COMPUTER PROGRAMS FOR PRESSURIZATION (RAMP) AND PRESSURIZED EXPULSION FROM A CRYOGENIC LIQUID PROPELLANT TANK

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SUMMARY

An analysis to predict the pressurant gas requirements for the discharge of cryogenic liquid propellants from storage tanks is presented, along with an algorithm and two computer programs. One program deals with the pressurization (ramp) phase of bringing the propellant tank up to its operating pressure. The other program deals with the expulsion of the liquid at a uniform pressure. The method of analysis involves a numerical solution of the temperature and velocity functions for the tank ullage at a discrete set of points in time and space. The input requirements of the program are the initial ullage conditions, the initial temperature and pressure of the pressurant gas, and the time for the expulsion or the ramp. Computations are performed which determine the heat transfer between the ullage gas and the tank wall. Heat transfer to the liquid interface and to the hardware components may be included in the analysis. The program output includes predictions of the mass of pressurant required, the total energy transfer, and the wall and ullage temperatures.

The analysis, the algorithm, a complete description of input and output, and the FORTRAN IV program listings are presented in this report. Sample cases are included to illustrate the use of the programs.

INTRODUCTION

Planning for space vehicle and mission requirements necessitates continuing optimization of propellant tank pressurization systems. This optimization is realized in an accurate determination of pressurant requirements for any given set of operating parameters, such as tank pressure, inlet gas temperature, liquid outflow rate, and tank size. This knowledge will allow the design of a system that carries only the weight (pressurant gas and associated tankage) necessary to accomplish the mission.
The analysis in reference 1, which is the basis for this report, provides a selected set of simplifying assumptions to predict the quantity of pressurant gas required during the pressurized discharge of liquid hydrogen. Evaluations of pressurant gas injectors based on this work are made in reference 2. These evaluations deal with small-scale tests made in a 0.82-cubic-meter (29-ft$^3$) cylindrical tank. The reference 1 analysis proved to be adequate (within ±10 percent) in predicting the pressurant gas requirements even though two of its major assumptions were shown to be invalid - namely, no heat transfer to the liquid surface and no mass transfer.

The purpose of this report is to revise and extend the analysis of reference 1 to include the energy transfer occurring at the gas-liquid interface in tanks of any arbitrary symmetric shape. The analysis was also modified and extended to cover the initial pressurization (ramp) period. The major limiting assumptions still remaining from the original analysis are one-dimensional flow and the exclusion of mass transfer.

The algorithm developed in the analysis employs numerical solutions to the gas temperature and velocity functions for the tank ullage at a discrete set of points (in space and time) called net points. Two separate computer programs, coded in FORTRAN IV, are given (each based on the use of a single-component pressurant): one for the pressurized expulsion of a cryogenic (single component) liquid from an axisymmetric storage tank, and the second for the pressurization (ramp) period which may precede an expulsion. The programs are used independently, although they may be coupled together to predict pressurant gas requirements as well as the ullage gas temperature distribution and the adjacent tank wall temperature distribution for the entire pressurization cycle.

Although prior knowledge of the operating conditions for a fluid system is needed for an analysis, the use of the analytical programs does not necessitate that experimental data derived from prototype systems be available.

The validity of the analysis presented herein has been verified in references 3 to 6 for 1.5- and 4-meter (5- and 13-ft) diameter spherical tanks using either gaseous hydrogen or helium as the pressurant over a range of inlet temperatures, tank pressures, and outflow rates. The predicted pressurant requirements for the expulsion period, for all cases, were 7.0 to 12.4 percent of the measured (experimental) values. The predictions for the ramp phase were ±0.5 to ±16.0 percent of the measured values.

The analysis, the algorithm, a complete description of input and output, and the FORTRAN IV listing are given in this report. Sample cases are included to illustrate the use of the programs.

ANALYSIS

The general method of analysis is developed in reference 1 and briefly summarized here. The general analytical model is shown in figure 1. It is based on an application of
the first law of thermodynamics to the fluids and materials within a cryogenic-liquid storage tank which has the pressure history shown in figure 2. The first law is represented by a general energy equation which is coupled with a transformed, one-dimensional equation of continuity. Substitutions involving the equation of state and the equation of heat transfer are made to effect the transformation.

In the analytical model shown in figure 1, the ullage volume in a partially filled liquid propellant tank is divided into a set of volume elements. This is done by establishing a series of equally spaced net points along the vertical axis of the tank to the liquid interface. In each volume element, convective heat transfer from (1) gas to wall, (2) gas to liquid, and (3) gas to internal hardware is treated in a steady-state manner by an equation which expresses gas temperature as a function of velocity and position.

The analysis treats the ullage as a single-component gas. For the ramp program, the ullage pressure is made functionally dependent on a discrete set of pressure-against-time coordinates which is submitted as part of the input data. The initial set of net points remains fixed throughout the ramp period and the hold period which may follow. For an expulsion, liquid propellant is expelled, as pressurant gas is added, to maintain the pressure within set limits in the ullage. A new net point is added to the ullage for each time increment necessary to advance the liquid interface as the liquid is discharged.

To determine a unique solution to the velocity and temperature functions at each net point, initial and boundary conditions are specified. These conditions are described fully in the section INPUT-OUTPUT REQUIREMENTS.

The form of the energy equation used in the analysis in reference 1 and modified to account for both arbitrary symmetric tank shapes and internal tank heat sinks may be written as

\[
\frac{\partial T}{\partial t} = \frac{2h_c}{r^2} \frac{ZRT}{\rho C_p} (T_w - T) \left[ 1 + \left( \frac{\partial}{\partial x} \right)^2 \right]^{1/2} - \frac{\bar{V} \partial T}{\partial x} + \frac{RTZ_1}{JH_p} \frac{\partial P}{\partial t} + \frac{\dot{Q}_H}{\rho C_p} + \frac{\dot{Q}_L}{\rho C_p}
\]  

(1)

where

- \(T_w\) temperature of tank wall
- \(\dot{Q}_H\) heat-transfer rate to internal hardware
- \(\dot{Q}_L\) heat-transfer rate at liquid interface

(All symbols are defined in appendix A.)

By a substitution involving the equation of state, the one-dimensional equation of continuity is transformed into a functional relation involving the velocity of the ullage gas as a function of temperature and position. For the one-dimensional expression of continuity,
\[ \frac{\partial}{\partial x} (\rho \bar{V} A) + \frac{\partial}{\partial t} (\rho A) = 0 \] (2)

The substitution \( A = \pi r^2 \) is made, where \( r \) is the position radius at location \( x \) along the vertical axis. The expression for density from the equation of state \( \rho = \frac{\bar{M}}{ZRT} \) is also substituted:

\[ p \frac{\partial}{\partial x} \left( \frac{\bar{V} r^2}{ZT} \right) + r^2 \frac{\partial}{\partial t} \left( \frac{p}{ZT} \right) = 0 \] (3)

The following velocity equation is obtained after performing the partial differentiation and after rearranging terms:

\[ \frac{\partial \bar{V}}{\partial x} = \left[ \frac{1}{T} + \frac{1}{ZT} \frac{\partial Z}{\partial T} \right] \left( \frac{\partial T}{\partial t} + \frac{\bar{V}}{ZT} \frac{\partial T}{\partial x} \right) + \left[ \frac{1}{Z} \left( \frac{\partial Z}{\partial P} \right)_T + \frac{1}{P} \frac{\partial P}{\partial T} - \frac{2\bar{V}}{r} \frac{\partial r}{\partial x} \right] \] (4)

Each of the bracketed terms may be simplified by differentiating the equation of state while holding the pressure constant and again while holding the temperature constant.

\[ Z_1 = Z + T \left( \frac{\partial Z}{\partial T} \right)_P \] (5)

\[ Z_2 = Z - P \left( \frac{\partial Z}{\partial P} \right)_T \] (6)

When the expressions for \( Z_1 \) and \( Z_2 \) are substituted into equation (4),

\[ \frac{\partial \bar{V}}{\partial x} = \frac{Z_1}{ZT} \left( \frac{\partial T}{\partial t} + \frac{\bar{V}}{ZT} \frac{\partial T}{\partial x} \right) - \frac{Z_2}{ZP} \frac{\partial P}{\partial t} - \frac{2\bar{V}}{r} \frac{\partial r}{\partial x} \] (7)

where the final term on the right is the contribution of the tank curvature.

The heat-transfer equation at a point in the tank wall can be written

\[ \frac{\partial T_W}{\partial t} = \frac{h_c}{l_W \rho_W c_W} (T - T_W) + \left( \frac{\partial q_W}{\partial t} \right) \] (8)

where \( q_W \) is the rate of heat addition per unit area to the tank wall from outside the tank.
The equations contained in the analysis are too complex for a closed-form solution. The numerical method used here and described in the algorithm is brought about by approximating the differential equations by algebraic equations. For example, the preceding equation is approximated by

\[
\frac{T'_{W,j} - T_{W,j}}{\Delta t} = \left( \frac{h_c}{l_{W}\rho_{W}C_{W}} \right) (T'_j - T'_{W,j}) + \left( \frac{q_W}{l_{W}\rho_{W}C_{W}} \right) \tag{9}
\]

where the prime refers to the new value of the variable. Solving the equation for \( T'_{W,j} \) gives

\[
T'_{W,j} = \frac{1}{1 + \left( \frac{h_c \Delta t}{l_{W}\rho_{W}C_{W}} \right)} \left[ T_{W,j} + \left( \frac{h_c \Delta t}{l_{W}\rho_{W}C_{W}} \right)^* \right] \tag{10}
\]

where the quantities marked with the asterisk may be evaluated at the beginning or the end of the time interval. The subsequent algorithms will proceed to show the transformation resulting when \( T'_{W,j} \) from equation (10) is substituted into the algebraic approximation of equation (1). The solution of the resulting transformed equation is coupled to the algebraic approximation of equation (7), and the solution techniques are described.

There are two parts to the algorithm in each computer program. The preliminary part deals with input data and problem definition. The main computation part is concerned with the determination of the amount of pressurant gas added during the expulsion or pressurization period.

The region of the distance-time plane in which the solution is carried out is defined by a set of net points equally spaced along the vertical axis. The entire set of net points is based on an assumed value of a specified number in the initial ullage. From experience, an assigned number of 5 to 6 net points per decimeter (15 to 20 net points/ft) of ullage is satisfactory for nearly all situations and generally provides the desired accuracy for a reasonable computer execution time. Too many net points in the initial ullage may result in using all the available storage for the variables before the expulsion is completed.
CALCULATION PROCEDURE

Expulsion Algorithm

A step-by-step description of the basic calculation procedure is given here. Steps 1 to 6 refer to the program listing shown in appendix B under PRELIMINARY COMPUTATION. For the solution to proceed, a set of boundary and initial conditions is required. These conditions are specified in the section INPUT-OUTPUT REQUIREMENTS. Steps 7 to 17 describe the main computation and the results. Figure 3 gives a logic diagram for the expulsion algorithm. A listing of the expulsion program is given in appendix B.

Step 1: make units conversion, make geometry calculations, and interpolate initial wall and gas temperatures and specific heats. - The program is structured so that, at the user's option, the input data are printed out in SI units or in U.S. customary units. First-value parameters are set equal to zero, and values for the constants are computed. The space between the points is established by setting the initial number of net points for the designated initial ullage.

Step 1A begins with a logic statement which provides three basic options to the program user. For a cylindrical tank, the radius is specified. Under this option the program solution is based on a tank with hemispherical end sections joined to the cylindrical midsection, as would be specified in the input data. If the end sections are not hemispherical, the radius is set equal to zero. Input coordinate values are specified (see Group II data in section INPUT-OUTPUT REQUIREMENTS), and the program interpolates the radius for each volume element. The same procedure is followed for spheroidal tanks; however, for a spherical tank, the tank radius is set equal to -1 and the coordinates for each volume element are determined from the tank diameter specified in the input (group I data).

Figure 1 establishes the program model and the tank configuration on a set of coordinate axes. The total number of points selected for the ullage is part of the input data. Although each point is located at the center of its element, each variable associated with the point is representative of the entire element. The distance separating the points, once fixed at the start, remains constant for all points throughout the run time. The first boundary point is at the top of the tank, where \( x = 0 \). The other boundary point is at the liquid-vapor interface, and each boundary element is one-half the thickness of the other elements. For an expulsion the interface is advanced one point for each time step, which is determined by the propellant discharge rate,

\[
\frac{dt}{dx} = \frac{A(N_Z)}{ML} \left( \frac{ML}{\rho_L} \right) \tag{11}
\]
For a spherical tank, the radius and flow area for each volume element at the point \( j \) are

\[
r_j = \left( D x_j - x_j^2 \right)^{0.5} \tag{12}
\]

\[
A_j = \pi x_j (D - x_j) \tag{13}
\]

The tank weight for the configuration is approximated by the relation

\[
M_T = \sum 2\pi \Delta x l_W \rho_W r_j \left[ 1 + \left( \frac{\Delta r}{\Delta x} \right)_j \right]^{0.5} \tag{14}
\]

The wall thickness \( l_W \) is evaluated by the interpolation subroutine from the discrete values of wall thickness as a function of distance from the top of the tank.

At the initial time \( (t = t_0) \) the gas temperatures and the wall temperatures as well as the specific heat for each net point in the initial ullage are defined based on a linear interpolation of the input data in step 1C.

**Step 2: compute initial values of heat-transfer coefficients.** - Gas transport properties at the mean of the gas and wall temperatures for each net point are computed and the free-convection correlation

\[
h_c = \frac{k}{L} n (GrPr)^m \tag{15}
\]

is employed to evaluate the heat-transfer coefficient at the point. Program options allow for input of multiplier \( n \) and exponent \( m \). The effect of the flow length \( L \) is canceled when the default value of 1/3 is used for the exponent since the length \( L \) is raised to the third power in the Grashof parameter. The pressurant gas properties are included for the subroutines where the computation is made; however, the coefficient \( h_c \) may be specified as a constant for an entire run.

**Step 3: compute initial values of \( \dot{q}_W, \dot{Q}, P, \) and \( \Delta P/\Delta t \).** - The outside-wall heating rate, the inside-hardware heating rate, the tank pressure, and its first time derivative are initialized. Typical values in references 3 to 6 are \( \dot{q}_W = 10 \text{ W/m}^2 \) (0.0009 Btu/ft\(^2\)-sec) and \( \dot{Q} = -8.7 \text{ W/m} \) (-0.0025 Btu/sec-lineal ft). A subsequent option under step 9 is provided in which the energy transferred to the internal tank hardware is computed. The hardware component temperatures are initialized here if the option is taken. If the option is not taken, positive input data values are negated in the program.
Step 4: compute initial value of compressibility factor and then its derivatives which are needed in continuity equation. The local compressibility factor for the gas temperature and tank pressure, as well as its derivatives, is defined. The equation of state for a real gas is commonly written in terms of a compressibility factor $Z(P, T)$

$$\frac{1}{\rho} = \frac{ZRT}{MP}$$

Upon differentiating and holding pressure constant,

$$\left[ \frac{\partial}{\partial T}\left( \frac{1}{\rho} \right) \right]_P = \frac{R}{MP} \left[ Z + T \left( \frac{\partial Z}{\partial T} \right)_P \right]$$

where the expression

$$Z + T \left( \frac{\partial Z}{\partial T} \right)_P = Z_1$$

Differentiating again but with respect to $P$, holding $T$ constant,

$$\frac{\partial}{\partial P}\left( \frac{1}{\rho} \right)_T = \frac{RT}{M} \frac{\partial}{\partial P} \left( \frac{Z}{P} \right)_T$$

$$= \frac{RT}{M} \left[ \frac{1}{P} \left( \frac{\partial Z}{\partial P} \right)_T - \frac{Z}{P^2} \right]$$

$$= \frac{R}{MP^2} \left[ \frac{1}{P} \left( \frac{\partial Z}{\partial P} \right)_T - \frac{Z}{P^2} \right]$$

where

$$Z - P \left( \frac{\partial Z}{\partial P} \right)_T = Z_2$$

Step 5: compute initial values of local ullage gas velocities. The parameters and temperatures evaluated in the previous steps are introduced into a substituted form of the continuity equation. This is obtained by substituting equation (1) into equation (7) and noting that $\dot{Q}_L$ is zero at time $t_1 = 0$. The equation is first solved at the point adjacent to the interface, and the solution is continued from point to point to the top of the tank.
The differential equation (eq. (25), ref. 1) has been modified here to include spherical tanks and approximated at net points \((x_j, t_j)\) by

\[
\frac{\bar{V}_{j+1} - \bar{V}_j}{\Delta x} = \frac{1}{2} \left[ \left( \frac{2h_c Z_1 R}{r \text{MPC}_p} \right)_j + \left( \frac{2h_c Z_1 R}{r \text{MPC}_p} \right)_{j+1} \right] \left( \frac{T_{W,j} + T_{W,j+1}}{2} - \frac{T_j + T_{j+1}}{2} \right)
\]

\[
\times \left[ 1 + \left( \frac{\Delta r}{\Delta x} \right)^2 \right]^{1/2} + \frac{1}{2} \left[ \left( \frac{RZ_1^2}{\text{MPZC}_p} - \frac{Z_1^2}{Z_2} \right) \frac{\Delta P}{\Delta t} + \frac{RZ_1 \dot{Q}_H}{\pi r^2 \text{MPC}_p} + \frac{RZ_1 \dot{Q}_L}{\pi r^2 \text{MPC}_p} - \frac{2V \Delta r}{r \Delta x} \right]_j
\]

\[
+ \left[ \left( \frac{RZ_1^2}{\text{MPZC}_p} - \frac{Z_2}{Z_2} \right) \frac{\Delta P}{\Delta t} + \frac{RZ_1 \dot{Q}_H}{\pi r^2 \text{MPC}_p} + \frac{RZ_1 \dot{Q}_L}{\pi r^2 \text{MPC}_p} - \frac{2V \Delta r}{r \Delta x} \right]_{j+1}
\]

\[
\text{(21)}
\]

**Step 6:** find gas in ullage at time zero by a numerical integration over ullage density profile. - The mass of the volume elements in the initial ullage is totaled. Since the interface is located at the center of its volume element and the first net point is a boundary condition, by definition, only one-half the masses in these two elements are included in the total.

\[
M_U = \int_{V_U} \rho \, dV \approx \sum_{n=1}^{N_f} \rho_n \Delta V_n
\]

\[
(22)
\]

where \(\rho_n = f(T_n, P)\).

**Step 7:** compute initial calculations. - All necessary input data required for the main part of the calculation are now available. The identification of key parameters, along with input and boundary conditions, is important when the output results are reviewed.

**Step 8:** find temperatures at new time. - When \(T_{W,j}'\) from equation (10) is substituted for the value of \(T_W\) in equation (1),

\[
T_j^2 + \left[ \alpha_j^* \left( 1 + \bar{V}_j^* \frac{\Delta t}{\Delta x} - \omega_j^* \right) - T_{W,j} - \left( \frac{q_W \Delta t}{\rho_W C_W} \right)_j \right] T_j^* - \alpha_j^* \left( \bar{V}_j^* \frac{\Delta t}{\Delta x} T_j'_{j-1} + T_j \right) = 0
\]

\[
(23)
\]

The equation is equation (C1) in references 3 to 6, in which the quadratic is evaluated for the gas temperature \(T_j\) beginning with the second net point \((j = 2)\) at the
top and the value for $T_{j-1}'$ as the boundary value. The solution to this equation is repeated from point to point until all the ullage temperatures are computed. The value of $T_{j-1}'$ is always the temperature evaluated at the previous point for the new time. The variable $T_{j-1}'$ is the temperature evaluated for the point at the previous time.

The program computes the real positive root of equation (23) by use of the quadratic formula. The wall temperature $T_{W,j}'$ is also computed under step 8 by equation (10), and the value required for $T_{j}'$ is obtained from the gas temperature quadratic (eq. (23)).

**Step 9: evaluate energy transfer to internal hardware.** A program option is provided in which the energy transferred to internal tank hardware may be computed. The computed value for step 9 would default any input value. The new hardware temperatures are computed by using the relation

$$T_{H} = h_{c,H}A_{H}T_{G,j} - \frac{T_{H,j}}{MC_{V}} \Delta t + T_{H,j}$$

(24)

The heat transferred is then

$$\Delta Q_{1} = \sum_{j=1}^{N} h_{H,j} \left( A_{H,1} \right) \left( T_{G} - T_{H,1} \right) \Delta t$$

(25)

If four hardware components make up the hardware, the average heat-transfer rate is

$$Q_{H} = \frac{\sum_{t_{1}}^{t_{f}} \left( \Delta Q_{1} + \Delta Q_{2} + \Delta Q_{3} + \Delta Q_{4} \right)}{t_{f} - t_{1}}$$

(26)

**Step 10: find compressibility factors at new time.** In step 10 the compressibility factor and its derivatives are reevaluated based on the new gas temperatures computed in step 8.

