NASA Technical Memorandum 102467

FLUSH: A Tool for the Design of Slush Hydrogen Flow Systems

Terry L. Hardy
Lewis Research Center
Cleveland, Ohio

February 1990

NASA

(NASA-TM-102467) FLUSH: A TOOL FOR THE DESIGN OF SLUSH HYDROGEN FLOW SYSTEMS (NASA) 71 p CSCL 21I
N90-17890
Unclas
G3/28 0264318

FLUSH: A TOOL FOR THE DESIGN OF SLUSH HYDROGEN FLOW SYSTEMS

Terry L. Hardy
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

E-5255

SUMMARY

As part of the National Aerospace Plane Project an analytical model was developed to perform calculations for in-line transfer of solid-liquid mixtures of hydrogen. This code, called FLUSH, calculates pressure drop and solid fraction loss for the flow of slush hydrogen through pipe systems. The model solves the steady-state, one-dimensional equation of energy to obtain slush loss estimates. A description of the code is provided as well as a guide for users of the program. Preliminary results are also presented showing the anticipated degradation of slush hydrogen solid content for various piping systems.

INTRODUCTION

Solid-liquid mixtures of hydrogen are currently being considered for use in the National Aerospace Plane (NASP) Project. These mixtures, known as slush hydrogen, offer the advantages of greater density and heat capacity than normal-boiling-point liquid hydrogen. An important consideration in the use of solid-liquid mixtures of hydrogen is the ability to transfer the fluid through flow lines. Previous studies (refs. 1 and 2) have shown that slush hydrogen with a solid fraction of 0.5 flows well through lines, valves, and other flow restrictions. However, few studies have shown calculations of the expected solid loss due to melting in these flow systems. Ewart and Dergance (ref. 3) performed such a study for the use of densified cryogenic propellants on advanced space transportation systems, but this effort concentrated on line sizes greater than 6 in. in diameter and the code it produced is not available in the open literature. Therefore, as part of the NASP project, an analytical model that performs calculations on the flow of slush in vacuum-jacketed lines was developed. This code, called FLUSH (FLow of slUSH), calculates the pressure drop and slush hydrogen solid fraction loss for steady-state, one-dimensional flow. These calculations can be useful in determining slush transfer parameters for experimental line analyses as well as parameters important in the design of slush transfer lines to the NASP vehicle itself.

This report summarizes the method of solution used in the code and provides a guide to the users of the code. The program solves the steady-state, one-dimensional energy equation and the Bernoulli equation for pipe flow. Slush hydrogen and liquid hydrogen properties are obtained by using the GASPLUS (ref. 4) physical properties code. The users guide gives input parameters required for FLUSH and example problems on the use of the code. The input requirements of the program include flow rate, upstream pressure, initial solid hydrogen fraction, element heat leak, and element parameters such as length and diameter. FLUSH also allows the user to specify pipe components such as elbows, valves, and straight pipe segments. FLUSH further allows the user to input friction factors and has the capability of calculating heat leak rates for vacuum-jacketed piping, if estimates of the heat leak are not available. If standard insulation is desired instead of vacuum-jacketed piping, the user may specify input parameters that will allow the program to calculate heat leak for these cases. In addition, the user may vary the flow rate to obtain the hydrogen solid fraction loss for a range of flows. A FORTRAN program listing of the code is provided, and tables that give basic engineering data for designing vacuum-jacketed piping systems are presented.

In addition to the method of solution and the users guide, a summary of initial results obtained with the code is presented. The solid fraction degradation calculated by FLUSH is compared with estimates from previous analyses. Tradeoffs between heat leak and friction losses are discussed for various pipe sizes and lengths. Finally, a preliminary calculation of the slush loss expected at the NASA Lewis Research Center Plum Brook Station's slush hydrogen test facility in Sandusky, Ohio, is presented.

FLUSH METHOD OF SOLUTION

The following section describes the method of solution used to calculate pressure drop and flow rate for slush hydrogen piping systems. Appendix A defines the symbols used below. Appendix B gives the actual program listing for FLUSH.

FLUSH solves the steady-state, one-dimensional energy equation given by

$$\Delta H + \frac{\Delta V^2}{2g_c J} + \frac{g}{g_c J}\,\Delta Z = \frac{Q}{\dot{m}} - W_s \tag{1}$$

and the Bernoulli equation given by

$$\frac{144\Delta P}{\rho} + \frac{\Delta V^2}{2g_c} + \frac{g}{g_c}\,\Delta Z + F + JW_s = 0 \tag{2}$$

where

$$F = \frac{fV^2L}{2g_c D} \tag{3}$$

In the analysis the following assumptions are made:

1. Steady-state flow exists in the system.

2. The fluid is incompressible.

3. The lines are precooled to triple-point temperature (assumed to be a constant) before the slush flows through the lines.

4. The slush is well mixed before entering the line, and the effects of settling are neglected.

5. The viscosity of slush is the viscosity of liquid hydrogen because the viscosity of slush hydrogen is not known.

6. Heat of fusion is a constant.

7. The heat leak into the slush is used to melt the solid until all the solid is gone; the temperature is assumed to stay constant during the melting process. Once all the solid has melted, the heat leak produces a temperature rise in the remaining liquid.

The assumptions that the fluid is well mixed and that the lines are precooled are probably the most significant of those listed.

FLUSH solves the preceding equations for each element specified by the user. An element can be a straight pipe length, a valve, a fitting, or any other piece of equipment in a piping system. Each element has two nodes; one node is at the beginning of the element, described by a set of initial or entrance conditions, and the other node is at the end of the element and is characterized by the final or exit conditions.

The following steps are used in solving these equations for the pressure drop through an element:

1. Initialize temperatures, pressures, slush solid fraction, and heat leak, as well as element length, diameter, and height.

2. Use GASPLUS to obtain initial-element liquid hydrogen properties.

$$\rho_l = \rho_l(T_i, P_i) \tag{4}$$

$$\mu_l = \mu_l(T_i, P_i) \tag{5}$$

3. Calculate an effective slush density at the inlet.

$$\rho_{mix} = x_i \rho_s + (1 - x_i)\rho_l \tag{6}$$

4. Calculate mass flow rate and Reynolds number. The Reynolds number for slush is calculated from the liquid viscosities.

$$\dot{m} = \frac{60\dot{q}\rho_{mix}}{7.48} \tag{7}$$

$$Re = \frac{4\dot{m}}{3600\pi\mu_l D} \tag{8}$$

5. Calculate a friction factor by using either standard liquid friction factor correlations (the default selection) or National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards) slush correlations. The standard friction factor correlation used is the Colbrook equation, which is a fit of data from the Moody plot of friction factor versus Reynolds number.

6. Calculate the downstream pressure from Bernoulli's equation.

$$P_f = P_i - \frac{\rho_{mix}}{144}\left(\frac{\Delta V^2}{2g_c} + \frac{g}{g_c}\,\Delta Z + F + JW_s\right) \tag{9}$$

Following calculation of the pressure drop the slush solid fraction exiting the element can be calculated. This is done in the following steps:

1. Obtain final-element hydrogen properties from GASPLUS.

$$\rho l = \rho l(T_f, P_f) \tag{10}$$

$$\mu l = \mu l(T_f, P_f) \tag{11}$$

2. Obtain initial- and final-element liquid enthalpies from GASPLUS.

$$H_{liq,f} = H_{liq,f}(T_f, P_f) \tag{12}$$

$$H_{liq,i} = H_{liq,i}(T_i, P_i) \tag{13}$$

3. Calculate initial mixture enthalpy.

$$H_{mix,i} = H_{liq,i} - x_i H_{fus} \tag{14}$$

4. Calculate final mixture enthalpy from the energy equation.

$$H_{mix,f} = H_{mix,i} + \frac{Q}{\dot{m}} - \frac{\Delta V^2}{2g_c J} - \frac{g}{g_c J}\,\Delta Z - W_s \tag{15}$$

The heat leak into the pipe element Q is normally a constant provided by manufacturers of cryogenic equipment. The value of W_s is zero unless a pump is used in the system.

5. Calculate the change in slush solid fraction due to heat input.

$$x_{f,h} = \frac{H_{liq,f} - H_{mix,f}}{H_{fus}} \tag{16}$$

6. Calculate the change in sluch solid fraction due to friction losses.

$$\Delta x_{frict} = \frac{F}{H_{fus} J} \tag{17}$$

7. Calculate the slush fraction at the element exit.

$$x_f = x_{f,h} - \Delta x_{frict} \tag{18}$$

If slush still exists at the exit, the calculations are repeated using the solid fraction x_f to obtain a new value of ρ_{mix}. The calculations are stopped when convergence is reached on density and pressure. The convergence criteria are 0.0001 lbm/ft^3 and 0.0001 psi, respectively.

If $x_f = 0$, calculations are performed to find the increase in liquid temperature due to heat input.

1. Obtain the initial element enthalpy, density, and viscosity by using GASPLUS.

2. Obtain the saturated liquid enthalpy and the saturation temperature.

3. Find the final liquid enthalpy from the energy equation.

4. Obtain a liquid temperature from GASPLUS.

$$T_{liq,f} = T_{liq,f}(H_{liq,f}, P_f) \tag{19}$$

If $T_{liq,f} \geq T_{sat}$, assume that $T_{liq,f} = T_{sat}$ and make a comment in the output. The program does not perform calculations for liquid-gas two-phase flow.

5. Repeat calculations to obtain convergence on temperature.

Once the slush solid fraction or the temperature at the output of the element has been obtained, the calculations can be repeated for a new element. Following completion of the calculations on a system of elements the initial slush flow rate is increased, if the user chose to vary the flow rate, and the entire process is repeated.

The code provides several options for determining heat transfer into a pipe element. If industry estimates are available, a constant value is used. If these estimates are not available for a vacuum-jacketed pipe or if layers of insulation are used on the pipe element, the FLUSH code can calculate the heat transfer values.

If the user desires to estimate the heat transfer into a vacuum-jacketed pipe element, a subroutine is provided in the code to perform this calculation. The method of calculating this heat transfer rate is discussed by Barron (ref. 5) and is described here.

The primary source of heat transfer across a vacuum-jacketed pipe is radiation. A cross section of a vacuum-jacketed pipe is shown in figure 1. The heat rate can be obtained by the equation

$$Q = F_e F_{1-2} \sigma A_1 \left(T_2^4 - T_1^4\right) \tag{20}$$

where, for no radiation shields, the emissivity factor F_e is defined as

$$\frac{1}{F_e} = \frac{1}{\varepsilon_1} + \frac{A_1}{A_2}\left[\frac{1}{\varepsilon_2} - 1\right] \tag{21}$$

Many vacuum-jacketed pipes contain radiation shielding to reduce the radiant heat transfer. In this case the emissivity factor is defined as

$$\frac{1}{F_e} = \left[\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_s} - 1\right] + (N - 1)\left[\frac{2}{\varepsilon_s} - 1\right] + \left[\frac{1}{\varepsilon_2} + \frac{1}{\varepsilon_s} - 1\right] \tag{22}$$

Ewart and Dergance (ref. 3) point out that actual values of the emissivity factor can be considerably higher (a factor of five or greater) than those calculated. Therefore, in this study the actual emissivity used will be five times that calculated. For cryogenic vessels the inner vessel is normally completely enclosed by the outer vessel, and $F_{1-2} = 1$.

For most vacuum-jacketed lines the vacuum space pressure is 1×10^{-5} torr or less. In this case, as shown by Ludtke and Voth (ref. 6), molecular conduction has little effect on the heat transfer. Therefore, calculations for molecular conduction in the vacuum space have not been included in the subroutine.

Note that the industry estimates of heat leak and those calculated by the subroutine are steady-state heat leak values. In an actual transfer line the heat leak may be higher owing to chilldown effects. Although this code assumes the line is chilled before the slush is placed in the line, it is possible to calculate transient effects (ref. 5). This transient analysis, however, is beyond the scope of the present work.

For most ground applications of slush hydrogen, vacuum-jacketed piping would be used for transfer. There may be cases, however, where vacuum-jacketed line is not feasible. In this case standard insulations may be required. Figure 2 shows a crosssection of piping with insulation. For conduction through insulation the heat transfer is calculated as

$$Q = UA_o(T_{air} - T_{fluid}) \tag{23}$$

where

$$\frac{1}{UA_o} = \frac{1}{h_i A_i} + \frac{\Delta r_a}{k_a A_{a,lm}} + \frac{\Delta r_b}{k_b A_{b,lm}} + \frac{\Delta r_c}{k_c A_{c,lm}} + \frac{\Delta r_d}{k_d A_{d,lm}} + \frac{1}{h_o A_o} \tag{24}$$

where the subscripts a, b, c, and d refer to the pipe material and the various types of insulation.

