK       1.54473024E-06     1,54473024E-06
     CHECK       5.68981361E-07     5.68981361E-07
A =  2.52794891E-07     B =  5.87464062E-09     C =  1.40590338E 00            MYLAR
     CHECK       1.30000000E-07     1.30000000E-07
     CHECK       2.05685447E-08     2,05685447E-08
     CHECK       6.08055684E-09     6.08055684E-09
```

where Q_n, t_n and α are the values given in the tables. In particular, if the given value of Q_n is that corresponding to one hour, then $A = Q_n$.

External Pressure P_0 (t)

The pressure of the environment must be known as a function of time in order to solve the system of differential equations. Two vacuum environment profiles will be encountered by a spacecraft – the pressure versus altitude during launch and orbiting, and the pressure produced by pumping devices in a test chamber.

The launch and orbiting pressure versus time profile for a spacecraft can be obtained by combining the pressures versus altitude as found in tables with the altitude versus time of the spacecraft (Ref. 17). For example, an equation for the external pressure can be written using simplifying assumptions, for a satellite having a period T_s in an elliptical geocentric orbit. Let P_{max} and P_{min} be the environmental pressures at perigee and apogee respectively, P_{av} the average pressure during orbiting and t_0 the time from launch to reach orbit altitude. Then one may write simply: For

$$0 < t < t_0, \quad P_0 = P_{atm} - \frac{P_{atm} - P_{av}}{t_0} t, \tag{35}$$

while for

$$t > t_0, \quad P_0 = \frac{P_{max} + P_{min}}{2} + \frac{P_{max} - P_{min}}{2} \sin \omega t, \tag{36}$$

where

$\omega = 2\pi/T_s$, and P_{atm} = atmospheric pressure at launch .

In the above equations, it has been assumed that the drop in pressure is linear with altitude during launch (which is approximately true for altitudes up to 125 km). For computing purposes, however, it will only be necessary to have pressure versus time in tabular form.

The evacuation of a test chamber is a function of its volume and the pumping speed of the system. It is dependent on the temperature, humidity, and surface conditions of the chamber, its material, the gases present and many other factors. It is thus quite possible that the results of one test will be somewhat different than another. The pressure versus time data for a particular chamber can be described analytically and used for the solution of the chamber-spacecraft system. As an example of this, Table 5 shows the pumpdown equations for an 8' × 8' chamber, in part derived from the data shown in Figure 3. The data at the 55°C and -10°C test chamber temperatures shown in this figure cover only pressures below 10^{-3} torr. The evacuation time from 760 torr down to 10^{-3} torr is a small fraction of the total evacuation time and was not shown on this graph. The pressure for this interval was assumed to decay exponentially from time zero to .9 hr., followed by a straight line decay to 1 hour. This is in accord with other experimental evidence. For the same time range, a straight line pressure drop can also be assumed. Calculations to fit these data and the above assumptions have provided the equations shown in Table 5 for the empty 8' × 8' test chamber at the two different chamber wall temperatures.

Equations for chamber pressure profiles like these indicated here can be derived for other chambers. However, test data on the evacuation of any chamber can also be used directly in tabular form for the solution of the pressure equations. The latter method will generally be used here to calculate pressure profiles.

Heat Transfer Considerations

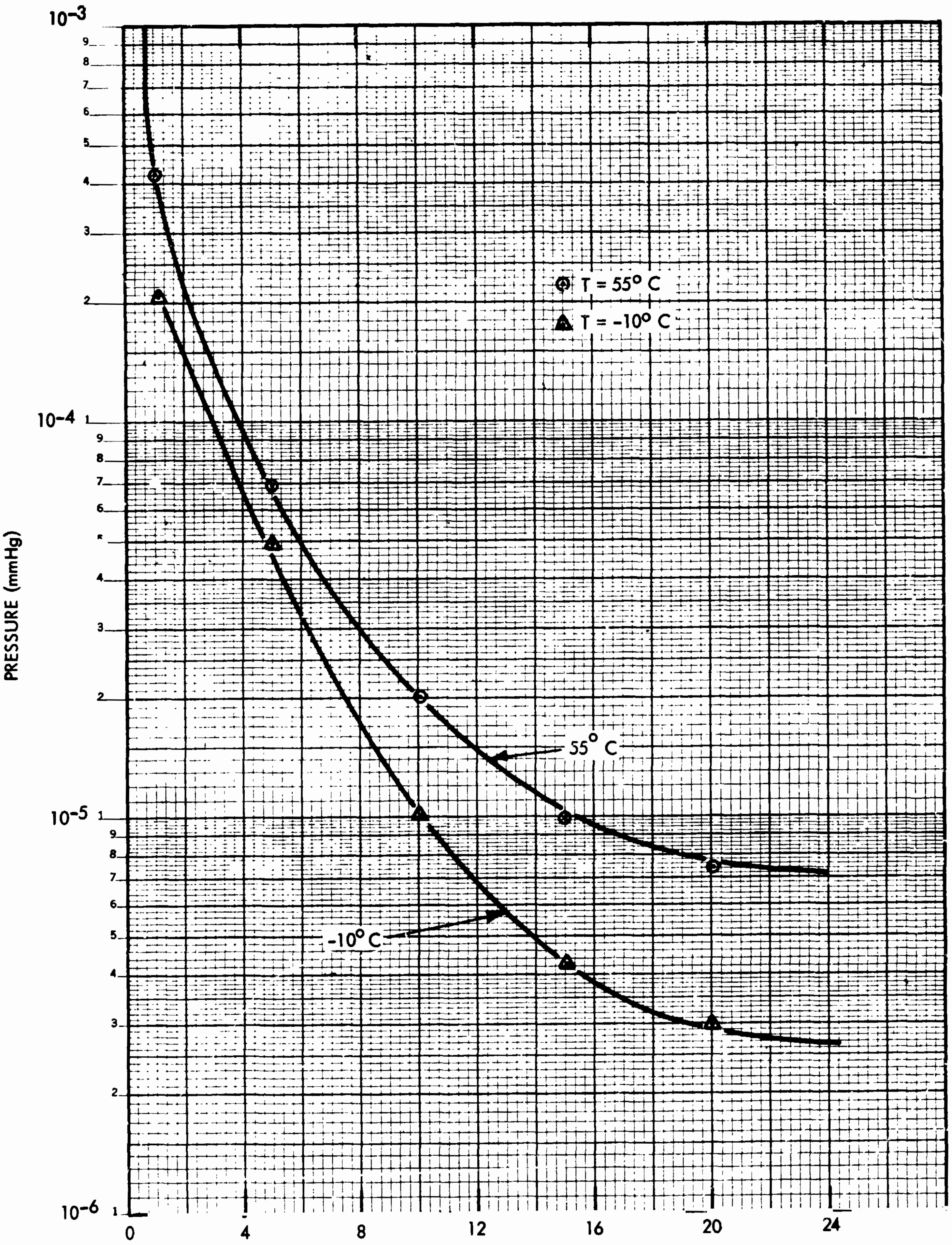
The pressure relation equation (2) has been derived under the assumption of isothermal flow conditions. This presupposes an average speed of evacuation and sufficient heat transfer from the container to the gas to maintain a constant temperature. This condition is in fact approached during evacuation of a test chamber or in actual flight, with the exception of the very start of evacuation. At the start, there is a very rapid evacuation to represent the pressure drop experienced during rocket ascent. The flow is turbulent and viscous, and is provided by the rapid changing environment or by large capacity displacement pumps. The rapid evacuation produces a sudden drop in temperature, 4-5°C for a large vacuum chamber, followed by a temperature recovery back to the ambient wall temperature. During this very short and rapid exhaust, the heat transfer from the wall is not sufficient to maintain the gas temperature constant and adiabatic expansion of the gas is approached. When the rate of expansion of the gas becomes moderate, and the rate of pressure drop is reduced, the heat input from the wall is sufficient to compensate for the heat loss caused by the expansion. An estimate of the temperature effect can be carried out as follows.

The heat gain of the gas in time dt is

$$d Q_g = h A_s (T_w - T_g) dt , \qquad (39)$$

Table 5
Pressure Profile Equations for an 8' × 8' Chamber

P_{Start}	P_{End}	t_{Start}	t_{End}	Equations, P_0		
(torr)	(torr)	(hr)	(hr)	(torr)		
(a) for T = -10°C						
760	1×10^{-2}	0	.9	$P_0 = 760\ e^{-12.5t}$		(37)
1×10^{-2}	2×10^{-4}	.9	1.0	$P_0 = \text{[illegible]}.8\text{[illegible]} \times 10^{-2} - 9.\text{[illegible]} \times 10^{-2}\ t$	$\approx P_0 = 760 - 759.9998\ t$	
2×10^{-4}	2.8×10^{-6}	1.0	22.0	$P_0 = \text{[illegible]} \times 10^{-4}\ t^{-1.38}$		(38)
(b) for T = 55°C						
760	1×10^{-2}	0	.9	$P_0 = 760\ e^{-12.5t}$		(37a)
1×10^{-2}	4.3×10^{-4}	.9	1.0	$P_0 = 9.61 \times 10^{-2} - 9.57 \times 10^{-2}\ t$	$\approx P_0 = 760 - 759.9996\ t$	
4.3×10^{-2}	7×10^{-6}	1.0	22.0	$P_0 = 4.3 \times 10^{-4}\ t^{-1.33}$		(38a)



TIME - HRS.

Figure 3–Evacuation of Clean, Dry, Empty 8' x 8' Vacuum Chamber for Vacuum Testing of Small Spacecraft

where A_s is the wall surface, T_w and T_g are respectively the wall and gas temperatures, and h is a heat transfer coefficient covering conductive, convective and radiative heat transfer and dependent on many variables such as flow regime, gas type, and initial temperature.

The heat gain of the wall in the same period is

$$dQ_w = c_p \rho V (T_w' - T_w) = C(T_w' - T_w) , \tag{40}$$

where C is the thermal capacitance of the container and T_w' is the container temperature before it changes to T_w. Setting $dQ_g = -dQ_w$, the heating or cooling rate of the wall due to gain or loss of heat to the gas is found to be

$$C \frac{dT_w}{dt} = h A_s (T_w - T_g) . \tag{41}$$

From this equation, the gas temperature can be obtained provided the coefficient h, the initial conditions, and the way in which the wall temperature varies with time are known. The solution would have to take into account heat gained or lost by the walls, including the gains due to solar radiation, aerodynamic heating, albedo and IR radiation, and power sources in the system together with the losses due to reradiation, conduction and convection from the walls.

One of the difficulties resides with the heat transfer coefficient. This coefficient changes radically from the viscous to the molecular flow regime and is related to the gas pressure by an "S" shaped curve. As shown in the kinetic theory of gases, the coefficient of heat conduction in the viscous flow regime is directly related to the gas viscosity and to the coefficient of heat capacity at constant volume (Refs. 10, 11, 14):

$$k = \frac{1}{3} \rho U C_v \lambda = \eta C_v . \tag{42}$$

Consequently, it varies directly with the temperature and is not affected by the pressure. Making appropriate substitutions in this equation and including the variation of specific heat with temperature leads to the Sutherland relation for the coefficient of heat conductivity for various gases (Ref. 11). One could use this coefficient of heat transfer at pressures in which viscous flow occurs. In this range, heat transfer by radiation is a negligible part of the total heat transfer because the emissivity of the internal surfaces is low, the temperatures involved are low, and the coefficient of conductivity is sufficiently high. For presure corresponding to the molecular flow regime, i.e., when $K_n > 1$, the heat transfer becomes orders of magnitude smaller than the viscous coefficient (Refs. 18 and 19). The heat transfer is then provided by radiation, and conduction and convection are almost inexistent. Depending on the dimension of the container, the changeover from high to low conduction heat transfer occurs between 1 torr and 10^{-5} or 10^{-6} torr.

From the above, it appears that as first approximation one could assume a coefficient of heat transfer varying inversely as the gas density,

$$h = h_0 \left(\frac{\rho}{\rho_0}\right) , \tag{43}$$

and that the heat balance equation would be

$$C\,(T_w' - T_w) = h_0 \left(\frac{\rho}{\rho_0}\right) A_s\ (T_w - T_g)\,dt. \tag{44}$$

In order to get the ratio of densities appearing in (44), one must estimate the gas temperature, which will change with the pressure. From the energy equation, assuming no inflow and the absence of external heat or work, the change in the total internal energy of the gas is equal to minus the enthalpy carried out by the gas, i.e.,

$$E' - E = \Delta H ,$$

or

$$C_v\ [m'\ T_g' - m\ T_g] = -\,(m - m')\ C_p\ T_g. \tag{45}$$

Rearranging, dividing by m', T_g and C_v and making the substitution $C_p/C_v = \gamma$,

$$\frac{T_g'}{T_g} = \frac{m}{m'}(1-\gamma) + \gamma . \tag{46}$$

Assuming the perfect gas law and that the process is isochoric,

$$m = \frac{PV}{T_g R} \quad \text{and} \quad m' = \frac{P'V}{RT_g'} ,$$

one has

$$\frac{m}{m'} = \frac{P}{p'} \frac{T_g'}{T_g} ,$$

which substituted into (46) gives

$$\frac{T_g'}{T_g} = \frac{\gamma}{1 + \left[(\gamma - 1)\frac{p}{p'}\right]} . \tag{47}$$

The ratio of masses in terms of pressure is

$$\frac{m'}{m} = \frac{1}{\gamma}\left[\frac{p'}{p} + (\gamma - 1)\right] , \tag{48}$$

and because $\rho = m/V$ and $\rho' = m'/V$ the following is obtained for the density ratio in terms of pressure ratio:

$$\frac{\rho'}{\rho} = \frac{1}{\gamma}\left[\frac{p'}{p} + (\gamma - 1)\right] . \tag{49}$$

This expression allows one to estimate the heat transfer coefficient as a function of the pressure ratio and the time, and hence to estimate the heat flow from the wall to the gas or vice versa. By an iterative procedure, one could therefore obtain a simultaneous solution of the pressure equations (2) and the heat transfer equation (44). The appropriate iterative procedure is as follows:

1. Assume, as a start, a constant gas temperature T_g ; calculate the conductance and outgassing; and upon integration of (2) obtain the pressure P', and the density ρ' from (49) and temperature $T_g{}'$ from (47).
2. Calculate the coefficient of heat transfer h from (43), and, from (44), knowing the wall temperature, evaluate the new gas temperature T_g .
3. Calculate as in step one the conductance for the next time interval and repeat the procedure.

The following points concerning the temperature and the isothermal flow conditions employed here should be kept in mind:

1. The temperature is approximately constant during the entire evacuation process with the exception of a very brief period at the start of evacuation.
2. A complete heat transfer analysis requires the inclusion of all forms of heat transfer and of heat flow from all directions. It would have to include radiation from space and from other radiating surfaces, conduction from adjacent walls, heat sources and other detailed properties of the walls.
3. Techniques for performing complex heat transfer calculations with a certain degree of confidence are being devised for spacecraft. Such calculations could provide temperature versus time for the surfaces which could then be used to estimate the gas temperature.
4. If the temperatures of the walls are known as a function of time, their effects can be utilized to establish the outgassing rates of surface materials and the gas temperature can be estimated and incorporated in the gas conductances.

METHOD OF SOLUTION – COMPUTER PROGRAM

The program for the solution of equations (2) was coded in Fortran language for the CDC 3100 computer. The numerical integration scheme used was of the fourth order Runge-Kutta type, which requires no starting values other than the initial conditions (X_0, Y_0) and which permits one to change the interval of integration, h, at any time without redoing the previous computations. The equations used in this procedure are:

$$Y_{n+1} = Y_n + 1/6\,(k_0 + 2k_1 + 2k_2 + k_3) + 0\,(h^5)\,, \tag{50}$$

where the k_i are calculated from

$$k_0 = hf\,(X_n, Y_n)$$

$$k_1 = hf\,(X_n + 1/2h,\ Y_n + 1/2k_0)$$

$$k_2 = hf\,(X_n + 1/2\,h,\ Y_n + 1/2\,k_1)$$

$$k_3 = hf\,(X_n + h,\ Y_n + k_2)$$

and 0 (h^5) is a truncation error on the order of h^5.

The integration time interval is increased exponentially from its initial value, h, to a final value of 2 h in order to speed up the computation and reflect the exponential behavior of the pressure time function. To prevent instability of the solution, however, the time interval is also modified in the process of integration as follows:

At each integration step, the program evaluates the parameter

$$\sigma = \frac{\sum_{i=1}^{4} |k_i - \bar{k}|}{\bar{k}} \tag{51}$$

where the k_i are the Runge-Kutta variables and $\bar{k}$ is their average.

If $\sigma < 1$, the time interval used for the integration has provided a value not too different from the previous value. The time interval is acceptable and the computation continues.

If $\sigma > 1$, the change from one value to the next has been too great and hence the interval is unacceptable. As a first step, the interval is reduced by 20%, the Runge-Kutta variables are reevaluated and the criteria above is rechecked. If the criteria that σ be less than one is still unsatisfied, the interval is reduced to 1/2 the previous time interval.

Examples of typical program inputs for the one- and three-volume cases, together with the corresponding solutions, are contained in Appendices A and B respectively; the program itself is documented in Appendix C.

COMPARISON OF EXPERIMENTAL AND COMPUTED RESULTS

In the process of developing the computer solution to the above system of equations with variable coefficients, several combinations of volumes, connecting passages, and outgassing materials were investigated. Some of the profiles computed will be presented in the next section together with an explanation of the parameters chosen to characterize these curves. In this section a comparison of the calculated profiles with experiment will be made.

The characteristics of the systems chosen for comparison, such as the volume dimensions, the passage dimensions, the type and amount of outgassing materials, and the external pressure profile were determined by the experimental investigation. The tests were also used to establish the pressures at which corona discharge between electrodes in the container would be initiated and extinguished and the corresponding times.