**Step 11: find velocities at new time.** The new gas velocities are reevaluated by using the new temperature profile and compressibility factors. The finite difference form of equation (4) is used. Although the ullage temperatures are computed starting at the top of the tank, the velocity equation is used to calculate the ullage gas velocity starting with the point $N_{v}$ (in fig. 1) near the interface. The velocity at the interface $N_{z}$, the boundary value, is determined from the propellant discharge rate which is part of the input data.
Step 12: find heat flow rate to wall and total heat added to wall; find gas flow rate and total gas added up to new time. - The heat transfer to the tank wall is computed by using the relation

\[ Q = M_W C_{v,w} \Delta T \]

\[ Q = \sum_{j} r_j \left[ 1 + \left( \frac{\Delta r}{\Delta x_j} \right)^2 \right]^{0.5} (T_{W,j} - T_{W,j}) k_j \]  

For the elapsed time \( t_1 \rightarrow t_2 \), the wall temperature changes from \( T_{W,j} \rightarrow T'_{W,j} \) and

\[ k_j = 2\pi \Delta x l_{W,j} \rho_{W} \]  

In step 12, the mass of pressurant in the tank is dependent on the outflow time as well as on the pressurant gas temperature and pressure. The mass of gas in the tank at any time \( t \) during outflow is based on a summation of the mass in all the volume elements in the ullage. The initial mass calculated at the start is subtracted, and the difference represents the pressurant mass added up to time \( t \).

\[ M_U = \int_{t=0}^{t=f} \rho \, dV = \int_{V_U}^{V_U} \rho \, dV \approx \sum_{n=1}^{N_n} \rho_n \Delta V_n - \sum_{t=1}^{N_t} \rho_n \Delta V_n \]  

An alternate method for determining the flow of pressurant into the tank is provided. The GASCHK parameter measures the velocity of the pressurant passing by an arbitrary area element near the top of the tank. With the gas density evaluated at the element, the mass flow into the tank for a given expulsion is summed over the entire expulsion time.
\[ M_U = \sum_{t=1}^{\infty} \left( \frac{V_n}{t} \right) \left( n \cdot A_n \right) \Delta t \]  

(31)

Step 13: find specific heats at new time. - The wall and gas specific heats from the top of the tank to the interface are evaluated at the new temperatures.

Step 14: find heat-transfer coefficient at new time. - In step 2 the use of the free-convection correlation is described. The gas-to-wall heat-transfer coefficient is obtained from the same correlation in step 14. This correlation is used for the conditions outlined in references 1 to 7. Reference 8 verifies that the gas-to-wall heat-transfer coefficient is in the free-convection regime for a helium expulsion experiment but reports that it is definitely within the forced-convection regime for oxygen test data. In step 14 this heat-transfer coefficient has been extended to include two component effects, if desired: a forced-convection component, as well as a natural-convection component. The following equations represent the manner in which reference 8 relates both convection components:

Free-convection correlation:

\[ \beta_W = 0.00117 \cdot r^2 \]  

(32)

\[ h_c = \frac{k}{L} \cdot n(GrPr)^m \]  

(33)

Forced-convection correlation:

\[ \frac{h_0^r}{k} = 0.06 \left( \frac{rM}{AdU} \right)^{0.8} \left( \frac{CpU}{k} \right)^{1/3} \]  

(34)

\[ h_{g,W} = h_c + h_0 e^{-\beta_W x} \]  

(35)

The last term in the combined equation represents the diminishing effect of forced convection as the distance \( x \) increases from the pressurant distributor.

The development of the gas-to-liquid heat-transfer coefficient is given in appendix B of references 3 to 6. It was shown that the conductance across the gas-liquid interface is similar in form to the empirical relation for free-convection flow across a horizontal surface.

\[ Nu = \frac{h_c L}{k} = 0.14(GrPr)^m \]  

(36)
This equation, with a value of \( m = 1/3 \), is used in step 14 to coincide with the references cited. The heat transferred to the liquid is given by

\[
\dot{Q}_L = h_{c,L}A_n(T_\delta - T_L,s)
\]

(37)

in which \( T_\delta \) is a representative temperature at the edge of the thermal boundary layer. For hydrogen or helium pressurant over liquid hydrogen, \( T_\delta \) was determined experimentally to average 1.3 times the adiabatic compression temperature given by

\[
T_{ad} = T_0 \left( \frac{P}{P_0} \right)^{(\gamma-1)/\gamma}
\]

(38)

Although the magnitude of \( \dot{Q}_L \) is computed from a \( \Delta T \) representing a gradient across a gas-liquid interface, the energy transferred to the liquid is represented in the energy equation (1) as being uniformly derived from the ullage.

Step 15: check to see if end of time has been reached. - The time increment is computed from the displacement of the interface to the succeeding net point. The time increments are summed to give the elapsed time, which is compared to the time specified for the discharge.

Step 16: end of time exceeded - interpolate conditions at end of time. - When the sum of the time steps has exceeded the specified discharge time, a back interpolation of the computed values is performed to comply with the end of time specified for the discharge.

Step 17: write out results. - The subroutine WRITE 2 is called and the computed values are printed.

Pressurization (Ramp) Algorithm

A separate computer program determines the mass of pressurant added, as well as tank wall energy requirements, during the ramp and hold periods. The same equations that describe the expulsion period are also applicable for the ramp and hold periods. Even though experimental results (refs. 3 to 6) indicate relatively large amounts of mass transfer during this period, mass transfer and heat transfer to the liquid are not included in the analysis because of the added complexity of the transport process occurring at the interface. A logic diagram for the ramp algorithm is given in figure 4.

The analysis computes the gas temperatures in the ullage at any time during the pressure rise (and hold period) from the gas energy equation. The corresponding gas
velocities are computed from the equation of continuity. An iterative technique is used here which describes how convergence is achieved in the solution for velocity.

The predicted mass of pressurant added is based on a summation of the mass of the volume elements by assuming a one-component ullage consisting of 100 percent pressurant at the end of the ramp and hold periods after subtracting the initial mass at the start. This is explicit for an autogenous pressurization system, for example, where pressurizing gas is derived from an engine jacket bleedoff. For a nonautogenous system, where the pressurizing gas differs from the propellant, a two-component ullage mixture is encountered once ramping is initiated. For a two-component mixture, the contribution to the final pressure by the component gas in the initial ullage is evident from the heat of compression. On a molar basis, the programmed procedure for obtaining the mass addition by the difference of the assumed single-component pressurant in the initial ullage from that in the final ullage would still appear satisfactory. This assumption is verified in references 5 to 7.

Steps 1 to 7: These steps follow the procedure described in the section Expulsion Algorithm, with the exception that hardware component temperatures are not initialized under step 3 since this computational option is not provided. A program listing for the ramp program is provided in appendix C.

Step 8: find temperature at new time, find miscellaneous quantities \( \dot{Q}_H \) and \( \dot{q}_W \) at new time, initialize an estimate for velocity. - The inlet gas temperature representing the upper boundary temperature is defined for the time \( t > 0 \). Likewise, the value of the saturation temperature is defined for the time \( t > 0 \) and is made equal to the lower gas boundary temperature at the interface. The boundary wall temperature at the interface is made equal to the bulk propellant temperature.

The option to compute heat transfer to the internal hardware \( \dot{Q}_H \) is not included during the ramp, since this effect during the ramp period is generally small. However, a substituted value for this parameter as well as the outside wall parameter (heat leak rate) \( \dot{q}_W \) may be made a part of the input data.

The initial gas velocity distribution used in solving the temperature function at each net point for each new time \( t \) is obtained from the previous time as follows:

\[
\bar{V}_t', 2 = \bar{V}_t, 1 \frac{\Delta P_{1-2}}{\Delta t_{1-2}} \frac{\Delta t_{1-2}}{\Delta P_{0-1}} \frac{\Delta P_{0-1}}{\Delta t_{0-1}}
\]

A solution to the ullage temperature function (expressed as a quadratic in the expulsion analysis) under the conditions encountered during ramp proved to be extremely
difficult. When the initial wall temperature distribution in the ullage was greater than the gas temperature distribution, heat transfer from wall to gas resulted in negative velocities, which made it impossible to evaluate the function. A satisfactory method is achieved, however, when the velocity at the net point $\bar{V}_j$ is eliminated from the function. Substituting the velocity function for $\bar{V}_j$ into the quadratic results in the following cubic equation (appendix C of refs. 3 to 6):

$$b_j T_j'^3 + \left[ \left( \frac{Z_1}{Z} \right)'_j T_{j+1}' + b_j c_j + \alpha_j^* \frac{\Delta t}{\Delta x} \bar{V}_{j+1}' + d_j \right] T_j'^2$$

$$+ \left[ c_j \left( \frac{Z_1}{Z} \right)'_j T_{j+1}' + \alpha_j^* \frac{\Delta t}{\Delta x} \left( \frac{Z_1}{Z} \right)'_j \frac{\Delta x}{\Delta t} T_j - \alpha_j^* \frac{\Delta t}{\Delta x} T_{j-1}' (\bar{V}_{j+1}' + d_j) - \alpha_j^* T_j \frac{\Delta t}{\Delta x} b_j \right] T_j'$$

$$- \alpha_j^* \frac{\Delta t}{\Delta x} \left( \frac{Z_1}{Z} \right)'_j \frac{\Delta x}{\Delta t} T_j T_{j-1}' - \alpha_j^* T_j \left( \frac{Z_1}{Z} \right)'_j T_{j+1}' = 0$$

(40)

The main purpose of step 8 is the evaluation of the preceding equation. Unlike the method employed in the expulsion program, the cubic equation is solved numerically by the Newton-Raphson method.

$$\left( T_j' \right)_f = \left( T_j' \right)_i - \frac{F(T_j')}{F'(T_j')_i}$$

(41)

where $F(T_j')$ represents the cubic function evaluated for the temperature $T$ at the new time $'f'$ for the point $j$. The term $F'(T_j')$ is its first derivative. The subscript $i$ for $T_j'$ represents the initial or previously evaluated temperature in the iterative process and $\left( T_j' \right)_f$ is the new value, which has converged closer to the true value (see fig. 5).

**Step 9:** find heat-transfer coefficient at new time. - Step 9 computes the gas-to-wall heat-transfer (natural convection) coefficient. Steps 9 to 11 together allow for the determination of the thermodynamic and transport properties as a function of $P$ and $T$ in the subroutines.

**Step 12:** find velocities at new time. - The velocity equation used to calculate ullage gas velocity starting with the point $N_y$ (fig. 1) is the same equation employed in step 11 of the expulsion algorithm. The boundary value of the velocity at the interface, point $N_y$, is zero with no expulsion. Figure 5 shows the iteration scheme by which convergence is achieved in the solution of the gas energy and continuity equation.
The ullage gas velocity is calculated from point to point until the top of the tank is reached. The new velocities are used in the cubic equation in step 8 along with the previous values of $T_{i+1}$, and the temperature distribution is redetermined. This process is repeated until the computed velocities are essentially unchanged from those computed in the previous iteration. When convergence is achieved over the entire ullage, the time is then advanced to $t_2$, and the process is continued as shown in figure 4.

**Step 13:** find gas flow rate and total gas added up to new time. Generally, the ramp rate is not accompanied by tank outflow. In step 13, the mass of pressurant in the tank is dependent on the pressurant gas temperature and pressure as a function of ramp time. The mass of gas in the tank at any time $t$ during the ramp is based on a summation of the mass in all the volume elements in the ullage. The initial mass calculated at the start is subtracted, and the difference represents the pressurant mass added up to time $t$

$$M_U = \int_{i}^{f} \rho \, dV - \int_{t=0}^{t=f} \rho \, dV \approx \sum_{n=1}^{N_f} \rho_n \Delta V_n - \sum_{n=1}^{N_t} \rho_n \Delta V_n$$

An alternate method for determining the flow of pressurant into the tank is provided. The GASCHK parameter establishes a velocity for the pressurant passing through the second area element from the top of the tank. With the known gas density at the cross section, the mass flow into the tank during the ramp is summed over the entire ramp time. This method generally did not give good agreement with the computed mass derived from the integration of all the volume elements

$$M = \sum_{t=i,f} \left( \overline{V}_2 \right)_t \left( \rho_2 A_2 \right)_t \Delta t$$

**Step 14:** find heat flow rate to wall and total heat added to wall. This step follows the description for step 12 in the expulsion program.

**Step 15:** check to see if end of time has been reached. The time increments are summed to give the elapsed time, which is compared to the specified time for the ramp or hold pressure. In general, ramp has never been experienced with significant tank outflow. However, this possibility does exist, and the time step would then become a function of the discharge rate. Under this condition, the procedure outlined by this step becomes severely constrained. The time involved for the interface to advance to the next point is in many instances too great and results in a serious discontinuity.
Nevertheless, the option to include tank discharge during ramp is provided and may be considered as an extension of the expulsion program with an iteration scheme which may provide some utility for a pressurization system under study.

Step 16: end of time exceeded - interpolate conditions at end of time; and step 17: write out results. In essence, steps 16 and 17 follow the corresponding steps of the expulsion program.

SUBROUTINES

The subroutines, which are common to both the pressurization and expulsion programs, are listed in appendix D.

Subroutine SINTS

SINTS is a subroutine which allows the user the option to program in SI units. This subroutine converts the input data in SI units to the units required by the program.

Subroutine SPHEAT

The "specific heat" subroutine SPHEAT provides 15 storage locations representing a set of 15 discrete values of specific heat as a function of temperature (°R) for the vessel wall, as well as a set of 15 values of specific heat (Btu/lbm-°R) as a function of temperature (°R) for the pressurant gas. These data may be substituted to fit the problem definition. The program interpolates values between the points.

Subroutine WRITE 1

Subroutine WRITE 1 contains the statements which print out the input data.

Subroutine WRITE 2

Subroutine WRITE 2 contains the statements which print out the problem solution (the calculated pressurant gas and temperature distributions) at any time t during the expulsion and/or the ramp, following the call statement.
Subroutine COMPRS

COMPRS is a subroutine which calculates the compressibility factor from a 20×17 matrix for hydrogen \( Z(T, P) \). For another gas pressurant the table may be replaced, or a value of \( Z(T, P) = 1.0 \) or \( Z(T, P) = \text{Constant} \) may be substituted.

Subroutine HCOEFF

Subroutine HCOEFF calculates heat-transfer coefficients for either of two pressurant gases (hydrogen or helium) at a specific pressure. Transport property data for each gas are keyed to the molecular weight and may be replaced for other gases.

Subroutine INTERP

Subroutine INTERP performs a straight-line interpolation between two discrete points.

INPUT-OUTPUT REQUIREMENTS

Input

The program input consists of a three-card description of the problem, although any or all of the cards may be blank. Any specific information may be entered in columns 2 to 80, but column 1 is left blank. The succeeding groups of data are defined in the expulsion program listing.

Group I data. - Group I data include the parameters (PARAMS) that relate to tank configuration and input options. These data are entered in NAMELIST FORM.

Group II data. - Group II data are also entered in NAMELIST FORM, which uses names in place of FORMAT numbers in the read (INPNTS) and write (OTPNTS) statements. The INPNTS series is a sequence of coded statements (words) giving the number of pairs of values read in as data which define the initial and boundary conditions for the ramp or expulsion programs. The flexibility of the NAMELIST FORM is demonstrated in the write statement (OTPNTS), which verifies the number of pairs of values that are specified. The number of pairs in each set printed under OTPNTS must agree with the number of paired values in each set submitted under the NAMELIST TABLES that follow. If a single pair is specified under TABLES at time \( t = 0 \) (i.e., \( TGAS = 400. \), \( TIME1 = 0. \)), the value of the variable (TGAS) is maintained constant for any subsequent time.
The expulsion program provides a maximum of 15 data entries under TABLES. The ramp program has the capability of utilizing only the first 11 data entries defined in the following list. The data for MRAD are necessary if the tank radius (as a function of distance from the top) is to be interpolated.

<table>
<thead>
<tr>
<th>Code</th>
<th>Number of pairs of data</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTGAS</td>
<td>inlet gas temperature (K; °R) as function of time (sec)</td>
</tr>
<tr>
<td>MPDATA</td>
<td>tank pressure (MN/m²; lbf/ft²) as function of time (sec)</td>
</tr>
<tr>
<td>MFLOW</td>
<td>volume flow rate (m³/sec; ft³/sec) as function of time (sec)</td>
</tr>
<tr>
<td>MTSAT</td>
<td>saturation temperature (K; °R) as function of time (sec)</td>
</tr>
<tr>
<td>MTBULK</td>
<td>liquid-propellant bulk temperature (K; °R) as function of time (sec)</td>
</tr>
<tr>
<td>MQOUT</td>
<td>outside-wall heating rate (J/m²·sec; Btu/ft²·sec) as function of time (sec)</td>
</tr>
<tr>
<td>MQIN</td>
<td>inside-hardware heating rate (J/m·sec; Btu/lineal ft·sec) as function of time (sec)</td>
</tr>
<tr>
<td>MTWIN</td>
<td>initial wall temperature (K; °R) as function of axial distance from top of tank (m; ft)</td>
</tr>
<tr>
<td>MTGIN</td>
<td>initial gas temperature (K; °R) as function of axial distance from top of tank (m; ft)</td>
</tr>
<tr>
<td>MRAD</td>
<td>tank radius (m; ft) as function of axial distance from top of tank (m; ft)</td>
</tr>
<tr>
<td>MTICK</td>
<td>tank thickness (m; ft) as function of axial distance from top of tank (m; ft)</td>
</tr>
<tr>
<td>MTBAK</td>
<td>initial temperature of phenolic internal hardware (K; °R) as function of axial distance from top of tank (m; ft)</td>
</tr>
<tr>
<td>MTCU</td>
<td>initial temperature of copper internal hardware (K; °R) as function of axial distance from top of tank (m; ft)</td>
</tr>
<tr>
<td>MTSS</td>
<td>initial temperature of stainless steel (TP304) internal hardware (K; °R) as function of axial distance from top of tank (m; ft)</td>
</tr>
<tr>
<td>MTAL</td>
<td>initial temperature of aluminum internal hardware (K; °R) as function of axial distance from top of tank (m; ft)</td>
</tr>
</tbody>
</table>

Group III data. - The term group III data refers to data that are entered directly into the appropriate subroutine.

Output

The output from a successfully executed case is written by the subroutine WRITE 2 after a printout of the initial problem conditions by subroutine WRITE 1. This output,
shown for a sample case in appendixes B and C, consists of a block of computed wall temperatures and gas temperatures as a function of distance above the liquid interface.

The block data are preceded by two lines of data. The top line gives the time (TIME) during the ramp or expulsion for which the temperatures are evaluated. Associated with the time, the GAS SUPPLIED, HEAT TO WALL, and INLET VEL (pressurant velocity) are included on the first line. For an expulsion, the second line of output includes the heat transfer to the liquid (propellant). Both programs provide the CHECK ON GAS computation, and the GAS FLOW or rate of pressurant into the tank.

Under group I data, the ENDTIM value specifies the ullage condition at the point in time for the termination. For the ramp program the ENDRMP value represents the ullage condition at the end of the pressure rise period, and ENDTIM represents the condition at the end of the hold period (fig. 2).

The OUTPUT parameter specifies the number of time steps for a "demand" requirement of the computational results.

Two techniques are used to determine the mass of pressurant required for any given time t. The primary method determines GAS SUPPLIED by summing the product of gas density and volume for all the volume elements for each net time. From this summed value, the initial ullage mass is subtracted. The alternate method, CHECK ON GAS, establishes a velocity for a given cross section near the tank inlet. With the gas density known at the cross section, the mass flow rate into the tank is summed over the entire time.

TYPICAL ERROR MESSAGES AND THEIR CAUSES

Ramp Program

Initial ullage velocities are unstable. - Since the wall and gas temperature distributions are specified in the initial ullage, the values for gas specific heat, heat-transfer coefficient, and compressibility factor are defined. The initial velocity at each net point is computed for time t = 0 and P = PDATA(1), where PDATA(1) is the initial pressure throughout the ullage for a series of discrete time-dependent values. This initial velocity distribution is printed out by the program. A negative value for a velocity indicates an incipient instability, and the program terminates itself because of a major overflow. The initial problem condition must be altered by selecting a greater number of net points (smaller net space between points) or by adjusting the initial slope of the pressure rise curve (fig. 1).

Solution to cubic equation requires more than 10 iterations. - Sometimes during the solution for the true ullage temperature, the Newton-Raphson programmed convergence is not achieved in 10 iterations. These occurrences are counted and when the number is
greater than 25, the program reduces the time step and starts the problem again. If the solution is not achieved by this procedure, the pressure rise for the interval is too great, or the instability may be attributed to a large difference between the upper-boundary gas temperature and the inlet pressurant temperature.

One or more negative gas velocities are computed after time zero. - If, during the ramp, one or more negative velocities are computed, the program reduces the time step and starts the problem again. It is programmed to do this three times and then prints out all the gas temperatures in the ullage.