The log-mean area is defined as

$$A_{lm} = 2\pi L(r_2 - r_1) \Bigg/ \left[\ln\left(\frac{r_2}{r_1}\right)\right] \tag{25}$$

For the case where a pump exists in the flow lines, additional calculations are required. For a pump the one-dimensional energy equation and Bernoulli equation (eqs. (1) and (2)) are solved with the addition of a shaft work term as discussed previously. The pump shaft work is defined as

$$W_s = -\frac{60(HP)}{0.02356\dot{m}} \tag{26}$$

In addition, the pressure rise can be calculated once the efficiency of the pump and the shaft work are known, as given in equation (2).

$$\frac{-144\Delta P}{\rho} = JW_{s,min} + \frac{\Delta V^2}{2g_c} + \frac{g}{g_c}\Delta Z \tag{27}$$

where $W_{s,min}$ is the minimum shaft work required, or the hydraulic horsepower This hydraulic horsepower is defined as

$$W_{s,min} = F/J + W_s = \eta W_s \qquad (28)$$

FLUSH USERS GUIDE

The standard input file for the FLUSH code is divided into two sections: a namelist section and an element description section. In addition, if it is desired to calculate the heat leak into any element, a radiation heat transfer parameter section must be added. This section is not required if the heat leak rates are known. Also, if standard insulation or bare pipes are used, two additional sections are required. These are described below. The input file must be named "FLUSH.INP" for the code to run. Additional notes for users on the NASA Lewis Research Center VAX system are provided in appendix C.

In the namelist $PARAMS section the variables are defined as follows:

FLOMIN minimum flow rate, if it is desired to vary the flow in the analysis, gpm

FLOMAX maximum flow rate, gpm

FLOINC flow increment, gpm

E pipe roughness, ft

P initial (upstream) pressure, psi

XI initial slush solid fraction

ZIN initial (entrance) height of element 1, ft

NUM number of elements in system

OUT output control flag. If OUT $\leq$ 0, only final output conditions will be printed to unit 9; otherwise, output conditions of each element are displayed

LONG output control flag for individual variable output. If LONG $\geq$ 0, the individual variables are printed to unit 8. This is useful in examining properties, etc.

XPUT input control flag. If XPUT $\geq$ 0, print input data

FRICT NIST friction factor option. If FRICT $\geq$ 0, use standard friction factor correlations; otherwise, use NIST relations for slush

HEAT element heat transfer flag. If HEAT $\geq$ 0, heat transfer into each element has units of Btu/hr ft; otherwise, units of Btu/hr are used

TAMB ambient temperature, °R

VAC number of elements that require a calculation for the heat leak rate

XRS number of radiation shields in vacuum-jacketed line. This is required for the heat leak calculation. Note: XRS is equivalent to N in equation (22)

NOJAC number of elements that do not have vacuum jacketing (see eqs. (23) and (24))

The element description section of the input requires the information necessary to define an element. These variables are defined as follows:

ELE element number

TYPE element type. The codes corresponding to the element type are given in table 1

DIA element diameter, in.

LENGTH element length, ft

TEMP element temperature, °R

Q element heat transfer rate, Btu/hr or Btu/ft hr

K flow resistance coefficient, normally used to define valves, pipe bends, and fittings

HT height of element at its exit, ft

Table 2 shows an example of a standard input file for the FLUSH program. In this example an analysis is performed on a 100-ft length of 1.5-in.-diameter Schedule 5S vacuum-jacketed pipe. The line is divided into five sections, with bellows and bayonet fittings installed in the line. In addition, two globe valves are placed in the line, one near the beginning of the flow and one near the end. The entire line is located 25 ft above the ground. It is desired to vary the flow from a minimum of 10 to 100 gpm in increments of 5 gpm and find how much slush is lost at the end of the flow length given an initial solid fraction of 0.5. In this case conditions at the end of the piping system will be printed for each flow rate; input conditions also will be printed. Standard friction factor correlations will be used, and the heat transfer will be defined in British thermal units per hour foot for each element. The ambient temperature is 530 °R, and no heat leak calculations are required (VAC = 0). The variable XRS is not needed here as no heat leak estimates are being calculated, but it is shown for completeness.

The element conditions are defined in the second section of the input. The temperature of the slush hydrogen is assumed to be 25.2 °R. This value for the triple-point temperature is required, rather than the normal value of 24.84 °R, owing to the limitations of GASPLUS. The heat transfer rates to each of the individual elements were obtained from estimates made in industry; therefore, the radiation parameter section is not required. Estimates of heat leak to liquid hydrogen for various size pipes are shown in table 3.

As discussed in the literature (ref. 7), valves are normally defined in terms of either a flow coefficient C_v or a resistance coefficient K where

$$C_v = \frac{29.9d^2}{\sqrt{K}} \tag{29}$$

$$K = f\frac{L}{D} \tag{30}$$

Typical C_v and heat leak values for valves and fittings are given in table 4. If K is set equal to zero, the code assumes that a straight vacuum-jacketed line is being used.

Output from this example is shown in table 5. The listing gives the initial conditions of each element in the first page of output. The output parameters include the initial volumetric flow rate in gallons per minute, the mass flow rate in pounds per second, the final solid fraction, the change in solid fraction, and the pressure drop in pounds per square inch. Had all the solid hydrogen melted before the piping system exit had been reached, the heat leakage through the lines would be used to increase the temperature of the liquid hydrogen remaining. In this case the output under the heading "Change in x" would show the final fluid temperature. If the variable OUT had been specified as greater than zero, the conditions at each node would have been listed in the output. An example of this output is given in table 6. In addition to the previously defined parameters this form of output includes the pressure at each node (a node is defined as a point at the exit or entrance of an element).

Table 7 shows an example input file for the case where the heat leak rate is calculated for various elements of the previous example. In this case it is desired to calculate the rate of heat leak into elements 1 and 9. The variable VAC is set equal to 2, and the heat leak rate Q is set less than zero for elements 1 and 9 in the second section of the input. In addition, radiation heat transfer parameters must be defined: the element number, the outside diameter (o.d.) of the inner pipe, the inside diameter (i.d.) of the outer pipe, the emissivity of the inner pipe ε_1 (Ei in the input), and the emissivity of outer pipe, ε_2 (Eo in the input). The i.d. and o.d. for Schedule 5S stainless steel pipe are given in table 8. For this example a 3-in. pipe is used for the outer pipe, and 10 radiation shields between the inner and outer pipes are used as defined by XRS = 10. Note that the user must leave a space between the element description section and the radiation heat transfer parameter section. Also, the heat leak must be defined in British thermal units per hour foot when calculating the heat leak. Typical output for this example is given in table 9.

The output for this example shows a calculated heat leak of 0.552 Btu/hr ft, a value somewhat lower than the estimates given in table 3. These differences could be the result of differences in the surrounding conditions assumed for the industry estimates. Figure 3 shows the calculated heat leak as a function of ambient temperature for various pipe sizes. These calculations were based on vacuum-jacketed line with 10 radiation shields. Emissivities were assumed to be 0.3 for both the inner and outer lines. This emissivity value corresponds to that of polished stainless steel (ref. 8). Ten radiation shields with emissivities of 0.03 were assumed for the analysis. Comparing the heat leak values given in the figure with industry estimates of heat leak shows that the calculated values are generally between 5 and 13 percent lower than industry estimates, assuming an ambient temperature of 540 °R. Therefore, the calculated values of heat leak are expected to be close to those given by industry as design values.

When standard insulation is used, the type of insulation and the thickness must be specified. An example of such a case is shown in table 10. Here, in the first part of the insulation parameters, ELE is the element number, O.D. is the pipe outer diameter, and T1, T2, and T3 are the thicknesses of the insulation. Up to three insulation layers are allowed by the code. In the second section of the insulation parameters the material types are specified. The material types corresponding to the codes are given in table 11. In this example five elements have either standard insulation or bare pipes, as specified by NOJAC=5. Various combinations of pipe materials and insulation schemes are shown. Note that the value of Q given in the element description section will be replaced by that calculated in this section; therefore, the Q specified will not be that given in the output. The output for this example is shown in table 12.

Finally, an example is presented in table 13 for the case where a pump exists in the flow system. In order to specify a pump in the line, the element type is set as either PP or PH. Element type PP signifies a pump with pressure rise and efficiency specified, while PH represents a pump with brake horsepower and efficiency given. In the example shown element 2 is set to type PH. In this case the horsepower is defined in the column under Q and the efficiency is input in the column under K. Also, element 4 is specified as type PP. The pressure drop for the pump in element 4 is input under the Q column and efficiency is placed in the column under K. Table 14 shows the output for the example; slush loss would occur in the pump owing to energy input by the pump.

The user should be aware that there are some limits on the code. These limits are summarized as follows:

1. The triple-point temperature of slush must be set equal to 25.2 °R, rather than 24.8 °R, owing to limitations on GASPLUS.

2. The exit pressure on the piping system must be greater than 1.1 psi (approximately the triple-point pressure of hydrogen). If this limit is not met because the inlet pressure was chosen to be too low, a message appears in the output file.

3. The maximum number of pipe elements the user can input is 90.

4. When all the slush has melted and the heat leak into the system causes a rise in temperature, the code is limited to a final temperature equal to that of the normal-boiling-point saturated liquid; gas-liquid two-phase flow is not included in FLUSH.

5. When using the NIST friction factor correlations, a maximum Reynolds number of only 1×10^6 is possible because of limits on the data.

6. Up to three layers of insulation can be used for the pipe if vacuum-jacketed piping is not used.

RESULTS

In order to obtain confidence in the code, a comparison was made with results from a previous analysis performed by Ewart and Dergance (ref. 3). In this study propellant heating due to heat leak and friction losses was considered, as in the present study. The losses due to friction were assumed to be the same as those for liquid hydrogen in the Ewart and Dergance study; therefore, standard friction factor correlations were used in this comparison. The line considered was a 12-in.-diameter Schedule 5S pipe, 1750 ft long, with a constant heat leak of 12 Btu/hr ft. This heat leak value was calculated for a vacuum-jacketed pipe with multilayer insulation.

Figure 4 compares the slush loss calculated by FLUSH with that of the Ewart and Dergance study. As can be seen from the data, the results are nearly the same over the entire range of flow rates. Also, as discussed in the previous study, a minimum slush loss is reached at a flow rate between 3000 and 4000 gpm owing tradeoffs in environmental heating and friction heating. At lower flow rates heat leak into the line is the major source of slush loss. At higher flow rates friction heating becomes significant. For example, in the Ewart and Dergance comparison at 500 gpm, the solid fraction loss due to environmental heating is 0.043, while that due to friction losses is essentially zero. At 10 000 gpm, the solid fraction loss due to environmental heating is 0.013, while the loss due to friction is 0.012. For cases with less heat leak the slush loss due to friction becomes the dominant loss mechanism.

Following a comparison against previous results the FLUSH code was run using various line sizes and pipe lengths. The results of these runs are shown in figure 5 for line lengths of 100, 200 and 500 ft, respectively. Each line was assumed to be only a straight section of Schedule 5S pipe, with no valves or fittings. As seen in each of these figures, a minimum solids loss was reached as in the case discussed previously. As the line size is decreased, it appears that the minimum occurs at a lower flow rate and at a higher solid fraction loss. This is due to the increased friction loss for smaller pipes, as can be seen in the equation

$$F = \frac{fV^2L}{2g_cD} \tag{3}$$

where F is the energy loss due to friction. The effect of a smaller pipe cross-sectional area is to increase the velocity which, coupled with a decreased diameter, leads to an increased friction loss. Hence, for a small pipe size the friction loss will begin manifesting itself at a lower flow rate, and, as the flow rate increases, the smaller pipe size will present higher solid fraction losses than do the larger pipe sizes. At low flow rates the larger pipes exhibit large slush losses. This is due to the higher surface area and hence higher heat leak into the larger pipes. For longer pipes the solid fraction losses increase owing to increases in both the friction loss and the environmental loss.