Figure 4 is a schematic of the pressure-time test setup and the orifice construction. The one-liter volume was fitted with one of three different orifices, .437 in diameter, .137 in diameter, and .040 in diameter, connecting the compartment to the simulated space environment of the 12-inch diameter by 18-inch height bell jar. The evacuation was provided by a 140-cfm mechanical roughing pump and 2-1500 lit/sec oil-diffusion pumps baffled with liquid nitrogen. The bell-jar pressure profile simulates the pressure profile encountered by a Thor-Agena B rocket carrying a 1000-pound payload into a 160-mile orbit. A Hastings thermocouple pressure gage and a nude ionization gage were used to record the pressure in the compartment. The pressure in the bell jar was recorded by a Hastings thermocouple gage and an ionization gage. The polymeric materials included in the compartment, selected as being typical of the encapsulants used in flight systems, were: Eccofoam FPH, with a density of 4 lb./cu.ft.;

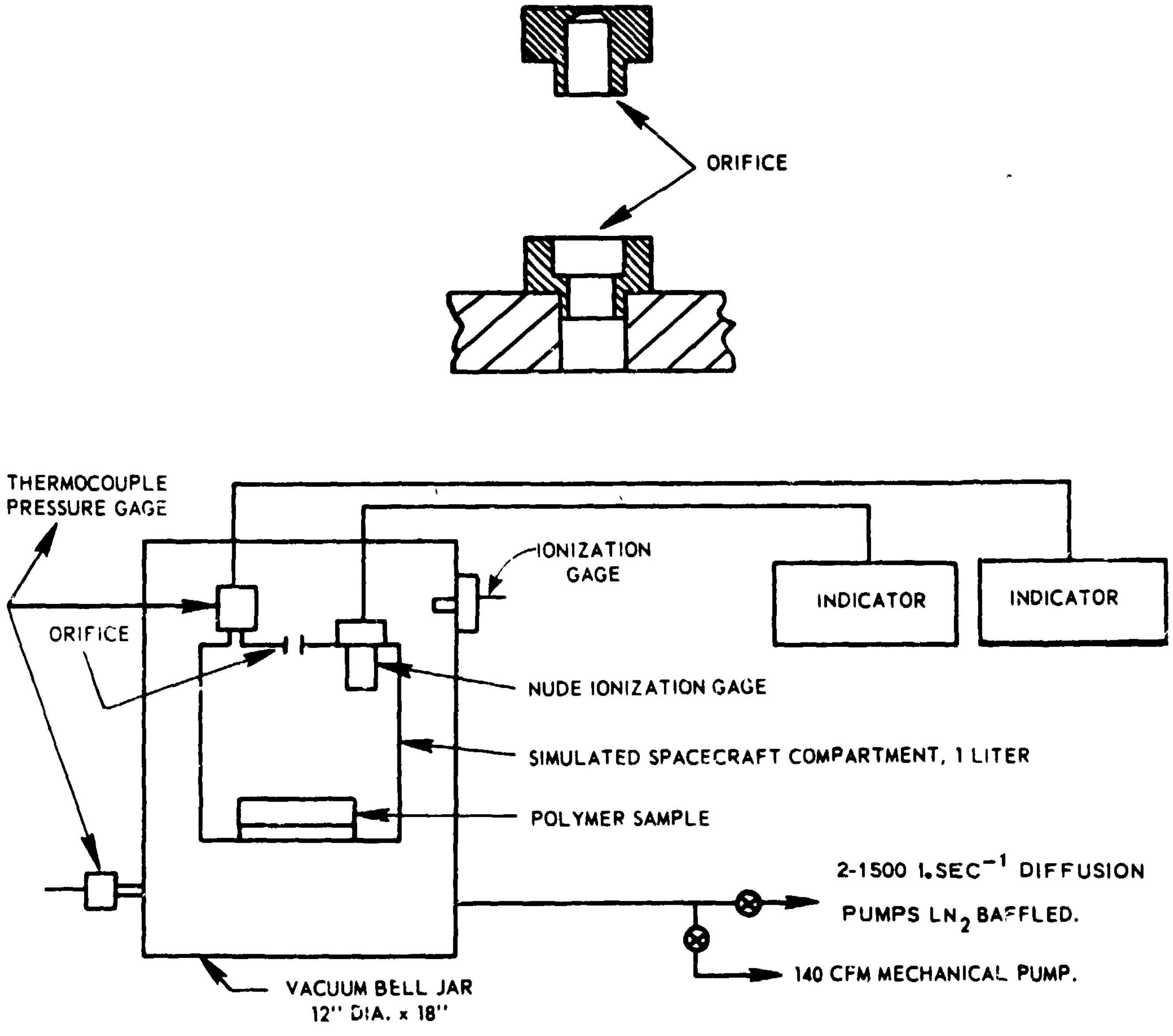


Figure 4—Pressure-Time Test Setup

silicone rubber, RTV 11; and epoxy, Biggs 823 resin. The test specimens of these materials were produced in the laboratory in accordance with accepted spacecraft application techniques. The Eccofoam and RTV samples had a surface area of 140 cm^2, while the epoxy sample consisted of a conformal coating about 0.015 inch thick over an aluminum tube with a surface area of 120 cm^2. The coating was vacuum-processed while curing. The RTV samples were outgassed for 24 hours before the test. Non-outgassed RTV caused fluctuating ionization-pressure gage readings in the 10^{-4} torr region. This was attributed to contamination of the gage elements, which rendered the gage useless for pressure measurements. The 24-hour outgassing phase is, however, typical of space hardware exposure in environment-chamber tests. The pressure versus time in the bell jar did not follow the same profile in each test but showed a variation of about one-half decade because of the influence of the variable gas load and orifice sizes. The temperature in these tests was about 21.1°C (70°F). Figures 5, 6, and 7 show both experimental and computed results for various combinations of orifice size and outgassing material. The pressure profiles for each combination were obtained separately and superposed in these figures for convenience.

Comparing these profiles, it is seen that the computed results agree very well with the experimental results. The difference (values in the same decade) may be attributed to:

- The difficulty of reproducing exactly the same pressure profile in the vacuum jar in the different runs.
- Gage errors and errors in gage-reading.
- Differences between actual material properties and those assumed in computation.

For the computation, a mathematical description of the outgassing material is used. The data for this representation are obtained from the literature and, unless data are available on the specific material being tested, divergence may be expected between test and analytical results.

It is expected that better definition of the materials should produce closer results, if needed. Also, improvements in computed results can be expected when temperature gradients between compartments are included.

APPLICATIONS AND PARAMETRIC PRESENTATIONS

Additional pressure profiles for single volumes containing various different outgassing materials were obtained. These are shown in Figures 8, 9, and 10, where they are labeled according to several parametric attributes. Profiles for the more complicated three-volume system were also computed, and these results are shown in Figure 11, parameterized in the same way.

The data obtained in the computation of these profiles can be used to estimate the length of time that should be allowed before certain electrical functions which are affected by pressure can be safely performed. They may also be used to estimate the size flow passages appropriate, for a given volume or set of volumes and given outgassing materials, to insure that suitable pressures are reached inside these volumes within a specified period of time. It would therefore be very useful to generalize the results of these computations for application

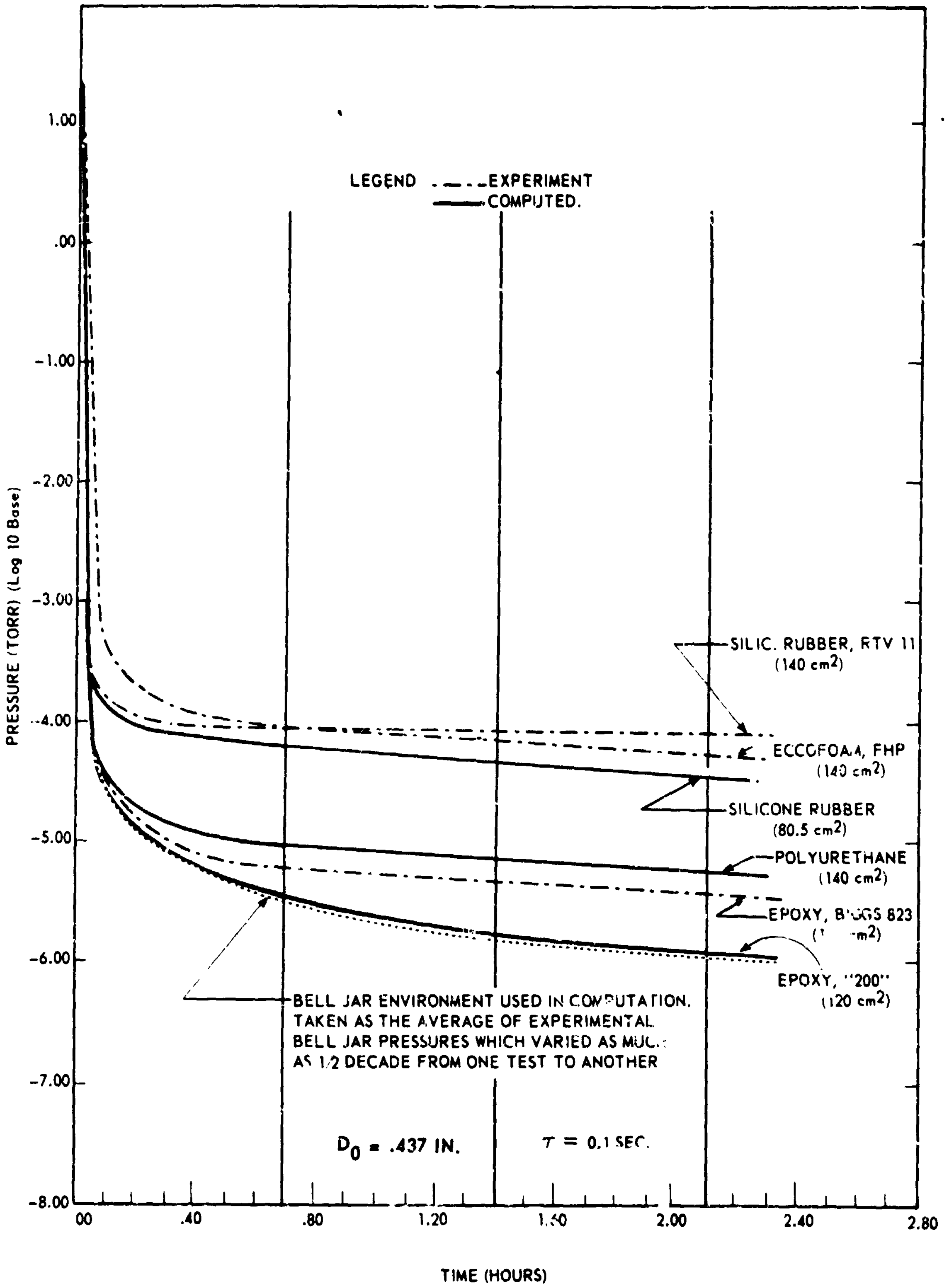
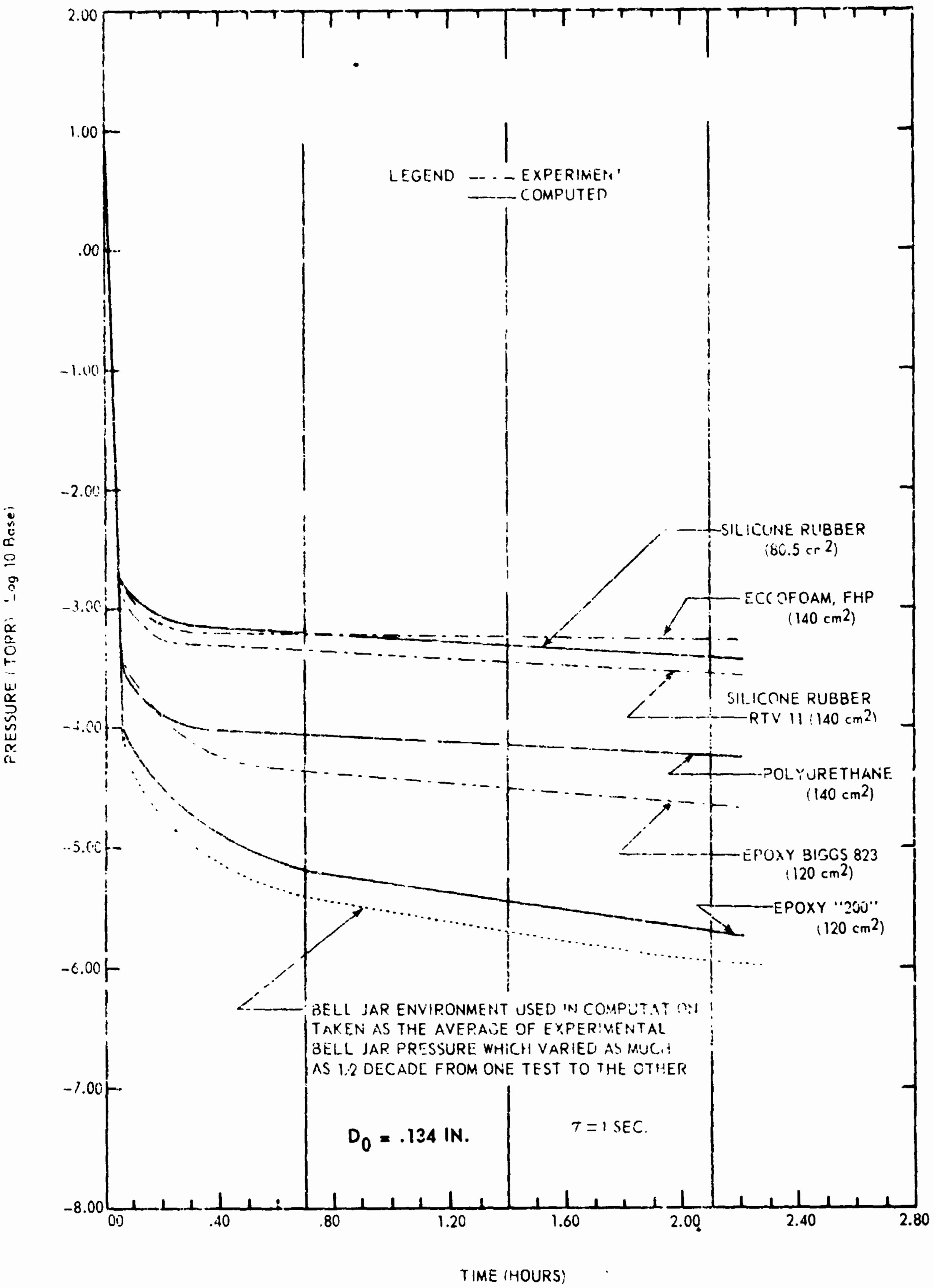


Figure 5-Comparison of Experimental and Computed Results for a 1-Liter Compartment with Orifice Diameter .437 in., $\tau = 0.1$ sec, Ambient temperature (Outgassing material types and surface areas are indicated; data on Outgassing rates used in the Computation were from ref. 15)



BELL JAR ENVIRONMENT USED IN COMPUTATION TAKEN AS THE AVERAGE OF EXPERIMENTAL BELL JAR PRESSURE WHICH VARIED AS MUCH AS 1/2 DECADE FROM ONE TEST TO THE OTHER

Figure 6—Comparison of Experimental and Computed Results for a 1-Liter Compartment with Orifice Diameter .134 in., $\tau = 1.0$ sec, Ambient temperature (Outgassing material types and surface areas are indicated; data on Outgassing rates used in the Computation were from ref. 15)

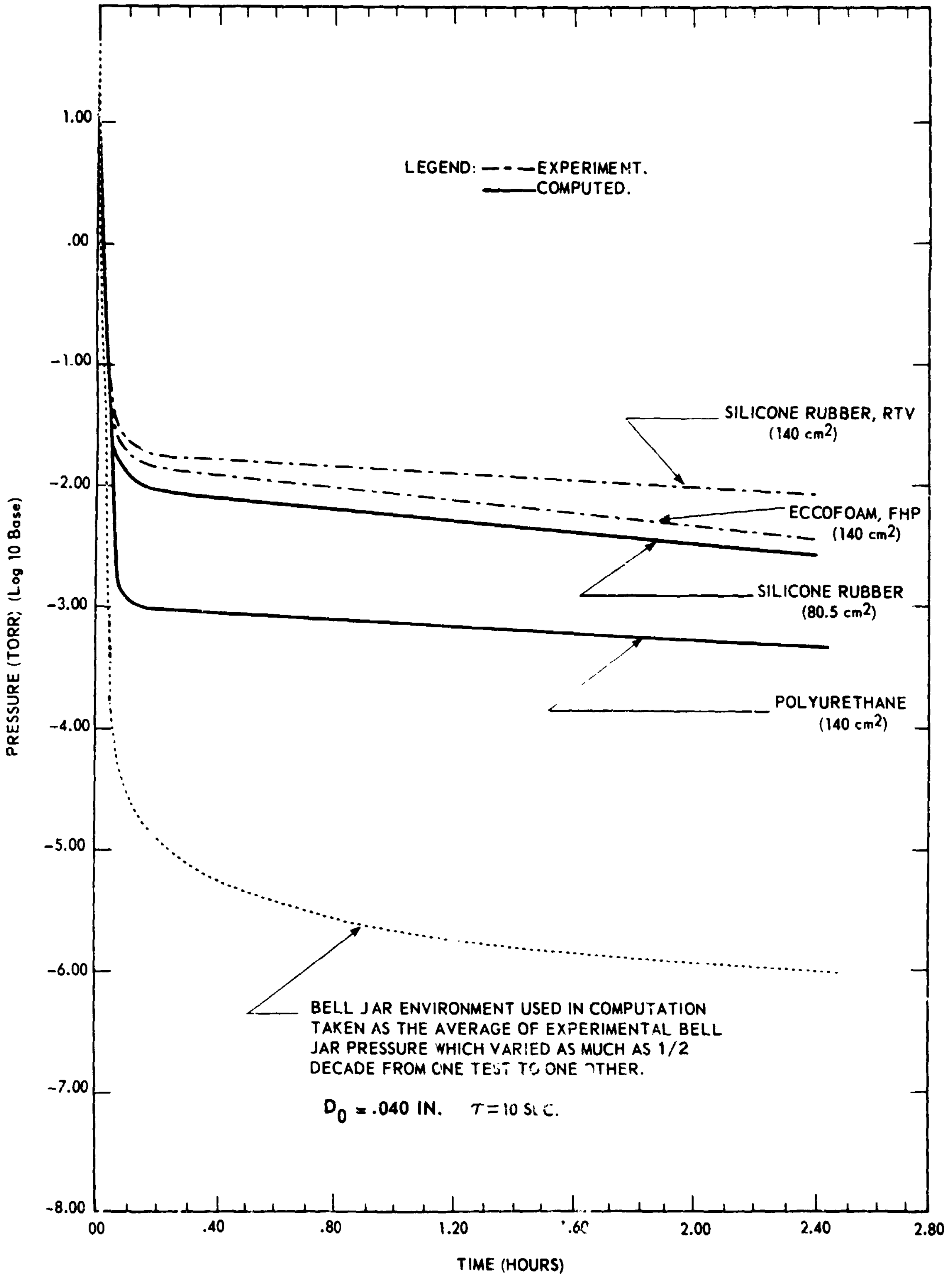


Figure 7—Comparison of Experimental and Computed Results for a 1-Liter Compartment with Orifice Diameter .040 in., τ=10 sec, Ambient Temperature (Outgassing material types and surface areas are indicated; data on Outgassing rates used in the computation were from ref. 15)

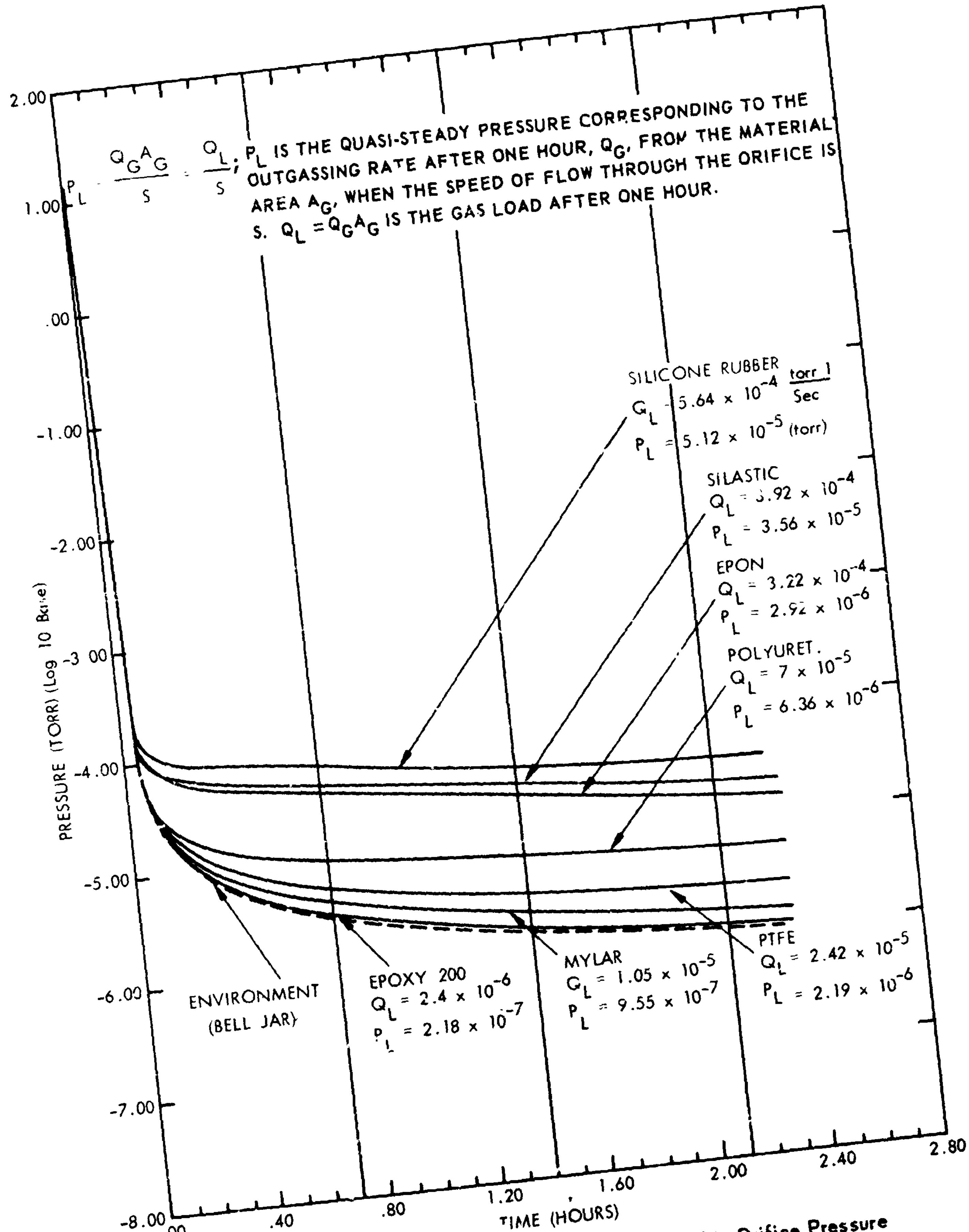


Figure 8–Parametric Curves for a One-Compartment Thin-Orifice Pressure Simulation ($\tau = 0.1$ sec) at Ambient Temperature

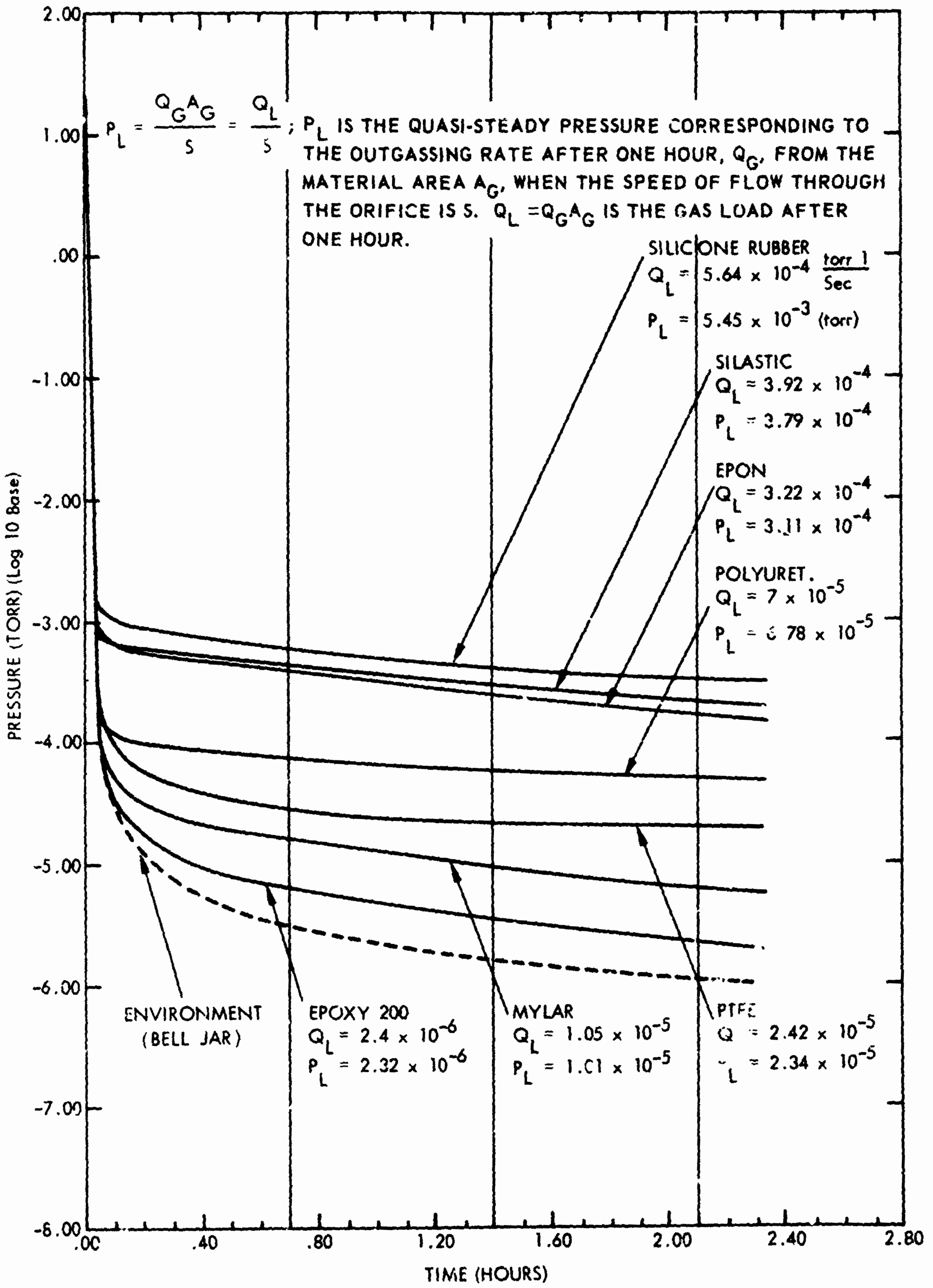


Figure 9–Parametric Curves for a One- Compartment Thin-Orifice Pressure Simulation ($\tau = 1.0$ sec) at Ambient Temperature

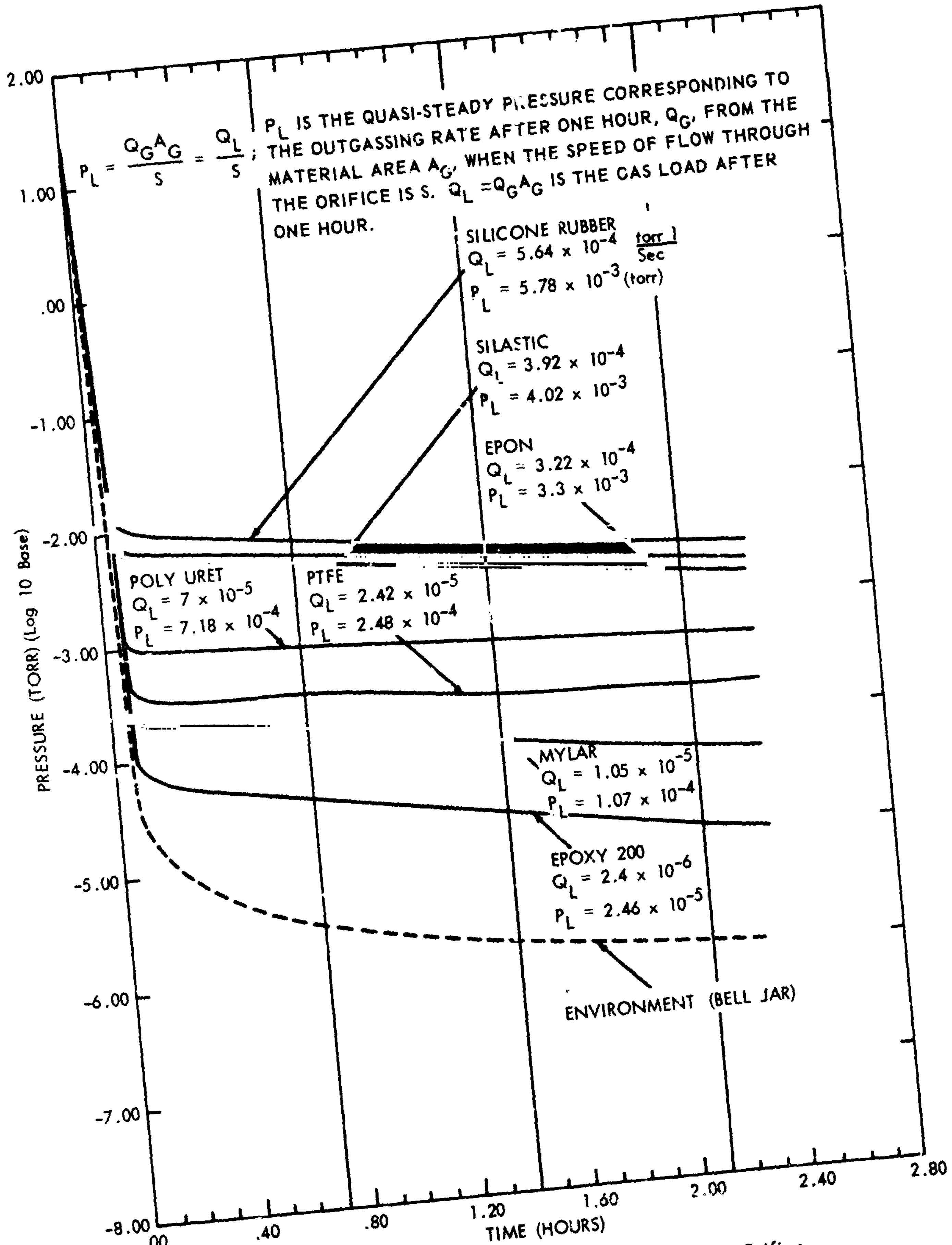


Figure 10–Parametric Curves for a One-Compartment Thin-Orifice Pressure Simulation (τ=10 sec) at Ambient Temperature

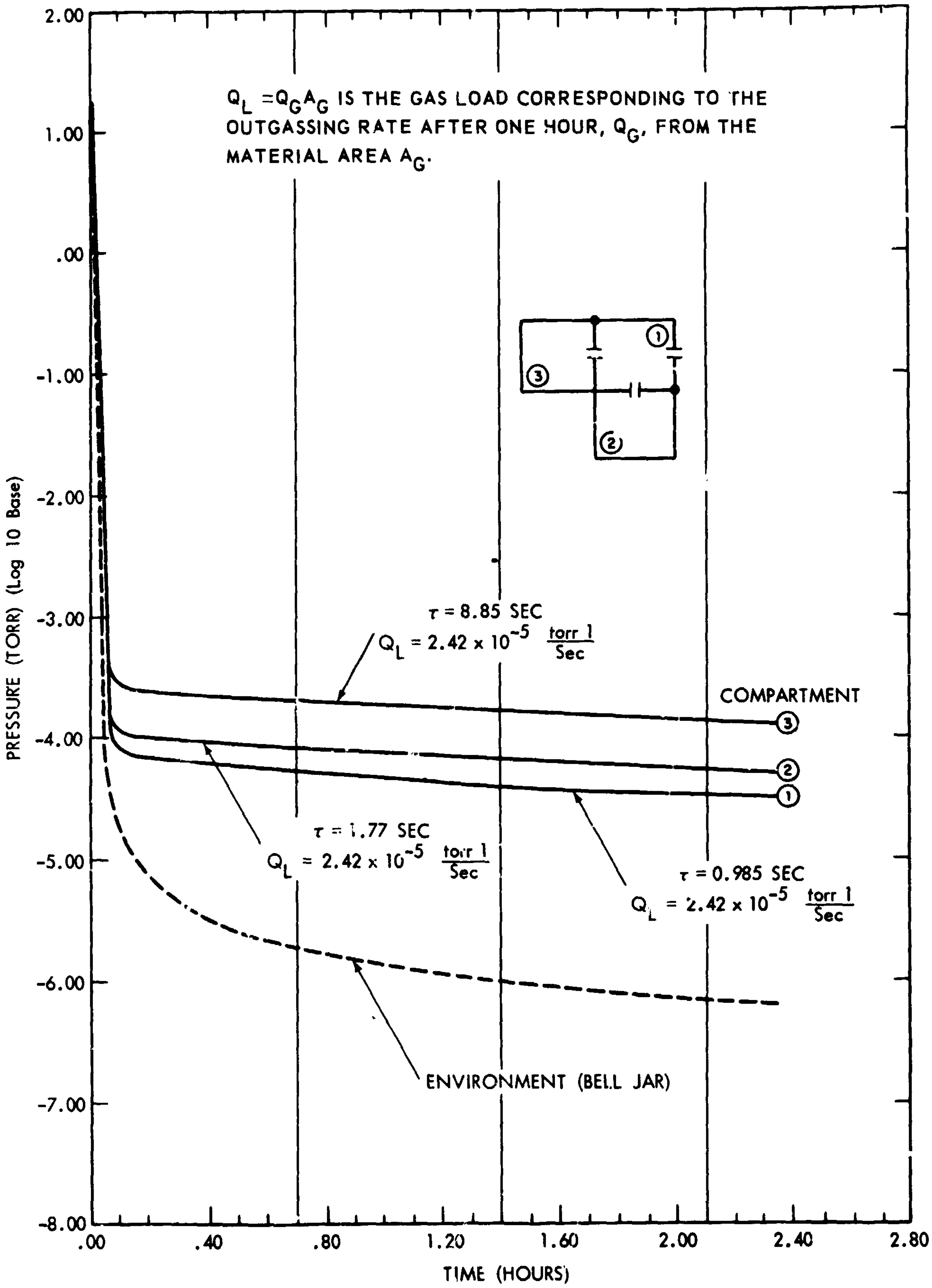


Figure 11–Parametric Curves for a Three-Compartment System having Thin Orifices, 80 cm^2 "PTFE" Outgassing Material in each Compartment, and T = 270° K.

to other cases (Ref. 20). This can be done through the use of certain parameters, namely those which have been used to label the various curves shown in the figures. The choice of these parameters is based on the following considerations.

The profiles show that within a very short period of time the pressure drops to a quasi-steady value. This sharp drop occurs in a region of viscous and transitional flow. In this region, the relations expressing the passage conductance are nonlinear and dependent on pressure and viscosity. Beyond this region, the flow is molecular and the conductance depends only on passage geometry. The quasi-steady pressure reached and the corresponding evacuation time for a given system are thus mainly a function of those parameters which characterize the flow in the free molecular regime. In view of this, the profile curves have been grouped in accordance with certain parameters in the molecular region of the curves which are amenable to generalization, namely the molecular time constant, τ, the outgassing material gas load at 1 hour vacuum exposure, Q_L, and the quasi-steady pressure, P_L.

The molecular time constant, which relates the size of the volume to the pumping speed in the molecular flow region of the passage, represents the time needed for the pressure to drop to $1/e = 0.368$ of the initial pressure and is

$$\tau = \frac{V}{S} \text{ (sec)}, \tag{52}$$

where V (liters) is the volume of the container to be evacuated and S (lit/sec) is the pumping speed of the passage. The pumping speed for an orifice of area A (cm ^{2}) in the molecular flow region (corresponding to a pressure of 10^{-2} to 10^{-3} torr for the present orifice diameters and for air at 20°C), is a constant:

$$S = 11.6 \ A \ (1/\text{sec}). \tag{53}$$

The time constant, which presupposes molecular flow with constant conductance and no source of gas in the volume being evacuated, is obtained from the solution of the linear differential equation expressing the flow balance; i.e.,

$$\left(- V \frac{dP}{dt} = SP \right)$$

in the molecular region and can be visualized as the slope of the log of the pressure profile at time zero.

If a constant i.e., independent of pressure and time, source of gas Q_L (torr-l/sec) exists, such as that provided by a leak into the volume, the differential equation will be

$$-V\frac{dP}{dt} = SP - Q_L\,, \tag{54}$$

the solution of which is

$$P = P_i\, e^{-S/V\ t} + \frac{Q_L}{S}. \tag{55}$$

This equation shows that as $t \to \infty$ the first term becomes very small, so that the second term controls the pumpdown. For Q_L constant, an equilibrium pressure,

$$P_L = \frac{Q_L}{S}\,, \tag{56}$$

is thus obtained. This pressure represents the condition for equilibrium between the inflow leakage, Q_L, and the outflow through the orifice, SP_L. But when the in-leakage is caused by material outgassing, the rate of inflow is not constant, but is a decreasing function of time. Consequently, after the initial rapid decay, the pressure continues to decay slowly, rather than stabilizing at an equilibrium value. However, one can define a quasi-steady-state outgassing rate Q_L as the outflow rate from the material after 1 hour of outgassing in vacuum, and then use the corresponding quasi-steady-state equilibrium pressure as one of the parameters describing the system. This equilibrium pressure will be:

$$P_L = \frac{Q_L}{S} = \frac{A_G\, Q_G}{S}\ . \tag{57}$$

where A_g (cm^2) is the surface area of the outgassing material;

$$Q_G\left(\frac{\text{torr lit}}{\text{sec-cm}^2}\right),$$

is the material rate of gas output after 1 hour of vacuum exposure, as given in Tables 2 and 3; and S (lit/sec) is the pumping speed for the orifice, as given by equation (53). This pressure is not the ultimate pressure obtained in the volume but is representative of the slowly decaying pressure. Table 6 lists for various systems the geometric data, the outgassing material, the characteristic rate Q_G, the corresponding load rate Q_L, the calculated pumping speed S, and, finally, the resulting parameters τ and P_L.

CONCLUSIONS

An analytical tool which provides internal pressure profiles for volumes exposed to vacuum has been developed. Comparison between calculated and experimentally obtained pressure profiles has shown sufficient agreement between the two. The computer program developed to provide this information by solving a system of differential equations is general and can be applied to a system having many volumes, interconnected with various types of passages and containing materials outgassing in a known manner, such as is the case in a spacecraft. The computer results, obtained in both numerical and graphical form, can be used to provide the following information:

- The long term pressure conditions in a compartment.
- The time required to reach the quasi-steady state pressure.
- The pressure differential across surfaces.
- The effects of variation of chamber volume and passage size on attainable pressures.
- The results for an assembly of experiment packages, given the results of tests of the individual packages.
- The equivalent conductance of an experimental package tested in a vacuum chamber, including the outgassing effect of materials and surfaces in the package.

Table 6
Volume/Orifice/Material Combinations and Calculated Parameters

Volu. V (l)	Orifice Area A_o (cm²)	Pumping Speed S (l/s)	Surface Area And Material A_G (cm²)	*Rate Material Outgassing @ 1 Hour Q_G (torr-l/sec-cm²)	System Outgassing Rate After 1 Hour Q_L (torr-l/sec)	Time Const. - (sec)	Quasi-Steady Equilibrium Pressure P_L (torr)	Time For Quasi-Steady Pressure t_L (hr)
1	.975	11	80.5 Silic. Rubb.	7.0×10^{-6}	5.64×10^{-4}	0.1	5.12×10^{-5}	.99
1	.975	11	80.5 Epon	4.0×10^{-6}	3.22×10^{-4}	0.1	2.92×10^{-5}	1.30
1	.975	11	80.5 PTFE	3.0×10^{-7}	2.42×10^{-5}	0.1	2.19×10^{-6}	2.80
1	.975	11	80.5 Mylar	1.3×10^{-7}	1.05×10^{-5}	0.1	9.55×10^{-7}	3.0
1	.975	11	120.0 Epoxy "200"	2.0×10^{-8}	2.4×10^{-6}	0.1	2.18×10^{-7}	4.4
1	.975	11	140.0 Polyuret.	5.0×10^{-7}	7.0×10^{-5}	0.1	6.36×10^{-6}	1.75
1	.975	11	140.0 Silastic	2.8×10^{-6}	3.92×10^{-4}	0.1	3.56×10^{-5}	1.35
1	.0914	1.032	80.5 Silic. Rubb.	7.0×10^{-6}	5.64×10^{-4}	1.0	5.45×10^{-4}	.82
1	.0914	1.032	80.5 Epon	4.0×10^{-6}	3.22×10^{-4}	1.0	3.11×10^{-4}	1.0
1	.0914	1.032	80.5 PTFE	3.0×10^{-7}	2.42×10^{-5}	1.0	2.34×10^{-5}	1.08
1	.0914	1.032	80.5 Mylar	1.3×10^{-7}	1.05×10^{-5}	1.0	1.01×10^{-5}	1.30
1	.0914	1.032	120.0 Epoxy "200"	2.0×10^{-8}	2.4×10^{-6}	1.0	2.32×10^{-6}	1.95
1	.0914	1.032	140.0 Polyuret.	5.0×10^{-7}	7.0×10^{-5}	1.0	6.78×10^{-5}	1.10
1	.0914	1.032	140.0 Silastic	2.8×10^{-6}	3.92×10^{-4}	1.0	3.79×10^{-4}	1.0
1	.00862	.0975	80.5 Silic. Rubb.	7.0×10^{-6}	5.64×10^{-4}	10.0	5.78×10^{-3}	1.09
1	.00862	.0975	80.5 Epon	4.0×10^{-6}	3.22×10^{-4}	10.0	3.3×10^{-3}	1.14
1	.00862	.0975	80.5 PTFE	3.0×10^{-7}	2.42×10^{-5}	10.0	2.48×10^{-4}	1.10
1	.00862	.0975	80.5 Mylar	1.3×10^{-7}	1.05×10^{-5}	10.0	1.075×10^{-4}	1.04
1	.00862	.0975	120.0 Epoxy "200"	2.0×10^{-8}	2.4×10^{-6}	10.0	2.46×10^{-5}	1.10
1	.00862	.0975	140.0 Polyuret.	5.0×10^{-7}	7.0×10^{-5}	10.0	7.18×10^{-4}	.90
1	.00862	.0975	140.0 Silastic	2.8×10^{-6}	3.92×10^{-4}	10.0	4.02×10^{-3}	.95

*Data from reference 15

- The behavior of a system in any other environment, given the results obtained in a vacuum chamber.

Many pressure profiles have been calculated both for a single volume and for multi-volume arrangements; some of these profiles have been included here. Parameters have been introduced to generalize the results of these particular test runs so that they may be used to estimate conditions for other similar systems.

RECOMMENDATIONS

Calculation of pressure profiles should be carried out in conjunction with a thermal analysis of the system, which provides the transient temperatures of the system walls. By the method delineated here, these temperatures can be used to estimate the gas temperature and consequently provide improved values of the flow passage conductances. The data from the thermal analysis can also be used to establish the temperatures of the compartment surface more accurately. This better knowledge of the outgassing surface temperatures should then, in turn, provide a better definition of the material outgassing rates. This requires, however, a better knowledge of the variation of material outgassing rates with temperature than is available at present.

As an additional improvement in the calculation of the pressure profiles, the computer program should be made more efficient to provide faster computation for very large systems.

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APPENDIX A

TYPICAL COMPUTER INPUT DATA AND CORRESPONDING SOLUTION FOR THE SINGLE CHAMBER CASE

APPENDIX A

TYPICAL COMPUTER INPUT DATA AND CORRESPONDING SOLUTION FOR THE SINGLE CHAMBER CASE