A computed temperature is greater than the boundary temperature. - Sometimes during the course of the solution of the cubic equation, there will be three real and unequal roots. Unfortunately, a distinction cannot be made as to the correct root. When the roots are near the boundary temperature or the inlet temperature, occasionally the converged value may be greater than the value of the inlet temperature. In this predicament, the root can be made equal to the value of the boundary temperature without interrupting the procedure.

Error greater than acceptable (program cannot converge on true ullage temperature). - Path B in the ramp block diagram, shown in figure 4, should not be construed as an alternate program path. It indicates a sequence of printed data values and their relative occurrence during the iterations.

If after 32 iterations, any of the ullage velocities differ from the value computed in the previous iteration by more than 1/2 percent, this condition is indicated by a printout of the velocities.

After 40 iterations, the program may still not converge on the true ullage temperatures. In this circumstance, the deviation of the velocities from those computed in the previous iteration may be greater than 10 percent. This situation is indicated by a printout of the ramp time, ullage temperature, and wall temperature distribution.

These data blocks are printed during steep ramp rates or when extremely nonlinear portions of the ramp curve (pressure rise as a function of time) are encountered. The ramp time parameters PM1, PM2, PM3, and PM4 should be examined and the time step selected accordingly. However, when the time steps are made exceedingly small, excessive computer run times are encountered. Time steps of 0.2 second or less, selected for a large percentage of the total ramp time, may consume more than 1/4 hour of computer time for a 40- to 50-second ramp even though the ullage volume may be only 5 percent of the tank volume.

Expulsion Program

For the expulsion program, error messages have not been found necessary. In general, if the program is terminated, the reason often appears obvious upon examining the
input data format. If the input data format is correct, a program completion is assured when the initial gas temperature boundaries are equivalent to the liquid interface condition and the pressurant temperature at the start. The wall temperature at the liquid interface should approximate the propellant bulk temperature.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 15, 1974,
### APPENDIX A

#### SYMBOLS

<table>
<thead>
<tr>
<th>Engineering symbol</th>
<th>FORTRAN name</th>
<th>Units in program</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>AREA</td>
<td>ft²</td>
<td>Tank cross section normal to vertical axis</td>
</tr>
<tr>
<td>-----</td>
<td>AAY</td>
<td></td>
<td>For cubic equation ( y^3 + Py^2 + qy + r = 0 ), ( AAY = (3q - P^2)/3 ).</td>
</tr>
<tr>
<td>-----</td>
<td>BEE</td>
<td></td>
<td>( BEE = (2P^3 - 9pq + 27r)/27 )</td>
</tr>
<tr>
<td>-----</td>
<td>TEST</td>
<td></td>
<td>Evaluate ( BEE^2/4 + AAY^3/27 ) to determine the nature of the roots.</td>
</tr>
<tr>
<td>b</td>
<td>G8</td>
<td></td>
<td>Coefficient of first term of gas temperature function, eq. (40), represented by cubic equation in ramp program</td>
</tr>
<tr>
<td>-----</td>
<td>BQUAD</td>
<td></td>
<td>Second term of quadratic temperature function in expulsion program</td>
</tr>
<tr>
<td>( C_p )</td>
<td>CP</td>
<td>Btu/(lbm·°R)</td>
<td>Specific heat at constant pressure</td>
</tr>
<tr>
<td>( C_v, C_W )</td>
<td>CPW</td>
<td>Btu/(lbm·°R)</td>
<td>Specific heat at constant volume, ( C_v ); specific heat of wall material, ( C_W )</td>
</tr>
<tr>
<td>c</td>
<td>Gl</td>
<td>°R</td>
<td>( \alpha - \alpha \omega - T_W - \frac{\Delta t \dot{q}_W}{\ell_W \rho_W C_W} )</td>
</tr>
<tr>
<td>-----</td>
<td>CQUAD</td>
<td></td>
<td>Final expression of quadratic temperature function in expulsion program</td>
</tr>
<tr>
<td>D</td>
<td>DIA</td>
<td>ft</td>
<td>Spherical or cylindrical diameter; vertical diameter when tank is a spheroid</td>
</tr>
<tr>
<td>-----</td>
<td>DISC</td>
<td></td>
<td>Discriminant of quadratic temperature function</td>
</tr>
<tr>
<td>d</td>
<td>G6</td>
<td>ft/sec</td>
<td>( \frac{Z_2 \Delta x (P' - P)}{Z \Delta t (P')} - \frac{Z_1 \Delta x}{Z \Delta t} )</td>
</tr>
<tr>
<td>Gr</td>
<td></td>
<td></td>
<td>Grashof number, ( L^3 \rho g^\beta \Delta T/\mu^2 )</td>
</tr>
<tr>
<td>-----</td>
<td>ERRP</td>
<td></td>
<td>A percent difference in velocity, computed in step 12 (ramp), from value of previous iteration</td>
</tr>
<tr>
<td>Engineering symbol</td>
<td>FORTRAN name</td>
<td>Units in program</td>
<td>Description</td>
</tr>
<tr>
<td>--------------------</td>
<td>--------------</td>
<td>------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>g</td>
<td></td>
<td>ft/sec²</td>
<td>Gravity acceleration</td>
</tr>
<tr>
<td>h&lt;sub&gt;c&lt;/sub&gt;</td>
<td>H</td>
<td>Btu/(ft&lt;sup&gt;2&lt;/sup&gt;-sec-°R)</td>
<td>Convective heat-transfer coefficient</td>
</tr>
<tr>
<td>---</td>
<td>HOPE</td>
<td></td>
<td>Temperature function, cubic in propellant temperature TP</td>
</tr>
<tr>
<td>---</td>
<td>ISTAR</td>
<td></td>
<td>Integer representing count of iteration</td>
</tr>
<tr>
<td>---</td>
<td>KSTAR</td>
<td></td>
<td>Counting integer - specifies the number of times the numerical solution for a gas temperature could not converge on the true value in 10 iterations</td>
</tr>
<tr>
<td>---</td>
<td>KLAMP</td>
<td></td>
<td>Integer counter equal to or less than 3. The ullage temperature computations are repeated so that temperature-dependent parameters are evaluated close to converged gas temperatures.</td>
</tr>
<tr>
<td>---</td>
<td>LOOM</td>
<td></td>
<td>Counting integer - if computed value for a gas velocity is less than zero, time step is reduced.</td>
</tr>
<tr>
<td>J</td>
<td>XJAY</td>
<td>(ft-lbf)/Btu</td>
<td>mechanical equivalent of heat</td>
</tr>
<tr>
<td>L</td>
<td>XL</td>
<td>ft</td>
<td>Flow length</td>
</tr>
<tr>
<td>l</td>
<td>TICK</td>
<td>ft</td>
<td>Wall thickness</td>
</tr>
<tr>
<td>(\dot{M})</td>
<td>GSRATE</td>
<td>lbm/sec</td>
<td>Pressurant flow rate addition</td>
</tr>
<tr>
<td>(\bar{M})</td>
<td>XMOLEC</td>
<td>lbm/(lbm-mol)</td>
<td>Molecular weight of pressurant gas</td>
</tr>
<tr>
<td>(\Delta M)</td>
<td>GAS (GASB - GSTART)</td>
<td>lbm</td>
<td>Amount of gas (pressurant) added by subtracting initial ullage gas from GASB</td>
</tr>
<tr>
<td>Engineering symbol</td>
<td>FORTRAN name</td>
<td>Units in program</td>
<td>Description</td>
</tr>
<tr>
<td>-------------------</td>
<td>--------------</td>
<td>------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>---</td>
<td>GASCHK</td>
<td>lbm</td>
<td>Mass of pressurant added by alternate calculation</td>
</tr>
<tr>
<td>M&lt;sub&gt;U&lt;/sub&gt;</td>
<td>GASB</td>
<td>lbm</td>
<td>Summed value of ullage gas over all volume elements for time into ramp or expulsion</td>
</tr>
<tr>
<td>m</td>
<td>HEXP</td>
<td>-----------------</td>
<td>Grashof, Prandtl exponent</td>
</tr>
<tr>
<td>N</td>
<td>N, NP</td>
<td>-----------------</td>
<td>Number of volume segments in tank, NP, refers to next time step</td>
</tr>
<tr>
<td>N&lt;sub&gt;i&lt;/sub&gt; to N&lt;sub&gt;f&lt;/sub&gt;</td>
<td>J</td>
<td>-----------------</td>
<td>Summing index, i = initial, f = final</td>
</tr>
<tr>
<td>N&lt;sub&gt;1&lt;/sub&gt; to N&lt;sub&gt;Z&lt;/sub&gt;</td>
<td></td>
<td>-----------------</td>
<td>Particular volume segments</td>
</tr>
<tr>
<td>Nu</td>
<td></td>
<td>-----------------</td>
<td>Nusselt number, h&lt;sub&gt;c&lt;/sub&gt;L/k</td>
</tr>
<tr>
<td>P, P&lt;sub&gt;0&lt;/sub&gt;</td>
<td>P, PHOLD</td>
<td>lbf/ft&lt;sup&gt;2&lt;/sup&gt;</td>
<td>Tank pressure; initial pressure</td>
</tr>
<tr>
<td>ΔP</td>
<td>PP - P</td>
<td>lbf/ft&lt;sup&gt;2&lt;/sup&gt;</td>
<td>Differential pressure</td>
</tr>
<tr>
<td>Pr</td>
<td></td>
<td>×</td>
<td>Prandtl number, C&lt;sub&gt;p&lt;/sub&gt;µ/k</td>
</tr>
<tr>
<td>PHE</td>
<td></td>
<td>×</td>
<td>Coefficient of second term (square in TP) of cubic equation in ramp program</td>
</tr>
<tr>
<td>Q</td>
<td>Q, CQTR</td>
<td>Btu</td>
<td>Heat transfer to wall; heat transfer to liquid interface</td>
</tr>
<tr>
<td>Q&lt;sub&gt;L&lt;/sub&gt;</td>
<td></td>
<td>Btu/sec</td>
<td>Heat-transfer rate to tank wall; heat-transfer rate to liquid</td>
</tr>
<tr>
<td>ΔQ&lt;sub&gt;1&lt;/sub&gt;, ΔQ&lt;sub&gt;2&lt;/sub&gt;</td>
<td>DQ&lt;sub&gt;1&lt;/sub&gt;, DQ&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Btu</td>
<td>Heat transfer to hardware components 1 and 2</td>
</tr>
<tr>
<td>Q&lt;sub&gt;L&lt;/sub&gt;</td>
<td></td>
<td>Btu/(ft&lt;sup&gt;2&lt;/sup&gt;-sec)</td>
<td>Heat-transfer rate to wall from outside tank</td>
</tr>
<tr>
<td>R</td>
<td>R</td>
<td>(ft-lbf)/(°R)(lbm-mol)</td>
<td>Gas constant</td>
</tr>
<tr>
<td>ROOT1</td>
<td></td>
<td>°R</td>
<td>Real positive root of temperature quadratic in expulsion program</td>
</tr>
<tr>
<td>Re</td>
<td></td>
<td></td>
<td>Reynolds number, L&lt;sub&gt;VP&lt;/sub&gt;/µ</td>
</tr>
<tr>
<td>r</td>
<td>RAD</td>
<td>ft</td>
<td>Tank radius</td>
</tr>
<tr>
<td>RR</td>
<td></td>
<td></td>
<td>Final term of cubic equation in ramp program</td>
</tr>
<tr>
<td>Engineering symbol</td>
<td>FORTRAN name</td>
<td>Units in program</td>
<td>Description</td>
</tr>
<tr>
<td>-------------------</td>
<td>--------------</td>
<td>-----------------</td>
<td>-------------</td>
</tr>
<tr>
<td>$T$</td>
<td>TP, TWP</td>
<td>$^0 R$</td>
<td>Ullage temperature; tank wall temperature</td>
</tr>
<tr>
<td>$T_{L,S}$</td>
<td>TP(N+1)</td>
<td>$^0 R$</td>
<td>Temperature of the saturated propellant</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>TDIFF</td>
<td>$^0 R$</td>
<td>Differential temperature</td>
</tr>
<tr>
<td>$T_\delta$</td>
<td>TADD</td>
<td>$^0 R$</td>
<td>Temperature at edge of thermal boundary layer</td>
</tr>
<tr>
<td>$t$</td>
<td>TIME</td>
<td>sec</td>
<td>Time into ramp, hold period, or expulsion</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>DT</td>
<td>sec</td>
<td>Time increment</td>
</tr>
<tr>
<td>$\Delta V$</td>
<td>V</td>
<td>$ft^3$</td>
<td>Ullage volume</td>
</tr>
<tr>
<td>$\Delta V$</td>
<td>$\bar{V}$</td>
<td>ft/sec</td>
<td>Gas velocity associated with a specific net point</td>
</tr>
<tr>
<td>$\Delta V$</td>
<td>VP</td>
<td>$ft^3$</td>
<td>Volume increment</td>
</tr>
<tr>
<td>$\Delta V$</td>
<td>VHOLD</td>
<td>ft/sec</td>
<td>Gas velocity associated with a specific net point at previous iteration</td>
</tr>
<tr>
<td>$X_n$</td>
<td>XN</td>
<td>-----</td>
<td>Number of net points in ullage</td>
</tr>
<tr>
<td>$x$</td>
<td>X</td>
<td>ft</td>
<td>Coordinate in direction of tank axis</td>
</tr>
<tr>
<td>$\Delta x$</td>
<td>DX</td>
<td>ft</td>
<td>Distance between net points</td>
</tr>
<tr>
<td>$Z$</td>
<td>Z</td>
<td>-----</td>
<td>Compressibility factor</td>
</tr>
<tr>
<td>$Z_1$</td>
<td>Z1</td>
<td>-----</td>
<td>$Z + T \left( \frac{\partial Z}{\partial T} \right)_P$</td>
</tr>
<tr>
<td>$Z_2$</td>
<td>Z2</td>
<td>-----</td>
<td>$Z - P \left( \frac{\partial Z}{\partial P} \right)_T$</td>
</tr>
</tbody>
</table>
Engineering symbol | FORTRAN name | Units in program | Description
--- | --- | --- | ---
\( \alpha \) | D3 | \( ^\circ_R \) | 

\[
1 + \frac{h_c \Delta t}{\rho_w \lambda_w C_w} \left( \frac{2h_c RZ \Delta t}{rMPC_p} \right) \left[ 1 + \left( \frac{\Delta f}{\Delta x} \right)^2 \right]^{1/2}
\]

\( \beta \) | BETA | \( 1/\rho_R \) | Coefficient of thermal expansion

\( \beta_w \) | ----- | -------- | Dimensional decay coefficient of ullage forced heat-transfer correlation

\( \gamma \) | ----- | -------- | Specific-heat ratio

\( \mu \) | VISC | lbm/(ft·sec) | Viscosity

\( \rho \) | RHO | lbm/ft\(^3\) | Density

\( \omega \) | D4 | -------- | 

\[
\left( \frac{R}{M} \right) \frac{Z_1}{J} \frac{\Delta P}{\Delta t} + \frac{RZQ_H}{M \pi R^2 \Delta x} + \frac{RZQ_L}{M \pi R^2 \Delta x} \right) \frac{\Delta t}{C_p P}
\]
APPENDIX B

LISTING OF EXPULSION PROGRAM

THIS IS THE EXPULSION PROGRAM

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

DIMENSION
1 TGAS(30), TIME1(30), PDATA(30), TIME2(30),
2 FLOW(30), TIME3(30), TSAT(30), TIME4(30),
3 TBULK(30), TIMEx5(30), QOUTD(30), TIME6(30),
4 CIND(30), TIME7(30), ZAV(150),
5 TWIN(30), DIST1(30), TGINO(30), DIST2(130),
6 X(150), T(150), TP(150), Tw(150), TW(150), V(150),
7 CP(150), CPw(150), H(150), ZL(150), ZL(150), Z2(150),
8 RAD(150), AREA(150), YRAD(150), XRAD(150), DRDX(150)

DIMENSION
1 CS(150), C9(150), YTICK(50), XXT(50), TICK(150)
2 TwBK(30), DIST7(30), TwCU(30), DIST8(30), TSN(30), DIST9(30),
3 TAW(30), DIS11(30), CPB(150), TW(150), T(150), CPCU(150),
4 TWC(150), TC(150), CPST(150), TST(150), T(150), CPAL(150),
5 TALS(150), TBC(150), TTT(150), PRAM(150)

COMMON
1 X, TP, TW, TWP, V, CP, CPw, TGAS, TIME1, MTGAS, PDATA, TIME2, MPDATA,
2 FLOW, TIME3, MFLOW, TSAT, TIME4, MTSAT, TBULK, TIME5, MTBULK, QOUTD,
3 TIME6, MQOUT, QINO, TIME7, MQIN, NP, XP, ULLAGE, RADIUS, DQ,
4 SPWGT, XMOLEC, GSTART, HCONST, TIME, GAS, Q, GASCHK, GSRATE, DT,
5 ZCONST, H, HMULT, HEXP, YRAD, XRAD, MRAD, TNKWT, CQTR, QIN, NUMS,
6 MTIN, MTGIN, MTICK, MBK, MTCU, MTSS, MTA,
7 TWIN, DIST1, TGINO, DIST2, YTICK, XXT, TWBK, DIST7,
8 TAW, DIS11, TWCU, DIST8, TSN, DIST9

COMMON
1 CARAD, ADIFU, SWSS, DIA, RCONST, TADD, AB, ALC, A3S, A5B, WTB, WTC,
2 WTSS, WT5B

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

READ 3 CARDS OF PROBLEM DESCRIPTION AND WRITE OUT. THERE
MUST BE THREE CARDS USED, ALTHOUGH ANY OR ALL OF THEM MAY
BE BLANK. LEAVE THE FIRST COLUMN OF EACH CARD BLANK AND
ENTER ANY INFORMATION IN COLUMNS 2 TO 80.