A piping system is presently being designed for the transfer of slush hydrogen at NASA Lewis Research Center's Plum Brook Station (ref. 9). This system, located in the K-Site facility, will require the transfer of slush hydrogen from a slush generator located approximately 100 ft from the slush test tank through 1.5-in.-diameter Schedule 5S pipe. An analysis of this piping system was performed by using the FLUSH code. The current system design contains two valves and five 20-ft sections of pipe. Bayonet fittings are used to connect these lines, and bellows are included in each of the lines. The heat leak used for the piping was obtained from industry estimates, provided in tables 3 and 4. The heat leak to the bellows was assumed to be that of the flexline. The roughness of the pipe was assumed to be 0.00015, typically the roughness of commercial steel. The flow rate was varied between 10 and 180 gpm and values of the slush loss were obtained.

The results of the slush loss analysis for K-Site are shown in figure 6. The results show that a fairly broad minimum occurs for this system. Between 35 and 60 gpm the solid loss is approximately 0.5 percentage point. In other words, the expected slush quality, if the fluid is transferred at a rate between 35 and 60 gpm, will be 49.5 percent when it reaches the test tank if the slush is initially 50 percent solid hydrogen. This represents a small loss when using standard vacuum-jacketed pipe with multilayer insulation. Therefore, helium transfer technology is not required for this system.

Finally, a comparison was done between the K-Site system for standard friction factor correlations and the same system for NIST friction factor results (refs. 1,2, and 10). The experimental NIST friction factor results, shown in figure 7, were obtained on a transfer line 0.652 in. i.d., and 48.4 ft long. The data were obtained for Reynolds numbers less than 8×10^5 and extrapolated to the lower flow rates. The solid line in the figure represents a standard friction factor correlation used by NIST. Because these friction factors were obtained empirically, it is not known how the friction factors will change outside the range of Reynolds numbers tested. In addition, the NIST results were obtained for smooth pipes. Therefore, the K-Site case discussed above was run again assuming a smooth pipe. The comparison is shown in figure 8 for an initial slush solid fraction of 0.5. As expected, the slush loss calculations are nearly identical at flow rates less than the minimum value because environmental heating dominates the loss of slush. At higher flow rates the slush loss estimates are quite close owing to the similar values of the friction factor. For the case using the NIST correlations values of slush loss are not shown for flow rates greater than 75 gpm owing to the constraint that the Reynolds number must be less than 1×10^6.

An additional issue that has not been addressed is that of critical velocity, the velocity where the solid hydrogen particles begin to settle. A previous study (ref. 1) has shown that for a 0.652-in.-i.d. pipe the critical velocity is 1.5 ft/sec. If this value is applied to larger pipe sizes, the critical flow rates range from 5.2 gpm for a 1-in.-diameter Schedule 5S pipe to 568 gpm for a 12-in.-diameter pipe, as shown in table 15. Below the critical flow rate the fluid becomes stratified, and the assumptions of one-dimensional flow and a well-mixed fluid are no longer valid. Therefore, the values produced by the code are not expected to be accurate at flow rates below the critical value. It is clear that more testing is required to obtain the critical velocities at larger pipe sizes as the values in table 15 are extrapolated from data for small lines. It has been postulated that the critical velocity depends on pipe diameter with the dependence ranging from direct proportionality to diameter to the 0.15 power (ref. 11).

CONCLUDING REMARKS

An analytical model was developed as part of the National Aerospace Plane Project to predict pressure drop and hydrogen solid fraction loss for a range of pipe sizes and flow rates. This code, called FLUSH, has direct application to the design of piping systems for slush hydrogen experimental test systems and for the flight and ground handling systems of the NASP vehicle. The code solves the one-dimensional, steady-state heat transfer equation to find the solid fraction loss. A listing of the program is provided, and a guide to the code's use is presented.

Results using FLUSH show that this code agrees well with previous analyses. Also, the data show that at low flow rates heat leak effects dominate the solid fraction loss, while at higher flow rates friction heating causes most of the solid hydrogen degradation. These two effects result in a minimum slush solid fraction loss for each pipe size. Further, as the pipe diameter increases, this minimum slush solid fraction loss decreases owing to the decreasing friction losses. An analysis of the NASA Plum Brook slush facility transfer line showed small losses for the piping system design being considered. The analysis will be compared with the test results upon completion of the facility. However, solid hydrogen losses appear to be in an acceptable range for fully chilled vacuum-jacketed lines designed for liquid hydrogen technology. Finally, comparing slush loss with standard friction factor correlations and with friction factor relations obtained in previous experiments showed similar values over the range of flow rates in this study.

APPENDIX A

SYMBOLS

$A_{a,lm}$, $A_{b,lm}$, $A_{c,lm}$, $A_{d,lm}$	log mean area of material a, b, c, or d, ft^2
A_i	inside surface area of pipe, ft^2
A_o	outside surface area of pipe, ft^2
A_1	area of surface 1 per foot, ft^2/ft
A_2	area of surface 2 per foot, ft^2/ft
C_v	flow coefficient
D	pipe diameter, ft
d	pipe diameter, in.
F	energy loss due to friction, ft lbf/lbm
F_e	emissivity factor
F_{1-2}	configuration factor
f	friction factor
g	acceleration due to gravity, 32.2 ft/sec^2
g_c	32.2 lbm ft/lbf sec^2
ΔH	change in enthalpy, Btu/lb
HP	brake horsepower, hp
H_{fus}	latent heat of fusion, Btu/lb
$H_{liq,f}$	enthalpy of liquid exiting element, Btu/lb
$H_{liq,i}$	enthalpy of liquid entering element, Btu/lb
$H_{mix,f}$	enthalpy of solid-liquid mixture exiting element, Btu/lb
$H_{mix,i}$	enthalpy of solid-liquid mixture exiting element, Btu/lb
h_i	inside heat transfer coefficient, Btu/hr ft^2 °R
h_o	outside heat transfer coefficient, Btu/hr ft^2 °R

J	mechanical equivalent of heat, 778.2 ft-lbf/Btu
K	resistance coefficient
k_a k_b k_c k_d	thermal conductivity of material a, b, c, or d, Btu/hr ft R
L	element length, ft
$\dot{m}$	mass flow rate, lb/hr
N	number of radiation shields
ΔP	change in pressure, psi
P_f	pressure at element exit, psi
P_i	pressure at element entrance, psi
Q	heat leak into element, Btu/hr
q	volumetric flow rate, gpm
Re	Reynolds number (also R)
Δr_a	thickness of material a $(r_a - r_i)$, ft
Δr_b	thickness of material b $(r_b - r_a)$, ft
Δr_c	thickness of material c $(r_c - r_b)$, ft
Δr_d	thickness of material d $(r_d - r_c)$, ft
r_a, r_b r_c, r_d	outside radius of material a, b, c, or d, ft
r_1	inside radius for log-mean radius calculation, ft
r_2	outside raidus for log-mean radius calcuation, ft
T_{air}	air temperaure, °R
T_f	temperature at element exit, °R
T_{fluid}	fluid temperature, °R
T_i	temperature at element entrance, °R

$T_{liq,f}$	liquid temperature at element exit, °R
T_{sat}	saturated liquid temperature, °R
T_1	temperature of surface 1 (equal to fluid temperature), °R
T_2	ambient temperature, °R
U	overall heat transfer coefficient, Btu/hr ft^2 °R
V	fluid velocity, ft/sec
W_s	shaft work, Btu/lb
$W_{s,min}$	minimum shaft work (hydraulic horsepower), Btu/lb
x_f	solid fraction at element exit
$x_{f,h}$	solid fraction at exit (heat leak considerations only)
Δx_{frict}	change in solid fraction due to friction losses
x_i	solid fraction at element inlet
ΔZ	change in element height, ft
ϵ_s	emissivity of radiation shielding
ϵ_1	emissivity of surface 1
ϵ_2	emissivity of surface 2
η	pump efficiency
μ	triple-point hydrogen viscosity
μ_l	liquid viscosity, lbm/ft sec
ρ	slush density, lbm/ft^3
ρ_{mix}	solid-liquid mixture density, lbm/ft^3
ρ_s	solid density, lbm/ft^3
ρ_l	liquid density, lbm/ft^3
σ	Stefan-boltzmann constant, 0.173×10^{-8} Btu/hr ft^2 °R^4

REFERENCES

1. Sindt, C.F.; and Ludtke, P.R.: Slush Hydrogen Flow Characteristics and Solid Fraction Upgrading. Advances in Cryogenic Engineering, Vol. 15., K.D. Timmerhaus, ed., Plenum Press, New York, 1970, pp. 382-390.

2. Sindt, C.F.; Ludtke, P.R.; and Daney, D.E.: Slush Hydrogen Fluid Characterization and Instrumentation. NBS Technical Note 377, Feb. 1969.

3. Ewart, R.O.; and Dergance, R.H.: Cryogenic Propellant Densification Study. (MCR-78-586, Martin Marietta Crop.; NASA Contract NAS3-21014) NASA CR-159438, 1978.

4. Fowler, J.R.: GASPLUS User's Manual. NASP CR-1012, Mar. 1988.

5. Barron, R.F.: Cryogenic Systems. 2nd ed., Oxford University Press, Oxford, 1985.

6. Ludtke, P.R.; and Voth, R.O.: A Study of LC-39 Cryogenic Systems. (NBS Report 10705, National Bureau of Standards, NASA CR-126386, 1971.

7. Flow of Fluids Through Valves, Fittings, and Pipe. Crane Co., Hydro-Aire Division, Chicago, IL, TP-410, 1965.

8. Siegel, R.; and Howell, J.R.: Thermal Radiation Heat Transfer. 2nd ed., McGraw-Hill, New York, 1981.

9. Hannum, N.P.: Technology Issues Associated With Fueling The National Aerospace Plane With Slush Hydrogen. NASA TM-101386, 1988.

10. Sindt, C.: A Summary of the Characterization Study of Slush Hydrogen. Cryogenics, vol. 10, no. 5, Oct., 1970, pp. 372-380.

11. Voth, R.O., et al: On Process Design Criteria, Data and Methodology Related to Slush Hydrogen Technology. NASP TM-1006, 1987.

