Rockwell Aerospace

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ZERO-G THERMODYNAMIC VENTING SYSTEM (TVS) PERFORMANCE PREDICTION PROGRAM

PREPARED BY

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VEHICLE AND SYSTEMS DESIGN

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ABSTRACT

This report documents the Zero-g Thermodynamic Venting System (TVS) performance prediction computer program. The zero-g TVS is a device that destratifies and rejects environmentally induced zero-g thermal gradients in the LH_2 storage transfer system. A recirculation pump and spray injection manifold recirculates liquid throughout the length of the tank, thereby destratifying both the ullage gas and liquid bulk. Heat rejection is accomplished by the opening of the TVS control valve which allows a small flow rate to expand to a low pressure thereby producing a low temperature heat sink which is used to absorb heat from the recirculating liquid flow. The program was written in FORTRAN 77 language on the HP-9000 and IBM PC computers. It can be run on various platforms with a FORTRAN compiler.

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SECTION 1

INTRODUCTION

1.1 Purpose

The purpose of the zero-g thermodynamic venting system (TVS) model is to define the pressure level requirements, propellant loss due to venting, total pump power consumption, venting system operation duration and frequency as a function of liquid level and acceleration environment.

1.2 Problem Description

Long-term storage of subcritical cryogens in space is subjected to thermal stratification which is more severe than experienced in a 1-g environment due to the absence of gravity-induced body forces. If left uncontrolled, the thermal gradients result in excessive tank pressure rise and formation of liquid/vapor mixtures within the liquid bulk, liquid acquisition device, and propellant transfer lines. A subsystem is therefore needed to reduce the thermal gradient to acceptable levels, and reject the environmental heat leakage in an efficient manner.

1.3 Areas of Application

This program is designed to predict the tank ullage pressure and temperature, pump flow rate and power consumption, propellant loss due to venting, venting duration and frequency for different liquid levels, accelerations and heat leak rates. It can also be used to model tank chill down and liquid fill in zero-g and one-g environments. The program therefore has general applicability in areas of long-term cryogenic fluid storage and transfer in space and on the ground.

1.4 Description of the Physical Model

The zero-g TVS concept, shown in Figure 1.1, has been defined to operate in a self-induced, forced convection environment. It includes a recirculation pump, located external to the tank, to flow liquid from the tank, a spray manifold and injection tube to mix and destratify the ullage and liquid bulk, a heat exchanger to absorb heat from the tank, and an overboard vent line to reject the heat. The concept operates in the following manner. When the vent pressure level is reached, the recirculation pump is activated, resulting in liquid flow through the spray injection manifold which destratifies the liquid bulk and ullage gas through forced convection. When the fluid bulk temperature reaches a predetermined level, the vent valve is opened, resulting in a temperature drop of the vent flow by isenthalpic expansion. This liquid is used to absorb heat from the recirculation flow via the heat exchanger, and subsequently vented overboard as a gas.

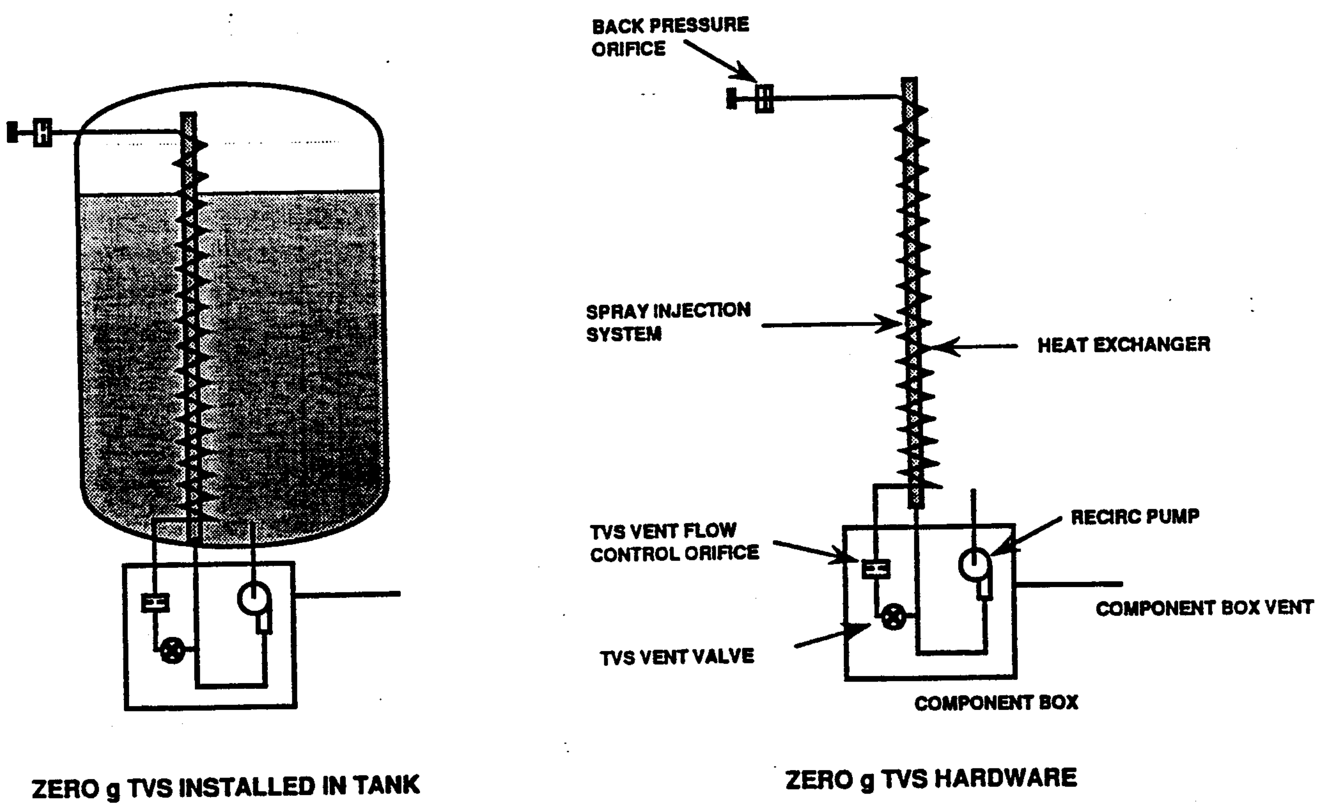


Figure 1.1 Zero-g Thermodynamic Venting System (TVS) Concept

SECTION 2

ANALYTICAL MODEL DESCRIPTION

The zero-g TVS model consists of the thermal-fluid models of the heat exchanger, spray manifold and injection tubes, recirculation pump, and tank. These models were developed and verified independently before they were integrated into the transient TVS model. Following is a description of each model.

2.1 Heat Exchanger Model

The heat exchanger model is based on the generalized two-phase cryogenic propellant dump model developed to evaluate the Space Shuttle Main Propulsion System (MPS) cryogenic propellant dump/vacuum inerting operations performance (Ref. 29). It is a multi-node finite difference model that simulates two-phase flow in a quasi steady-state mode.

The model uses the fluid properties at the inlet of the spray manifold as the input to the first node. With one of the inlet fluid property, namely the total enthalpy of the fluid at the inlet, the total enthalpy at the exit can be calculated based on the First Law of Thermodynamics. The total enthalpy at the exit, and an assumed mass flow rate are used to determine the exit static pressure. The exit static pressure is determined by an iterative process: with the flow assumed choked at the exit, the exit static pressure is increased incrementally until the maximum entropy is achieved (sonic flow), or when it becomes greater than the back pressure (subsonic flow). From the calculated exit pressure, the other exit fluid properties of the last node, the total pressure loss between the inlet and outlet can then be calculated and the inlet fluid properties can be determined.

The following sections will provide the equations used in the heat exchanger model.

2.1.1 Fluid Quality At Heat Exchanger Outlet

The outlet static pressure is calculated, assuming choked or sonic flow, where the entropy point is maximum. The following equations are solved simultaneously for the liquid quality of the fluid at the outlet

$$h_O = h_I + \frac{\dot{Q}}{\dot{m}} + \Delta Ha \quad (2.1.1)$$

$$V_O = \frac{\dot{m}}{\rho_O A} \quad (2.1.2)$$

$$\rho_O = \frac{1}{\frac{1}{(\rho_L)_O} + Y_O\left[\frac{1}{(\rho_V)_O} - \frac{1}{(\rho_L)_O}\right]} \quad (2.1.3)$$

$$h_O = (1 - y_O)(h_L)_O + Y_O(h_V)_O + \frac{V_O^2}{2g_c J} \quad (2.1.4)$$

where the following fluid properties are based on the outlet static pressure

$(h_L)_O$ = the outlet liquid enthalpy
$(h_V)_O$ = the outlet vapor enthalpy
$(\rho_L)_O$ = the outlet liquid density
$(\rho_V)_O$ = the outlet vapor density

$\dot{Q}$ = total heat-transfer rate to a specific node
ΔH = change in height of the line between inlet and outlet
$a = \frac{g}{g_c}$ = acceleration
h_O = total enthalpy at the outlet
ρ_O = total density at the outlet
V_O = fluid velocity at the outlet
Y_O = fluid quality at the outlet

With the outlet quality, the total entropy then can be calculated using the following equation

$$\left\{(S)_O = (1 - y_O)(S_L)_O + Y_O(S_V)_O\right\}_{max} \tag{2.1.5}$$

where $(S_L)_O$ = the outlet liquid entropy
$(S_V)_O$ = the outlet vapor entropy

Iteration of the above outlet equations can be performed to obtain the maximum entropy point and the outlet static pressure.

2.1.2 Two-Phase Pressure Loss in the Heat Exchanger

To calculate the two-phase pressure loss (momentum and friction) between the inlet and outlet of the heat exchanger, the Lockhart-Martinelli correlation is used. The outlet pressure is

$$P_O = (P_S)_O + (P_D)_O \tag{2.1.6}$$

The total pressure loss term is further defined as

$$\Delta P_T = \Delta P_m + \Delta P_f \tag{2.1.7}$$

where ΔP_m =pressure loss due to momentum change
ΔP_f = pressure loss due to frictional forces

The momentum pressure loss is defined as

$$\Delta P_m = \frac{\dot{m}}{g_c A}(V_O - V_I) \tag{2.1.8}$$

The frictional pressure loss is defined as

$$\Delta P_f = \frac{144K}{2\bar{\rho}_L g_c}\left[\frac{\dot{m}(1-\bar{Y})}{A}\right]^2 \Phi_L^2 \qquad (2.1.9)$$

where $K = \left(f\frac{L}{D}\right)$ = the line loss coefficient

$\bar{\rho}_L$ = the average liquid density between the inlet and outlet

$\bar{Y}$ = the average total liquid quality between the inlet and outlet

$\Phi_L = f(X)$ is the Lockhart-Martinelli correlation factor

The Lockhart-Martinelli correlation is approximately defined as

$$\Phi_L^2 = 1 + \frac{1}{X} + \frac{1}{X^2} \qquad (2.1.10)$$

X is defined as

$$X = \left(\frac{\bar{\mu}_L}{\bar{\mu}_V}\right)^{0.1}\left(\frac{1-\bar{Y}}{\bar{Y}}\right)^{0.9}\left(\frac{\bar{\rho}_V}{\bar{\rho}_L}\right)^{0.5} \qquad (2.1.11)$$

where $\bar{\rho}_V$ = the average vapor density between the inlet and outlet

$\bar{\mu}_L$ = the average liquid viscosity between the inlet and outlet

$\bar{\mu}_V$ = the average vapor viscosity between the inlet and outlet

2.1.3 Forced Convection Heat -Transfer Model

The heat-transfer equations used in the steady-state model are as follows

Two-phase heat transfer using the correlation proposed by John C. Chen (1963)

$$\frac{Q}{A} = [h_{FC}F + h_{FZ}S]\Delta T \qquad (2.1.12)$$

where

$$h_{FC} = 0.023\left(\frac{DG}{\mu_L}\right)^{0.8}\left(\frac{\mu_L C_L}{k_L}\right)^{0.4}\left(\frac{k_L}{D}\right) \qquad (2.1.13)$$

$$h_{FZ} = 0.00122\frac{k_L^{0.79} C_L^{0.45} \rho_L^{0.49} g_c^{0.25} \Delta T^{0.24} \Delta P^{0.75}}{\sigma^{0.5} \mu_L^{0.29} \lambda^{0.24} \rho v^{0.24}} \qquad (2.1.14)$$

$$F = f(X_{tt}) \tag{2.1.15}$$

$$Re_L = \frac{DG(1-Y)}{\mu_L} \tag{2.1.16}$$

$$\Delta T = T_W - T_S \tag{2.1.17}$$

$$\Delta P = \frac{\Delta T \rho_V \lambda}{T_S} \tag{2.1.18}$$

The single-phase heat-transfer correlation used in the model (liquid and superheated gas)

$$\frac{Q}{A} = h\Delta T \tag{2.1.19}$$

$$h = 0.023\left(\frac{DG}{\mu_L}\right)^{0.8}\left(\frac{\mu_L C_L}{k_L}\right)^{0.4}\left(\frac{k_L}{D}\right) \tag{2.1.20}$$

2.1.4 Spray Temperature

To shorten the run time of the zero-g TVS model, an alternative was provided to calculate the spray temperature as a function of the liquid subcooling and tank pressure. This is obtained from an energy balance between the hot and cold fluids of the heat exchanger

$$T_S = T_P - \frac{\dot{m}_V}{\dot{m}_P}\frac{\Delta h}{c_{PL}} \tag{2.1.21}$$

where T_S is the spray temperature
T_P is the pump temperature
$\dot{m}_V$ is the vent flow rate
$\dot{m}_P$ is the pump flow rate
Δh is the heat absorption capability of the vent flow
c_{PL} is the heat capacity of the liquid

The TVS vent flow rate and heat absorption capability were calculated as a function of the liquid subcooling and tank flow rate and are shown in Figs. 2.1 and 2.2, respectively. This data is provided as a table look-up to the zero-g TVS model.

2.2 Spray Manifold and Injection Tube Model

Fluid is recirculated from the tank to the spray manifold and injection tubes where it is sprayed into the ullage and liquid. A one-dimensional, incompressible fluid dynamic model was developed to determine the pressures in the spray manifold and injection tubes, and to calculate the spray flow rates and velocities leaving the injection orifices. Following is a description of the model.

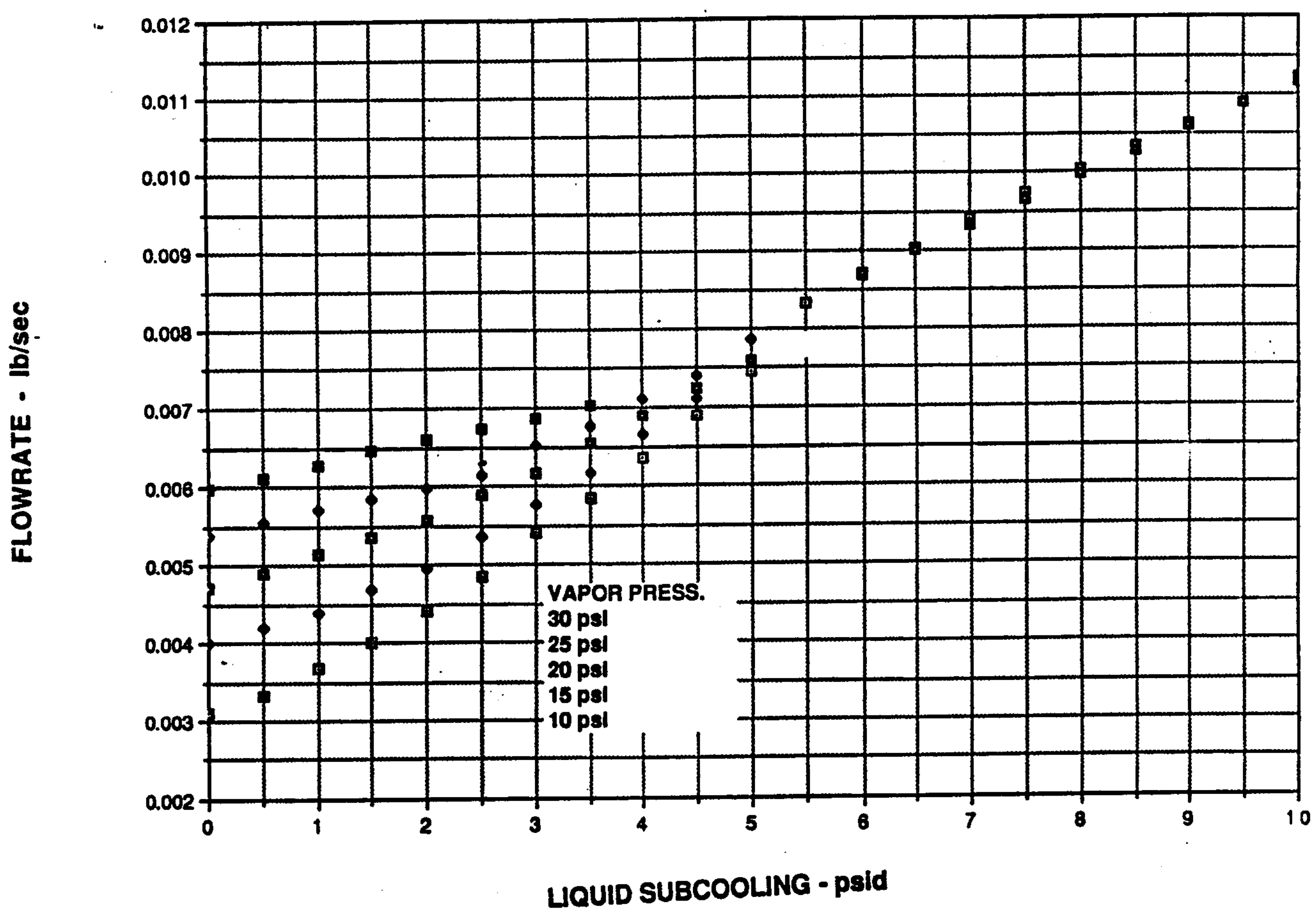


Figure 2.1.1 TVS Vent Flow Rate as a Function of Liquid Subcooling

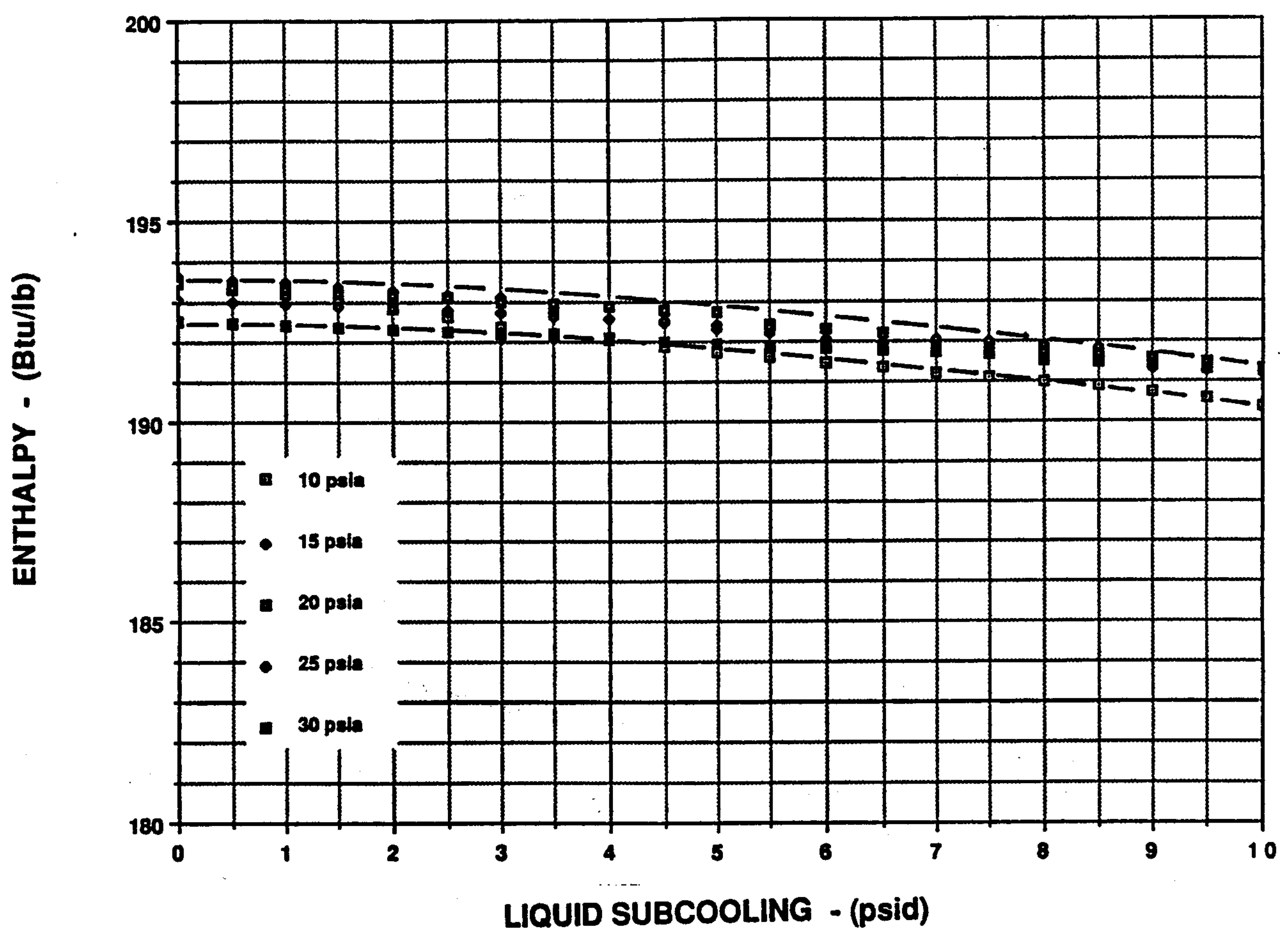


Figure 2.1.2 Heat Absorption Capability of Vent Flow as a Function of Liquid Subcooling

2.2.1 Spray Manifold

The spray manifold calculates the pressure drop through the manifold and determines the pressure at the inlet of the spray injection tubes (Fig. 2.2.1). The model accounts for frictional pressure drop in the manifold, and pressure losses resulting from flow turning and contraction at the exit of the manifold. From Bernoulli equation

$$\frac{(p_{SM})_i}{\rho} + \frac{V_{SM}^2}{2g_c} + az_i = \frac{(p_{SM})_o}{\rho} + \frac{V_{SM}^2}{2g_c} + az_o + (h_L)_{SM} \qquad (2.2.1)$$

where $(p_{SM})_i$ is the spray manifold inlet pressure
$(p_{SM})_o$ is the spray manifold outlet pressure
V_{SM} is the velocity in the spray manifold
z_i, z_o are the inlet and outlet elevations
$a = \frac{g}{g_c}$ is the acceleration

The total head loss is defined as

$$(h_L)_{SM} = K_{SM} \frac{V_{SM}^2}{2g_c} \qquad (2.2.2)$$

The total loss coefficient K_{SM} is given by

$$K_{SM} = (K_f)_{SM} + (K_b)_{SM} + (K_c)_{SM} \qquad (2.2.3)$$

and includes

$$(K_f)_{SM} = f_{SM}\left(\frac{L}{D}\right)_{SM} \quad \text{(spray manifold frictional loss coefficient)} \qquad (2.2.4a)$$

$$(K_b)_{SM} = f_{SM}\left(\frac{L_e}{D}\right) \quad \text{(90-degree bend resistance at the manifold exit)} \qquad (2.2.4b)$$

$$(K_c)_{SM} = 0.5\left[1-\left(\frac{D_{SI}}{D_{SM}}\right)^2\right] \quad \text{(sudden contraction at the manifold exit)} \qquad (2.2.4c)$$

In Eqs. 2.2.4,
$L_{SM} = z_o - z_i$ is the spray manifold length
L_e is the bend equivalent length
D_{SI} is the spray injection tube ID
D_{SM} is the spray manifold ID
f_{SM} is the friction coefficient in the spray manifold obtained from

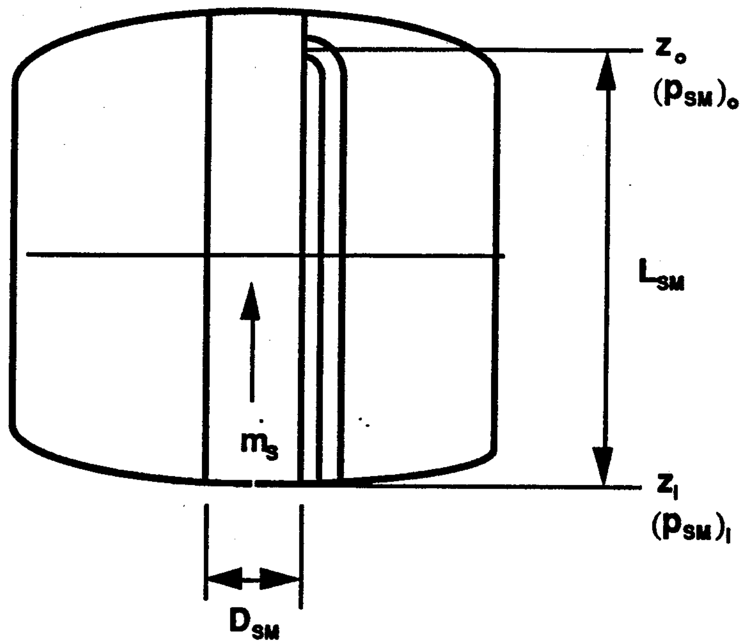


Figure 2.2.1 Spray Manifold Model

$$f_{SM} = \frac{1}{4\left\{\log_{10}\left[\frac{\varepsilon / D}{3.7} + \frac{2.51}{Re\sqrt{0.0056 + \frac{0.5}{(Re)^{0.32}}}}\right]\right\}^2}, Re > 3000 \qquad (2.2.5)$$

$$f_{SM} = \frac{64}{Re}, Re \leq 3000$$

Eq. 2.2.1 can be solved for the spray manifold outlet pressure

$$(p_{SM})_o = (p_{SM})_i - K_{SM} q_{SM} - \rho a L_{SM} \qquad (2.2.6)$$

where the dynamic pressure q_{SM} in the spray manifold is given by

$$q_{SM} = \rho \frac{V_{SM}^2}{2g_c} = \frac{1}{2\rho g_c}\left(\frac{\dot{m}_S}{A_{SM}}\right)^2 \qquad (2.2.7)$$

2.2.2 Spray Injection Tube

The spray injection tube model is a multinode model which assigns a node to each orifice (Fig 2.2.2). Bernoulli equation is first applied to find the pressure downstream of the inlet 90 degree bend of the injection tube (pressure at the inlet of the straight section)

$$p_i = (p_{SM})_o - q_i (K_b)_{SI} \qquad (2.2.8)$$

In Eq. 2.2.8, $(K_b)_{SI}$ is the 90 degree bend resistance and q_i is the inlet dynamic pressure given by

$$q_i = \frac{1}{2\rho g_c}\left(\frac{\dot{m}_i}{A_{SI}}\right)^2 \qquad (2.2.9)$$

where A_{SI} is the flow area of an injection tube and $\dot{m}_i$ is the mass flow rate in each tube (equal to the flow rate in the manifold divided by the number of tubes).

The straight section of the spray injection tube is divided into 45 equal nodes corresponding to the 45 spray orifices. Each node has a pressure and a mass flow rate at the inlet (i), center, and outlet (o) of the node. The outlet pressure and mass flow rate of one node is therefore the inlet pressure and mass flow rate of the preceding node

$$(p_i)_n = (p_o)_{n-1} \qquad (2.2.9a)$$

$$(\dot{m}_i)_n = (\dot{m}_o)_{n-1} \qquad (2.2.9b)$$

Bernoulli equation is applied successively from inlet to center, and from center to outlet to determine the pressure at the center and outlet of a node n.

From inlet to center,

$$p_n = (p_i)_n + \rho a \frac{\Delta z}{2} - K_f (q_i)_n \tag{2.2.10}$$

where Δz is the nodal length and K_f is the frictional loss coefficient.

From center to outlet,

$$(p_o)_n = p_n + \rho a \frac{\Delta z}{2} - K_f (q_o)_n \tag{2.2.11}$$

where the outlet dynamic pressure $(q_o)_n$ of node n is given by

$$(q_o)_n = \frac{1}{2\rho g_c} \left[\frac{(\dot{m}_o)_n}{A_{SI}} \right]^2 \tag{2.2.12}$$

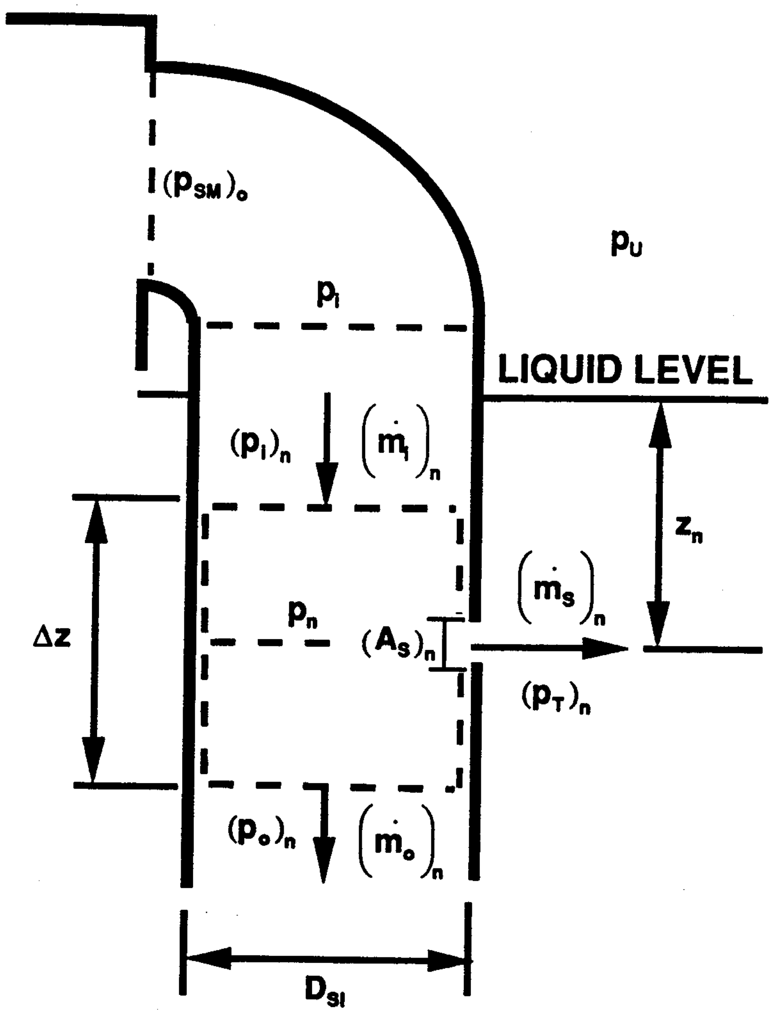


Figure 2.2.2 Spray Injection Tube Model

The mass flow rate at node n outlet $\left(\dot{m}_o\right)_n$ is obtained from

$$\left(\dot{m}_o\right)_n = \left(\dot{m}_i\right)_n - \left(\dot{m}_S\right)_n \tag{2.2.13}$$

$\left(\dot{m}_S\right)_n$ in Eq. 2.2.13 is the spray flow rate calculated from an incompressible flow relation

$$\left(\dot{m}_S\right)_n = \left(A_S\right)_n \sqrt{\frac{2\rho g_c\left[p_n - \left(p_T\right)_n\right]}{K_S}} \tag{2.2.14}$$

In Eq. 2.2.14, K_S is the loss coefficient of an orifice in a duct given by

$$K_S = \left[\frac{1}{C_d} - \frac{A_S}{A_T}\right]^2 \tag{2.2.15}$$

where C_d is the discharge coefficient (C_d=0.8), and A_S/A_T is the ratio of the orifice to the tank area (A_S/A_T=0). Thus, K_s is determined to be 1.56.

The tank pressure $\left(p_T\right)_n$ at node n is calculated as

$$\begin{aligned} \left(p_T\right)_n &= p_U && \text{(ullage nodes)} \\ &= p_U + \rho_L g z_n, && \text{(liquid nodes)} \end{aligned} \tag{2.2.16}$$

where z_n is the distance from the liquid surface to node n.

2.2.3 Spray Manifold and Injection Tube Model Algorithm

The flow chart of the spray manifold and injection tube model is given in Section 3.1.2. The model starts out with a guess of the pump flow rate and calculates the pressures and mass flow rates at each node. Knowing the pressure and spray flow rate of the last node N, it then calculates the tank pressure corresponding to that last node by solving the incompressible flow relation of Eq. 2.2.14

$$\left(p_T\right)_{N,calc} = p_N - \frac{K_S}{2\rho g}\sqrt{\frac{\left(\dot{m}_s\right)_N}{\left(A_s\right)_N}} \tag{2.2.17}$$

Next, $\left(p_T\right)_{N,calc}$ is compared with $\left(p_T\right)_N$ obtained from the ullage pressure and hydrostatic head (Eq. 2.2.16). If they are not equal within a specified tolerance (0.001 psi), a new guess of the pump flow rate will be made and the process repeated until convergence on $\left(p_T\right)_N$ is achieved.

2.3 Recirculation Pump Model

The zero-g TVS LH2 recirculation pump is a centrifugal pump which is a constant output pressure device since it imparts kinetic pressure to the fluid due to rotation. Consequently, the pump pressure rise (Δp_p) is only a function of rotation speed (N) and tip velocity (U)

$$U = \frac{\pi D_m N}{720} \tag{2.3.1}$$

where D_m is the impeller diameter.

The fluid horsepower required by the pump flow ($\dot{m}$), raised to Δp_p pressure, is equal to

$$HP_o = \frac{\dot{m} \Delta p_P}{\eta_P \rho} \tag{2.3.2}$$

where η_P is the pump mechanical efficiency.

The pump operating speed then changes as a result of the energy absorbed by the fluid and the power supplied to the pump through a power source. The instantaneous rate of change in pump operating speed is

$$\frac{dN}{dt} = \left(\frac{HP_I - HP_O}{I_P N} \right) 6.0185x10^5 \tag{2.3.3}$$

where I_P is the polar moment of inertia of the pump and HP_I is the input power to the pump.

Integration of the pump acceleration results in the pump speed at any given time

$$N = (N)_{IC} + \int \left(\frac{dN}{dt} \right) dt \tag{2.3.4}$$

By specifying the initial pump speed at zero, a pump start transient may be simulated.

A pump head-flow curve was provided by the pump manufacturer, Barber-Nichols Engineering Co. (Fig. 2.3.1). The curve was fitted with a polynomial function to give the head coefficient (ψ) as a function of the flow coefficient (ϕ)

$$\psi = 0.52889 - 1.4956\phi + 47.819\phi^2 - 485.93\phi^3 + 1633.9\phi^4 - 1833.5\phi^5 \tag{2.3.5}$$

The flow coefficient ϕ is obtained from test data in terms of the flow rate (in gpm) and the pump speed as

$$\phi = \frac{gpm}{0.0531N} \tag{2.3.6}$$

The pump head is calculated from the pump speed and head coefficient

$$H = 4.507x10^{-6} N^2 \psi \tag{2.3.7}$$

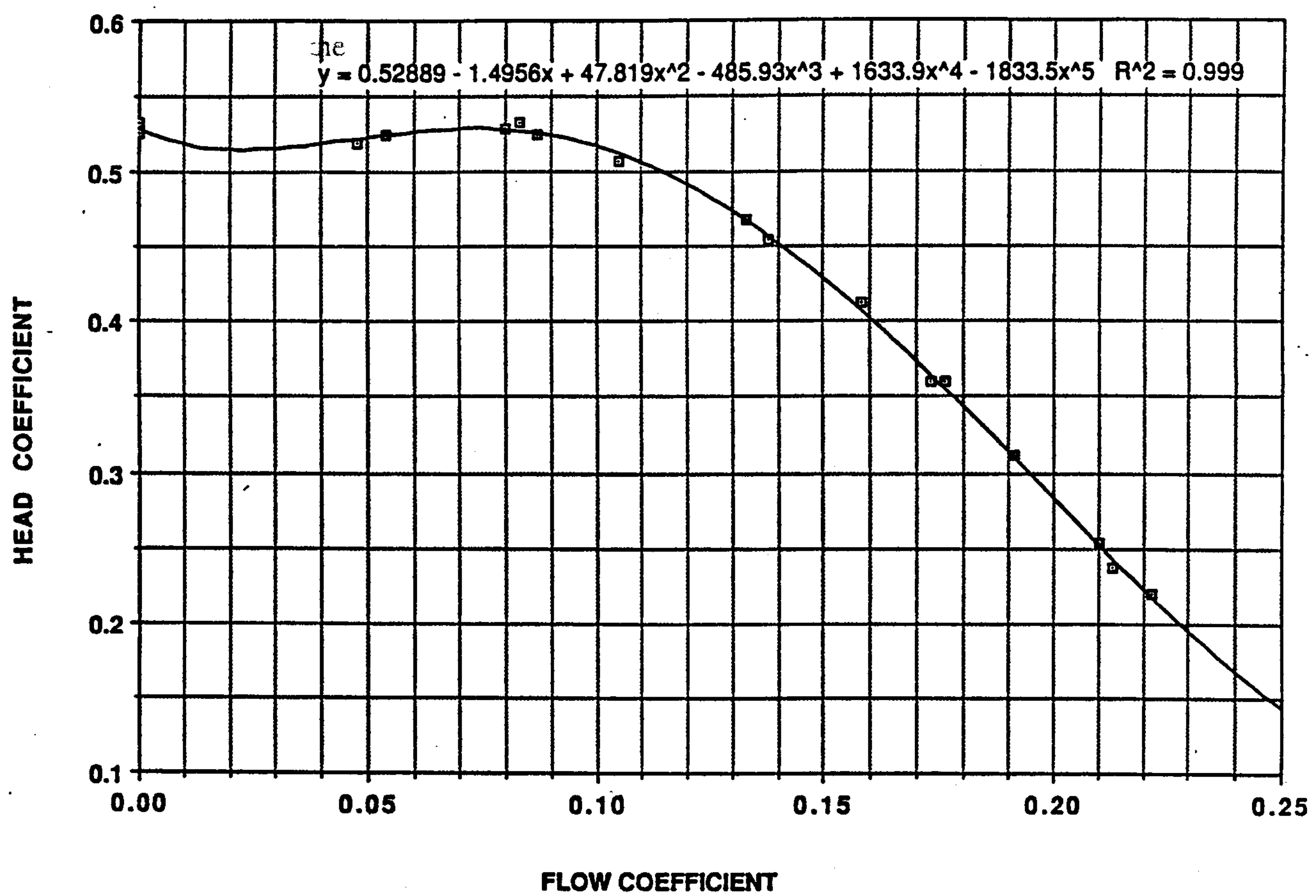


Figure 2.3.1 LH_2 Recirculation Pump Head-Flow Curve

The pump pressure rise is then obtained as

$$\Delta p_p = \frac{\rho H}{144} \qquad (2.3.8)$$

The lumped pump model requires the pump design flow rate (Q_D) and speed (N_D) in order to define the other operating characteristics (HP_I, I_P) required by the model.