```
                                * I N P U T   D A T A *
                 ***************************************************************

                                NUMBER OF CHAMBERS = 1

                         TEMPERATURE =  290.0000 DEGREES KELVIN

                        MOLECULAR WEIGHT OF GAS =   29.0000 GRAMS

              SIMULATION PERFORMED FROM        0 SECONDS UP TO    8400.000 SECONDS

                  WITH INITIAL INTEGRATION STEP SIZE OF    .001000000 SECONDS

*******************************************************************************************

CHAMBER 1          VOLUME =     1.0000 LITERS              INITIAL PRESSURE -  760.0000 TORR

                   SURFACE AREA NO. 1 =   140.0000 SQ.CM.,  MATERIAL IS POLYURET.
                                                 1) Q(INI[illegible]) = 5.3142E-07 TORR-LITER/SEC/SQ.CM.
                      OUTGASSING CHARACTERISTICS - 2) Q([illegible])     1.4994E-07 TORR-LITER/SEC/SQ.CM.
                                                 3) [illegible]240E 03 SECONDS

                   CONDUCTANCE NO. 1 - C( 1, 0) OF TYPE 1    8.62000E-03              0              0

*******************************************************************************************

                              TIME VERSUS PRESSURE ENVIRONMENT
               1)             0 SECONDS   -    760.0000000000 TORR
               2)     120.000000 SECONDS  -       .0001800000 TORR
               3)     240.000000 SECONDS  -       .0000500000 TORR
               4)     360.000000 SECONDS  -       .0000250000 TORR
               5)     480.000000 SECONDS  -       .0000180000 TORR
               6)     600.000000 SECONDS  -       .0000145000 TORR
               7)     720.000000 SECONDS  -       .0000120000 TORR
               8)     840.000000 SECONDS  -       .0000100000 TORR
               9)     960.000000 SECONDS  -       .0000085000 TORR
              10)    1080.000000 SECONDS  -       .0000072000 TORR
              11)    1200.000000 SECONDS  -       .0000065000 TORR
              12)    1320.000000 SECONDS  -       .0000058000 TORR
              13)    1440.000000 SECONDS  -       .0000053000 TORR
              14)    1560.000000 SECONDS  -       .0000046000 TORR
              15)    1680.000000 SECONDS  -       .0000043000 TORR
              16)    1800.000000 SECONDS  -       .0000040000 TORR
              17)    1920.000000 SECONDS  -       .0000037500 TORR
              18)    2040.000000 SECONDS  -       .0000035000 TORR
              19)    2160.000000 SECONDS  -       .0000034000 TORR
              20)    2280.000000 SECONDS  -       .0000033000 TORR
              21)    2400.000000 SECONDS  -       .0000032500 TORR
              22)    2760.000000 SECONDS  -       .0000027500 TORR
              23)    3120.000000 SECONDS  -       .0000025000 TORR
              24)    3600.000000 SECONDS  -       .0000022500 TORR
              25)    4200 000000 SECONDS  -       .0000019000 TORR
              26)    4800.000000 SECONDS  -       .0000016500 TORR
              27)    5400.000000 SECONDS  -       .0000015000 TORR
              28)    6000.000000 SECONDS  -       .0000014000 TORR
              29)    7200.000000 SECONDS  -       .0000011000 TORR
              30)    8400.000000 SECONDS  -       .0000010000 TORR
              31)   43200.000000 SECONDS  -       .0000007000 TORR

                              * *   S O L U T I O N   * *

            T =         0        0)  7.60000000E 02        1)  7.60000000E 02
            T =    84.1355       0)  2.27142149E 02        1)  2.30314632E 02
            T =   173.9956       0)  1.21504745E-04        1)  1.85907475E-01
            T =   266.1143       0)  4.45595118E-05        1)  1.14773874E-03
            T =   339.4261       0)  2.92862237E-05        1)  9.71821231E-04
            T =   432.0815       0)  2.07952440E-05        1)  9.52124784E-04
            T =   531.1716       0)  1.65074955E-05        1)  9.39300091E-04
            T =   599.2311       0)  1.45224276E-05        1)  9.31724315E-04
            T =   707.9405       0)  1.22512394E-05        1)  9.20547410E-04
            T =   789.1608       0)  1.08473197E-05        1)  9.12580641E-04
            T =   882.3989       0)  9.47001430E-06        1)  9.03711672E-04
            T =   935.7704       0)  8.80287044E-06        1)  8.98995357E-04
            T =  1025.7402       0)  7.78781437E-06        1)  8.90717563E-04
            T =  1119.8364       0)  6.96762109E-06        1)  8.82688798E-04
            T =  1183.9344       0)  6.59371626E-06        1)  8.77398674E-04
            T =  1284.8116       0)  6.00526595E-06        1)  8.60157684E-04
```

```
T = 1358.3974     0)  5.64001079E-06      1)  8.63248024E-04
T = 1441.0975     0)  5.29359789E-06      1)  8.56748687E-04
T = 1538.4996     0)  4.72541878E-06      1)  8.48987249E-04
T = 1667.5807     0)  4.33104836E-06      1)  8.37895927E-04
T = 1695.5807     0)  4.26104836E-06      1)  8.36737530E-04
T = 1789.6607     0)  4.02584836E-06      1)  8.30160636E-04
T = 1853.3245     0)  3.88890710E-06      1)  8.25512391E-04
T = 1952.2068     0)  3.68290240E-06      1)  8.18364828E-04
T = 2022.8399     0)  3.53575623E-06      1)  8.13307634E-04
T = 2100.7274     0)  3.44939387E-06      1)  8.07839556E-04
T = 2190.1394     0)  3.37488382E-06      1)  8.01662231E-04
T = 2297.6204     0)  3.29265815E-06      1)  7.94322756E-04
T = 2370.8099     0)  3.26216255E-06      1)  7.89407651E-04
T = 2447.8099     0)  3.18359739E-06      1)  7.84253123E-04
T = 2531.8099     0)  3.06693077E-06      1)  7.78598602E-04
T = 2615.8099     0)  2.95026406E-06      1)  7.73055377E-04
T = 2699.8099     0)  2.83359739E-06      1)  7.67508076E-04
T = 2783.8099     0)  2.73346536E-06      1)  7.62084392E-04
T = 2867.8099     0)  2.67513203E-06      1)  7.56689195E-04
T = 2951.8099     0)  2.61679870E-06      1)  7.51422111E-04
T = 3035.8099     0)  2.55846536E-06      1)  7.46130381E-04
T = 3119.8099     0)  2.50013203E-06      1)  7.40963285E-04
T = 3203.8099     0)  2.45634902E-06      1)  7.35784074E-04
T = 3287.8099     0)  2.41259902E-06      1)  7.30733062E-04
T = 3371.8099     0)  2.36884902E-06      1)  7.25653482E-04
T = 3455.8099     0)  2.32509902E-06      1)  7.20698557E-04
T = 3539.8099     0)  2.28134902E-06      1)  7.15716433E-04
T = 3623.8099     0)  2.23611090E-06      1)  7.10854588E-04
T = 3707.8099     0)  2.18711090E-06      1)  7.05964194E-04
T = 3791.8099     0)  2.13811190E-06      1)  7.01189710E-04
T = 3875.8099     0)  2.08911090E-06      1)  6.96393176E-04
T = 3959.8099     0)  2.04011090E-06      1)  6.91709405E-04
T = 4043.8099     0)  1.99111090E-06      1)  6.87004905E-04
T = 4127.8099     0)  1.94211091E-06      1)  6.82320686E-04
T = 4211.8099     0)  1.89507922E-06      1)  6.76299808E-04
T = 4301.9493     0)  1.85752114E-06      1)  6.72957932E-04
T = 4378.2386     0)  1.82573392E-06      1)  6.68891970E-04
T = 4467.8271     0)  1.78840536E-06      1)  6.64159932E-04
T = 4555.8326     0)  1.75173641E-06      1)  6.59564655E-04
T = 4637.8048     0)  1.71758134E-06      1)  6.55559902E-04
T = 4714.8921     0)  1.68546163E-06      1)  6.51437687E-04
T = 4793.5315     0)  1.65269527E-06      1)  6.47392579E-04
T = 4876.4495     0)  1.63088762E-06      1)  6.43221782E-04
T = 4969.7741     0)  1.60755648E-06      1)  6.39666314E-04
T = 5053.7115     0)  1.58657214E-06      1)  6.34519523E-04
T = 5127.6451     0)  1.56808872E-06      1)  6.30838776E-04
T = 5231.5201     0)  1.54211997E-06      1)  6.25812798E-04
T = 5320.1376     0)  1.51996559E-06      1)  6.21594333E-04
T = 5389.7050     0)  1.50257376E-06      1)  6.18408762E-04
T = 5472.5345     0)  1.48791092E-06      1)  6.14501614E-04
T = 5549.7596     0)  1.47504007E-06      1)  6.10859925E-04
T = 5630.1204     0)  1.46164661E-06      1)  6.07154418E-04
T = 5718.2506     0)  1.44695823E-06      1)  6.03161618E-04
T = 5815.9234     0)  1.43067943E-06      1)  5.98965045E-04
T = 5888.5251     0)  1.41857915E-06      1)  5.95533271E-04
T = 5988.0210     0)  1.40199649E-06      1)  5.91109161E-04
T = 6068.4699     0)  1.38288254E-06      1)  5.87589348E-04
T = 6161.6690     0)  1.35958276E-06      1)  5.83572149E-04
T = 6229.1726     0)  1.34270686E-06      1)  5.80776011E-04
T = 6311.3259     0)  1.32216853E-06      1)  5.77239071E-04
T = 6387.9206     0)  1.30301985E-06      1)  5.73950253E-04
T = 6495.5343     0)  1.27611643E-06      1)  5.69447944E-04
T = 6555.0361     0)  1.26124097E-06      1)  5.67000068E-04
T = 6651.9116     0)  1.23702211E-06      1)  5.63161361E-04
T = 6729.9213     0)  1.21751968E-06      1)  5.59902556E-04
T = 6827.3831     0)  1.19315423E-06      1)  5.55940031E-04
T = 6904.8387     0)  1.17379032E-06      1)  5.52859541E-04
T = 6992.0153     0)  1.15199615E-06      1)  5.49433897E-04
T = 7060.4514     0)  1.13488715E-06      1)  5.46810049E-04
T = 7143.7517     0)  1.11406207E-06      1)  5.43574912E-04
T = 7233.3363     0)  1.09722197E-06      1)  5.40111525E-04
T = 7329.8655     0)  1.08917788E-06      1)  5.36470726E-04
T = 7414.8326     0)  1.08209728E-06      1)  5.33303253E-04
T = 7483.5755     0)  1.07636871E-06      1)  5.30786348E-04
T = 7575.9119     0)  1.06867401E-06      1)  5.27452738E-04
T = 7655.7966     0)  1.06201695E-06      1)  5.24515765E-04
T = 7738.9250     0)  1.05508958E-06      1)  5.21522216E-04
T = 7830.0904     0)  1.04749246E-06      1)  5.18336827E-04
T = 7909.9289     0)  1.04083926E-06      1)  5.15477140E-04
T = 8003.6138     0)  1.03303218E-06      1)  5.12168054E-04
T = 8078.0679     0)  1.02682768E-06      1)  5.09595955E-04
T = 8161.8661     0)  1.01984445E-06      1)  5.06730331E-04
T = 8265.3065     0)  1.01122446E-06      1)  5.03292884E-04
T = 8324.9540     0)  1.00625383E-06      1)  5.01332075E-04
T = 8404.7491     0)  9.99959059E-07      1)  4.98623339E-04
```

APPENDIX B

TYPICAL COMPUTER INPUT DATA AND CORRESPONDING SOLUTION FOR THE THREE-CHAMBER CASE

APPENDIX B

TYPICAL COMPUTER INPUT DATA AND CORRESPONDING SOLUTION FOR THE THREE-CHAMBER CASE