APPENDIX B

PROGRAM LISTING

```
      PROGRAM FLUSH
C
C----------------------------------------------------------------------
C     THIS PROGRAM CALCULATES PRESSURE LOSS AND SLUSH HYDROGEN
C     SOLID FRACTION LOSS IN STEADY STATE FLOWS IN PIPE SYSTEMS
C     (SIMPLE PUMP EQUATIONS ARE INCLUDED)
C
C     THE PROGRAM SOLVES THE STEADY-STATE, ONE DIMENSIONAL
C     ENERGY EQUATION.
C
C     H2-H1 + (V2**2-V1**2)/2GC + (G/GC)(Z2-Z1) = Q - WS
C
C     AND THE BERNOULLI EQUATION
C
C     (P2-P1)/RHO + (V2**2-V1**2)/2GC + (G/GC)(Z2-Z1) + F + WS = 0
C
C
C----------------------------------------------------------------------
C
C      TERRY HARDY
C      NASA LEWIS RESEARCH CENTER
C      CLEVELAND, OHIO 44135
C      (216) 433-2411
C
C      4-17-89
C
C----------------------------------------------------------------------
C
      DATA ID/'PH2'/
      DIMENSION EDIA(90),ELEN(90),ET(90),EX1(90),EZ2(90),EQIN(90),
     * ERHO(90),EP1(90),EMDOT(90),EQUAL(90),EDP2(90),
     + NODE(90),TS(90),HF1(90),ETNEW(90),ECLD(90),RE1(90),
     + NVAC(90),EVDI(90),EVDO(90),EEI(90),EEO(90),PTYPA(90),
     + QFL(90),QL(90),PXTYP(10,90),INSUL(90)
C
      COMMON /FLUX/ EPOD(90),ETI1(90),ETI2(90),ETI3(90),
     * NNOVJ(90),NOJAC,NXMAT(20,90),
     + EXLEN(90),EXDIA(90),EXT(90),TAMB,P,X1,FLOV,EPID(90),K
C
      REAL MDOT,LEN,MPHR,LONG
      CHARACTER*12 PXTYP
      CHARACTER*10 TIM,TONE,TAM,TANE
      CHARACTER*4 PTYP,TYPE,PTYPA
C
C----------------------------------------------------------------------
C     READ IN INPUT DATA
C----------------------------------------------------------------------
C
      OPEN(UNIT=7,FILE=' FLUSH.INP ', STATUS='OLD')
C
C      PARAMS NAMELIST SECTION
C
      NAMELIST / PARAMS / FLOMIN,FLOMAX,FLOINC,E,P,X1,ZIN,NUM,OUT,
     + LONG,XPUT,FRICT,HEAT,TAMB,VAC,XRS,NOJAC
      READ (7,PARAMS)
      READ(7,800)
800   FORMAT(A80)
      NUMB   = NUM
      TOTLEN = 0.
C
```

```
C       ELEMENT DESCRIPTION SECTION
C
        DO 31 I=1,NUMB
        READ(7,300) NELEM,TYPE,DIAM,LEN,T,QIN,CLD,ZHT
  300   FORMAT(I4,A4,6F10.2)
        NODE(I) = NELEM
        PTYPA(I)= TYPE
        EDIA(I) = DIAM
        ECLD(I) = CLD
        ELEN(I) = LEN
        ET(I)   = T
        ETNEW(I)= T
        EQIN(I) = QIN
        EZ2(I+1)= ZHT
        EZ2(1)  = ZIN
        EX1(I)  = X1
        TOTLEN  = LEN + TOTLEN
   31   CONTINUE
C
C-    ------------------------------------------------------------
C
C       FLOMIN= MINIMUM FLOW RATE, GAL/MIN
C       FLOMAX= MAXIMUM FLOW RATE, GAL/MIN
C       FLOINC= INCREMENT FOR FLOW INCREASE, GAL/MIN
C       QIN   = CONSTANT HEAT LEAK TO VJ PIPE,BTU/HR OR BTU/HR FT
C               IF A PUMP ELEMENT, PH OR PP, IS USED
C               QIN = BRAKE HORSEPOWER, HP (PH) OR HEAD LOSS, PSI (PP)
C       TYPE  = ELEMENT TYPE
C               PI.....PIPE ELEMENT
C               PP.....PUMP, PRESSURE LOSS SPECIFIED
C               PH.....PUMP, BRAKE HORSEPOWER SPECIFIED
C               BE.....BELLOWS
C               VA.....STANDARD GLOBE VALVE
C               BA.....BAYONET FITTING
C               EL.....90 DEGREE ELBOW
C               E4.....45 DEGREE ELBOW
C               FX.....FLEXIBLE TUBING
C               YV.....Y-PATTERN GLOBE VALVE
C               AV.....ANGLE VALVE
C               GV.....GATE VALVE
C               BV.....BALL VALVE
C       E     = PIPE ROUGHNESS
C       CLD   = RESISTANCE COEFFICIENT, K (VALVES, ELBOWS, ETC.)
C               K = F (L/D)
C               CLD = 0 => STRAIGHT PIPE
C               IF PUMP ELEMENT (PP OR PH), CLD = PUMP EFFICIENCY
C       DIAM  = PIPE DIAMETER, INCHES
C       T     = INITIAL FLUID TEMPERATURE, R
C       P     = INITIAL (UPSTREAM) PRESSURE, PSIA
C       X1    = INITIAL SLUSH SOLID FRACTION
C       LEN   = PIPE LENGTH, FT
C       NUM   = NUMBER OF ELEMENTS
C       TOTLEN= TOTAL PIPE LENGTH, FT
C       ZHT   = FLUID HEIGHT AT NODE N, FT
C       ZIN   = FLUID HEIGHT AT NODE 1, FT
C       OUT   = OUTPUT CONTROL FLAG (UNIT 9)
C               < 0 => SHORT OUTPUT (FINAL CONDITIONS ONLY)
C       LONG  = OUTPUT CONTROL FLAG FOR INDIVIDUAL VARIABLE OUTPUT
C               (UNIT 8)
C               < 0 => NO INDIVIDUAL VARIABLE OUTPUT
```

```
C       XPUT  = INPUT PRINT CONTROL FLAG
C               < 0 => DO NOT PRINT INPUT DATA
C       HEAT  = HEAT TRANSFER PER ELEMENT FLAG
C               < 0 => BTU/HR,   > 0 => BTU/HR-FT
C       FRICT = NBS SLUSH FRICTION FACTOR OPTION
C               < 0 => USE NBS CORRELATION FOR F
C       VAC   = NUMBER OF ELEMENTS WHICH REQUIRE A CALCULATION FOR
C               THE HEAT LEAK RATE (VACUUM JACKETED PIPING)
C       XRS   = NUMBER OF RADIATION SHIELDS FOR VJ LINE CALCULATIONS
C       TAMB  = AMBIENT TEMPERATURE, R
C       NOJAC = NUMBER OF ELEMENTS WHICH REQUIRE A CALCULATION FOR
C               THE HEAT LEAK RATE (BARE PIPE OR STANDARD INSULATION)
C
C-----------------------------------------------------------------------
C
C       CALCULATE THE HEAT LEAK RATE THROUGH VACUUM-JACKETED PIPES
C       IF VAC > 0
C
        IE = 1
        IF (VAC .LE. 0.0) GO TO 95
        DO 802 I=1,4
        READ(7,801)
 801    FORMAT(A80)
 802    CONTINUE
        DO 13 IB=1,NUMB
        NEWQ = EQIN(IB)
        TINRAD = ET(IB)
        IF (NEWQ .LT. 0.0) GO TO 14
            GO TO 13
  14    READ(7,301) NELEM, DIN, DOUT, EI, EO
 301    FORMAT(I4,2X,4F10.3)
        NVAC(IE) = NELEM
        EVDI(IE) = DIN
        EVDO(IE) = DOUT
        EEI(IE)  = EI
        EEO(IE)  = EO
        CALL VACUUM(QIN1,TAMB,XRS,DIN,DOUT,TINRAD,EI,EO)
        EQIN(IB) = QIN1
        IE = IE + 1
  13    CONTINUE
  95    CONTINUE
C
C----------------------------------------------------------------------
C       CALCULATE HEAT LEAK FOR PIPE WITHOUT VACUUM JACKET IF
C       NOJAC > 0
C----------------------------------------------------------------------
C
        IF (NOJAC .LE. 0) GO TO 150
        DO 311 I=1,4
        READ(7,310)
 310    FORMAT(A80)
 311    CONTINUE
        DO 213 I=1,NOJAC
        READ (7,312) NELE, POD, TI1,TI2,TI3
 312    FORMAT(I4,4F10.2)
        N        = NELE
        EPOD(N) = POD/12.0
        ETI1(N) = TI1
        ETI2(N) = TI2
        ETI3(N) = TI3
```

```
      NNOVJ(I)= NELE
 213  CONTINUE
      DO 214 I=1,3
      READ(7,314)
 314  FORMAT(A80)
 214  CONTINUE
      DO 215 I=1,NOJAC
      READ(7,315) NELE, MAT1, MAT2, MAT3, MAT4
 315  FORMAT(I4,6X,I5,5X,I5,5X,I5,5X,I5,5X)
      N          = NELE
      NXMAT(1,N) = MAT1
      NXMAT(2,N) = MAT2
      NXMAT(3,N) = MAT3
      NXMAT(4,N) = MAT4
      NNOVJ(I)   = NELE
      EXLEN(N)   = ELEN(N)
      EXDIA(N)   = EDIA(N)/12.0
      EPID(N)    = EDIA(N)/12.0
      EXT(N)     = ET(N)
 215  CONTINUE
      FLOV = FLOMIN
      DO 216 I=1,NOJAC
      K = NNOVJ(I)
      CALL QFLUX(QFL(I),QL(I))
      IF (HEAT .LT. 0.) GO TO 217
         GO TO 218
 217  EQIN(NNOVJ(I)) = QFL(I)
         GO TO 219
 218  EQIN(NNOVJ(I)) = QL(I)
 219  CONTINUE
 216  CONTINUE
 150  CONTINUE
C
C
      WRITE(9,500)
 500  FORMAT(' FLUSH CODE'/)
C
C---------------------------------------------------------------
C     CALL SYSTEM DATE AND TIME ROUTINES
C    ------------------------------------------------------
C
      CALL DATE(TIM)
      CALL TIME(TONE)
      WRITE(9,130) TIM,TONE
 130  FORMAT(/' ', A10,2X,A10)
C
C    -----------------------------------------------------
C     WRITE INPUT PARAMETERS TO OUTPUT FILES IF XPUT > 0
C    ------------------------------------------------------
C
      IF (XPUT .LT. 0.0) GO TO 42
       WRITE(9,405)
 405   FORMAT(/'*********************************************
     +***********************************'/)
       WRITE(9,400)
 400   FORMAT(/' INPUT PARAMETERS ')
       WRITE(9,401)
 401   FORMAT(/' ELEMENT',2X,'TYPE',2X,'DIA., IN.',3X,'LENGTH, FT'
     + ,3X,'TEMP., R', 4X,' Q, BTU/HR-FT',3X,' K-F L/D '/)
       DO 43 IA=1,NUM
```

```
      IF (HEAT .LT. 0.0) GO TO 434
         GO TO 433
433   QALT = EQIN(IA)
         GO TO 435
434   QALT = EQIN(IA)/ELEN(IA)
435   CONTINUE
      WRITE(9,402) NODE(IA),PTYPA(IA),EDIA(IA),ELEN(IA),ET(IA),
     + QALT,ECLD(IA)
402   FORMAT(I4,5X,A4,3X,F7.3,5X,F8.3,5X,F8.2,4X,F10.3,4X,F10.3)
      WRITE(9,403)
403   FORMAT('-------------------------------------------------------
     + ---------------------------------------')
43    CONTINUE
C
C       IF VAC > 0 PRINT RADIATION HEAT TRANSFER PARAMETERS
C
      IF (VAC .LE. 0) GO TO 97
      WRITE (9,410)
410   FORMAT(/' RADIATION HEAT TRANSFER PARAMETERS ')
      WRITE(9,406)
406   FORMAT(/' ELEMENT',4X,'INNER O.D.',2X,'OUTER I.D.',6X,
     + ' EI ',8X,'EO')
      DO 96 IC=1,VAC
      WRITE(9,407) NVAC(IC),EVDI(IC),EVDO(IC),EEI(IC),EEO(IC)
407   FORMAT(/I4,7X,F8.3,5X,F8.3,5X,F8.5,3X,F8.5)
96    CONTINUE
      WRITE(9,408)