2.4 Tank Thermal Model

The tank model is a lumped model consisting of four control volumes (Fig. 2.4.1): (1) ullage, (2) tank wall, (3) liquid on the tank wall, and (4) bulk liquid. The thermal model of each control volume is described in the following.

2.4.1 Ullage

The ullage thermal model applies conservation of mass and energy to determine the ullage pressure, temperature and mass (Fig. 2.4.2). From conservation of mass, the change in the ullage mass (M_U) is due to all masses entering and leaving the ullage control volume

(1) droplet evaporation rate in the ullage ($\dot{m}_{DU}$)

(2) boiling rate of the liquid on the tank wall ($\dot{m}_{bW}$)

(3) bulk liquid boiling rate ($\dot{m}_{LU}$), or ullage condensation ($\dot{m}_{UL}$)

(4) liquid surface condensation ($\dot{m}_{COND}$)

$$\frac{dM_U}{dt} = \dot{m}_{DU} + \dot{m}_{bW} + \dot{m}_{LU} - \dot{m}_{UL} - \dot{m}_{COND} \qquad (2.4.1)$$

These mass flow rates are defined in Section 2.4.6. The ullage mass is obtained by integrating its time rate of change with respect to time

$$M_U = (M_U)_{IC} + \int \left(\frac{dM_U}{dt} \right) dt \qquad (2.4.2)$$

From conservation of energy, the change in the ullage temperature (T_U) is the result of

(1) heat transfer to the ullage (q_U)
(2) work done on the ullage (w_U)
(3) energy added to the ullage by incoming and leaving masses ($ENTH_U$)

$$\frac{dT_U}{dt} = \frac{q_U - w_U - ENTH_U - c_{VU} T_U \dfrac{dM_U}{dt}}{M_U c_{VU}} \qquad (2.4.3)$$

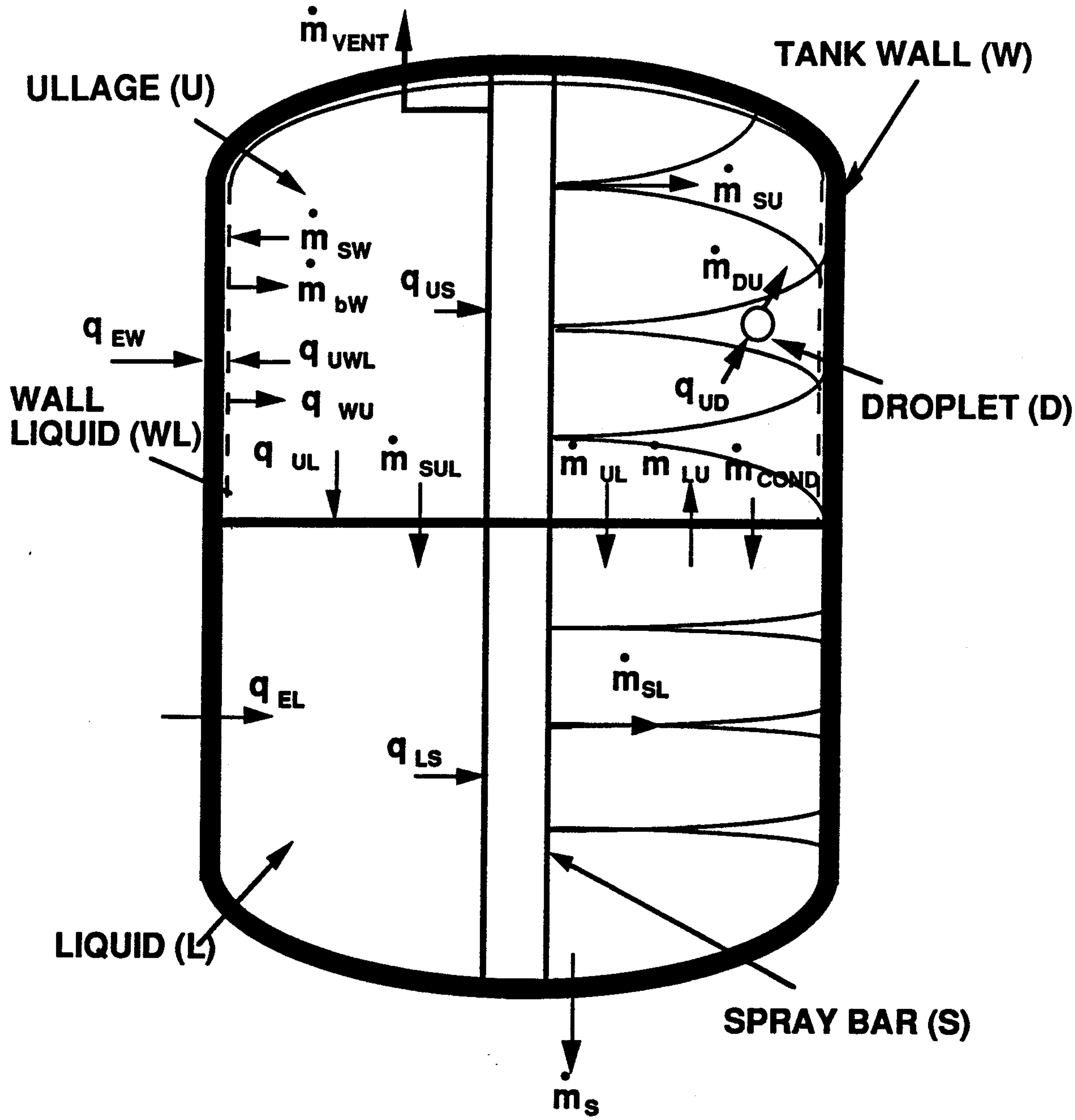


Figure 2.4.1 Tank Thermal Model

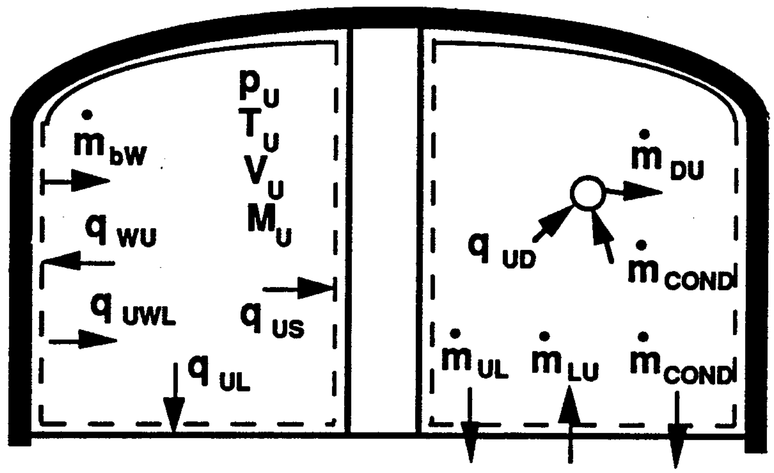


Figure 2.4.2 Ullage Thermal Model

The terms in Eq. 2.4.3 are defined as follows

(1) $q_U = q_{WU} - q_{UWL} - q_{UL} - q_{UD} - q_{US}$ (heat transfer to ullage)

where
q_{WU} is the heat-tranfer rate between the tank wall and ullage,
$|q_{WU}| > 0$ for a dry wall
$= 0$ for a wet wall
q_{UWL} is the heat-transfer rate between the ullage and wall liquid,
$|q_{UWL}| = 0$ for a dry wall
> 0 for a wet wall
q_{UL} is the heat-transfer rate between the ullage and bulk liquid
q_{UD} is the heat-transfer rate between the ullage and liquid droplet
q_{US} is the heat-transfer rate between the ullage and (unsubmerged) spray bars

The above heat-transfer rates are defined in Section 2.4.5.

(2) $w_U = p_U \frac{dV_U}{dt}$ (work done on ullage)

where the change in the ullage volume ($\frac{dV_U}{dt}$) is equal and opposite to the change in the liquid and wall liquid volumes

$$\frac{dV_U}{dt} = -\frac{dV_L}{dt} - \frac{dV_{WL}}{dt} \tag{2.4.4}$$

(3) $ENTH_U = \left(\frac{dM_U}{dt}\right) h_{gsat}$

where $h_{gsat} = h_{sat}(p_U)$ is the saturated vapor enthalpy of the ullage.

The ullage volume is obtained as the difference between the tank volume and the bulk liquid and wall liquid volumes

$$V_U = V_T - V_L - V_{WL} \tag{2.4.5}$$

Eq. 2.4.3 is integrated with respect to time to obtain the ullage temperature

$$T_U = (T_U)_{IC} + \int \left(\frac{dT_U}{dt}\right) dt \tag{2.4.6}$$

With the ullage mass, temperature and volume determined, the ullage pressure is calculated from the equation of state

$$p_U = \frac{M_U R_U T_U}{V_U} \quad (2.4.7)$$

2.4.2 Tank Wall

The tank wall is divided into two sections, one facing the liquid and the other facing the ullage. The tank wall facing the bulk liquid is assumed to be at the same temperature as the liquid. Thus, the tank wall thermal model described in this section applies to the section facing the ullage (Fig. 2.4.3). Since liquid can form on the tank wall as a result of spraying, the model must account for both dry and wet wall cases.

From conservation of energy, the change in the tank wall temperature is due to

(1) heat input to the wall from the environment (q_{EW})
(2) heat-transfer rate between the wall and ullage (q_{WU})
$|q_{WU}| > 0$ for a dry wall
$= 0$ for a wet wall
(3) heat-transfer rate between the wall and liquid on the wall (q_{WL}),
$|q_{WL}| = 0$ for a dry wall
> 0 for a wet wall

$$\frac{dT_W}{dt} = \frac{q_{EW} - q_{WU} - q_{WL}}{M_W c_{pW}} \quad (2.4.8)$$

Section 2.4.5 defines these heat-transfer rates. Eq. 2.4.8 can be integrated with respect to time to obtain the tank wall temperature

$$T_w = (T_w)_{IC} + \int\left(\frac{dT_w}{dt}\right) \quad (2.4.9)$$

2.4.3 Wall Liquid

The wall liquid thermal model is also governed by the laws of conservation of mass and energy (Fig. 2.4.4). From conservation of mass, the change in the wall liquid mass (M_{WL}) is equal to the difference between the liquid mass reaching the wall and the liquid mass boiled off from the wall

$$\frac{dM_{WL}}{dt} = \dot{m}_{sw} - \dot{m}_{bw} \quad (2.4.10)$$

where $\dot{m}_{sw}$ is the spray flow rate reaching the wall and $\dot{m}_{bw}$ is the liquid boil-off rate from the wall.

These mass flow rates will be defined in Section 2.4.6. Eq. 2.4.10 can be integrated to obtain the wall liquid mass

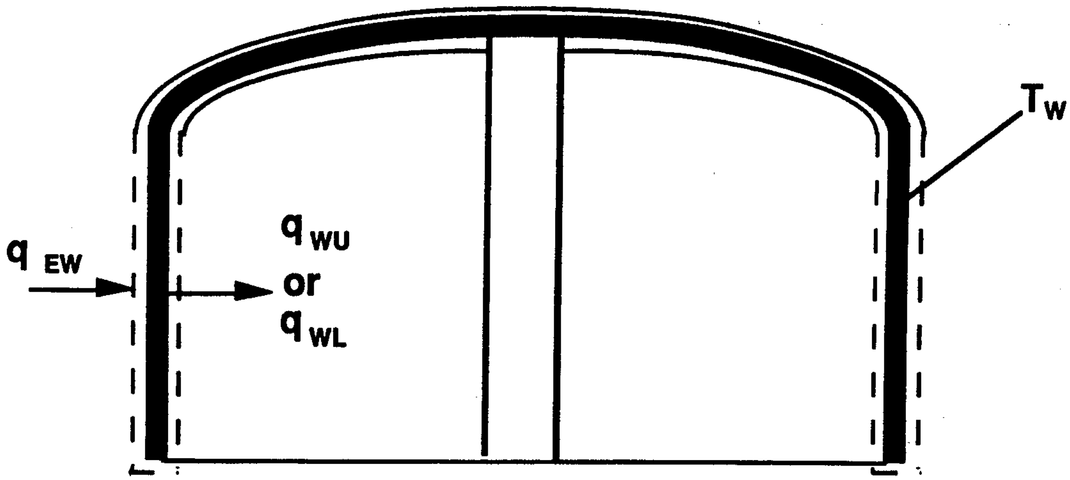


Figure 2.4.3 Tank Wall Thermal Model

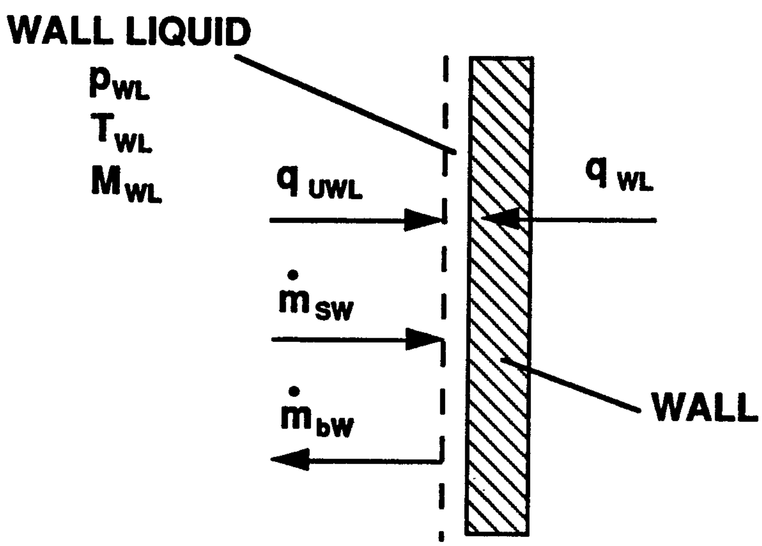


Figure 2.4.4 Wall Liquid Thermal Model

$$M_{WL} = (M_{WL})_{IC} + \int\left(\frac{dM_{WL}}{dt}\right) \tag{2.4.11}$$

From conservation of energy, the change in the wall liquid temperature (T_W) is the result of heat transfer to the wall liquid and sensible energy added to the spray to raise its temperature (T_{SW}) to the wall liquid temperature. Heat transfer to the wall liquid includes heat-transfer rate between the wall and wall liquid (q_{WL}), and heat-transfer rate between the ullage and wall liquid (q_{UWL}).

$$\frac{dT_{WL}}{dt} = \frac{q_{WL} + q_{UWL} - \dot{m}sw\, c_{pL}(T_{WL} - T_{SW})}{M_{WL} c_{pWL}} \tag{2.4.12}$$

These heat-transfer rates are defined in Section 2.4.5. Eq. 2.4.12 can be integrated to obtain the wall liquid temperature

$$T_{WL} = (T_{WL})_{IC} + \int\left(\frac{dT_{WL}}{dt}\right)dt \tag{2.4.13}$$

The wall liquid vapor pressure is then obtained from the thermodynamic data base as

$$p_{WL} = p_{sat}(T_{WL}) \tag{2.4.14}$$

The volume rate of change of the wall liquid is determined from Eq. 1.9 as

$$\frac{dV_{WL}}{dt} = \frac{1}{\rho_{WL}} \frac{dM_{WL}}{dt} \tag{2.4.15}$$

where $\rho_{WL} = \rho_{sat}(T_{WL})$ is the wall liquid density.

Eq. 2.4.15 is integrated to obtain the wall liquid volume

$$V_{WL} = (V_{WL})_{IC} + \int\left(\frac{dV_{WL}}{dt}\right)dt \tag{2.4.16}$$

2.4.4 Bulk Liquid

Originally conceived as multi-node, the bulk liquid thermal model is made single node since (1) mixing will destratify the liquid and create a uniform bulk, and (2) uncertainty in heat-transfer modeling does not justify the added complexities of a multinode model.

The liquid thermal model is also based on the laws of conservation of mass and energy. From conservation of mass, the change in the liquid mass must be balanced by a change in the ullage mass and any mass vented overboard (Fig. 2.4.5).

$$\frac{dM_L}{dt} = \dot{m}_{SL} + \dot{m}_{SUL} + \dot{m}_{COND} + \dot{m}_{UL} - \dot{m}_{LU} - \dot{m}_S - \dot{m}_V \tag{2.4.17}$$

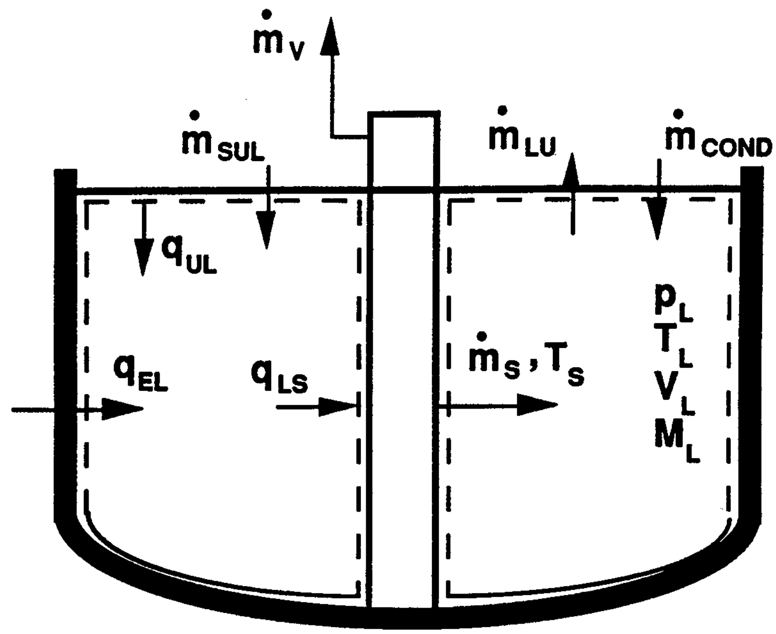


Figure 2.4.5 Bulk Liquid Thermal Model

where $\dot{m}_{SL}$ is the liquid spray flow rate into the bulk liquid

$\dot{m}_{SUL}$ is the unevaporated droplet flow rate

$\dot{m}_{COND}$ is the liquid surface condensation flow rate

$\dot{m}_{UL}$ is the ullage condensation flow rate

$\dot{m}_{LU}$ is the liquid boil-off rate

$\dot{m}_{S}$ the pump flow rate

$\dot{m}_{V}$ is the overboard venting flow rate.

The liquid mass is obtained by integrating its time rate of change

$$M_L = (M_L)_{IC} + \int\left(\frac{dM_L}{dt}\right) \quad (2.4.18)$$

From conservation of energy, the change in the liquid temperature is caused by

(1) heat transfer to the liquid
(2) heat added by the unevaporated droplets
(3) sensible energy added to the liquid spray to raise its temperature (T_S) to the liquid temperature
(4) latent heat of vaporization of the liquid

$$\frac{dT_L}{dt} = \frac{q_L + \dot{m}_{SUL}\, c_{pL}(T_d - T_L) - \dot{m}_{LU}(h_{fg})_L - \dot{m}_{SU}\, c_{pL}(T_L - T_S)}{M_L c_{pL}} \quad (2.4.19)$$

The heat-transfer rate to the liquid (q_L) is given by

$$q_L = q_{EL} + q_{UL} - q_{LS}$$

where q_{EL} is the heat added to the liquid by the environment

q_{UL} is the heat-transfer rate between the ullage and liquid

q_{LS} is the heat-transfer rate between the liquid and (submerged) spray bars

These heat-transfer rates are given in Section 2.4.5. Eq. 2.4.19 is integrated with respect to time to give the liquid temperature

$$T_L = (T_L)_{IC} + \int\left(\frac{dT_L}{dt}\right)dt \quad (2.4.20)$$

The liquid vapor pressure is obtained from the thermodynamic data base as

$$p_L = p_{sat}(T_L) \quad (2.4.21)$$

The liquid volume rate of change is determined from the rate of change of the liquid mass

$$\frac{dV_L}{dt} = \frac{1}{\rho_L}\frac{dM_L}{dt} \tag{2.4.22}$$

where $\rho_L = \rho_{sat}(T_L)$ is the liquid density.

Eq. 2.4.22 is integrated to give the liquid volume

$$V_L = (V_L)_{IC} + \int\left(\frac{dV_L}{dt}\right)dt \tag{2.4.23}$$

2.4.5 Heat Transfer

This section defines the heat-transfer rates which are found in the energy balances of Section 2.4.1 to 2.4.4. These heat-transfer rates can be divided into two groups: free convection and forced convection. Free convection is the dominant heat-transfer mode in the ullage and liquid, while forced convection characterizes liquid droplet heat transfer in the ullage.

The convection heat-transfer rate is generally defined as

$$q = hA\Delta T$$

where h is the convection heat-transfer coefficient
A is the surface area of heat transfer
ΔT is the temperature difference between the heat source and sink

The heat-transfer coefficient is obtained from the Nusselt Number (Nu) as

$$h = \left(\frac{k_F}{L_c}\right)Nu$$

where k_F is the fluid thermal conductivity and L_c is the surface characteristic length.

The Nusselt number is a function of the Rayleigh number (Ra) defined as

$$Ra = \frac{a\beta\Delta T L_c^3 \rho^2 c_p}{\mu k} \tag{2.4.24}$$

where a is the acceleration
β is the thermal expansion coefficient,
$\beta = \frac{1}{T_f}$ for gas, $\frac{1}{\rho}\left(\frac{\partial\rho}{\partial T}\right)_p$ for liquid
L_c is the characteristic length
ρ is the density
c_p is the specific heat at constant pressure
μ is the dynamic viscosity
k is the thermal conductivity

All properties must be evaluated at the film temperature (T_f) which is defined as the average of the fluid and surface temperatures.

2.4.5.1 Free Convection

Two free convection heat-transfer correlations are used in the model. The first one is a free convection correlation for interior surfaces of vertical ducts, vertical plates and cylinders, and horizontal cylinders (Ref. 28) (Fig 2.4.6)

$$Nu = 0.555 Ra^{0.25} + 0.447 \quad (2.4.25)$$

This correlation is used to calculate the heat-transfer coefficients

(1) between the ullage and wall (h_{UW})
(2) between the ullage and bulk liquid (h_{UL})
(3) between the ullage and wall liquid (h_{UWL})
(4) between the ullage and (unsubmerged) spray bars (h_{US})
(5) between the bulk liquid and (submerged) spray bars (h_{LS})

The characteristic length for h_{UW}, h_{UL} and h_{UWL} is the internal tank diameter while that of h_{US} and h_{LS} is the spray bar diameter.

The second correlation is the McAdams correlation for free convection of vertical surfaces in the turbulent range (Ref. 17)

$$Nu = 0.13 Ra^{1/3} \quad (2.4.26)$$

This correlation is used to calculate the heat-transfer coefficient between the wall and wall liquid (h_{WL}). Because of the 1/3 power in Ra, h_{WL} can be obtained without knowing the characteristic length, thereby removing the uncertainty in determining the wall liquid layer.

2.4.5.2 Forced Convection

The forced convection heat-transfer coefficient between the ullage and liquid droplets (h_{UD}) is based on a McAdams recommended correlation for flow over a sphere (Ref. 8) (Fig. 2.4.7)

$$Nu = 0.3125 Re^{0.602} \quad (2.4.27)$$

The Reynolds number of the spray flow (Re) is defined as

$$Re = \frac{\rho Vel_D D_D}{\mu} \quad (2.4.28)$$

where Vel_D is the droplet velocity in the ullage
D_D is the droplet diameter assumed to be equal to the orifice diameter
ρ, μ are the density and viscosity of the ullage gas

Since the droplet diameter and velocity vary with the orifice size, the droplet heat-transfer

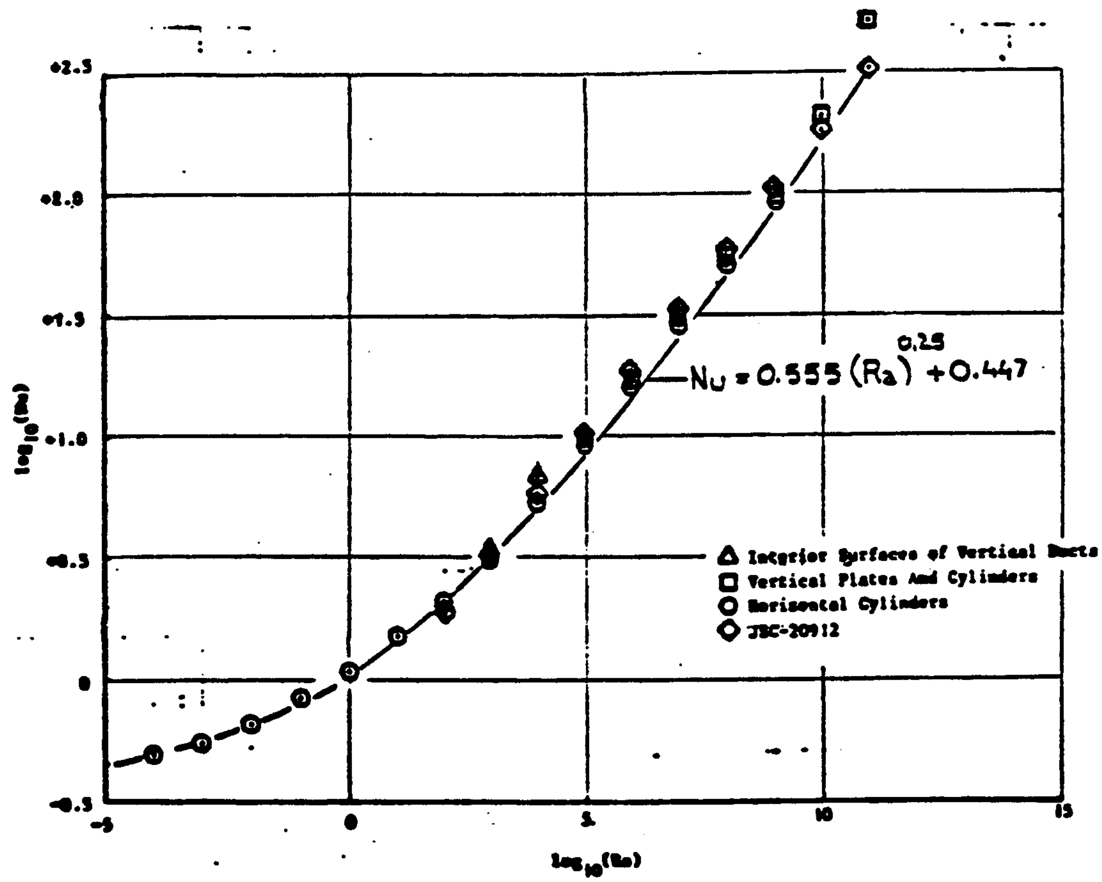


Figure 2.4.6 Free Convection Heat-Transfer Correlation for Interior Surfaces of Vertical Ducts, Vertical Plates and Cylinders, and Horizontal Cylinders

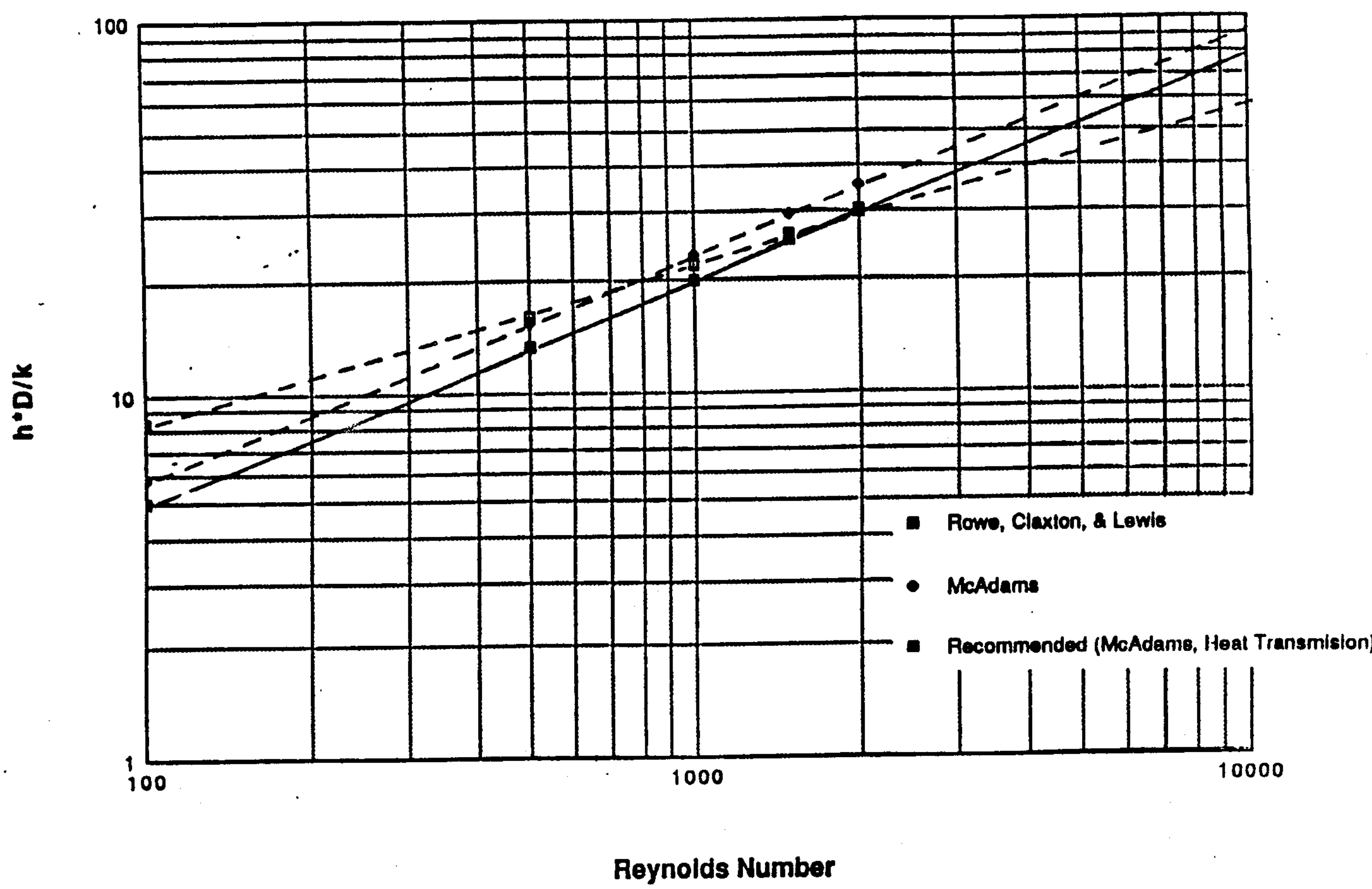


Figure 2.4.7 Forced Convection Heat-Transfer Correlation for Flow Over a Sphere

coefficient must be determined for each orifice. The total droplet heat-transfer rate is obtained by summing the droplet heat-transfer rates from each orifice

$$q_{drop} = \sum_{i=1}^{n} \left(n_{drop}\right)_i \left(q_{drop}\right)_i \qquad (2.4.29)$$

where $\left(n_{drop}\right)_i$ is the number of droplets sprayed from orifice i into the ullage. This is given by

$$\left(n_{drop}\right)_i = \frac{\left(\dot{m}_{SU}\right)_i D_{CHAR}}{2\rho_D \left(V_D\right)_i \left(Vel_D\right)_i} \qquad (2.4.30)$$

where $\left(\dot{m}_{SU}\right)_i$ is the spray flow rate into the ullage from orifice i

$\left(V_D\right)_i$ and $\left(Vel_D\right)_i$ are the droplet volume and velocity from orifice i

ρ_D is the droplet density

D_{CHAR} is a characteristic length determined empirically.

By correlating the zero-g TVS model with LeRC ullage pressure collapse data, this characteristic length was determined to be 1/4 of the tank diameter.

2.4.6 Mass Transfer

This section defines the mass-transfer rates found in the mass balance equations of Section 2.4.1 to 2.4.4 which include

(1) Bulk liquid boiling ($\dot{m}_{LU}$)

(2) Liquid boiling from the tank wall ($\dot{m}_{bW}$)

(3) Liquid droplet evaporation in the ullage ($\dot{m}_{DU}$)

(4) Liquid spray falling into the bulk liquid ($\dot{m}_{SUL}$) or accumulating on the tank wall ($\dot{m}_{SW}$)

(5) Ullage condensation ($\dot{m}_{UL}$)

(6) Liquid surface condensation ($\dot{m}_{COND}$)

2.4.6.1 Bulk Liquid Boiling

Bulk liquid boiling occurs when the liquid vapor pressure is equal to the tank ullage pressure. It can be the result of heat transfer to the liquid and/or pressure decay in the ullage. It must also include sensible energy added to the liquid spray to increase its temperature to the liquid temperature.

If $p_L = p_U$,

$$\dot{m}_{LU} = \frac{1}{\left(h_{fg}\right)_L}\left[q_L - \dot{m}_{SL}\, c_{pL}\left(T_L - T_s\right)\right], \qquad \frac{dp_U}{dt} < 0$$

$$= \frac{1}{(h_{fg})_L}\left[q_L - \dot{m}_{SL}\, c_{pL}(T_L - T_S) - M_L c_{pL}\left(\frac{\partial T}{\partial p}\right)_{sat}\left(\frac{dp_U}{dt}\right)\right], \qquad \frac{dp_U}{dt} > 0 \qquad (2.4.31)$$

A polynomial fit of the LH_2 saturation temperature vs. pressure curve was obtained and its derivative taken to give an expression for $\left(\frac{\partial T}{\partial p}\right)_{sat}$

$$\left(\frac{\partial T}{\partial p}\right)_{sat} = 0.37781 - 4.9170\text{x}10^{-3} p_L + 21.7623\text{x}10^{-6} p_L^{\,2} \qquad (2.4.32)$$

If the ullage pressure increases above the liquid vapor pressure, boiling stops

$\dot{m}_{LU} = 0$, if $p_L < p_U$.

2.4.6.2 Wall Liquid Boiling

Wall liquid boiling from the tank wall follows the same mechanism as bulk liquid boiling

If $p_{WL} = p_U$,

$$\dot{m}_{bW} = \frac{1}{(h_{fg})_L}\left[q_{WL} + q_{UWL} - \dot{m}_{SW}\, c_{pL}(T_{WL} - T_{SW})\right], \qquad \frac{dp_U}{dt} < 0$$

$$= \frac{1}{(h_{fg})_L}\left[q_{WL} + q_{UWL} - \dot{m}_{SW}\, c_{pL}(T_{WL} - T_{SW}) - M_{WL} c_{pL}\left(\frac{\partial T}{\partial p}\right)_{sat}\left(\frac{dp_U}{dt}\right)\right], \quad \frac{dp_U}{dt} > 0 \qquad (2.4.33)$$

$$\text{where} \left(\frac{\partial T}{\partial p}\right)_{sat} = 0.37781 - 4.9170\text{x}10^{-3} p_{WL} + 21.7623\text{x}10^{-6} p_{WL}^{\,2} \qquad (2.4.34)$$

If $p_{WL} < p_U$, $\dot{m}_{bW} = 0$.

As with bulk boiling, wall liquid boiling includes heat transfer to the wall liquid and sensible energy added to the spray liquid to bring its temperature to the wall liquid temperature.

2.4.6.3 Liquid Droplet Evaporation in the Ullage

Liquid droplets in the ullage will start boiling once the subcooled liquid spray is brought to saturation. From an energy balance on the liquid droplets, an expression for the liquid droplet boiling is obtained

$$\dot{m}_{DU} = \frac{1}{(h_{fg})_U}\left[q_{UD} - \dot{m}_{SU}\, c_{pL}(T_{Usat} - T_S)\right] \qquad (2.4.35)$$

where $T_{Usat} = T_{sat}(p_U)$ is the ullage saturation temperature.