```
                              * I N P U T   D A T A *
                  ****************************************************
                              NUMBER OF CHAMBERS = 3
                        TEMPERATURE =  270.0000 DEGREES KELVIN
                      MOLECULAR WEIGHT OF GAS =   29.0000 GRAMS
           SIMULATION PERFORMED FROM        0 SECONDS UP TO    8400.000 SECONDS
              WITH INITIAL INTEGRATION STEP SIZE OF     .001000000 SECONDS
 ****************************************************************************************
CHAMBER 1        VOLUME =     1.0000 LITERS             INITIAL PRESSURE =  760.0000 TORR
                 SURFACE AREA NO. 1 =    80.9000 SQ.CM.,  MATERIAL IS  PTFE
                                             1) Q(INITIAL) = 3.1005E-07 TORR-LITER/SEC/SQ.CM.
                    OUTGASSING CHARACTERISTICS - 2) Q(FINAL) = 6.9963E-08 TORR-LITER/SEC/SQ.CM.
                                             3) TAU = 8.6230E 03 SECONDS
                 CONDUCTANCE NO. 1 - C( 1, 0) OF TYPE 1    9.00000E-02          0          0
                 CONDUCTANCE NO. 2 - C( 1, 2) OF TYPE 1    5.00000E-02          0          0
                 CONDUCTANCE NO. 3 - C( 1, 3) OF TYPE 1    1.00000E-02          0          0
 ****************************************************************************************
CHAMBER 2        VOLUME =     1.0000 LITERS             INITIAL PRESSURE =  760.0000 TORR
                 SURFACE AREA NO. 1 =    80.5000 SQ.CM.,  MATERIAL IS EPOXY
                                             1) Q(INITIAL) = 7.2869E-06 TORR-LITER/SEC/SQ.CM.
                    OUTGASSING CHARACTERISTICS - 2) Q(FINAL) = 2.4260E-07 TORR-LITER/SEC/SQ.CM.
                                             3) TAU = 5.4324E 03 SECONDS
                 CONDUCTANCE NO. 1 - C( 2, 1) OF TYPE 1    5.00000E-02          0          0
 ****************************************************************************************
CHAMBER 3        VOLUME =     1.0000 LITERS             INITIAL PRESSURE =  760.0000 TORR
                 SURFACE AREA NO. 1 =    80.5000 SQ.CM.,  MATERIAL IS  RTV
                                             1) Q(INITIAL) = 1.2819E-05 TORR-LITER/SEC/SQ.CM.
                    OUTGASSING CHARACTERISTICS - 2) Q(FINAL) = 5.4900E-07 TORR-LITER/SEC/SQ.CM.
                                             3) TAU = 5.7800E 03 SECONDS
                 CONDUCTANCE NO. 1 - C( 3, 1) OF TYPE 1    1.00000E-02          0          0
 ****************************************************************************************


                            TIME VERSUS PRESSURE ENVIRONMENT


                    1)            0 SECONDS   -    760.0000000000 TORR
                    2)   120.000000 SECONDS   -        .0001000000 TORR
                    3)   240.000000 SECONDS   -        .0000500000 TORR
                    4)   360.000000 SECONDS   -        .0000250000 TORR
                    5)   480.000000 SECONDS   -        .0000180000 TORR
                    6)   600.000000 SECONDS   -        .0000145000 TORR
                    7)   720.000000 SECONDS   -        .0000120000 TORR
                    8)   840.000000 SECONDS   -        .0000100000 TORR
                    9)   960.000000 SECONDS   -        .0000085000 TORR
                   10)  1080.000000 SECONDS   -        .0000072000 TORR
                   11)  1200.000000 SECONDS   -        .0000065000 TORR
                   12)  1320.000000 SECONDS   -        .0000059000 TORR
                   13)  1440.000000 SECONDS   -        .0000053000 TORR
                   14)  1560.000000 SECONDS   -        .0000046000 TORR
                   15)  1680.000000 SECONDS   -        .0000043000 TORR
                   16)  1800.000000 SECONDS   -        .0000040000 TORR
                   17)  1920.000000 SECONDS   -        .0000037500 TORR
                   18)  2040.000000 SECONDS   -        .0000035000 TORR
                   19)  2160.000000 SECONDS   -        .0000034000 TORR
                   20)  2280.000000 SECONDS   -        .0000033000 TORR
                   21)  2400.000000 SECONDS   -        .0000032500 TORR
                   22)  2700.000000 SECONDS   -        .0000027900 TORR
                   23)  3120.000000 SECONDS   -        .0000025000 TORR
                   24)  3600.000000 SECONDS   -        .0000022900 TORR
                   25)  4200.000000 SECONDS   -        .0000019600 TORR
                   26)  4800.000000 SECONDS   -        .0000018500 TORR
                   27)  5400.000000 SECONDS   -        .0000019000 TORR
                   28)  6000.000000 SECONDS   -        .0000014000 TORR
                   29)  7200.000000 SECONDS   -        .0000011000 TORR
                   30)  8400.000000 SECONDS   -        .0000010000 TORR
                   31) 43200.000000 SECONDS   -        .0000007690 TORR
```

** SOLUTION **

```
T =         0     0) 7.60000000E 02    1) 7.60000000E 02    2) 7.60000000E 02    3) 7.60000000E 02
T =  168.5189     0) 1.27437836E-04    1) 5.43379987E-03    2) 7.78920165E-03    3) 4.01949213E-02
T =  252.4824     0) 4.73994914E-05    1) 1.64313648E-03    2) 2.69383548E-03    3) 1.04938276E-02
T =  336.5346     0) 2.98886220E-05    1) 1.60172320E-03    2) 2.63654501E-03    3) 1.02000019E-02
T =  422.1280     0) 2.13758674E-05    1) 1.57032879E-03    2) 2.58926110E-03    3) 1.01865222E-02
T =  507.7033     0) 1.71896539E-05    1) 1.54305162E-03    2) 2.54781369E-03    3) 9.98012073E-03
T =  588.3855     0) 1.48387549E-05    1) 1.52189262E-03    2) 2.51833065E-03    3) 9.84603417E-03
T =  673.4919     0) 1.29689196E-05    1) 1.49703177E-03    2) 2.47223408E-03    3) 9.70702981E-03
T =  756.4319     0) 1.13928013E-05    1) 1.47581541E-03    2) 2.43594551E-03    3) 9.57373649E-03
T =  841.5878     0) 9.98015204E-06    1) 1.45365835E-03    2) 2.39943036E-03    3) 9.43920395E-03
T =  926.1241     0) 8.92344922E-06    1) 1.43240784E-03    2) 2.36408480E-03    3) 9.30782452E-03
T = 1008.7747     0) 7.97160716E-06    1) 1.41218120E-03    2) 2.32988445E-03    3) 9.18130103E-03
T = 1092.3219     0) 7.12812246E-06    1) 1.39154271E-03    2) 2.29623839E-03    3) 9.05539400E-03
T = 1176.2980     0) 6.63826169E-06    1) 1.37179018E-03    2) 2.24319046E-03    3) 8.93093168E-03
T = 1261.7563     0) 6.13975471E-06    1) 1.35194120E-03    2) 2.22998302E-03    3) 8.80617094E-03
T = 1347.5875     0) 5.68505204E-06    1) 1.33171181E-03    2) 2.19750099E-03    3) 8.68277595E-03
T = 1428.2647     0) 5.34889728E-06    1) 1.31638872E-03    2) 2.16695270E-03    3) 8.56444885E-03
T = 1512.2454     0) 4.87856872E-06    1) 1.29577210E-03    2) 2.13580140E-03    3) 8.45110798E-03
T = 1596.1080     0) 4.50973000E-06    1) 1.27720411E-03    2) 2.10532804E-03    3) 8.33965464E-03
T = 1680.5957     0) 4.29851063E-06    1) 1.25958309E-03    2) 2.07506608E-03    3) 8.22118874E-03
T = 1764.0559     0) 4.08986029E-06    1) 1.24212953E-03    2) 2.04578510E-03    3) 8.10976041E-03
T = 1849.0270     0) 3.89786044E-06    1) 1.22462649E-03    2) 2.01628003E-03    3) 7.99797145E-03
T = 1932.0735     0) 3.72484593E-06    1) 1.20772859E-03    2) 1.98794570E-03    3) 7.88832040E-03
T = 2018.5800     0) 3.54462498E-06    1) 1.19049950E-03    2) 1.95891496E-03    3) 7.77979725E-03
T = 2102.2693     0) 3.44810889E-06    1) 1.17378594E-03    2) 1.93143389E-03    3) 7.67452780E-03
T = 2184.0800     0) 3.37993332E-06    1) 1.15825349E-03    2) 1.90477339E-03    3) 7.57309250E-03
T = 2268.2623     0) 3.30978139E-06    1) 1.14233219E-03    2) 1.87781467E-03    3) 7.47821682E-03
T = 2352.0768     0) 3.26996799E-06    1) 1.12666921E-03    2) 1.85143215E-03    3) 7.36929939E-03
T = 2436.3212     0) 3.19955390E-06    1) 1.11113063E-03    2) 1.82528695E-03    3) 7.26931624E-03
T = 2520.7049     0) 3.08235428E-06    1) 1.09574557E-03    2) 1.79943960E-03    3) 7.17056191E-03
T = 2605.8105     0) 2.96415209E-06    1) 1.08045723E-03    2) 1.77376384E-03    3) 7.07241279E-03
T = 2689.8301     0) 2.84745822E-06    1) 1.06558546E-03    2) 1.74879371E-03    3) 6.97692412E-03
T = 2772.7375     0) 2.74115451E-06    1) 1.05113079E-03    2) 1.72452586E-03    3) 6.88405392E-03
T = 2856.0571     0) 2.68329365E-06    1) 1.03686344E-03    2) 1.70054554E-03    3) 6.79210739E-03
T = 2941.8068     0) 2.62374527E-06    1) 1.02168626E-03    2) 1.67453800E-03    3) 6.69890112E-03
T = 3024.4572     0) 2.56634919E-06    1) 1.00865929E-03    2) 1.65316570E-03    3) 6.61027820E-03
T = 3108.2361     0) 2.50816939E-06    1) 9.94935719E-04    2) 1.63011037E-03    3) 6.52177472E-03
T = 3193.2410     0) 2.46185363E-06    1) 9.81224096E-04    2) 1.60709997E-03    3) 6.43328974E-03
T = 3278.6056     0) 2.41739293E-06    1) 9.67442974E-04    2) 1.58442623E-03    3) 6.34574956E-03
T = 3363.2311     0) 2.37331716E-06    1) 9.53671674E-04    2) 1.56241713E-03    3) 6.26025487E-03
T = 3444.2015     0) 2.33114508E-06    1) 9.41785535E-04    2) 1.54121488E-03    3) 6.17954936E-03
T = 3528.7398     0) 2.28711469E-06    1) 9.29089966E-04    2) 1.51959556E-03    3) 6.09651556E-03
T = 3612.2492     0) 2.24285465E-06    1) 9.16582358E-04    2) 1.49861957E-03    3) 6.01968646E-03
T = 3696.2114     0) 2.19387668E-06    1) 9.04185916E-04    2) 1.47783895E-03    3) 5.93598438E-03
T = 3780.5487     0) 2.14467991E-06    1) 8.91916630E-04    2) 1.45727753E-03    3) 5.85628827E-03
T = 3868.2021     0) 2.09354879E-06    1) 8.79912690E-04    2) 1.43641609E-03    3) 5.77512008E-03
T = 3950.7263     0) 2.04540965E-06    1) 8.67188331E-04    2) 1.41693477E-03    3) 5.69970848E-03
T = 4032.8310     0) 1.99 51524E-06    1) 8.56278508E-04    2) 1.39759275E-03    3) 5.62580407E-03
T = 4116.4764     0) 1.94812218E-06    1) 8.44885019E-04    2) 1.37839705E-03    3) 5.55168777E-03
T = 4200.2346     0) 1.90590227E-06    1) 8.33490641E-04    2) 1.35944839E-03    3) 5.47846016E-03
T = 4284.3232     0) 1.86486532E-06    1) 8.22384462E-04    2) 1.34072859E-03    3) 5.40681440E-03
T = 4369.0036     0) 1.82958182E-06    1) 8.11196088E-04    2) 1.32216610E-03    3) 5.33412452E-03
T = 4452.6819     0) 1.79474922E-06    1) 8.00415612E-04    2) 1.30418372E-03    3) 5.26417627E-03
T = 4538.7159     0) 1.75886838E-06    1) 7.89460465E-04    2) 1.28578427E-03    3) 5.19317510E-03
T = 4620.7946     0) 1.72466890E-06    1) 7.79178875E-04    2) 1.26858416E-03    3) 5.12647062E-03
T = 4706.2122     0) 1.68907624E-06    1) 7.68598995E-04    2) 1.25095973E-03    3) 5.05887172E-03
T = 4789.3734     0) 1.65276104E-06    1) 7.57391888E-04    2) 1.23340044E-03    3) 4.99  38846E-03
T = 4872.4150     0) 1.63189625E-06    1) 7.48495113E-04    2) 1.21743742E-03    3) 4.92    099E-03

T = 4956.1407     0) 1.61896402E-06    1) 7.38649588E-04    2) 1.20091057E-03    3) 4.86364027E-03
T = 5040.6253     0) 1.58984367E-06    1) 7.28723869E-04    2) 1.18453906E-03    3) 4.79981981E-03
T = 5124.7166     0) 1.56832885E-06    1) 7.18880522E-04    2) 1.16844751E-03    3) 4.73728148E-03
T = 5208.9917     0) 1.54775207E-06    1) 7.09634522E-04    2) 1.15253816E-03    3) 4.67535194E-03
T = 5292.6392     0) 1.52684028E-06    1) 7.00280984E-04    2) 1.13785618E-03    3) 4.61486838E-03
T = 5376.6970     0) 1.50582576E-06    1) 6.91174920E-04    2) 1.12160660E-03    3) 4.55493003E-03
T = 5460.0989     0) 1.48998351E-06    1) 6.82176483E-04    2) 1.10658320E-03    3) 4.49633835E-03
T = 5544.4796     0) 1.47592086E-06    1) 6.73196897E-04    2) 1.09161222E-03    3) 4.43791717E-03
T = 5628.3893     0) 1.46193512E-06    1) 6.64483986E-04    2) 1.07684783E-03    3) 4.38066284E-03
T = 5712.1468     0) 1.44797553E-06    1) 6.55754712E-04    2) 1.06252818E-03    3) 4.32433622E-03
T = 5798.2845     0) 1.43361926E-06    1) 6.47989616E-04    2) 1.04792364E-03    3) 4.26729522E-03
T = 5880.6375     0) 1.41989374E-06    1) 6.36736919E-04    2) 1.03416819E-03    3) 4.21347292E-03
T = 5965.5675     0) 1.40573876E-06    1) 6.30336495E-04    2) 1.02019891E-03    3) 4.15888556E-03
T = 6048.9189     0) 1.38777026E-06    1) 6.22327645E-04    2) 1.00668099E-03    3) 4.10992634E-03
T = 6132.4541     0) 1.36686648E-06    1) 6.14214325E-04    2) 9.93335889E-04    3) 4.05368788E-03
T = 6216.1200     0) 1.34597000E-06    1) 6.06300214E-04    2) 9.80168303E-04    3) 4.00211972E-03
T = 6300.8033     0) 1.32499918E-06    1) 5.98472483E-04    2) 9.67166728E-04    3) 3.95116282E-03
T = 6386.8607     0) 1.30326483E-06    1) 5.90482746E-04    2) 9.53910375E-04    3) 3.89917386E-03
T = 6468.5672     0) 1.28285821E-06    1) 5.83077588E-04    2) 9.41686729E-04    3) 3.85097667E-03
T = 6552.3959     0) 1.26198184E-06    1) 5.75639354E-04    2) 9.29108751E-04    3) 3.80222825E-03
T = 6637.1947     0) 1.24878133E-06    1) 5.68180820E-04    2) 9.16818310E-04    3) 3.75363374E-03
T = 6720.7571     0) 1.21981873E-06    1) 5.60955114E-04    2) 9.04794678E-04    3) 3.70643873E-03
T = 6804.8841     0) 1.19876644E-06    1) 5.53781195E-04    2) 8.92882108E-04    3) 3.65962731E-03
T = 6888.0555     0) 1.17798712E-06    1) 5.46787120E-04    2) 8.81272318E-04    3) 3.61390270E-03
T = 6973.2217     0) 1.15669458E-06    1) 5.39737669E-04    2) 8.69564582E-04    3) 3.56793193E-03
T = 7056.4778     0) 1.13588054E-06    1) 5.32937688E-04    2) 8.58291174E-04    3) 3.52356776E-03
T = 7143.5851     0) 1.11418373E-06    1) 5.25872382E-04    2) 8.46689607E-04    3) 3.47783483E-03
T = 7224.8299     0) 1.09793084E-06    1) 5.19501826E-04    2) 8.36085059E-04    3) 3.43579211E-03
T = 7308.8419     0) 1.08892984E-06    1) 5.12954888E-04    2) 8.25144593E-04    3) 3.39299830E-03
T = 7392.9836     0) 1.08391883E-06    1) 5.06494830E-04    2) 8.14429850E-04    3) 3.35066290E-03
T = 7476.1815     0) 1.07698487E-06    1) 5.00200439E-04    2) 8.03892988E-04    3) 3.30945141E-03
T = 7560.8085     0) 1.06999929E-06    1) 4.93990915E-04    2) 7.93633074E-04    3) 3.26859461E-03
T = 7644.8446     0) 1.06280628E-06    1) 4.87737887E-04    2) 7.83462330E-04    3) 3.22886787E-03
T = 7728.5263     0) 1.05595614E-06    1) 4.81682510E-04    2) 7.73271347E-04    3) 3.18802586E-03
T = 7812.8674     0) 1.04906938E-06    1) 4.75605678E-04    2) 7.63374713E-04    3) 3.14804366E-03
T = 7896.8763     0) 1.04192697E-06    1) 4.69743090E-04    2) 7.53934297E-04    3) 3.10991908E-03
T = 7980.8862     0) 1.03499948E-06    1) 4.63907387E-04    2) 7.44085494E-04    3) 3.07218844E-03
T = 8064.6125     0) 1.02794896E-06    1) 4.58215123E-04    2) 7.34491683E-04    3) 3.03432946E-03
T = 8148.7805     0) 1.02094888E-06    1) 4.52888887E-04    2) 7.25888348E-04    3) 2.99728415E-03
T = 8232.8715     0) 1.01392737E-06    1) 4.46957396E-04    2) 7.15088578E-04    3) 2.96068054E-03
T = 8316.9896     0) 1.00692480E-06    1) 4.41493063E-04    2) 7.06888044E-04    3) 2.92468981E-03
T = 8400.6174     0) 9.99994677E-07    1) 4.36116677E-04    2) 6.97987141E-04    3) 2.88935834E-03
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APPENDIX C

COMPUTER DOCUMENTATION

Input Cards

Program Listing

Program Flow Charts

INPUT CARDS

CARD NO.	CARD COLUMN	SYMBOL	IDENTIFICATION
1	1 - 10	N Press	Number of Pairs of Entries in the Time Versus Pressure Table. This is the Table which also Defines the Forcing Function.
	11 - 20	Factor	Floating Point Number which Multiplies all Time Entries of the Forcing Function to Get Time in Seconds.
2+	1 - 10	Tim (i)	Time Corresponding to Pressure.
	11 - 20	Table (i)	Pressure in Torr (i = 1,2,3.....N Press) (as many cards as N Press).
3	1 - 10	N	Number of Chambers.
	11 - 20	Temp	Temperature in Degree Kelvin.
	21 - 30	GRMS	Molecular Weight of Gas in GRM.
	21 - 40	TIMAX	Maximum Time in Sec. at which Computer is to Stop.
4	1 - 10	P 1	Initial Pressure of Chamber 1
	11 - 20	P 2	" " " " 2
	21 - 30	P 3	" " " " 3
	31 - 40	P 4	" " " " 4
	41 - 50	P 5	" " " " 5
	51 - 60	P 6	" " " " 6
	61 - 70	P 7	" " " " 7
	71 - 80	P 8	" " " " 8
	-	p 9	Another Card Should be Used for More Chambers, i.e., for more than 8 Chambers.