408   FORMAT('-------------------------------------------------------
     +------------------------------')
C
C       IF NOJAC > 0 PRINT BARE PIPE/STANDARD INSULATION PARAMETERS
C
97    IF (NOJAC .LE. 0) GO TO 197
      WRITE(9,411)
411   FORMAT(/' BARE PIPE OR STANDARD INSULATION PARAMETERS')
      WRITE(9,412)
412   FORMAT(/' ELEMENT',4X,' PIPE O.D.',3X,'INSULATION 1',
     + 4X,'INSULATION 2',4X,'INSULATION 3')
      WRITE(9,413)
413   FORMAT(25X,'THICKNESS, FT',3X,'THICKNESS, FT',3X,
     + 'THICKNESS, FT')
      DO 196, I=1,NOJAC
      K = NNOVJ(I)
      FORD = EPOD(K)*12.
      WRITE(9,414) K, FORD,ETI1(K),ETI2(K),ETI3(K)
414   FORMAT(/I4,10X,F7.4,6X,F7.4,9X,F7.4,9X,F7.4)
196   CONTINUE
      WRITE(9,419)
419   FORMAT(A80)
      WRITE(9,415)
415   FORMAT(/' ELEMENT',4X,'PIPE MATERIAL',4X,'INSULATION 1',
     + 4X, 'INSULATION 2', 4X,'INSULATION 3')
C
      DO 954 I = 1,NOJAC
      K = NNOVJ(I)
      IF (NXMAT(2,K) .LE. 0.0) GO TO 971
         IF (NXMAT(3,K) .LE. 0.0) GO TO 972
            IF (NXMAT(4,K) .LE. 0.0) GO TO 973
               GO TO 974
971   INSUL(I) = 1
```

```
      GO TO 975
972   INSUL(I) = 2
      GO TO 975
973   INSUL(I) = 3
      GO TO 975
974   INSUL(I) = 4
975   CONTINUE
954   CONTINUE
C
      DO 950 I = 1,NOJAC
         DO 951 J = 1,4
            K = NNOVJ(I)
C
C     -----------------------------------------------
C     MATCH MATERIAL CODE TO WORD DESCRIPTION
C     -----------------------------------------------
C
      IF (NXMAT(J,K) .EQ. 101) GO TO 911
       IF (NXMAT(J,K) .EQ. 102) GO TO 912
        IF (NXMAT(J,K) .EQ. 103) GO TO 913
         IF (NXMAT(J,K) .EQ. 104) GO TO 914
          IF (NXMAT(J,K) .EQ. 201) GO TO 921
           IF (NXMAT(J,K) .EQ. 202) GO TO 922
            IF (NXMAT(J,K) .EQ. 203) GO TO 923
             IF (NXMAT(J,K) .EQ. 204) GO TO 924
              IF (NXMAT(J,K) .EQ. 205) GO TO 925
               IF (NXMAT(J,K) .EQ. 301) GO TO 931
                IF (NXMAT(J,K) .EQ. 302) GO TO 932
                   GO TO 942
911     PXTYP(J,K) = 'TEFLON'
       GO TO 970
912     PXTYP(J,K) = '304 ST STEEL'
       GO TO 970
913     PXTYP(J,K) = 'CARBON STEEL'
       GO TO 970
914     PXTYP(J,K) = '6063 ALUM.'
       GO TO 970
921     PXTYP(J,K) = 'FOAM GLASS'
       GO TO 970
922     PXTYP(J,K) = 'SILICA'
       GO TO 970
923     PXTYP(J,K) = 'POLYURETHANE'
       GO TO 970
924     PXTYP(J,K) = 'POLYSTYRENE'
       GO TO 970
925     PXTYP(J,K) = 'FOAM RUBBER'
       GO TO 970
931     PXTYP(J,K) = 'FIBER GLASS'
       GO TO 970
932     PXTYP(J,K) = 'PERLITE'
       GO TO 970
942     PXTYP(J,K) = '            '
970     CONTINUE
951     CONTINUE
950     CONTINUE
       DO 426 I=1,NOJAC
       K = NNOVJ(I)
       WRITE(9,427) K,PXTYP(1,K),PXTYP(2,K),PXTYP(3,K),PXTYP(4,K)
427    FORMAT(/I4,7X,A13,4X,A13,3X,A13,3X,A13)
426    CONTINUE
```

```
      WRITE(9,428)
428   FORMAT('-----------------------------------------------------------
     +------------------------------')
C
197   WRITE(9,404)
404   FORMAT(/'**********************************************
     ***********************************'//)
 42   CONTINUE
C
C
C
      FLOW = FLOMIN
      TO   = T
      PIN1 = P
      XIN  = X1
C
      IF (OUT .GE. 0.0) GO TO 65
      WRITE(9,522)
522   FORMAT('1',' FLUSH CODE OUTPUT')
      WRITE(9,527)
527   FORMAT(/'^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
     +^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^')
      WRITE(9,524) DIAM,FLOW
524   FORMAT(/' PIPE DIAMETER = ',F6.2,1X,'IN.',9X,'FLOW     ',
     +F7.2,2X,'GPM')
      WRITE(9,525) TOTLEN,XIN
525   FORMAT(/' TOTAL PIPE LENGTH = ',F8.2,1X,'FT',4X,'INITIAL
     + SOLID FRACTION = ',F5.3)
      WRITE(9,529) E, TO
529   FORMAT(/' PIPE ROUGHNESS = ',F9.6,9X,'INITIAL TEMPERATURE    ',
     + F7.2,1X,'R')
      WRITE(9,537)
537   FORMAT(/'^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
     +^^^^^^^^^^^^^^^^^^^^^^^^^^^')
C
      IF (XIN .LE. 0.0) GO TO 66
      WRITE(9,523)
523   FORMAT(/2X,' FLOW, GPM',3X,'FLOW, LB/S',6X,' FINAL SOLID',5X,
     +' CHANGE IN X ',6X,'PRESSURE ')
      WRITE(9,528)
528   FORMAT(32X,'FRACTION',27X,'DROP, PSI'/)
      GO TO 65
C
 66   WRITE(9,533)
533   FORMAT(/2X,' FLOW, GPM',3X,'FLOW, LB/S',6X,' FINAL SOLID',5X,
     +' FINAL TEMP, R ',4X,'PRESSURE ')
      WRITE(9,538)
538   FORMAT(32X,'FRACTION',27X,'DROP, PSI'/)
C
 65   CONTINUE
C
 50   CONTINUE
C
C ---------------------------------------------------------------
C       RERUN CALCULATIONS FOR A NEW FLOW RATE
C ---------------------------------------------------------------
C
C ---------------------------------------------------------------
C       CALCULATE NEW HEAT LOSS DUE TO CONDUCTION FOR PIPES
C       WITHOUT VACUUM JACKETING
```

```
C-----------------------------------------------------------------------
C
      IF (NOJAC .LE. 0) GO TO 151
      DO 220 I=1,NOJAC
      FLOV = FLOW
      K = NNOVJ(I)
      CALL QFLUX(QFL(I),QL(I))
      IF (HEAT .LT. 0.) GO TO 221
          GO TO 222
 221  EQIN(NNOVJ(I)) = QFL(I)
          GO TO 223
 222  EQIN(NNOVJ(I)) = QL(I)
 223  CONTINUE
C      WRITE(15,271) FLOW,K,EQIN(K),FLOV
C 271  FORMAT(F10.3,3X,I4,5X,F14.3,5X,F14.3)
 220  CONTINUE
 151  CONTINUE
C
C------------------------------------------------------------------------
C     RESET TEMPERATURES TO INITIAL VALUES FOR NEW FLOW RATE
C     -----------------------------------------------------
C
      DO 23 JA=1,NUM+1
      TS(JA)= 0.
      ET(JA) = ETNEW(JA)
  23  CONTINUE
C
C     ------------------------------------------
C     PRINT OUTPUT HEADER
C         ---------------------------------
C
      IF (LONG .LT. 0.0) GO TO 44
C
C     -------------------------------------------------
C     WRITE HEADER FOR LONG OUTPUT
C     -----------------------------------------------------
C
      WRITE(8,120)
 120  FORMAT(/' FLUSH CODE OUTPUT')
      CALL DATE(TAM)
      CALL TIME(TANE)
      WRITE(8,134) TAM,TANE
 134  FORMAT(/' ', A10,2X,A10)
      WRITE(8,121)
 121  FORMAT(/'000000000000000000000000000000000000000000000000
     +0000000000000000000000000000000000')
C
 44   CONTINUE
C
C     ---------------------------------------------------
C     WRITE HEADER FOR TOTAL NODE CONDITION OUTPUT IF OUT > 0
C         -----------------------------------------
C
      IF (OUT .LT. 0.0) GO TO 68
      WRITE(9,122)
 122  FORMAT('1',' FLUSH1 CODE OUTPUT')
      WRITE(9,127)
 127  FORMAT(/'**************************************************
     +****************************')
      WRITE(9,124) DIAM,FLOW
```

```
 124    FORMAT(/' PIPE DIAMETER = ',F6.2,1X,'IN.',9X,'FLOW  = ',
     +F7.2,2X,'GPM')
        WRITE(9,125) TOTLEN,XIN
 125    FORMAT(/' TOTAL PIPE LENGTH = ',F8.2,1X,'FT',4X,'INITIAL
     + SOLID FRACTION = ',F5.3)
        WRITE(9,129) E, TO
 129    FORMAT(/' PIPE ROUGHNESS = ',F9.6,9X,'INITIAL TEMPERATURE = ',
     +F7.2,1X,'R')
        WRITE(9,126)
        IF (XIN .LE. 0.0) GO TO 11
        WRITE(9,123)
 123    FORMAT(/' NODE',3X,' PRESSURE',4X,
     +'FLOW, LB/S',5X,' FINAL SOLID',3X,' CHANGE IN X ',4X,
     +'PRESSURE, ')
        WRITE(9,128)
 128    FORMAT(9X,'DROP,PSI',21X,'FRACTION',23X,' PSI'/)
        GO TO 12
C
  11     WRITE(9,133)
 133    FORMAT(/' NODE',3X,' PRESSURE',4X,
     +'FLOW, LB/S',5X,' FINAL SOLID',3X,' FINAL TEMP.,R ',3X,
     +'PRESSURE, ')
        WRITE(9,138)
 138    FORMAT(9X,'DROP,PSI',21X,'FRACTION',23X,' PSI'/)
C
  12    CONTINUE
 126    FORMAT(/'^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
     +^^^^^^^^^^^^^^^^^^^^^^^^^^')
  68    CONTINUE
C
C ------------------------------------------------------------------
C      REINITIALIZE VARIABLES
C ------------------------------------------------------------------
C
        HP        = 0.0
        WS        = 0.0
        EP1(1)    = PIN1
        EQUAL(1)  = XIN
C
C-------------------------------------------------------------------
C       BEGIN CALCULATION LOOP FOR DIFFERENT PIPE ELEMENTS
C-------------------------------------------------------------------
C
        DO 32 J=1,NUM
        DIAM = EDIA(J)
        WS   = 0.0
        EFFP = 0.0
        LEN  = ELEN(J)
        T    = ET(J)
        TYPE = PTYPA(J)
C
C ------------------------------------------------------------------
C       IF A PUMP IS USED, REINITIALIZE QIN AS HORSEPOWER (TYPE = PH)
C       OR PRESSURE RISE (TYPE = PP) AND CLD AS EFFICIENCY
C ------------------------------------------------------------------
C
        IF ((TYPE .EQ. '  PP') .OR. (TYPE .EQ. '  PH')) GO TO 781
          IF ((TYPE .EQ. ' PP ') .OR. (TYPE .EQ. ' PH ')) GO TO 781
            IF ((TYPE .EQ. 'PP  ') .OR. (TYPE .EQ. 'PH  ')) GO TO 781
              GO TO 782
```

```
782    QIN   = EQIN(J)
       CONLD= ECLD(J)
       GO TO 783
781    EFFP = ECLD(J)