2.4.6.4 Liquid Spray Falling into the Bulk Liquid or Accumulating on the Tank Wall

The unevaporated sprayed mass in the ullage is assumed to fall into the bulk liquid under 1 g, or to accumulate on the tank wall under 0 g (Fig. 2.4.8), i.e.,

$$\dot{m}_{SUL} = \dot{m}_{SU} - \dot{m}_{DU} \quad \text{(for 1 g)} \tag{2.4.36}$$

$$\dot{m}_{SW} = \dot{m}_{SU} - \dot{m}_{DU} \quad \text{(for 0 g)}$$

2.4.6.5 Ullage Condensation

Ullage condensation occurs whenever the ullage temperature is equal to the saturation temperature corresponding to the ullage pressure. It is the result of heat removal from the liquid droplet (when there is spraying) and the wall liquid (Figure 2.4.9)

$$\dot{m}_{UL} = \frac{q_{UD} + q_{UL} + q_{UWL}}{\left(h_{fg}\right)_U} \qquad T_U = T_{sat}\left(p_U\right) \tag{2.4.37}$$

2.4.6.6 Liquid Surface Condensation

When helium is not present to act as a barrier to mass transfer, bulk liquid mixing during pump operation induces condensation on the liquid surface. This condensation rate is controlled by the heat transfer rate from the ullage to the liquid

$$\dot{m}_{COND} = \frac{q_{UL}}{\left(h_{fg}\right)_U} \tag{2.4.38}$$

2.5 References

1. Chato, D. J., "Analysis of the Nonvented Fill of a 4.96-Cubic-Meter Lightweight Liquid Hydrogen Tank," NASA TM-102039.

2. Chen, I. M., "Thermodynamic Model for On-Orbit Cryogen Transfer," Summary Report, Rockwell International, IR&D Project 28601, September 1982.

3. Chen, I. M. and Moses, R. A., "A Shuttle Flight Experiment for On-Orbit Transfer of Cryogenic Hydrogen," AIAA 20th Joint Propulsion Conference, June 1984.

4. Chen, J. C., "A Correlation for Boiling Heat Transfer to Saturated Fluids in Convective Flow," ASME Paper No. 63-HT-34, ASME-AIChE Heat Transfer Conference and Exhibit, Boston, MA, August 1963.

5. Fischer, M. F., Schmidt, G. R., and Martin, J. J., "Analysis of Cryogenic Propellant Behavior in Microgravity and Low Thrust Environments," AIAA Paper 91-2173, June 1991.

6. Hubbard, G. L., Denny, V. E., and Mills, A. F., "Droplet Evaporation: Effects of Transients and Variable Properties," Int. J. Heat Mass Transfer, Vol. 18, pp. 1003-1008, 1975.

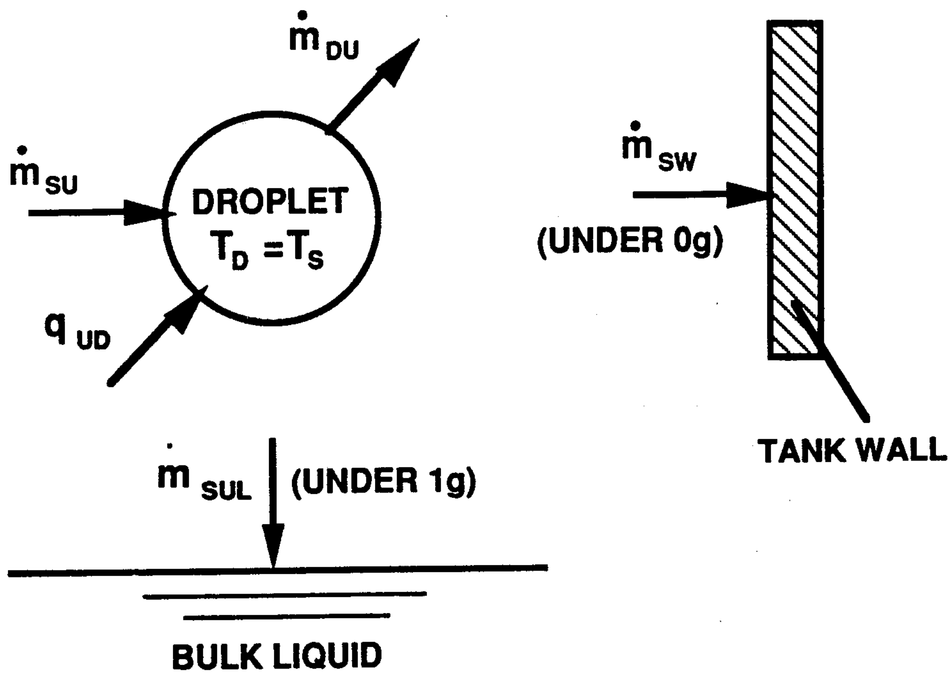


Figure 2.4.8 Droplet Evaporation Model

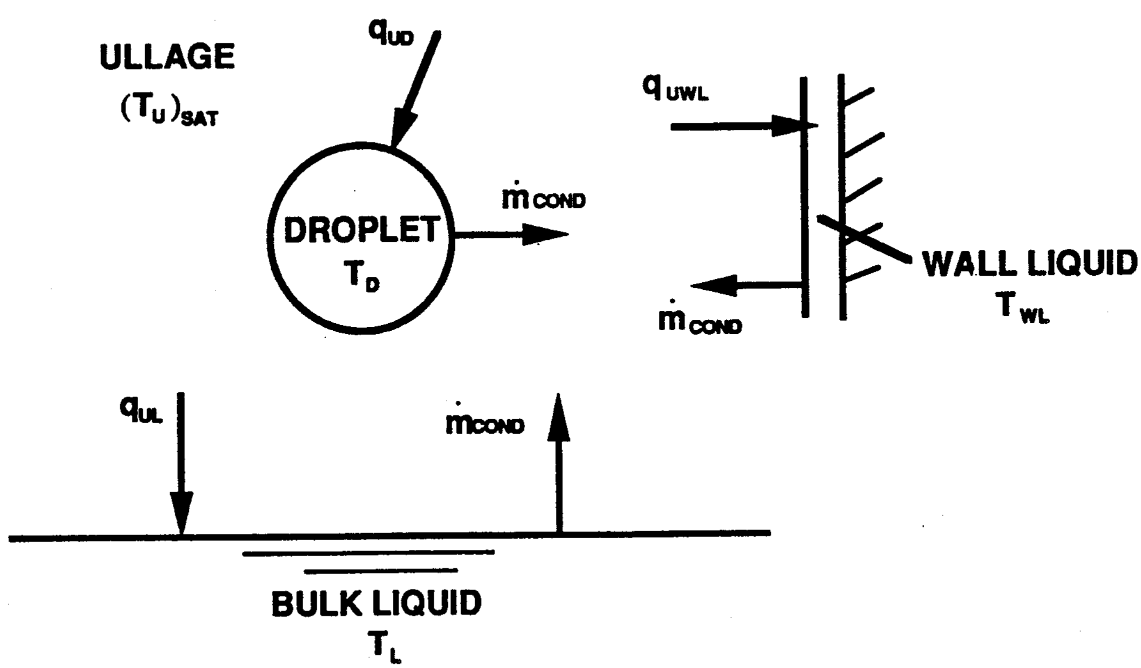


Figure 2.4.9 Ullage Condensation Model

7. Ingebo, R. D., "Vaporization Rates and Heat Transfer Coefficients for Pure Liquid Droplets," NASA TN 2368, July 1951.

8. Kreith, H., "Principles of Heat Transfer," 3rd edition, New York, 1973.

9. Lebedev, P. I., Rybanin, S. S., and Stesik, L. N., "Heat and Mass Transfer of a Liquid Drop Evaporating into a Flow of Gas Capable of Condensing," Int. J. Heat Mass Transfer, Vol. 24, No. 4, pp. 611-620, 1981.

10. Lefebvre, A. H., "Gas Turbine Combustion," Hemisphere Publishing Corporation, 1983.

11. Lin, C.-S., Van Dresar, N. T. and Hasan, M. M., "A Pressure Control Analysis of Cryogenic Storage Systems," AIAA Paper 91-2405, June 1991.

12. Miller, W. S., Kalvinskas, L. A., and Seader, J. D., "Boiling Heat Transfer for Cryogenics," NASA Report CR-243, 1965.

13. Moran, M. E. and Nyland, T. W., "Hydrogen No-Vent Fill Testing in a 5 Cubic Foot (142 Liter) Tank Using Spray Nozzle and Spray Bar Liquid Injection," AIAA Paper 92-3063, June 1992.

14. Ostroumov, G. A., "Free Convection Under the Conditions of the Internal Problem," State Publishing House, Technico-Theoretical Literature, Moscow-Leningrad, 1952, NACA TM 1407.

15. Ranz, W. E. and Marshall, W. R., "Evaporation from Drops, Parts I," Chemical Engineering Progress, Vol. 48, No. 3. pp. 141-146, March 1952.

16. Ranz, W. E. and Marshall, W. R., "Evaporation from Drops, Parts II," Chemical Engineering Progress, Vol. 48, No. 4. pp. 173-180, April 1952.

17. Ring, E., "Rocket Propellant and Pressurization Systems," Prentice-Hall, Inc., Englewood Cliff, N. J.

18. Sabnis, J. S. and de Jong, F. J., "Calculation of the Two-Phase Flow in an Evaporating Spray Using an Eulerian-Lagrangian Analysis," AIAA Paper 90-0447, January 1990.

19. Schmidt, G. R., Carrigan, R. W., Hahs, J. E., Vaughan, D. A., and Foust, D. C., "No-Vent Fill Pressurization Tests Using a Cryogen Simulant," NASA TM-103561.

20. Schmidt, G. and Hastings, L., "Cryogenic Fluid Management at MSFC," AIAA Paper 90-3711, September, 1990.

21. Taylor, W. J. and Chato, D. J., "Comparing the Results of an Analytical Model of the No-Vent Fill Process With No-Vent Fill Test Results for a 4.96 m^3 (175 ft^3) Tank," AIAA Paper 92-3078, July 1992.

22. Taylor, W. J. and Chato, D. J., "Improved Thermodynamic Modeling of the No-Vent Fill Process and Correlation With Experimental Data," NASA TM-104492.

23. Taylor, W. J., Chato, D. J., Moran, M. M., and Nyland, T. W., "On-Orbit Cryogenic Fluid Transfer Research at NASA Lewis Research Center," Cryogenics, Vol. 32, No. 2, 1992.

24. Van Drasar, N. T., "Pressurization of Cryogens: A Review of Current Technology and Its Applicability to Low-Gravity Conditions," AIAA Paper 92-3061, July 1992.

25. Vaughan, D. A. and Schmidt, G. R., "Analytical Modeling of No-Vent Fill Process," J. Spacecraft, Vol. 28, No. 5, pp. 574-579, Sept.-Oct. 1991.

26. Yuen, M. C. and Chen, L. W., "Heat Transfer Measurements of Evaporating Liquid Droplets," Int. J. of Heat Mass Transfer," Vol. 21, pp. 537-542, 1978.

27. "COOLANT: The Cryogenic On-Orbit Liquid Analytical Tool User's Manual," Vol. I, Version 2.0, General Dynamics Report No. GDSS-CRAD-88-005, Rev. A, October 1989.

28. "Generic Fluid Transfer Model, Computer Model Description Document," Rockwell International, December 1987.

29. "MPS Propellant Dump and Vacuum Inerting (The Generalized Two-Phase Cryogenic Propellant Dump Model)," Program No. MPS-17, 287-104-91-MPS-017, Rockwell International, June 1991.

30. "SAE Aerospace Applied Thermodynamics Manual," Developed by SAE Committee AC-9, Aircraft Enveronmental System.

2.6 Sample Cases

The sample cases shown are for a tank with 90% and 25% liquid quantities and a 0.25 Btu/hr-ft^2 heat flux. The tank is the 639-ft^3 Multi-purpose Hydrogen Test Bed (MTHB) tank which is a cylindrical tank with elliptical bulkheads at both ends.The cylinder measures 5 ft in length and 10 ft in diameter while the bulkhead has a height of 2.5 ft. The tank has a wall thickness of 0.5 in and is made of aluminum. One-g acceleration is assumed and no helium is present in the tank. The results show the ullage and liquid vapor pressures, recirculation and vent flow rates, time between destratification and venting, destratification time, and TVS operation frequency.

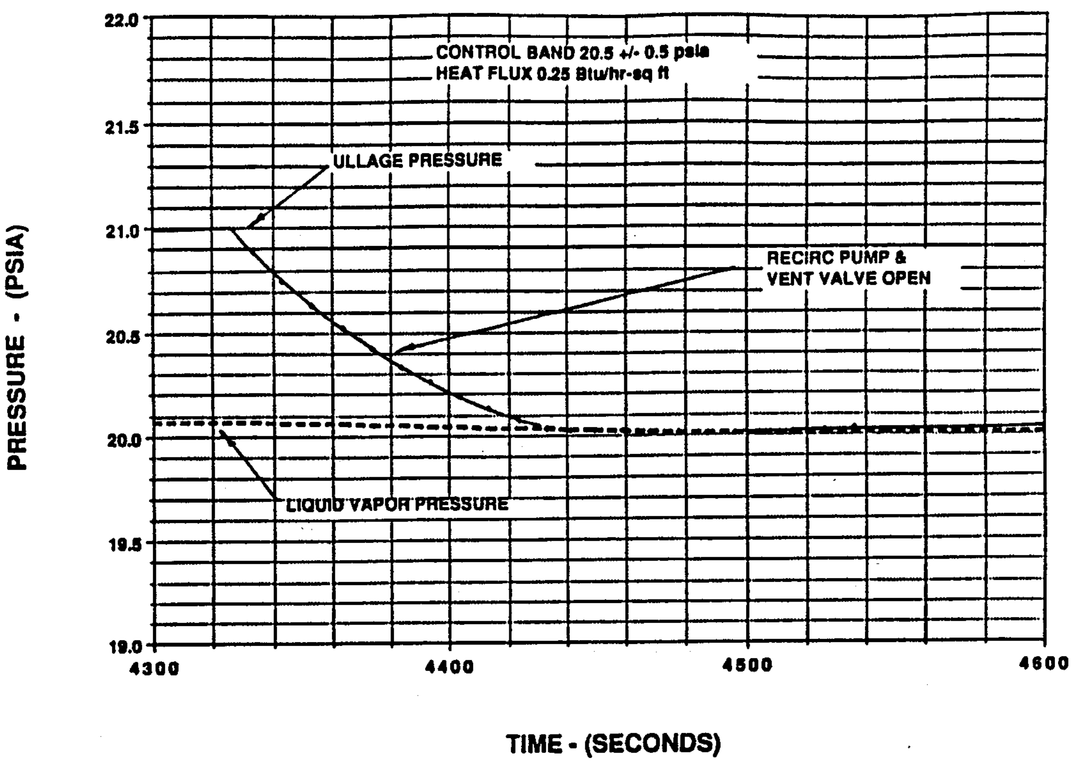


Figure 2.6.1 TVS Performance Simulation at 90% Liquid Quantity

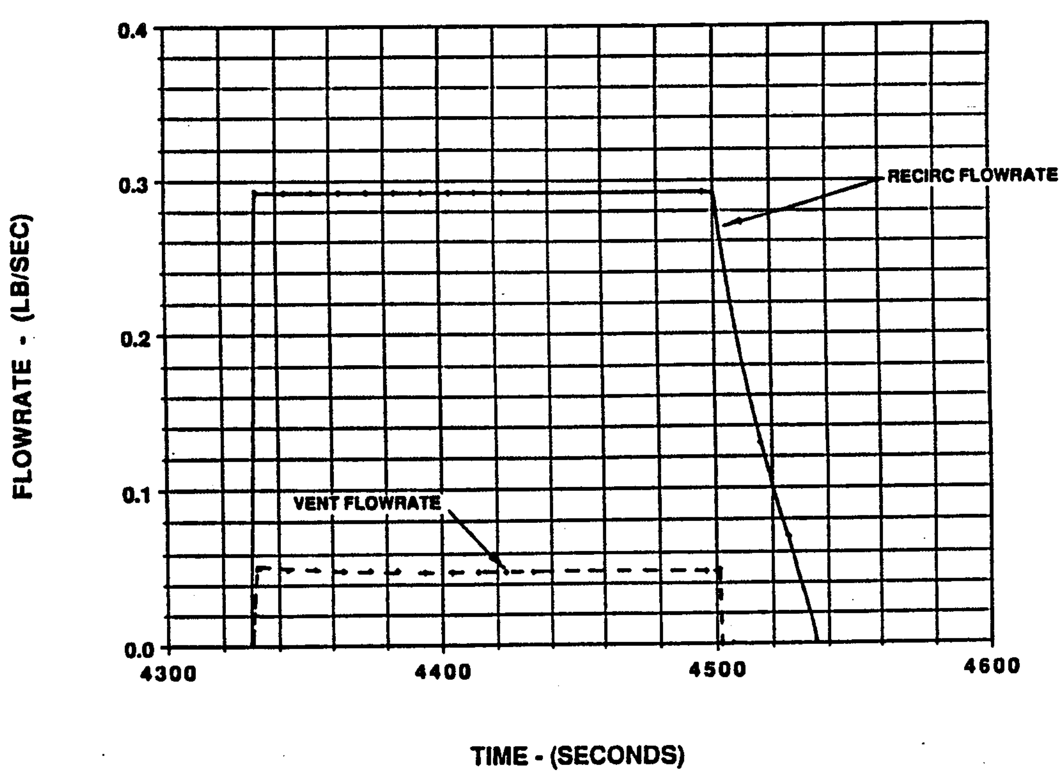


Figure 2.6.2 TVS Recirculation Pump and Vent Valve Flow Rate Transient During Ullage Destratification (90% Liquid Quantity)

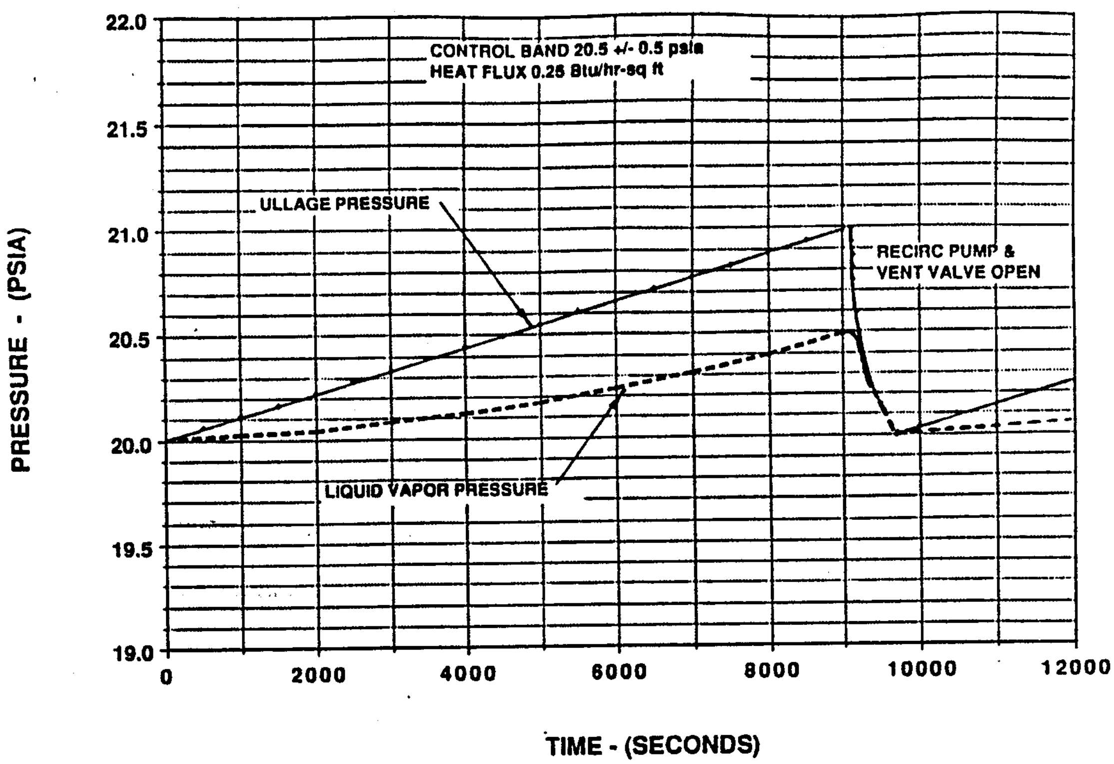


Figure 2.6.3 TVS Performance Simulation at 25% Liquid Quantity

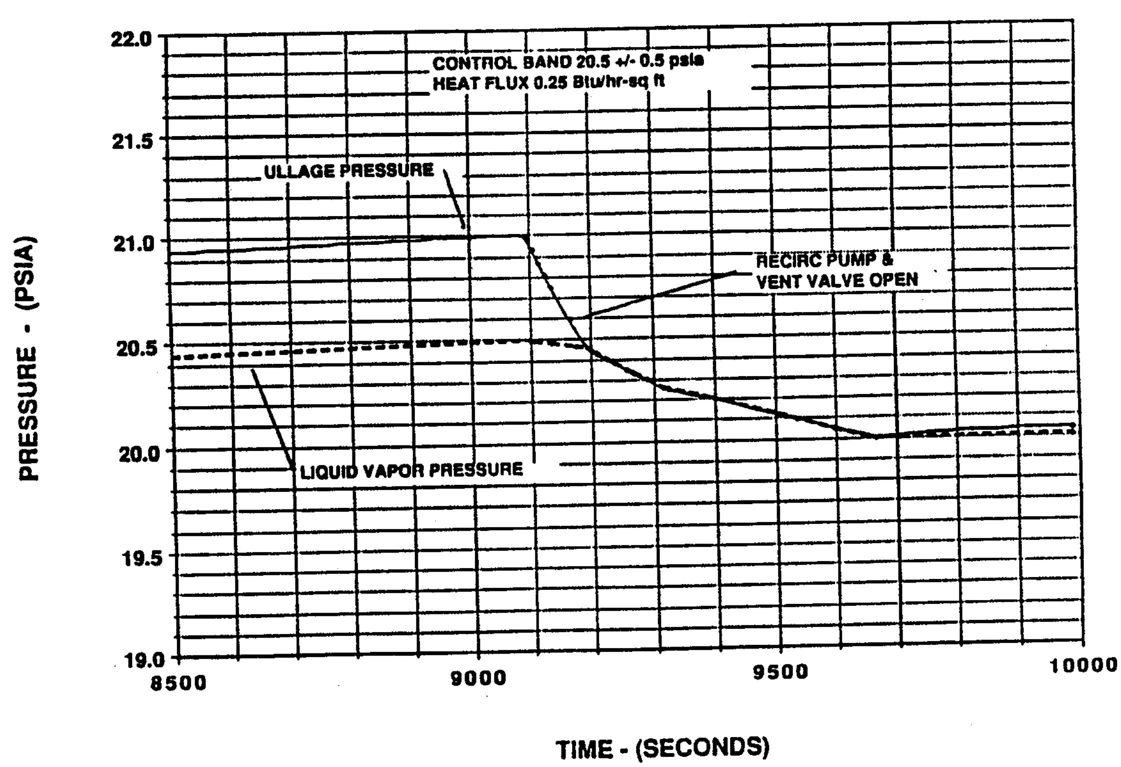


Figure 2.6.4 TVS Performance Simulation at 25% Liquid Quantity

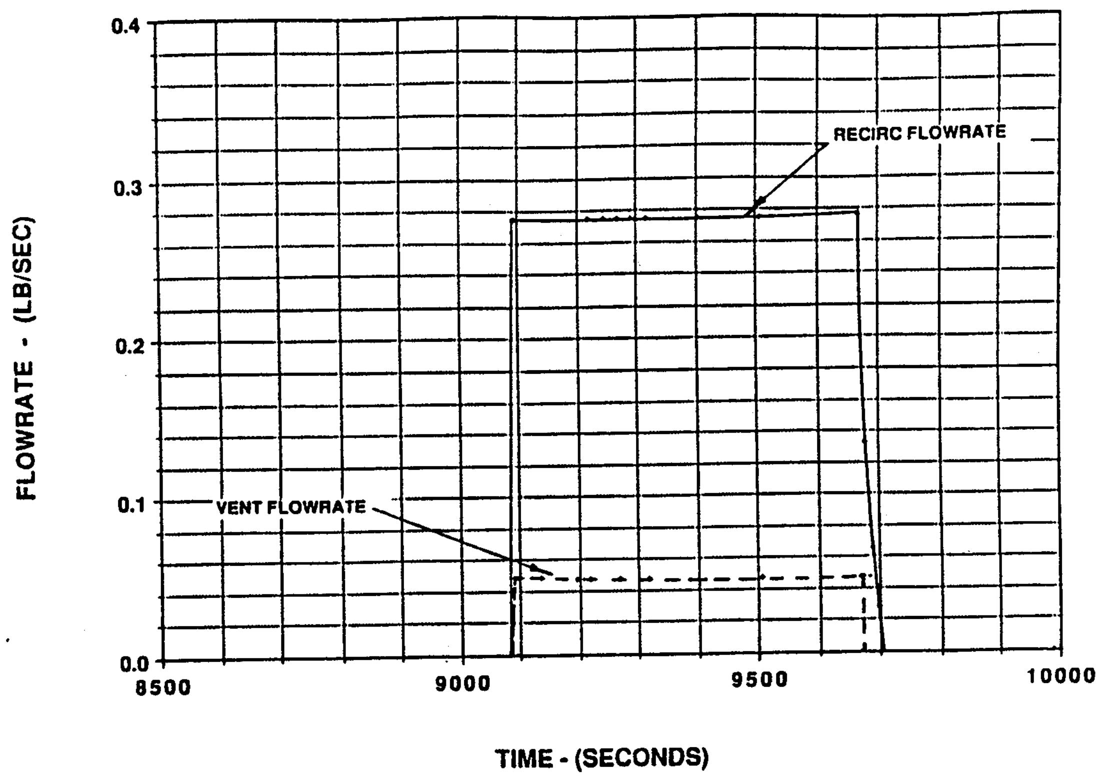


Figure 2.6.5 TVS Recirculation Pump and Vent Valve Flow Rate Transient During Ullage Destratification (25% Liquid Quantity)

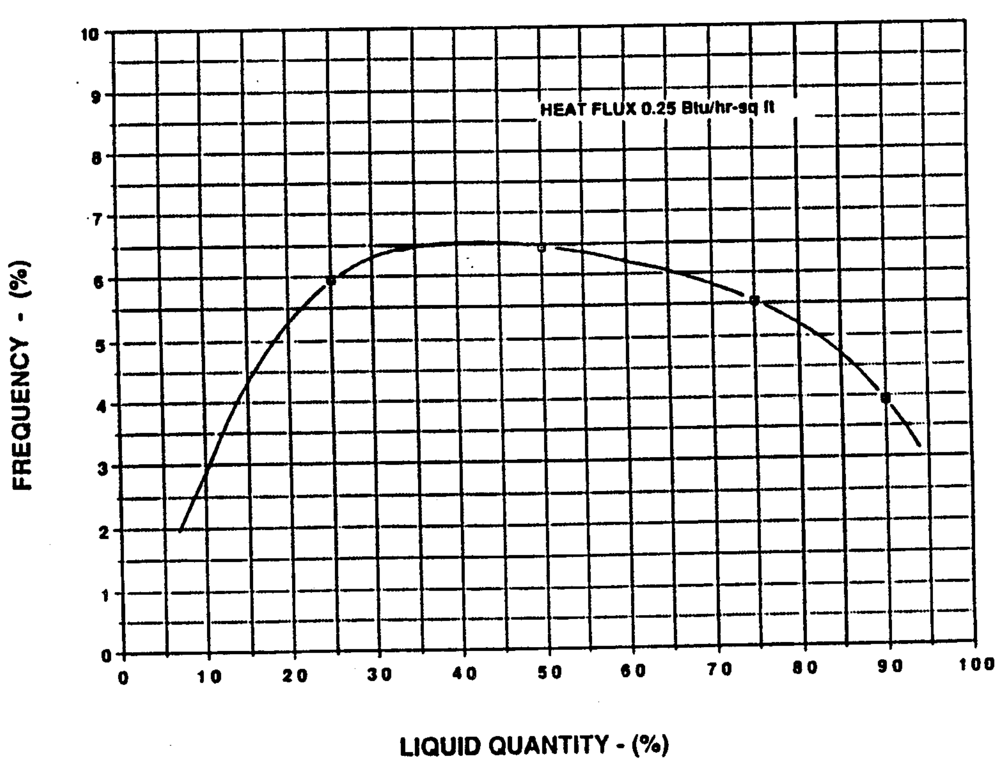


Figure 2.6.6 TVS Operation Frequency (Percent) as a Function of Liquid Quantity

SECTION 3

COMPUTER MODEL DESCRIPTION

3.1 Programming Description

The Zero-g TVS performance prediction program was developed on the following system

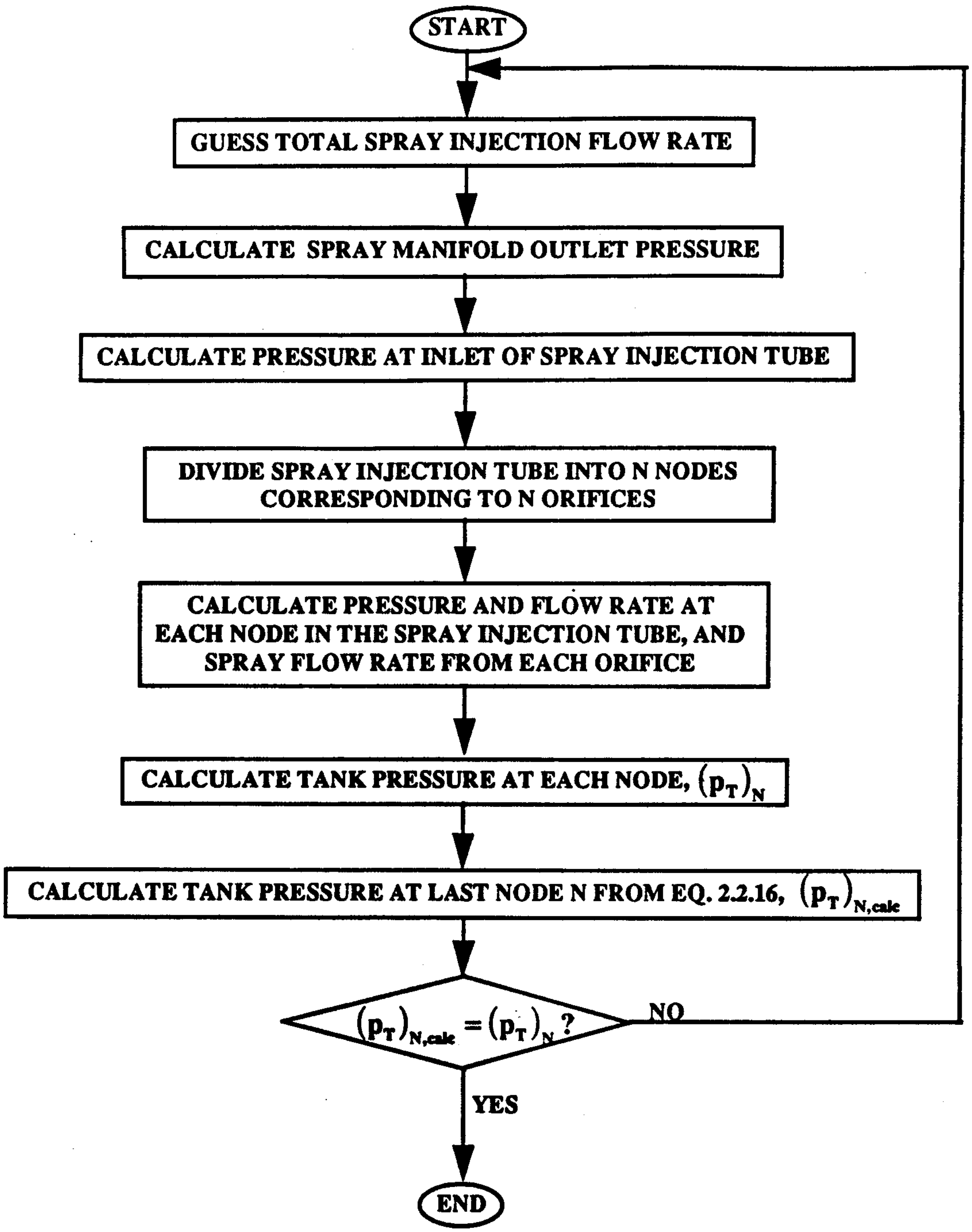
Computer	HP-9000 Series 500
Operating System	HP-UX rel. 5.2.1
Language	FORTRAN 77 rel. 5.12
Plotter	HP-7550
Plotting Software	CRTPLT

3.2 Flow Charts

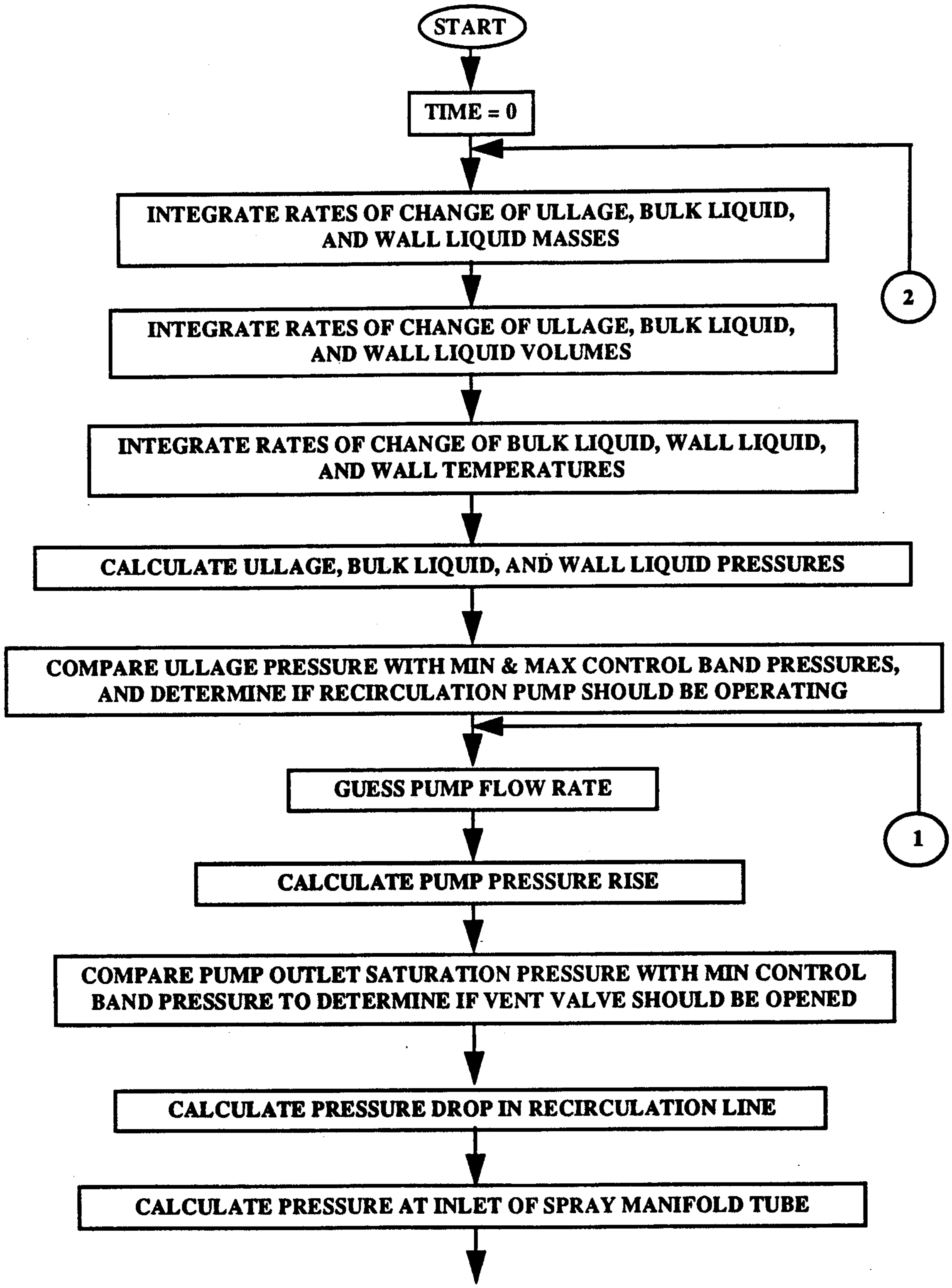
3.2.1 Heat Exchanger Model

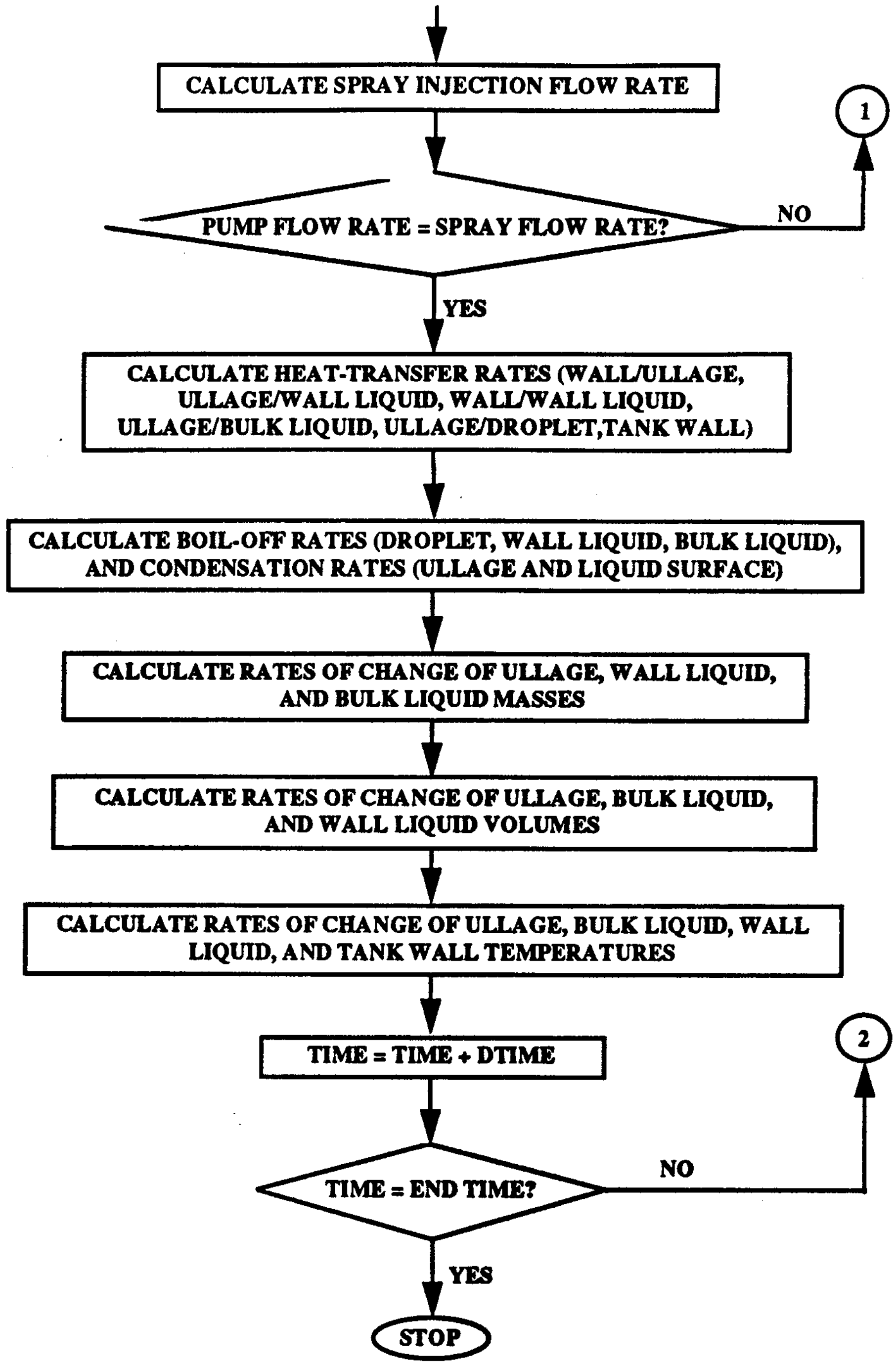
The flow chart of the heat exchanger model is shown in Section 1.4 of Reference 29.