CARD NO.	CARD COLUMN	SYMBOL	IDENTIFICATION
5	1 - 10	V 1	Volume in Liters of Chamber 1
	11 - 20	V 2	" " " " " 2
	21 - 30	V 3	" " " " " 3
	31 - 40	V 4	" " " " " 4
	41 - 50	V 5	" " " " " 5
	51 - 60	V 6	" " " " " 6
	51 - 70	V 7	" " " " " 7
	71 - 80	V 8	" " " " " 8
	-	V 9	Another Card Should be Used for More than 8 Volumes.
6	1 - 10	NAREA 1	Number of Surface Areas for Chamber 1
	11 - 20	NAREA 2	" " " " " " 2
	21 - 30	NAREA 3	" " " " " " 3
	31 - 40	NAREA 4	" " " " " " 4
	41 - 50	NAREA 5	" " " " " " 5
	51 - 60	NAREA 6	" " " " " " 6
	61 - 70	NAREA 7	" " " " " " 7
	71 - 80	NAREA 8	" " " " " " 8
	-	NAREA 9	Use Another Card as for Card 4 and 5.
7+	1 - 10	AREA GAS (I,K)	Area, (cm^2) of Surface K in Chamber I.
	11 - 20	Gas (I,K)	Title of Material of Surface K in Chamber I.
	21 - 30	QI	Initial Outgassing Rate of Surface K.
	31 - 40	QF	Final Outgassing Rate of Surface K.
	41 - 50	τ	Time Constant, Outgassing of Surface K.

CARD NO.	CARD COLUMN	SYMBOL	IDENTIFICATION
5	1 - 10	V 1	Volume in Liters of Chamber 1
	11 - 20	V 2	" " " " " 2
	21 - 30	V 3	" " " " " 3
	31 - 40	V 4	" " " " " 4
	41 - 50	V 5	" " " " " 5
	51 - 60	V 6	" " " " " 6
	61 - 70	V 7	" " " " " 7
	71 - 80	V 8	" " " " " 8
	-	V 9	Another Card Should be Used for More than 8 Volumes.
6	1 - 10	NAREA 1	Number of Surface Areas for Chamber 1
	11 - 20	NAREA 2	" " " " " " 2
	21 - 30	NAREA 3	" " " " " " 3
	31 - 40	NAREA 4	" " " " " " 4
	41 - 50	NAREA 5	" " " " " " 5
	51 - 60	NAREA 6	" " " " " " 6
	61 - 70	NAREA 7	" " " " " " 7
	71 - 80	NAREA 8	" " " " " " 8
	-	NAREA 9	Use Another Card as for Card 4 and 5.
7+	1 - 10	AREA GAS (I,K)	Area, (cm^2) of Surface K in Chamber I.
	11 - 20	Gas (I,K)	Title of Material of Surface K in Chamber I.
	21 - 30	QI	Initial Outgassing Rate of Surface K.
	31 - 40	QF	Final Outgassing Rate of Surface K.
	41 - 50	τ	Time Constant, Outgassing of Surface K.

```
      PROGRAM MAIN
      COMMON TIME,T,N,NN,TM,IPRINT,TEMP,GRAMS,H,ETA,TEMP2,P( 8),XP( 9),
     1 DP( 7),V( 7),VINVERSE( 7),NAREA( 7),AREAOGAS(7,7 ),QI( 7,7),
     1 JCOND( 7,7),INDEX( 7,7),C1(7,7,5 ),C2(7,7,5 ),C3(7,7,5 ),TIM(50),
     1 OUTGAS1( 7,7),OUTGAS2(7,7 ),TABLE(50),NPRESSUR,  ERROR,
     1 QF( 7,7),TAU( 7,7),NCOND( 7),NP( 8),AREA( 7),ISEARCH,IDELTA
     1 , TDELTA
      DIMENSION WORKAREA(120),READY(2),PARRAY( 9,101)
      INTEGER WORKAREA,READY
      COMMON/DATA/ MESSAGE1(3),MESSAGE2(8),MESSAGE3(7),MESSAGE4(2),
     1 DELTA(20),TABLA(9),ATA(9),TABLX(11),TX(11),T1(10),T2(10),T3(10),
     2 T4(6),T5(6)
      DATA ((MESSAGE1(I),I=1,3) = 4HTIME,4H (HO, 4HURS)  )
      DATA ((MESSAGE2(I),I=1,8)=4HPRES,4HSURE,4H IN ,4HTORR,4H (LO,
     1 4HG 10, 4H BAS,4HE)    )
      DATA ((MESSAGE3(I),I=1,7) = 4H VOL,4HUME ,4HPRES,4HSURE, 4H SIM,
     1 4HULAT,4HION   )
      DATA ((MESSAGE4( ,I=1,2) = 4HCHAM,4HBER )
      DATA((DELTA(I),I=  20) = 1., 1., 1., 1.01, 1.01, 1.01, 1.02, 1.02,
     1 1.03, 1.04, 1.05, 1.06, 1.07, 1.085, 1.1, 1.1, 1.3, 1.5,1.75,2.)
      DATA ((TABLA(I),I=1,9) =2,02,4.,17.,18.,28.,28.7,32.,30.9,44.)
      DATA ((ATA(I),I=1,9) = 2.1,.93,1.06,1.9,1.04,1...0..82,1.24)
      DATA((TABLX(I),I=1,11)=.02,.04,.06,.08,.1,.2,.4,.6,.8,1.,2.)
      DATA((TX(I),I=1,11)=1.1,1.4,1.7,2.,2.3,3.0,6.9,9.0,13.,16.,31.)
      DATA((T1(I),I=1,10)=.1,.2,.3,.4,.5,.6,.7,.8,.9,1.)
      DATA((T2(I),I=1,10)=.23,.42,.58,.71,.82,.9,.95,.98,.99,1.)
      DATA((T3(I),I=1,10)=1.444,1.297,1.198,1.175,1.151,1.124,1.122,
     1 1.117,1.113,1.108)
      DATA ((T4(I),I=1,6) = 0.,.259,.5,.707,.866,.966)
      DATA ((T5(I),I=1,6) = 1.,1.072,1.154,1.294,1.438,1.679)
       EXTERNAL SIN
      READY(1) = 7751292l0
      READY(2) = 2470177770
C     READY(1) =     READY,QUESTION MARK
C
C     L E G E N D
C
C     P(I) = PRESSURE OF CHAMBER I
C     DP(I) RATE OF CHANGE OF PRESSURE IN CHAMBER I
C     V(I) = VOLUME OF CHAMBER I
C     NAREA(I) = NUMBER OF AREAS FOR CHAMBER I
C     C(I,J) = CONDUCTANCE BETWEEN CHAMBER I AND J
C     VINVERSE(I) = 1.0/V(I) FOR SPEEDING COMPUTATIONS
C     XP(I) = PRESSURES OF CHAMBER I, EQUIVALENT TO P(I), BUT USED DURING
C          RUNGE-KUTTS CALCULATIONS AND DESTROYED
C     TIME = ACTUAL TIME OF TEST
C     T = VARIABLE TIME, USED IN RUNGE-KUTTA METHOD
C     AREACOND(I,J) = AREA OF THE CONDUCTANT HOLE BETWEEN CHAMBER I AND J
C     QI(I) = INITIAL OUTGASSING RATE OF SURFACE I
C     QF(I) = FINAL OUTGASSING RATE OF SURFACE I
C     TAU(I) = TIME CONSTANT OF OUTGASSING OF SURFACE I
C
C
C     R E A D   I N P U T   D A T A
C
C • • • • • • • • • • • • • • • • • • • • • • • • • • • • • • • • • • • •
C
C     READ TIME-PRESSURE (EXTERNAL FORCING FUNCTION) HISTORY TABLE
C
C     NPRESSUR = NUMBER OF PAIRS OF ENTRIES


C     FACTOR = FLOATING POINT NUMBER TO MULTIPLY THE GIVEN TIME VALUES
C          IN ORDER TO GET TIME IN SECONDS
C     TIM(I) = TIME IN SECONDS
C     TABLE(I) = PRESSURE IN TORR
C
      READ (60,3001) PRESSUR ,FACTOR
      NPRESSUR = PRESSUR    + .3
      DO 3017 I = 1,NPRESSUR
      READ (60,3010) TI,TABLE(I)
 3010 FORMAT ( 2F10.0)
 3017 TIM(I) = TI*FACTOR
C
      ISEARCH = 2
      IDELTA = 1
C
C     INITIALIZE PARAMETER VALUES
C
      DO 2000 I = 1,8
      NP(I) = I - 1
      P(I) = XP(I)= 0.0
 2000 CONTINUE
      DO 2001 I = 1,7
      NCOND(I) = 0
      AREA(I) = 0.0
      DO 2001 J = 1,7
      AREAOGAS(I,J) =QI(I,J)=QF(I,J)=TAU(I,J)=0.0
      JCOND(I,J) = INDEX(I,J) = 0
 2001 CONTINUE
C
C     READ PARAMETER CARD
C
C     XN = NUMBER OF CHAMBERS, NOT INCLUDING ENVIRONMENT CHAMBER ZERO
C     TEMP = TEMPERATURE IN DEGREES KELVIN
C     GRAMS = MOLECULAR WEIGHT OF GAS IN ALL CHAMBERS
C     TIME = START TIME OF SIMULATION, IN SECONDS
C     TIMAX = UPPER TIME LIMIT OF SIMULATION
C     TDELTA = LOGARITHM EXPONENT OF TIME INCREMENT, = 10**TDELTA
C     H = INTEGRATION STEP SIZE FOR RUNGE-KUTT- METHOD
C     ERROR = ERROR OF RUNGE-KUTTA INTEGRATION STEP
C     PRINT = 0 FOR NO PRINT, 1 FOR DIAGNOSTIC PRINT
C
      READ (60,3001) XN,TEMP,GRAMS,TIMIN,TIMAX,H,ERROR,PRINT
      N = XN + .3
      NN = N + 1
      IPRINT = PRINT    + .3
      TM = SQRT(TEMP/GRAMS)
      TEMP2 = SQRT(TEMP)
      ETA = TABLETA(GRAMS)
      P(1) = 760.
      READ (60,3001) (P(I),I=2,NN)
 3001 FORMAT (8F10.0)
      READ (60,3001) (V(I),I=1,N)
      DO 3007 I = 1,N
 3007 VINVERSE(I) = 1./V(I)
      READ (60,3001) ( AREA(I),I=1,N)
      DO 3002 I = 1,N
 3002 NAREA(I) = AREA(I)  + .3
      DO 3003 I = 1,N
      NA = NAREA(I)
      DO 3003 K = 1,NA
      READ (60,3004) AREAOGAS(I,K),OUTGAS1(I,K),OUTGAS2(I,K)
     1, QI(I,K),QF(I,K),TAU(I,K)
```

```
 3004 FORMAT (F10.0,2A5,3E10.0)
C     CONVERT TAU FROM HOURS TO SECONDS
      TAU(I,K) = 3600.*TAU(I,K)
 3003 CONTINUE
 3006 READ (60,3001) XI,XJ,XL,CC1,CC2,CC3
      I = XI + .3
C     IGNORE CONDUCTANCES OF FORM C(0,N)
      IF(I) 3500,3006,3005
 3005 NCOND(I) = NCOND(I) + 1
      K = NCOND(I)
      J = XJ + 1.3
      JCOND(I,K) = J  - 1
      INDEX(I,J) = XL  + .3
      C1(I,J,K) = CC1
      C2(I,J,K) = CC2
      C3(I,J,K) = CC3
      GO TO 3006
C
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
C     W R I T E   I N P U T   D A T A
C
 3500 WRITE (61,8880) N
      WRITE (61,8880) N
 8880 FORMAT ( 1H1, 11(/1H0) ,
     1  /45X,45(1H*) ,
     1  /45X,45(1H*) ,
     1  /45X,2H**,41X,2H**,
     1  /45X,2H**,41X,2H**,
     1/45X,2H**,11X,I2,16H - C H A M B E R ,12X,2H** ,
     1  /45X,2H**,41X,2H**,
     1  /45X,45H**  P R E S S U R E   S I M U L A T I O N  ** ,
     1  /45X,2H**,41X,2H**,
     1  /45X,2H**,41X,2H**,
     1  /45X,45(1H*) ,
     1  /45X,45(1H*) )
C
C     IS THIS A RESTART
C
      WRITE (59,7777)   READY
 7777 FORMAT ( 32HIF THIS IS RE-START, PUT JS 4 ON  , 2A4)
      READ (58,5102) DUMMY
      GO TO (4601,4602)SSWTCHF(4)
 4601 WRITE (61,4600)
 4600 FORMAT ( 13(/1H0), 67(2H *),/1H0,  61X,13HR E S T A R T/1H0,
     1 67(2H *)  /1H1)
      GO TO 4603
 4602 CONTINUE
      WRITE (61,3010)   N,TEMP,GRAMS,TIMIN,TIMAX,H
 3010 FORMAT (1H1,55X,25H*  I N P U T   D A T A  */1H0,38X,57(1H*)/
     1 1H0,57X,
     2 20HNUMBER OF CHAMBERS =,I2 /1H0,49X,13HTEMPERATURE =,F10.4,
     3 15H DEGREES KELVIN /1H0, 40X,25HMOLECULAR WEIGHT OF GAS =,F10.4,
     4 6H GRAMS /1H0,34X,25HSIMULATION PERFORMED FROM,F8.3,
     5 14H SECONDS UP TO ,F12.3,8H SECONDS /
     6  1H0,38X,37HWITH INITIAL INTEGRATION STEP SIZE OF,F14.9,
     7 8H SECONDS/ 1H0,6X,123(1H*) )
      DO 4000 I = 1,N
      WRITE (61,4001)I, V(I),P(I+2)
 4001 FORMAT (1H0,9X,7HCHAMBER ,I2,11X,8HVOLUME =,F11.4,7H LITERS ,
     1 14X,18HINITIAL PRESSURE =,F10.4,5H TORR )
      NA = NAREA(I)


      DO 4002 K = 1,NA
 4002 WRITE (61,4003) K,AREAOGAS(I,K),OUTGAS1(I,K),OUTGAS2(I,K)
     1,QI(I,K),QF(I,K),TAU(I,K)
 4003 FORMAT (1H0,29X,16HSURFACE AREA NO.,I2,2H =,F11.4,
     1 22H SQ.CM.,  MATERIAL IS ,2A5,
     1/64X,15H1) Q(INITIAL) = ,E11.4,22H TORR-LITER/SEC/SQ.CM.,
     1/35X,42HOUTGASSING CHARACTERISTICS - 2) Q(FINAL) = ,E11.4,
     1 22H TORR-LITER/SEC/SQ.CM.,
     1/64X,8H3) TAU = ,E11.4, 8H SECONDS )
      NC = NCOND(I)
      DO 4004 K = 1,NC
      J1= JCOND(I,K)
      J = J1 + 1
      L = INDEX(I,J)
      WRITE (61,4005) K,I,J1,L ,C1(I,J,K),C2(I,J,K),C3(I,J,K)
 4005 FORMAT (1H0,29X,15HCONDUCTANCE NO. ,I2,5H - C( ,I2,1H,I2,
     2 9H) OF TYPE ,I2, 3E15.5)
 4004 CONTINUE
      WRITE (61,4006)
 4006 FORMAT (1H0,6X,123(1H*) )
 4000 CONTINUE
      WRITE (61,4100)
 4100 FORMAT (1H1, 51X, 32HTIME VERSUS PRESSURE ENVIRONMENT /1H0/1H0)
      WRITE (61,4101) (I,TIM(I),TABLE(I),I=1,NPRESSUR)
 4101 FORMAT (41X,I2,1H),F15.0,11H SECONDS  - ,F18.10,5H TORR )
      WRITE(61,8500)
 8500 FORMAT ( 1H1, 59X,25HINTERMEDIATE CALCULATIONS/1H0)
C
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
C     C O M P U T E
C
 4603 EXECTIME = EXPONENT = 0.0
      TIME = TIMIN
      IARRAY = 1
      DO 4200 I = 1,NN
 4200 PARRAY(I,1) = P(I)
      PARRAY( 9,1) = TIME
      GO TO (4202,4203),SSWTCHF(4)
C
C     THE FOLLOWING IS AN EMERGENCY RESTART OPTION
C
 4202 READ(3,8999)XMINUS,(XP(J),J=1,9)
      IF(XMINUS) 4204,4204,4205
 4205 IARRAY = XMINUS       + .2
      DO 4206 J = 1,9
 4206 PARRAY(J,IARRAY) = XP(J)
      GO TO 4202
 4204 TIME = XP(1)
      EXPONENT = XP(2)
      EXECTIME = XP(3)
      READ(3,8999)XMINUS,(P(J),J=1,9)
      DO 8998 J = 1,4
 8998 BACKSPACE 3
 4203 CALL TIC
      TDELTA = .01*(TIMAX-TIMIN)
      TIMOUT = EXPONENT + TDELTA
      GO TO (1007,1000) SSWTCHF(2)
C
 1000 CALL  RUNGKUTA
C
      GO TO (1001,1002),SSWTCHF(1)
```

```
      CALL TOC(ITIME)
      EXECTIME = EXECTIME + FLOATF(ITIME)/3600000.
      XMINUS = -1.0
      WRITE (3,8999)XMINUS,TIME,EXPONENT,EXECTIME,(P(J),J=1,6)
      WRITE (3,8999)XMINUS,(P(J),J=1,9)
      REWIND 3
      WRITE (59,1003)
 1003 FORMAT ( 30HLOGIC 3 IS THE RESTART TAPE     /
     1 80HTO CONTINUE THE PROGRAM, SET RESTART TAPE ON 3, PUT JS 4 ON,
     1/52HAND RE-SUBMIT THE COMPLETE PROGRAM (INCLUDING DATA).          )
      CALL DUMP
 1002 GO TO (1005,1006) SSWTCHF(5)
 1005 WRITE (61,8999) TIME,(P(J),J=1,NN)
 1006 GO TO (1007,1008),SSWTCHF(2)
 1008 IF(TIME-TIMOUT) 1000,1500,1500
 1500 GO TO (1502,1503),SSWTCHF(6)
 1502 WRITE (59,1501)IARRAY
 1501 FORMAT ( I3, 8H PERCENT)
 1503 CALL TOC(ITIME)
      EXECTIME = EXECTIME + FLOATF(ITIME)/3600000.
      CALL TIC
      IARRAY = IARRAY + 1
      IF (IARRAY - 101) 5300,5300,5400
 5300 DO 5200 J = 1,NN
 5200 PARRAY(J,IARRAY) = P(J)
      PARRAY( 9,IARRAY) = TIME
      WRITE (61,8999) TIME,(P(J),J=1,NN)
C
C     SAVE ON BCD TAPE
C
      ARRAY = IARRAY
      WRITE (3,8999)  ARRAY,(PARRAY(J,IARRAY),J=1,9)
 8999 FORMAT ( 6E19.11)
 5400 EXPONENT = EXPONENT + TDELTA
      TIMOUT = EXPONENT + TDELTA
      IF(TIME - TIMAX) 1000,1000,5100
C
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
C     P R I N T
C
 5100 WRITE (59,5101)   READY
 5101 FORMAT ( 36HREADY PRINTER AND SCRATCH TAPE ON 3   /
     1 40HLOGIC 3 IS INPUT TO 1033C PLOT PROGRAM      , 2A4)
      READ (58,5102) DUMMY
 5102 FORMAT (A1)
      CALL TOC(ITIME)
      EXECTIME = EXECTIME + FLOATF(ITIME)/3600000.
      IARRAY = 101
 1007 WRITE (61,4500) PARRAY( 9,1),(NP(I),PARRAY(I,1),I=1,NN)
 4500 FORMAT (1H1, 55X, 25H* *  S O L U T I O N  * * /1H0/   1H0,
     1          1X,3HT =,F10.4,(5(5X,I2,1H),E16.8)))
      DO 4550 I = 2,IARRAY
 4550 WRITE (61,2500) PARRAY( 9,I),(NP(J), PARRAY(J,I),J=1,NN)
 2500 FORMAT (2X,3HT =,F10.4,(5(5X,I2,1H),E16.8)))
      WRITE (61,5001) EXECTIME
      WRITE (59,5001) EXECTIME
 5001 FORMAT ( 1H0,5X,19HTHIS EXECUTION TOOK ,F10.4,6H HOURS )
      REWIND 3
C
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C


C     P L O T
C
      CALL PLOTS(WORK/REA,120,3)
C     GET TIME SCALE
C
      HOURS = .7
      M = 1
      THOURS = TIMAX/3600.
 7000 IF (THOURS - HOURS) 7002,7002,7001
 7001 HOURS = HOURS + .7
      M = M + 1
      GO TO 7000
 7002 TIMAX = HOURS
C
C     SCALE TIME TO 7 INCH AXIS
C
      XS = 7.0/FLOATF(M)
      X = 7.0/3600./TIMAX
      DO 7005 I = 1,IARRAY
 7005 PARRAY( 9,I) = PARRAY( 9,I)*X
C
C     PRESSURE SCALE IS FROZEN AT 10 LOG LINES WITH EXPONENTS
C     GOING FROM -8 TO +2 IN INCREMENTS OF 1
C
C
C     COMPREHENSIVE PLOT
C
      CALL GRID(0.,0.,XS,1.,M,-10)
      CALL AXIS(0.,0.,MESSAGE1,-12,7.,0.,0.,TIMAX/7.)
      CALL AXIS(0.,0.,MESSAGE2,30,10.,90.,-8.,1.)
      CALL NUMBER(0.5,10.1,.21,FLOATF(M),0.,-1)
      CALL SYMBOL(1.,10.1,.21,MESSAGE3,0.,27)
C
      CALL PLOT(0.,10.,3)
      ITEM = 2
      DO 7110 I = 1,IARRAY
      Y = PARRAY(1,I)
      IF (Y - 100.) 7111,7111,7110
 7111 IF (Y - 1.E-8) 7110,7112,7112
 7112 YPAGE = 8.0 + ALOG10(Y)
      CALL PLOT(PARRAY( 9,I),YPAGE,ITEM)
      ITEM = 5 - ITEM
 7110 CONTINUE
C
      DO 7100 J = 2,NN
      CALL PLOT(0.,10.,3)
      DO 7100 I = 1,IARRAY
      Y = PARRAY(J,I)
      IF (Y - 100.) 7101,7101,7100
 7101 IF (Y - 1.E-8) 7100,7102,7102
 7102 YPAGE = 8. + ALOG10(Y)
      CALL PLOT(PARRAY( 9,I),YPAGE,2)
 7100 CONTINUE
      CALL PLOT(10.,0.,-3)
C
C     INDIVIDUAL PLOTS
C
      DO 7500 J = 2,NN
      CALL GRID(0.,0.,XS,1.,M,-10)
      CALL AXIS(0.,0.,MESSAGE1,-12,7.,0.,0.,TIMAX/7.)
      CALL AXIS(0.,0.,MES   GE2,30,10.,90.,-8.,1.)
      CALL SYMBOL(2.3,10    15,MESSAGE4,0.,7)
```