       IF (TYPE .EQ. '   PH') GO TO 785
         IF (TYPE .EQ. ' PH ') GO TO 785
           IF (TYPE .EQ. 'PH   ') GO TO 785
             GO TO 784
785    HP    = EQIN(J)
       GO TO 783
784    DPP   = -EQIN(J)
783    CONTINUE
       P     = EP1(J)
       X1      EQUAL(J)
       Z2      EZ2(J+1)
       Z1      EZ2(J)
       ELEMI   NODE(J)
       JA      J + 1
C
C     SET CONSTANTS
C
       N       0
       N1    = 0
       N2    = 0
       HFUS  = 25.02
       TOLD  = ET(J)
       PI      3.14159
       GC    = 32.2
       DIA   = DIAM/12.0
       ED      E/DIA

       IF ((TYPE .EQ. '   PP') .OR. (TYPE .EQ. '   PH')) GO TO 786
         IF ((TYPE .EQ. ' PP ') .OR. (TYPE .EQ. ' PH ')) GO TO 786
           IF ((TYPE .EQ. 'PP   ') .OR. (TYPE .EQ. 'PH   ')) GO TO 786

C      CHECK TO SEE IF HEAT LEAK INTO ELEMENT IS IN
C      BTU/HR OR BTU/FT-HR
C
       IF (HEAT .LT. 0.) GO TO 64
          GO TO 67
64     QINTOT = QIN
       GO TO 69
67     QINTOT = QIN*LEN
69     CONTINUE
C
786    CONTINUE
C
       RHOS      5.40
C
C     RHOS   DENSITY OF SOLID HYDROGEN, LB/CU.FT
C
C
C      CHECK TO MAKE SURE THE LAST NODE WAS NOT AT THE
C      SATURATION TEMPERATURE. IF SATURATION CONDITIONS EXIST
C      USE THE APPROPRIATE GASPLUS ROUTINES (NORMAL LIQUID
C      ROUTINES WILL NOT WORK FOR SATURATED CONDITIONS)
C
       IF (TS(1) .GE. ET(J)) GO TO 33
          GO TO 34
       RHOL    DLPSAT(P,ID)
```

```
      VIS1 = VLPSAT(P,ID)
      GO TO 35
 34   CONTINUE
      RHOL = DENLPC(TOLD,P,ID)
      VIS1 = VISLPC(TOLD,P,ID)
 35   CONTINUE
C
C     USE GASPLUS TO CALCULATE LIQUID HYDROGEN PROPERTIES
C      (VISCOSITY HAS UNITS OF LB/FT-SEC)
C
C-------------------------------------------------------------
C      CALCULATE FLOW PARAMETERS
C-------------------------------------------------------------
C
      RHOMIX  = X1*RHOS + (1.-X1)*RHOL
      AREA    = PI*DIA**2*0.25
      EMDOT(J)= FLOW*RHOMIX*60./7.48
      MDOT    = EMDOT(1)
      VELI    = MDOT/(AREA*RHOMIX*3600.)
      RE      = DIA*RHOMIX*VELI/VIS1
      RE1(J)  = RE
C
C      CALL THE DESIRED FRICTION FACTOR ROUTINE
C
      IF (X1 .LE. 0.0) GO TO 17
         IF (FRICT .GE. 0.0) GO TO 17
            IF (RE .GT. 1.0E+06) GO TO 17
               GO TO 18
 18   CALL FRICT1(X1,F,RE)
      GO TO 19
 17   CALL FRICT2(F,RE,ED)
 19   CONTINUE
C
C-------------------------------------------------------------------
C      SET EQUIVALENT PIPE LENGTH
C-------------------------------------------------------------------
C
C-------------------------------------------------------------------
C  IF A PUMP IS USED, THEN EFFICIENCY IS USED IN PLACE OF FLOW COEFF.
C-------------------------------------------------------------------
C
      IF (TYPE .EQ. '  PH') GO TO 788
        IF (TYPE .EQ. ' PH ') GO TO 788
          IF (TYPE .EQ. 'PH  ') GO TO 788
            IF (TYPE .EQ. '  PP') GO TO 789
              IF (TYPE .EQ. ' PP ') GO TO 789
                IF (TYPE .EQ. 'PP  ') GO TO 789
C
      IF (CONLD .GT. 0.0) GO TO 47
          GO TO 48
 47   CNLD = CONLD/F
      GO TO 49
 48   CNLD = LEN/DIA
 49   CONTINUE
C
      GO TO 799
C
C          ----------------------------------------------------
C    IF HORSEPOWER IS SPECIFIED CALCULATE SHAFT WORK, THEN PRESSURE
C          ----------------------------------------------------
```

```
C
788   WS     = HP*60./(.02356*MDOT)
      DP1A   = 0.0
      CNLD   = 0.0
      QINTOT = 0.0
      GO TO 790
C
C       WS IS IN UNITS OF BTU/LB
C
C     ----------------------------------------------------------
C     IF PRESSURE IS SPECIFIED, THEN CALCULATE MINIMUM SHAFT WORK, WSMIN,
C     ALSO KNOWN AS HYDRAULIC HORSEPOWER, THEN CALCULATE BRAKE
C     HORSEPOWER, HP
C     ----------------------------------------------------------
C
789   DP1B   = DPP
      DP1A   = 0.0
      CNLD   = 0.0
      QINTOT = 0.0
      WSMIN  = DPP*MDOT*144./RHOMIX
      WSMIN IS IN UNITS OF FT-LB/HR
      HP1    = WSMIN/EFFP
      WS     = HP1/(MDOT*778.)
      HP     =   HP1/(3600.*550.)
      GO TO 791

      CONTINUE
      DP1A   =  (RHOMIX*CNLD*VELI**2*F)/(2.0*144.*GC)
790   CONTINUE
      DP1B   =  RHOMIX*(Z2-Z1)*(32.2/(GC*144.)) +
     . QFLOW*778.*RHOMIX/144. + EFFP*WS*778.*RHOMIX/144.
      CONTINUE
      DP1    =  DP1A + DP1B
      IF ((ABS(Z2-Z1)/LEN) .GT. 0.00001) GO TO 610
         GO TO 620
610   WRITE(9,611) ELEMI
611   FORMAT(5X,' CHANGE IN HEIGHT > ELEMENT LENGTH AT ELEMENT',
     .F6.0)
      DELZ = ABS(Z2-Z1)
      WRITE(9,613) DELZ,LEN
613   FORMAT(5X,' HEIGHT CHANGE = ',F7.2,1X,'FT.',2X,'LENGTH = ',
     . F7.2,'FT.')
      WRITE(9,612)
612    FORMAT(8X,' RE-EVALUATE SELECTED FLOW SYSTEM '/)
620   CONTINUE
C
C     ----------------------------------------------------------
C
C     VELI   INITIAL FLOW VELOCITY, FT/SEC
C     RE     INITIAL FLUID REYNOLDS NUMBER
C     MDOT   FLOW RATE, LB/HR
C     F      FRICTION FACTOR
C     DP1    PRESSURE DROP FROM BERNOULLI'S EQUATION
C     ----------------------------------------------------------
C
C
C
C     CALCULATE THE CHANGE IN SOLID FRACTION
C     ----------------------------------------------------------
C
      X2 = X1
```

```
 30     IF (X2 .LE. 0.) GO TO 80
C
C       CHECK TO MAKE SURE THAT THERE IS SLUSH AT THE
C       BEGINNING OF THE NODE-- IF NOT, JUMP TO LIQUID ROUTINES
C
        P2 = P - DP1
        IF (P2 .LE. 1.3) GO TO 198
        GO TO 199
 198    WRITE(9,900)
        WRITE(9,901)
 900    FORMAT(/' EXIT PRESSURE IS LESS THAN 1.1 PSIA - THE TRIPLE
     + POINT OF HYDROGEN')
 901    FORMAT(/'  RESET INITIAL PRESSURE AND TRY AGAIN.' )
        GO TO 70
 199    CONTINUE
        EP1(J+1) = P2
        IF (P1 .GE. 190.) GO TO 70
C
C       P2 = FINAL (DOWNSTREAM) PRESSURE
C
        PAVG = (P2 + P)/2.0
C
        RHONEW = DENLPC(TOLD,P2,ID)
        RHOMIX = X2*RHOS + (1.-X2)*RHONEW
        VELFA  = MDOT/(RHOMIX*AREA*3600.)
        QFLOWA = (VELFA**2-VELI**2)/(2.*GC*778.)
        QZ     = (Z2-Z1)/778.
        HLIQI  = ENTLPC(TOLD,P,ID)
        HFUS   = 25.02
        HMIXI  = -X1*HFUS + HLIQI
        HMIXF  = HMIXI + QINTOT/MDOT - QZ - QFLOWA - WS
        HLIQF  = ENTLPC(TOLD,P2,ID)
C
C       ---------------------------------------------------
C       RHOMIX = MIXTURE DENSITY, LB/CU.FT
C       QFLOWA = KINETIC ENERGY TERM, BTU/LB
C       QZ     = POTENTIAL ENERGY TERM, BTU/LB
C       HLIQI  = INITIAL ENTHALPY OF THE LIQUID AT T & P , BTU/LB
C       HFUS   = HEAT OF FUSION, BTU/LB
C       HMIXI  = INITIAL ENTHALPY OF THE MIXTURE, BTU/LB
C       HMIXF  = FINAL MIXTURE ENTHALPY, BTU/LB
C       WS     = SHAFT WORK, BTU/LB
C-----------------------------------------------------------
C
        IF (HLIQF .LE. HMIXF) GO TO 80
C
C       CHECK TO SEE THAT THE ENTHALPY BALANCES
C
        QUALE = (HLIQF-HMIXF)/HFUS
        DQUALP = (144.*DP1A)/(778.*RHOMIX*HFUS)
        QUAL = QUALE - DQUALP
        EQUAL(J+1) = QUAL
C
C       ---------------------------------------------------
C       QUALE    FINAL SOLID FRACTION AFTER HEAT LEAKS HAVE BEEN
C                TAKEN INTO ACCOUNT
C       DQUALP   SLUSH LOSS DUE TO FRICTION LOSSES
C       QUAL     FINAL SOLID FRACTION
C       ---------------------------------------------------
C
```

```
      IF (QUAL .LE. 0.0) GO TO 80
C
C     CHECK TO SEE THAT SLUSH EXISTS AT THE NODE EXIT; IF NOT,
C     JUMP TO LIQUID ROUTINES
C
C     REPEAT CALCULATIONS IN THE PROCESS OF CONVERGENCE
C
      RHOMIX2   = QUAL*RHOS + (1.-QUAL)*RHONEW
      RHOLI     = DENLPC(TOLD,P,ID)
      RHOMI     = QUAL*RHOS + (1.-QUAL)*RHOLI
      VIS2      = VISLPC(TOLD,P2,ID)
      VELF      = MDOT/(RHOMIX2*AREA*3600.)
      QFLOW     = (VELF**2-VELI**2)/(2.*GC*778.)
      REY2      = DIA*RHOMIX2*VELF/VIS2
      RE1(J)    = REY2
C

      IF (X2 .LE. 0.0) GO TO 71
         IF (FRICT .GE. 0.0) GO TO 71
            IF (RE .GT. 1.0E+06) GO TO 71
      CALL FRICT1(QUAL,F2,REY2)
      GO TO 74
      CALL FRICT2(F2,REY2,ED)
      CONTINUE


     IF (TYPE .EQ. '  PH')  GO TO 888
       IF (TYPE .EQ. ' PH ') GO TO 888
         IF (TYPE .EQ. 'PH  ') GO TO 888
           IF (TYPE .EQ. '  PP') GO TO 889
             IF (TYPE .EQ. ' PP ') GO TO 889
               IF (TYPE .EQ. 'PP  ') GO TO 889
        GO TO 894


      WS        HP*60./(.02356*MDOT)
      DP2A      0.0
      GO TO 890

        WS IS IN UNITS OF BTU/LB

      DP2B      DPP
      DP2A      0.0
      WSMIN     DPP*MDOT*144./RHOMIX
      WSMIN IS IN UNITS OF FT-LB/HR
      HP1       WSMIN/EFFP
      WS        HP1/(MDOT*778.)
      HP         HP1/(3600.*550.)
      GO TO 891

      CONTINUE
      DP2A           (RHOMIX2*CNLD*VELF**2*F2)/(2.0*144.*GC)
      CONTINUE
      DP2B           RHOMIX2*QZ*778./144. + QFLOW*778.*RHOMIX2/144
                     + EFFP*WS*RHOMIX2*778./144.