WRITE (6, 100)
DO 2 J=1, 3
READ (5, 101)
2 WRITE (6, 101)
AUCMENCLATURE FOR INPUT DATA

XN, NUMBER OF NET POINTS AT TIME ZERO (MUST BE 3 OR MORE)
NET POINTS AVAILABLE 150 (SEE DIMENSION STATEMENTS)
REQUIRED INPUT GROUP I DATA
OUTPUT, NUMBER OF TIME STEPS TAKEN BEFORE EACH OUTPUT
ULLAGE, INITIAL ULLAGE HEIGHT, (CANNOT BE ZERO)
RADIUS, TANK RADIUS
IF RADIUS = 0, THE RADIUS IS INTERPOLATED BASED ON THE TANK RADIUS
(VS DISTANCE FROM TOP) DATA READ INTO THE PROGRAM.
IF RADIUS = -1, THE TANK IS A SPHERE (DIA = DIAMETER)
SPWGT, TANK WALL SPECIFIC WEIGHT
SPWSS, SPECIFIC WEIGHT OF TANK LID MATERIAL
ENDTIM, TIME AT WHICH OUTFLOW ENDS, SECONDS
XMOLEC, MOLECULAR WEIGHT OF PRESSURIZING GAS
ZCONST, COMpressIBILITY FACTOR (1. FOR IDEAL GAS, BLANK FOR REAL)
HCONST, HEAT TRANSFER COEFF. (BLANK IF H IS TO BE CALCULATED)
IF HCONST IS BLANK H WILL BE COMPUTED FROM THE EQUATION
H = HMULT * COND/XL * (GRASHOF * PRANDTL)**HEXP
HMULT, CONSTANT IN ABOVE EQUATION (0.13 IS USED IF LEFT BLANK)
HEXP, CONSTANT IN ABOVE EQUATION (0.333 IS USED IF LEFT BLANK)
DIA, DIAMETER WHEN THE TANK IS A SPHERE OR CYLINDER
SPECIFY DIAMETER ON VERTICAL AXIS WHEN TANK IS SPHEROID
RCONST, INITIAL HEIGHT USED IN CALCULATION OF H
TR1,TR2 GOVERNS THE MODE OF TRANSFER BETWEEN PRESSURANT GAS AND
TANK WALL. IF TR2 IS BLANK AND TR1=1, HEAT TRANSFER
IS BY FREE CONVECTION, IF TR2=1, TR1 IS BLANK, HEAT
TRANSFER IS BY FORCED CONVECTION
TADD, A TEMPERATURE AT THE EDGE OF THE THERMAL BOUNDARY
LAYER TO DETERMINE THE DRIVING POTENTIAL, (TADD-TSAT).
FOR HYDROGEN PRESSURANT OVER LIQ H2, TADD WAS DETERMINED
EXPERIMENTALLY TO BE 1.2-1.5 TIMES THE ADIABATIC
COMPRESSIBILITY TEMPERATURE
SEE NASA TN D-5336, 5367
UNUMS, SET GREATER THAN 0. FOR SI UNITS

QQOO, IF QQOO IS BLANK, PROGRAM ASSUMES NO INTERNAL HARDWARE
UNLESS THE GIND VS TIME? VALUES ARE GIVEN UNDER INPUT
DATA. IF QQOO=1, THEN SOME OR ALL PARAMETERS
AB THRU WT58 ARE SPECIFIED

AB, EFFECTIVE AREA PHENOLIC HARDWARE EXPOSED TO THE
PRESSURANT GAS IN THE VOLUME ELEMENT
AIC, EFFECTIVE AREA OF COPPER HARDWARE EXPOSED TO THE
PRESSURANT GAS IN THE VOLUME ELEMENT
A3S, EFFECTIVE AREA OF THE 304 SS HARDWARE EXPOSED TO THE
PRESSURANT GAS IN THE VOLUME ELEMENT
A5B, EFFECTIVE AREA OF ALUMINUM HARDWARE EXPOSED TO THE
PRESSURANT GAS IN THE VOLUME ELEMENT
WT8, WEIGHT OF THE PHENOLIC HARDWARE IN THE VOLUME ELEMENT
WT1C, WEIGHT OF COPPER HARDWARE IN THE VOLUME ELEMENT
WT3S, WEIGHT OF 304 SS HARDWARE IN THE VOLUME ELEMENT
WT58, WEIGHT OF ALUMINUM HARDWARE IN THE VOLUME ELEMENT
OPTION 2 DATA

PARAMETER USED IN CALCULATING GAS TO WALL, FORCED CONVECTION HEAT TRANSFER
ADIFU PRESSURANT DISTRIBUTOR AREA
CARAD CHARACTERISTIC RADIUS OF THE TANK WHEN FORCED CONVECTION IS A MODE OF HEAT TRANSFER

END OF OPTION II DATA
BEXPO, WBEXPO PARAMETERS INVOLVING DECAY COEFFICIENTS
SEE NASA TM X - 53165

GROUP I DATA
NAMELIST / PARAMS / XN, OUTPUT, ULLAGE, RADIUS, SPWGT, ENDTIM, XMOLEC, 1HCONST, DIA, RCNST, ZCONST, HMULT, HEXP, AB, A1C, A3S, A5B, WTB, WTC, 2W3S, WT5B, SPWSS, OGOO, TADD, C1C, TR1, TR2, CARAD, ADIFU, CYLN, UNUMS
READ(5, PARAMS)

GROUP II CATA EXPULSION DATA- CONTINUED
NAMELIST / INPNTS / MTGAS, MPDATA, MFLOW, MTSAT, MTBULK, MQOUT, MQIN, 1MTWIN, MTGIN, MRAD, MTICK, MTBAK, MTCU, MTSS, MTAL
READ(5, INPNTS)
NAMELIST / OTPNTS / MTGAS, MPDATA, MFLOW, MTSAT, MTBULK, MQOUT, MQIN, 1MTWIN, MTGIN, MRAD, MTICK, MTBAK, MTCU, MTSS, MTAL
WRITE(6, OTPNTS)
NAMELIST / TABLES / 1 TGAS TIME1 PDATA TIME2 FLOW TIME3 , 2 TSAT TIME4 TBULK TIME5 QOUTD TIME6 , 3 WIND TIME7 TWIND DIST1 TGIND DIST2 , 4 YRAD XRAD YTICK XXT TWBK DIST7 , 5 TWCU DIST8 TSN DIST9 TWAL DIS11 READ(5, TABLES)

GROUP III PROPERTY DATA-SEE SUBROUTINE-
NOTE - THE DATA BLOCKS IN THE SUBROUTINES MAY BE SUBSTITUTED FOR DIFFERENT GASES OR WALL MATERIAL CONSISTENT WITH HYDROGEN/HELIUM BEHAVIOR.
1 - SUBROUTINE SPHEAT - MATERIAL AND GAS SPECIFIC HEATS
NOTE -- THE SPECIFIC HEAT SUBROUTINE FOR HYDROGEN HAS NO PROVISION FOR PRESSURE VARIATION
NOTE -- THE WALL SPECIFIC HEAT DATA IN THE SUBROUTINE DOES NOT PROVIDE STORAGE FOR MORE THAN ONE MATERIAL
2 - SUBROUTINE COMPRS - GAS COMPRESSIBILITY
3 - SUBROUTINE HCOEFF - TRANSPORT PROPERTIES

********************************************************************
TEST CASE TO EXAMINE THE HARDWARE OPTION USING SI UNITS
CYLINDRICAL TEST SECTION - CIRCUMFERENTIAL ALUM. BAFFLES
100 SECOND EXPULSION - 0.61 METER TANK RADIUS

$PARAMS

XI=1.5, OUTPUT=1.0, ULLAGE=.3249168, RADIUS=0., SPWGT=2603.231,
ENDTM=100., XMOL=2., HCON=0., DIA=1.21920, RCON=0.3249168,
ZCON=0., HMULT=0., HEXP=0., AB=0., AIC=0., AS=0., A5=0.0825788,
W=0., W1C=0., W2S=0., W5B=0.01061406, SPWSS=2603.231, QQQ=1,
TADD=0., D1C=0., TR1=1., TR2=0., CARAD=0., ADIFU=0., CYLN=3.249168,
UN=1.0

$INPUTS

MTG=1, MPDATA=1, MFLOW=1, MSAT=1, MTBULK=1, MQOUT=0, MQIN=0, MTWIN=2,
MTGIN=2, MRAD=2, MTICK=2, MTBAK=0, MTCU=0, MTSS=0, MTAL=2

$TABLES

TG=2.77, 7.77, TIME1=0., PDATA=.69774942, TIME2=0.,
FLOW=.02845843, TIME3=0., TSAT=29.222, TIME4=0.,
TBULK=20.833, TIME5=0., QOUT=0., TIME6=0.,
QIND=0., TIME7=0., TWIND=55.555, 20.833, DIST1=0., 3249168,
TGIND=163.888, 29.222, DIST2=0., 0.3249168,
YRAD=.6096, 60.96, XRAD=0., 3.249168,
YTICK=4.3280E-05, 4.3280E-05, XXT=0., 3.249168,
TWAL=55.555, 20.833, DIST1=0., 3.249168

$END
DO2=0.
DO3=0.
DO4=0.

CALL WRITE1

IF (UNUMS .EQ. 0.) GO TO 301
CALL SINTS

301 CONTINUE
XPI=3.14159
R=1545.4
XJAY=778.2
HCCNST=HCONST/3600.
N=XN
NP=N+1

DX=ULLAGE/(XN-1.0)
WRITE=OUTPUT

C

C

0IFU = SQRT(4.*ACIFU/XPI)
C8=R/XMOLEC
C3 = DX * C8
C1 = C3/2.
C2 = C1/XJAY
C4 = DX/C8
C6 = 2.*C8
C7 = C8/XJAY

C

DO 3 J=2,150
XTICK=J-1
X(J)=DX*XTICK
CALL INTERP (YTICK,XT,TICK,X(J),TICK(J))
C5(J)=1.0/(TICK(J)*SPWGT)
3 C9(J)=2.0*XPI*DX*TICK(J)*SPWGT
X(1)=0.0
TICK(1)=YTICK(1)

C

C

STEP-1A-
MAKE GEOMETRY CALCULATIONS

IF (RADIUS) 8,4,6

4 DO 5 J=2,150
CALL INTERP (YRAD,XRAD,MRAD,X(J),RAD(J))
5 AREA(J)= XPI*RAD(J)**2
KAC(1)=RAD(2)
AREA(1)=AREA(2)
GO TO 12

C

6 CONTINUE
DO 7 J=2,150
IF(X(J) - DIA/2.)199,299
199 KAC(J) = SQRT(DIA * X(J) - X(J)**2)
AREA(J) = XPI * RAD(J)**2
GO TO 7
IF(X(J) * GT* (CYLN + RAD(J))) GO TO 399
RAD(J) = RADIUS
AREA(J) = XPI * RAD(J)**2
GO TO 7

399 PLEG = X(J) - CYLN - RADIUS
IF(PLEG * GE* RADIUS) GO TO 499
RAC(J) = SQRT(RADIUS**2 - PLEG**2)
AREA(J) = XPI * RAD(J)**2

7 CONTINUE

499 RAC(1) = RAD(2)
AREA(1) = AREA(2)
GO TO 12

8 DO 10 J=2,150
IF (X(J)-DIA) 9,9,11
9 RAD(J) = SQRT(DIA * X(J) - X(J)**2)
10 AREA(J) = XPI * X(J) * (DIA - X(J))
11 AREA(1) = AREA(2)
RAD(1) = RAD(2)
C
12 CONTINUE
DO 16 J=2,149
13 DRDX(J) = (RAD(J+1)-RAD(J))/(X(J+1)-X(J))
C
C TANK WEIGHT DOES NOT INCLUDE WEIGHT OF LID OR CONNECTORS AT TOP
C
15 TANKWT = TANKWT + C9(J)*RAD(J)*SQRT(1.0 + DRDX(J)**2)
16 CONTINUE
17 DRDX(1) = (RAD(2)-RAD(1))/X(2)
DRDX(150) = DRDX(149)
DT = DX*AREA(N)/FLOW(1)
CALL INTERP (FLOW,TIME,DFLOW,DT,FLO)
DT = DX*AREA(N)/FLOW(1)+FLO)*2.0
VP = FLOW(1)/AREA(N)
TIME = GT
C
STEP-1B-
COMPUTE INITIAL WALL AND GAS TEMPERATURES
C
DO 19 J=1,N
CALL INTERP (TWIND,DIST1,MTWIN,X(J),TW(J))
19 CALL INTERP (TGINO,DIST2,MTGIN,X(J),T(J))
C
C
STEP-1C-
COMPUTE INITIAL VALUES OF SPECIFIC HEAT
C
19 CALL SPHEAT (T(J),TW(J),CP(J),CPW(J),XMOLEC)
C
C
STEP-2-
COMPUTE INITIAL VALUES OF HEAT TRANSFER COEFFICIENT
C
IF (HCONST) 1,22,20
C
20 DO 21 J=1,150
21 H(J)=HCONST
GO TO 31
IF (HMULT) 1,23,24
HMULT=0.13

IF (HEXP) 1,25,26
HEXP=0.333

DO 30 J=1,N
IF (X(J)-RCONST) 27,27,28
XL=DIA
GO TO 29

XL=DIA
TTI(J)=Tw(J)
CALL HCOEFF (T(J),TTT(J),PDATA(1),XL,H(J),PRAM(J),ZCONST,HMULT,HEX
1P,XMOLEC)
CONTINUE

STEP-3-

COMPUTE INITIAL VALUES OF QOUT, QIN, P AND DPDT
QOUT=COUTC(1)
QIN =-CIND(1)
P=PDATA(1)
PHCLD=P
IF (MPDATA=1) 1,32,33
PP=P
GO TO 34

CALL INTERP (PDATA,TIME2,MPDATA,TIME,PP)
DPDT=(PP-P)/DT
IF(CGQQ = 0. )144,144,42

DO 43 J=1,N
CALL INTERP (TWBK,DIST7,MTBAK,X(J),TWB(J))
CALL INTERP (TWCU,DIST8,MTCU,X(J),TWC(J))
CALL INTERP (TSTN,DIST9,MTCU,X(J),TST(J))
CALL INTERP (TWAL,DIST11,MTAL,X(J),TALS(J))
CONTINUE

STEP-4-

COMPUTE INITIAL VALUES OF COMPRESSIBILITY FACTOR AND DERIVATIVES
IF (ZCONST) 1,37,35

DO 36 J=1,150
Z(J)=1.0
Z1(J)=1.0
Z2(J)=1.0
ZHOLD=1.0
GO TO 39

DO 38 J=1,N
CALL CMPRS (T(J),PDATA(1),Z(J),Z1(J),Z2(J),XMOLEC)
CONTINUE

STEP-5-

COMPUTE INITIAL VALUES OF LOCAL ULLAGE GAS VELOCITY
PX = PCDATA(1)
\[ V(N) = \frac{\text{FLOW}(1)/\text{AREA}(N)}{NTEMP} = N-1 \]

\[ \text{DO 40 L=1,NTEMP} \]

\[ J = A - L \]

\[ C10 = ((h(J+1)+h(J))\times(z1(J+1)+z1(J)))/(px*(\text{RAD}(J+1)+\text{RAD}(J))\times(\text{CP}(J+1) \times \text{CP}(J))) \]

\[ C11 = \text{SQRT}(1.0+((\text{DRDX}(J+1)+\text{DRDX}(J))/2.0)^2) \]

\[ C12 = \text{DX}*((\text{DRDX}(J+1)+\text{DRDX}(J))/(\text{RAD}(J+1)+\text{RAD}(J))) \]

\[ C13 = ((z1(J+1)**2+z1(J)**2)/(xjay*pX*(z(J+1)+z(J))\times(\text{CP}(J+1)+\text{CP}(J))) \]

\[ C14 = (z2(J+1)+z2(J))/((z(J+1)+z(J))*\text{P}X) \]

\[ C15 = ((z1(J+1)+z1(J))\times(2.0*qjin)\times((\text{AREA}(J+1)+\text{AREA}(J))\times\text{P}X*(\text{CP}(J+1)+\text{CP}(J)))\]

\[ \text{STEP-6} - \]

\[ \text{FIND GAS IN ULLAGE AT TIME ZERO BY INTEGRATING DENSITY} \]

\[ \text{GASA} = (0.5\times\text{AREA}(1)/(T(1)\times z(1)) + \times 0.5\times \text{AREA}(N))/(T(N)\times z(N)) \]

\[ \text{NTEMP} = N-1 \]

\[ \text{DO 41 J=2,NTEMP} \]

\[ \text{GASA} = \text{GASA} + \text{AREA}(J)/T(J)/Z(J) \]

\[ \text{GASA} = \text{GASA} \times C4\times P \]

\[ \text{GSTART} = \text{GASA} \]

\[ \text{STEP-7} - \]

\[ \text{WRITE PROBLEM IDENTIFICATION AND INPUT DATA} \]

\[ \text{WRITE (6,1022)} \]

\[ \text{DT} \]

\[ \text{IF(UNUMS)250,251,250} \]

\[ 250 \text{ CONTINUE} \]

\[ \text{GSTART} = \text{GSTART} \times 45359237 \]

\[ \text{WRITE (6,2015)} \]

\[ \text{GSTART} = \text{GSTART}/45359237 \]

\[ \text{Q} = \text{Q} \times 1054.3503 \]

\[ \text{WRITE (6,2050)} \]

\[ \text{Q} = \text{Q}/1054.3503 \]

\[ \text{TNKW} = \text{TNKW} \times 45359237 \]

\[ \text{WRITE (6,4000)} \]

\[ \text{TNKW} \]

\[ \text{GO TO 44} \]

\[ 251 \text{ CONTINUE} \]

\[ \text{WRITE (6,1015)} \]

\[ \text{GSTART} \]

\[ \text{WRITE (6,1050)} \]

\[ \text{Q} \]

\[ \text{WRITE (6,3000)} \]

\[ \text{TNKW} \]

\[ \text{C} \]

\[ \text{GIA} = \text{GINI} \]

\[ \text{C} \]

\[ \text{***************} \]
BEGIN MAIN PART OF CALCULATION

STEP-8-
FIND TEMPERATURES AT NEW TIME

CONTINUE
CALL INTERP (TGAS*TIME1,MTGAS,TIME,TP(1))
CALL INTERP (TSAT,TIME4,MTSAT,TIME,TP(N+1))
CALL INTERP (TBULK,TIME5,MTBULK,TIME,TWP(N+1))

DO 48 J=2,N
   D1=C5(J)*DT*QOUT/CPW(J)
   D2=1.*0+C5(J)*DT*H(J)/CPW(J)
   D3=D2/(1.(C6/RAD(J))*H(J)*Z(J)*DT/P/CP(J))
   D3 = D3/QUAD(1.0+(DRX(J+1)+DRX(J))/2.)*20)
   D4=(C7*Z1(J)*DPDT+(C8/AREA(J))*Z(J)*(1.-QIN)+C8/X(N)*Z(J)/AREA(J)
   D4=1*(-U)*/DT/CP(J)/P

BUQUAD=C3*(1.0+V(J)*DT/DX-D4)-Tw(J)-D1
CQUAD=-C3*(T(J)+V(J)*DT/DX*TP(J-1))
RX1 = -BUQUAD/2.
DISC = RX1*RX1 - CQUAD
IF(DISCC45.45.46
45 RQCT1= 0.5 * (T(J) + TP(J-1))
TP(J) = RQCT1
GO TO 47
46 PX2 = SQRT(DISC)
RQCT1 = RX1 + PX2
IF(RQCT1>450,450,460
450 TP(J) = 0.5 * (T(J) + TP(J-1))
GO TO 47
460 TP(J) = RQCT1
C
47 TWP(J)=(Tw(J)+(D2-1.)*TP(J)+D1)/D2
CONTINUE
DO 49 J=2,N
   D1=C5(J)*DT*QOUT/CPW(J)
   D2=1.*0+C5(J)*DT*H(J)/CPW(J)
49 CONTINUE

C SPECIFIC HEAT OPTION FOLLOWING STATEMENTS 51,52 IS USED WHEN THE
C TANK LID IS (18-8) STAINLESS STEEL. THE EQUIVALENT THICKNESS
C FOR THE LID MASS IS CONCENTRATED IN THE FIRST VOLUME ELEMENT.
IF(SPISS - 499.0)53.50.50
50 IF(Tw(1) - 75.0)125.51.51
125 CPW(1) = 0.010
GO TO 53
51 IF(Tw(1) < GT. 220.)GO TO 52
CPW(1) = 0.000418* TW(1) - 0.0203
GO TO 53
52 W = (Tw(1) - 220.)/126.67
CPW(1) = (((0.0018 * W - 0.0127)*W + 0.0374)*W + 0.071
53 C5(1)=1.0/(TICK(1)*SPWSS)
C6(1)=XP*DX*D1A*TICK(1)*SPWSS
D1=C5(1)*DT*QOUT/CPW(1)
D2=1.0+C5(1)*DT*H(1)/CPW(1)
TWP(1) = (TWP(1) + (D2 - 1.0) * TP(1) + 0.0) / 0.0

CALL INTERP (QOUTD, TIME6, MQOUT, TIME, QOUT)
CALL INTERP (QIND, TIME7, MQIN, TIME, QIN)
GO TO 54

IF (MPCATA-1) = 56, 55

PHCLD = P
CALL INTERP (PDATA, TIME2, MPCATA, TIME, P)
TIME = TIME + DT
CALL INTERP (PDATA, TIME2, MPCATA, TIME, P)
DPOT = (PP-P) / DT

CCONTINUE

IF (QQQO) = 73, 73, 57
CONTINUE
IF (AB *EQ. 0.) GO TO 122

STEP-9-
EVALUATE ENERGY TRANSFER TO INTERNAL HARDWARE

NOTE- CP-SPECIFIC HEAT, BK-PHENOLIC, CU-COPPER, ST-STAINLESS, AL-ALUM
PHENOLIC SPECIFIC HEAT DATA ESTIMATED FROM TPRC PUB. VOL 6 PT. II
(THERMOPHYSICAL PROPERTIES RESEARCH CENTER-PURDUE UNIV.)