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR.

```
      MAX.REC.SIZE 134210
      SUBROUTINE RUKUTA
      COMMON TIME,T,N,NN,TM,IPRINT,TEMP,GRAMS,H,ETA,TEMP2,P(11),XP(12),
     1 DP(10),V(10),VINVER(10),NAREA(10),AROGAS(10,5),QI(10,5),QF(10,5),
     1 TAU(10,5),NCOND(10),JCOND(10,5),INDEX(10,5),C1(10,10,5),
     1 C2(10,10,5),C3(10,10,5),OUTGS1(10,5),OUTGS2(10,5),NPRESS,
     1 TIM(50),TABLE(50),NP(11),AREA(10),ISRCH,IDELTA
      DIMENSION DELTA (20)
      DATA  DELTA    /              1.0,1.01,1.02,1.03,1.04,1.05,1.06,
     1 1.07,1.08,1.09,1.1,1.2,1.3,1.4,1.5,1.6,1.7,1.8,1.9,2.0/
      DIMENSION K1(10),K2(10),K3(10),K4(10)
      REAL K1,K2,K3,K4

      K1
  150 T = TIME
      H2 = H*.5
      P(1) = PZERO(T)
      DO 100 I = 1,NN
  100 XP(I) = P(I)
      CALL EVAL
      DO 101 I = 1,N
  101 K1(I) = DP(I)

      K2
      T = TIME + H2
      DO 102 I = 2,NN
  102 XP(I) = P(I) + K1(I-1)*H2
      P(1) = PZERO(T)
      XP(1) = P(1)
      CALL EVAL
      DO 103 I = 1,N
  103 K2(I) = DP(I)

      K3
      DO 104 I = 2,NN
  104 XP(I) = P(I) + K2(I-1)*H2
      CALL EVAL
      DO 105 I = 1,N
  105 K3(I) = DP(I)

      K4
      T = TIME + H
      DO 106 I = 2,NN
  106 XP(I) = P(I) + K3(I-1) *H
      P(1) = PZERO(T)
      XP(1) = P(1)
      CALL EVAL
      DO 107 I = 1,N
  107 K4(I) = DP(I)

      CHECK ERROR

      DO 120 I = 1,N
      AX    =(K1(I) + K2(I) + K3(I) + K4(I)) * .25
      STD=ABS (AX-K1(I))+ABS (AX-K2(I))+ABS (AX-K3(I))+ABS (AX-K4(I))
      IF (.25*STD/ABS (AX) - 1.0) 120,120,130
  120 CONTINUE
      TIME = TIME + H
      DO 140 I = 2,NN
      J = I-1
      AX = (K1(J)+K2(J)+K2(J)+K3(J)+K3(J)+K4(J)) * H / 6.0
      XP(I) = XP(I) + AX


      IF (XP(I) - XP(1)) 135,140,140
  140 CONTINUE
      DO 145 I = 2,NN
  145 P(I) = XP(I)
      IF(IDELTA- 20) 141,142,142
  141 IDELTA = IDELTA + 1
  142 H = H*DELTA(IDELTA)
      RETURN
  130 IDELTA = 1
      H = .8*H
      GO TO 150
  135 IDELTA = 1
      H = .5*H
      GO TO 150
      END
    76 BCD RECORD(S) COPIED
       EOF


      JJ = J - 1
      CALL NUMBER (5.,10.1,.35,FLOATF(JJ) ,0.,-1)
      ITEM = 2
      CALL PLOT(0.,10.,3)
      DO 7510 I = 1,IARRAY
      Y = PARRAY(1,I)
      IF (Y - 100.) 7511,7511,7510
 7511 IF (Y - 1.E-8) 7510,7512,7512
 7512 YPAGE = 8.0 + ALOG10(Y)
      CALL PLOT(PARRAY( 9,I),YPAGE,ITEM)
      ITEM = 5 - ITEM
 7510 CONTINUE
C
      CALL PLOT(0.,10.,3)
      DO 7520 I = 1,IARRAY
      Y = PARRAY(J,I)
      IF (Y - 100.) 7521,7521,7520
 7521 IF (Y - 1.E-8) 7520,7522,7522
 7522 YPAGE = 8. + ALOG10(Y)
      CALL PLOT(PARRAY( 9,I),YPAGE,2)
 7520 CONTINUE
 7500 CALL PLOT(10.,0.,-3)
      CALL PLOT(0.,0.,999)
      WRITE (59,5000)
 5000 FORMAT ( 20HPROGRAM FINISHED - REJOICE )
      STOP
      END
```

```
      SUBROUTINE EVALUATE
C
C     THIS ROUTINE COMPUTES THE FOLLOWING SUM
C     ( (P(I)-P(J))*C(I,J) + (QI(I)*E**-T/TAU+QF)*AREA  )  /  VOLUME
C
      COMMON TIME,T,N,NN,TM,IPRINT,TEMP,GRAMS,H,ETA,TEMP2,P( 8),XP( 9),
     1 DP( 7),V( 7),VINVERSE( 7),NAREA( 7),AREAOGAS(7,7 ),QI( 7,7),
     1 JCOND( 7,7),INDEX( 7,7),C1(7,7,5 ),C2(7,7,5 ),C3(7,7,5 ),TIM(50),
     1 OUTGAS1( 7,7),OUTGAS2(7,7 ),TABLE(50),NPRESSUR,  ERROR,
     1 QF( 7,7),TAU( 7,7),NCOND( 7),NP( 8),AREA( 7),ISEARCH,IDELTA
      DIMENSION G(1)
      DO 100 I = 1,N
      G(I) = SUM = 0.0
      XPI = XP(I+1)
  15. CONTINUE
      NA = NAREA(I)
      DO 101 K = 1,NA
      IF(IPRINT) 101,101,110
  110 WRITE (61,200) I,K,QI(I,K),TAU(I,K),QF(I,K),AREAOGAS(I,K)
  200 FORMAT (5H EVAL,2X,2HI=,I2,3H K=,I2,2X,3HQI=,E12.5,3X,2HT=,E12.5,
     1 3X, 3HQF=,E12.5,3X,5HAREA=,E12.5)
  101 G(I)=G(I) +(QI(I,K)*EXPF(-T/TAU(I,K))+QF(I,K))*AREAOGAS(I,K)
  15. CONTINUE
      NC = NCOND(I)
      DO 102 K = 1,NC
      J = JCOND(I,K) + 1
  102 SUM = SUM + (XP(J)-XPI) * CONDUCT(I,J,K,XPI,XP(J))
      DP(I) = (SUM+G(I))*VINVERSE(I)
      IF(IPRINT) 100,100,120
  120 WRITE (61,202) I,DP(I)
  202 FORMAT (21H * * * DERIVATIVE DP( ,I2,3H) = ,E12.5,5(2H *) )
  100 CONTINUE
      RETURN
      END

      FUNCTION CONDUCT (I,J,K,PI,PJ)
      COMMON TIME,T,N,NN,TM,IPRINT,TEMP,GRAMS,H,ETA,TEMP2,P( 8),XP( 9),
C THE DERIVATIVE ARRAY DP(7) HAS SAME NAME AS THE EQUIVALENT DIMENSION DP HERE
     1 DPP(7),V( 7),VINVERSE( 7),NAREA( 7),AREAOGAS(7,7 ),QI( 7,7),
     1 JCOND( 7,7),INDEX( 7,7),C1(7,7,5 ),C2(7,7,5 ),C3(7,7,5 ),TIM(50),
     1 OUTGAS1( 7,7),OUTGAS2(7,7 ),TABLE(50),NPRESSUR,  ERROR,
     1 QF( 7,7),TAU( 7,7),NCOND( 7),NP( 8),AREA( 7),ISEARCH,IDELTA
C
C      L E G E N D
C
C          C1(I,J,K)              C2(I,J,K)              C3(I,J,K)
C
C  1.      A
C  2.      D                      L
C  3.      A                      D                      L
C  4.      A                      B                      L
C  5.      D1                     D2                     L
C
      L = INDEX(I,J)
      PI4 = 4./3.1415926536
      GO TO (2001,2002,2001,2001,2005),L
 2001 D = SQRT(PI4 * C1(I,J,K)   )
      GO TO 2006
 2002 D = C1(I,J,K)
      GO TO 2006
 2005 D = ABSF(C1(I,J,K) - C2(I,J,K)) * .5
 2006 DP = .5*D*(PI+PJ)
      GO TO (1,2,3,4,5),L
C
C     TYPE 1 * CIRCULAR APERTURE
C
    1 AP = C1(I,J,K)
      IF(DP - .015) 101,100,100
  100 RATIO = PI/PJ
      U = RATIO
      IF(ABSF(U)-.97) 102,102,103
  103 U = 1./U
      IF(ABSF(U) - .97) 102,102,104
  104 U = U*.97/ABSF(U)
  102 IF(U- .52) 105,106,106
  106 CONDUCT = 23.97*TM*(U**.712)*SQRT(1.-U**.288)*AP/(1.-U)
      GO TO 110
  105 IF(U-.1) 108,109,109
  109 CONDUCT = 6.27*TM*AP/(1.-U)
      GO TO 110
  108 CONDUCT = 6.27*TM*AP
  110 IF(DP - .5 ) 111,112,112
  111 CONDUCT = (CONDUCT + 3.62*TM*AP)*.5
  112 GO TO (150,150,350),L
  101 CONDUCT = 3.62*TM*AP
      GO TO (150,150,350),L
  150 GO TO 9999
C
C     TYPE 2 - LONG CIRCULAR PIPE
C
    2 IF (DP - .015) 201,200,200
  200 IF (DP - .5 ) 202,203,203
  201 CONDUCT = 3.8*TM*C1(I,J,K)**3/C2(I,J,K)
      GO TO 240
  202 XJ = TABLEJ(PI)
```

```
      CONDUCT = 3.8*TM*XJ*C1(I,J,K)**3/C2(I,J,K)
      GO TO 240
  203 CONDUCT = 3120.*ETA/TEMP2*.5*(PI+PJ)*C1(I,J,K)**4/C2(I,J,K)
  240 GO TO (250,250,351),L
  250 GO TO 9999
C
C     TYPE 3 - SHORT TUBE
C
    3 IF (DP - .015) 301,300,300
  300 IF (DP - .5 ) 302,303,303
  301 CONDUCT = 3.8*TM*C2(I,J,K)**3/
     1 (C3(I,J,K) + 4./(3.*C2(I,J,K)))
      GO TO 9999
  302 XJ = TABLEJ(PI)
      CONDUCT = 3.8*TM*C2(I,J,K)**3*XJ/
     1 (C3(I,J,K) + 4./(3.*C2(I,J,K)))
      GO TO 9999
  303 GO TO 1
  350 CAP = CONDUCT
      GO TO 2
  351 CPIP = CONDUCT
      CONDUCT = 1./(1./CAP + 1./CPIP)
      GO TO 9999
C
C     TYPE 4 - RECTANGULAR DUCT
C
    4 A = C1(I,J,K)
      B = C2(I,J,K)
      XL = C3(I,J,K)
      CALL DUCT(A,B,Y,ALPHA)
      IF (DP - .015)400,403,403
  400 CONDUCT = 9.68*ALPHA*TM*(A*B)**2/(XL*(A+B))
      IF (DP - .015) 401,402,402
  401 GO TO 9999
  402 CONDUCT = CONDUCT * TABLEJ(PI)
      GO TO 9999
  403 CONDUCT = 4455.*ETA/TEMP2*Y*(A*B)**2*.5*(PI+PJ)/XL
      GO TO 9999
C
C     TYPE 5 - LONG ANNULAR TUBE
C
    5 IF (DP - .5 ) 500,503,503
  500 XK = TABLEK(C1(I,J,K),C2(I,J,K))
      CONDUCT = 3.81*TM*XK*(C1(I,J,K)**2-C2(I,J,K))**2 *
     1 (C1(I,J,K) + C2(I,J,K))/C3(I,J,K)
      IF (DP - .015) 501,502,502
  501 GO TO 9999
  502 CONDUCT = CONDUCT * TABLEJ(PI)
      GO TO 9999
  503 CONDUCT = 3050.*ETA*(C1(I,J,K)**4 - C2(I,J,K)**4 -
     1  (C1(I,J,K)**2-C2(I,J,K)**2)/ALOG(C1(I,J,K)/C2(I,J,K)))*
     1 (PI+PJ)*.5/ (TEMP2*C3(I,J,K) )
 9999 IF(IPRINT) 9998,9998,9997
 9997 WRITE (61,9996) I,J,K,PI,PJ,CONDUCT
 9996 FORMAT ( 8H CONDUCT, 2X,2HI=,I2,2X,2HJ=,I2,2X,2HK=,I2,2X,
     1 3HPI=,E12.5,3X,3HPJ=,E12.5,3X,2HC=,E12.5)
 9998 RETURN
      END

      FUNCTION PZERO(S)
      COMMON TIME,T,N,NN,TM,IPRINT,TEMP,GRAMS,M,ETA,TEMP2,P( 8),XP( 9),
     1 DP( 7),V( 7),VINVERSE( 7),NAREA( 7),AREADGAS(7,7 ),Q1( 7,7),
     1 JCOND( 7,7),INDEX( 7,7),C1(7,7,5 ),C2(7,7,5 ),C3(7,7,5 ),TIM(50),
     1 OUTGAS1( 7,7),OUTGAS2(7,7 ),TABLE(50),NPRESSUR,  ERROR,
     1 QF( 7,7),TAU( 7,7),NCOND( 7),NP( 8),AREA( 7),ISEARCH,IDELTA
      DO 1 I = 2,NPRESSUR
      IF (S - TIM(I)) 2,2,1
    1 CONTINUE
    2 PZERO =
     1 TABLE(I-1)+(TABLE(I)-TABLE(I-1))*(S-TIM(I-1))/(TIM(I)-TIM(I-1))
      RETURN
      END
      FUNCTION TABLETA(GRAMS)
      COMMON/DATA/ MESSAGE1(3),MESSAGE2(8),MESSAGE3(7),MESSAGE4(2),
     1 DELTA(20),TABLA(9),ATA(9),TABLX(11),TX(11),T1(10),T2(10),T3(10),
     2 T4(6),T5(6)
      DO 1 I = 1,9
      IF (ABSF(GRAMS - TABLA(I))  - .5) 2,1,1
    1 CONTINUE
      PAUSE 777
    2 TABLETA = ATA(I)
      RETURN
      END

      FUNCTION TABLEJ(P)
      COMMON/DATA/ MESSAGE1(3),MESSAGE2(8),MESSAGE3(7),MESSAGE4(2),
     1 DELTA(20),TABLA(9),ATA(9),TABLX(11),TX(11),T1(10),T2(10),T3(10),
     2 T4(6),T5(6)
      DO 1 I = 2,11
       IF (P - TABLX(I)) 2,2,1
    1 CONTINUE
    2 TABLEJ =TX(I-1) + (TX(I)-TX(I-1))*(P-TABLX(I -1))/
     1 (TABLX(I) - TABLX(I-1))
      RETURN
      END

      SUBROUTINE DUCT(A,B,Y,ALPHA)
      COMMON/DATA/ MESSAGE1(3),MESSAGE2(8),MESSAGE3(7),MESSAGE4(2),
     1 DELTA(20),TABLA(9),ATA(9),TABLX(11),TX(11),T1(10),T2(10),T3(10),
     2 T4(6),T5(6)
      AB = A/B
      DO 1 I = 2,10
      IF (AB- T1(I)) 2,2,1
    1 CONTINUE
    2 Y = T2(I)
      ALPHA = T3(I)
      RETURN
      END

      FUNCTION TABLEK(C1,C2)
      COMMON/DATA/ MESSAGE1(3),MESSAGE2(8),MESSAGE3(7),MESSAGE4(2),
     1 DELTA(20),TABLA(9),ATA(9),TABLX(11),TX(11),T1(10),T2(10),T3(10),
     2 T4(6),T5(6)
      R = C2/C1
      DO 1 I = 2,6
      IF (R - T4(I)) 2,2,1
    1 CONTINUE
    2 TABLEK = T5(I-1)+ (T5(I)-T5(I-1))*(R-T4(I-1))/(T4(I)-T4(I-1))
      RETURN
      END
```

```
      SUBROUTINE GRID (X,Y,XS,YS,M,N)                                   GRID0000
C     X AND Y ARE THE PAGE LOCATIONS OF THE LOWER LEFT HAND CORNER OF THGRID0010
C     XS AND YS ARE THE INCREMENTAL WIDTHS FOR LINEAR GRIDS , OR THE LENGRID0020
C         ONE CYCLE FOR LOG GRIDS.                                      GRID0030
C     IF M OR N IS POSITIVE, IT SIGNIFIES THE NUMBER OF DIVISIONS IN THEGRID0040
C         DIRECTIONS RESPECTIVELY.                                      GRID0050
C     IF M OR N IS NEGATIVE, IT SIGNIFIES A LOG GRID IN THE RESECTIVE DIGRID0060
C         AND EQUALS THE NUMBER OF CYCLES.                              GRID0070
C     SIZE OF GRID EQUALS XS*M BY YS*N.                                 GRID0080
      REAL LOGF                                                         GRID0085
      X1 = X                                                            GRID0090
      Y2= ABSF (FLOATF(N)) * YS + Y                                     GRID0100
      Y1 = Y                                                            GRID0110
      CALL PLOT (X,Y,3)                                                 GRID0120
      IF(M) 50,900,40                                                   GRID0130
 40   X2 = XS                                                           GRID0140
      MM=M+1                                                            GRID0150
      DO 140 I =1,MM                                                    GRID0160
        CALL PLOT (X1,Y1,2)                                             GRID0170
        CALL PLOT (X1,Y2,2)                                             GRID0180
        X1 = X1 + X2                                                    GRID0190
        BUFF = Y1                                                       GRID0200
        Y1 = Y2                                                         GRID0210
 140    Y2 = BUFF                                                       GRID0220
      X1=X1-X2                                                          GRID0230
      GO TO 160                                                         GRID0240
 50   MM = -M                                                           GRID0250
      X2 =  X                                                           GRID0260
      DO 155 I=1,MM                                                     GRID0270
          DO 150 J =1,10                                                GRID0280
          CALL PLOT (X1,Y1,2)                                           GRID0290
          CALL PLOT (X1,Y2,2)                                           GRID0300
          BUFF = Y1                                                     GRID0310
          Y1 = Y2                                                       GRID0320
          Y2 = BUFF                                                     GRID0330
 150      X1 = .43429448*LOGF(FLOATF(J)+1.)* XS + X2                    GRID0340
       X2 = (FLOATF(I))*XS + X                                          GRID0350
 155   X1 = X2                                                          GRID0360
 160  CALL PLOT (X1,Y,3)                                                GRID0370
      Y1=Y                                                              GRID0380
      X2  =  X                                                          GRID0390
      IF(N) 250,900,240                                                 GRID0400
 240  Y2 = YS                                                           GRID0410
      NN=N+1                                                            GRID0420
      DO 340  I = 1,NN                                                  GRID0430
        CALL PLOT (X1,Y1,2)                                             GRID0044
      CALL PLOT (X2,Y1,2)                                               GRID0450
      Y1 = Y1+ Y2                                                       GRID0460
      BUFF = X1                                                         GRID0470
      X1 = X2                                                           GRID0480
 340  X2 = BUFF                                                         GRID0490
      GO TO 900                                                         GRID0500
 250  NN = -N                                                           GRID0510
      Y2 =  Y                                                           GRID0520
      Y1 =  Y                                                           GRID0530
      DO 355  I =1,NN                                                   GRID0540
        DO 350 J =1,10                                                  GRID0550
          CALL PLOT (X1,Y1,2)                                           GRID0560
          CALL PLOT (X2,Y1,2)                                           GRID0570
          BUFF = X1                                                     GRID0580


          X1 = X2                                                       GRID0590
          X2 = BUFF                                                     GRID0600
 350      Y1 = .43429448 * LOGF(FLOATF(J)+1.)* YS +Y2                   GRID0610
        Y2 = FLOATF(I)*YS + Y                                           GRID0620
 355    Y1 = Y2                                                         GRID0630
 900   RETURN                                                           GRID0640
      END                                                               GRID0650

      FUNCTION ALOG10(X)
      ALOG10 = ALOG(X)*.4342944819
      RETURN
      END
```

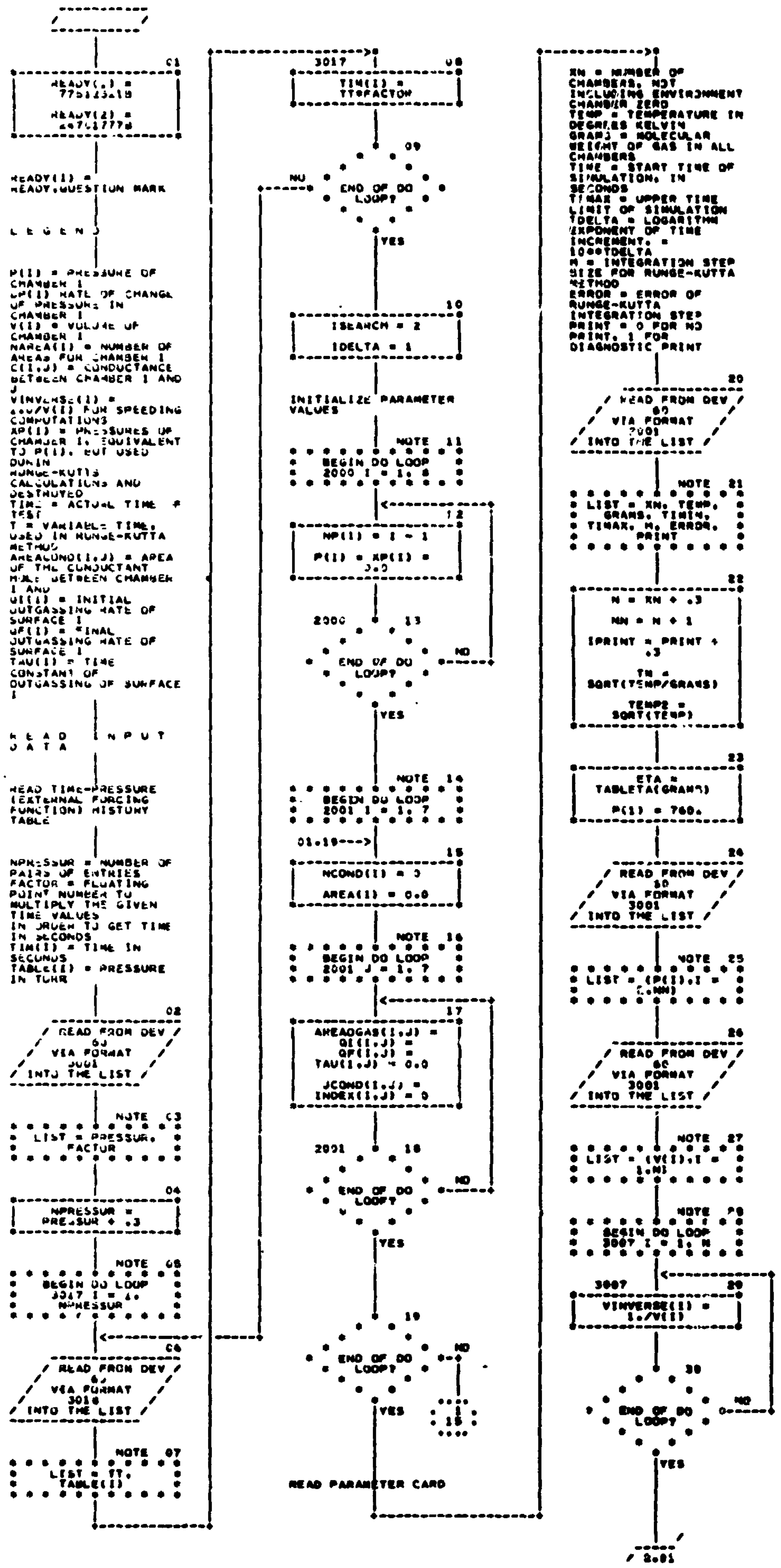
```
55 0 COMPASS/RTS VER 1.1
                                               ENTRY      TIC,TOC
             TIME
                                               TIME SUBROUTINE TO YIELD TIME DIFFERENCE
                                               BETWEEN CALLS OF TIC AND TOC

                                               TO INITIALIZE ROUTINE --   CALL TIC
                                               TO GET TIME INCREMENT   --  CALL TOC(X)
                                               WHERE X IS THE TIME CHANGE IN MILLISECONDS

00000  01077777 01 0  77777 0   TIC        UJP        **
00001  53010022 53 0  10022 0              TMQ        22B
00002  41000016 41 0 P00016 0              STQ        STORE
00003  01400000 01 1 P00000 0              UJP,I      TIC

00004  01077777 01 0  77777 0   TOC        UJP        **
00005  53010022 53 0  10022 0              TMQ        22B
00006  20000004 20 0 P00004 0              LDA        *-2
00007  44000014 44 0 P00014 0              SWA        ADDRESS
00010  15600001 15 1  00001 2              INA        1
00011  44000004 44 0 P00004 0              SWA        TOC
00012  24000016 24 0 P00016 0              LCA        STORE
00013  53040000 53 0  40000 0              AQA
00014  40477777 40 1  77777 0   ADDRESS    STA,I      **
00015  01400004 01 1 P00004 0              UJP,I      TOC
00016                           STORE      BSS        1
                                           END
```