      CONTINUE
      DP2            DP2A + DP2B
      EDP2(J+1)      DP2
      FLOWF          (MDOT*7.48)/(RHOMIX2*60.)
```

```
      HMIXF      = HMIXI + QINTOT/MDOT - QZ - QFLOW - WS
      QUALE      = (HLIQF-HMIXF)/HFUS
C
      DQUALP     = (144.*DP2A)/(778.*RHOMIX2*HFUS)
C
      QUAL       = QUALE-DQUALP
      EQUAL(J+1) = QUAL
      ERHO(J+1)  = RHOMIX2
C
C     RECHECK TO SEE IF SLUSH EXISTS AT THE NODE EXIT
C
      IF (QUAL .LE. 0.0) GO TO 80
C
C     CHECK TO MAKE SURE THE DENSITY AND PRESSURE CONVERGE
C
      IF (ABS(DP2-DP1) .LE. 0.0001) GO TO 10
         GO TO 20
 20   DP1 = DP2
      N = N+1
      IF (N .GE. 400) GO TO 15
      X2 = QUAL
      GO TO 30
C
C
 10   DELRHO = ABS(RHOMIX2 - RHOMIX)
      IF ((DELRHO) .LE. 0.0001) GO TO 15
         GO TO 16
 16   RHOMIX = RHOMIX2
      N1 = N1+1
      X2 = QUAL
      IF (N1 .GE. 400) GO TO 15
      GO TO 30
C
C     ---------------------------------------------------------------
C     LIQUID HYDROGEN AT ENTRANCE OR EXIT
C     ---------------------------------------------------------------
C
 80   CONTINUE
C
C     FIRST CHECK TO SEE IF SLUSH EXISTS AT THE ENTRANCE.
C
      IF (XIN .GT. 0.0) GO TO 27
         GO TO 28
 27   MDOT  = EMDOT(1)
 28   CONTINUE
      TIN   = TOLD
      T     = TOLD
C
C     CALCULATE THE SATURATION TEMPERATURE AT THE INITIAL NODE
C     PRESSURE. IF THE SAT. TEMP. IS EQUAL TO THE INITIAL NODE
C     TEMPERATURE ASSUME SATURATED CONDITIONS AND CALCULATE
C     SATURATED PROPERTIES USING APPROPRIATE GASPLUS ROUTINES.
C
      TSAT1 = TS(J)
      TSAT2 = TSAT(P,ID)
      IF (TS(J) .GE. ET(J)) GO TO 21
         IF (ABS(TSAT2-T) .LE. .05) GO TO 21
            GO TO 82
C
C     ASSUME THE PRESSURE DROP IS EQUAL TO THAT INITIALLY CALCULATED.
```

```
C        P       INITIAL PRESSURE, PSI
C        PIN     FINAL NODE PRESSURE, PSI
C
 21      DP       DP1
         PIN       P   DP
         RHOLIN   DLPSAT(PIN,ID)
         HLIN   - HLPSAT(P,ID)
         RHOL   - DLPSAT(P,ID)
         GO TO 86
 82      CONTINUE
C
C       CALCULATE LIQUID PROPERTIES
C        (IF NO SLUSH EXISTS AT ENTRANCE OR EXIT)
C
         X2        0.0
         QUAL      0.0
         DP        DP1
         PIN       P   DP
         TSAT3     TSAT(PIN,ID)
         HLIN      ENTHPC(TIN,P,ID)
         RHOLIN    DENSPC(TIN,P,ID)
         RHOL      DENSPC(T,PIN,ID)
         HLIQL     ENTHPC(T,PIN,ID)
         CP1       CPPC(TIN,PIN,ID)
         CP2       CPPC(T,PIN,ID)
         CPLIQ     (CP1+CP2)/2.
         MDOT      FLOW*RHOL*60./7.48
C         WRITE(3,853) P,PIN,T,HLIQL,HLIN
C 853     FORMAT(/' P =',F5.2,2X,' PIN = ',F6.2,2X,' T =',
     .   F6.2,2X,' HLIQL = ',F7.2,2X,' HLIN = ',F8.2)
  86      CONTINUE
         IF (J .GT. 1) MDOT=EMDOT(1)
C
         P         INITIAL PRESSURE, PSI
         PIN       FINAL PRESSURE

         EP1(J+1)   PIN
         VEL2       MDOT/(RHOLIN*AREA*3600.)
         VELIN      MDOT/(RHOL*AREA*3600.)
         QFLOWL     (VEL2**2   VELIN**2)/(2.*GC*778.)
         QZ         (Z2 Z1)/(778.)
         HSAT       HLPSAT(PIN,ID)

         INCLUDE THE HEAT CAPACITY OF THE SOLID IN THE SLUSH

         IF (XIN  LE. 0.0) GO TO 90
              GO TO 91
         HMELT    0.0
         GO TO 92
         IF (X1  LE  0.0) GO TO 93
         HMELT    (X1)*HFUS
         GO TO 92
 93      HMELT    0.0
 92      CONTINUE


         HF    HLIN + QINTOT/MDOT   QZ - QFLOWL   HMELT   WS
         HF(J+1)    HF
         IF (HF  GE  HSAT) GO TO 83
         T1    TEMPPC(HF,PIN,ID)
```

```
      IF (TL .LE. 0.) GO TO 83
         GO TO 84
C
C     IF (T > TSAT) ASSUME T=TSAT AND MAKE A COMMENT
C
 83   TL        = TSAT(PIN,ID)
      TS(J+1)   = TL
      HF        = HSAT
      HF1(J+1)= HSAT
      RHOL      = DLPSAT(PIN,ID)
 84   RHONEW    = RHOL
      VIS2      = VIS1
      DP2       = DP
      HLIQI     = HLIN
      HLIQF     = HF
      REY2      = RE
      P1        = P
      P2        = PIN
      F2        = F
      VELI      = VELIN
      VELF      = VEL2
      QFLOW     = QFLOWL
C
C     SET OUTPUT TEMPERATURE AND PRESSURE EQUAL TO INITIAL
C       TEMP. & PRESSURE OF NEXT NODE
C
      ET(J+1)   = TL
      EDP2(J+1) = DP
      IF (ET(J+1) .LT. 25.20) ET(J+1)=25.20
C
C     CHECK TEMPERATURE CONVERGENCE
C
      IF ((TL-T) .GE. 0.01) GO TO 81
         GO TO 15
 81   N2 = N2 + 1
      IF (N2 .GE. 400) GO TO 15
      T = TL
      IF (HF .GE. HSAT) GO TO 88
      GO TO 82
 88   RHOLIN = DLPSAT(PIN,ID)
      HLIQL  = HSAT
      GO TO 86
 15   CONTINUE
      IF (LONG .LT. 0.0) GO TO 32
         CONTINUE
C
C            ---------------------------------------------
C     WRITE LONG, INDIVIDUAL VARIABLE OUTPUT IF LONG > 0
C            ---------------------------------------------
C
      WRITE(8,146) TYPE
 146  FORMAT(/' ELEMENT TYPE = ',A4)
C
      WRITE(8,100) QINTOT,FLOW,E,DIAM
      WRITE(8,141) OUT,LONG,XPUT,FRICT,HEAT
      WRITE(8,142) TAMB,XRS,VAC,DIN,DOUT
      WRITE(8,109) JA, CNLD,RHOS,RHONEW
      WRITE(8,101) T,P,X1,LEN
      WRITE(8,102) MDOT,RHOMIX2
      WRITE(8,106) VIS2,HLIQI
```

```
      WRITE(8,103) HMIXI,HMIXF
      WRITE(8,107) REY2,F2,HLIQF
      WRITE(8,115) DP1A,DP1B,DP2A,DP2B
      WRITE(8,104) P2,DP2,QUAL
      WRITE(8,108) N,N1,PIN1
      WRITE(8,110) QUALE,DQUALP
      WRITE(8,111) Z2,Z1,QZ
      WRITE(8,112) VELI,VELF,QFLOW
      WRITE(8,113) HF,TL,HLIQL,N2
      WRITE(8,114) HSAT,TIN,HLIN
      WRITE(8,145) WS,EFFP,DPP,HP
100   FORMAT(/' QIN = ',F10.3,1X,'BTU/HR',2X,'FLOW = ',F9.2,1X,
     .'GPM', 1X,' E = ',F8.6,1X,' DIA = ',F7.3,1X,'IN.')
141   FORMAT(/' OUT = ',F5.2,2X,' LONG = ',F5.2,2X,' XPUT =',
     .F5.2,2X,'FRICT = ',F5.2,2X,'HEAT = ',F5.2)
142   FORMAT(/' TAMB = ',F6.2,2X,'XRS = ',F4.1,2X,' VAC = ',
     .F5.2,2X,'DIN = ',F6.2,2X,'DOUT = ',F6.2)
101   FORMAT(/' T = ',F7.2,1X,'R',2X,' PI = ',F8.3,1X,'PSIA',2X,
     . ' XI = ',F7.4,2X,' LENGTH = ',F10.4,1X,'FT')
109   FORMAT(/ ' NODE =',I4,2X,' L/D = ',F8.3,2X,
     .' RHOS = ',F9.4,2X,'RHOL = ',F9.4,1X,'LB/CU.FT')
102   FORMAT(/' MDOT = ',F9.2,1X,'LB PER HR',2X,' RHO,MIX = ',F8.3,1X,
     . 'LB PER CU.FT.')
106    FORMAT(/' MU, MIX = ',1PE14.7,1X,'LB PER FT-S',3X,
     .  'HLIQI = ',OPF9.3, 1X,'BTU PER LB')
103    FORMAT(/' HMIX,I = ',F9.3,1X,'BTU PER LB',3X,'HMIX,F = ',F9.3,
     . 1X, 'BTU/LB')
107   FORMAT(/ ' RE = ',1PE14.7,2X,' F = ',OPF10.7,2X,'HLIQF = ',F9.3)
115   FORMAT(/' DP1A = ',F8.4,2X,'DP1B = ',F8.4,2X,'DP2A = ',F8.4,2X,
     .  ' DP2B = ',F8.4)
104    FORMAT(/' PF = ',F8.3,1X,'PSIA',2X,' DP2 = ',F9.5,1X,'PSID',2X,
     .'SOLID FRACTION = ',F10.7)
108    FORMAT(/' N = ',I3,2X,' N1 = ',I3,2X,' PIN = ',F9.5)
110   FORMAT(/ ' QUALE = ', F10.6,2X,'DQUALP = ',F10.6)
111   FORMAT(/' Z2 = ',F7.2,3X,'Z1 = ',F7.2,3X,'QZ = ',F9.3,1X,
     . 'BTU/LB')
112   FORMAT(/' VI = ',F8.3,2X,' VF = ',F8.3,1X,'FT/S',2X,
     .'QFLOW = ',1PE14.7, 2X,' BTU/LB')
113   FORMAT(/' HF = ',F9.3,2X,'TLIQ = ',F7.2,1X,'R',
     .2X,'HLIQL = ',F9.3,2X,'N2 = ',I3)
114   FORMAT(/' HSAT = ',F9.3,2X,'TIN = ',F7.2,2X,'HLIN =',F9.3,
     .1X,' BTU/LB')
145   FORMAT(/' WS = ',F10.3,2X,' EFFP = ',F5.3,2X,' DPP = ',F8.3
     .,2X,'HP = ',F8.3)
      WRITE(8,105)
105   FORMAT(/'****************************************************
     .****************************')

C
C     PRINT OUT INDIVIDUAL NODE CONDITIONS OR END NODE CONDITIONS
C

      CONTINUE
      FPNEW = 0
      FQP2(1) = 0
      DO 26 J = 1,NUM+1
      NODE(J) = J
      IF (EQUAL(J) .LE. 0.0) GO TO 85
      EMDOT(NUM+1) = EMDOT(NUM)
```

```
      MPHR = MDOT/3600.
      EPNEW = EDP2(J) + EPNEW
      DELQ = XIN - EQUAL(J)
      DELTP = PIN1 - EP1(J)
      IF (OUT .LT. 0.0) GO TO 36
      WRITE(9,200)NODE(J),EPNEW,MPHR,EQUAL(J), DELQ,EP1(J)
 200  FORMAT(I3,3X,F10.5,5X,F8.4,9X,F7.4,9X,F7.4,4X,F10.4)
      IF ((RE1(J) .GT. 1.0E+06) .AND. (FRICT .LT. 0.)) GO TO 72
       GO TO 703
 72   WRITE (9,701)
 701  FORMAT(/' RE > 1.0E+06 - RE LIMIT EXCEEDED ')
 703   CONTINUE
      WRITE(9,201)
 201  FORMAT('-----------------------------------------
     + ------------------------------------')
      GO TO 87
C
C
 85   CONTINUE
       EMDOT(NUM+1)=EMDOT(NUM)
       MPHR=MDOT/3600.
       EPNEW = EDP2(J) + EPNEW
      IF (OUT .LT. 0.0) GO TO 36
      WRITE(9,202) NODE(J),EPNEW,MPHR,QUAL,ET(J),EP1(J)
 202  FORMAT(I3,3X,F10.5,5X,F8.4,9X,F7.4,6X,F10.3,6X,F10.4)
      IF (HF1(J) .GE. HSAT) GO TO 98
          GO TO 99
 98   IF (J .LT. 2) GO TO 99
      WRITE (9,204)
 204  FORMAT(' TEMPERATURE EXCEEDS SATURATION TEMPERATURE')
 99   WRITE(9,203)
 203  FORMAT( '---------------------------------------------------
     +----------------------------------------')
 87    CONTINUE
 36    CONTINUE
C
C
       IF (OUT .GE. 0.0) GO TO 56
       IF (QUAL .LE. 0.0) GO TO 76
       WRITE(9,600) FLOW,MPHR,QUAL, DELQ,EPNEW