DO 60 J=1, N
IF (TP(J) - TWP(J)) = 56, 58, 152
58 TWP(J) = TP(J)
GO TO 60

CPCU(J) = 0.000664 * TWP(J)
59 TTT(J) = TWP(J)
CALL HCOEFF (T(J), TTT(J), P, XL, H(J), PRAM(J), ZCONST, HMULT, HEXP, XMOL
1C)
TB(J) = H(J) * AB * (T(J) - TWP(J)) / (WTB * CPCU(J)) * DT + TWP(J)
DO1 = DO1 + H(J) * AB * (T(J) - TWP(J)) * DT
60 CCONTINUE

122 IF (A1C * EQ. 0.) GO TO 123

CURVE FIT-COPPER SPECIFIC HEAT DATA FROM WADD TECH REPT 60-56 1960
DO 63 J=1, N
IF (TP(J) - TWC(J)) = 61, 61, 151
61 TWC(J) = TP(J)
GO TO 63

W = (TWC(J) - 25.0) / 125.
CPCU(J) = (0.0021 * W - 0.02) * W + 0.06683) * W
62 TTT(J) = TWC(J)
CALL HCOEFF (T(J), TTT(J), P, XL, H(J), PRAM(J), ZCONST, HMULT, HEXP, XMOL
1C)
TC(J) = H(J) * A1C * (T(J) - TWC(J)) / (WT1C * CPCU(J)) * DT + TWC(J)
DO2 = DO2 + H(J) * A1C * (T(J) - TWC(J)) * DT
63 CCONTINUE

123 IF (A3S * EQ. 0.) GO TO 124

CURVE FIT (18-8) STAINLESS STEEL SP HEAT FROM SCOTT CRYO ENGR.
DO 66 J=1, N

D = VAH * NOstrand
IF(TP(J) - TST(J))64,64,135
135 IF(TST(J) - 75.0)130,131.131
140 CPST(J) = 0.01
GO TO 65
131 IF(TST(J) *GT. 220.0)GO TO 133
CPST(J) = 0.000418 * TST(J) - 0.0203
GO TO 65
133 W = (TST(J) - 220.0)/126.67
CPST(J) = ((0.0018*W - 0.0127)*W + 0.0374)*W + 0.071
64 T7(J) = TP(J)
GO TO 66
65 TTT(J) = TST(J)
CALL HCOEFF (T(J), TTT(J), P, XL, H(J), PRAM(J), ZCONST, HMULT, HEXP, XMOL
61E IC)
T7(J) = H(J)*A3S*(T(J) - TST(J))/(WT3S*CPST(J))*DT+TST(J)
DT = DQ3 + H(J)*A3S*(T(J) - TST(J))*DT
66 CONTINUE
124 IF(T5B*EQ. 0.) GO TO 126
C CURVE FIT GF AL. ALLOY 6061-T6 SPECIFIC HEAT DATA FROM TPRC
GO 72 J=1,N
IF(TP(J) = TALS(J))70,70,153
70 T8C(J) = TP(J)
GO TO 72
153 IF(TALS(J) = 70.0)67,68,68
67 CPAL(J) = 0.000397 * TALS(J) - 0.013
IF(TALS(J) *LT. 36.0)CPAL(J) = 0.0012
GO TO 69
68 W = (TALS(J) - 70.0)/117.5
CPAL(J) = ((0.00334*W - 0.0351)*W + 0.13666)*W + 0.015
IF(TALS(J) *GT. 540.) CPAL(J) = 0.212
69 CONTINUE
71 TTT(J) = TALS(J)
CALL HCOEFF (T(J), TTT(J), P, XL, H(J), PRAM(J), ZCONST, HMULT, HEXP, XMOL
61E IC)
T8C(J) = H(J)*A5B*(T(J) - TALS(J))/(WT5B*CPAL(J))*DT+TALS(J)
DT = DQ4 + H(J)*A5B*(T(J) - TALS(J))*DT
72 CONTINUE
126 QIN = (DQ1 + DQ2 + DQ3 + DQ4)/(TIME * X(N))
73 CONTINUE
C C C
C FIND COMPRESSIBILITY FACTORS AT NEW TIME
C
74 IF (ZCNST) 1.74,76
75 ZHLD = Z(5)
GO 200 K=1,N
200 ZAV(K) = Z(K)
GO 75 J=1,NP
25 CALL CCMPRS (TP(J), P, Z(J), Z1(J), Z2(J), XMOLC)
76 CONTINUE
C C

38
STEP-11-
FIND VELOCITIES AT NEW TIME

VHOLD = V(5)
CALL INTERP (FLCW, TIME3, MFLOW, TIME, FLOWNP)
V(NP) = FLOWNP/AREA(NP)

DO 77 J = 1, N
    K = NP - J
    V(K) = (TP(K)*V(K+1) - (DX/(DT*Z(K)))*(Z(K)*TP(K) - T(K))
         + Z2(K)*DPDT*DX/(Z(K)*PP)/(TP(K) + Z1(K)/Z(K))*TP(K+1)
         - TP(K)) - (2.0*DX * TP(K) * (DRDX(K+1) + DRDX(K))) / (RAD(K+1)
         + RAD(K))

STEP-12-
FIND HEAT FLOW RATE TO WALL AND TOTAL HEAT ADDED TO WALL

Q = C9*QD

DO 78 J = 1, N
    Q = Q + RAD(J)*SQRT(1.0 + DRDX(J)**2)*CPW(J)*(TP(J) - TW(J))*C9(J)
DO 79
Q = C + QD

STEP-13-
FIND SPECIFIC HEATS AT NEW TIME

CALL SPHEAT (TP(J), TWP(J), CP(J), CPW(J), XMOLEC)

STEP-14-
FIND HEAT TRANSFER COEFFICIENT AT NEW TIME

300 HSUR = H2H * 14/HMUL
QTR = HSUR*AREA(NP+1)*(TADD-T(NP+1))
CQTR = CQTR + QTR*DT
GO TO 83
83 IF (HCCNST) 1, 84, 89
84 CONTINUE
DC 88 J=1.NP
IF (X(J)-RCONST) 85,85,86
C IN TURBULENT RANGE HEXP = 0.333, CHOICE OF XL IS IMMATERIAL
 85 XL=CIA
  GO TO 87
 86 XL=CIA
 87 TTT(J)=TP(J)
  CALL hCOEFF (TP(J),TTT(J),P,XL,H(J),PRAM(J),ZCONST,HMULT,HEXP,XMOL
  IEC)
  IF (TR2.EQ.0.) GC TO 88
  WBEXPO = EXP(-0.00117 * CARAD**2*X(J))
  MHSC=Dic/CARAD**.2*(GSRATE/ADIFU)**.8*PRAM(J)
 88 H(J)=H(J)*TR1+MHSC*WBEXPO*TR2
  C
  89 CONTINUE
  C
  ITER1 = ITER1 + 1
  IF (ITER1-IWRITE) 92,91,91
  91 CALL WRITE2
  ITER1=0
  C
  STEP-15-
  CHECK TO SEE IF END TIME HAS BEEN REACHED
  C
  92 IF (TIME=ENDTIM) 93,98,98
  93 Tyme=TIME+DT
  C
  END TIME NOT REACHED - PREPARE FOR ANOTHER STEP
  C
  CALL INTERP (FLOW,TME3,MFLOW,TYME,FLOWP)
  VP=FLOWP/AREA(NP)
  DT = Dx/(V(NP)+VP) * 2.
  TIME=TIME+DT
  C
  DO 94 J=1,NP
  T(J)=TP(J)
  94 T(J)=TP(J)
  IF(GQGC)97,97,95
  DO 96 J=1,N
  TWB(J)=TB(J)
  TM(J)=TC(J)
  TST(J)=TZ(J)
  96 TWB(J)=TB(J)
  TM(J)=TC(J)
  TST(J)=TZ(J)
  C
  TALS(J)=TB(J)
  TWB(N+1)=TP(N+1)
  TM(N+1)=TP(N+1)
  TST(N+1)=TP(N+1)
  TALS(N+1)=TP(N+1)
  C
  CONTINUE
  C
  N=N+1
  NP=NP+1
  CN=CN+1.0
  GASA=GAS8
  C

  GC TO 44
STEP-16-
END TIME EXCEEDED - INTERPOLATE CONDITIONS AT END TIME

98  RATIO = (ENDTIM - TIME + DT) / DT
TIME = ENDTIM

DG 99 J = 1, N
TP (J) = T (J) + RATIO * (TP (J) - T (J))

99  TW (J) = TW (J) + RATIO * (TW (J) - TW (J))

Q = c-DG + RATIO * DO
GAS = GAS - GASB + GAS + RATIO * (GASB - GAS)
GASCHK = GASCHK - GASB + GAS + RATIO * (GASB - GAS)
X(NP) = X(N) + RATIO * DX

STEP-17-
WRITE OUT RESULTS REFER TO SUBROUTINE WRITE 2
CALL WRITE2
GO TO 1

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

FORMAT STATEMENTS

100  FORMAT (1H1, 30X, 24H TANK EXPULSION PROGRAM/1HJ)
101  FORMAT (60H )
102  FORMAT (8F10.0)
103  FORMAT (F10.0)
1015 FORMAT (1HK, 23H INITIAL ULLAGE GAS = F6.3, 5H LBS)
1022 FORMAT (1HK, 27H INITIAL TIME INCREMENT = F6.1, 9H SECONDS)
1050 FORMAT (1HK, 25H INITIAL HEAT TO WALL = F7.1, 5H BTU)
2015 FORMAT (1HK, 23H INITIAL ULLAGE GAS = F6.3, 10H KILOGRAM)
2050 FORMAT (1HK, 25H INITIAL HEAT TO WALL = £11.4, 7H JOULE)
3000 FORMAT (1HK, 29H THE TANK WEIGHT LESS LID = F7.1, 5H LBS)
4000 FORMAT (1HK, 29H THE TANK WEIGHT LESS LID = F7.2, 10H KILOGRAM)
END
TANK EXPULSION PROGRAM

TEST CASE TO EXAMINE THE HARDWARE OPTION USING SI UNITS
CYLINDRICAL TEST SECTION – CIRCUMFERENTIAL ALUM. BAFFLES
100 SEC. EXPULSION – 0.61 METER TANK RADIUS

$TOPNOS

MKGAS = 1, MPDATA = 1, MFLOW = 1, MTSAT = 1, MTBULK = 1
MOOUT = 0, MOIN = 0, MTWIN = 2, MTCIN = 2, MRAD = 2
MTICK = 2, MTBAK = 0, MTCU = 0, MTSS = C, MTAL = 2
$ENC

INPUT DATA

INITIAL NUMBER OF NETPCINTS = 15.
INITIAL ULLAGE = 0.325 METER
TANK RADIUS = 0. METER
TANK WALL SPECIFIC WEIGHT = 2803.2 KG/CUBIC METER
MOLLEcular WEIGHT = 2.0

GAS TEMP, DEG K VS TIME, SECONDS
277.8 0.

PRESSURE, M-NEWTON/SQ M VS TIME, SECONDS
0.7 0.

FLOW RATE, CU M/SEC VS TIME, SECONDS
0.0285 0.

SATURATION TEMP, DEG K VS TIME, SECONDS
29.2 0.

PULX TEMP, DEG K VS TIME, SECONDS
20.8 0.

ELECTRIC HEATING RATE, JOULE/360 M-SEC VS TIME, SECONDS
C. 0.

INSIDE HEATING RATE, JOULE/METER-SEC VS TIME, SECONDS
C. 0.
INITIAL TEMPERATURE=850.0 KELVIN

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<th>WALL TEMPERATURE</th>
<th>GAS TEMPERATURE</th>
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HEAT TRANSFER COEFFICIENT WILL BE COMPUTED
PMULT = 0.   PEXP = 0.

TANK RADIUS (METER) VS AXIAL DISTANCE (METER)

0.610         0.
0.610         3.25

A REAL GAS IS ASSUMED

THE PRESSURANT IS HYDROGEN

INITIAL TIME INCREMENT = 1.0 SECONDS

INITIAL VOLUME GAS = 0.887 KILOGRAM

INITIAL HEAT TO WALL = 0.

THE TANK WEIGHT IS 1.654 KILOGRAM

TIME = 9.5 SECONDS
GAS SUPPLIED = 0.1614 KILOGRAM

HAT TO WALL = 0.1175E+05 JOULES

INLET VEL = 0.3258 METER/SEC

HAT TO LID = 0.

J CHECK ON GAS = 0.225 KG

GAS FLOW = 0.0181 KG/SEC

HEAT TO HARD = 0.3058E+04 J/(M-SEC)

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48
### Time = 15.6 Seconds

**GAS SUPPLIED:** 0.3356 KILOGRAM

**HEAT TO WALL:** 0.2356 + 0.5 JOULE

**INLET VEL:** 0.0262 METER/SEC

**HEAT TO LIG =** 0.0

**GAS FLOW:** 0.0184 KG/SEC

**HEAT TO HARD:** 0.2302 + 0.5 J/(M-SEC)

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### Time = 28.6 Seconds

**GAS SUPPLIED:** 0.5132 KILOGRAM

**HEAT TO WALL:** 0.3578 + 0.5 JOULE

**INLET VEL:** 0.0265 METER/SEC

**HEAT TO LIG =** 0.0

**GAS FLOW:** 0.0187 KG/SEC

**HEAT TO HARD:** 0.1521 + 0.5 J/(M-SEC)

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TIME = 1.00 X 0.0100 S, GAS SUPPLY = 1.6690 KILOGRAM HEAT TO WALL = 0.0317 X 10^-4 J/SEC INLETT VEL = 0.0266 MLTR/SEC

HEAT TO LIG = J, J CHECK OK GAS = 1.0724 KW, GAS FLOW = 0.0119 KG/SEC HEAT TO HARD = 0.05867 X 10^-4 J/(M-SEC)
APPENDIX C

LISTING OF RAMP PROGRAM

THIS IS THE PRESSURIZATION MAIN PROGRAM

***************
DIMENSION TGAS(100), TIME1(100), PDATA(100), TIME2(100), FLOW(25),
1 TIME3(25), TSAT(50), TIME4(50), TBULK(25), TIMES(25), QOUTD(25),
2 TIME6(25), QIND(25), TIME7(25), ZAV(250), TWIND(100), DIST1(100),
3 TGIN(100), DIST2(100), X(250), T(250), TP(250), TW(250), TP(250),
4, V(250), VP(250), CP(250), CPW(250), H(250), Z(250), Z(250), Z(250), Z(250),
RAD(250), AREA(250), YRAD(250), XRAD(250), DRAX(250), TEST(250)

DIMENSION C5(250), C9(250), YTICK(250), XXT(250), TCK(250), XR(3)
1, AQI(3)
COMMON X, T, TP, TW, TWP, V, CP, CPW, TGAS, TIME1, MTGAS, PDATA, TIME2, MPDATA,
1, FLOW, TIME3, MFLOW, TSAT, TIME4, MTBS, TBULK, TIMES, MTBULK, QOUTD, TIME6,
2 M2OUT, QIND, TIME7, MQIN, N, NC, XN, ULLAGE, RADIUS, TLI, SPWGT, XMOLEC, GSTAR
3, TCONST, TIME, GAS, Q, GASCHK, GSRA, DT, ZCONST, H, HMUL, HEXP, YRAD, XRAD
4, MRAD, DQ, DIN, UNUMs, TWIND, DIST1, MTEX1, TGIN, DIST2, MTGINS, DIA,
5, TADC, YTICK, XXT, MTICK

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

READ 3 CARDS OF PROBLEM DESCRIPTION AND WRITE OUT. THERE
MUST BE THREE CARDS USED, ALTHOUGH ANY OR ALL OF THEM MAY
BE BLANK. LEAVE THE FIRST COLUMN OF EACH CARD BLANK AND
ENTER ANY INFORMATION IN COLUMNS 2 TO 30.

WRITE (6, 106)
DO 2 J = 1, 3
READ (5, 107)
WRITE (6, 107)

THIS IS THE PRESSURIZATION PROGRAM

NOMENCLATURE FOR INPUT DATA

XN, NUMBER OF NETPOINTS AT TIME ZERO (MUST BE 3,0 OR MORE)
OUTPUT, NUMBER OF TIME STEPS TAKEN BEFORE EACH OUTPUT
ULLAGE, INITIAL ULLAGE LENGTH, FEET (CANNOT BE ZERO)
RADIUS, TANK RADIUS, - SPECIFY WHEN TANK IS A CYLINDER
THE PROGRAM THEN Assumes SPHERICAL END SECTIONS.
IF RADIUS = 0, THE RADIUS IS INTERPOLATED BASED ON THE
TANK RADIUS (VS DISTANCE FROM TOP) DATA READ INTO THE
PROGRAM. IF RADIUS = 1, THE TANK IS A SPHERE.
SPWGT, TANK WALL SPECIFIC
SPWSS, SPECIFIC WEIGHT OF TANK LID MATERIAL
ENDTIM, TIME TO COMPLETE THE HOLD PERIOD
XMOLEC, MOLECULAR WEIGHT OF PRESSURIZING GAS
ZCONST, COMPRESSIBILITY FACTOR (1. FOR IDEAL GAS, BLANK FOR REAL)
Heat transfer coeff. (Blank if \( H \) is to be calculated)

\[ BTU/HR/\text{SQ}.\text{FT.}/\text{DEG}.F. = \text{WATTS/SQ. M/DEG K} \]

Initial time step (seconds)

Time to complete the ramp period (seconds)

Diameter when the tank is a sphere, or cylinder.

Specify diameter on vertical axis when tank is spherical

Time coordinates (seconds) along the pressure rise curve

These control the initial selection of the time step

When radius is specified, the cylindrical length between

the tank end sections must be defined.

If \( H \) const is blank \( H \) will be computed from the equation

\[ H = H\text{MUL}\text{T} \times \text{COND} / \text{XL} \times (\text{NUSSEL}\text{T} \times \text{PRANDTL}) \times \text{HEXP} \]

Constant in above equation (0.13 is used if left blank)

Constant in above equation (0.333 is used if left blank)

The mass of the tank lid and flange made equivalent

to the first wall thickness

Specify greater than 0. to program in SI units

GROUP I DATA RAMP DATA

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

NAMELIST / PARAMS / XN, OUTPUT, ULLAGE, RADIUS, SPWGT, ENSDTIM, XMCLEC, 1
HCONST, DIA, ZCONST, HMULT, HEXP, SPWSS, DT, ENDRMP, PM1, PM2, PM3, PM4, CYLN,
2
UNUMS
READ (5, PARAMS)

GROUP II DATA RAMP DATA CONTINUED

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

NAMELIST / INPNTS / MTGAS, MPDATA, MFLOW, MTSAT, MTBULK, MQOUT, MQIN,
1
MTWIN, MTGIN, MRAD, MTICK
READ (5, INPNTS)

NAMELIST / OTPNTS / MTGAS, MPDATA, MFLOW, MTSAT, MTBULK, MQOUT, MQIN,
1
MTWIN, MTGIN, MRAD, MTICK
WRITE (6, OTPNTS)

NAMELIST / TABLES /

1
TGAS, TIME1, PDATA, TIME2, FLOW, TIME3,

2
TSAT, TIME4, TBULK, TIME5, QOUTD, TIME6,

3
QIND, TIME7, TWIND, DIST1, TGIND, DIST2,

4
YRAD, XRAD, YTICK, XXT
READ (5, TABLES)

PRELIMINARY COMPUTATION

GSTART=0.0
TIMY=0.0
LOOM=0
ITER1=0
Q=0.
GASCHK=C.

TICK(1)=YTICK(1)
TLID=TICK(1)
CALL WRITE1
C IF(IJNUMS .EQ. 0. ) GO TO 301
CALL SINTS
301 CONTINUE
TPP=1.
XPI=3.14159
R=1545.4
XJAY=778.2
HCONST=HCONST/3600.
C N=XN
NP=N+1
DX=ULLAGE/(XN-1.0)
IWRITE=OUTPUT
CHECK=FLOW(1)
DETY=DT
C C8=R/XMOLEC
C3=DX*C8
C1=C3/2.
C2=C1/XJAY
C4=DX/C8
C6=2.*C8
C7=C8/XJAY
UWTP = 2.0*XPI*DX*SPWGT
DO 3 J=2,250
XJTICK=J-1
X(J)=DX*XJTICK
CALL INTERP (YTICK,XXT,MTICK,X(J),TICK(J))
C5(J)=1.0/(TICK(J)*SPWGT)
3 C9(J) = UWTP * TICK(J)
X(1)=0.
C C
C C
STEP-IA-
MAKE GEOMETRY CALCULATIONS
C
4 IF (RADIUS) 12,4,6
DO 5 J=2,250
XJTEMP=J-1
CALL INTERP (YRAD,XRAD,MRAD,X(J),RAD(J))
AREA(J)=XPI*RAD(J)**2
RAD(1)=RAD(2)
AREA(1)=AREA(2)
GO TO 16
6 CONTINUE
DO 10 J=2,250
IF (X(J)-DIA/2.) 7,8,8
7 RAD(J)=SORT(DIA*X(J)-X(J)**2)
AREA(J)=XPI*RAD(J)**2
GO TO 10
8 IF (X(J).GT.(CYLN+RADIUS)) GO TO 9
RAD(J)=RADIUS
AREA(J)=XPI*RAD(J)**2
GO TO 10
9 PLEG=X(J)-CYLN-RADIUS
48
IF (PLEG $\geq$ RADIUS) GO TO 11
RAD(J) = $\sqrt{\text{RADIUS}^2 - \text{PLEG}^2}$
AREA(J) = $\pi \times \text{RAD(J)}^2$
10 CONTINUE
11 RAD(1) = RAD(2)
AREA(1) = AREA(2)
GO TO 16