CHART TITLE - PROCEDURES



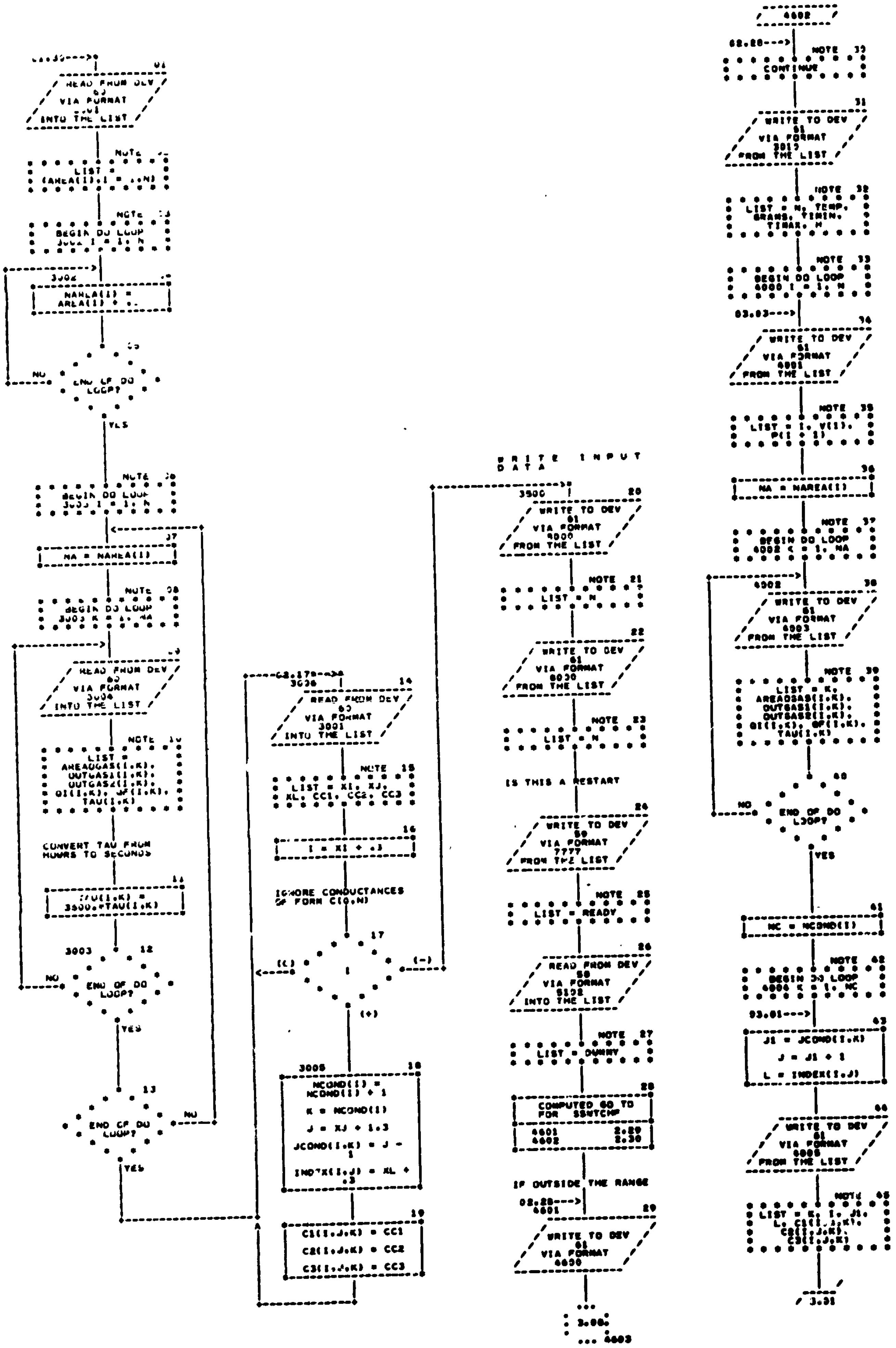
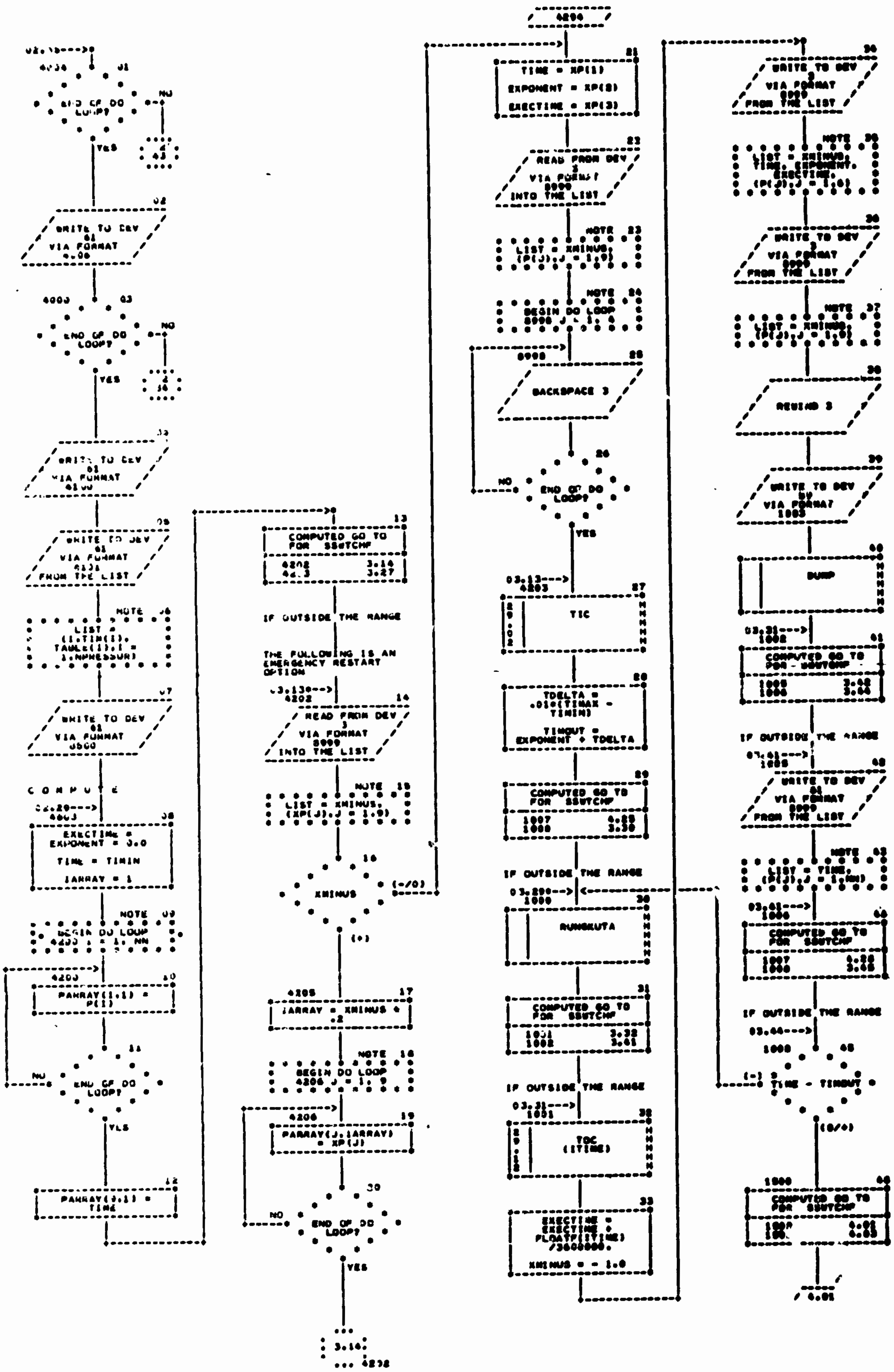
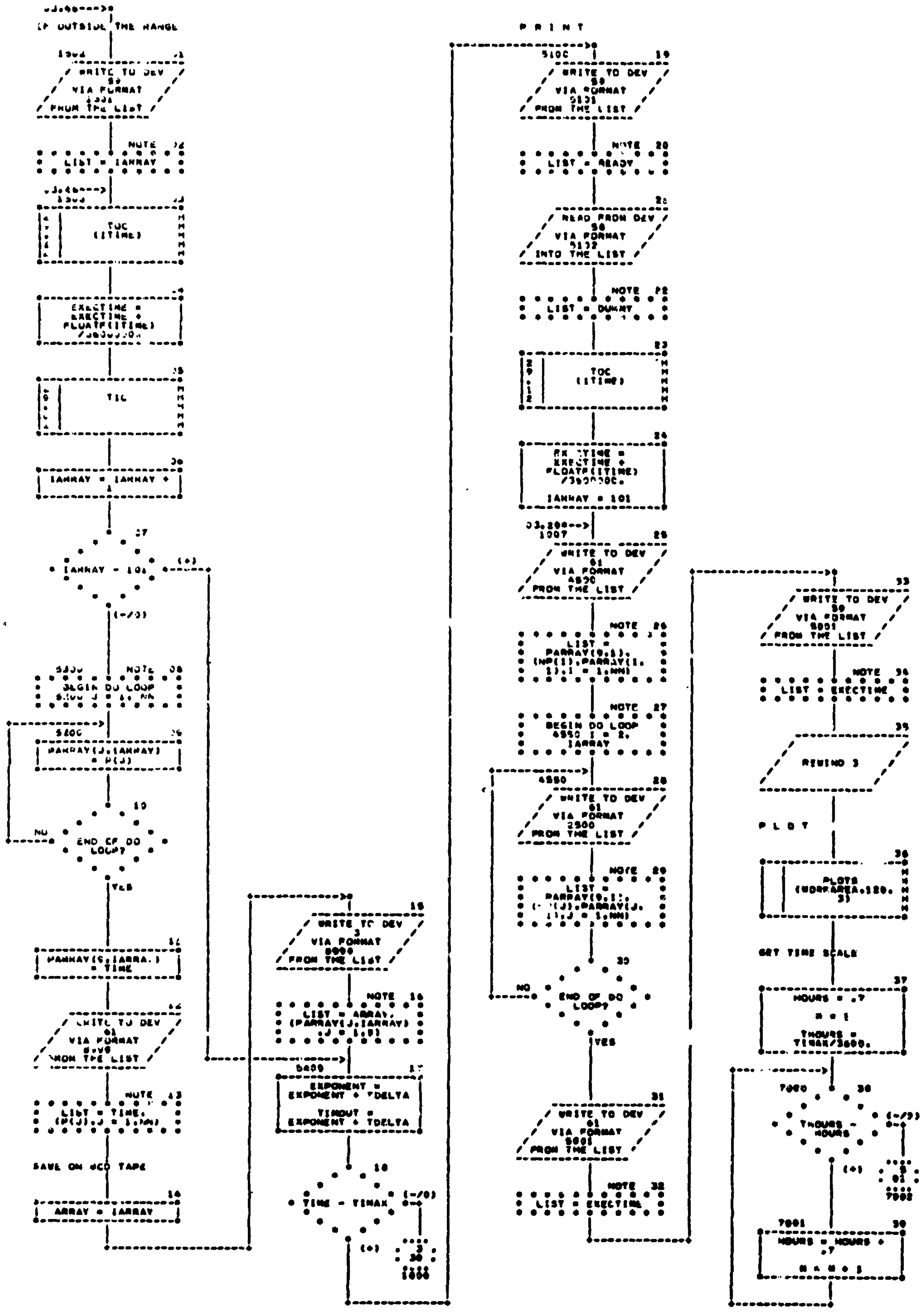

01.30--->
01
READ FROM DEV 63 VIA FORMAT 3001 INTO THE LIST
NOTE 02
LIST = (AREA(I),I = 1,N)
NOTE 03
BEGIN DO LOOP 3002 I = 1, N
3002
04
NAREA(I) = AREA(I) + 1.
05
NO
END OF DO LOOP?
YES
NOTE 06
BEGIN DO LOOP 3003 I = 1, N
07
NA = NAREA(I)
NOTE 08
BEGIN DO LOOP 3003 K = 1, NA
09
READ FROM DEV 63 VIA FORMAT 3004 INTO THE LIST
NOTE 10
LIST = AREAOGAS(I,K), OUTGAS1(I,K), OUTGAS2(I,K), QI(I,K), QF(I,K), TAU(I,K)
CONVERT TAU FROM HOURS TO SECONDS
11
TAU(I,K) = 3600.*TAU(I,K)
3003
12
NO
END OF DO LOOP?
YES
13
END OF DO LOOP?
NO
YES
02.17B--->
3036
14
READ FROM DEV 63 VIA FORMAT 3001 INTO THE LIST
NOTE 15
LIST = XI, XJ, XL, CC1, CC2, CC3
16
I = XI + .3
IGNORE CONDUCTANCES OF FORM C(0,N)
17
(0)
I
(-)
(+)
3005
18
NCOND(I) = NCOND(I) + 1
K = NCOND(I)
J = XJ + 1.3
JCOND(I,K) = J - 1
INDEX(I,J) = XL + .3
19
C1(I,J,K) = CC1
C2(I,J,K) = CC2
C3(I,J,K) = CC3
WRITE INPUT DATA
3500
20
WRITE TO DEV 61 VIA FORMAT 9000 FROM THE LIST
NOTE 21
LIST = N
22
WRITE TO DEV 61 VIA FORMAT 8030 FROM THE LIST
NOTE 23
LIST = N
IS THIS A RESTART
24
WRITE TO DEV 59 VIA FORMAT 7777 FROM THE LIST
NOTE 25
LIST = READY
26
READ FROM DEV 58 VIA FORMAT 5102 INTO THE LIST
NOTE 27
LIST = DUMMY
28
COMPUTED GO TO FOR SSWTCHP
4601 2.29
4602 2.30
IF OUTSIDE THE RANGE
02.28--->
4601
29
WRITE TO DEV 61 VIA FORMAT 4600
3.00
4603
4602
02.28--->
NOTE 30
CONTINUE
31
WRITE TO DEV 61 VIA FORMAT 3019 FROM THE LIST
NOTE 32
LIST = N, TEMP, GRAMS, TIMIN, TIMAX, M
NOTE 33
BEGIN DO LOOP 4000 I = 1, N
03.03--->
34
WRITE TO DEV 61 VIA FORMAT 4001 FROM THE LIST
NOTE 35
LIST = I, V(I), P(I + 1)
36
NA = NAREA(I)
NOTE 37
BEGIN DO LOOP 4002 K = 1, NA
4002
38
WRITE TO DEV 61 VIA FORMAT 4003 FROM THE LIST
NOTE 39
LIST = K, AREAOGAS(I,K), OUTGAS1(I,K), OUTGAS2(I,K), QI(I,K), QF(I,K), TAU(I,K)
40
NO
END OF DO LOOP?
YES
41
NC = NCOND(I)
NOTE 42
BEGIN DO LOOP 4006 K = 1, NC
03.01--->
43
J1 = JCOND(I,K)
J = J1 + 1
L = INDEX(I,J)
44
WRITE TO DEV 61 VIA FORMAT 4005 FROM THE LIST
NOTE 45
LIST = K, I, J1, L, C1(I,J,K), C2(I,J,K), C3(I,J,K)
3.01

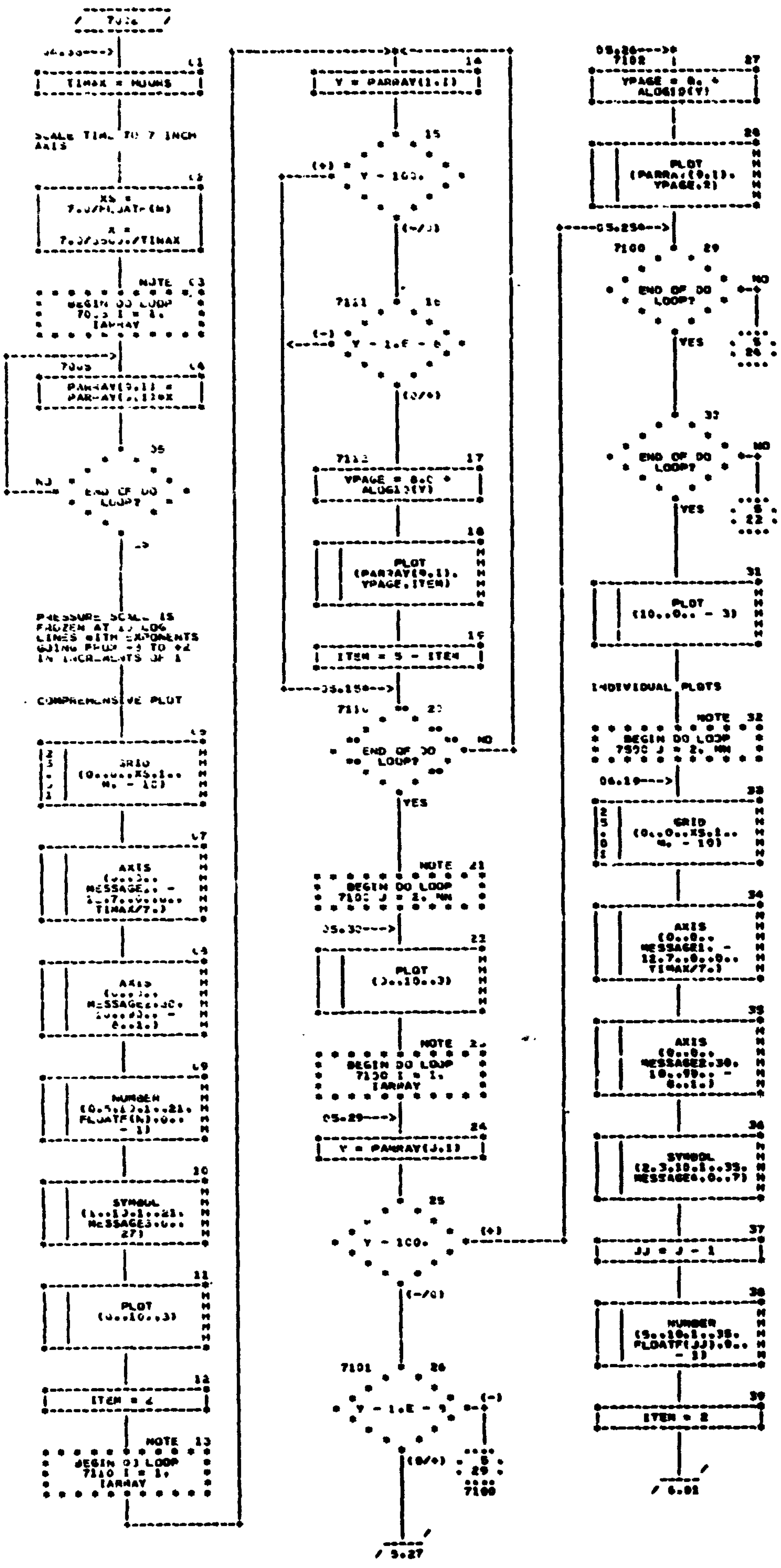
CHART TITLE - PROCEDURES



REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR.