3.2.2 Spray Manifold/Injection Tube Model



3.2.3 Integrated Zero-g TVS Model




CALCULATE SPRAY INJECTION FLOW RATE
1
PUMP FLOW RATE = SPRAY FLOW RATE?
NO
YES
CALCULATE HEAT-TRANSFER RATES (WALL/ULLAGE, ULLAGE/WALL LIQUID, WALL/WALL LIQUID, ULLAGE/BULK LIQUID, ULLAGE/DROPLET,TANK WALL)
CALCULATE BOIL-OFF RATES (DROPLET, WALL LIQUID, BULK LIQUID), AND CONDENSATION RATES (ULLAGE AND LIQUID SURFACE)
CALCULATE RATES OF CHANGE OF ULLAGE, WALL LIQUID, AND BULK LIQUID MASSES
CALCULATE RATES OF CHANGE OF ULLAGE, BULK LIQUID, AND WALL LIQUID VOLUMES
CALCULATE RATES OF CHANGE OF ULLAGE, BULK LIQUID, WALL LIQUID, AND TANK WALL TEMPERATURES
TIME = TIME + DTIME
2
TIME = END TIME?
NO
YES
STOP

3.3 Definition of Variables

3.3.1 Input Variables

3.3.1.1 Heat Exchanger Model

The input variables of the heat exchanger model are described in Section 3.2.1 of Reference 29.

3.3.1.2 Spray Manifold/Injection Tube Model

SYMBOL	UNIT	DESCRIPTION
dsm	in	spray manifold diameter
zsm	in	spray manifold length
dsi	in	spray injection tube diameter
zsi	in	spray injection tube length
norf		number of orifices
nbar		number of spray bars
ks		spray orifice loss coefficient
cds		spray orifice discharge coefficient
roverd		bend r/d of spray manifold
dmdot	lb_m/sec	flow rate increment
tol	psia	convergence tolerance on tank pressure
nlim		max number of iterations
nsec		number of sections with the same orifice sizes
node		node number
dorf	in	orifice diameter

3.3.1.3 Recirculation Pump Model

SYMBOL	UNIT	DESCRIPTION

mdotd	lb_m/sec	design pump flow rate
dpd	psid	design pump pressure rise
npumpi	rpm	initial pump speed
npumpd	rpm	design pump speed
xhp		multiplier to determine design input horsepower
xn		fraction of design pump speed used to determine the pump speed operating band
deltat	sec	time needed to reach design speed
effp		pump efficiency

3.3.1.4 Integrated Zero-g TVS Model

SYMBOL	UNIT	DESCRIPTION
xd		multiplier for spray injection orifice size (to determine droplet size)
xchar	in	characteristic length used in the equation to calculate the number of droplets
he		helium injection indicator (1 = yes, 0 = no)
xcond		multiplier for liquid surface condensation rate
prtsp		time indicator to print output of subroutine spray (output is printed prtsp<time<prtsp+0.1)
pui	psia	initial ullage pressure
tui	R	initial ullage temperature
pli	psia	initial ullage temperature
twi	R	initial wall temperature
twli	R	initial wall liquid temperature
full	%	percent full level

xl1	in	length of straight section downstream of recirculation line 90-degree bend
dtank	in	tank diameter
hcyl	in	cylinder height
hbulk	in	tank bulkhead height
tkw	in	tank wall thickness
dsb	in	spray bar diameter
d1	in	diameter of recirculation line upstream of reducer
d2	in	diameter of recirculaton line downstream of reducer
mdvent	lb_m/sec	overboard venting flow rate
mdsi	lb_m/sec	initial spray (pump) flow rate
dthex	R	heat exchanger temperature drop
qflux	Btu/hr-ft^2	heat flux
g	ft/sec^2	acceleration level
pmin	psia	control band min pressure
pmax	psia	control band max pressure
delt2	sec	integration time step when pump is off
iprnt2		number of time steps between output printing when pump is off
iplot2		number of time steps between output plotting when pump is off
fintim	sec	end time
delt1	sec	integration time step when pump is on
iprnt1		number of time steps between output printing when pump is on

iplot1		number of time steps between output plotting when pump is on
nline		number of output lines printed per page
o*variable*		option to plot *variable* (1=yes)
subhd		plot subheading
xtitl		plot x-title
y*variable*		y-title of *variable* plot

3.3.1.5 LH$_2$ saturation properties

nsat		number of data points
tsat	R	saturation temperature
psat	psia	saturation pressure
enthf	Btu/lb$_m$	saturated liquid enthalpy
shpf	Btu/lb$_m$-R	saturated liquid specific heat
densf	lb$_m$/ft^3	saturated liquid density
texpf	R^{-1}	saturated liquid thermal expansition coefficient
condf	Btu/hr-ft-R	saturated liquid thermal conductivity
viscf	lb$_m$/ft-sec	saturated liquid dynamic viscosity
enthg	Btu/lb$_m$	saturated vapor enthalpy

3.3.1.6 GH$_2$ Properties

np (nt)	number of pressures (temperatures)	
tnrm		normalized temperature
tconst	R	reference temperature
pvap	psia	pressure
tvap	R	temperature

enth	Btu/lb_m	enthalpy
shv	Btu/lb_m-R	specific heat at constant vapor
shp	$Btu//lb_m$-R	specific heat at constant pressure
dens	lb_m/ft^3	density
cond	Btu/hr-ft-R	thermal conductivity
visc	lb_m/ft-sec	dynamic viscosity

3.3.2 Output Variables

3.3.2.1 Heat Exchanger Model

The output variables of the heat exchanger model are described in Section 3.2.2 of Reference 29.

3.3.2.2 Spray Manifold/Injection Tube Model

SYMBOL	UNIT	DESCRIPTION
mdot	lb_m/sec	spray (pump) flow rate
dppump	psid	pump pressure rise
dpsm	psi	spray manifold tube pressure drop
dpsi	psi	spray injection tube pressure drop
pin	psia	nodal inlet pressure
pout	psia	nodal outlet pressure
pnode	psia	nodal pressure
ptank	psia	tank pressure
mdin	lb_m/sec	nodal inlet mass flow rate
mdout	lb_m/sec	nodal outlet mass flow rate
mds	lb_m/sec	spray flow rate through each orifice

veld	ft/sec	droplet velocity
as	in^2	spray orifice area

3.3.2.3 <u>Tank Model</u>

SYMBOL	UNIT	DESCRIPTION
pu	psia	ullage pressure
tu	R	ullage temperature
vu	ft^3	ullage volume
mu	lb_m	ullage mass
tw	R	wall temperature
pl	psia	bulk liquid pressure
tl	R	bulk liquid temperature
vl	ft^3	bulk liquid volume
ml	lb_m	bulk liquid mass
pwl	psia	wall liquid pressure
twl	R	wall liquid temperature
vwl	ft^3	wall liquid volume
mwl	lb_m	wall liquid mass
mv	lb_m	mass vented overboard
ts	R	spray temperature
mdlu	lb_m/sec	bulk liquid boil-off rate
mds	lb_m/sec	spray (pump) flow rate
mdsl	lb_m/sec	spray flow rate into bulk liquid
mdsu	lb_m/sec	spray flow rate into ullage

mddu	lb_m/sec	dropplet evaporation rate
mdbw	lb_m/sec	wall liquid boil-off rate
mdul	lb_m/sec	ullage condensation rate
mdcond	lb_m/sec	liquid surface condensation rate
qwu	Btu/sec	heat-transfer rate between wall and ullage
quwl	Btu/sec	heat-transfer rate between ullage and wall liquid
qwl	Btu/sec	heat-transfer rate between wall and wall liquid
qul	Btu/sec	heat-transfer rate between ullage and bulk liquid
qud	Btu/sec	heat-transfer rate between ullage and droplet
qus	Btu/sec	heat-transfer rate between ullage and (unsubmerged) spray bar
qls	Btu/sec	heat-transfer rate between bulk liquid and (submerged) spray bar
npump	rpm	pump speed
dppump	psid	pump pressure rise