C
12 DO 14 J = 2, 250
XJTEMP = J - 1
IF (X(J) = DIA) 13, 13, 15
RAD(J) = $\sqrt{\text{DIA} \times (\text{J} - X(J))^2}$
14 AREA(J) = $\pi \times (\text{J} \times (\text{DIA} - X(J))$
15 AREA(1) = AREA(2)
RAD(1) = RAD(2)
C
16 CONTINUE
C THE NEXT 3 CARDS ARE SKIPPED SINCE THE FLOW DATA IS ZERO IN RAMP
C
C DT = D*AREA(N)/FLOW(1)
C CALL INTERP(FLOW, TIME3, MFLOW, DT, FLO)
C DT = D*AREA(N)/(FLOW(1)+FLO)*2.0
C TIME = DT
C
C STEP - 1B -
C COMPUTE INITIAL WALL AND GAS TEMPERATURES
C
C DO 17 J = 1, N
CALL INTERP (TWIN, DI1, MTWIN, X(J), TW(J))
CALL INTERP (TGIND, DI2, MTGIND, X(J), T(J))
C
C STEP - 1C -
C COMPUTE INITIAL VALUES OF SPECIFIC HEAT
C
17 CALL SPHEAT (T(J), TW(J), CP(J), CPW(J), XMolec)
C
C STEP - 2 -
C COMPUTE INITIAL VALUES OF HEAT TRANSFER COEFFICIENT
C
C IF (HCONST) 1, 20, 18
C
18 DO 19 J = 1, 250
H(J) = HCONST
GO TO 26
C
19 IF (HMULT) 1, 21, 22
HMULT = C * 13
C
22 IF (HEXP) 1, 23, 24
HEXP = 0.333
C
24 DO 25 J = 1, N
XJ = ULLAGE + X(J)
25 CALL HDDEFF (T(J), TW(J), PDATA(1), XL, H(J), ZCONST, HMULT, HEXP, XMolec)
26 CONTINUE
**STEP-3**
COMPUTE INITIAL VALUES OF COMPRESSION FACTOR AND ITS DERIVATIVES

IF (ZCCNST) 1, 29, 27

DO 28 J=1, 250
7(J)=1.0
Z1(J)=1.0
28 Z2(J)=1.0
7 HOLD=1.0
GO TO 21

DO 30 J=1, N
CALL COMPRS (T(J), PDATA(1), Z(J), Z1(J), Z2(J), XMOLEC)
31 CONTINUE

**STEP-4**
INITIALIZE VALUES FOR QOUT, QIN, P AND DPDT

QOUT=QOUTD(1)
QIN =-QIND(1)
P=PDATA(1)
P HOLD=P

IF (MPDATA-1) 1, 32, 33
32 PP=P
GO TO 24

CALL INTERP (PDATA, TIME2, MPDATA, TIME, PP)
DPDT=(PP-P)/DT
DPDTPV=DPDT

DO 35 J=2, N
35 DRDX(J)=(RAD(J+1)-RAD(J))/(X(J+1)-X(J))
DRDX(N+1)=DRDX(N)
DRDX(1)=(RAD(2)-RAD(1))/X(2)

**STEP-5**
COMPUTE INITIAL VALUES OF LOCAL ullage GAS VELOCITY

V(N)=FLOW(1)/AREA(N)
NTEMP=N-1
DO 37 L=1, NTEMP
J=N-L
C12=DX*{(DRDX(J+1)+DRDX(J))/(RAD(J+1)+RAD(J))}
C10=H(J)*Z1(J)/(P*RAD(J)*CP(J))
C11=SQRT(1.0+((DRDX(J+1)+DRDX(J))/2.0)**2)
VA=C3*C10*(TW(J)-T(J))*C11+(C1/AREA(J))*Z1(J)*CIN/P/CP(J)+{(C2*Z1(J)
1)**2/CP(J)-.5*DX*Z2(J)*DPDT/P/Z(J)
VA=VA/(1.0-C12)
K=J+1
C20=P(K)*Z1(K)/(P*RAD(K)*CP(K))
VB=C3*C20*(Tw(K)-T(K))*C11+(C1/AREA(K))*Z1(K)*QIN/P/CP(K)+(C2*Z1(K)
1)**2/CP(K)-5*DX*Z2(K))**DPT/P/Z(K)
VB=VB/(1.0-C12)
37 V(J)=(1.0+12)/(1.0-C12)*V(J+1)-VA-VB
WRITE (6,111)
WRITE (6,112) (V(J), J=1,N,10)
IF (GSTART.GT.0.) GO TO 40

STEP-6-
FIND GAS IN ULLAGE AT TIME ZERO BY INTEGRATING DENSITY

GASA=0.5*AREA(1)/T(1)/Z(1)+0.5*AREA(N)/T(N)/Z(N)
NTEMP=N-1
DO 38 J=2,NTEMP
38 GASA=GASA+AREA(J)/T(J)/Z(J)
GASA=GASA*C4*P
GSTART=GASA

***************
STEP-7-
WRITE PROBLEM IDENTIFICATION AND INPUT DATA
IF(UNUMS.1250, 251, 250
CONTINUE
GSTART = GSTART * .4535924
WRITE (6,2015) GSTART
GSTART = GSTART/4535924
Q = Q * 1054.3503
WRITE (6,2050) Q
Q = Q/1054.3503
GO TO 120

CONTINUE
WRITE (6,1015) GSTART
WRITE (6,1050) Q

CONTINUE
**************
BEGIN MAIN PART OF CALCULATION
T(1)=T6AS(1)
INITIALIZE AN ESTIMATE FOR TP(J)
NJ=N-1
DC 39 KI=1,N
39 TP(KI)=T(KI)
STEP-8-
FIND TEMPERATURES AT NEW TIME

CALL INTERP (TGAS,TIME1,MTGAS,TIME,TP(1))
CALL INTERP (TSAT,TIME4,MTSAT,TIME,TP(N))
CALL INTERP (TBLK,TIME5,MTBLK,TIME,TWP(N))

KSTAR=C
ZMOLD=Z(2)
VHOLD=V(2)

FIND MISCELLANEOUS QUANTITIES AT NEW TIME

CALL INTERP (QOUT,TIME6,MQOUT,TIME,QOUT)
CALL INTERP (QIND,TIME7,MQIN,TIME,QIN)
QIN = -QIN
IF (MPDATA-1) 1,42,41
PHOLD=P
CALL INTERP (PDATA,TIME2,MPDATA,TIME,P)
TIME=TIME+DT
CALL INTERP (PDATA,TIME2,MPDATA,TIME,PP)
DPDT=(P-PHOLD)/DT

CONTINUE

INITIALIZE AN ESTIMATE FOR VELOCITY
DO 45 J=2,NJ
IF (DPDTPV<0.) 43,43,44
V(J)=V(J)
GO TO 45
V(J)=V(J)*DPDT/DPDTPV
45 CONTINUE
DPDTPV=DPDT

KLAMP=0

ISTAR=C

CONTINUE
DO 54 J=2,NJ

D1=C5(J)*DT*QOUT/CPW(J)
D2=1.0+C5(J)*DT*H(J)/CPW(J)
D3=D2/((C6/RAD(J))*H(J)*Z(J)*DT/P/CP(J))
D3=D3/SORT(1.0+((DRDX(J+1)+DRDX(J))/2.)**2)
D4=(C7*Z1(J)*DPDT+(C8/AREA(J))*Z(J)*QIN)*DT/CP(J)/P
G1=D3-C3*DP4-TW(J)-D1
G2=C3*DT/DR
G3=D3*T(J)

G4=Z1(J)/Z(J)*DX/DT
G5=Z2(J)/Z(J)*DX*DPDT/P

G6=G5-C4
G7=G4*T(J)
G8=1.0-Z1(J)/Z(J)-2.*DX/RAD(J)*DRDX(J)

PHE=Z1(J)/Z(J)*TP(J+1)+G1*G8+G2*(V(J+1)+G6)
UU=GI*ZI(J)/Z(J)*TP(J+1)+G2*G7-G2*TP(J-1)*(V(J+1)+G6)-G3*G8
AY=1./Z.*G*(3.*UU-PHE**2)
RR=-G2*G7*TP(J-1)-G3*ZI(J)/Z(J)*TP(J+1)
BEE=1./27.*(2.*PHE**3-9.*PHE*UU+27.*RR)
C
DIS1=UL**2-4.*PHE*RR
IF (DIS1.LE.0.) GO TO 47
TP(J)=(-UU+SQRT(DIS1))/(2.*PHE)
GO TO 48
47
TP(J)=C.5*(T(J)+TP(J-1))
48
DO 49 LEL=1,10
HOPE=G8*TP(J)**3+PHE*TP(J)**2+UU*TP(J)+RR
HOP=ABS(HOPE)
DHOPT=3.*G8*TP(J)**2+2.*PHE*TP(J)+UU
AZ9=800.
AZ8=.0C01*DHOPT
IF (AZ8.LT.AZ9) AZ9=AZ8
IF (HOPE.LT.AZ9) GO TO 50
TP(J)=TP(J)-HOPE/DHOPT
XR(1)=TP(J)
49 CONTEUE
WRITE (6,105)
KSTAR=KSTAR+1
IF (KSTAR.GT.25) GO TO 55
50 CONTEUE
TEST(J)=BEE**2/4.*AAY**3/27.
IF (TEST(J).LE.0.*AND. TP(J).GT.TPP) GO TO 51
GO TO 54
51
AQ(1)=G8
AQ(2)=PHE*XR(1)*G8
AQ(3)=UU*XR(1)*AQ(2)
XQ1=1./AQ(2)/(G2*AQ(1))
DISC=XQ1*XQ1-AQ(3)/AQ(1)
52 IF (DISC .LT. 0.) GO TO 54
C
53
XQ2=SQRT(DISC)
TP(J)=XQ1*XQ2
IF (TP(J).GE.TPP) TP(J)=XR(1)
C
C--- FOR SIGNIFICANCE OF TEST(J), SEE COMMENT UNDER STEP 13
54
TPW(J)=(TW(J)+(D2-1.0)*TP(J)+D1)/D2
GO TO 56
55 IF (TIME.GT.PM1) DETY=DETY-.005
IF (TIME.LE.PM1) DETY=DETY-.01
DT=DETY
TIME=TIME+DT
IF (TIME.LE.TIMY) GO TO 1
GO TO 36
C
THE FOLLOWING TWO EQUATIONS ARE SPECIFIC HEAT VS TEMP. FOR AN
ASSUMED MASSIVE STAINLESS STEEL LID AT THE TOP OF THE TANK
56 IF (SP+SS=499.0) 61,57,57
57 IF (TW(1)-75.0) 58,59,59
58 CPW(1)=C.010
GO TO 61
59 IF (TW(1).GT.22.0.) GO TO 60
CPW(1)=C.000418*TW(1)-.0203
GO TO 61
C
53
W=(TW(1)-220.)/126.67
CPW(1)=((0.0018*W-0.0127)*W+0.0374)*W+0.071
C
C5(1)=1.0/C(TICK(1)*SPWSS)
C9(1)=XP1*DX*DIA*TICK(1)*SPWSS
C
D1=C5(1)*DT*QOUT/CPW(1)
D2=1.0+C5(1)*DT/H(1)/CPW(1)
KLAMP=KLAMP+1
C
TWP(1)=(TW(1)+(D2-1.0)*TP(1)+D1)/D2
C
IF (KLAMP.LT.3) GO TO 62
IF (ERPP.LT.05) GO TO 62
IF (ERPP.GT.05AND.ISTAR.GT.6) GO TO 62
GO TO 71
C
C
STEP-9-
FIND HEAT TRANSFER COEFFICIENT AT NEW TIME
C
IF (HCONST) 1,63,65
DO 64 J=1,N
XL=ULLACE*X(J)
CALL +COEFF (TP(J),TWP(J),P,XL,H(J),ZCONST,HMUL8,HEXP,XMOLEC)
CONTINUE
C
STEP-10-
FIND COMPRESSIBILITY FACTORS AT NEW TIME
C
DO 66 K=1,N
ZAV(K)=Z(K)
IF (ZCONST) 1,67,69
DO 68 J=1,N
CALL CCMPRS (TP(J),P,Z(J),Z1(J),Z2(J),XMOLEC)
CONTINUE
C
STEP-11-
FIND SPECIFIC HEATS AT NEW TIME
C
DO 70 J=1,N
CALL SPHEAT (TP(J),TWP(J),CP(J),CPW(J),XMOLEC)
CONTINUE
IF (KLAMP.LT.3) GO TO 46
C
STEP-12-
FIND VELOCITIES AT NEW TIME
C
CALL INTERP (FLOW,TIME3,MFLOW,TIME,FLOWNP)
V(N)=FLOWNP/AREA(N)
IF (LCOM.GE.3) GO TO 89
72 CONTINUE
ERRP=0.
GO TO 82

73 LONM=LONM+1
WRITE (6,119)
GO TO 55

74 DO 75 J=1,N
VP(J)=.5
75 CONTINUE
DO 76 J=1,N
VP=VP(J)
IF (VP.EQ.0.) GO TO 78
ERR=(V(J)-VP(J))/VP(J)
ERR=ABS(ERR)
IF (ERR=ERRP) 78,78,77
77 ERR=ERR
78 CONTINUE
IF (ERRP=.004) 89,89,79
IF (ISTAR.EQ.36) GO TO 87
80 DO 81 J=1,N
VP(J)=V(J)
81 CONTINUE
ISTAR=ISTAR+1
IF (ISTAR.GT.32) GO TO 103
82 IF (ISTAR=40) 46,46,84
83 IF (ISTAR) 74,74,76
84 IF (ERRP=10) 85,85,86
85 ERROR=ERRP*100.
GO TO 104
86 WRITE (6,108)
WRITE (6,114) ERROR
WRITE (6,115) TIME
WRITE (6,110)
WRITE (6,112) (TP(J),J=1,N,10)
WRITE (6,116)
WRITE (6,112) (TP/J),J=1,N,10

C AT THIS POINT THE PROGRAM WILL CONTINUE REGARDLESS OF THE ERROR
C OPTION II IS TO REDUCE THE TIME INCREMENT, PROCEED TO STEP 5
GO TO 89
87 DO 88 J=1,N
88 V(J)=(V(J)+VP(J))/2.
GO TO 8C

C C
C STEP-13-
C FIND GAS FLOW RATE AND TOTAL GAS ADDED UP TO THE NEW TIME
C
89 CONTINUE
IF (TP(1).LT.TPP) TPP=TP(1)
C IF TEST(J) IS GREATER THAN 1-ONE REAL AND TWO CONJUGATE
IMAGINARY ROOTS -- IF TEST(J)=0., THERE WILL BE THREE
REAL ROOTS -- IF TEST(J) IS LESS THAN J THERE WILL BE
THREE REAL AND UNEQUAL ROOTS.

DO 91 J=1,N
IF (TP(J)-TPP) 91,91,90
90 WRITE (6,109) TP(J),J,TIME,TEST(J)
91 CONTINUE
GAS=C*AREA(1)/TP(1)/Z(1)+0.5*AREA(N)/TP(N)/Z(N)
DO 92 J=2,N
92 GAS=GASA+AREA(J)/TP(J)/Z(J)
GASA=GASA*C4*P

GSTAGE=(GASA-GASA)/DT
GASA=GASA-GSTART
GASCHK=GASCHK+0.25*(V(2)+VHOLD)/(C8/AREA(2))*DT*(PHCLD/ZHOLD/T(2)+
P/Z(2)/TP(2))

STEP-14-
FIND HEAT FLOW RATE TO WALL AND TOTAL HEAT ADDED TO WALL

DO=9(1)*CPW(1)*(TP(1)-TW(1))
DO 93 J=2,N
93 DO=DO+RAD(J)*SQRT(1.0+DROX(X(J)**2))*CPW(J)*
(TP(J)-TW(J))*C9(J)
Q=Q+DO

WRITE OUT RESULTS
ITER1=ITER1+1
IF (ITER1=WRITE) 95,94,94
94 CALL WRITE2
ITER1=C
95 IF (TIME .GE. ENDRMP) CALL WRITE2
IF (TIME .GE. ENDRMP) RAMP=1000.

STEP-15-
CHECK TO SEE IF END TIME HAS BEEN REACHED

IF (TIME .LT. ENDTIM) 96,101,101
END TIM NOT REACHED PREPARE FOR ANOTHER STEP

96 IF (TIME .GT. PM1) DT=0.1
IF (TIME .GT. PM2) DT=0.2
IF (TIME .GT. PM3) DT=0.5
IF (TIME .GT. PM4) DT=1.0
DETY=DT
TIME=TIME
TYME=TIME+DT
TE1=TYME+.1
IF (TIME .LT. ENDTIM) TYME=ENDTIM
CALL INTERP (FLOW,TIME3,MFLOW,TYME,FLOWP)
CHECK=FLOWP
VP = FLOW / AREA(N)

IF (TYME .EQ. ENDTIM) DT = ENDTIM - TIME
IF (CHECK .EQ. 0.) GO TO 97

97 DT = DX / (V(N) + VP) * 2.
TIME = TIME + DT

C
DO 98 J = 1, N
TP(J) = TP(J)
98 TW(J) = TWP(J)
GASA = GASB
LOCM = C
C
IF (CHECK = 0.) SS, 99, 10C
99 NJ = N - 1
GO TO 40
100 NJ = N
N = N + 1
NP = N + 1
DRDX(N) = (RAD(NP) - RAD(N)) / (X(NP) - X(N))
DRDX(NP) = DRDX(N)
GO TO 40
C
C
STEP-16-
END TIME EXCEEDED - INTERPOLATE CONDITIONS AT END TIME
C
101 RAT = (ENDTIM - TIME + DT) / DT
TIME = ENDTIM
C
DO 102 J = 1, N
TP(J) = T(J) + RATI0 * (TP(J) - T(J))
102 TW(J) = TW(J) + RATI0 * (TW(J) - Th(J))
C
Q = Q - DQ + RATI0 * DQ
GAS = GAS - GASB + GAS * RATI0 * (GASB - GAS)
GASCHK = GASCHK - GASB + GAS * RATI0 * (GASB - GAS)
C
C
STEP-17-
C
CALL WRITE
GO TO 1
C
103 WRITE (6, 111)
WRITE (6, 112) (V(J), J = 1, N, 10)
WRITE (6, 113) ISTAR
GO TO 82
104 WRITE (6, 114) ERROR
WRITE (6, 110)
WRITE (6, 112) (TP(J), J = 1, N, 10)
WRITE (6, 115) TIME
WRITE (6, 111)
WRITE (6, 112) (V(J), J = 1, N, 10)
GO TO 89
C
C
**************************
C FORMAT STATEMENTS

C
C
C 105 FORMAT (1HK, 71H SOLUTION TO CUBIC BY NEWTON-RAPHSON REQUIRES MORE
   1 THAN 10 ITERATIONS)
106 FORMAT (1H, 3CX, 29H TANK PRESSURIZATION PROGRAM/1HJ)
107 FORMAT (80H
   1)
108 FORMAT (1HK, 32H ERROR GREATER THAN ACCEPTABLE)
109 FORMAT (1HL, 5X, 13H GAS T(R) = F6.1,5H J = 13,9H TIME = F5.1,9H
   15SECONDS, 9H TEST = E13.5,2X,40H COMPUTED TEMP. GREATER THAN BOUND
   2ARY)
110 FORMAT (1HL, 10X, 43H ULLAGE GAS TEMP PROFILE IN PROGRAM UNITS /1X)
111 FORMAT (1HL, 10X, 108H INSTANTANEOUS ULLAGE GAS FLOW MATURES FROM TOP TO
   1 INTERFACE-NEGATIVE VALUES ARE UNSTABLE-RATES IN PROGRAM UNITS /1X)
112 FORMAT (1P8G15.7)
113 FORMAT (1HL, 10X, 15H ITERATIONS = 13)
114 FORMAT (1HL, 10X, 18H PERCENT ERROR = F5.1,10H PERCENT /1X)
115 FORMAT (1HL, 10X, 17H TIME IN RAMP = F5.1,10H SECONDS /1X)
116 FORMAT (1HL, 10X, 43H ULLAGE WALL TEMP PROFILE - PROGRAM UNITS /1X)
117 FORMAT (1HL, 2X, 17H GAS SUPPLIED = F7.3,5H LBS, 2X, 14H GAS CHECK
   1 = F7.3,5H LBS, 2X, 14H RAMP TIME = F7.2,9H SECONDS)
118 FORMAT (1HK, 2X, 13H GAS FLOW = E13.5,9H LBS/SEC, 2X, 15H ITERATION
   1S = I3,2X,17H HEAT TO WALL = E13.5,5H BTU)
119 FORMAT (1HK, 50H ONE OR MORE NEGATIVE GAS VELOCITIES ARE COMPUTED)
120 FORMAT (1HK, 23H INITIAL ULLAGE GAS = F6.3,5H LBS)
121 FORMAT (1HK, 25H INITIAL HEAT TO WALL = F7.1, 5H BTU)
122 FORMAT (1HK, 23H INITIAL ULLAGE GAS = F6.3,10H KILOGRAM)
123 FORMAT (1HK, 25H INITIAL HEAT TO WALL = E11.4, 7H JOCUL)
END
TANK PRESSURIZATION PROGRAM
PRESSURIZATION OF 13 FT. ALUMINUM TANK
FIVE PERCENT VOLUME HYDROGEN PRESSURANT
END OF FILL 10.0 SECONDS

INPUT DATA

INITIAL NUMBER OF DATA POINTS = 40.
INITIAL VOLUME = 1.881 FEET
TANK RADIUS = 1.000 FEET
TANK WALL SPECIFIC WEIGHT = 169.3 LBS/CUBIC FOOT
Molecular Weight = 2.0

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<th>TIME, SECONDS</th>
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<th>FLOW RATE, CFM/SEC</th>
<th>TIME, SECONDS</th>
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### Saturation Temp, deg F vs Time, Seconds