CHART TITLE - PROCEDURES




7036
04.35--->
11
TIMAX = HOURS
SCALE TIME TO 7 INCH AXIS
12
XS = 7.0/FLOATF(N)
X = 7.0/3600./TIMAX
NOTE 13
BEGIN DO LOOP 7035 I = 1, IARRAY
7035
14
PARRAY(9,I) = PARRAY(9,I)*X
35
NO
END OF DO LOOP?
YES
PRESSURE SCALE IS FROZEN AT 13 LOG LINES WITH EXPONENTS GOING FROM -9 TO +2 IN INCREMENTS OF 1
COMPREHENSIVE PLOT
15
GRID (0.,0.,XS,1.,N, - 10)
17
AXIS (0.,0.,MESSAGE1, - 12,7.,0.,0.,TIMAX/7.)
18
AXIS (0.,0.,MESSAGE2,30,10.,90., - 8.,1.)
19
NUMBER (0.,5.12,.21,FLOATF(N),0., - 1)
10
SYMBOL (1.,13.1,.21,MESSAGE3,0.,27)
11
PLOT (0.,10.,3)
12
ITEM = 4
NOTE 13
BEGIN DO LOOP 7110 I = 1, IARRAY
14
Y = PARRAY(1,I)
15
(+)
Y - 100.
(-/0)
7111
16
(-)
Y - 1.E - 9
(0/+)
7112
17
YPAGE = 8.0 + ALOG10(Y)
18
PLOT (PARRAY(9,I), YPAGE, ITEM)
19
ITEM = 5 - ITEM
05.150--->
7110
20
END OF DO LOOP?
NO
YES
NOTE 21
BEGIN DO LOOP 7100 J = 2, NN
05.30--->
22
PLOT (0.,10.,3)
NOTE 23
BEGIN DO LOOP 7100 I = 1, IARRAY
05.29--->
24
Y = PARRAY(J,I)
25
Y - 100.
(+)
(-/0)
7101
26
Y - 1.E - 9
(-)
(0/+)
5
29
7100
5.27
05.26--->
7102
27
YPAGE = 8. + ALOG10(Y)
28
PLOT (PARRAY(9,I), YPAGE,2)
05.250--->
7100
29
END OF DO LOOP?
NO
YES
5
24
30
END OF DO LOOP?
NO
YES
5
22
31
PLOT (10.,0., - 3)
INDIVIDUAL PLOTS
NOTE 32
BEGIN DO LOOP 7500 J = 2, NN
06.19--->
33
GRID (0.,0.,XS,1.,N, - 10)
34
AXIS (0.,0.,MESSAGE1, - 12,7.,0.,0.,TIMAX/7.)
35
AXIS (0.,0.,MESSAGE2,30,10.,90., - 8.,1.)
36
SYMBOL (2.3,10.1,.35,MESSAGE4,0.,7)
37
JJ = J - 1
38
NUMBER (5.,10.1,.35,FLOATF(JJ),0., - 1)
39
ITEM = 2
6.01

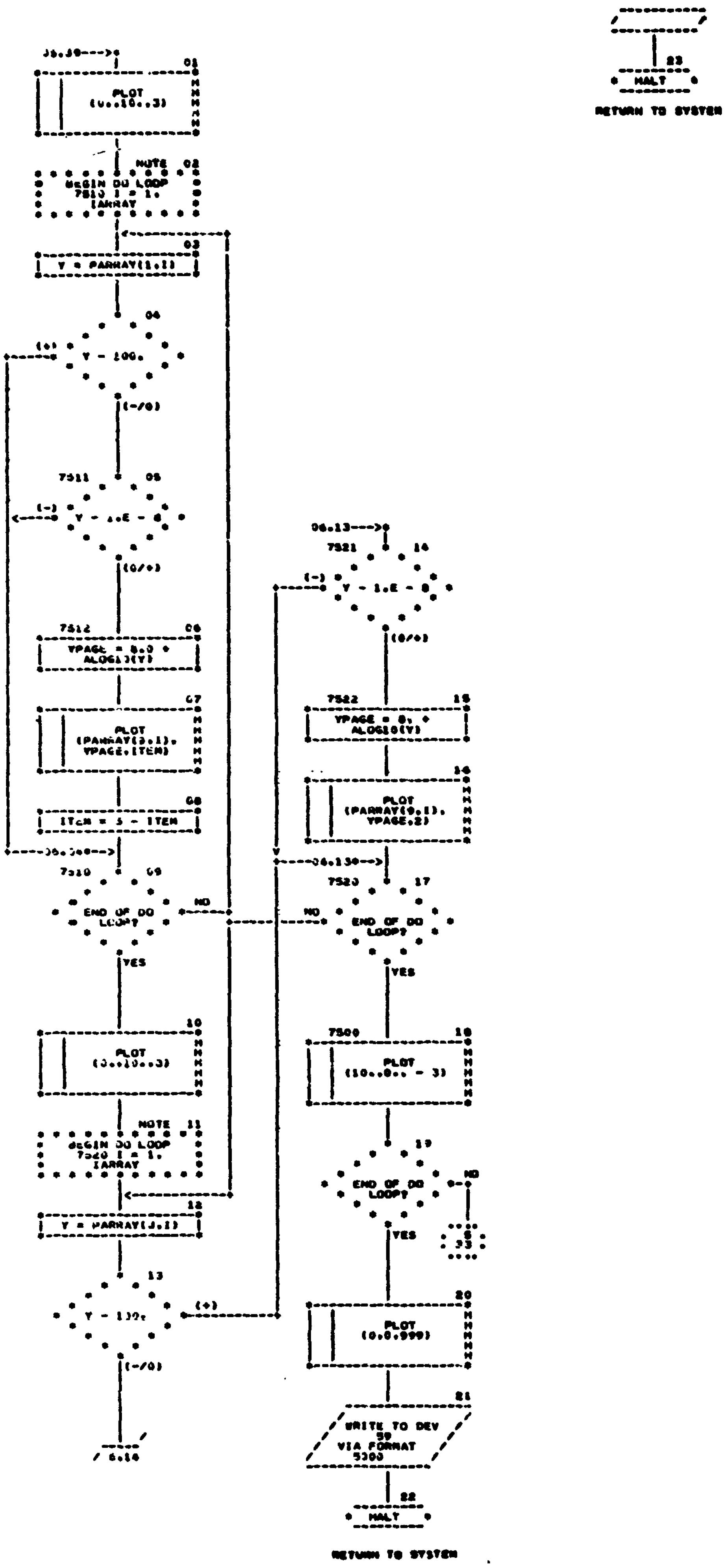

23
HALT
RETURN TO SYSTEM
06.09--->
01
PLOT (0.,10.,3)
NOTE 02
BEGIN DO LOOP 7510 I = 1, IARRAY
03
Y = PARRAY(1,I)
04
(+)
Y - 100.
(-/0)
7511
05
(-)
Y - 1.E - 8
(0/+)
7512
06
YPAGE = 5.0 + ALOG10(Y)
07
PLOT (PARRAY(3,I), YPAGE,ITEM)
08
ITEM = 3 - ITEM
06.090-->
7510
09
END OF DO LOOP?
NO
YES
10
PLOT (0.,10.,3)
NOTE 11
BEGIN DO LOOP 7520 I = 1, IARRAY
12
Y = PARRAY(3,I)
13
Y - 100.
(+)
(-/0)
6.14
06.13--->
7521
14
(-)
Y - 1.E - 8
(0/+)
7522
15
YPAGE = 8. + ALOG10(Y)
16
PLOT (PARRAY(9,I), YPAGE,2)
06.130-->
7520
17
NO
END OF DO LOOP?
YES
7500
18
PLOT (10.,0., - 3)
19
END OF DO LOOP?
NO
YES
5
23
20
PLOT (0,0,999)
21
WRITE TO DEV 59 VIA FORMAT 5300
22
HALT
RETURN TO SYSTEM

CHART TITLE - SUBROUTINE EVALUATE

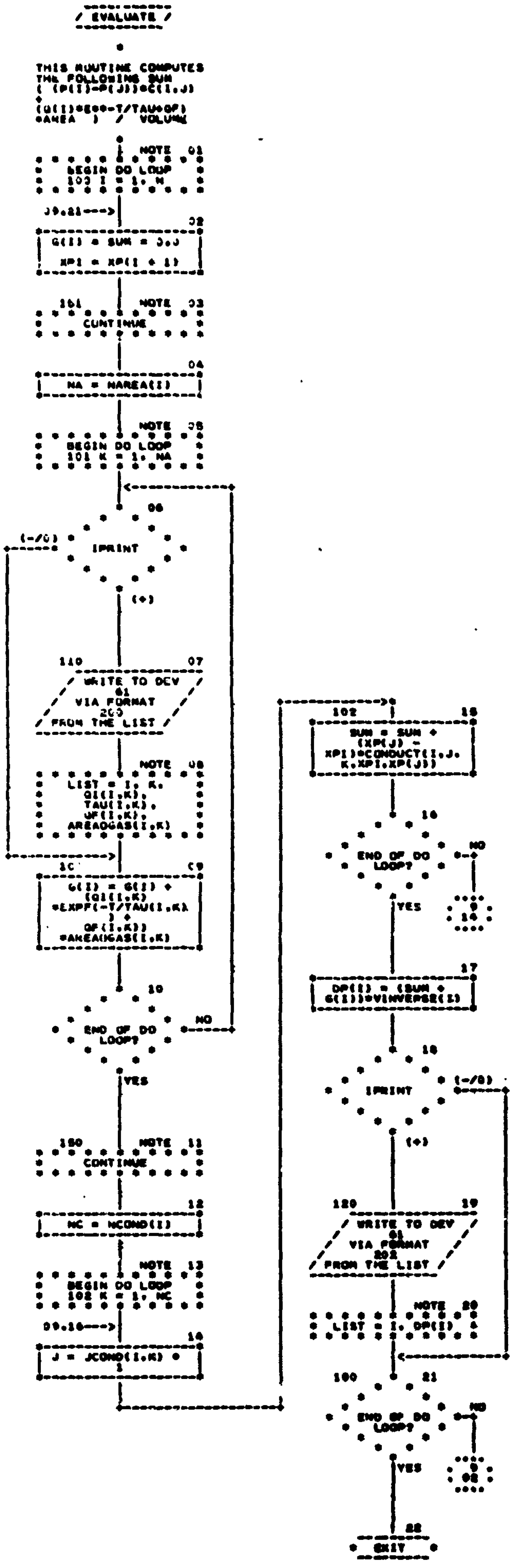


CHART TITLE - FUNCTION CONDUCT(I,J,K,PI,PJ)

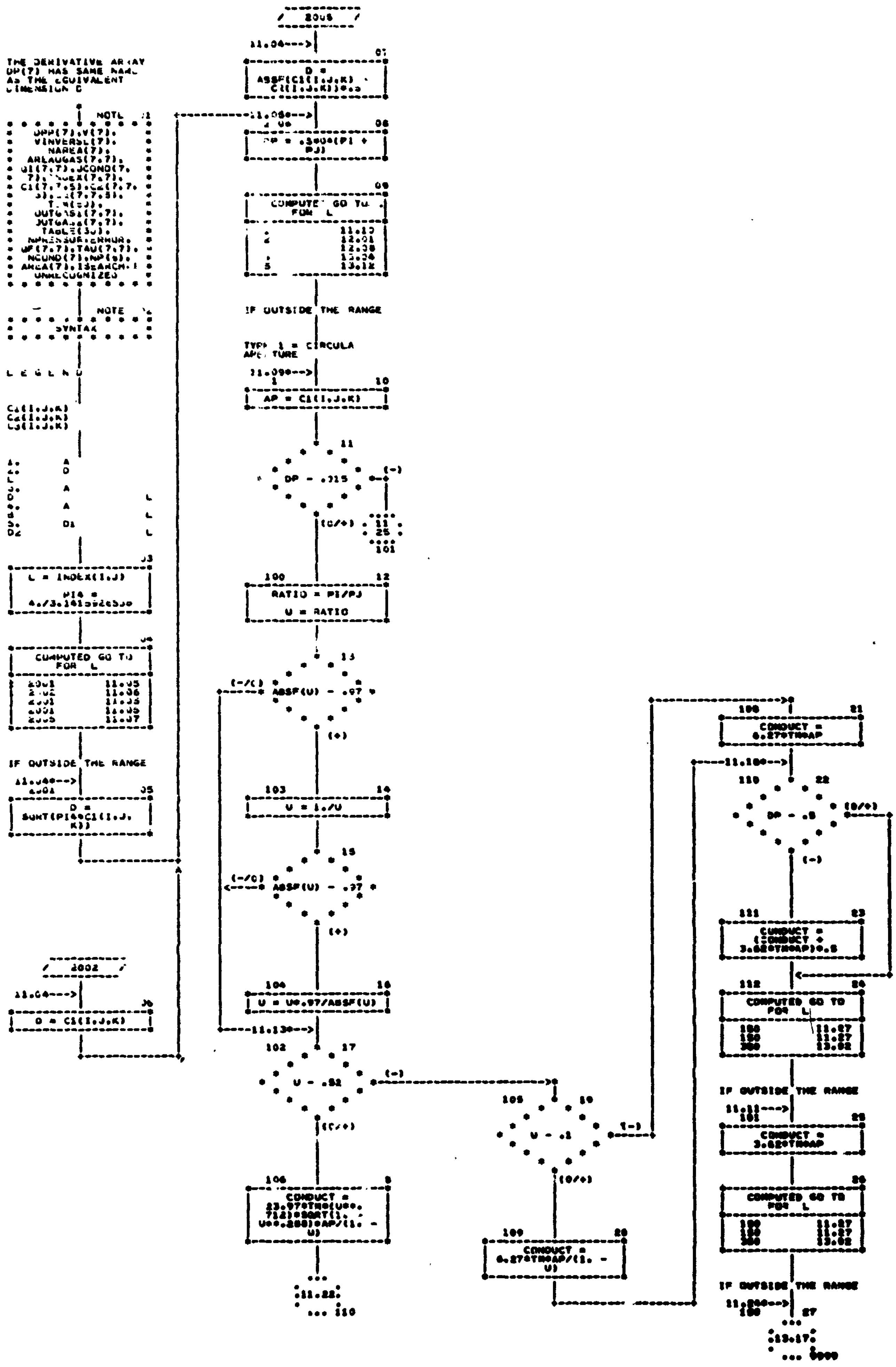


CHART TITLE - FUNCTION CONDUCT(I,J,K,PI,PJ)

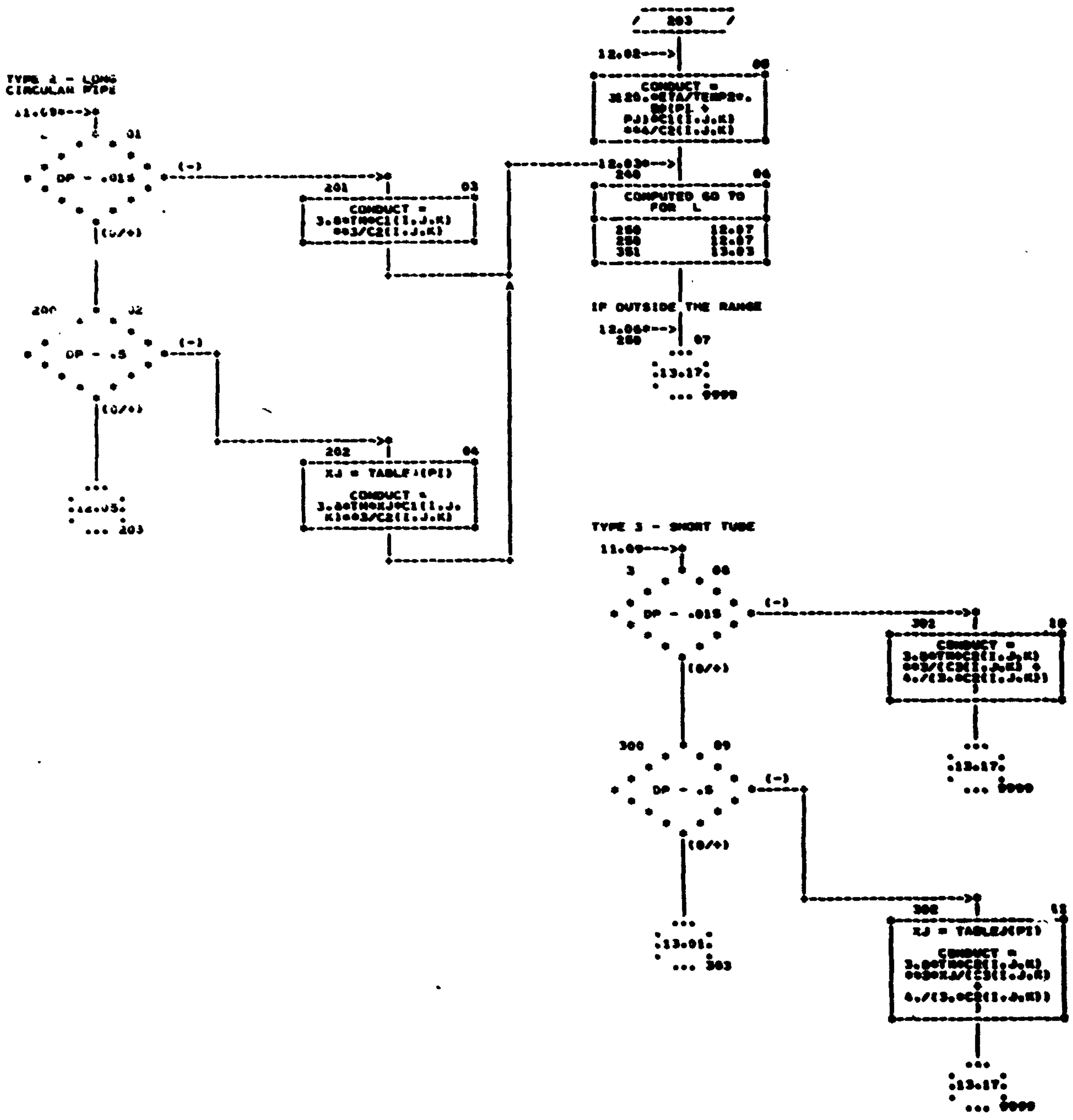


CHART TITLE - FUNCTION CONDUCT(I,J,K,PI,PJ)

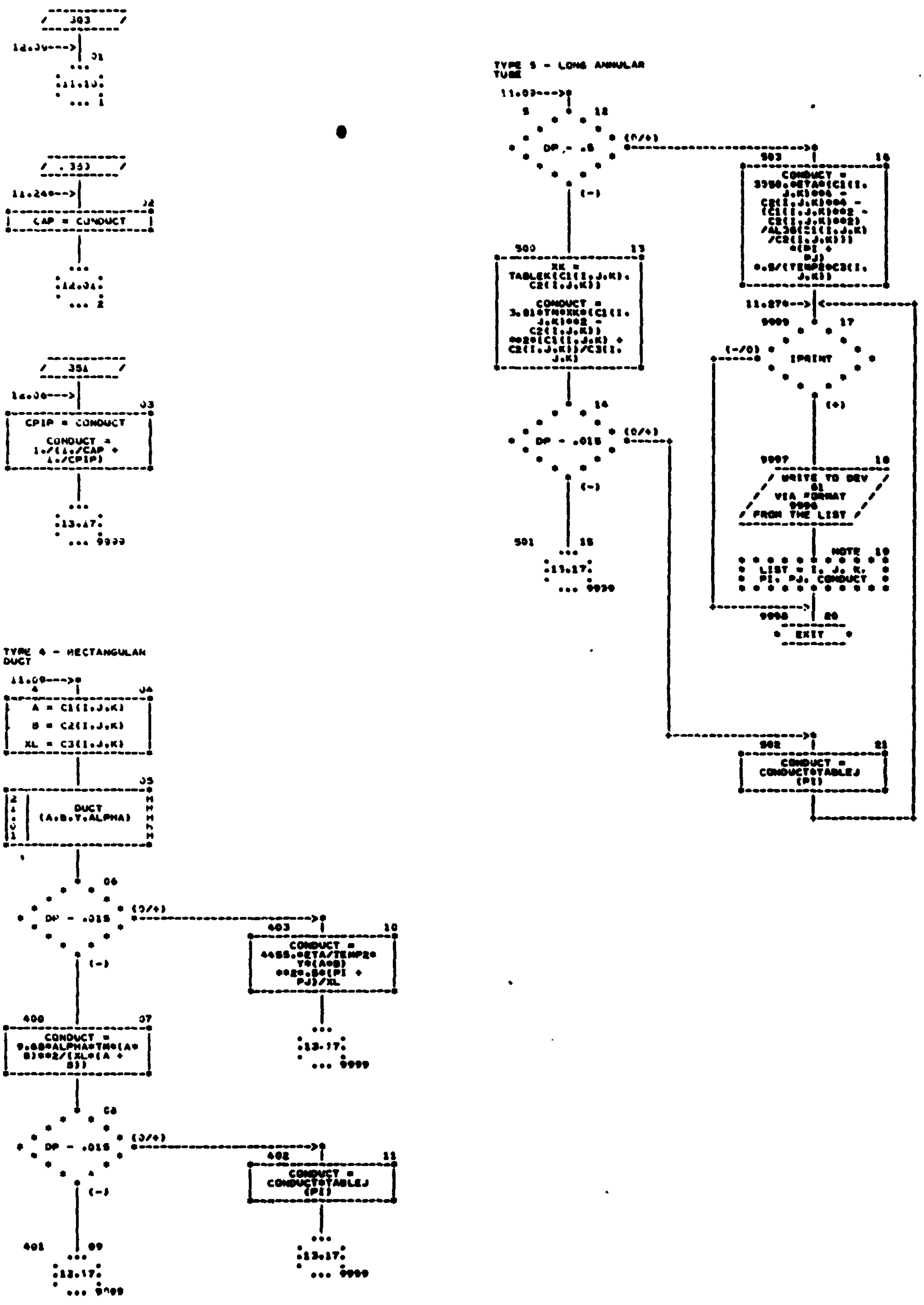


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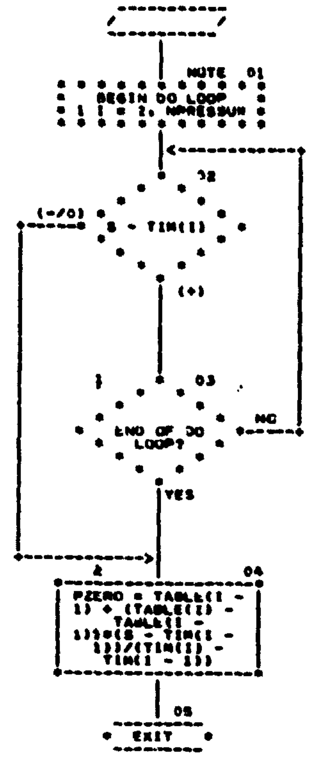
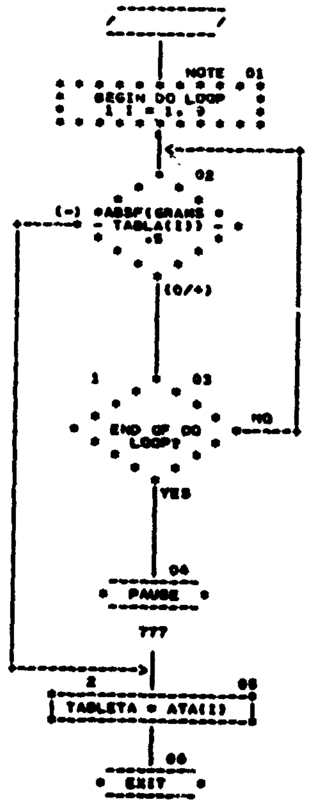
CHART TITLE - FUNCTION PZERO(S)



04/17/69 AUTOFLOW CHART SET - CHAMBER PRESSURE PAGE 17

CHART TITLE - FUNCTION TABLETA(GRAMS)



02/19/69

CHART TITLE - SUBROUTINE RUKUTA

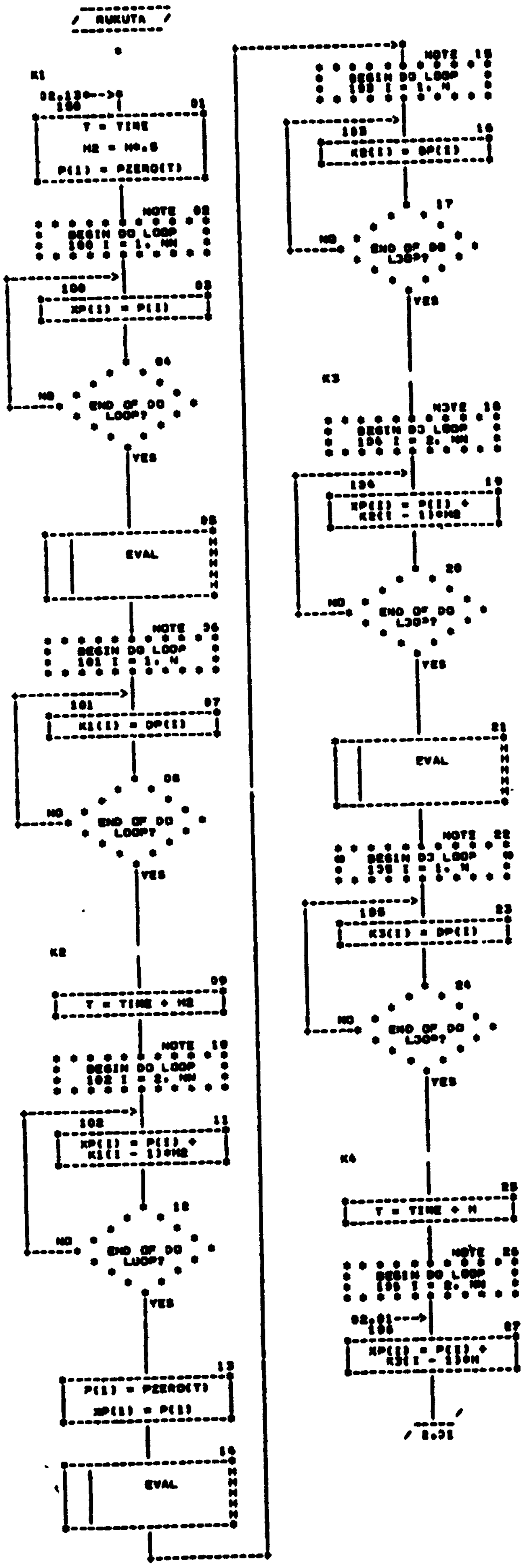


CHART TITLE - SUBROUTINE RUKUTA