3.4 Program Listing

3.4.1 Heat Exchanger Model

```
*
*  Zero G Venting System Integrated Steady State Heat Exchanger
*  Performance Program
*
*   By Tibor Lak, David Soo Hoo, & Dr. Han Nguyen
*
*  A HP-9000 Program adapted from the Shuttle Venting Program, Rev. 3
*  Includes single & two phase flow heat transfer & pressure losses.
*
*   May 8, 1992
*
* INITIAL CONDITITONS:
*
*  MASSIC - MASS IN THE TANK OR MANIFOLD TO BE VENTED (LBM)
*  PIC   - SATURATED PRESSURE OF THE TANK OR MANIFOLD (PSIA)
*  PSTI  - INITIAL GUESS AT THE INLET PRESSURE DURING BOILING (PSIA)
*  MDOT  - INITAL GUESS AT THE VENT OR LEAK FLOWRATE (LB/SEC)
*
* FLUID PROPERTIES:
*
*  Prop  - Type of Propellant (1.0 = Hydrogen, 2.0 = Oxygen)
*  PTP   - TRIPLE POINT PRESSURE (PSIA)
*  AVLIG - SONIC VELOCITY IN LIQUID (FT/SEC)
*
* EXTERNAL CONDITITONS:
*
*  PAMB  - AMBIENT PRESSURE (PSIA)
*  G     - GRAVITY
*
* INTERNAL CONDITIONS & CONFIGURATIONS:
*
*  M     - NUMBER OF NODES IN THE VENT PATH (Maxium is 20 nodes)
*  VT    - TANK OR MANIFOLD VOLUME (CUBIC IN)
*  AX    - EXIT AREA (SQ IN)
*  A(1-M) - FLOW AREA OF THE VENT PATH PER NODE (SQ IN)
*  K(1-M) - FLOW LOSS COEFFICIENT PER NODE
*  DH(1-M)- CHANGE IN HEIGHT BETWEEN NODES (IN)
*  QDOT  - HEAT FLUX INTO THE FLUID PER NODE (BTU/SEC)
*  (1-M)
*  SAREA - SURFACE AREA OF THE NODE: USED TO CALCULATE THE
*  (1-M)  HEAT TRANSFER COEFFICIENT
```

```
*   LENGTH - LENGTH OF NODES (IN)
*   (1-M)
*
* VARIABLE EXIT AREA VARIABLES:
*
*   VA     - Change in area (1 = yes , 0 = no)
*   G1     - Acceleration in number of gravities.
*   DIAM   - Line diameter (in)
*   SMAX   - Maximum exposed surface area (sq inches)
*
* PROGRAM CONTROL VARIABLES:
*
*   FINTIM - MAXIMUM RUN TIME (SEC)
*   PRDEL  - PRINT INTERVAL (SEC)
*   QDTERR - QDOT ITERATION ERROR
*   Delptp - Delta Exit Pressure From the Triple Point Pressure
*   DELT   - TIME INTERVAL BETWEEN ITERATIONS (SEC)
*   OT     - option to plot time vs various parameters (0 = no plot)
*   OM     - option to plot mass vs various parameters (0 = no plot)
*   OP     - option to plot pressure vs various parameters (0 = no plot)
*   DEBUG  - option to print different information between iterations
*    [0.0 = no debug]                [1.0 = results from mdot loop]
*    [2.0 = results from PST loop]       [3.0 = results from PES loop]
*    [4.0 = results from PSFO loop]      [5.0 = results from PSFI loop]
*    [6.0 = results from Liq PSFO loop]  [7.0 = results from PXS loop]
*    [8.0 = results from gas calc. loops]
*    [9.0 = results from all 1 thru 7 loops]
*
      double precision pic,psti,ptp,avliq,pamb,vt,errmx,perrmx
      double precision delt,delptp,ys,sic,time,rhot,tsp,tts
      double precision pst,pst1,slt,sgt,rholt,rhogt,yt,rhotv,ptsc,ts1
      double precision berr,ps,pliq,tliq,hls,hgs,dmdot,pl,ph
      double precision rhole,rhoge,hle,hge,sle,sge,he,qdterr
      double precision rholfo,rhogfo,hlfo,hgfo,slfo,sgfo,hfo,rhofo,pdfo
      double precision htot,pfo,psfo,visgfo,vislfo,asvo,drhdt1,to,qerr
      double precision rholfi,rhogfi,hlfi,hgfi,slfi,sgfi,hfi,rhofi,pdfi
      double precision xf,psfi,visgfi,vislfi,asvi,lgxf,phisqf,dpff,psfn
      double precision dptf,dpmf,perr,del,pxs,hlx,hgx,slx,sgx,rholx,yx
      double precision hx,vx,rhox,rhoxv,pxsc,gerr,tx,pxd,px,thrust
      double precision isp,dpx,sfo1,hlf,slf,psx1,fm,fp,rhogx
      double precision tdim,ti,tw,pback
*
      double precision pes(2),tes(2),htote(2),pde(2),rhoe(2),hs(2)
*
      double precision RHOLI(45,2),RHOLO(45,2),RHOGI(45,2),RHOGO(45,2)
```

```
      double precision PSO(45,2),PDI(45,2),PDO(45,2),HI(45,2),HO(45,2),
     1                 TSI(45,2),tave(45,2)
      double precision RHOO(45,2),SI(45,2),SO(45,2),pi(45,2),po(45,2),
     1                 tso(45,2)
      double precision VI(45,2),VO(45,2),MACHI(45,2),MACHO(45,2)
      double precision DPF(45,2),PHISQ(45,2),DPT(45,2),DPM(45,2),
     1                 ERR(45,2),rhoi(45,2)
      double precision XTT(45,2),QDTT(45,2),RN(45,2),psi(45,2)
      double precision x1(50),p2(50),p3(50),p4(50),p5(50),p6(50),p7(15)
      double precision p8(50),p9(50),p10(50),lmxpar(50),lvisp(50)
      double precision lrhop(50),grhop(50),rhovp(50),lent(50),lentp(50)
      double precision gent(50),sclent(15,15),p11(50),p12(50),drhdto(50)
      double precision t7(15,15),gvisp(50),gentp(50)
      double precision cpg(6,14),thkg(6,14),t14(14),viscg(6,14),
     1                 p14(6),delta(45)
      real yo(45,2),yi(45,2),a(45,2),k(45,2),qdot(45,2),dh(45,2)
      real mass,kf,massic,mlow,mhigh,mdot(2),twall(45),ye(2),mdt,m8
      character *8 name(10),subt(10)
      integer exit,ot,om,op,num(15),va
*
*     Define Heat Transfer Variables
*
      real length(45),sarea(45,2)
      double precision p13(50),surft(50),q(45,2),cpl(50),thkl(50),
     1                 stemp(50),cp,ts,st,cond
*
*     Define Plot Variables
*
      real ptitle(18,4)
      real subhd(18),name1(10),name2(10),name3(10),name4(10)
      real name6(10),name7(10),name8(10),name9(10),name10(10)
      real name11(10),name12(10),name5(10)
      common /pltcom/ misc(3),nc,miss(13),dclim,ltick,nfig,nptmin,
     1           nlines,nchlin,ptitle
c
      data name/'mdot    ','isp     ','thrust  ','qerr    '
     1       ,'rhot    ','pst     ','pes     ','htot    '
     2       ,'ext area','twall   '/
*
*     Read Input Data
*
      read (5,100) lable
      read (5,101) massic,pic,psti,mdot(1),pback
      read (5,100) lable
      read (5,101) prop,ptp,avliq,pamb,g
```

```
      read (5,100) lable
      read (5,102) m,vt,ax,va,tw
      read (5,100) lable
      read (5,*) mdot(2),disp,dth,vtdi,ed
      read (5,100) lable
      read (5,101) dpinc,errmx,perrmx,debug,exdi
      read (5,100) lable
      read (5,101) fintim,prdel,qdterr,delt,delptp
      read (5,100) lable
      read (5,104) ot,om,op,dq
      read (5,100) lable
      do i=1,m
         read (5,105) a(i,1),dh(i,1),qdot(i,1),length(i)
      enddo
      read (5,106) subhd
      read (5,107) subt
  100 format (//,a1)
  101 format (5f10.0)
  102 format (i10,2f10.0,i10,f10.0)
  103 format (4f10.0,e10.1)
  104 format (3i10,f10.0)
  105 format (4f10.0)
  106 format (/,18a4)
  107 format (10a8)
*
*    Write Input Data
*
      if (debug .eq. 1.0 .or. debug .ge. 10.0) then
       write (6,101) massic,pic,psti,mdot(1),pback
       write (6,101) prop,ptp,avliq,pamb,g
       write (6,102) m,vt,ax,va,tw
       write (6,*) mdot(2),disp,dth,vtdi,ed
       write (6,101) dpinc,errmx,perrmx,debug,exdi
       write (6,101) fintim,prdel,qdterr,delt,delptp
       write (6,104) ot,om,op,dq
        do i=1,m
           write (6,105) a(i,1),dh(i,1),qdot(i,1),length(i)
        enddo
      endif
*
*    read tables of data file misc.data
*
      if (prop.eq.1.0) then
          open (unit=2, file='h2misc.data',status='unknown')
      else
```

```
   open (unit=2, file='o2misc.data',status='unknown')
  endif
  read (2,150) n1
  do i=1,n1
    read (2,155) x1(i),lmxpar(i)
  enddo
*
  read (2,150) n2
  do i=1,n2
    read (2,155) p2(i),lvisp(i)
  enddo
*
  read (2,150) n3
  do i=1,n3
    read (2,155) p3(i),gvisp(i)
  enddo
*
  if (prop .ne. 1.0) then
   read (2,150) n12
   do i=1,n12
    read (2,155) p12(i),drhdto(i)
   enddo
  endif
*
*   read tables of data file rho.data
*
  if (prop.eq.1.0) then
     open (unit=3, file='h2rho.data',status='unknown')
  else
   open (unit=3, file='o2rho.data',status='unknown')
  endif
  read (3,150) n4
  do i=1,n4
    read (3,155) p4(i),lrhop(i)
  enddo
*
  read (3,150) n5
  do i=1,n5
    read (3,155) p5(i),grhop(i)
  enddo
*
  read (3,150) n6
  do i=1,n6
    read (3,155) rhovp(i),p6(i)
  enddo
```

```
*
    read (3,151) n7,maxt
    do i=1,n7
     read (3,*) p7(i),num(i)
     do j=1,num(i)
       read (3,155) t7(i,j),sclent(i,j)
     enddo
    enddo
*
*     read tables of data file enthalpy & entropy data
*
    if (prop.eq.1.0) then
        open (unit=4, file='h2ent.data',status='unknown')
    else
     open (unit=4, file='o2ent.data',status='unknown')
    endif
    read (4,150) n8
    do i=1,n8
      read (4,155) p8(i),lentp(i)
    enddo
*
    read (4,150) n9
    do i=1,n9
      read (4,155) p9(i),gentp(i)
    enddo
*
    read (4,150) n10
    do i=1,n10
      read (4,155) p10(i),lent(i)
    enddo
*
    read (4,150) n11
    do i=1,n11
      read (4,155) p11(i),gent(i)
    enddo
*
*     read tables of data file thermal conductivity & surface tension data
*
    if (prop.eq.1.0) then
        open (unit=10, file='h2thermo.data',status='unknown')
*
    read (10,150) n13
    do i=1,n13
      read (10,*) p13(i),cpl(i),thkl(i),surft(i),stemp(i)
    enddo
```

```
*
      read (10,154) n14,num1,tcnst
      do i=1,n14
        read (10,152) p14(i)
        do j=1,num1
          read (10,153) cpg(i,j),thkg(i,j),viscg(i,j)
        enddo
      enddo
      do j=1,num1
        read (10,152) t14(j)
      enddo
      endif
  150 format (//,i3)
  151 format (//,i3,4x,i3)
  152 format (f10.2)
  153 format (f14.0,2e14.3)
  154 format (//,i3,4x,i3,4x,f10.0)
  155 format (2f14.0)
*
*     Define Program Constants & working variables
*
      ys = 0.0
      AI = A(M,1)
      AE = A(1,1)
      tsp = PTP
      K(M,1) = 0.5
      K(1,1) = 0.5
      PES(1) = PTP
      PES(2) = PTP
      m1 = m - 1
      mass = massic
      call value(n10,p10,lent,pic,sic)
      beta = 1.0
      gamma =1.0
      time = 0.0
      m8 = m * 0.8
*     pltime = -pltdel
      prtime = -prdel
      ncount1 = 1
      ncount2 = 1
      exit = 0
      pyi = 3.14159
*
      do ij = 1, m
          twall(ij) = tw
```

```
        a(ij,2) = pyi * disp ** 2.0 / 4.0
        sarea(ij,1) = pyi * (disp + 2.0 * dth) * length(ij)
        sarea(ij,2) = pyi * disp * length(ij)
        qdot(ij,2) = -qdot(ij,1)
      enddo
*
*     Define Plot Constants
*
      nc = 0
      nfig = 0
      nlines = 0
*
*     Check to Determine the Correct Time increment is Used
*
      IF (delt.gt.pltdel) delt = pltdel
      IF (delt.gt.prdel) delt = prdel
*
*     CALCULATE INITIAL TANK OR MANIFOLD CONDITIONS
*
    1 RHOT = MASS/VT
         tagl = 0.0
         tagh = 0.0
         mlow = 0.0
         mhigh = 0.0
       pst = PSTI
       pst1 = 0.0
       j1 = 0
*
*     Loop to Calculate Initial Pst
*
    5 call value(n10,p10,lent,PST,slt)
       call value(n11,p11,gent,PST,sgt)
       call value(n4,p4,lrhop,PST,rholt)
       call value(n5,p5,grhop,PST,rhogt)
       YT = (SIC-SLT)/(SGT-SLT)
          if (yt .lt. 0.0) yt = 0.0
          if (yt .gt. 1.0) yt = 1.0
       RHOTV = YT/(1.0/RHOT-1.0/RHOLT*(1.0-YT))
       call value(n6,rhovp,p6,RHOTV,ptsc)
c         if (j1 .eq. 0) pst1 = ptsc
c         beta = dabs(pst - pst1)
c       pst1 = pst
c       berr = ptsc - pst
c       IF (dabs(berr) .gt. 0.001) then
c         if (berr .gt. 0.0) then
```

```
c          pst = pst + beta/2.0
c         else
c            pst = pst - beta/2.0
c         endif
c          j1 = j1 + 1
c          if (j1.gt.100) go to 6
c          go to 5
c         endif
  6  PS=PST
*
     IF (debug .eq. 2.0 .or. debug .ge. 10.0) THEN
       write (6,110) j1,pst,slt,sgt,rholt,rhogt,ptsc,mass,yt
 110    format ('counter = ',i4,4x,'PST = ',f8.3,/,7(3x,f8.3))
        ENDIF
*
     PSTI=PST
     PLIQ=PST
     if (prop.eq.1.0) then
       call H2SAT(PST,tliq)
     else
       call o2sat(PST,tliq)
         endif
     YS=YT
*
*    SATURATED LIQUID AT SOURCE
*
     IF(PLIQ.le.PST) then
       call value(n8,p8,lentp,PST,hls)
       call value(n9,p9,gentp,PST,hgs)
       HS(1) = (1.0-YS)*HLS+YS*HGS
          HS(2) = HS(1)
     else
*
*       SUBCOOLED LIQUID AT SOURCE
*
       YS=0.0
       call value3(np7,maxt,num,p7,t7,sclent,pliq,tliq,hls)
       HS(1) = HLS
          HS(2) = HS(1)
     endif
*
*       Set Constants for Mdot Calculation
*
    tsp = PTP
c-----------------------------------------------------------------------
```

```
c    START ITERATION ON THE FLOWRATE CONVERGENCE BASED ON CHOKE
FLOW  |
c    AT THE ORIFICE BY THE OUTLET OF THE TANK FOR THE TVS SYSTEM      |
c---------------------------------------------------------------------
      THETA = 1.05
      DO L1 = 1, 1000
       if (tagl .ne. 0.0 .and. tagh .ne. 0.0) then
        mdot(1) = mlow + dm * (pl / (pl - ph))
       else
        mdot(1) = (theta + 1.0) * mdot(1)/2.0
       endif
*
*    DEFINITION OF TANK EXIT CONDITION (SONIC/SUBSONIC FLOW)
*          (CHOKE FLOW AT THE TANK EXIT NODE M)
*
        HTOTE(1)=HS(1)+QDOT(M,1)/MDOT(1)-G*DH(M,1)/(12.0*1728.0)
        AT = A(M,1)
          seold = 0.0
          xpes = 0.9
        tsp = xpes * tsp
          do i = 1,400
            tsp = tsp + dpinc
          IF(tsp.GT.PST) GO TO 15
           IF(tsp.LT.PTP) tsp = ptp
           call value(n4,p4,lrhop,tsp,rhole)
           call value(n5,p5,grhop,tsp,rhoge)
           call value(n8,p8,lentp,tsp,hle)
           call value(n9,p9,gentp,tsp,hge)
           call value(n10,p10,lent,tsp,sle)
           call value(n11,p11,gent,tsp,sge)
           call TPHS(HTOTE(1),RHOLE,RHOGE,MDOT(1),AT,HLE,HGE,SLE,
     1            sge,ye(1),he,se,rhoe(1),pde(1))
            if (se .le. seold) goto 15
              seold = se
          enddo
   15     continue
        if (prop.eq.1.0) then
         call H2SAT(tsp,tts)
        else
         call o2sat(tsp,tts)
          endif
*
*
         PO(M,1)=tsp+PDE(1)
         YO(M,1)=YE(1)
```

```
*
*     PRESSURE LOSS CALCULATION THROUGH NODE M
*
      KF=K(M,1)
      AREA=A(M,1)
*
*    CHANGE IN ELEVATION
*
      DHI=DH(M,1)
      DHO=DH(M+1,1)
      HO(M,1)=HS(1)+QDOT(M,1)/MDOT(1)-G*DH(M,1)/(12.0*1728.0)
      HTOT=HO(M,1)
*
*    TWO-PHASE FLOW REGION
*
      PFO=PO(M,1)
      PSFO=PFO
*
*    DETERMINE THE OUTLET CONDITIONS AT NODE N, GIVEN THE TOTAL
*    PRESSURE AT THE OUTLET
*
        DO I1 = 1,5
         IF(PSFO.LT.PTP) PSFO=PTP
         IF(PSFO.GT.PST) PSFO=PST
         call value(n4,p4,lrhop,PSFO,rholfo)
         call value(n5,p5,grhop,PSFO,rhogfo)
         call value(n8,p8,lentp,PSFO,hlfo)
         call value(n9,p9,gentp,PSFO,hgfo)
         call value(n10,p10,lent,PSFO,slfo)
         call value(n11,p11,gent,PSFO,sgfo)
         call value(n3,p3,gvisp,PSFO,visgfo)
         call value(n2,p2,lvisp,PSFO,vislfo)
         call TPHS(HTOT,RHOLFO,RHOGFO,MDOT(1),AREA,HLFO,HGFO,SLFO,
     1          sgfo,yfo,hfo,sfo,rhofo,pdfo)
         PSFO=PFO-PDFO
*
*     End of I1 Loop (To Determine Node M Outlet Conditions)
*
        enddo
     if (prop.eq.1.0) then
      call H2SAT(PSfo,ts1)
     else
      call o2sat(PSfo,ts1)
        endif
*
```

```
      PSO(M,1)=PSFO
      PDO(M,1)=PDFO
      RHOLO(M,1)=RHOLFO
      RHOGO(M,1)=RHOGFO
      RHOO(M,1)=RHOFO
      YO(M,1)=YFO
      HO(M,1)=HFO
      SO(M,1)=SFO
      VO(M,1)=144.0*MDOT(1)/(A(M,1)*RHOO(M,1))
        TSO(M,1)=ts1
      if (prop.le.1.0) then
       call H2SVEL(YFO,PSFO,RHOLFO,RHOGFO,asvo)
      else
       call value(n12,p12,drhdto,psfo,drhdt1)
       call o2sat(psfo,to)
       call o2svel(yfo,to,rholfo,rhogfo,drhdt1,asvo)
      endif
      MACHO(M,1)=VO(M,1)/ASVO
      IF(MACHO(M,1).LT.0.0) MACHO(M,1)=0.0
      IF(MACHO(M,1).GT.1.0) MACHO(M,1)=1.0
*
*    INITIAL GUESS AT NODE INLET BASED ON COMPRESSIBLE LOSS
*
      call INITL(PSFO,KF,MDOT(1),AREA,RHOLFO,psfi)
*
*    TOTAL ENTHALPY AT NODE INLET
*
       HI(M,1)=HS(1)+QDOT(M+1,1)/MDOT(1)-G*DH(M,1)/(12.0*1728.0)
       HTOT=HI(M,1)
*
*    DEFINITION OF STATIC PRESSURE AT NODE INLET
*
       DO I2 = 1,50
        IF(PSFI.LT.PTP) PSFI=PTP
        IF(G.LE.0.0.AND.PSFI.LT.PSFO) PSFI=PSFO
        IF(PSFI.GT.PST) PSFI=PST
        call value(n4,p4,lrhop,PSFI,rholfi)
        call value(n5,p5,grhop,PSFI,rhogfi)
        call value(n8,p8,lentp,PSFI,hlfi)
        call value(n9,p9,gentp,PSFI,hgfi)
        call value(n10,p10,lent,PSFI,slfi)
        call value(n11,p11,gent,PSFI,sgfi)
        call value(n3,p3,gvisp,PSFI,visgfi)
        call value(n2,p2,lvisp,PSFI,vislfi)
        call TPHS(HTOT,RHOLFI,RHOGFI,MDOT(1),AREA,HLFI,HGFI,SLFI,
```

```
 1          sgfi,yfi,hfi,sfi,rhofi,pdfi)
      PFI=PSFI+PDFI
*
*   LOCKHART-MARTINELLI TWO-PHASE FLOW PARAMETER
*
      call XPARAM(YFO,VISLFO,VISGFO,RHOLFO,RHOGFO,YFI,VISLFI,
 1          visgfi,RHOLFI,RHOGFI,xf)
      IF(XF.LT.0.01) XF=0.01
      LGXF=LOG10(XF)
      call value(n1,x1,lmxpar,LGXF,phisqf)
      PHISQF=(10.0**PHISQF)**2
*
*   TWO-PHASE FLOW PRESSURE LOSS AND NODE INLET PRESSURE (PSFN)
*
      call TPS(AREA,G,DHI,DHO,KF,PSFO,YFO,RHOLFO,RHOGFO,YFI,
 1          rholfi,RHOGFI,MDOT(1),PHISQF,dpff,psfn,dptf,
 2          dpmf)
      ERR(M,1)=ABS(PSFN-PSFI)
      PSFI=(PSFI+PSFN)/2.0
*
* CONDITION WHERE THE INLET STATIC PRESSURE OF THE NODE IS
DETERMINED
*
      IF(ERR(M,1).LE.ERRMX) GO TO 20
*
*    End of I2 Loop (To Determine Node N Inlet Conditions)
*
      enddo
 20   PFI=PSFI+PDFI
*
*   CALCULATE THE INLET CONDITIONS OF THE NODE M
*
      RHOLI(M,1)=RHOLFI
      RHOGI(M,1)=RHOGFI
      RHOI(M,1)=RHOFI
      DPM(M,1)=DPMF
      DPF(M,1)=DPFF
      DPT(M,1)=DPTF
      PI(M,1)=PFI
      PDI(M,1)=PDFI
      PSI(M,1)=PSFI
      YI(M,1)=YFI
      HI(M,1)=HFI
      SI(M,1)=SFI
      PHISQ(M,1)=PHISQF
```

```
      VI(M,1)=144.0*MDOT(1)/(A(M,1)*RHOI(M,1))
        if (prop.le.1.0) then
       call H2SVEL(YFI,PSFI,RHOLFI,RHOGFI,asvi)
      else
       call value(n12,p12,drhdto,psfi,drhdt2)
       call o2sat(psfi,ti)
       call o2svel(yfi,ti,rholfi,rhogfi,drhdt2,asvi)
      endif
      MACHI(M,1)=VI(M,1)/ASVI
      IF(MACHI(M,1).LT.0.0) MACHI(M,1)=0.0
      IF(MACHI(M,1).GT.1.0) MACHI(M,1)=1.0
*
*    CALCULATE THE TWO PHASE HEAT TRANSFER COEFFICIENT FOR NODE M
*    BASED ON INLET PRESSURE
*
      call value(n13,p13,cpl,psfi,cp)
      call value(n13,p13,thkl,psfi,cond)
      call value(n13,p13,surft,psfi,st)
      call value(n13,p13,stemp,psfi,ts)
        if (tave(m,1) .le. 0.0) then
          tave(m,1) = ts
        endif
        hgl = hgfi - hlfi
*
      dtemp = twall(m) - tave(m,1)
*
        di = exdi
*
      dpress = 778.2 * dtemp * rhogfi * hgl / ts
      if (yfi .gt. 0.7) then
       re = 48.0 * mdot(1) * (1.0-0.7)/(pyi * vislfi * di)
      else
       re = 48.0 * mdot(1) * (1.0-yfi)/(pyi * vislfi * di)
      endif
*
      call htcoeff(phase,dtemp,dpress,cp,cond,vislfi,rholfi,
     1            rhogfi,st,hgl,re,xf,di,qdott)
      if (yfi .ge. 0.7) then
         tdim = 0.0
        call value2(n14,num1,p14,t14,cpg,psfi,tdim,cp)
        call value2(n14,num1,p14,t14,thkg,psfi,tdim,cond)
        call value2(n14,num1,p14,t14,viscg,psfi,tdim,visgfi)
        re = 48.0 * mdot(1) /(pyi * visgfi * di)
        call htcoeff(3.0,dtemp,dpress,cp,cond,visgfi,rholfi,
     1            rhogfi,st,hgl,re,xf,di,qtt)
```

```
          qdott = qdott*(1-yfi) + qtt*yfi
        endif
      q(m,1) = qdott * (twall(m) - tave(m,1)) * sarea(m,1)/144.0
*
        TSI(M,1) = TS
        XTT(M,1) = XF
        RN(M,1) = RE
        QDTT(M,1) = QDOTT
        TAVE(M,1) = (tsi(m,1) + tso(m,1))/2.0
*
       theta = ps/pi(m,1)
       perr = ps-pi(m,1)
      if (perr .lt. 0.0) then
       del = mlow - mdot(1)
       tagl = 1.0
       mlow = mdot(1)
       pl = perr
      else
       del = mhigh - mdot(1)
       tagh = 1.0
       mhigh = mdot(1)
       ph = perr
      endif
      dm = mhigh - mlow
c
       if (dabs(perr) .le. permx .or. dabs(del) .le. 0.0001) goto 30
       enddo
c-----------------------------------------------------------------------
c   END OF MDOT CALCULATION LOOP
c-----------------------------------------------------------------------
 30 continue
c
c   Determine the Back Pressure to the Heat Exchanger part of the Spray
c   Bar
c
    ptk = psti
    mdt = mdot(2)
    dspry = disp
    call spray(mdt,ptk,dspry,ed,pback)
******************************************************************************
*   START ITERATION ON THE HEAT TRANSFER COEFFICIENT                         *
******************************************************************************
     DO L=1,150
      if (l .gt. 1) then
       do ii = 1,m1
```

```
          nn = m - ii
          qdot(nn,1) = qdot(nn+1,1) + q(nn,1)
          qdot(nn,2) = qdot(nn+1,2) - q(nn,2)
           if (sarea(ii,1) .le. 0.0 .or. qdtt(ii,1) .lt. 0.0) then
             c1 = 1.0
         else
             c1 = sarea(ii,2) * qdtt(ii,2)/(sarea(ii,1)*qdtt(ii,1))
           endif
         if (dabs(delta(ii)) .gt. dq) then
             tw = twall(ii)
             twall(ii) = (c1 * tave(ii,2) + tave(ii,1))/(1+c1)
             twall(ii) = (tw + twall(ii))/2.0
             if(twall(ii) .lt. 24.845) twall(ii) = 24.845
           endif
         enddo
        endif
      qdt = 0.0
      qdt1 = 0.0
c--------------------------------------------------------------------
c   START THE VENT & SPRAY NODAL NETWORK FLOW PROPETIES
CALCULATION  !
c--------------------------------------------------------------------
      do il = 1, 2
*
*   DEFINITION OF EXIT CONDITION (SONIC/SUBSONIC FLOW)
*         (CHOKE FLOW AT THE EXIT NODE)
*
       HTOTE(il)=HS(il)+QDOT(1,il)/MDOT(il)+G*(DH(M+1,il)-DH(1,il))/
    1        (12.0*1728.0)
       AE = A(1,il)
          seold = 0.0
          xpes = 0.9
       PES(il) = xpes * PES(il)
          do i = 1,500
           if (il .eq. 1) then
            PES(il) = PES(il) + dpinc
         else
          PES(il) = pback
         endif
          IF(PES(il).GT.PST) GO TO 40
           IF(PES(il).LT.PTP) PES(il)=PTP
           call value(n4,p4,lrhop,PES(il),rhole)
           call value(n5,p5,grhop,PES(il),rhoge)
           call value(n8,p8,lentp,PES(il),hle)
           call value(n9,p9,gentp,PES(il),hge)
```

```
         call value(n10,p10,lent,PES(il),sle)
         call value(n11,p11,gent,PES(il),sge)
         call TPHS(HTOTE(il),RHOLE,RHOGE,MDOT(il),AE,HLE,HGE,SLE,
     1          sge,ye(il),he,se,rhoe(il),pde(il))
          if (se .le. seold) goto 40
           seold = se
        enddo
 40     continue
*
        IF (debug .eq. 3.0 .or. debug .ge. 10.0) THEN
         write (6,111) i,pes(il),mdot(il),ye(il),pde(il),sle,sge,
     1            rhole,rhoge,se,seold
 111      format ('counter = ',i4,4x,'PES = ',f8.3,4x,'MDOT = ',
     1          f10.5,2(f8.3,3x),/,6(3x,f8.3))
          ENDIF
      if (prop.eq.1.0) then
       call H2SAT(PES(il),tes(il))
      else
       call o2sat(PES(il),tes(il))
        endif
*
*
       PO(1,il)=PES(il)+PDE(il)
       YO(1,il)=YE(il)
c+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++++
c     PRESSURE LOSS CALCULATION THROUGH EACH NODE               +
c   (NODE 1 IS AT THE EXIT & NODE M IS AT THE INLET)             +
c+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++++
       DO N=1,M
          if(il .eq. 1 .and. n .eq. m) goto 60
        IF(N.GT.1) PO(N,il)=PI(N-1,il)
        IF(N.GT.1) YO(N,il)=YI(N-1,il)
        IF(N.GT.1) TSO(N,il)=TSI(N-1,il)
        AREA=A(N,il)
*
      if (N .eq. 1 .and. PSFO .le. 0.0) psfo = po(n,il)
      call value(n2,p2,lvisp,PSFO,vislfo)
      visc = vislfo
      if (il .eq. 1) then
         if (n .ne. 1) then
          dd = vtdi / 12.0
          call frict(dd,ed,mdot(1),visc,ff)
        K(n,1) = ff * length(n)/vtdi
```

```
        else
           K(1,1) = 0.5
          endif
      else
          dd = disp / 12.0
          call frict(dd,ed,mdot(2),visc,ff)
        K(n,2) = ff * length(n)/disp
      endif
      KF=K(N,il)
*
*   CHANGE IN ELEVATION
*
        DHI=DH(N,il)
        DHO=DH(N+1,il)
        HO(N,il)=HS(il)+QDOT(N,il)/MDOT(il)+G*(DH(M+1,il)-DH(N,il))/
   1          (12.0*1728.0)
        HTOT=HO(N,il)
        IF(YO(N,il).LE.0.0) PHASE=1.0
        IF(YO(N,il).GT.0.0) PHASE=2.0
*
*    DETERMINE THE PHASE OF THE FLUID
*
        IF(PHASE.ge.2.0) then
*::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
*   TWO-PHASE FLOW REGION
*::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
          PFO=PO(N,il)
          PSFO=PFO
*
*   DETERMINE THE OUTLET CONDITIONS AT NODE N, GIVEN THE TOTAL
*   PRESSURE AT THE OUTLET
*
          DO I1 = 1,5
           IF(PSFO.LT.PTP) PSFO=PTP
           IF(PSFO.GT.PST) PSFO=PST
           call value(n4,p4,lrhop,PSFO,rholfo)
           call value(n5,p5,grhop,PSFO,rhogfo)
           call value(n8,p8,lentp,PSFO,hlfo)
           call value(n9,p9,gentp,PSFO,hgfo)
           call value(n10,p10,lent,PSFO,slfo)
           call value(n11,p11,gent,PSFO,sgfo)
           call value(n3,p3,gvisp,PSFO,visgfo)
           call value(n2,p2,lvisp,PSFO,vislfo)
           call TPHS(HTOT,RHOLFO,RHOGFO,MDOT(il),AREA,HLFO,HGFO,
   1            slfo,sgfo,yfo,hfo,sfo,rhofo,pdfo)
```

```
          PSFO=PFO-PDFO
*
*     End of I1 Loop (To Determine Node N Outlet Conditions)
*
         enddo
*
         IF (debug .eq. 4.0 .or. debug .ge. 10.0) THEN
          write (6,112) n,i1,psfo,slfo,sgfo,rhofo,yfo,sfo,hfo,pdfo
 112       format ('node #',i2,4x,'counter = ',i4,4x,'PSFO = ',
  1             f8.3,/,7(3x,f8.3))
           ENDIF
*
         PSO(N,il)=PSFO
         PDO(N,il)=PDFO
         RHOLO(N,il)=RHOLFO
         RHOGO(N,il)=RHOGFO
         RHOO(N,il)=RHOFO
         YO(N,il)=YFO
         HO(N,il)=HFO
         SO(N,il)=SFO
         VO(N,il)=144.0*MDOT(il)/(A(N,il)*RHOO(N,il))
*
* calculate the outlet temperature at node 1
*
           if (n .eq. 1) then
         call H2SAT(psfo,ts1)
         call value(n13,p13,cpl,psfo,cp)
            hgl = hgfo - hlfo
            qq = qdot(1,il)/mdot(il)
            if (yo(1,il) .gt. 0.99) then
             if (il .eq. 1) then
              tso(1,1) = tsi(m,1) + (qq - hgl)/cp
          else
           tso(1,2) = tliq + (qq + hgl)/cp
             endif
            else
               tso(1,il) = ts1
            endif
           endif
*
           if (prop.le.1.0) then
          call H2SVEL(YFO,PSFO,RHOLFO,RHOGFO,asvo)
         else
               call value(n12,p12,drhdto,psfo,drhdt1)
               call o2sat(psfo,to)
```

```
            call o2svel(yfo,to,rholfo,rhogfo,drhdt1,asvo)
        endif
        MACHO(N,il)=VO(N,il)/ASVO
        IF(MACHO(N,il).LT.0.0) MACHO(N,il)=0.0
        IF(MACHO(N,il).GT.1.0) MACHO(N,il)=1.0
*
*   INITIAL GUESS AT NODE INLET BASED ON COMPRESSIBLE LOSS
*
        call INITL(PSFO,KF,MDOT(il),AREA,RHOLFO,psfi)
*
*   TOTAL ENTHALPY AT NODE INLET
*
        HI(N,il)=HS(il)+QDOT(N+1,il)/MDOT(il)+
     1          G*(DH(M,il)-DH(N+1,il))/(12.0*1728.0)
        HTOT=HI(N,il)
*
*   DEFINITION OF STATIC PRESSURE AT NODE INLET
*
        DO I2 = 1,50
         IF(PSFI.LT.PTP) PSFI=PTP
         IF(G.LE.0.0.AND.PSFI.LT.PSFO) PSFI=PSFO
         IF(PSFI.GT.PST) PSFI=PST
         call value(n4,p4,lrhop,PSFI,rholfi)
         call value(n5,p5,grhop,PSFI,rhogfi)
         call value(n8,p8,lentp,PSFI,hlfi)
         call value(n9,p9,gentp,PSFI,hgfi)
         call value(n10,p10,lent,PSFI,slfi)
         call value(n11,p11,gent,PSFI,sgfi)
         call value(n3,p3,gvisp,PSFI,visgfi)
         call value(n2,p2,lvisp,PSFI,vislfi)
         call TPHS(HTOT,RHOLFI,RHOGFI,MDOT(il),AREA,HLFI,HGFI,
     1        slfi,sgfi,yfi,hfi,sfi,rhofi,pdfi)
         PFI=PSFI+PDFI
*
*   LOCKHART-MARTINELLI TWO-PHASE FLOW PARAMETER
*
         call XPARAM(YFO,VISLFO,VISGFO,RHOLFO,RHOGFO,YFI,VISLFI,
     1        visgfi,RHOLFI,RHOGFI,xf)
         IF(XF.LT.0.01) XF=0.01
         LGXF=LOG10(XF)
         call value(n1,x1,lmxpar,LGXF,phisqf)
         PHISQF=(10.0**PHISQF)**2
*
*   TWO-PHASE FLOW PRESSURE LOSS AND NODE INLET PRESSURE (PSFN)
*
```

```
        call TPS(AREA,G,DHI,DHO,KF,PSFO,YFO,RHOLFO,RHOGFO,YFI,
     1       rholfi,RHOGFI,MDOT(il),PHISQF,dpff,psfn,dptf,
     2       dpmf)
        ERR(N,il)=ABS(PSFN-PSFI)
        PSFI=(PSFI+PSFN)/2.0
*
*  CONDITION WHERE THE INLET STATIC PRESSURE OF THE NODE IS
DETERMINED
*
        IF(ERR(N,il).LE.ERRMX) GO TO 50
*
*     End of I2 Loop (To Determine Node N Inlet Conditions)
*
       enddo
 50     PFI=PSFI+PDFI
*
       IF (debug .eq. 5.0 .or. debug .ge. 10.0) THEN
        write (6,113) n,i2,psfi,slfi,sgfi,rhofi,yfi,sfi,hfi,
     1                  phsiqf
 113     format ('node #',i2,4x,'counter = ',i4,4x,'PSFI = ',
     1        f8.3,/,6(3x,f8.3),/,3x,f8.3)
        ENDIF
*
*   CALCULATE THE INLET CONDITIONS OF THE NODE N
*
       RHOLI(N,il)=RHOLFI
       RHOGI(N,il)=RHOGFI
       RHOI(N,il)=RHOFI
       DPM(N,il)=DPMF
       DPF(N,il)=DPFF
       DPT(N,il)=DPTF
       PI(N,il)=PFI
       PDI(N,il)=PDFI
       PSI(N,il)=PSFI
       YI(N,il)=YFI
       HI(N,il)=HFI
       SI(N,il)=SFI
       PHISQ(N,il)=PHISQF
       VI(N,il)=144.0*MDOT(il)/(A(N,il)*RHOI(N,il))
         if (prop.le.1.0) then
        call H2SVEL(YFI,PSFI,RHOLFI,RHOGFI,asvi)
       else
            call value(n12,p12,drhdto,psfi,drhdt2)
            call o2sat(psfi,ti)
            call o2svel(yfi,ti,rholfi,rhogfi,drhdt2,asvi)
```

```
          endif
          MACHI(N,il)=VI(N,il)/ASVI
          IF(MACHI(N,il).LT.0.0) MACHI(N,il)=0.0
          IF(MACHI(N,il).GT.1.0) MACHI(N,il)=1.0
*
*    CALCULATE THE TWO PHASE HEAT TRANSFER COEFFICIENT FOR NODE N
*    BASED ON INLET PRESSURE
*
          call value(n13,p13,cpl,psfi,cp)
          call value(n13,p13,thkl,psfi,cond)
          call value(n13,p13,surft,psfi,st)
          call value(n13,p13,stemp,psfi,ts)
*
*        do nn1 = 1, 2
*
            if (tave(n,il) .le. 0.0) then
                tave(n,il) = ts
          endif
            hgl = hgfi - hlfi
*
            if (il .eq. 1) then
           dtemp = twall(n) - tave(n,il)
                di = exdi
            else
           dtemp = tave(n,il) - twall(n)
                di = disp
            endif
*
            dpress = 778.2 * dtemp * rhogfi * hgl / ts
            if (yfi .gt. 0.7) then
             re = 48.0 * mdot(il) * (1.0-0.7)/(pyi * vislfi * di)
            else
             re = 48.0 * mdot(il) * (1.0-yfi)/(pyi * vislfi * di)
            endif
c           write (6,*) dtemp,dpress,cp,cond,vislfi,rholfi,rhogfi,
c    1                     st,hgl,re,xf
*
            call htcoeff(phase,dtemp,dpress,cp,cond,vislfi,rholfi,
     1                     rhogfi,st,hgl,re,xf,di,qdott)
         if (yfi .ge. 0.7) then
              tdim = 0.0
           call value2(n14,num1,p14,t14,cpg,psfi,tdim,cp)
           call value2(n14,num1,p14,t14,thkg,psfi,tdim,cond)
           call value2(n14,num1,p14,t14,viscg,psfi,tdim,visgfi)
           re = 48.0 * mdot(il) /(pyi * visgfi * di)
```

```
         call htcoeff(3.0,dtemp,dpress,cp,cond,visgfi,rholfi,
   1                 rhogfi,st,hgl,re,xf,di,qtt)
            qdott = qdott*(1-yfi) + qtt*yfi
          endif
          if (il .eq. 1) then
        q(n,il) = qdott * (twall(n) - tave(n,il)) * sarea(n,il)
   1            /144.0
       else
        q(n,il) = qdott * (tave(n,il) - twall(n)) * sarea(n,il)
   1            /144.0
       endif
*
* calculate the inlet temperature at node il
*
        call value(n13,p13,cpl,psfi,cp)
           if (yi(n,il) .gt. 0.99) then
            if (il .eq. 1) then
             tsi(n,il) = tso(n,il) - q(n,il)/(mdot(il) * cp)
               else
             tsi(n,il) = tso(n,il) + q(n,il)/(mdot(il) * cp)
               endif
           else
               tsi(n,il) = ts
        endif
*
           XTT(N,il) = XF
           RN(N,il) = RE
           QDTT(N,il) = QDOTT
           TAVE(N,il) = (tsi(n,il) + tso(n,il))/2.0
*
*      enddo
*
           if (debug .ge. 10.0) then
            write (6,120) tsi(n,il),twall(n),tave(n,il),re,qdott,
   1                     q(n,il),sarea(n,il)
 120       format(4(2x,f14.4),/,3(2x,f14.4))
           endif
       ELSE
*::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
*   SINGLE PHASE FLOW (PHASE=1.0, LIQUID FLOW)
*::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
*   CALCULATION OF OUTLET CONDITIONS GIVEN TOTAL PRESSURE AT NODE
*   OUTLET   (PO(N))
*
        PFO=PO(N,il)
```

```
          PSFO=PFO
          DO I3 = 1,5
           IF(PSFO.LT.PTP) PSFO=PTP
           IF(PSFO.GT.PST) PSFO=PST
           call value(n4,p4,lrhop,PSFO,rholfo)
           PDFO=144.0*MDOT(il)/A(N,il)*MDOT(il)/A(N,il)/
     1          (2.0*RHOLFO*32.2)
           PSFO=PFO-PDFO
c
c     End of I3 Loop (To Determine Node N Outlet Conditions)
c
          enddo
c
          IF(PSFO.LT.PTP) PSFO=PTP
          IF(PSFO.GT.PST) PSFO=PST
          call value(n8,p8,lentp,PSFO,hfo)
          call value(n10,p10,lent,PSFO,sfo1)
          call value(n13,p13,cpl,psfo,cp)
          call value(n2,p2,lvisp,PSFO,vislfo)
*
            if (n .eq. 1) then
             if (il .eq. 1) then
               tso(1,il) = tsi(m,il) + qdot(1,il)/(mdot(il) * cp)
           else
               tso(1,il) = tliq + qdot(1,il)/(mdot(il) * cp)
             endif
            endif
          PSO(N,il)=PSFO
          PDO(N,il)=PDFO
          RHOLO(N,il)=RHOLFO
          RHOGO(N,il)=0.0
          RHOO(N,il)=RHOLFO
          YO(N,il)=0.0
          HO(N,il)=HS(il)+QDOT(N,il)/MDOT(il)+G*
     1           (DH(M+1,il)-DH(N,il))/(12.0*1728.0)
          SO(N,il)=SFO1
          VO(N,il)=144.0*MDOT(il)/(A(N,il)*RHOO(N,il))
          ASVO=AVLIQ
          MACHO(N,il)=VO(N,il)/ASVO
          IF(MACHO(N,il).LT.0.0) MACHO(N,il)=0.0
          IF(MACHO(N,il).GT.1.0) MACHO(N,il)=1.0
c
          IF (debug .eq. 6.0 .or. debug .ge. 10.0) THEN
           write (6,114) n,i3,psfo,pdfo,tso(n,il),rholfo,hfo,
     1          so(n,il),vo(n,il),htote(il),tso(n,il)
```

```
 114        format ('Node # = ',i4,4x,'Counter = ',i4,4x,
   1            'Liquid PSFO = ',f8.3,/,8(3x,f8.3))
          ENDIF
*
*   INLET CONDITION CALCULATIONS
*
        RHOLI(N,il)=RHOLO(N,il)
        RHOGI(N,il)=0.0
        RHOI(N,il)=RHOLI(N,il)
        DPM(N,il)=0.0
        DPF(N,il)=144.0*K(N,il)/(2.0*RHOLI(N,il)*32.2)*
   1                (MDOT(il)/A(N,il))**2
        DPT(N,il)=DPF(N,il)
        PI(N,il)= PO(N,il)+DPF(N,il)-G*RHOLI(N,il)*
   1            (DH(N,il)-DH(N+1,il))/1728.0
        PDI(N,il)=144.0*(MDOT(il)/A(N,il))**2/
   1            (2.0*RHOLI(N,il)*32.2)
        PSI(N,il)=PI(N,il)-PDI(N,il)
        YI(N,il)=0.0
        VI(N,il)=144.0*MDOT(il)/(RHOLI(N,il)*(A(N,il)))
        ASVI=AVLIQ
        MACHI(N,il)=VI(N,il)/ASVI
        PSFI=PSI(N,il)
        IF(PSFI.LT.PTP) PSFI=PTP
        IF(PSFI.GT.PST) PSFI=PST
        call value(n2,p2,lvisp,PSFI,vislfi)
        call value(n8,p8,lentp,PSFI,hlf)
        call value(n10,p10,lent,PSFI,slf)
*        HI(N,il)=HLF
        HI(N,il)=HS(il)+QDOT(N+1,il)/MDOT(il)+
   1              G*(DH(M,il)-DH(N+1,il))/(12.0*1728.0)
        SI(N,il)=SLF
        PHISQ(N,il)=1.0
c
        IF (debug .eq. 6.0 .or. debug .ge. 10.0) THEN
         write (6,214) n,psfi,pdi(n,il),dpm(n,il),
   1              dpf(n,il),dpt(n,il),vi(n,il)
 214       format ('Node # = ',i4,4x,'Liquid PSFI = ',f8.3,/,
   1           5(3x,f8.3))
          ENDIF
*
*   CALCULATE THE HEAT TRANSFER COEFFICIENT FOR NODE N
*   BASED ON INLET PRESSURE
*
        call value(n13,p13,cpl,psfi,cp)
```

```
         call value(n13,p13,thkl,psfi,cond)
         call value(n13,p13,surft,psfi,st)
         call value(n13,p13,stemp,psfi,ts)
            if (tave(n,il) .le. 0.0) then
                 tave(n,il) = tso(n,il)
         endif
            hgl = hgfi - hlfi
*
            if (il .eq. 1) then
          dtemp = twall(n) - tave(n,il)
                 di = exdi
            else
          dtemp = tave(n,il) - twall(n)
                 di = disp
            endif
*
            dpress = 778.2 * dtemp * rhogfi * hgl / ts
            re = 48.0 * mdot(il)/(pyi * vislfi * di)
            call htcoeff(phase,dtemp,dpress,cp,cond,vislfi,rholfi,
     1                    rhogfi,st,hgl,re,xf,di,qdott)
          if (il .eq. 1) then
        q(n,il) = qdott * (twall(n) - tave(n,il)) * sarea(n,il)
     1          /144.0
        else
        q(n,il) = qdott * (tave(n,il) - twall(n)) * sarea(n,il)
     1          /144.0
        endif
*
            if (il .eq. 1) then
             tsi(n,il) = tso(n,il) - q(n,il)/(mdot(il) * cp)
            else
             tsi(n,il) = tso(n,il) + q(n,il)/(mdot(il) * cp)
            endif
            XTT(N,il) = XF
            RN(N,il) = RE
            QDTT(N,il) = QDOTT
            TAVE(N,il) = (tsi(n,il) + tso(n,il))/2.0
*
          IF (debug .eq. 6.0 .or. debug .ge. 10.0) THEN
           write (6,314) tsi(n,il),q(n,il),dtemp,xf,re,qdott,
     1          hgl,cp,di,tave(n,il)
 314       format ('Liquid TSI = ',f8.3,3x,f10.4,2(3x,f8.3),3x,
     1          f12.2,/,5(3x,f8.3))
           ENDIF
*
```

```
        ENDIF
*        PO(N+1,il)=PI(N,il)
c++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++
c   End of N do loop (Conditions for Both the Inlet & Outlet of the    +
c                Nodal Network are Defined)                      +
c++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++
  60    continue
       ENDDO
c..................................................................
c   RE-CALCULATE THE NODAL PROPERTIES OF THE NODES THAT ARE 100% GAS
.
c..................................................................
          if (il .eq. 1) then
           do ig = m1, 1, -1
            if (yo(ig,1) .gt. 0.99) goto 130
           enddo
 130      phase = 3.0
           dummy = 1.4 * 766.55232 * 32.2
           do ia = ig, 1, -1
            if (yo(ia,1) .ge. 0.99) then
            iia = ia + 1
             psi(ia,1) = pso(iia,1)
             tsi(ia,1) = tso(iia,1)
             hi(ia,1) = ho(iia,1)
             rhogi(ia,1) = psi(ia,1) * 144.0 / (766.55232 * tsi(ia,1))
             rholi(ia,1) = 0.0
             rhoi(ia,1) = rhogi(ia,1)
             vi(ia,1) = 144.0 * mdot(il) / (a(ia,1) * rhoi(ia,1))
             asvi = (dummy * dabs(tsi(ia,1)))**0.5
             machi(ia,1) = vi(ia,1)/asvi
   if (debug .eq. 8.0 .or. debug .ge. 10.0) then
      write(6,9990) ia,psi(ia,1),tsi(ia,1),hi(ia,1)
      write(6,9991) vi(ia,1),asvi,machi(ia,1)
      write(6,9992) rhoi(ia,1),rholi(ia,1),rhogi(ia,1)
9990    format('node # =',3x,i3,3x,'ps, ts, h (in) =',3(2x,f10.4))
9991    format('vel, a, m (in) =',3(2x,f10.4))
9992    format('rho(in) =',3(2x,f10.4))
   endif
*
*   CALCULATE THE HEAT TRANSFER COEFFICIENT FOR 100% GAS NODES
*   BASED ON INLET PRESSURE
*
        call value(n13,p13,stemp,psi(ia,1),ts)
```

```
            tdim = (tsi(ia,1)-ts)/(tcnst-ts)
            if (tdim .lt. 0.0) tdim = 0.0
          call value2(n14,num1,p14,t14,cpg,psi(ia,1),tdim,cp)
          call value2(n14,num1,p14,t14,thkg,psi(ia,1),tdim,cond)
          call value2(n14,num1,p14,t14,viscg,psi(ia,1),tdim,visgfi)
          ti = tsi(ia,1) * (1.0 + 0.2 * machi(ia,1) ** 2.0)
          pi(ia,1) = psi(ia,1) * (1.0 + 0.2 * machi(ia,1) ** 2.0)
            pdi(ia,1) = pi(ia,1) - psi(ia,1)
          hgl = hgfi - hlfi
*
          dtemp = 0.0
          dpress = 0.0
          re = 48.0 * mdot(il) /(pyi * visgfi * exdi)
          call htcoeff(phase,dtemp,dpress,cp,cond,visgfi,rholfi,
     1                 rhogfi,st,hgl,re,xf,exdi,qdott)
      if (debug .eq. 8.0 .or. debug .ge. 10.0) then
        write(6,9993) cp,cond,visgfi
        write(6,9994) ti,pi(ia,1),pdi(ia,1),re,qdott,
     1                  twall(ia),tave(ia,1)
 9993   format('cp, k, mu =',3(2x,f10.4))
 9994   format('To, Po, Pd(in) =',3(2x,f12.4),/,
     1        'Re, Hc ,Twall, Tave =',4(2x,f12.4))
      endif
*
*   CALCULATE THE OUTLET PROPERTIES OF THE GAS NODE
*
         do nn1 = 1, 2
          if(tave(ia,1) .le. 0.0) tave(ia,1) = ti
*          if(nn1 .eq. 1) tave(ia,1) = ti
          dtemp = twall(ia) - tave(ia,1)
*
            to = ti + (pyi * length(ia) * qdott * (twall(ia)-ti) *
     1          exdi / (mdot(il) * cp * 144.0))
            if (to .lt. 0.0) to = ti/2.0
            call htandf(machi(ia,1),ti,to,twall(ia),macho(ia,1))
          ratio = (1+0.2*machi(ia,1)**2.0)/(1+0.2*macho(ia,1)**2.0)
            tso(ia,1) = tsi(ia,1) * (to/ti) * ratio
            pso(ia,1) = psi(ia,1) * (machi(ia,1)/macho(ia,1)) *
     1               (tso(ia,1)/tsi(ia,1))**0.5
            vo(ia,1) = vi(ia,1) * (machi(ia,1)/macho(ia,1)) *
     1              (tso(ia,1)/tsi(ia,1))**0.5
            po(ia,1) = pi(ia,1) * (tso(ia,1)/tsi(ia,1)) * ratio**3.5
            pdo(ia,1) = po(ia,1) - pso(ia,1)
          ho(ia,1) = hi(ia,1) + cp * (to-ti)
            rhoo(ia,1) = rhoi(ia,1) * pso(ia,1) * tsi(ia,1) /
```

```
     1             (psi(ia,1) * tso(ia,1))
              rholo(ia,1) = 0.0
              rhogo(ia,1) = rhoo(ia,1)
              q(ia,1) = qdott * dtemp * sarea(ia,1)/144.0
              tave(ia,1) = (tsi(ia,1) + tso(ia,1))/2.0
              qdtt(ia,1) = qdott
      if (debug .eq. 8.0 .or. debug .ge. 10.0) then
         write(6,9995) pso(ia,1),to,tso(ia,1),ho(ia,1),rhoo(ia,1),
     1             vo(ia,1),asvi,macho(ia,1),q(ia,1),dtemp,
     2           twall(ia),tave(ia,1)
 9995    format('Ps, To, Ts(out) =',3(2x,f12.4),/,'H, rho, vel(out) ='
     1        ,3(2x,f12.4),/,'a, M, Qdot (out) =',3(2x,f12.4),/,
     2        'Dt , Twall ,Tave =',3(2x,f12.4))
      endif
            enddo
             endif
             rn(ia,1) = re
            enddo
           endif
c..................................................................
c   END OF RE-CALCULATING GAS NODES
c..................................................................
           enddo
c---------------------------------------------------------------------
c   END OF THE VENT & SPRAY NODAL NETWORK FLOW PROPETIES
CALCULATION !
c---------------------------------------------------------------------
*
*   CALCULATE THE TOTAL QDOT & NEW TWALL FOR ALL THE ELEMENTS IN
THE NETWORK
*
           flag1 = 0.0
         do jj = 1,m
          qdt = qdt + q(jj,1)
            qdt1 = qdt1 + q(jj,2)
            delta(jj) = q(jj,1)-q(jj,2)
          if (dabs(delta(jj)) .le. dq) flag1 = flag1 + 1.0
           enddo
         qerr = qdt1 - qdt
*         qerr = qdot(1,1) - qdt
*
         IF (debug .eq. 1.0 .or. debug .ge. 10.0) THEN
          write (6,116) l,time,mass,mdot(1),ps,qerr,pes,po(1,1),
     1            po(2,1),po(3,1),po(4,1),po(11,1),po(12,1),
     2          pi(1,1),pi(2,1),pi(3,1),pi(4,1),pi(11,1),
```

```
  3             pi(12,1)
116     format ('iteration # ',i3,2x,'time =',f8.3,3x,'mass =',
  1         f8.3,4x,'mdot =',f10.5,/,'pst =',f8.3,4x,'qerr =',
  2         f8.3,4x,'pes =',f8.3,/,6(3x,f8.3),/,6(3x,f8.3))
        ENDIF
        if (debug .eq. 9.0) then
          write(6,117) l,qdt,qdt1,qerr
          do jj = 1,m
           write(6,118) jj,twall(jj),q(jj,1),q(jj,2),delta(jj),
  1                     tsi(jj,1),tso(jj,1),tsi(jj,2),tso(jj,2),
  2                      qdtt(jj,1),qdtt(jj,2)
          enddo
117     format ('iteration # ',i3,2x,'Gas Qdot =',f8.3,3x,
  1       'Liq Qdot =',f8.4,3x,'Q error =',f8.4,//,t3,'Node #',
  2    t13,'T wall',t23,'Gas Q',t33,'Liq Q',t43,'Delta Q',t53,
  3    'G Tsi',t63,'G Tso',t73,'L Tsi',t83,'L Tso',t93,'G Hc',
  4    t103,'L Hc',/)
118     format (6x,i4,10(2x,f8.4))
        endif
************************************************************************
*    CONDITION TO END THE QDOT CONVERGENCE LOOP                       *
*                                                *
      IF (dabs(qerr) .le. qdterr .or. flag1 .ge. m8) goto 200
*                                                *
*     End of L do loop (The Calculated Qdot to the Nodal          *
*                  Model is Within the Error Margin of PERRMX   *
*                   to the past Qdot)                 *
*
      ENDDO
************************************************************************
 200  do ii = 1,m1
       nn = m - ii
       qdot(nn,1) = qdot(nn+1,1) + q(nn,1)
       qdot(nn,2) = qdot(nn+1,2) - q(nn,2)
        enddo
c
c    DETERMINE THE EXIT PLANE CONDITIONS
c
        j2 = 0
        if (va .eq. 1) ax = sa
      PXS=PSO(1,1)
 205    IF(PXS.LT.PTP) PXS=PTP
       IF(PXS.GT.PST) PXS=PST
       call value(n8,p8,lentp,PXS,hlx)
       call value(n9,p9,gentp,PXS,hgx)
```

```
      call value(n10,p10,lent,PXS,slx)
      call value(n11,p11,gent,PXS,sgx)
      call value(n4,p4,lrhop,PXS,rholx)
      call value(n5,p5,grhop,PXS,rhogx)
      YX=(SO(1,1)-SLX)/(SGX-SLX)
      HX=YX*HGX+(1.0-YX)*HLX
      VX=SQRT(2.0*32.2*777.649*ABS(HTOTE(1)-HX))
      RHOX=144.0*MDOT(1)/(VX*AX)
      RHOXV=YX/(1.0/RHOX-1.0/RHOLX*(1.0-YX))
      call value(n6,rhovp,p6,RHOXV,pxsc)
        if (j2 .eq. 0) psx1 = pxsc
        gamma = dabs(pxs - psx1)
      psx1 = pxs
      gerr = pxsc - pxs
      IF (dabs(gerr) .gt .0.001) then
       if (gerr .gt. 0.0) then
        pxs = pxs + gamma/2.0
       else
          pxs = pxs - gamma/2.0
       endif
         j2 = j2 + 1
         if (j2.gt.150) go to 210
         go to 205
        endif
*
 210    IF (debug .eq. 7.0 .or. debug .ge. 10.0) THEN
       write (6,115) j2,pxs,time,gerr,mass,slx,sgx,rhox,yx,sx,hx
 115     format ('counter = ',i4,4x,'PXS = ',f8.3,3(3x,f8.3),/,
  1           6(3x,f8.3))
        ENDIF
*
     if (prop.eq.1.0) then
      call H2SAT(pxs,tx)
     else
      call o2sat(pxs,tx)
       endif
     PXD=144.0/(2.0*RHOX*32.2)*(MDOT(1)/AX)*(MDOT(1)/AX)
     PX=PXS+PXD
     FM=MDOT(1)*VX/32.2
     FP=PXS*AX
     THRUST=FM+FP
     ISP=THRUST/MDOT(1)
       dpx = pxs - ptp
       flag = 0.0
       flag1 = 0.0
```

```
      flag3 = 0.0
      IF (dpx .le. delptp) then
       exit = 1
    ENDIF
*
*     Print Output
*
   do l1 = 1, 2
   if (l1 .eq. 1) then
    write (6,1000) subhd,subt
      write (6,1430)
    write (6,1100) name(1),mdot(l1),name(2),isp,name(3),thrust,
   1            name(4),qerr,name(5),rhot,name(6),pst,name(7),
   2            pes(l1),name(8),htot,name(9),a(1,l1)
    write (6,1200)
    write (6,1300) pxs,tx,rhox,yx,hx,vx
    write (6,1400) pes(l1),tes(l1),rhoe(l1),ye(l1),htote(l1)
   else
    write (6,1000) subhd,subt
      write (6,1460)
    write (6,1100) name(1),mdot(l1),name(2),isp,name(3),thrust,
   1            name(4),qerr,name(5),rhot,name(6),pst,name(7),
   2            pes(l1),name(8),htot,name(9),a(1,l1)
    write (6,1200)
    write (6,1400) pes(l1),tes(l1),rhoe(l1),ye(l1),htote(l1)
   endif
   do nc1 = 1,m
   write (6,1500) nc1,pso(nc1,l1),tsi(nc1,l1),rhoo(nc1,l1),
   1      yo(nc1,l1),ho(nc1,l1),vo(nc1,l1),qdot(nc1,l1),
   2      a(nc1,l1),phisq(nc1,l1),length(nc1),dpf(nc1,l1),
   3      dpm(nc1,l1),dpt(nc1,l1),xtt(nc1,l1),rn(nc1,l1),
   4      qdtt(nc1,l1)
   enddo
   write (6,1600) pst,tliq,rholt,yt,hs(l1)
   enddo
*
   write (6,1000) subhd,subt
   write (6,1700) ps,tsp,tts,mdot(1)
   do l1 = 1, 2
   if (l1 .eq. 1) then
      write (6,1430)
    write (6,1800)
   else
      write (6,1460)
    write (6,1800)
```

```
      endif
      do nc2 = 1,m
      write (6,1900) nc2,pi(nc2,l1),psi(nc2,l1),pdi(nc2,l1),
     1          po(nc2,l1),pso(nc2,l1),pdo(nc2,l1),tsi(nc2,l1),
     2          tso(nc2,l1),twall(nc2),tave(nc2,l1),q(nc2,l1),
     3          delta(nc2),k(nc2,l1)
      enddo
      enddo
*
 1000 format('1',//,18a4,/,10a8,/)
 1100 format(9(4x,a8,f9.4,/))
 1200 format(t2,'NODE #',t11,'STATIC P',t23,'TEMP',t32,'DENSITY',
     1    t42,'QUALITY',t51,'ENTHALPY',t61,'VELOCITY',t73,'QDOT',
     2    t83,'AREA',t93,'PHISQ',t102,'LENGTH',t114,'DPF',t124,'DPM',
     3    t134,'DPT',t144,'Xtt',t153,'Re #',t160,'Ht Trans C')
 1300 format(/,t2,'OUTLET',t11,f9.4,4(x,f9.4),x,f9.2)
 1400 format(/,t2,'EXIT',t11,f9.4,3(x,f9.4),x,f9.2)
 1430 format(/,t2,'FLOW PROPERTIES OF THE VENT PART OF THE SYSTEM')
 1460 format(/,t2,'FLOW PROPERTIES OF THE HEAT EXCHANGER PART OF',
     1    ' THE SYSTEM')
 1500 format(t4,i3,t11,f9.4,7(x,f9.4),x,f9.2,5(x,f9.4),x,f9.2,x,f9.4)
 1600 format(/,t2,'INLET',t11,f9.4,5(x,f9.4))
 1700 format(/,t2,'Ptank static',t21,f9.4,/,t2,'Pchoke',t21,f9.4,/,t2,
     1    'Tchoke',t21,f9.4,/,t2,'Mdot',t21,f9.4)
 1800 format(/,t2,'NODE #',t13,'Pt in',t25,'Ps in',t34,'Pd in',
     1    t44,'Pt out',t53,'Ps out',t63,'Pd out',t73,'Ts in',t83,
     2    'Ts out',t93,'T wall',t103,'T ave',t113,'Qdot',t123,
     3    'Del Q',t133,'K loss',/)
 1900 format(t4,i3,t11,f9.4,12(x,f9.4))
      STOP
      END

      subroutine H2SAT(PST,tsat)
c
      double precision pst,tsat,fp,t
c
      FP=LOG(PST/187.506)
      T=1.00003+FP*(2.12094E-1+FP*(2.83129E-2+FP*1.75686E-3))
      TSAT=59.3568*T
      return
      END

      subroutine h2SVEL(Y,PS,RSL,RSV,as)
c
      double precision ps,rsl,rsv,as,p,fpf,tst1,ts,tsm,tc,tfun,t,tk
```

```
      double precision pa,dpvdt,d2pvt1,d2pvdt,csatt1,csatt2,csat
      double precision drodt1,tt,drodt2,drodt,rho,dsdrho,dsdp1,dsdp
c
      P=PS/187.506264
      FPF=LOG(P)
      TST1=FPF*(2.83128E-2+FPF*(1.75686E-3))
      TS=1.00002+FPF*(2.12094E-1+TST1)
      TSM=TS*32.976
      TC=32.976
      TFUN=(TC-TSM)**0.33333
      T=TSM*1.8
      IF(Y.LE.0.0) Y=0.0
      TK=T/1.8
      PA=10.0**(2.00062-50.0970/(TK+1.0044)+1.74849E-2*TK)*14.696
      DPVDT=PA*2.30258*(50.0970/(TK+1.0044)**2+1.74849E-2)/1.8
      D2PVT1=DPVDT**2/PA
      D2PVDT=D2PVT1+PA*2.30258/1.8**2*(-2.0*50.0970/(TK+1.00044)**3)
      CSATT1=1.68157*TK/(32.976-TK)**0.1-32.8027
      CSATT2=TK*(3.35743E-2+TK*(-7.68297E-4+6.90292E-6*TK))
      CSAT=(CSATT1+TK*(6.81698+TK*(-0.731943+CSATT2)))/2.01572
      DRODT1=-0.38* 7.32346E-3/(32.976-TK)**0.62+4.40742E-4
      TT=(32.976-TK)**0.333333
      DRODT2=TT*TT*(1.66667*2.92263E-04-2.0*4.00849E-05*TT)
      DROLDT=(DRODT1-1.33333*6.62079E-4*TT+DRODT2)*69.9099
      RHO=1.0/(1.0/RSL+Y*(1.0/RSV-1.0/RSL))
      DSDRHO=-1.0/RHO/RHO*DPVDT*144.0
      DSDP1=777.649/144.0*CSAT/(T*DPVDT)+1.0/RSL/RSL*DROLDT
      DSDP=DSDP1+(1.0/RHO-1.0/RSL)*D2PVDT/DPVDT
      AS=SQRT(ABS(-DSDRHO/DSDP*32.2))
      return
      END

      subroutine htcoeff(phase,dt,dp,cp,k,mu,rhol,rhov,st,lambda,re,x,
     1                   diam,qdot)
c
c  This subroutine calculates the two phase heat transfer coefficent
c
      double precision cp,k,mu,rhol,rhov,st,x
      double precision lgx(12),lgf(12),lgsf(12),sf(12),f,s,c2,d3
      real lambda
c
      data lgx/-1.0,-0.824,-0.745,-0.699,-0.585,0.0,0.176,0.398,0.663,
     1        0.778,1.778,2.0/
      data lgf/0.0,0.0212,0.0414,0.0569,0.1139,0.4472,0.5563,0.699,
     1        0.8751,0.9542,1.699,1.8692/
```

```
      data lgsf/0.176,0.415,0.672,1.0,1.19,1.29,1.398,1.544,1.602,
     1        1.663,1.778,2.0/
      data sf/0.84,0.73,0.58,0.37,0.25,0.2,0.16,0.12,0.11,0.1,0.09,
     1      0.09/
c
      dtemp = abs(dt)
      dpress = abs(dp)
      gc = 32.2
      a1 = .023
      a2 = re**0.8
      a3 = (cp * mu * 3600. / k)**0.4
      a4 = (k * 12.) / (3600. * diam)
      hfc = a1 * a2 * a3 * a4
      if (phase .lt. 1.5 .or. phase .ge. 3.0) then
         qdot = hfc
c      write(6,*) cp,mu,k,diam,a1,a2,a3,a4,qdot
         return
      endif
c      write(6,*) a1,a2,a3,a4
c
      b1 = .00122
      b2 = ((k/3600.)**0.79) * (cp**0.45) * (rhol**0.49) * (gc**0.25) *
     1     (dtemp**0.24) * (dpress**0.75)
      b3 = ((st*12.)**0.5) * (mu**0.29) * (lambda**0.24) * (rhov**0.24)
      hfz = b1 * b2 / b3
c      write(6,*) b1,b2,b3
c
      c1 = 1 / x
      c2 = log10(c1)
      if (c2 .gt. 2.0) c2 = 2.0
      call value(12,lgx,lgf,c2,f)
      f = 10.0**f
c      write(6,*) c1,c2,f
c
      d1 = re * f**1.25
      d2 = d1 / 10000.0
      d3 = log10(d2)
      if (d3 .gt. 2.0) d3 = 2.0
      call value(12,lgsf,sf,d3,s)
c      write(6,*) d1,d2,d3
      qdot = hfc*f + hfz*s
c      write (6,100) b2,b3,c1,c2,d1,d2
c      write (6,100) re,hfc,f,hfz,s,qdot
c100  format (3(3x,f14.4),/,3(3x,f14.4))
      return
```

```
      END

      subroutine INITL(PO,K,MDOT,A,RHO,pin)
      double precision po,rho,pin,dpf
c
      real k,mdot
c
      DPF=144.0*K*((MDOT/A)**2.0)/(2.0*RHO*32.2)
      PIN=PO+DPF
      return
      END

      subroutine spray(mdot,psmi,dsm,ed,pback)
c
c  subroutine spray.f to model flow in the spray injection tube
c
      character*1 label
      double precision rod(12),lod(12),roverd,loverd,pback
      real mdin(200),mdout(200),mds(200),as(200),vel(200)
      real pin(200),pout(200),pnode(200),ptank(200),x(200),delpt(200)
      real node(10),asec(10)
      real subhd(18),xtitl(18),yp(18),ymdot(18),ymds(18),
     1    yvel(18),yas(18)
      real mdot,mdoti,mdoto,mdots,mdotp
      real kfsm,kbsm,kcsm,kbsi,ks
      integer*2 ibox,iloc
      common /contrl/ibox,iloc
      data nb/12/rod/1.,1.5,2.,3.,4.,6.,8.,10.,12.,14.,16.,20./
      data lod/20.,14.,12.,12.,14.,17.,24.,30.,34.,38.,42.,50./
      ibox = 1
      iloc = 0
*
      open (unit=8, file='spray.data',status='unknown')
*
      read (8,100) label
      read (8,*) pu,zliq,ztank,dmdot
      read (8,100)
      read (8,*) zsm,dsi,zsi,n,nbar
      read (8,100)
      read (8,*) ks,cds,acc,rho,visc,roverd
      read (8,100)
      read (8,*) tol,nlim
      read (8,100)
      read (8,*) opn,opt,omdin,omds,ovel,oas
      read (8,101) subhd,xtitl,yp,ymdot,ymds,yvel,yas
```

```
      read (8,*) nsec
      do i = 1,nsec
         read (8,*) node(i),asec(i)
      enddo
  100 format (//a1)
  101 format (18a4/18a4/18a4/18a4/18a4/18a4/18a4)
      write (6,1)
  1   format (5x,'SPRAY MANIFOLD AND INJECTION TUBE FLOW MODEL'/)
      write (6,2) zliq,pu,psmi,acc,rho,zsm,dsm
  2   format (5x,'Liquid Level                    = ',f6.1,' in'/
     1        5x,'Ullage Pressure                 = ',f6.2,' psia'/
     2        5x,'Spray Manifold Inlet Pressure   = ',f6.3,' psia'/
     3        5x,'Acceleration Level              = ',f6.1,' g'/
     4        5x,'Liquid Density                  = ',f6.3,' lbm/ft3'/
     5        5x,'Spray Manifold Tube Length      = ',f6.1,' in'/
     6        5x,'Spray Manifold Tube ID          = ',f6.2,' in')
      dzsi = zsi/n
      write (6,3) nbar,zsi,dsi,n,dzsi,ks
  3   format (5x,'Number of Spray Injection Tubes = ',i6/
     1        5x,'Spray Injection Tube Length     = ',f6.1,' in'/
     2        5x,'Spray Injection Tube ID         = ',f6.3,' in'/
     3        5x,'Number of Orifices              = ',i6/
     4        5x,'Orifice Spacing                 = ',f6.2,' in'/
     5        5x,'Orifice Loss Coefficient        = ',f6.2/)
      pu = 144.*pu
      psmi = 144.*psmi
      tol = 144*tol
      zliq = zliq/12.
      ztank = ztank/12.
      dsm = dsm/12.
      dsi = dsi/12.
      zsm = zsm/12.
      zsi = zsi/12.
      dzsi = dzsi/12.
      asm = 3.14159*dsm*dsm/4.
      asi = 3.14159*dsi*dsi/4.
      do j = 1,nsec
         n1 = n2 + 1
         n2 = node(j)
         do i = n1,n2
           as(i) = asec(j)/144.
        enddo
      enddo
      kcsm = .5*(1. - (dsi/dsm)**2)
      call value(nb,rod,lod,roverd,loverd)
```

```
zu = ztank - zliq
gc = 32.2
do 10 j = 1,nlim
    qsm = (mdot/asm)**2/(2.*rho*gc)
  call frict(dsm,ed,mdot,visc,fsm)
  kfsm = fsm*zsm/dsm
  kbsm = fsm*loverd
  dpfsm = qsm*(kfsm + kbsm + kcsm)
  dpf1 = qsm*(kfsm)
    phsm = rho*acc*zsm
  psmo = psmi - dpfsm - phsm
  pback = psmi - dpf1
  pback = pback/144.0
    dpsm = dpfsm + phsm
  mdoti = mdot/nbar
    qi = (mdoti/asi)**2/(2.*rho*gc)
  call frict(dsi,ed,mdoti,visc,fsi)
  kbsi = fsi*loverd
    dpsi = qi*kbsi
  pi = psmo - dpsi
  do i = 1,n
      x(i) = i*dzsi - dzsi/2.
    aorf = as(i)
      z = ztank - zsi + x(i)
      if (z .lt. zu) pt = pu
      if (z .ge. zu) pt = pu + rho*acc*(z - zu)
    call pres(i,n,pi,po,pn,pt,dpf,ph,mdoti,mdoto,mdots,
1           dzsi,dsi,ed,asi,aorf,ks,rho,visc,acc)
      if (aorf .le. 0.0) vel(i) = 0.0
      if (aorf .gt. 0.0) vel(i) = mdots/(rho*cds*aorf)
      pin(i) = pi
      pout(i) = po
      pnode(i) = pn
      ptank(i) = pt
      mdin(i) = mdoti
      mdout(i) = mdoto
      mds(i) = mdots
      pi = pout(i)
      mdoti = mdout(i)
      if (i .lt. n) dpsi = dpsi + dpf - ph
      if (i .eq. n) dpsi = dpsi + dpf - ph/2.
  enddo
ptcal = pn - ks/(2.*rho*gc)*(mdots/aorf)**2
delpt(j) = ptcal - pt
if (j .eq. 1) then
```

```
        if (delpt(j) .lt. 0.) mdot = mdot - dmdot
        if (delpt(j) .gt. 0.) mdot = mdot + dmdot
    else
        prod = delpt(j)*delpt(j-1)
        if (delpt(j) .lt. 0. .and. prod .gt. 0.) mdot = mdot - dmdot
        if (delpt(j) .gt. 0. .and. prod .gt. 0.) mdot = mdot + dmdot
        if (delpt(j) .lt. 0. .and. prod .lt. 0.) then
          dmdot = dmdot/2.
          mdot = mdot - dmdot
      endif
        if (delpt(j) .gt. 0. .and. prod .lt. 0.) then
          dmdot = dmdot/2.
          mdot = mdot + dmdot
      endif
    endif
10  continue
    if (abs(delpt(j)) .gt. tol) write (6,1002) delpt(j)
1002 format ('*** tank pressure does not converge, delpt = ',
   1      f8.4,' psi ***')
15  dppump = (psmi - pt)/144.
    dpsm = dpsm/144.
    dpsi = dpsi/144.
    write (6,200) mdot,dppump,dpsm,dpsi
200 format (5x,'Pump Flow Rate                  = ',f6.3,' lbm/sec'/
   1      5x,'Pump Pressure Rise            = ',f6.3,' psi'/
   2      5x,'Spray Manifold Tube Delta p   = ',f6.3,' psi'/
   3      5x,'Spray Injection Tube Delta p  = ',f6.3,' psi'//)
    write (6,4)
4   format (5x,'Node',2x,'Distance',3x,'Inlet',2x,'Outlet',
   1      3x,'Nodal',3x,'Tank',5x,'Inlet',4x,'Outlet',
   2      3x,'Injection',3x,'Injection',3x,'Orifice')
    write (6,5)
5   format (24x,'p',7x,'p',7x,'p',7x,'p',
   1      7x,'mdot',5x,'mdot',7x,'mdot',6x,'Velocity',
   2      5x,'CdA')
    write (6,6)
6   format (13x,'(in)',4x,'(psia)',2x,'(psia)',2x,'(psia)',2x,'(psia)',
   1      2x,'(lbm/sec)',1x,'(lbm/sec)',1x,'(lbm/sec)',5x,'(fps)',
   2      6x,'(in2)'/)
    do i = 1,n
        pin(i) = pin(i)/144.
        pout(i) = pout(i)/144.
        pnode(i) = pnode(i)/144.
        ptank(i) = ptank(i)/144.
        as(i) = 144.*as(i)
```

```
        x(i) = 12.*x(i)
      write (6,210) i,x(i),pin(i),pout(i),pnode(i),ptank(i),
     1            mdin(i),mdout(i),mds(i),vel(i),as(i)
210   format (5x,i3,4x,f6.2,3x,4(f6.3,2x),
     1      3(e9.3,1x),4x,f5.2,4x,f7.5)
      enddo
      if (opn .eq. 0.) go to 20
      call crtplt(-11,11,2,00,0,1,subhd,xtitl,yp,0.,0.,
     1        0.,0.,n,x,pnode,0,0)
20    if (opt .eq. 0.) go to 21
      call crtplt(0,0,0,01,0,0,0,0,0,0.,0.,
     1        0.,0.,n,x,ptank,0,0)
21    if (omdin .eq. 0.) go to 22
      call crtplt(-11,11,2,00,0,1,subhd,xtitl,ymdot,0.,0.,
     1        0.,0.,n,x,mdin,0,0)
22    if (omds .eq. 0.) go to 23
      call crtplt(-11,11,2,00,0,1,subhd,xtitl,ymds,0.,0.,
     1        0.,0.,n,x,mds,0,0)
23    if (ovel .eq. 0.) go to 24
      call crtplt(-11,11,2,00,0,1,subhd,xtitl,yvel,0.,0.,
     1        0.,0.,n,x,vel,0,0)
24    if (oas .eq. 0.) go to 25
      call crtplt(-11,11,2,00,0,1,subhd,xtitl,yas,0.,0.,
     1        0.,0.,n,x,as,0,0)
25    return
      end

      subroutine TPHS(HI,RHOL8,RHOG8,MDOT,AN8,HL8,HG8,SL8,SG8,
     1            y8,h8,s8,rho8,p8d)
      double precision hi,rhol8,rhog8,hl8,hg8,sl8,sg8,h8,rho8,p8d
      real k,mdot
c
c
      K=0.41405*(MDOT*MDOT)/(AN8*AN8)
      A1=K*(1.0/RHOG8-1.0/RHOL8)*(1.0/RHOG8-1.0/RHOL8)
      B1=HG8-HL8+2.0*K/RHOL8*(1.0/RHOG8-1.0/RHOL8)
      C1=HL8-HI+K/(RHOL8*RHOL8)
      Y8=(-B1+SQRT(ABS(B1*B1-4.0*A1*C1)))/(2.0*A1)
      IF(Y8.LE.0.00) then
         y8=0.00
      endif
      IF(Y8.GE.1.0) then
         y8=1.00
      endif
      H8=Y8*HG8+(1.0-Y8)*HL8
```

```
      S8=Y8*SG8+(1.0-Y8)*SL8
      RHO8=1.0/(1.0/RHOL8+Y8*(1.0/RHOG8-1.0/RHOL8))
      P8D=144.0/(2.0*32.2*RHO8)*(MDOT/AN8)*(MDOT/AN8)
      return
      END

         subroutine TPS(A,G,HI,HO,K,P,YO,RLO,RGO,YI,RLI,RGI,MDT,PHISQ,b,
     1            d,e,f)
      double precision p,rlo,rgo,rli,rgi,phisq,b,d,e,f
      double precision dpf1,dpf,vo,vi,dpm,dpt,ph,pinlet
      real k,mdt
c
      RHOO=1.0/(1.0/RLO+YO*(1.0/RGO-1.0/RLO))
      RHOI=1.0/(1.0/RLI+YI*(1.0/RGI-1.0/RLI))
      RHO=(RHOO+RHOI)/2.0
      YA=(YI+YO)/2.0
      IF(YA.GT.1.0) then
         ya=0.999
      endif
      RHOLA=(RLI+RLO)/2.0
      aa = ((1.0-ya)**2.0)*PHISQ/(RHOLA)
      bb = 1.0 / rho
      cc = aa
      if (bb .ge. aa) cc = bb
      DPF1=(MDT/A)**2
      DPF=144.0*K*(DPF1)*cc/(2.0*32.2)
      B=DPF
      VO=MDT/(RHOO*A)*144.0
      VI=MDT/(RHOI*A)*144.0
      DPM=ABS(MDT/A*(VO-VI)/32.2)
      DPT=DPM+DPF
      PH=G*RHO*(HI-HO)/1728.0
      PINLET=P+DPT-PH
      D=PINLET
      E=DPT
      F=DPM
      return
      END

      subroutine value(np,x,y,xin,yout)
c
c  This subroutine performs lagrangian interpolation within a set
c  of (x,y) pairs to give yout corresponding to xin
c
      double precision x(np),y(np),xin,yout
```