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### Allk Temp, deg F vs Time, Seconds

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### Outside Heating Rate, RTU/sq ft-sec vs Time, Seconds

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<th>Time (sec)</th>
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### Inside Heating Rate, RTU/linear ft-sec vs Time, Seconds

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(Note: Q IND = (-Q IN) by the program)

### Initial Temperature - deg. Rankine

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<th>Gas Temperature (deg F)</th>
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1.12 159.2 89.7
1.16 144.2 83.9
1.21 99.1 78.1
1.25 94.3 72.5
1.29 90.2 66.9
1.34 85.7 61.7
1.38 81.2 56.5
1.42 78.3 52.0
1.47 75.2 48.1
1.51 72.9 44.5
1.55 70.1 41.9
1.59 67.8 39.3
1.64 65.4 38.1
1.68 63.0 37.0

TANK RADIUS (FEET) VS AXIAL DISTANCE (FEET)
-0.000 0.000
HEAT TRANSFER COEFFICIENT WILL BE COMPUTED
HMAUL = 0.  HEXP = 0.
A REAL GAS IS ASSUMED
THE PRESSURANT IS HYDROGEN

RESULTS
INSTANTANEOUS VOLUME GAS FLOW RATES FROM TOP TO INTERFACE-NEGATIVE VALUES ARE UNSTABLE-RATES IN PROGRAM LNTS
0.3354664 2.36E28CH-2 5.6440085C-23 3.0610921E-23
INITIAL VOLUME GAS = 2.578 LBS
INITIAL HEAT TO WALL = 0.  BTU

TIME = 6.70 SECONDS  GAS SUPPLIED = 0.0575 LBS  HEAT TO WALL = 5.6 BTU  INLET VEL = 1.8756 FEET/SEC
CHECK IN GAS = 0.078 LBS  GAS FLOW = 0.0174 LPS/SEC  OUTLET VEL = 0.0000 FEET/SEC

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<th>GAS T(R)</th>
<th>X, FEET</th>
<th>WALL T(R)</th>
<th>GAS T(R)</th>
<th>X, FEET</th>
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<td>253.6</td>
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<td>1.43</td>
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<td>235.6</td>
<td>2.47</td>
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<td>114.1</td>
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<td>GAS (R)</td>
<td>X, FEET</td>
<td>WALL (R)</td>
<td>GAS (R)</td>
<td>X, FEET</td>
<td>WALL (R)</td>
<td>GAS (R)</td>
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<td>111.0</td>
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<td>1.61</td>
<td>97.4</td>
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<td>1.64</td>
<td>166.8</td>
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<tr>
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<td>81.6</td>
<td>262.8</td>
<td>1.95</td>
<td>81.6</td>
<td>262.8</td>
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</table>

**TIME = 15.40 SECONDS**  **GAS SUPPLIED = 0.7970 LBS **  **HEAT TO WALL = 55.5 BTU**  **INLET VEL = 6.1440 FEET/SEC**

**CHECK ON GAS = 0.513 LBS**  **GAS FLOW = 0.1443 LBS/SEC**  **OUTLET VEL = C.9000 FEET/SEC**

**GAS TEMPERATURE = 318.0**  **J = 14**  **TIME = 19.6 SECONDS**  **TEST = 0.17640E+21**  **COMPUTER TEMP. GREATER THAN BOUNDARY**

**GAS TEMPERATURE = 310.4**  **J = 15**  **TIME = 19.6 SECONDS**  **TEST = 0.11034E+21**  **COMPUTER TEMP. GREATER THAN BOUNDARY**

**GAS TEMPERATURE = 318.0**  **J = 16**  **TIME = 19.6 SECONDS**  **TEST = 0.34588E+20**  **COMPUTER TEMP. GREATER THAN BOUNDARY**

**GAS TEMPERATURE = 311.2**  **J = 17**  **TIME = 19.6 SECONDS**  **TEST = 0.91494E+19**  **COMPUTER TEMP. GREATER THAN BOUNDARY**

**GAS TEMPERATURE = 311.3**  **J = 18**  **TIME = 19.6 SECONDS**  **TEST = 0.26148E+20**  **COMPUTER TEMP. GREATER THAN BOUNDARY**

**GAS TEMPERATURE = 311.0**  **J = 19**  **TIME = 19.6 SECONDS**  **TEST = 0.50505E+20**  **COMPUTER TEMP. GREATER THAN BOUNDARY**

**GAS TEMPERATURE = 311.3**  **J = 20**  **TIME = 19.6 SECONDS**  **TEST = 0.63250E+20**  **COMPUTER TEMP. GREATER THAN BOUNDARY**
APPENDIX D

SUBROUTINES - COMMON TO BOTH PROGRAMS

SUBROUTINE SINTS
DIMENSION
1  TGAS(30),TIME1(30),PCATA(30),TIME2(30),
2  FLOW(30),TIME3(30),TSAT(30),TIME4(30),
3  TBULK(30),TIME5(30),UCUTD(30),TIME6(30),
4  CIND(30),TIME7(30),ZAV(150),
5  TWIND(30),DIST1(30),TGIND(30),DIST2(30),
6  X(150),T(150),TP(150),TW(150),TWP(150),V(150),
7  CP(150),CPM(150),H(150),Z(150),Z1(150),Z2(150),
8  RAD(150),AREA(150),YRAD(150),XRAD(150),ORDX(150)
C
DIMENSION
1  CS(150),CPH(150),YTIME(50),XTIME(50),TIME(150),
2  TWA(30),DIST7(30),TMCU(30),DIST8(30),TSLN(30),DIST9(30),
3  TWAL(30),DIST11(30),CPEK(150),TWPB(150),TB(150),CPCU(150),
4  TWIC(150),TC(150),CPST(150),TSLT(150),TZL(150),CPAL(150),
5  TALS(150),TCPA(150),TTI(150),PRAM(150)
C
COMMON
1  X,T,TP,TW,TMP,V,CP,CPM,TGAS,TIME1,MTGAS,PCATA,TIME2,MPDATA,
2  FLOW,TIME3,MFLUW,TSAT,TIME4,MTSAT,TBULK,TIME5,MTBULK,WOUTD,
3  TIME6,MPOUT,GIND,TIME7,MININ,NNP,XN,ULLAGE,RADIUS,DU,
4  SPWGT,XMOLEC,GSTART,HCCNST,TIME,GAS,W,GASCHK,GSRATE,DT,
5  ZCCNST,H,MMULT,HEXP,YRAD,YRAD,MKAD,TNKWT,CUTR,QIN,UNUMS,
6  PTWIN,MTGIN,MTICK,MTBKE,MCU,MTSS,MTAL,
7  TWIND,DIST1,TGIND,DIST2,YTIME,XTIME,TWPB,DIST7,
8  TWAL,DIST11,TCM,DISHT,TSLN,DIST9
C
COMMON
1  CARAD,ADIFU,SPWSS,DOC,HCONST,TADD,AB,ALC,A3S,A5B,WTB,WTLC,
2  *135*15B
C
*******************************************************************
C WHEN USING THIS SUBROUTINE FOR THE PRESSURIZATION PROGRAM - USE
C THE SAME DIMENSION AND COMMON APPEARING IN THE MAIN PROGRAM.
C*******************************************************************
C IF(RADIUS .LE. 0.0) GO TO 10
RADIUS = RADIUS/0.0048
10 ULLAGE = ULLAGE/0.003048
CARAD = CARAD/0.003048
HCCNST = HCCNST/3.1524808/1.8
ADIFU = ADIFU/0.000290304
SPWGT = SPWGT/1.0630463
SPWSS = SPWSS/1.0630463
UFA = E1A/0.3048
HCCNST = HCCNST/0.3048
TADD = TADD * 1.8
AR = AR/0.929034
A1C = A1C/0.929034
A3S = A3S/0.929034
A5B = A5B/0.929034

64
$\textit{WTF} = \textit{TB} / 45359237
\textit{WTIC} = \textit{TIC} / 45359237
\textit{WTS} = \textit{TSS} / 45359237
\textit{WTB} = \textit{TB} / 45359237
\textit{IF} (\textit{MTGAS} < \textit{LT}) \text{ GO TO } 102
\text{ DC } 101 \text{ J} = 1, \textit{MTGAS}
101 \text{ TGAS(J)} = \text{ TGAS(J)} * 1.8
102 \text{ IF} (\textit{MDATA} < \textit{LT}) \text{ GO TO } 106
\text{ DC } 104 \text{ J} = 1, \textit{MDATA}
104 \text{ PDATA(J)} = \text{ PDATA(J)} / 4.7880258 * 0.1000000E+07
106 \text{ IF} (\textit{MFLOW} < \textit{LT}) \text{ GO TO } 109
\text{ DC } 108 \text{ J} = 1, \textit{MFLOW}
108 \text{ FLOW(J)} = \text{ FLOW(J)} / 3048**3
109 \text{ IF} (\textit{MTSAT} < \textit{LT}) \text{ GO TO } 112
\text{ DC } 110 \text{ J} = 1, \textit{MTSAT}
110 \text{ TSAT(J)} = \text{ TSAT(J)} * 1.8
112 \text{ IF} (\textit{MRTBUL} < \textit{LT}) \text{ GO TO } 116
\text{ DC } 114 \text{ J} = 1, \textit{MRTBUL}
114 \text{ TBULK(J)} = \text{ TBULK(J)} * 1.8
116 \text{ IF} (\textit{MCGC} < \textit{LT}) \text{ GO TO } 120
\text{ DC } 117 \text{ J} = 1, \textit{MCGC}
117 \text{ COUTD(J)} = \text{ COUTD(J)} / 11348.931
120 \text{ IF} (\textit{MGIN} < \textit{LT}) \text{ GO TO } 130
\text{ DC } 121 \text{ J} = 1, \textit{MGIN}
121 \text{ QIND(J)} = \text{ QIND(J)} / 1054.3503 * 3048
130 \text{ IF} (\textit{MTWIN} < \textit{LT}) \text{ GO TO } 134
\text{ DC } 131 \text{ J} = 1, \textit{MTWIN}
131 \text{ Twind(J)} = \text{ Twind(J)} * 1.8
134 \text{ IF} (\textit{MTGIN} < \textit{LT}) \text{ GO TO } 138
\text{ DC } 135 \text{ J} = 1, \textit{MTGIN}
135 \text{ TGIND(J)} = \text{ TGIND(J)} * 1.8
138 \text{ IF} (\textit{MRAD} < \textit{LT}) \text{ GO TO } 141
\text{ DC } 139 \text{ J} = 1, \textit{MRAD}
139 \text{ YRAD(J)} = \text{ YRAD(J)} / 0.3048
141 \text{ IF} (\textit{MTICK} < \textit{LT}) \text{ GO TO } 144
\text{ DC } 142 \text{ J} = 1, \textit{MTICK}
142 \text{ YTICK(J)} = \text{ YTICK(J)} / 0.3048
144 \text{ IF} (\textit{MTBAK} < \textit{LT}) \text{ GO TO } 147
\text{ DC } 145 \text{ J} = 1, \textit{MTBAK}
145 \text{ Twk(J)} = \text{ Twk(J)} * 1.8
147 \text{ IF} (\textit{MTCU} < \textit{LT}) \text{ GO TO } 150
\text{ DC } 148 \text{ J} = 1, \textit{MTCU}
148 \text{ Twcu(J)} = \text{ Twcu(J)} * 1.8
150 \text{ IF} (\textit{MTSS} < \textit{LT}) \text{ GO TO } 153
\text{ DC } 151 \text{ J} = 1, \textit{MTSS}
151 \text{ Tsn(J)} = \text{ Tsn(J)} * 1.8
153 \text{ IF} (\textit{MTAL} < \textit{LT}) \text{ GO TO } 156
\text{ DC } 154 \text{ J} = 1, \textit{MTAL}
154 \text{ Tmal(J)} = \text{ Tmal(J)} * 1.8
156 \text{ CONTINUE}
C
\textit{RETURN}
C
FOR THE PRESSURIZATION PROGRAM - REMOVE ALL STATEMENTS FROM 144
THROUGH 154 - CHANGE STATEMENT NUMBER 156 TO 144.

END

SUBROUTINE SPHEAT(T,TW,CP,CPW,XMOLEC)
DIMENSION CTEMP(15),CPWALL(15),CTEMP(15),CGAS(15)
DATA FOR SPECIFIC HEAT OF ALUM ALLOYS - 2215-7852
(THERMOPHYSICAL PROPERTIES RESEARCH CENTER-PURDUE UNIV.)
DATA (CTEMP(J),CPWALL(J),J=1,15)/36***0020,45***0042,54***0074,72
1***0181,9C***0330,108***0513,126***0692,144***0837,162***0994,180
2***1052,270***1600,315***1726,360***1830,432***2029,540***2080/

DATA FOR SPECIFIC HEAT OF HYDROGEN AT 50 PSIA (NBS)
DATA (CTEMP(J),CGAS(J),J=1,15)/45.5,3.65,48.8,3.40,50.0,3.30,55.0
1.305,58.0,2.792,60.0,2.85,65.0,2.76,70.0,2.65,80.0,2.62,100.0,
22.6C,200.0,2.72,250.0,2.88,300.0,3.08,350.0,3.28,450.0,3.42/

IF (TW-CTEMP(I)) 1,1.3
1 CPW = CPWALL(1)
   GO TO 9
4 DC 7 I=2,15
   IF (TW-CTEMP(I)) 5,5,7
5 CPW = CPWALL(I-1) + (TW-CTEMP(I-1))/((CTEMP(I)-CTEMP(I-1))
   *(CPWALL(I)-CPWALL(I-1))
   GO TO 9

7 CONTINUE
   CPW = CPWALL(15)

9 IF (XMOLEC>3.0) 13,13,11
11 CP = 1.24
   RETURN

13 IF (T-CTEMP(1)) 15,15,17
15 CP = CGAS(1)
   RETURN

17 DC 21 J=2,15
   IF (T-CTEMP(J)) 19,19,21
19 CP = CGAS(J-1)+(T-CTEMP(J-1))/((CTEMP(J)-CTEMP(J-1))
   *(CGAS(J)-CGAS(J-1))
   RETURN

21 CONTINUE
   CP = CGAS(15)
   RETURN

END
SUBROUTINE WRITE 1

DIMENSION
1 TGSAS(30), TIME1(30), PCATA(30), TIME2(30),
2 FLO(30), TIME3(30), TSAT(30), TIME4(30),
3 TBULK(30), TIME5(30), QOUTD(30), TIME6(30),
4 CIND(30), TIME7(30), PAUL(150),
5 TWIN(30), DIST1(30), TGIND(30), DIST2(30),
6 T(150), T(150), TP(150), TW(150), TWP(150), T0(150),
7 CP(150), CPW(150), H(150), Z(150), ZL(150), Z2(150),
8 RAD(150), AREA(150), YR(150), XRAD(150), ORDFX(150)

DIMENSION
1 C5(150), C5(150), YTICK(50), XXT(50), TICK(50),
2 XBBK(30), DIST7(30), TWCU(30), DIST8(30), TSTN(30), DIST9(30),
3 TVAL(30), DIST11(30), CPB(150), TWA(150), TB(150), TPCU(150),
4 TWE(150), TC(150), CPST(150), TST(150), TSL(150), CPAL(150),
5 TALS(150), TAC(150), TTT(150), PRAM(150)

COMMON
1 X.T, TP, TW, TPV, CP, CPW, TGSAS, TIME1, MTGAS, DATA, TIME2, MPDATA,
2 FLO, TIME3, MFD, TSAT, TIME4, MTSAT, TBULK, TIME5, MTBULK, QOUTD,
3 TIMES, MODOUT, QIND, TIMEI, MNXN, NP, XN, ULLAGE, RADIUS, DQ,
4 SPWGT, XMELC, GSTART, HCONST, MTSAT, TIME6, GASQ, GASCHK, GSRATE, DT,
5 ZCONST, HMULT, HEXP, HRAD, XRAD, MRAD, TNK, T, CTX, CTG, CTN, UNUMS,
6 TWE(150), CPIN, MTGK, MTBK, MTAC, TPCU, MTSS, MTAL,
7 TWIN, DISTT, TGINDIO, DIST2, YTICK, XXT, TBBK, CIST7,
8 TVAL, DIST11, TWCU, DIST8, TSTN, DIST9

COMMON
1 CARAD, ADIFU, SPWSS, DIAR, HCONST, TADB, AB, ALC, A3S, A5B, TDB, TIC,
2 T3S, T5B

WHERE USING THIS SUBROUTINE FOR THE PRESSURIZATION PROGRAM - USE
THE SAME DIMENSION AND COMMON APPEARING IN THE MAIN PROGRAM

WRITE (6, 1007)

1007 FORMAT (1HL, 12H INPUT DATA)

N = XN
UX = ULLAGE/(1XN-1.0)
0G 30 J=2-N
XJTICK = J-1
30 X(J) = UX * XJTICK
X(1) = 0.
0G 31 J=1-N
CALL INTERP (TWIN, DIST1, MTWIN, X(J), TW(J))
31 CALL INTERP (TGIND, DIST2, MTGIND, X(J), T(J))
IF (UNUMS) .GE. 100, 101, 100
  WRITE (6,1010) XN, ULLAGE, RADIUS, SPWGT, XMULEG
C
1010 FORMAT (1HL,9X.32H INITIAL NUMBER OF NETPOINTS = F3.0/
  1 10X,14H INITIAL ULLAGE = F6.3,6H FEET/
  2 10X,16H TANK RADIUS = F6.3,6H FEET/
  3 10X,30H TANK WALL SPECIFIC WEIGHT = F6.1,16H LBS/CUBIC FOOT/
  4 10X,21H MOLECULAR WEIGHT = F3.1
  WRITE (6,1008)
C
1008 FORMAT (1HL,9X,4CH GAS TEMP, DEG R VS TIME, SECONDS /IX)
C
  WRITE (6,1009) (TGAS(J), TIME1(J), J = 1, MTGAS)
C
1009 FORMAT (F20.1, F25.1)
C
  WRITE (6,1030)
C
1030 FORMAT (1HL,9X,47H PRESSURE, LBS/SQ FT VS TIME, SECONDS /
  1 /IX)
C
  WRITE (6,1009) (PDATA(J), TIME2(J), J = 1, MPDATA)
C
  WRITE (6,1031)
C
1031 FORMAT(1HL,9X,44H FLOW RATE, CU FT/SEC VS TIME, SECONDS /
  11X)
C
  WRITE (6,1032) (FLOW(J), TIME3(J), J = 1, MFLOW)
C
1032 FORMAT (F20.1, F25.1)
C
  WRITE (6,1033)
C
1033 FORMAT(1HL,9X,49H SATURATION TEMP, DEG R VS TIME, SECONDS /
  1 /IX)
C
  WRITE (6,1009) (TSAT(J), TIME4(J), J = 1, MTSAT)
C
  WRITE (6,1034)
C
1034 FORMAT (1HL,9X,44H BULK TEMP, DEG R VS TIME, SECONDS /
  11X)
C
  WRITE (6,1009) (TBULK(J), TIME5(J), J = 1, MBULK)
C
  WRITE (6,1035)
C
1035 FORMAT (1HL,9X,63H OUTSIDE HEATING RATE, BTU/SC FT-SEC VS /
  1 TIME, SECONDS /1X)
C
  WRITE (6,1032) (QOUTD(J), TIME6(J), J = 1, MQOUT)
C
  WRITE (6,1036)
C
1036 FORMAT (1HL,9X,62H INSIDE HEATING RATE, BTU/LINEAR FT-SEC VS /
  1 TIME, SECONDS /1X)
1. HEAT TRANSFER COEFFICIENT will be computed

\[ k_T = \frac{F402}{F23H} \text{ BTU/SECOND} \]

2. INITIAL ULLAGE = F7.38 METER

3. INITIAL NUMBER OF NETPOINTS = F3.0

4. GAS TEMPERATURE (DEG K) vs TIME (SECONDS/1X)

5. PRESSURE (M-NEWTON/SQ M) vs TIME (SECONDS/1X)

6. FLOW RATE (M/SEC) vs TIME (SECONDS / 1X)

C \[\text{WRITE (6,1032) } (\text{CIND(J)\times TIME(J)\times J=1\times MQIN})\]

C \[\text{WRITE (6,1013)}\]

1013 FORMAT (1H4,9X,35H INITIAL TEMPERATURE-DEG. RANKINE /1HK, 1 9X,14H X COORDINATE,5X,18H WALL TEMPERATURE,5X, 2 17H GAS TEMPERATURE/1X)

C \[\text{WRITE (6,1014) } (\text{X(J),Tm(J),T(J)\times J=1\times N})\]

C 1014 FORMAT (F15.2, F22.1, F23.1)

C \[\text{WRITE (6,2050)}\]

2050 FORMAT (1H4,9X,48H TANK RADIUS (FEET) VS AXIAL DISTANCE (FEET) ) \[\text{WRITE (6,2051) } (YRAD(J),XRAD(J)\times J=1\times MRAD)\]