(l-2)

```
c
      if (xin .le. x(1)) yout = y(1)
      if (xin .le. x(1)) return
      if (xin .ge. x(np)) yout = y(np)
      if (xin .ge. x(np)) return
      do 10 i = 1,np
          k = i
          if (xin .lt. x(i)) go to 30
 10   continue
 30   ffr = (xin - x(k - 1))/(x(k) - x(k - 1))
      yout = y(k - 1) + ffr*(y(k) - y(k -1))
c     write (6,*) np,x,y,xin,yout
      return
      end

      SUBROUTINE VALUE2(NPX,NPY,X,Y,Z,XIN,YIN,ZOUT)
c     DIMENSION X(NPX),Y(NPY),Z(NPX,NPY)
      double precision X(NPX),Y(NPY),Z(NPX,NPY),XIN,YIN,ZOUT
C
      IF(XIN .LE. X(1) .AND. YIN .LE. Y(1))ZOUT=Z(1,1)
      IF(XIN .LE. X(1) .AND. YIN .LE. Y(1))RETURN
C
      IF(XIN .GE. X(NPX) .AND. YIN .LE. Y(1))ZOUT=Z(NPX,1)
      IF(XIN .GE. X(NPX) .AND. YIN .LE. Y(1))RETURN
C
      IF(XIN .LE. X(1) .AND. YIN .GE. Y(NPY))ZOUT=Z(1,NPY)
      IF(XIN .LE. X(1) .AND. YIN .GE. Y(NPY))RETURN
C
      IF(XIN .GE. X(NPX) .AND. YIN .GE. Y(NPY))ZOUT=Z(NPX,NPY)
      IF(XIN .GE. X(NPX) .AND. YIN .GE. Y(NPY))RETURN
C
      IF(XIN .GT. X(1))GO TO 30
      DO 20 I=1,NPY
        M=I
        IF(YIN .LT. Y(I))GO TO 25
 20   CONTINUE
 25   FFRY=(YIN-Y(M-1))/(Y(M)-Y(M-1))
      ZOUT=Z(1,M-1)+FFRY*(Z(1,M)-Z(1,M-1))
      RETURN
C
 30   IF(XIN .LT. X(NPX))GO TO 60
      DO 50 I=1,NPY
        M=I
        IF(YIN .LT. Y(I))GO TO 55
 50   CONTINUE
```

```
 55 FFRY=(YIN-Y(M-1))/(Y(M)-Y(M-1))
    ZOUT=Z(NPX,M-1)+FFRY*(Z(NPX,M)-Z(NPX,M-1))
    RETURN
C
 60 IF(YIN .GT. Y(1))GO TO 90
    DO 80 I=1,NPX
      L=I
      IF(XIN .LT. X(I))GO TO 85
 80 CONTINUE
 85 FFRX=(XIN-X(L-1))/(X(L)-X(L-1))
    ZOUT=Z(L-1,1)+FFRX*(Z(L,1)-Z(L-1,1))
    RETURN
C
 90 IF(YIN .LT. Y(NPY))GO TO 120
    DO 110 I=1,NPX
      L=I
      IF(XIN .LT. X(I))GO TO 115
 110 CONTINUE
 115 FFRX=(XIN-X(L-1))/(X(L)-X(L-1))
    ZOUT=Z(L-1,NPY)+FFRX*(Z(L,NPY)-Z(L-1,NPY))
    RETURN
C
 120 DO 130 I=1,NPX
      L=I
      IF(XIN .LT. X(I))GO TO 135
 130 CONTINUE
 135 FXR=(XIN-X(L-1))/(X(L)-X(L-1))
    DO 140 I=1,NPY
      M=I
      IF(YIN .LT. Y(I))GO TO 145
 140 CONTINUE
 145 FYR=(YIN-Y(M-1))/(Y(M)-Y(M-1))
C
    ZXLO=Z(L-1,M-1)+FYR*(Z(L-1,M)-Z(L-1,M-1))
    ZXHI=Z(L,M-1)+FYR*(Z(L,M)-Z(L,M-1))
C
    ZOUT=ZXLO+FXR*(ZXHI-ZXLO)
    RETURN
    END

    SUBROUTINE VALUE3(NPX,MAXY,NPY,X,Y,Z,XIN,YIN,ZOUT)
    integer npy(maxy)
    double precision X(NPX),Y(NPX,MAXY),Z(NPX,maxy),xin,yin,zout
c   double precision X(15),Y(15,15),Z(15,15),xin,yin,zout
    dimension a(50),b(50),c(50),d(50)
```

```
C
    IF(XIN .LE. X(1) .AND. YIN .LE. Y(1,1)) then
       ZOUT=Z(1,1)
     RETURN
    endif
C
    IF(XIN .GE. X(NPX) .AND. YIN .LE. Y(npx,1)) then
       ZOUT=Z(NPX,1)
     RETURN
    endif
C
    IF(XIN .LE. X(1) .AND. YIN .GE. Y(1,NPY(1))) then
       ZOUT=Z(1,NPY(1))
     RETURN
    endif
C
    IF(XIN .GE. X(NPX) .AND. YIN .GE. Y(npx,NPY(npx))) then
       ZOUT=Z(NPX,NPY(npx))
     RETURN
    endif
C
    IF(XIN .GT. X(1))GO TO 30
    DO I=1,NPY(1)
      M=I
      IF(YIN .LT. Y(1,I))GO TO 25
    enddo
 25 FFRY=(YIN-Y(1,M-1))/(Y(1,M)-Y(1,M-1))
    ZOUT=Z(1,M-1)+FFRY*(Z(1,M)-Z(1,M-1))
    RETURN
C
 30 IF(XIN .LT. X(NPX))GO TO 60
    DO I=1,NPY(npx)
      M=I
      IF(YIN .LT. Y(npx,I))GO TO 55
    enddo
 55 FFRY=(YIN-Y(npx,M-1))/(Y(npx,M)-Y(npx,M-1))
    ZOUT=Z(NPX,M-1)+FFRY*(Z(NPX,M)-Z(NPX,M-1))
    RETURN
C
 60 DO I=1,NPX
      L=I
      IF(XIN .LT. X(I))GO TO 85
    enddo
 85 do j = 1, npy(l)
       a(j) = y(l,j)
```

```
          b(j) = z(l,j)
      enddo
      call value(npy(l),a,b,yin,z1)
      do k = 1, npy(l-1)
          c(k) = y(l-1,k)
          d(k) = z(l-1,k)
      enddo
      call value(npy(l-1),c,d,yin,z2)
      FFRX=(XIN-X(L-1))/(X(L)-X(L-1))
      ZOUT=Z2+FFRX*(Z1-Z2)
      RETURN
      END

      subroutine XPARAM(YO,VLO,VGO,RLO,RGO,YI,VLI,VGI,RLI,RGI,x)
c
      double precision vlo,vgo,rlo,rgo,vli,vgi,rli,rgi,x
      double precision visla,visga,rhola,rhoga,x1
c
      YA=(YI+YO)/2.0
      VISLA=(VLI+VLO)/2.0
      VISGA=(VGI+VGO)/2.0
      RHOGA=(RGI+RGO)/2.0
      RHOLA=(RLI+RLO)/2.0
      IF(YA.LE.1.0E-06) then
          ya=1.0e-06
      endif
      IF(YA.GE.1.0) then
          ya=1.0
      endif
      X1=((ABS(VISLA/VISGA))**0.1)*(((1.0-YA)/YA)**0.9)
      X= X1*SQRT(ABS(RHOGA/RHOLA))
c     write (6,10) yi,yo,ya,vli,vlo,visla,vgi,vgo,visga,rgi,rgo,rhoga,
c    1         rli,rlo,rhola,x1,x
c  10 format (6(3x,f8.4)/,6(3x,f8.4)/,3(3x,f8.4),2(3x,f10.4))
      return
      END
```

3.4.2 <u>Integrated Zero-g TVS Model</u>

```
c
c program tvs.f to model zero-g Thermodynamic Venting System (TVS)
c transient performance
c
      character*1 label
      real ptitl(18,4),subhd(18),xtitl(18),ketitl(4,2),
     1   ypu(18),ytu(18),ymu(18),ypl(18),ytl(18),yml(18),
```

```
2    ytw(18),ymwl(18),ymdv(18),ymdsu(18),ymddu(18),ymdbw(18),
3    ymdif(18),ymds(18),ynpump(18),ydppmp(18)
     real tsat(25),psat(25),enthf(25),enthg(25),
1    shpf(25),densf(25),condf(25),viscf(25),texpf(25)
     real pvap(8),tvap(8),tnrm(11),enth(8,11),shv(8,11),
1    shp(8,11),dens(8,11),cond(8,11),visc(8,11)
     real tal(12),shpal(12),node(10),dorf(10)
     real as(100),ddrop(100),ad(100),vd(100),veld(100),ndrop(100)
     real ton(100),toff(100),tcyc(100),pton(100),
1    mvent(100),mvnt(100),sfc(100)
     real mup,mlp,mwlp,mvp,mdvp
     real mdsp,mdslp,mdsup,mddup,mdbwp,mdlup,npumpp
     real mu,ml,mwl,mw,mv,mui,mli,mwli,mvi,mwlmax
     real kwu,muwu,kuwl,muuwl,kwl,muwl,muul,kul
     real kus,muus,kls,muls,kud,muud,nud
     real ks,mds,mdsl,mdsu,mddu,mdsw,mdbw,mdbwmx,mdlu,mdul
     real mdv,mdvent,mdp,mdpump,mdsne,mdsul,mdcond,mdcndp,mdsi
     real mdotd,npumpd,npump,npumpi,nmax,nmin,ip
     integer jsymb(2)
     integer*2 ibox,iloc
     common /pltcom/misc(3),nc,miss(13),dclim,ltick,nfig,nptmin,
1      nlines,nchlin,ptitl
     common /contrl/ibox,iloc
     common /sprayin/dsm,zsm,dsi,zsi,norf,nbar,
1      ks,cds,as,vd,roverd,dmdot,tol,nlim,
2      rhos,viscs
     common /pumpin/npumpd,nmin,nmax,hpid,hpmotr,effp,ip,dm
     common /tankdim/dtank,hcyl,hbulk,tkw,c1
     common /tankvol/v1,v2,vbi,vbo,vci,vco
     common /tankarea/ab,ac,at
     common /tankout/j,nline,iprint,timep(3000),
1      pup(3000),tup(3000),vup(3000),mup(3000),twp(3000),
2      plp(3000),tlp(3000),vlp(3000),mlp(3000),
3      pwlp(3000),twlp(3000),vwlp(3000),mwlp(3000),
4      mvp(3000),tsp(3000),mdlup(3000),mdsp(3000),mdslp(3000),
5    mdsup(3000),mddup(3000),mdbwp(3000),mdulp(3000),mdcndp(3000),
6      qwup(3000),quwlp(3000),qwlp(3000),qulp(3000),qudp(3000),
7      qusp(3000),qlsp(3000),npumpp(3000),dppmp(3000)
     nc = 2
     nfig = 0
     nlines = 4
     ibox = 257
     jsymb(1) = 40
     jsymb(2) = 43
     data ketitl/4hEVAP,4hORAT,4hTION,4h    ,
```

```
     1    4hCOND,4hENSA,4hTION,4h   /
      data ru,rhow,gc,ed/766.0,176.3,32.2,1.0e-6/
      data tal/0.0,25.0,50.0,75.0,100.0,125.0,150.0,180.0,260.0,
     1    485.0,760.0,1000.0/nal/12/
      data shpal/0.0,0.001,0.0075,0.02,0.0525,0.09,0.11,0.125,0.15,
     1    0.2,0.225,0.25/
c
c  read input data for tank model
c
      read (5,100) label
      read (5,*) xd,xchar,he,xcond,prtsp,outp
      read (5,100) label
      read (5,*) pui,tui,pli,twi,twli,full,xl1
      read (5,100) label
      read (5,*) dtank,hcyl,hbulk,tkw,dsb,d1,d2
      read (5,100) label
      read (5,*) mdvent,mdsi,dthex,qflux,g,hwliq
      read (5,100) label
      read (5,*) pmin,pmax,delt2,iprnt2,iplot2
      read (5,100) label
      read (5,*) fintim,delt1,xdelt1,iprnt1,iplot1,nline
      read (5,100) label
      read (5,*) opu,otu,omu,opl,otl,oml
      read (5,100) label
      read (5,*) otw,omwl,omdv,omdsu,omddu,omdbw
      read (5,100) label
      read (5,*) omdlu,omdul,omds,onpump,odppmp
      read (5,200) subhd,xtitl,ypu,ytu,ymu,ypl
      read (5,200) ytl,yml,ytw,ymwl,ymdv,ymdsu
      read (5,200) ymddu,ymdbw,ymdif,ymds,ynpump,ydppmp
      read (5,201) ptitl
c
c  read input data for pump model
c
      read (5,100) label
      read (5,*) mdotd,dpd,npumpi,npumpd,xhp,xn
      read (5,100) label
      read (5,*) deltat,effp
c
c  read input data for spray manifold/injection tubes model
c
      read (5,100) label
      read (5,*) dsm,zsm,dsi,zsi,norf,nbar
      read (5,100) label
      read (5,*) ks,cds,roverd,dmdot,tol,nlim
```

```
      read (5,*) nsec
      do i = 1,nsec
          read (5,*) node(i),dorf(i)
      enddo
 100  format (//a1)
 200  format (18a4/18a4/18a4/18a4/18a4/18a4)
 201  format (18a4)
c
c  read LH2 saturation properties
c
      open(unit=2,file='h2prop',status='old')
      read (2,*) nsat
      do i = 1,nsat
          read (2,*) tsat(i),psat(i),enthf(i),dumvar,shpf(i),densf(i),
     1         texpf(i),condf(i),viscf(i)
          read (2,*) enthg(i)
      enddo
c
c  read GH2 properties as a function of pressure and temperature
c
      read (2,*) np,nt
      read (2,*) (tnrm(i),i=1,nt),tcnst
      do i = 1,np
          read (2,*) pvap(i),tvap(i)
        do j = 1,nt
            read (2,*) enth(i,j),shv(i,j),shp(i,j),dens(i,j),
     1           cond(i,j),visc(i,j)
        enddo
      enddo
      if (outp .eq. 1.0) then
      write (6,1)
 1    format (5x,'TANK DIMENSIONS'/)
      write (6,2) dtank,tkw,hcyl,hbulk
 2    format (5x,'Tank Diameter                  ',f6.1,' in'/
     1       5x,'Tank Wall Thickness            ',f6.2,' in'/
     2       5x,'Cylinder Height                ',f6.1,' in'/
     3       5x,'Bulkhead Height                ',f6.1,' in'//)
      write (6,3)
 3    format (5x,'SPRAY MANIFOLD/INJECTION TUBE DIMENSIONS'/)
      write (6,4) zsm,dsm,zsi,dsi,nbar,norf,ks,cds
 4    format (5x,'Spray Manifold Tube Length      ',f6.1,' in'/
     1       5x,'Spray Manifold Tube ID          ',f6.3,' in'/
     2       5x,'Spray Injection Tube Length     ',f6.1,' in'/
     3       5x,'Spray Injection Tube ID         ',f6.3,' in'/
     4       5x,'Number of Spray Injection Tubes ',i6/
```

```
     5      5x,'Number of Orifices               ',i6/
     6      5x,'Orifice Loss Coefficient         ',f6.2/
     7      5x,'Orifice Discharge Coefficient    ',f6.2/)
      write (6,5)
 5    format (t2,'Time',t10,'pU',t18,'TU',t26,'VU',t34,'MU',
     1      t42,'pL',t50,'TL',t58,'VL',t66,'ML',t74,'TW',
     2      t82,'TWL',t90,'Npump',t98,'dppump',t106,'dTpump',
     3      t114,'HPO',t122,'mdS',t130,'mdSU',t138,'mdDU',
     4      t146,'mdBW',t154,'mdLU',t162,'mdcond')
      write (6,6)
 6    format (t2,'sec',t9,'psia',t19,'R',t25,'ft3',t33,'lbm',
     1      t41,'psia',t51,'R',t57,'ft3',t65,'lbm',t75,'R',
     2      t83,'R',t91,'rpm',t99,'psid',t109,'R',
     3      t114,'HP',t120,'lbm/sec',t128,'lbm/sec',t136,'lbm/sec',
     4      t144,'lbm/sec',t152,'lbm/sec',t160,'lbm/sec'/)
      endif
      do j = 1,nsec
           node1 = node2 + 1
           node2 = node(j)
           do i = node1,node2
             ds = dorf(j)/12.0
             as(i) = 3.14159*ds**2/4.0
             ddrop(i) = xd*ds
             ad(i) = 3.14159*ddrop(i)**2
             vd(i) = 3.14159*ddrop(i)**3/6.0
        enddo
      enddo
      dtank = dtank/12.0
      hcyl = hcyl/12.0
      hbulk = hbulk/12.0
      htank = hcyl + 2.0*hbulk
      tkw = tkw/12.0
      dsb = dsb/12.0
      dsm = dsm/12.0
      zsm = zsm/12.0
      dsi = dsi/12.0
      zsi = zsi/12.0
      xl1 = xl1/12.0
      d1 = d1/12.0
      d2 = d2/12.0
      dzsi = zsi/norf
      dchar = xchar*dtank
c
c  initial ullage and liquid masses
c
```

```
      call volarea(vt)
      dtanki = dtank - 2.0*tkw
      call value(nsat,psat,tsat,pli,tli)
      call value(nsat,tsat,densf,tli,rhol)
      call value(nsat,tsat,densf,twli,rhowl)
      vli = full/100.0*vt
      mli = rhol*vli
      vui = vt - vli
      mui = 144.0*pui*vui/(ru*tui)
      ts = tli
      tsw = ts
c
c  in 1 g, set maximum thickness of wall liquid layer to 0.01 in
c  due to liquid run-off and calculate maximum wall liquid mass
c
      call area(vli,y,awu,aul,awl,hliq,hu)
      if (g .ge. 1.0) mwlmax = rhol*awu*0.01/12.0
c
c  pump design conditions
c
      dm = 720.0/(3.14159*npumpd)*(2.0*144.0*dpd/rhol)**0.5
      hpid = xhp*mdotd*dpd*144.0/(550.0*effp*rhol)
      hpmotr = hpid
      nmax = npumpd*(1.0 + xn)
      nmin = npumpd*(1.0 - xn)
      ip = 6.018e+05*hpid*deltat/(npumpd*(nmax - nmin))/2.0
      if (pui .ge. pmax) mdp = mdsi
      if (pui .le. pmin) mdp = 0.0
      mdpump = mdsi
c
c  time integration of variables
c
      i = 0
      j = 0
 85   if (npump .gt. 0.0) then
          delt = delt1
          if (pu .le. pl) delt = xdelt1*delt1
          iprint = iprnt1/xdelt1
          iplot = iplot1
      else
          delt = delt2
          iprint = iprnt2
          iplot = iplot2
      endif
      mu = mui + dmudt*delt
```

```
      ml = mli + dmldt*delt
      if (ml .le. 0.0) ml = 0.0
      mwl = mwli + dmwldt*delt
      if (mwl .le. 0.0) mwl = 0.0
      if (g .ge. 1.0 .and. mwl .ge. mwlmax) mwl = mwlmax
      mv = mvi + mdv*delt
      vl = vli + dvldt*delt
      if (vl .le. 0.0) vl = 0.0
      vwl = mwl/rhowl
      vu = vt - vl - vwl
      tl = tli + dtldt*delt
      tu = tui + dtudt*delt
      call value(nsat,psat,tsat,pu,tusat)
      if (tu .le. tusat) tu = tusat
      twl = twli + dtwldt*delt
      if (twl .ge. tusat) twl = tusat
      if (twl .le. ts) twl = ts
      tw = twi + dtwdt*delt
      qpump = qpumpi + hpo*0.707*delt
      mui = mu
      mli = ml
      mwli = mwl
      mvi = mv
      vli = vl
      tui = tu
      tli = tl
      twli = twl
      twi = tw
      qpumpi = qpump
c
c  ullage, bulk liquid, and wall liquid pressures
c
      pu = mu*ru*tu/(144.0*vu)
      call value(nsat,tsat,psat,tl,pl)
      call value(nsat,tsat,psat,twl,pwl)
c
c  pump control logic
c
      if (pu .ge. pmax) flag1 = 1.0
      if (pu .le. pmin) flag1 = 0.0
c
c  performance calculations
c
      if (flag1 .eq. 0.0) then
        if (cyc .eq. 0.0) ncyc = ncyc + 1
```

```
         toff(ncyc) = time - timeon
         timeof = time
         cyc = 1.0
      endif
      if (flag1 .eq. 1.0) then
         ton(ncyc) = time - timeof
         tcyc(ncyc) = ton(ncyc) + toff(ncyc)
         pton(ncyc) = 100.0*ton(ncyc)/tcyc(ncyc)
         sfc(ncyc) = 3600.0*mv/time
         mvent(ncyc) = mv
         pup(ncyc) = pu
         tup(ncyc) = tu
         mup(ncyc) = mu
         plp(ncyc) = pl
         tlp(ncyc) = tl
         mlp(ncyc) = ml
         twp(ncyc) = tw
         mdsp(ncyc) = mds
         timeon = time
         cyc = 0.0
      endif
c
c  pump model
c
      call value(nsat,tsat,shpf,tl,cpl)
      nmdot = 0
 87   call pump(flag1,npump,npumpi,delt,mdpump,rhol,cpl,dppump,dtpump,
     1     dnt,hpo)
      if (dppump .le. 0.01) mdp = 0.0
      if (dppump .gt. 0.01) mdp = mdpump
      tpump = tl + dtpump
c
c  vent control logic
c
      psatp = -36.37 + 4.6054*tpump - 0.20369*tpump*tpump
     1      + 0.0031745*tpump*tpump*tpump
      if (psatp .gt. pmin) flag2 = 1.0
      if (psatp .le. pmin) flag2 = 0.0
      mdv = 0.0
      if (flag1 .gt. 0.0 .and. flag2 .gt. 0.0) mdv = mdvent
c
c  pressure drop in the recirculation line (between the pump outlet
c  and spray manifold inlet)
c
      if (mdp .le. 0.0) dprec = 0.0
```

```
      if (mdp .gt. 0.0 ) then
        call value(nsat,tsat,densf,tpump,rhop)
        call value(nsat,tsat,viscf,tpump,viscp)
          call pdrop(mdp,rhop,viscp,xl1,d1,d2,dprec)
      endif
c
c  spray manifold/injection tube model
c
      call area(vl,y,awu,aul,awl,hliq,hu)
      dhn = htank - hu - dzsi/2.0
      ptn = pu + rhol*g*dhn/144.0
      psmi = ptn + dppump - dprec
      if (mdp .gt. 0.0) ts = tpump - dthex
      if (mdp .le. 0.0) ts = tpump
      call value(nsat,tsat,densf,ts,rhos)
      call value(nsat,tsat,viscf,ts,viscs)
      if (mdp .gt. 0.0) then
          call spray(psmi,mdp,pu,hu,hliq,htank,dchar,rhol,g,ed,
     1        time,prtsp,mds,mdsu,mdsl,veld,ndrop,norfu)
          if (mds .le. 0.0) mds = mdsi
          mdpump = (mdp + mds)/2.0
          delmd = mdp - mds
          if (abs(delmd) .lt. 0.01) go to 86
          nmdot = nmdot + 1
          if (nmdot .lt. 10) go to 87
          write (6,8) time,delmd
 8      format ('***  pump flow rate does not converge at time = ',
     1        f10.2,' sec, delmd = ',f8.4,' lbm/sec  ***')
      else
          mdsu = 0.0
          mdsl = 0.0
      endif
c
c  heat-transfer rates
c
c  wall-to-ullage
c
 86   if (mwl .gt. 0.0) qwu = 0.0
      if (mwl .le. 0.0) then
        twu = (tw + tu)/2.0
          betawu = 1.0/twu
        twun = (twu - tusat)/(tcnst - tusat)
        call value2(np,nt,pvap,tnrm,shp,pu,twun,cpwu)
        call value2(np,nt,pvap,tnrm,dens,pu,twun,rhowu)
        call value2(np,nt,pvap,tnrm,cond,pu,twun,kwu)
```

```
          call value2(np,nt,pvap,tnrm,visc,pu,twun,muwu)
          call htc(tw,tu,dtanki,cpwu,rhowu,betawu,kwu,muwu,g,hwu)
          qwu = hwu*awu*(tw - tu)
        endif
c
c  ullage-to-wall liquid
c
        if (mwl .le. 0.0) quwl = 0.0
        if (mwl .gt. 0.0) then
          tuwl = (tu + twl)/2.0
            betuwl = 1.0/tuwl
          call value(nsat,psat,tsat,pu,tusat)
          tuwln = (tuwl - tusat)/(tcnst - tusat)
          call value2(np,nt,pvap,tnrm,shp,pu,tuwln,cpuwl)
          call value2(np,nt,pvap,tnrm,dens,pu,tuwln,rhouwl)
          call value2(np,nt,pvap,tnrm,cond,pu,tuwln,kuwl)
          call value2(np,nt,pvap,tnrm,visc,pu,tuwln,muuwl)
          call htc(tu,twl,dtanki,cpuwl,rhouwl,betuwl,kuwl,muuwl,g,huwl)
          quwl = huwl*awu*(tu - twl)
        endif
c
c  wall-to-wall liquid
c
        if (mwl .le. 0.0) qwl = 0.0
        if (mwl .gt. 0.0) then
          call value(nsat,tsat,shpf,twl,cpwl)
          call value(nsat,tsat,texpf,twl,betawl)
          call value(nsat,tsat,condf,twl,kwl)
          call value(nsat,tsat,viscf,twl,muwl)
          call value(nsat,tsat,densf,twl,rhowl)
            hwl = 0.13*(3600.0*32.2*g*betawl*abs(tw - twl)*rhowl**2
     1        *kwl**2*cpwl/muwl)**(1.0/3.0)
            if (hwl .gt. hwliq) hwl = hwliq
          qwl = hwl*awu*(tw - twl)
        endif
c
c  ullage-to-liquid
c
        tul = (tu + tl)/2.0
        betaul = 1.0/tul
        tuln = (tul - tusat)/(tcnst - tusat)
        call value2(np,nt,pvap,tnrm,shp,pu,tuln,cpul)
        call value2(np,nt,pvap,tnrm,dens,pu,tuln,rhoul)
        call value2(np,nt,pvap,tnrm,cond,pu,tuln,kul)
        call value2(np,nt,pvap,tnrm,visc,pu,tuln,muul)
```

```
      call htc(tu,tl,dtanki,cpul,rhoul,betaul,kul,muul,g,hul)
      qul = hul*aul*(tu - tl)
c
c ullage-to-droplet
c
      td = ts
      tud = (tu + td)/2.0
      tudn = (tud - tusat)/(tcnst - tusat)
      call value2(np,nt,pvap,tnrm,dens,pu,tudn,rhoud)
      call value2(np,nt,pvap,tnrm,visc,pu,tudn,muud)
      call value2(np,nt,pvap,tnrm,cond,pu,tudn,kud)
      qud = 0.0
      if (mdp .le. 0.0) go to 17
      do io = 1,norfu
        red = rhoud*veld(io)*ddrop(io)/muud
c
c textbook heat-transfer correlation for liquid droplets (Kreith)
c
        nud = 0.3125*red**0.602
        if (ddrop(io) .gt. 0.0) hud = nud*kud/ddrop(io)
        qud = qud + ndrop(io)*hud*ad(io)*(tu - td)
      enddo
 17   call value(nsat,tsat,densf,td,rhod)
c
c ullage-to-spray bar
c
      tus = (tu + ts)/2.0
      betaus = 1.0/tus
      tusn = (tus - tusat)/(tcnst - tusat)
      call value2(np,nt,pvap,tnrm,shp,pu,tusn,cpus)
      call value2(np,nt,pvap,tnrm,dens,pu,tusn,rhous)
      call value2(np,nt,pvap,tnrm,cond,pu,tusn,kus)
      call value2(np,nt,pvap,tnrm,visc,pu,tusn,muus)
      call htc(tu,ts,dsb,cpus,rhous,betaus,kus,muus,g,hus)
      aus = 3.14159*dsb*hu
      qus = nbar*hus*aus*(tu - ts)
      qus = 0.0
c
c liquid-to-spray bar
c
      tls = (tl + ts)/2.0
      call value(nsat,tsat,shpf,tls,cpls)
      call value(nsat,tsat,densf,tls,rhols)
      call value(nsat,tsat,texpf,tls,betals)
      call value(nsat,tsat,condf,tls,kls)
```

```
      call value(nsat,tsat,viscf,tls,muls)
      call htc(tl,ts,dsb,cpls,rhols,betals,kls,muls,g,hls)
      als = 3.14159*dsb*hliq
      qls = nbar*hls*als*(tl - ts)
      qls = 0.0
c
c  environment-to-wall
c
      qew = qflux*awu
      qel = qflux*awl
c
c  mass-transfer rates
c
c  droplet-to-ullage boil-off
c
      call value(nsat,psat,enthf,pu,hf)
      call value(nsat,psat,enthg,pu,hgsat)
      hfgu = hgsat - hf
      mddu = (qud/3600.0 - mdsu*cpl*(tusat - ts))/hfgu
      if (mddu .lt. 0.0) mddu = 0.0
      if (mddu .lt. 0.0) qud = 3600.0*mdsu*cpl*(tusat - ts)
      if (mddu .lt. 0.0) ts = tusat - qud/(3600.0*mdsu*cpl)
      if (mddu .gt. mdsu) mddu = mdsu
      if (mddu .gt. mdsu) qud = mdsu*(hfgu + cpl*(tusat - ts))*3600.0
c
c  non-evaporated spray droplet
c
      mdsne = mdsu - mddu
      if (g .ge. 1.0) then
           mdsw = 0.0
           mdsul = mdsne
      else
           mdsw = mdsne
           mdsul = 0.0
      endif
c
c  droplet boil-off from wall
c
      call value(nsat,tsat,enthf,tl,hf)
      call value(nsat,tsat,enthg,tl,hg)
      hfgl = hg - hf
      dpudt = pu*(dmudt/mu + dtudt/tu - dvudt/vu)
      if (mwl .le. 0.0) mdbw = 0.0
      if (mwl .gt. 0.0) then
        if (pu .gt. pwl) mdbw = 0.0
```

```
      if (pu .lt. pwl .and. dpudt .gt. 0.0)
     1  mdbw = ((qwl + quwl)/3600.0 - mdsw*cpl*(twl - tsw))/hfgl
      if (pu .lt. pwl .and. dpudt .le. 0.) then
        dtdp = 0.37781 - 4.9170e-3*pwl + 21.7623e-6*pwl*pwl
        mdbw = ((qwl + quwl)/3600.0 - mdsw*cpl*(twl - tsw)
     1         - mwl*cpl*dtdp*dpudt)/hfgl
      endif
    endif
    mdbwmx = mwl/delt
    if (mdbw .ge. mdbwmx) mdbw = mdbwmx
c
c liquid-to-ullage boil-off
c
    if (pu .gt. pl) mdlu = 0.0
    if (pu .le. pl .and. dpudt .gt. 0.0)
   1  mdlu = (ql/3600.0 - mdsl*cpl*(tl - ts))/hfgl
    if (pu .le. pl .and. dpudt .le. 0.0) then
      dtdp = 0.37781 - 4.9170e-3*pl + 21.7623e-6*pl*pl
      mdlu = (ql/3600.0 - mdsl*cpl*(tl - ts)
   1       - ml*cpl*dtdp*dpudt)/hfgl
    endif
c
c condensation
c
    if (tu .gt. tusat) mdul = 0.0
    if (tu .le. tusat) mdul = (qud + qul + quwl)/(3600.0*hfgu)
    if (he .eq. 0.0 .and. flag1 .eq. 1.0)
   1  mdcond = xcond*qul/(3600.0*hfgu)
    if (flag1 .eq. 0.0) mdcond = 0.0
    if (he .eq. 1.0) mdcond = 0.0
c
c rates of change of ullage, wall liquid, and bulk liquid masses
c
    dmudt = mddu + mdbw + mdlu - mdul - mdcond
    dmwldt = mdsw - mdbw
    dmldt = mdsl + mdul + mdcond + mdsul - mdlu - mds - mdv
    if (g .ge. 1.0 .and. mwl .ge. mwlmax) dmldt = dmldt + dmwldt
c
c rates of change of ullage, liquid, and wall liquid volumes
c
    call value(nsat,tsat,densf,tl,rhol)
    dvldt = dmldt/rhol
    if (mwl .le. 0.0) dvwldt = 0.0
    if (mwl .gt. 0.0) dvwldt = dmwldt/rhowl
    dvudt = -dvldt - dvwldt
```

```
c
c rates of change of temperature
c
c ullage
c
      qu = qwu - quwl - qul - qud - qus
      if (mdcond .eq. 0.0) qu = qwu - quwl - qud - qus
      enthu = dmudt*hgsat
      tun = (tu - tusat)/(tcnst - tusat)
      call value2(np,nt,pvap,tnrm,shv,pu,tun,cvu)
      dtudt = (qu/3600.0 - 144.0/778.0*pu*dvudt + enthu
     1       - cvu*tu*dmudt)/(mu*cvu)
c
c bulk liquid
c
      ql = qel + qul - qls
      if (mddu .lt. 0.0) td = ts
      if (mddu .ge. 0.0) td = tusat
      if (ml .gt. 0.0) dtldt = (ql/3600.0 - mdlu*hfgl
     1  + mdsul*cpl*(td - tl) - mdsl*cpl*(tl - ts))/(ml*cpl)
      if (ml .le. 0.0) dtldt = 0.0
c
c wall liquid
c
      qudchk = 3600.0*mdsu*cpl*(tusat - ts)
      if (qud .gt. qudchk) tsw = tusat
      if (qud .le. qudchk) tsw = ts + qud/3600.0/((mdsu + 0.0001)*cpl)
      if (mwl .gt. 0.0) dtwldt = ((qwl + quwl)/3600.0
     1                  - mdsw*cpl*(twl - tsw))/(mwl*cpl)
      if (mwl .le. 0.0) dtwldt = 0.0
c
c tank wall
c
      call vwall(hliq,vw)
      mw = rhow*vw
      call value(nal,tal,shpal,tw,cpw)
      qw = qew - qwu - qwl
      dtwdt = qw/3600.0/(mw*cpw)
c
c output listing
c
      if (outp .eq. 0.0) go to 19
      if (mod(i,iprint) .eq. 0.0)
     1  write (6,7) time,pu,tu,vu,mu,pl,tl,vl,ml,tw,ts,npump,
     2         dppump,dtpump,hpo,mds,mdsu,mddu,mdbw,mdlu,mdcond
```

```
7     format (f7.0,f6.2,9(2x,f6.2),2x,f6.1,
 1        3(2x,f6.3),6(1x,f7.4))
      if (mod(i,iplot) .ne. 0.0) go to 19
      j = j + 1
      timep(j) = time
      pup(j) = pu
      tup(j) = tu
      vup(j) = vu
      mup(j) = mu
      twp(j) = tw
      plp(j) = pl
      tlp(j) = tl
      vlp(j) = vl
      mlp(j) = ml
      pwlp(j) = pwl
      twlp(j) = twl
      vwlp(j) = vwl
      mwlp(j) = mwl
      mvp(j) = mv
      mdvp(j) = mdv
      tsp(j) = ts
      mdlup(j) = mdlu
      mdsp(j) = mds
      mdslp(j) = mdsl
      mdsup(j) = mdsu
      mddup(j) = mddu
      mdbwp(j) = mdbw
      mdulp(j) = mdul
      mdcndp(j) = mdcond
      qwup(j) = qwu
      quwlp(j) = quwl
      qwlp(j) = qwl
      qulp(j) = qul
      qudp(j) = qud
      qusp(j) = qus
      qlsp(j) = qls
      npumpp(j) = npump
      dppmp(j) = dppump
19    i = i + 1
      time = time + delt
      if (time .le. fintim) go to 85
      if (ton(ncyc) .eq. 0.0) ncyc = ncyc - 1
      write (6,999)
999   format ('1')
      do i = 1,ncyc
```

```
        ston = ston + ton(i)
        stoff = stoff + toff(i)
        stcyc = stcyc + tcyc(i)
        if (i .eq. 1) mvnt(i) = mvent(i)
        if (i .gt. 1) mvnt(i) = mvent(i) - mvent(i-1)
      write (6,1000) i,ton(i),toff(i),tcyc(i),pton(i),mvnt(i),sfc(i)
1000    format (5x,'Cycle No.                  = ',i12/
  1        5x,'On Time                  = ',f12.3,' sec'/
  2        5x,'Off Time                 = ',f12.3,' sec'/
  3        5x,'Cycle Time               = ',f12.3,' sec'/
  4        5x,'% On Time                = ',f12.3,' %'/
  5        5x,'Vented Mass              = ',f12.3,' lbm'/
  6        5x,'Specific Fuel Consumption = ',f12.3,' lbm/hr'/)
        write (6,1001) pup(i),tup(i),mup(i),plp(i),tlp(i),mlp(i),
  1              twp(i),mdsp(i)
1001    format (5x,'Ullage pressure          = ',f12.3,' psia'/
  1        5x,'Ullage temperature       = ',f12.3,' R'/
  2        5x,'Ullage mass              = ',f12.3,' lbm'/
  3        5x,'Liquid pressure          = ',f12.3,' psia'/
  4        5x,'Liquid temperature       = ',f12.3,' R'/
  5        5x,'Liquid mass              = ',f12.3,' lbm'/
  6        5x,'Wall temperature         = ',f12.3,' R'/
  7        5x,'Pump flow rate           = ',f12.3,' lbm/sec'/)
  enddo
  ptonav = 100.0*ston/stcyc
  sfcav = 3600.0*mvent(ncyc)/stcyc
  write (6,1002) ston,stoff,stcyc,ptonav,mvent(ncyc),sfcav
1002 format (5x,'On Time                  = ',f12.3,' sec'/
  1      5x,'Off Time                 = ',f12.3,' sec'/
  2      5x,'Cycle Time               = ',f12.3,' sec'/
  3      5x,'% On Time                = ',f12.3,' %'/
  4      5x,'Vented Mass              = ',f12.3,' lbm'/
  5      5x,'Specific Fuel Consumption = ',f12.3,' lbm/hr')
c
c  output listing
c
  call prtout
c
c  output plotting
c
  if (opu .eq. 1.0) call crtplt(-11,12,2,00,0,0,subhd,xtitl,
  1              ypu,0.,0.,0.,0.,j,timep,pup,0,0)
  if (opl .eq. 1.0) call crtplt(12,12,2,00,0,0,subhd,xtitl,
  1              ypl,0.,0.,0.,0.,j,timep,plp,0,0)
  if (otu .eq. 1.0) call crtplt(21,00,2,00,0,0,subhd,xtitl,
```

```
1             ytu,0.,0.,0.,0.,j,timep,tup,0,0)
 if (otl .eq. 1.0) call crtplt(22,00,2,00,0,0,subhd,xtitl,
1             ytl,0.,0.,0.,0.,j,timep,tlp,0,0)
 if (omu .eq. 1.0) call crtplt(-11,22,2,00,0,0,subhd,xtitl,
1             ymu,0.,0.,0.,0.,j,timep,mup,0,0)
 if (oml .eq. 1.0) call crtplt(12,00,2,00,0,0,subhd,xtitl,
1             yml,0.,0.,0.,0.,j,timep,mlp,0,0)
 if (omwl .eq. 1.0) call crtplt(21,00,2,00,0,0,subhd,xtitl,
1             ymwl,0.,0.,0.,0.,j,timep,mwlp,0,0)
 if (omdsu .eq. 1.0) call crtplt(-11,22,2,00,0,0,subhd,xtitl,
1             ymdsu,0.,0.,0.,0.,j,timep,mdsup,0,0)
 if (omddu .eq. 1.0) call crtplt(12,00,2,00,0,0,subhd,xtitl,
1             ymddu,0.,0.,0.,0.,j,timep,mddup,0,0)
 if (omdbw .eq. 1.0) call crtplt(21,00,2,00,0,0,subhd,xtitl,
1             ymdbw,0.,0.,0.,0.,j,timep,mdbwp,0,0)
 if (omdlu .eq. 1.0) call crtplt(22,00,2,10000,jsymb(1),0,subhd,
1             xtitl,ymdif,0.,0.,0.,0.,j,timep,mdlup,0,0)
 if (omdul .eq. 1.0) call crtplt(00,00,0,10001,jsymb(2),0,0,0,
1             0,0.,0.,0.,0.,j,timep,mdulp,0,0)
 if (omdlu .eq. 1.0 .and. omdul .eq. 1.0)
1  call crtkey(2,jsymb,ketitl,-1,-1)
 if (omds .eq. 1.0) call crtplt(-11,12,2,00,0,0,subhd,xtitl,
1             ymds,0.,0.,0.,0.,j,timep,mdsp,0,0)
 if (omdv .eq. 1.0) call crtplt(12,12,2,00,0,0,subhd,xtitl,
1             ymdv,0.,0.,0.,0.,j,timep,mdvp,0,0)
 if (onpump .eq. 1.0) call crtplt(-11,12,2,00,0,0,subhd,xtitl,
1             ynpump,0.,0.,0.,0.,j,timep,npumpp,0,0)
 if (otw .eq. 1.0) call crtplt(21,00,2,00,0,0,subhd,xtitl,
1             ytw,0.,0.,0.,0.,j,timep,twp,0,0)
 if (odppmp .eq. 1.0) call crtplt(12,12,2,00,0,0,subhd,xtitl,
1             ydppmp,0.,0.,0.,0.,j,timep,dppmp,0,0)
 stop
 end

 subroutine area(vl,y,awu,aul,awl,z,hu)
c
c subroutine area.f to calculate the heat transfer areas,
c and liquid and gas heights of an elliptical bulkhead tank
c
 real l
 common /tankdim/do,l,ho,t,c1
 common /tankvol/v1,v2,vbi,vbo,vci,vco
 common /tankarea/ab,ac,at
 data tol,nlim/.01,40/
 r = do/2. - t
```

```
      h = ho - t
      vb = vbi
      vc = vci
c
c  liquid level is in upper bulkhead
c
      if (vl .gt. v2) then
          v = vl - vb - vc
          do i = 1,nlim
            fy = y*y*y - 3.*h*h*y + 3.*v*h*h/(3.14159*r*r)
            dfy = 3.*y*y - 3.*h*h
            dely = fy/dfy
            y = y - dely
            if (abs(dely) .le. tol) go to 5
        enddo
    5   z = y + h + l
          awl = ab + ac
     1      + 3.14159*(y*(c1*y*y + r*r)**.5 + r*r/c1**.5
     2      *(log(y*c1**.5 + (c1*y*y + r*r)**.5) - log(r)))
          rul = r*(1. - y/h)
          aul = 3.14159*rul*rul
c
c  liquid level is in cylindrical segment
c
      else
        if (vl .gt. v1) then
          z = (vl - vb)/(3.14159*r*r) + h
          awl = ab + 2.*3.14159*r*(z - h)
            rul = r
            aul = 3.14159*rul*rul
c
c  liquid level is in lower bulkhead
c
        else
          if (vl .gt. 0.) then
              v = vb - vl
              do i = 1,nlim
                fy = y*y*y - 3.*h*h*y + 3.*v*h*h/(3.14159*r*r)
                dfy = 3.*y*y - 3.*h*h
                  dely = fy/dfy
                y = y - dely
                if (abs(dely) .le. tol) go to 10
            enddo
   10         z = h - y
            else
```

```
            z = 0.
          endif
          awl = 3.14159*(h*(c1*h*h + r*r)**.5
     1        - (h - z)*(c1*(h - z)*(h - z) + r*r)**.5
     2        + r*r/c1**.5*(log(h*c1**.5 + (c1*h*h + r*r)**.5)
     3      - log((h - z)*c1**.5 + (c1*(h - z)*(h - z) + r*r)**.5)))
          rul = z*r/h
          aul = 3.14159*rul*rul
        endif
      endif
      awu = at - awl
      dul = 2.*rul
      hu = 2.*h + 1 - z
      return
      end

      subroutine frict(d,ed,mdot,visc,f)
c
c  subroutine frict.f to calculate the friction coefficient
c  for flow in a pipe
c
      real mdot
      re = 4.*mdot/(3.14159*visc*d)
      if (re .lt. 2300.) f = 64./(re + 1.)
      if (re .gt. 2300.)
     1  f = 0.25/(log10(ed/3.7 + 2.51/(re*sqrt(.0056 +
     2       .5/(re**.32)))))**2
      return
      end

      subroutine htc(t1,t2,d,cp,rho,beta,k,mu,a,h)
c
c  This subroutine computes the free convection heat-transfer
c  coefficient for horizontal and vertical surfaces
c
      real k,mu,nu
      if (d .eq. 0.) h = 0.
      if (d .eq. 0.) return
      ra = 3600*32.2*a*beta*abs(t1 - t2)*d**3*rho*rho*cp
     1    /(mu*k)
      nu = 0.555*ra**0.25 + 0.447
      h = nu*k/d
      return
      end
```

```
      subroutine pdrop(mdot,rho,mu,l1,d1,d2,dptot)
c
c subroutine pdrop.f to calculate the pressure drops
c between the pump outlet and spray manifold inlet
c
      real reno(9),kloss1(9),kloss2(9)
      real mdot,mu,l1,kb1,kb2,kb3,kb4,kc,kflm
      data reno/1.5e+5,2.0e+5,3.0e+5,4.0e+5,6.0e+5,8.0e+5,1.0e+6,
     1    2.0e+6,3.0e+6/
      data kloss1/0.32,0.26,0.21,0.19,0.173,0.168,0.163,0.160,0.158/
      data kloss2/0.20,0.15,0.14,0.128,0.12,0.118,0.117,0.115,0.114/
      ed = 1.0e-6
      gc = 32.2
      a1 = 3.14159*d1*d1/4.0
      a2 = 3.14159*d2*d2/4.0
c
c 90-degree bend at pump outlet
c
      re1 = 4.0*mdot/(3.14159*mu*d1)
      call value(9,reno,kloss1,re1,kb1)
c
c straight section downstream of 90-degree bend
c
      call frict(d1,ed,mdot,mu,f1)
      k1 = f1*l1/d1
c
c reducer
c
      kc = 0.5*(1.0 - (d2/d1)**2)
c
c 132.5-degree bend
c
      re2 = 4.0*mdot/(3.14159*mu*d2)
      call value(9,reno,kloss1,re2,kb2)
      kb2 = 1.22*kb2
c
c flowmeter
c
      kflm = 1.308
c
c 95.5-degree bend downstream of flowmeter
c
      call value(9,reno,kloss2,re2,kb3)
      kb3 = 1.03*kb3
c
```

```
c  48-degree bend
c
      call value(9,reno,kloss2,re2,kb4)
      kb4 = 0.66*kb4
c
c  pressure drops
c
      const = mdot*mdot/(2.0*rho*gc*144.0)
      dpb1 = kb1*const/a1**2
      dp1 = k1*const/a1**2
      dpc = kc*const/a2**2
      dpb2 = kb2*const/a2**2
      dpflm = kflm*const/a2**2
      dpb3 = kb3*const/a2**2
      dpb4 = kb4*const/a2**2
      dptot = dpb1 + dp1 + dpc + dpb2 + dpflm + dpb3 + dpb4
c     write (6,12) dpb1,dp1,dpc,dpb2,dpflm,dpb3,dpb4,dptot
c12   format (3x,'dpb1 = ',f8.5,3x,'dp1   = ',f8.5,3x,'dpc  = ',f8.5/
c    1        3x,'dpb2 = ',f8.5,3x,'dpflm = ',f8.5,3x,'dpb3 = ',f8.5/
c    2        3x,'dpb4 = ',f8.5,3x,'dptot = ',f8.5)
      return
      end

      subroutine prtout
c
c  subroutine prtout.f to print the complete output of
c  program tvs.f in a file named outdat
c
      real mu,ml,mwl,mv
      real mdlu,mds,mdsl,mdsu,mddu,mdbw,mdul,mdcond,npump
      common /tankout/nstep,nline,iprint,time(3000),
     1       pu(3000),tu(3000),vu(3000),mu(3000),tw(3000),
     2       pl(3000),tl(3000),vl(3000),ml(3000),
     3       pwl(3000),twl(3000),vwl(3000),mwl(3000),
     4       mv(3000),ts(3000),mdlu(3000),mds(3000),mdsl(3000),
     5       mdsu(3000),mddu(3000),mdbw(3000),mdul(3000),mdcond(3000),
     6       qwu(3000),quwl(3000),qwl(3000),qul(3000),qud(3000),
     7       qus(3000),qls(3000),npump(3000),dppump(3000)
      open (unit=15,file='outdat')
      icount = nstep/(nline*iprint) + 1
      do j = 1,icount
          imin = imax + 1
          imax = j*nline*iprint
          if (imax .gt. nstep) imax = nstep
        write (15,1)
```

```
1     format ('1',t6,'Time',t18,'pU',t28,'TU',t38,'VU',t48,'MU',
  1        t58,'TW',t68,'pL',t78,'TL',t88,'VL',t98,'ML',
  2        t107,'pWL',t117,'TWL',t127,'VWL',t137,'MWL',
  3        t148,'MV',t158,'TS',t166,'mdLU')
      write (15,2)
2     format (t7,'sec',t16,'psia',t29,'R',t37,'ft3',t47,'lbm',
  1        t59,'R',t66,'psia',t79,'R',t87,'ft3',t97,'lbm',
  2        t106,'psia',t119,'R',t127,'ft3',t137,'lbm',
  3        t147,'lbm',t159,'R',t163,'lbm/sec'/)
        do 20 i = imin,imax
          if (mod(i-1,iprint) .ne. 0.0) go to 20
        write (15,3) time(i),pu(i),tu(i),vu(i),mu(i),
  1             tw(i),pl(i),tl(i),vl(i),ml(i),
  2             pwl(i),twl(i),vwl(i),mwl(i),
  3             mv(i),ts(i),mdlu(i)
3       format (f9.1,15(1x,f9.3),1x,e9.3)
c3 .     format (f10.1,15(1x,e10.4))
20     continue
        write (15,4)
4     format ('1',t6,'Time',t17,'mdS',t26,'mdSL',t36,'mdSU',
  1        t46,'mdDU',t56,'mdBW',t66,'mdUL',t74,'mdCOND',
  2        t87,'qWU',t96,'qUWL',t107,'qWL',t117,'qUL',
  3        t127,'qUD',t137,'qUS',t147,'qLS',
  4        t155,'Npump',t164,'dppump')
        write (15,5)
5     format (t7,'sec',t13,'lbm/sec',t23,'lbm/sec',t33,'lbm/sec',
  1       t43,'lbm/sec',t53,'lbm/sec',t63,'lbm/sec',t73,'lbm/sec',
  2        t84,'Btu/hr',t94,'Btu/hr',t104,'Btu/hr',t114,'Btu/hr',
  3        t124,'Btu/hr',t134,'Btu/hr',t144,'Btu/hr',
  4        t157,'rpm',t167,'psi'/)
        do 30 i = imin,imax
          if (mod(i-1,iprint) .ne. 0.0) go to 30
        write (15,6) time(i),mds(i),mdsl(i),mdsu(i),
  1             mddu(i),mdbw(i),mdul(i),mdcond(i),
  2             qwu(i),quwl(i),qwl(i),qul(i),
  3             qud(i),qus(i),qls(i),
  4             npump(i),dppump(i)
6       format (f9.1,7(1x,e9.3),9(1x,f9.3))
30     continue
    enddo
    return
    end

    subroutine spray(pman,mdoti,pull,zu,zliq,ztank,dchar,rhol,acc,ed,
  1            time,prtsp,mdot,mdsu,mdsl,veld,ndrop,norfu)
```

```
c
c  subroutine spray.f to model flow in the spray injection tube
c
      real rod(12),lod(12),roverd,loverd
      real mdin(100),mdout(100),mds(100),as(100),asp(100)
      real vd(100),veld(100),ndrop(100)
      real pin(100),pout(100),pnode(100),ptank(100),x(100),delpt(200)
      real mdot,mdoti,mdotsi,mdoto,mdots,mdsu,mdsl
      real kfsm,kbsm,kcsm,kbsi,ks
      common /sprayin/dsm,zsm,dsi,zsi,n,nbar,
     1            ks,cds,as,vd,roverd,dmdt,tol,nlim,
     2            rho,visc
      data nb/12/rod/1.,1.5,2.,3.,4.,6.,8.,10.,12.,14.,16.,20./
      data lod/20.,14.,12.,12.,14.,17.,24.,30.,34.,38.,42.,50./
      psmi = 144.*pman
      pu = 144.*pull
      dmdot = dmdt
      dzsi = zsi/n
      asm = 3.14159*dsm*dsm/4.
      asi = 3.14159*dsi*dsi/4.
      kcsm = .5*(1. - (dsi/dsm)**2)
      call value(nb,rod,lod,roverd,loverd)
      gc = 32.2
      mdot = mdoti
      do 10 j = 1,nlim
          qsm = (mdot/asm)**2/(2.*rho*gc)
        call frict(dsm,ed,mdot,visc,fsm)
        kfsm = fsm*zsm/dsm
        kbsm = fsm*loverd
        dpfsm = qsm*(kfsm + kbsm + kcsm)
          phsm = rho*acc*zsm
          dpsm = dpfsm + phsm
        psmo = psmi - dpsm
        mdotsi = mdot/nbar
          qi = (mdotsi/asi)**2/(2.*rho*gc)
        call frict(dsi,ed,mdotsi,visc,fsi)
        kbsi = fsi*loverd
        pi = psmo - qi*kbsi
          mdsu = 0.
          mdsl = 0.
          norfu = 0
        do i = 1,n
            x(i) = i*dzsi - dzsi/2.
          aorf = as(i)
            z = ztank - zsi + x(i)
```

```
          if (z .lt. zu) pt = pu
          if (z .ge. zu) pt = pu + rhol*acc*(z - zu)
        call pres(i,n,pi,po,pn,pt,dpf,ph,mdotsi,mdoto,mdots,
     1          dzsi,dsi,ed,asi,aorf,ks,rho,visc,acc)
          pin(i) = pi
          pout(i) = po
          pnode(i) = pn
          ptank(i) = pt
          mdin(i) = mdotsi
          mdout(i) = mdoto
          pi = pout(i)
          mdotsi = mdout(i)
          mds(i) = mdots
          if (aorf .gt. 0.0) veld(i) = mdots/(rho*cds*aorf)
          if (aorf .le. 0.0) veld(i) = 0.0
          if (veld(i) .gt. 0.0)
     1     ndrop(i) = nbar*mdots*dchar/(rho*vd(i)*veld(i))
          if (veld(i) .le. 0.0) ndrop(i) = 0.0
          if (z .lt. zu) norfu = norfu + 1
          if (z .lt. zu) mdsu = mdsu + mdots
          if (z .ge. zu) mdsl = mdsl + mdots
        enddo
      mdsu = nbar*mdsu
      mdsl = nbar*mdsl
      ptcal = pn - ks/(2.*rho*gc)*(mdots/aorf)**2
      delpt(j) = ptcal - pt
      dpt = delpt(j)/144.0
      if (abs(dpt) .lt. tol) go to 15
      if (j .eq. 1) then
        if (delpt(j) .lt. 0.) mdot = mdot - dmdot
        if (delpt(j) .gt. 0.) mdot = mdot + dmdot
      else
        prod = delpt(j)*delpt(j-1)
        if (delpt(j) .lt. 0. .and. prod .gt. 0.) mdot = mdot - dmdot
        if (delpt(j) .gt. 0. .and. prod .gt. 0.) mdot = mdot + dmdot
        if (delpt(j) .lt. 0. .and. prod .lt. 0.) then
          dmdot = dmdot/2.
          mdot = mdot - dmdot
        endif
        if (delpt(j) .gt. 0. .and. prod .lt. 0.) then
          dmdot = dmdot/2.
          mdot = mdot + dmdot
        endif
      endif
   10 continue
```

```
      if (abs(dpt) .gt. tol) write (6,1002) time,dpt
1002  format ('*** tank pressure does not converge at time = ',f10.2,
     1       ' sec,',' delpt = ',e9.3,' psi ***')
15    if (time .ge. prtsp .and. time .le. (prtsp + 0.1)) then
      dppump = (psmi - pt)/144.
      dpsm = dpsm/144.
      dpsi = (pi - pt)/144.
      hliq = 12.*zliq
      write (6,1)
1     format (/5x,'SPRAY MANIFOLD/INJECTION TUBE FLOW MODEL'/)
      write (6,2) acc,pull,pman,hliq,rho,visc
2     format (5x,'Acceleration Level              ',f6.1,' g'/
     1       5x,'Ullage Pressure                  ',f6.3,' psia'/
     2       5x,'Spray Manifold Inlet Pressure    ',f6.3,' psia'/
     3       5x,'Liquid Level                     ',f6.1,' in'/
     4       5x,'Liquid Density                   ',f6.3,' lbm/ft3'/
     5       5x,'Liquid Viscosity                 ',e9.3,' lbm/ft-sec'/)
      write (6,3) mdot,dppump,dpsm,dpsi
3     format (5x,'Pump Flow Rate                  ',f6.3,' lbm/sec'/
     1       5x,'Pump Pressure Rise              ',f6.3,' psi'/
     2       5x,'Spray Manifold Tube Delta p     ',f6.3,' psi'/
     3       5x,'Spray Injection Tube Delta p    ',f6.3,' psi'/)
      write (6,4)
4     format (5x,'Node',2x,'Distance',3x,'Inlet',2x,'Outlet',
     1       3x,'Nodal',3x,'Tank',5x,'Inlet',4x,'Outlet',
     2       3x,'Injection',3x,'Injection',3x,'Orifice')
      write (6,5)
5     format (24x,'p',7x,'p',7x,'p',7x,'p',
     1       7x,'mdot',5x,'mdot',7x,'mdot',6x,'Velocity',
     2       5x,'CdA')
      write (6,6)
6     format (13x,'(in)',4x,'(psia)',2x,'(psia)',2x,'(psia)',2x,'(psia)',
     1       2x,'(lbm/sec)',1x,'(lbm/sec)',1x,'(lbm/sec)',5x,'(fps)',
     2       6x,'(in2)'/)
      do i = 1,n
         pin(i) = pin(i)/144.
         pout(i) = pout(i)/144.
         pnode(i) = pnode(i)/144.
         ptank(i) = ptank(i)/144.
       asp(i) = 144.*as(i)
         x(i) = 12.*x(i)
       write (6,7) i,x(i),pin(i),pout(i),pnode(i),ptank(i),
     1              mdin(i),mdout(i),mds(i),veld(i),asp(i)
7      format (5x,i3,4x,f6.2,3x,4(f6.3,2x),
     1          3(e9.3,1x),4x,f5.2,4x,f8.6)
```

```
      enddo
      endif
      return
      end

      subroutine value(np,x,y,xin,yout)
c
c  This subroutine performs lagrangian interpolation within a set
c  of (x,y) pairs to give yout corresponding to xin
c
      dimension x(np),y(np)
      if (xin .le. x(1)) yout = y(1)
      if (xin .le. x(1)) return
      if (xin .ge. x(np)) yout = y(np)
      if (xin .ge. x(np)) return
      do 10 i = 1,np
          k = i
          if (xin .lt. x(i)) go to 30
 10   continue
 30   ffr = (xin - x(k - 1))/(x(k) - x(k - 1))
      yout = y(k - 1) + ffr*(y(k) - y(k -1))
      return
      end

      SUBROUTINE VALUE2(NPX,NPY,X,Y,Z,XIN,YIN,ZOUT)
      DIMENSION X(NPX),Y(NPY),Z(NPX,NPY)
C
      IF(XIN .LE. X(1) .AND. YIN .LE. Y(1))ZOUT=Z(1,1)
      IF(XIN .LE. X(1) .AND. YIN .LE. Y(1))RETURN
C
      IF(XIN .GE. X(NPX) .AND. YIN .LE. Y(1))ZOUT=Z(NPX,1)
      IF(XIN .GE. X(NPX) .AND. YIN .LE. Y(1))RETURN
C
      IF(XIN .LE. X(1) .AND. YIN .GE. Y(NPY))ZOUT=Z(1,NPY)
      IF(XIN .LE. X(1) .AND. YIN .GE. Y(NPY))RETURN
C
      IF(XIN .GE. X(NPX) .AND. YIN .GE. Y(NPY))ZOUT=Z(NPX,NPY)
      IF(XIN .GE. X(NPX) .AND. YIN .GE. Y(NPY))RETURN
C
      IF(XIN .GT. X(1))GO TO 30
      DO 20 I=1,NPY
        M=I
        IF(YIN .LT. Y(I))GO TO 25
 20   CONTINUE
 25   FFRY=(YIN-Y(M-1))/(Y(M)-Y(M-1))
```

```
      ZOUT=Z(1,M-1)+FFRY*(Z(1,M)-Z(1,M-1))
      RETURN
C
   30 IF(XIN .LT. X(NPX))GO TO 60
      DO 50 I=1,NPY
        M=I
        IF(YIN .LT. Y(I))GO TO 55
   50 CONTINUE
   55 FFRY=(YIN-Y(M-1))/(Y(M)-Y(M-1))
      ZOUT=Z(NPX,M-1)+FFRY*(Z(NPX,M)-Z(NPX,M-1))
      RETURN
C
   60 IF(YIN .GT. Y(1))GO TO 90
      DO 80 I=1,NPX
        L=I
        IF(XIN .LT. X(I))GO TO 85
   80 CONTINUE
   85 FFRX=(XIN-X(L-1))/(X(L)-X(L-1))
      ZOUT=Z(L-1,1)+FFRX*(Z(L,1)-Z(L-1,1))
      RETURN
C
   90 IF(YIN .LT. Y(NPY))GO TO 120
      DO 110 I=1,NPX
        L=I
        IF(XIN .LT. X(I))GO TO 115
  110 CONTINUE
  115 FFRX=(XIN-X(L-1))/(X(L)-X(L-1))
      ZOUT=Z(L-1,NPY)+FFRX*(Z(L,NPY)-Z(L-1,NPY))
      RETURN
C
  120 DO 130 I=1,NPX
        L=I
        IF(XIN .LT. X(I))GO TO 135
  130 CONTINUE
  135 FXR=(XIN-X(L-1))/(X(L)-X(L-1))
      DO 140 I=1,NPY
        M=I
        IF(YIN .LT. Y(I))GO TO 145
  140 CONTINUE
  145 FYR=(YIN-Y(M-1))/(Y(M)-Y(M-1))
C
      ZXLO=Z(L-1,M-1)+FYR*(Z(L-1,M)-Z(L-1,M-1))
      ZXHI=Z(L,M-1)+FYR*(Z(L,M)-Z(L,M-1))
C
      ZOUT=ZXLO+FXR*(ZXHI-ZXLO)
```

```
      RETURN
      END

      subroutine volarea(vt)
c
c  subroutine volarea.f to calculate the volumes and areas of
c  an elliptical bulkhead tank
c
      real l
      common /tankdim/do,l,ho,t,c1
      common /tankvol/v1,v2,vbi,vbo,vci,vco
      common /tankarea/abi,aci,ati
      ro = do/2.
      ri = ro - t
      hi = ho - t
      xk1 = ri/hi
      c1 = xk1**4 - xk1*xk1
c
c  internal bulkhead
c
      vbi = 2./3.*3.14159*ri*ri*hi
      abi = 3.14159*(hi*(c1*hi*hi + ri*ri)**.5
     1      + ri*ri/c1**.5*(log(hi*c1**.5
     2      + (c1*hi*hi + ri*ri)**.5) - log(ri)))
c
c  external bulkhead
c
      vbo = 2./3.*3.14159*ro*ro*ho
      abo = 3.14159*(ho*(c1*ho*ho + ro*ro)**.5
     1      + ro*ro/c1**.5*(log(ho*c1**.5
     2      + (c1*ho*ho + ro*ro)**.5) - log(ro)))
c
c  internal cylinder
c
      vci = 3.14159*ri*ri*l
      aci = 2.*3.14159*ri*l
c
c  external cylinder
c
      vco = 3.14159*ro*ro*l
      aco = 2.*3.14159*ro*l
c
c  tank
c
      v1 = vbi
```

```
      v2 = vbi + vci
      vt = 2.*vbi + vci
      ati = 2.*abi + aci
      return
      end

      subroutine vwall(hliq,vtw)
c
c  subroutine vwall.f to calculate the wall volume exposed to
c  the ullage gas
c
      real l
      common /tankdim/do,l,ho,t,c1
      common /tankvol/v1,v2,vbi,vbo,vci,vco
      ro = do/2.
      ri = ro - t
      hi = ho - t
      vbw = vbo - vbi
      vcw = vco - vci
      if (hliq .gt. (hi + l)) then
          h = hliq - (hi + l)
          vi = 3.14159*h*(ri/hi)**2*(hi*hi - h*h/3.)
          vo = 3.14159*h*(ro/ho)**2*(ho*ho - h*h/3.)
          v = vo - vi
          vtw = vbw - v
      else
          if (hliq .gt. hi) then
            h = hi + l - hliq
            vi = 3.14159*ri*ri*h
            vo = 3.14159*ro*ro*h
            v = vo - vi
            vtw = vbw + v
        else
            h = hi - hliq
            vi = 3.14159*h*(ri/hi)**2*(hi*hi - h*h/3.)
            vo = 3.14159*h*(ro/ho)**2*(ho*ho - h*h/3.)
            v = vo - vi
            vtw = vbw + vcw + v
        endif
      endif
      return
      end
```