2051 FORMAT (F20.3,F25.2)

C IF (HCCNST) 5,5,7

C \[\text{WRITE (6,1039)}\]

C 1039 FORMAT (1H4,46H HEAT TRANSFER COEFFICIENT WILL BE COMPUTED ) \[\text{WRITE (6,1051) } (\text{MULT,HEXP})\]

1051 FORMAT (1H4,10H MMULT = F6.4,SH HEXP = F6.4)

GO TO 9

C \[\text{HCCNST} = 3600\times HCCNST\]

\[\text{WRITE (6,1040) } \text{HCCNST}\]

C 1040 FORMAT (1H4,33H CONSTANT HEAT TRANSFER COEFF = F6.2,23H BTU/SQ FT-HOUR-DEG R )

\[\text{HCCNST} = \text{HCONST}/3600\]

GO TO 9

100 \[\text{WRITE (6,4010) } \text{XN,ULLAGE,RADIUS,SPMGT,XMOLEC}\]

C 4010 FORMAT (1H4,9X,32H INITIAL NUMBER OF NETPOINTS = F3.0/ 1 10X,19H INITIAL ULLAGE = F7.3,7H METER/ 2 10X,16H TANK RADIUS = F6.3,7H METER/ 3 10X,30H TANK WALL SPECIFIC WEIGHT = F6.1,16H KG/CUBIC METER/ 4 10X,21H MOLECULAR WEIGHT = F3.1) \[\text{WRITE (6,4008)}\]

C 4008 FORMAT (1H4,9X,40H GAS TEMP,DEG K VS TIME,SECONDS/1X) \[\text{WRITE (6,4009) } (\text{TGAS(J)\times TIME(J)\times J=1\times MTGAS})\]

4009 FORMAT (F20.1, F25.1)

C \[\text{WRITE (6,4030)}\]

4030 FORMAT (1H4,9X,44H PRESSURE,M-NEWTON/SQ M VS TIME,SECONDS/1X) \[\text{WRITE (6,4009) } (\text{PDATA(J)\times TIME2(J)\times J=1\times MPDATA})\]

\[\text{WRITE (6,4031) } \text{FLOW RATE, M/SEC VS TIME,SECONDS / 11X}\]

\[\text{WRITE (6,4032) } (\text{FLOW(J)\times TIME3(J)\times J=1\times MFLOW})\]

4032 FORMAT (F20.4,F25.1)

\[\text{WRITE (6,4033)}\]
4033 FORMAT (1HL,9X,49H SATURATION TEMP,DEG K VS TIME,SECONDS /)
WRITE (6,4039) (TSAT(J),TIME4(J),J=1,MTSAT)
WRITE (6,4034)
4034 FORMAT (1HL,9X,44H BULK TEMP,DEG K VS TIME,SECONDS /)
WRITE (6,4009) (TBULK(J),TIME5(J),J=1,MTBULK)
WRITE (6,4035)
4035 FORMAT (1HL,9X,63H OUTSIDE HEATING RATE,JOULE/SQ M-SEC VS
1TIME,SECONDS /1X)
WRITE (6,4032) (GOUTD(J),TIME6(J),J=1,MCOUT)
WRITE (6,4036)
4036 FORMAT (1HL,9X,62H INSIDE HEATING RATE,JOULE/METER-SEC VS
1TIME,SECONDS /1X)
WRITE (6,4032) (WIND(J),TIME7(J),J=1,MIQIN)
WRITE (6,4013)
4013 FORMAT (1HL,9X,34H INITIAL TEMPERATURE-DEG. KELVIN /1HK,
19X,14H X COORDINATE,5X,18H WALL TEMPERATURE,5X,
217H GAS TEMPERATURE/1X)
WRITE (6,4014) (X(J),TW(J),T(J), J=1,N)
4014 FORMAT (F15.2,F22.4,F23.1)
IF (HCCNST) 50,5C,70
50 WRITE (6,4039)
4039 FORMAT (1HK, 46H HEAT TRANSFER COEFFICIENT WILL BE COMPUTED )
WRITE (6,4051) F1MULT, HEXP
C
4051 FORMAT (1HJ,10H HMULT = F6.4,FH *HEXP = F6.4)
GO TO 70
70 WRITE (6,4040)
4040 FORMAT (1HK, 33H CONSTANT HEAT TRANSFER COEFF = F6.2,24H WATTS/S
1M-METER-DEG K )
50 CONTINUE
WRITE (6,4050)
4050 FORMAT (1HL,9X,48H TANK RADIUS (METER) VS AXIAL DISTANCE (METER)
1)
WRITE (6,2051) (XRAD(J),XRAD(J), J=1,MRAD)
C
9 CONTINUE
C
IF (7CCNST) 13,13,15
13 WRITE (6,1042)
C
1042 FORMAT (1HK, 25H A REAL GAS IS ASSUMED )
GO TO 17
C
15 WRITE (6,1041)
C
1041 FORMAT (1HK, 27H AN IDEAL GAS IS ASSUMED )
C
17 CONTINUE
C
IF (XWLEC = 3.0) 22,22,23
22 WRITE (6,1011)
C
1011 FORMAT (1HK, 281. THE PRESSURANT IS HYDROGEN/1H1.9X, 9H RESULTS)
C       GC TC 25
C  23 WRITE (6,1012)
C 1012 FORMAT (1HK, 261. THE PRESSURANT IS HELIUM/1H1.9X, 9H RESULTS)
C       CONTINUE
C       RETURN
C       FAC
SUBROUTINE COMPRES (T,P,ZZ,ZL,Z2,XMCLEC)

C
C DIMENSION PX(17),TX(20),Z(20,17)
C
1 IF (3.0=XMCLEC) 3, 5, 5
77 = 1.0
71 = 1.0
72 = 1.0
C
RETURN
C
5 CONTINUE
C
COMPRESSIBILITY DATA (Z(T,P) VALUES COMPUTED FROM DATA OF
C NRS TN 120A)
C
DATA(PX(J),J=1,17)/ 14400., 2117., 2880., 4320., 5760., 7200.,
1 8640., 10080., 11520., 12960., 14400., 17280.,
7 20160., 23040., 25920., 28800., 33600.0/
C
DATA(TX(J),J=1,20)/ 30., 38., 42., 44., 50., 54., 58., 62.,
1 66., 70., 74., 78., 82., 86., 90., 100.,
7 120., 140., 160., 200.0/
C
DATA(Z(J,K),J=1,20),K=1,9) /
1 9.805, 8.092, 8.052, 8.391, 8.827, 8.963, 9.139, 9.273, 9.378, 9.462,
1 9.725, 7.257, 7.257, 7.257, 7.516, 8.380, 8.697, 8.528, 9.102, 9.236, 9.343,
1 9.739, 7.392, 7.392, 7.392, 8.002, 8.416, 8.708, 8.926, 9.092, 9.222,
C
DATA(Z(J,K),J=1,20),K=10,17) /
1 9.533, 6.533, 6.593, 6.593, 6.593, 6.593, 6.450, 7.589, 8.364, 8.641, 8.848,
1 6.735, 6.735, 6.735, 6.735, 6.735, 7.063, 7.723, 8.163, 8.484, 8.718,
2 7.952, 8.401, 8.603, 8.655, 8.933, 8.988, 9.563, 9.744, 9.943, 9.947,
1 5.126, 5.126, 5.126, 5.126, 5.126, 5.126, 5.126, 5.126, 5.126, 5.126,
2 7.792, 8.123, 8.412, 8.654, 8.823, 9.027, 9.524, 9.726, 9.836, 9.953,
IF (TX(20)-T) 11,13,13

11 Z7 = 1.0
71 = 1.0
Z2 = 1.0
RETURN

13 GO 17 J=1.19
JJ = 20 - J
IF (TX(JJ)-T) 15,15,17

15 NT = JJ
GO TO 19

17 CONTINUE
GO TO 11

19 IF(P-PX(J)) 11,23,23
23 GO 27 J=2.17
IF (P-PX(J)) 25,25,27

25 NP = J-1
GO TO 31

27 CONTINUE
GO TO 11

31 ZA = Z(T+NP)+(P-PX(NP))/(FX(NP+1)-PX(NP))*Z(NP+1)-Z(NP))
ZR = Z(NP+1, NP)+(P-PX(NP))/(PX(NP+1)-PX(NP))*
1 (Z(NP+1, NP+1)-Z(NP+1, NP))
ZZ = ZA + (T-TX(NP))/TX(NP+1)-TX(NP))*ZB-ZA
OZCT = (ZB-ZA)/(TX(NP+1)-TX(NP))
Z1 = ZZ+T*CZDT

OZDP = (Z(NP+1)-Z(NP)+1, NP)/(TX(NP+1)-TX(NP))*
1 (Z(NP+1, NP+1)-Z(NP+1, NP)-Z(NP+1, NP+1)+Z(NP, NP))]/(PX(NP+1)-PX(NP))

Z2 = ZZ-P*DZDP
RETURN

FAC
SUBROUTINE COEFF (T,T'TT,P,X,L,H,PRM,CCNST,HCNVT,HEXP,XMOLEC)

DIMENSION VIY(2,7),VIX(2,7),COY(2,7),COX(2,7)

HYDROGEN VISCOSITY DATA ((LB)(SEC)/(SQ FT))
(C DATA FROM HILSENRATH, ET AL)
DATA(VIY(1,1),VIX(1,1),J=1,7)/ 1.064E-7,1.8, 600.5E-7,108, 1.001E-7,2.16, 1.324E-7,3.24, 1.654E-7,4.50, 1.954E-7,5.76,
   2.195E-7,6.84/

HYDROGEN THERMAL CONDUCTIVITY DATA (BTU/(SEC)(FT)(DEG R/FT))
(C DATA FROM HILSENRATH, ET AL)
DATA(COY(1,1),CCX(1,1,J=1,7)/ 1.187E-5,18, 6780E-5,108, 1.268E-5,216, 1.871E-5,3.24, 2.505E-5,4.50, 3.075E-5,5.76,
   3.520E-5,6.84/

HELIUM VISCOSITY DATA (LB-SEC/SQ FT) (VANCE AND DUKE)
DATA (VIY(2,1),VIX(2,1),J=1,7)/ 3.76E-7,10, 668E-7,30, 1.002E-7, 60, 1.420E-7,100, 2.257E-7,200, 3.528E-7,400, 6.075E-7,800/

HELIUM THERMAL CONDUCTIVITY DATA (BTU/SEC-FT-DEG R) (VANCE AND DUKE)
DATA (COY(2,1),CCX(2,1,J=1,7)/ 1.806E-5,10, 375E-5,30, 597E-5, 60, 834E-5,100, 1.277E-5,200, 2.500E-5,400, 3.445E-5,800/

M = 5*XMOLEC
R = 1545.4
C = XMOLEC*P/R

TAV = 0.5*(T+T'TT)**2
RHOS0 = (C/TAV)**2

DO 1 J=2,7
   IF (TAV-VIX(M,J)) 3,3,7
   3 VISC = VIY(M,J-1)+(TAV-VIX(M,J-1))/(VIY(M,J)-VIX(M,J-1))
      1 (VIY(M,J)-VIX(M,J-1))
      GO TO 9
   7 CONTINUE
   VISC = VIY(M,7)
   9 DO 15 J=2,7
      IF (TAV-COX(M,J)) 11,11,15
      11 CGND = COY(M,J-1)+(TAV-COX(M,J-1))/(COX(M,J)-CCX(M,J-1))
         1 (CGY(M,J)-COY(M,J-1))
         GO TO 17
      15 CONTINUE
      CGND = COY(M,7)
      17 CALL SPHEAT (TAV,TAV,CP,CP*,XMOLEC)

74
TCIff = AHS(TTT-T)
IF (TCIff-1.0) 19,23,23
19 TCIff = 1.0
23 IF (ZCCAST) 27,27,25
25 HETA = 1.0/TAV
G0 TO 29
27 CALL CCMPS1(TAV*P*Z1*Z2*XMCLEC)
BETA = Z1/Z/TAV
29 XHCLD = ALOG(XL**3*RHOSQ*CP*TCIff/VISC/CGND*BETA)
X+CLD = HEXP*XHOLD
X+CLD = HEXP(XHOLD)
C
M = HMULT*(CGND/XL)*XHOLD
PVC = CGND * ( 1.0/(32.17*VISC)**0.8
PDL = (CP * VISC/CGND * 32.17)**0.333
PRAM = PDL * PVC
C
RETURN
C
END
SUBROUTINE INTERP (Y,X,M,ARG,ANS)
C
C
DIMENSION Y(100),X(100)
C
1  IF (M-1) 3.5.7
3  RETURN
C
5  ANS = Y(1)
RETURN
C
7  IF (ARG-X(1)) 5.5.9
C
9  DO 13 J=2,M
11  IF(ARG-X(J)) 11.11.13
C
11  ANS = Y(J-1)+(ARG-X(J-1))/(X(J)-X(J-1))*(Y(J)-Y(J-1))
RETURN
C
13  CONTINUE
ANS = Y(M)
C
RETURN
C
END
DO 201 J=1,NP
   X(J) = X(J)*0.3048
   TP(J) = TP(J)/1.8
   TwP(J) = TP(J)/1.8
201 CONTINUE

GAS = GAS * 0.45359237
RT = C * 1054.3503
V(2) = V(2)*0.3048
COLA = CGTR * 1054.3503
OBLCK = GASCHK * 0.45359237
GSRATE = GSRATE * 0.45359237
WIN = CIN * 3459.1475
WRITE (6,300) TIME,GAS,RT,V(2)
300 FORMAT (1HL/1HL,5H TIME = F6.1,9H SECONDS,5X,16H GAS SUPPLIED =
   1F7.4,5H KILOGRAM,1X,17H HEAT TO WALL = E11.4,6H JOULE,1X,14H INL
   2ET VEL = F6.4,1CH METER/SEC)
   WRITE (6,305) COLA,OBLCK,GSRATE,WIN
305 FORMAT (1HK,16H HEAT TO LIQ = E12.5,2H J,1X,17H CHECK ON GAS = F
   17.3,4H KG,1X,13H GAS FLOW = F7.4,8H KG/SEC,1X,16H HEAT TO HARD
   2= E11.4,10H J/(M-SEC))
   WRITE (6,310)
310 FORMAT (1HK,10H X, METER,1X,13H WALL TEMP-K,14H GAS TEMP-K,3X
   1.10H X, METER,1X,13H WALL TEMP-K,14H GAS TEMP-K,3X,10H X, ME
   2TER,1X,13H WALL TEMP-K,14H GAS TEMP-K/1X)
   WRITE (6,311) X(J),ThP(J),TP(J),J=1,NP)
311 FORMAT (F10.4,F12.1,F12.1,F17.4,F12.1,F12.1,F17.4,F12.1,F12.1)
210 CONTINUE
   DO 211 J=1,NP
   X(J) = X(J)*0.3048
   TP(J) = TP(J) * 1.8
   TwP(J) = TP(J) * 1.8
211 CONTINUE
   GAS = GAS / 0.45359237
   V(2) = V(2)*0.3048
   CIN = CIN/3459.1475
C
C
RETURN
C
END
SUBROUTINE WRITE2

DIMENSION TGAS(100), TIME1(100), PDATA(100), TIME2(100), FLCH(25),
1 TIME3(25), TSAT(501), TIME4(50), TBULK(25), TIMES(25), COUTD(25),
2 TIME6(25), QIND(25), TIME7(25), ZAV(250), TWIND(100), DIST1(100),
3 TGINO(100), DIST2(100), X(250), T(250), TP(250), TWP(250)
4, V(250), WP(250), CP(250), CPW(250), H(250), Z(250), Z2(5250),
5 RAD(250), AREA(250), YRAD(250), XRAD(250), DRCX(250), TEST(2650)
DIMENSION CS(250), C9(250), YTICK(250), XXT(250), TICK(250), XR(3)
1, AQ(3)

COMMON X,T,TP,TWP,V,CP,CPW,TGAS,TIME1,MTGAS,PDATA,TIME2,MPDATA,
1 FLOW, TIME3,MFLOW,TSAT,TIME4,MTSAT,TBULK,TIMES,MTBULK,QOUTD,TIME6,M
2 QOUTD,QIND,TIME7,MQIN,N,XP,XT,ULLAGE,RADIUS,TLID,SPWGT,XMOLEC,GSSTAR
3 T,HCNOST,TIME,GAS,Q,GASCHK,GSRATE,D,T,ZCONST,EST,HEMUL,HEXP,YRAD,XRAD
4,MRAI,DQ,QIN,UNUMS,TDWIND,DIST1,MTWIN,TGINO,DI ST2,MTGIN,DIA,
5 STADD,YTICK,XTT,MTICK

IF(UNUMS .GT. 0.) GO TO 200
WRITE (6,1) TIME,GAS,Q,V(1)

WRITE (6,2) GASCHK,GSRATE,V(NP)

WRITE (6,3)

WRITE (6,4) (X(J),TWP(J),TP(J),J=1,N)

RETURN

200 CONTINUE
DO 201 J=1,N
X(J) = X(J)*0.3048
TP(J) = TP(J)/1.8
TWP(J) = TWP(J)/1.8

201 CONTINUE
GAS = GAS * 0.4535524
Q = Q * 1054.3503
V(1) = V(1) * 0.3048
GASCHK = GASCHK * 0.4535924
GSRATE = GSRATE * 0.4535524
WRITE (6,300) TIME,GAS,Q,V(1)
WRITE (6,305) GASCHK,GSRATE,V(NP)
WRITE (6,310)
WRITE (6,311) (X(J),TWP(J),TP(J),J=1,N)

210 CONTINUE
DO 211 J=1,N
X(J) = X(J)/.3048
TP(J) = TP(J) * 1.8
TWP(J) = TWP(J) * 1.8

211 CONTINUE
GAS = GAS/4535524
Q = Q/1054.3503

79
V(1) = V(1)/.3048
GASCHK = GASCHK/.4535924
GSPATE = GSPATE/.4535924
RETURN

C
C
C

1 FORMAT (1HL/1HL,9H TIME = F6.2,9H SECONDS,5X,17H GAS SUPPLIED =
1 F7.4,5H LBS,5X,17H HEAT TO WALL = F8.1,5H BTU,5X,14H INLET VE
2L = F6.4,10H FEET/SEC)

2 FORMAT (1HK,16X,17H CHECK ON GAS = F7.3,5H LBS,5X,13H GAS FLOW
1 L = F7.4,5H LBS/SEC,5X,15H OUTLET VEL = F6.4,10H FEET/SEC)

3 FORMAT (1HK,10H X, FEET,2X,11H WALL T(R),11H GAS T(R),7X,10H
1 X, FEET,2X,11H WALL T(R),11H GAS T(R),7X,10H X, FEET,2X,11H
2 WALL T(R),11H GAS T(R)/1X)

4 FORMAT (F10.2,F12.1,F12.1,F17.2,F12.1,F12.1,F12.1,F12.1,F12.1)

300 FORMAT (1HL/1HL,9H TIME = F6.1,9H SECONDS,5X,16H GAS SUPPLIED =
1 F7.4,5H KILOGRAM,1X,17H HEAT TO WALL = E11.4,6H JOULE,1X,14H INL
2ET VEL = F6.4,10H METER/SEC)

305 FORMAT (1HK,16X,17H CHECK ON GAS = F7.3,4H KG,6X,13H GAS FLOW =
1 F7.4,9H KGS/SEC,5X,15H OUTLET VEL = F6.4,11H METER/SEC)

310 FORMAT (1HK,10H X, METER,1X,13H WALL TEMP-K,14H GAS TEMP-K,3X
1,10H X, METER,1X,13H WALL TEMP-K,14H GAS TEMP-K,3X,10H X, ME
2TER,1X,13H WALL TEMP-K,14H GAS TEMP-K/1X)

311 FORMAT (F10.2,F12.1,F12.1,F17.2,F12.1,F12.1,F12.1,F17.2,F12.1,F12.1)
END
REFERENCES


Figure 1. - Analytical model. Coordinate system is positive in the downward direction from $x = 0$ at $N_1$ to $x = n$ at the interface $N_2$.

Figure 2. - Typical curve showing tank pressure as function of time during initial pressurization period.
Three cards specify problem definition

NAMELIST: basic parameters - configuration

See 15 data entries - input variables

Define first Δtime

Interpolate ullage temperatures

Calculate volume element characteristics

Complete problem identification and initial calculations

Find temperatures at new time

Compute velocity distribution based on initial condition

Compute heat transfer to wall, liquid, and hardware

If time limit is exceeded, back up. Print results.

End of time

Yes

Interpolate compressibility factors

Calculate velocity at new time

Compute gas flow rate and total gas added

Advance the interface one net point

P r i n t results.

Call subroutines

Figure 3. - Logic diagram of expulsion program.
Figure 4. - Logic diagram of ramp program.
Figure 5. - Flow diagram showing temperature-velocity iteration in energy and continuity equations.