3.5 Input Data

3.5.1 Heat Exchanger Model

```
*********|*********|*********|*********|*********|
 MASSIC |  PIC  |  PSTI |MDOT(VNT)|  PBACK  | Program is vent2
*********|*********|*********|*********|*********|
  270.0   20.590   20.645   0.00475   19.5
*********|*********|*********|*********|*********|
 PROP  |  PTP  | AVLIQ  | PAMB  |  G   |
*********|*********|*********|*********|*********|
  1.0     1.021    3500.0   0.0      0.0
*********|*********|*********|*********|*********|
   M   |   VT  |   AX   |   VA   | Twall |
*********|*********|*********|*********|*********|
    25   68.9342  0.04500    0      32.00
*********|*********|*********|*********|*********|
MDOT(sp)| DI (sp) | THKNESS | VFLW DI |  E/D   |
*********|*********|*********|*********|*********|
  0.32     1.18     0.035     0.25   1.0e-6
*********|*********|*********|*********|*********|
 DPINC  | ERRMX  | PERRMX | DEBUG  | EQ DIAM |
*********|*********|*********|*********|*********|
  0.005   0.005     0.0010   0.0     0.134
*********|*********|*********|*********|*********|
FINTIM | PRDEL | QDTERR |  DELT  | DELPTP |
*********|*********|*********|*********|*********|
  2.2     0.02     0.03     0.01      0.08
*********|*********|*********|*********|*********|
  OT   |   OM  |  OP   | DEL Qdot|         |
*********|*********|*********|*********|*********|
     0       0        0  0.0010
*********|*********|*********|*********|
 A(1-M) | DH(1-M) |QDOT(1-M)| LENGTH |
*********|*********|*********|*********|
0.04500    0.0     1.00      0.0
0.27721    0.0     1.00      6.0
0.27721    0.0     0.975     6.0
0.27721    0.0     0.95      6.0
0.27721    0.0     0.925     6.0
0.27721    0.0     0.90      6.0
0.27721    0.0     0.875     6.0
0.27721    0.0     0.85      6.0
0.27721    0.0     0.825     6.0
0.27721    0.0     0.80      6.0
```

0.27721	0.0	0.75	6.0
0.27721	0.0	0.70	6.0
0.27721	0.0	0.65	6.0
0.27721	0.0	0.60	6.0
0.27721	0.0	0.500	6.0
0.27721	0.0	0.450	4.0
0.27721	0.0	0.400	4.0
0.27721	0.0	0.350	4.0
0.27721	0.0	0.300	4.0
0.27721	0.0	0.250	4.0
0.27721	0.0	0.200	4.0
0.27721	0.0	0.150	4.0
0.27721	0.0	0.100	4.0
0.27721	0.0	0.050	4.0
0.00372	0.0	0.000	0.0

Simulation of LH2 Vent Thru Zero g Vent System Heat Exchanger (4/6/93)
Baseline Vent Area of 0.00372 in2 (Mdot & Qdot Trade) delta q = 0.0010

H2 MISC DATA

LMXPAR

18

-2.0	2.107
-1.699	1.835
-1.3979	1.585
-1.1549	1.3874
-1.0	1.2672
-0.6990	1.0492
-0.3979	0.8482
-0.1549	0.7024
0.0	0.6232
0.3010	0.4914
0.6020	0.3766
0.8451	0.2923
1.0	0.2430
1.301	0.1703
1.602	0.1106
1.8451	0.0682
2.0	0.0453
10.0	0.04

LVISP

31

0.0	1.985e-5
1.021	1.751e-5

2.553	1.4e-5
4.17	1.24e-5
6.446	1.11e-5
9.527	1.006e-5
13.561	0.917e-5
15.984	0.877e-5
18.694	0.84e-5
21.723	0.805e-5
25.089	0.773e-5
28.813	0.742e-5
32.915	0.713e-5
37.415	0.685e-5
42.334	0.659e-5
47.693	0.634e-5
53.514	0.609e-5
59.817	0.586e-5
66.625	0.563e-5
73.957	0.54e-5
81.838	0.519e-5
90.287	0.497e-5
99.329	0.476e-5
108.987	0.454e-5
119.297	0.433e-5
130.299	0.410e-5
142.027	0.387e-5
154.522	0.362e-5
167.848	0.333e-5
182.136	0.292e-5
187.510	0.24e-5

GVISP
24

0.0	0.045e-5
1.021	0.05e-5
2.553	0.057e-5
9.527	0.07e-5
18.694	0.079e-5
32.915	0.089e-5
37.415	0.092e-5
42.334	0.095e-5
47.693	0.097e-5
53.514	0.1e-5
59.817	0.103e-5
66.625	0.106e-5
73.957	0.109e-5

81.838	0.112e-5
90.287	0.116e-5
99.329	0.12e-5
108.987	0.124e-5
119.297	0.129e-5
130.299	0.135e-5
142.027	0.143e-5
154.522	0.153e-5
167.848	0.168e-5
182.136	0.196e-5
187.51	0.24e-5

H2 RHO DATA

LRHOP

39

0.0325	5.385
1.01	5.385
1.021	4.80827
1.073	4.80377
1.462	4.77434
1.950	4.74423
2.553	4.71359
3.288	4.68219
4.170	4.65003
5.217	4.61705
6.446	4.58321
7.877	4.54844
9.527	4.51266
11.416	4.47582
13.561	4.43782
15.984	4.39858
18.694	4.35801
21.723	4.31600
25.089	4.27243
28.813	4.22718
32.915	4.18010
37.415	4.13102
42.334	4.07975
47.693	4.02608
53.514	3.96975
59.817	3.9105
66.625	3.8479
73.957	3.7815
81.838	3.7108
90.287	3.635

99.33	3.5534
108.987	3.4646
119.297	3.3668
130.299	3.2572
142.027	3.1314
154.522	2.9808
167.848	2.7851
182.136	2.4567
187.51	1.9620

GRHOP
40

0.0325	0.000345
0.1137	0.00108
0.3163	0.002742
1.021	0.00784
1.073	0.00819
1.462	0.01077
1.950	0.01391
2.553	0.01765
3.288	0.02207
4.170	0.02724
5.217	0.03322
6.446	0.04008
7.877	0.04790
9.527	0.05675
11.416	0.06671
13.561	0.07787
15.984	0.09011
18.694	0.10395
21.723	0.11930
25.089	0.13629
28.813	0.15504
32.915	0.17568
37.415	0.19839
42.334	0.22335
47.693	0.25078
53.514	0.28094
59.817	0.3141
66.625	0.35076
73.957	0.39126
81.838	0.43621
90.287	0.48635
99.329	0.54266
108.987	0.60647

119.297 0.67967
130.299 0.76511
142.027 0.86751
154.522 0.99566
167.848 1.17023
182.136 1.4779
187.510 1.96202

RHOVP
20
0.000345 0.0325
0.00108 0.1137
0.002742 0.3163
0.00784 1.021
0.00819 1.073
0.01077 1.462
0.01391 1.950
0.01765 2.553
0.02207 3.288
0.02724 4.170
0.03322 5.217
0.04008 6.446
0.0479 7.877
0.05675 9.527
0.06671 11.416
0.07787 13.561
0.09011 15.984
0.10395 18.694
0.11930 21.723
0.13629 25.089

SCLENT
10 7
10.0 3
34.0 -115.878
34.263 -115.318
36.483 -110.59
14.7 4
34.0 -115.740
36.0 -111.351
36.483 -110.240
36.608 -109.95
15.0 4
34.0 -115.731
36.0 -111.343

36.608	-109.942
38.444	-105.71
20.0	5
34.0	-115.583
36.0	-111.201
38.0	-106.489
38.444	-105.395
39.975	-101.62
25.0	5
34.0	-115.435
36.0	-111.059
38.0	-106.356
39.975	-101.358
41.299	-98.01
30.0	6
34.0	-115.287
36.0	-110.917
38.0	-106.223
40.0	-101.170
41.299	-97.667
42.475	-94.5
35.0	7
34.0	-115.139
36.0	-110.775
38.0	-106.090
40.0	-101.052
42.0	-95.584
42.475	-94.227
43.536	-91.2
40.0	7
34.0	-114.991
36.0	-110.633
38.0	-105.957
40.0	-100.929
42.0	-95.477
43.536	-90.977
45.406	-85.50
45.0	7
34.0	-114.842
36.0	-110.491
38.0	-105.823
40.0	-100.806
42.0	-95.370
44.0	-89.454
45.406	-85.08

50.0	7
34.0	-114.694
36.0	-110.348
38.0	-105.689
40.0	-100.682
42.0	-95.262
44.0	-89.366
45.406	-84.890

LH2 SATURATED PROPERTIES

* Pressure * Cp * Thermal Cond* Surface T * Sat Temp *

16

1.021	1.557	0.04199	1.7076e-5	24.845
1.462	1.619	0.04551	1.6469e-5	26.0
2.553	1.723	0.05004	1.5419e-5	28.0
4.17	1.849	0.05297	1.4374e-5	30.0
6.446	1.985	0.05489	1.3333e-5	32.0
9.527	2.125	0.05601	1.2298e-5	34.0
13.561	2.27	0.05690	1.1267e-5	36.0
18.694	2.443	0.05793	1.0243e-5	38.0
25.089	2.637	0.05843	0.9225e-5	40.0
28.813	2.743	0.05851	0.8718e-5	41.0
32.915	2.848	0.05848	0.8213e-5	42.0
42.334	3.097	0.05811	0.7209e-5	44.0
53.514	3.393	0.05734	0.6214e-5	46.0
66.625	3.772	0.05616	0.5228e-5	48.0
81.838	4.307	0.05459	0.4253e-5	50.0
99.329	5.074	0.05258	0.3292e-5	52.0

GH2 PROPERTIES

* Cp * Thermal Cond* Viscosity *

6 14 50.0

1.0

2.511	7.21e-3	5.0e-7
2.506	7.35e-3	5.2e-7
2.499	7.63e-3	5.6e-7
2.493	7.92e-3	6.1e-7
2.489	8.24e-3	6.5e-7
2.486	8.56e-3	6.9e-7
2.483	8.96e-3	7.3e-7
2.481	9.47e-3	7.7e-7
2.479	9.98e-3	8.1e-7
2.478	1.049e-2	8.5e-7
2.477	1.10e-2	8.9e-7
2.475	1.151e-2	9.3e-7
2.474	1.202e-2	9.7e-7

2.474	1.252e-2	1.0e-6
5.0		
2.652	6.33e-3	6.3e-7
2.636	7.815e-3	6.43e-7
2.610	8.707e-3	6.72e-7
2.589	8.879e-3	7.03e-7
2.574	9.174e-3	7.35e-7
2.561	9.550e-3	7.73e-7
2.551	9.933e-3	8.05e-7
2.543	1.032e-2	8.32e-7
2.536	1.070e-2	8.56e-7
2.524	1.109e-2	8.87e-7
2.524	1.148e-2	9.18e-7
2.52	1.186e-2	9.49e-7
2.516	1.224e-2	9.79e-7
2.512	1.262e-2	1.01e-6
10.0		
2.790	7.04e-3	7.1e-7
2.768	7.892e-3	7.21e-7
2.726	9.425e-3	7.43e-7
2.696	9.714e-3	7.68e-7
2.671	1.001e-2	7.93e-7
2.649	1.030e-2	8.19e-7
2.633	1.061e-2	8.38e-7
2.619	1.092e-2	8.61e-7
2.607	1.122e-2	8.93e-7
2.596	1.153e-2	9.19e-7
2.587	1.183e-2	9.43e-7
2.578	1.214e-2	9.62e-7
2.571	1.245e-2	9.85e-7
2.564	1.276e-2	1.01e-6
15.0		
2.912	9.84e-3	7.6e-7
2.886	9.95e-3	7.72e-7
2.837	1.017e-2	7.94e-7
2.800	1.040e-2	8.16e-7
2.766	1.064e-2	8.37e-7
2.740	1.088e-2	8.59e-7
2.717	1.113e-2	8.78e-7
2.698	1.138e-2	8.94e-7
2.681	1.163e-2	9.13e-7
2.666	1.188e-2	9.34e-7
2.653	1.213e-2	9.56e-7
2.641	1.239e-2	9.77e-7
2.631	1.264e-2	9.99e-7

2.621	1.290e-2	1.02e-6
20.0		
3.029	1.054e-2	8.0e-7
3.001	1.063e-2	8.09e-7
2.946	1.080e-2	8.27e-7
2.904	1.098e-2	8.45e-7
2.865	1.117e-2	8.64e-7
2.833	1.137e-2	8.82e-7
2.805	1.158e-2	9.01e-7
2.781	1.178e-2	9.19e-7
2.760	1.199e-2	9.38e-7
2.741	1.220e-2	9.56e-7
2.725	1.241e-2	9.75e-7
2.710	1.262e-2	9.92e-7
2.697	1.284e-2	1.01e-6
2.684	1.305e-2	1.02e-6
30.0		
3.261	1.173e-2	8.7e-7
3.228	1.178e-2	8.8e-7
3.171	1.189e-2	8.95e-7
3.121	1.201e-2	9.06e-7
3.072	1.212e-2	9.16e-7
3.032	1.225e-2	9.29e-7
2.998	1.239e-2	9.43e-7
2.964	1.253e-2	9.57e-7
2.937	1.267e-2	9.70e-7
2.912	1.281e-2	9.84e-7
2.887	1.295e-2	9.98e-7
2.868	1.310e-2	1.01e-6
2.849	1.324e-2	1.02e-6
2.83	1.339e-2	1.02e-6
0.0		
0.04		
0.12		
0.2		
0.28		
0.36		
0.44		
0.52		
0.6		
0.68		
0.76		
0.84		
0.92		
1.0		

```
************************************************************
pu      zliq    ztank   dmdot
************************************************************
20.     120.    120.    .005
************************************************************
zsm     dsi     zsi     n       nbar
************************************************************
132.    .444    120.    45      4
************************************************************
ks      acc     rho     visc    roverd
************************************************************
.5      1.      4.339   0.817e-5 2.
************************************************************
tol     nlim
************************************************************
.001    50
************************************************************
opn     opt     omdin   omds    ovel    ocdas
************************************************************
0.      0.      0.      0.      0.      0.
20 PSIA ULLAGE, 0.2 LBM/SEC, 1 G, FULL TANK, 45 ORF
DISTANCE FROM SPRAY TUBE INLET (IN)
PRESSURE (PSIA)
FLOW RATE THROUGH SPRAY TUBE (LBM/SEC)
INJECTION FLOW RATE (LBM/SEC)
INJECTION VELOCITY (FT/SEC)
ORIFICE CDA (IN2)
8
4  .001901
8  .002224
12  .002534
16  .002821
20  .003079
25  .003629
30  .004122
45  .004647
```

3.5.2 Integrated Zero-g TVS Model

```
************************************************************ tvs.f
xd      xchar   he      xcond   prtsp   outp                 input
************************************************************ data
1.0     0.25    0.0     1.0     13200.0 1.0
**********************************************************************
```

```
pui     tui     pli     twi     twli     full     xl1
**********************************************************************
20.0    38.431   20.0    38.841   38.841   10.0    5.375
**********************************************************************
dtank   hcyl    hbulk   tkw     dsb     d1      d2
**********************************************************************
120.0   60.0    30.0    0.5     0.25    1.902   1.402
**********************************************************************
mdvent  mdsi    dthex   qflux   g       hwliq
************************************************************
0.0052  0.001   2.2167  0.25    1.0e-6  25.0
************************************************************
pmin    pmax    delt2   iprnt2  iplot2
************************************************************
20.0    21.0    1.0     15      15
************************************************************
fintim  delt1   xdelt1  iprnt1  iplot1  nline
************************************************************
12500.0  0.1    0.1     10      10      40
************************************************************
opu     otu     omu     opl     otl     oml
************************************************************
1.0     0.0     0.0     1.0     0.0     0.0
************************************************************
otw     omwl    omdv    omdsu   omddu   omdbw
************************************************************
0.0     0.0     1.0     0.0     0.0     0.0
************************************************************
omdlu   omdul   omds    onpump  odppmp
************************************************************
0.0     0.0     1.0     1.0     1.0
```

TIME (SEC)
ULLAGE PRESSURE (PSIA)
ULLAGE TEMPERATURE (R)
ULLAGE MASS (LBM)
BULK LIQUID PRESSURE (PSIA)
BULK LIQUID TEMPERATURE (R)
BULK LIQUID MASS (LBM)
WALL TEMPERATURE (ULLAGE SIDE) (R)
WALL LIQUID MASS (LBM)
OVERBOARD VENT FLOW RATE (LBM/SEC)
ULLAGE SPRAY FLOW RATE (LBM/SEC)
LIQUID DROPLET BOILING RATE (LBM/SEC)
WALL LIQUID BOILING RATE (LBM/SEC)

INTERFACIAL MASS-TRANSFER RATE (LBM/SEC)
PUMP FLOW RATE (LBM/SEC)
PUMP SPEED (RPM)
PUMP PRESSURE RISE (PSI)
ZERO-g TVS TRANSIENT PERFORMANCE
(0g, 10% FULL, 0.25 BTU/HR-FT2, NO He)

```
************************************************************* pump.f
mdotd   dpd     npumpi  npumpd  xhp     xn      input
************************************************************* data
0.3     0.500   0.0     3134.0  5.0     0.01
*************************************************************
deltat  effp
*************************************************************
0.2     0.65
************************************************************* spray.f
dsm     zsm     dsi     zsi     norf    nbar    input
************************************************************* data
1.18    132.0   0.444   120.0   45      4
*************************************************************
ks      cds     roverd  dmdot   tol     nlim
*************************************************************
1.56    0.8     2.0     0.005   0.001   200
1
45      0.0670

 24     p       h       cv      cp      rho     beta    k       mu  Saturated hydrogen
properties
24.845  1.021   -132.892 1.126  1.557   4.80827 .0058609 .04199  1.751e-5
                60.357  1.484   2.513   .00784  .0417855 .00719  .050e-5
25.     1.073   -132.647 1.129  1.568   4.80377 .0059353 .04250  1.730e-5
                60.699  1.484   2.518   .00819  .0415883 .00721  .050e-5
26.     1.462   -131.030 1.151  1.619   4.77434 .0061184 .04551  1.605e-5
                62.879  1.487   2.532   .01077  .0404077 .00739  .052e-5
27.     1.950   -129.360 1.174  1.669   4.74429 .0063005 .04800  1.496e-5
                65.002  1.491   2.551   .01391  .0393821 .00756  .054e-5
28.     2.553   -127.633 1.198  1.723   4.71359 .0064909 .05004  1.400e-5
                67.062  1.496   2.573   .01765  .0384993 .00775  .057e-5
29.     3.288   -125.846 1.221  1.786   4.68219 .0067848 .05168  1.315e-5
                69.056  1.501   2.598   .02207  .0377489 .00793  .059e-5
30.     4.170   -123.995 1.245  1.849   4.65003 .0070405 .05297  1.240e-5
                70.977  1.507   2.627   .02724  .0371221 .00813  .061e-5
31.     5.217   -122.077 1.267  1.915   4.61705 .0073258 .05402  1.172e-5
                72.821  1.513   2.659   .03322  .0366118 .00834  .063e-5
```

32. 6.446 -120.090 1.289 1.985 4.58321 .0076421 .05489 1.112e-5
74.584 1.520 2.695 .04008 .0362124 .00856 .066e-5
33. 7.877 -118.029 1.310 2.051 4.54844 .0079185 .05555 1.056e-5
76.261 1.527 2.734 .04790 .0359198 .00880 .068e-5
34. 9.527 -115.893 1.329 2.125 4.51266 .0082741 .05601 1.006e-5
77.848 1.535 2.778 .05675 .0357318 .00904 .070e-5
35. 11.416 -113.678 1.348 2.195 4.47582 .0085840 .05631 .959e-5
79.339 1.543 2.826 .06671 .0356477 .00929 .072e-5
36. 13.561 -111.380 1.365 2.270 4.43782 .0089505 .05690 .917e-5
80.729 1.551 2.879 .07787 .0356683 .00962 .075e-5
37. 15.984 -108.997 1.380 2.360 4.39858 .0094522 .05748 .877e-5
82.105 1.559 2.935 .09011 .0357690 .00998 .077e-5
38. 18.694 -106.524 1.395 2.443 4.35801 .0099007 .05793 .840e-5
83.256 1.567 2.998 .10395 .0360086 .01036 .079e-5
39. 21.723 -103.956 1.408 2.532 4.31600 .0103939 .05824 .805e-5
84.290 1.576 3.068 .11930 .0363705 .01076 .082e-5
40. 25.089 -101.289 1.420 2.637 4.27243 .0110382 .05843 .773e-5
85.199 1.584 3.146 .13629 .0368634 .01117 .084e-5
41. 28.813 -98.517 1.431 2.743 4.22718 .0117045 .05851 .742e-5
85.976 1.592 3.233 .15504 .0374994 .01159 .087e-5
42. 32.915 -95.636 1.441 2.848 4.18010 .0123677 .05848 .713e-5
86.614 1.601 3.331 .17568 .0382948 .01204 .089e-5
43. 37.415 -92.637 1.451 2.969 4.13102 .0131689 .05835 .685e-5
87.103 1.610 3.441 .19839 .0392710 .01251 .092e-5
44. 42.334 -89.513 1.459 3.097 4.07975 .0140457 .05811 .659e-5
87.431 1.619 3.566 .22335 .0404560 .01301 .095e-5
45. 47.693 -86.254 1.467 3.242 4.02608 .0150803 .05778 .634e-5
87.584 1.629 3.709 .25078 .0418864 .01354 .097e-5
50. 81.838 -67.493 1.507 4.307 3.71079 .0235331 .05459 .519e-5
85.043 1.693 4.919 .43621 .0551860 .01694 .112e-5
55. 130.299 -42.122 1.564 7.528 3.25720 .0531428 .04960 .410e-5
73.413 1.831 9.187 .76511 .1048799 .02422 .135e-5
8 11 h cv cp rho beta k mu T Superheated hydrogen properties
0. .01 .02 .03 .04 .05 .06 .07 .08 .09 .1 600.
1. 25.000
60.765 1.483 2.511 .00763 .00721 .050e-5 25.000
75.138 1.481 2.492 .00617 .00804 .063e-5 30.750
89.438 1.480 2.483 .00518 .00915 .074e-5 36.500
103.700 1.480 2.478 .00447 .01055 .086e-5 42.250
117.938 1.480 2.474 .00393 .01202 .097e-5 48.000
132.160 1.480 2.473 .00351 .01347 .108e-5 53.750
146.372 1.480 2.471 .00317 .01477 .117e-5 59.500
160.577 1.480 2.470 .00297 .01607 .128e-5 65.250
174.782 1.481 2.470 .00265 .01737 .137e-5 71.000
187.139 1.484 2.472 .00248 .01850 .146e-5 76.750

203.223	1.489	2.477	.00228	.01996	.156e-5	82.500
10.	30.806					
78.249	1.537	2.790	.05926	.00704	.071e-5	34.263
93.566	1.502	2.649	.04952	.01030	.082e-5	39.920
108.372	1.493	2.591	.04274	.01168	.093e-5	45.578
122.930	1.489	2.558	.03766	.01306	.103e-5	51.235
137.339	1.487	2.537	.03370	.01439	.114e-5	56.892
151.651	1.486	2.523	.03051	.01564	.124e-5	62.550
165.892	1.485	2.513	.02788	.01692	.133e-5	68.207
180.088	1.486	2.506	.02570	.01819	.142e-5	73.865
194.258	1.489	2.503	.02382	.01944	.151e-5	79.522
208.423	1.493	2.504	.02220	.02071	.160e-5	85.179
222.605	1.502	2.509	.02080	.02198	.169e-5	90.837
15.	36.608					
81.613	1.556	2.912	.08508	.00984	.076e-5	36.608
97.298	1.511	2.722	.07143	.01107	.087e-5	42.242
112.381	1.499	2.640	.06178	.01239	.098e-5	47.876
127.120	1.493	2.595	.05459	.01374	.108e-5	53.510
141.657	1.490	2.566	.04898	.01500	.118e-5	59.144
156.056	1.489	2.546	.04445	.01625	.128e-5	64.778
170.360	1.488	2.532	.04072	.01751	.137e-5	70.412
184.599	1.489	2.524	.03759	.01876	.147e-5	76.045
198.803	1.492	2.519	.03491	.02001	.155e-5	81.679
212.996	1.498	2.519	.03260	.02126	.164e-5	87.313
227.201	1.507	2.524	.03057	.02252	.172e-5	92.947
20	38.444					
83.731	1.571	3.029	.11058	.01054	.080e-5	38.444
99.896	1.519	2.790	.09269	.01169	.091e-5	44.060
115.240	1.504	2.689	.08029	.01297	.102e-5	49.675
130.163	1.498	2.631	.07106	.01427	.112e-5	55.291
144.826	1.494	2.594	.06384	.01550	.121e-5	60.906
159.318	1.491	2.568	.05801	.01674	.131e-5	66.522
173.683	1.490	2.552	.05327	.01799	.140e-5	72.137
187.979	1.492	2.541	.04921	.01923	.149e-5	77.753
202.224	1.495	2.534	.04574	.02047	.158e-5	83.368
216.452	1.502	2.533	.04273	.02171	.167e-5	88.984
230.687	1.512	2.538	.04010	.02296	.175e-5	94.600
25	39.975					
85.177	1.584	3.144	.13584	.01116	.084e-5	39.975
101.806	1.526	2.857	.11368	.01224	.094e-5	45.575
117.424	1.509	2.734	.09846	.01348	.105e-5	51.176
132.526	1.501	2.665	.08719	.01473	.115e-5	56.776
147.319	1.497	2.620	.07839	.01594	.125e-5	62.376
161.903	1.493	2.590	.07131	.01717	.134e-5	67.976
176.339	1.493	2.570	.06554	.01841	.143e-5	73.577

190.690	1.494	2.556	.06058	.01964	.152e-5	79.177
204.980	1.498	2.548	.05634	.02087	.161e-5	84.177
219.242	1.505	2.546	.05269	.02210	.169e-5	90.377
233.514	1.517	2.550	.04952	.02335	.177e-5	95.978
30.	41.299					
86.182	1.595	3.261	.16101	.01173	.087e-5	41.299
103.265	1.533	2.924	.13441	.01274	.098e-5	46.886
119.156	1.514	2.779	.11635	.01393	.108e-5	52.473
134.439	1.505	2.697	.10303	.01523	.117e-5	58.060
149.354	1.499	2.646	.09273	.01634	.127e-5	63.647
164.030	1.495	2.610	.08442	.01756	.136e-5	69.234
178.543	1.495	2.587	.07756	.01878	.146e-5	74.821
192.947	1.496	2.571	.07178	.02000	.155e-5	80.408
207.282	1.500	2.562	.06685	.02122	.163e-5	85.995
221.586	1.509	2.559	.06257	.02245	.171e-5	91.582
235.893	1.521	2.563	.05881	.02369	.179e-5	97.169
35.	42.475					
86.865	1.605	3.381	.18169	.01226	.090e-5	42.475
104.432	1.539	2.987	.15482	.01319	.100e-5	48.050
120.569	1.518	2.822	.13404	.01434	.110e-5	53.626
136.023	1.508	2.730	.11876	.01551	.120e-5	59.201
151.065	1.501	2.670	.10690	.01671	.129e-5	64.776
165.833	1.498	2.630	.09737	.01791	.139e-5	70.351
180.418	1.497	2.604	.08953	.01912	.147e-5	75.927
194.879	1.499	2.586	.08291	.02033	.156e-5	81.502
209.264	1.503	2.576	.07724	.02155	.165e-5	87.077
223.610	1.512	2.572	.07231	.02277	.173e-5	92.652
237.956	1.524	2.575	.06799	.02399	.181e-5	98.228
40.	43.536					
87.300	1.615	3.506	.21148	.01278	.093e-5	43.536
105.311	1.545	3.056	.17544	.01362	.103e-5	49.101
121.728	1.523	2.866	.15163	.01472	.113e-5	54.665
137.369	1.512	2.761	.13427	.01587	.122e-5	60.230
152.534	1.503	2.694	.12088	.01705	.132e-5	65.795
167.379	1.500	2.651	.11027	.01823	.140e-5	71.359
182.041	1.499	2.621	.10139	.01943	.149e-5	76.924
196.562	1.500	2.601	.09390	.02063	.158e-5	82.488
210.999	1.506	2.589	.08750	.02185	.166e-5	88.053
225.389	1.515	2.584	.08193	.02306	.175e-5	93.618
239.769	1.528	2.586	.07706	.02428	.183e-5	99.182