 600  FORMAT(1X,F10.3,5X,F8.3,9X,F7.4,11X,F7.4,7X,F10.4)
      IF ((REY2 .GT. 1.0E+06) .AND. (FRICT .LT. 0.)) GO TO 37
       GO TO 77
 37   WRITE (9,702)
 702  FORMAT(/' RE > 1.0E+06 - RE LIMIT EXCEEDED ')
 77   CONTINUE
      WRITE(9,601)
 601  FORMAT(3X,'--------------------------------------------------
     + ---------------------------')
      GO TO 56
C
C
 76   CONTINUE
      IF (TL .LT. 25.2) TL = 25.2
    WRITE(9,602) FLOW,MPHR,QUAL, TL,EPNEW
 602  FORMAT(1X,F10.3,5X,F8.3,9X,F7.4,8X,F10.3,8X,F10.4)
      IF (HF .GE. HSAT) GO TO 78
          GO TO 79
 78   WRITE (9,604)
 604  FORMAT(/10X,' TEMPERATURE EXCEEDS SATURATION TEMPERATURE')
```

```
79    WRITE(9,603)
603   FORMAT(3X,'--     -- --          -- - -- ------- ---- -----
     .                                    ..')
C
56     CONTINUE
C
C      -----------------------------------------------
C      RESET FLOW RATE AND REPEAT CALCULATIONS
C      -----------------------------------------------
C
       IF (FLOINC .LE. 0.0) GO TO 63
       IF (FLOW .LT. FLOMAX) GO TO 60
         GO TO 70
60    FLOW = FLOW + FLOINC
      GO TO 50
63    WRITE(9,999)
999   FORMAT(' FLOW INCREMENT, FLOINC, WAS NOT INCLUDED
     . IN THE INPUT - REVIEW INPUT DATASET')
70    CONTINUE
      END
C
      SUBROUTINE FRICT1(X,F,RE)
C
C      -----------------------------------------------
C     THIS PROGRAM CALCULATES THE FRICTION FACTOR AS A
C     FUNCTION OF REYNOLDS NUMBER FOR SLUSH HYDROGEN.
C      THIS DATA WAS OBTAINED USING A SMOOTH, VACUUM-JACKETED
C      PIPE 0.652 INCH IN DIAMETER AS DESCRIBED IN
C      SINDT,LUDTKE, AND DANEY,
C      NBS TECHNICAL NOTE 377,
C     "SLUSH HYDROGEN FLUID CHARACTERIZATION AND
C     INSTRUMENTATION," FEB. 1969. DATA WAS CURVE-FITTED
C     TO OBTAIN THE EQUATIONS IN THIS PROGRAM.
C
C     NOTES: THE GEOMETRIC CURVE FIT, FG, TENDS TO GIVE
C     THE BEST FIT OVER THE ENTIRE RANGE; THIS IS EXPECTED
C     AS THE FRICTION FACTOR NORMALLY TAKES THE FORM
C       F = A/RE**B
C
C     STANDARD FRICTION FACTORS GIVEN IN THE LITERATURE
C     ARE, FOR TURBULENT FLOW,
C     F = 4*0.079*RE**-.25    AND
C     F = 4*0.046*RE**-.20
C      THE SECOND EQUATION GIVES A BETTER FIT TO EXPERIMENTAL
C     DATA. IN ADDITION, THE EQUATION OFTEN USED IS
C      F**-0.5 = 4.06*LOG(RE/F**0.5) - 0.60
C     THIS IS USED TO COMPARE DATA IN THE NBS DATA.
C
C     FOR LAMINAR FLOW, F = 64/RE
C
C                              ----------------
C      THE FRICTION FACTOR CALCULATIONS CAN ONLY BE USED FOR
C      RE < 1E06
C
C
C  1     GEOMETRIC FIT (Y = AX**B) OF THE FRICTION FACTOR
```

```
      IF (X .GE. 0.5 ) GO TO 1
          GO TO 2
2     IF (X .GE. 0.4) GO TO 3
          GO TO 4
4     IF  (X .GE. 0.3) GO TO 5
          GO TO 6
6     IF   (X .GE. 0.2) GO TO 7
           GO TO 7
1     FG = 3.0775*RE**-.41267
      F = FG
      GO TO 10
3     FG4 = 1.94175*RE**-.38524
      FG5 = 3.0775*RE**-.41267
      F = FG4*(.5-X)*10. + FG5*(1.-(.5-X)*10.)
      GO TO 10
5     FG4 = 1.94175*RE**-.38524
      FG3 = 0.70205*RE**-.309898
      F = FG3*(.4-X)*10. + FG4*(1.-(.4-X)*10.)
      GO TO 10
7     FG2 = 0.421259*RE**-.27205
      FG3 = 0.70205*RE**-.309898
      IF (X .LE. 0.2) GO TO 11
          GO TO 13
11    AX = .2
      GO TO 12
13    AX = X
12    F = FG2*(.3-AX)*10. + FG3*(1.-(.3-AX)*10.)
 10   CONTINUE
      RETURN
      END
C
C
      SUBROUTINE VACUUM (QRAD,TAMB,XRS,DIN,DOUT,TIN,E1,E2)
        REAL L,XMFP,MU
C-----------------------------------------------------------------
C     THIS PROGRAM CALCULATES THE HEAT TRANSFER THROUGH
C     VACUUM JACKETED LINES AS A FUNCTION OF OUTSIDE
C     TEMPERATURE AND PIPE DIAMETER FOR SLUSH HYDROGEN SYSTEMS.
C-----------------------------------------------------------------
C      VARIABLES:
C            E1----EMISSIVITY OF INSIDE SURFACE,UNITLESS
C            E2----EMISSIVITY OF OUTER SURFACE,UNITLESS
C            DIN---OUTER DIAMETER OF THE INSIDE PIPE, IN
C            DOUT--INNER DIAMETER OF THE OUTER PIPE, IN
C            TAMB--AMBIENT TEMPERATURE, R
C            TIN---FLUID TEMPERATURE, R
C            XRS---NUMBER OF RADIATION SHIELDS
C            QRAD--RADIATION HEAT TRANSFER, BTU/FT-HR
C            F12---CONFIGURATION FACTOR
C            FE----EMISSIVITY FACTOR
C            SIG---STEFAN-BOLTZMANN CONSTANT
C         ------------------------------------------------
C
C     CALCULATE HEAT LOSS DUE TO RADIATION
C
      T2 = TAMB
      T1 = TIN
C

 10   CONTINUE
```

```
      IF (XRS .GT. 0.) GO TO 15
          GO TO 16
 15   F12 = 1.0
      E1IN = 1./E1
      E2IN = 1./E2
      ES = 0.03
C
C     ES - ALUMINUM SHIELD EMISSIVITY
C
      ESIN = 1./ES
      CON1 = E1IN + ESIN -1.
      CON2 = (XRS-1.)*(2.0*ESIN - 1.)
      CON3 = E2IN + ESIN -1.
      FEIN = CON1 + CON2 + CON3
      FECALC= 1./FEIN
      FEACT = 5.0*FECALC
      FE    = FEACT
      GO TO 17
 16   F12  = 1.0
      A1A2 = DIN/DOUT
      E1IN = 1./E1
      E2IN = 1./E2
      FEIN = E1IN + A1A2*(E2IN-1.0)
      FE   = 1.0/FEIN
 17   PI   = 3.14159
      SIG  = 0.173E-08
      A1   = PI*DIN/12.
      TP2  = T2**4.
      TP1  = T1**4.
      QRAD = F12*FE*SIG*A1*(TP2 - TP1)
C
C     QRAD HAS UNITS OF BTU/HR-FT
C
 20    RETURN
       END

      SUBROUTINE FRICT2(F2,RE,ED)
C
C     THIS SUBROUTINE CALCULATES FRICTION FACTORS FOR
C     TURBULENT FLOW USING THE COLBROOK EQUATION.
C
       WRITE(14,201) RE,ED,F2
C201   FORMAT(1PE15.8,2X,E15.8,2X,E15.8)
      F1 = 1.325/(ABS(ALOG(ED/3.7 + 5.74/RE**0.9)))**2.0
      N = 0
      F2A = 0.021
 30   CONTINUE
      CON1 = (ED/3.7 + 2.51/(RE*SQRT(F2A)))
      CONF2 = 2.*ALOG10(CON1)
      F2B = 1.0/(CONF2)**2.
      IF (ABS(F2B-F2A) .LE. 0.000001) GO TO 20
        F2A = F2B
        N = N+1
C      WRITE(15,203) RE,N
C203   FORMAT(1PE15.8,2X,I5)
        IF (N .GT. 400) GO TO 23
         GO TO 30
 20   CONTINUE
        WRITE(9,206) RE,F2,CON1
C206    FORMAT(1PE15.8,2X,E15.8,2X,E15.8)
```

```
      F2 = F2B
 23   RETURN
      END
C
      SUBROUTINE QFLUX(QFLA,QLA)
C
C     PROGRAM TO CALCULATE THE HEAT TRANSFER RATE
C     TO SLUSH HYDROGEN BEING TRANSFERRED IN
C     PIPING WITHOUT VACUUM-JACKETING.
C
C     QFLUX ALLOWS UP TO 3 LAYERS OF INSULATION AROUND
C     A BARE PIPE
C
C     TERRY HARDY       12-16-88
C
      DATA ID/'PH2'/
      DIMENSION NELEM(90),
     . TK(10,90),
     . INSUL(90),HIN(90),HOUT(90),U(90),QFLX(90),AREA(90),
     . VELI(90),QL(90)


      COMMON /FLUX/ EPOD(90),ETI1(90),ETI2(90),ETI3(90),
     .  NNOVJ(90),NOJAC,NXMAT(20,90),
     .  EXLEN(90),EXDIA(90),EXT(90),TAMB,P,X1,FLOV,EPID(90),K
C
C
      CHARACTER*10 TIM,TONE,MIM,MONE
      INTEGER INSUL,NXMAT
      REAL MDOT
C
      I   = 1
      NUM = 1
      AIRV = 0.01
C
      CALL DATE(TIM)
      CALL TIME(TONE)
C      WRITE(10,130) TIM,TONE
C 130  FORMAT(/' ', A10,2X,A10)
C

      DO 54 I = 1,NUM
      IF (NXMAT(2,K) .LE. 0.0) GO TO 71
         IF (NXMAT(3,K) .LE. 0.0) GO TO 72
            IF (NXMAT(4,K) .LE. 0.0) GO TO 73
               GO TO 74
 71   INSUL(I) = 1
      GO TO 75
 72   INSUL(I) = 2
      GO TO 75
 73   INSUL(I) = 3
      GO TO 75
 74   INSUL(I) = 4
 75   CONTINUE
 54   CONTINUE
C
C
C        INITIALIZE PROPERTIES
C
C
```

```
      DO 55 I = 1,NUM
      TFL     = EXT(K)
      RHOL    = DENLPC(TFL,P,ID)
      RHOS    = DNSOPC(TFL,P,ID)
      RHOMIX  = X1*RHOS + (1.-X1)*RHOL
      PI      = 3.14159
      AREA(I)= PI*EPID(K)**2/4.0
      MDOT    = FLOV*RHOMIX*60./7.48
      VELI(I)= MDOT/(AREA(I)*RHOMIX*3600.)
 55   CONTINUE
      DO  50 I = 1,NUM
         DO 51 J = 1,INSUL(I)

      MATCH MATERIAL CODE TO THERMAL CONDUCTIVITY VALUES

      IF (NXMAT(J,K) .LE. 101) GO TO 11
       IF (NXMAT(J,K) .EQ. 102) GO TO 12
        IF (NXMAT(J,K) .EQ. 103) GO TO 13
         IF (NXMAT(J,K) .EQ. 104) GO TO 14
          IF (NXMAT(J,K) .EQ. 201) GO TO 21
           IF (NXMAT(J,K) .EQ. 202) GO TO 22
            IF (NXMAT(J,K) .EQ. 203) GO TO 23
             IF (NXMAT(J,K) .EQ. 204) GO TO 24
              IF (NXMAT(J,K) .EQ. 205) GO TO 25
               IF (NXMAT(J,K) .EQ. 301) GO TO 31
                IF (NXMAT(J,K) .EQ. 302) GO TO 32
                   GO TO 11
       TK(J,K) = 0.112
       GO TO 70
       TK(J,K) = 2.717
       GO TO 70
       TK(J,K) = 22.31
       GO TO 70
       TK(J,K) = 156.0
       GO TO 70
       TK(J,K) = 0.020
       GO TO 70
       TK(J,K) = 0.032
       GO TO 70
       TK(J,K) = 0.019
       GO TO 70
       TK(J,K) = 0.019
       GO TO 70
       TK(J,K) = 0.021
       GO TO 70
       TK(J,K) = 0.014
       GO TO 70
       TK(J,K) = 0.015
       GO TO 70
       CONTINUE
       CONTINUE
       CONTINUE


         THE FOLLOWING MATERIAL CODES APPLY

         CODE              MATERIAL
```

```
C
C         101              TEFLON
C         102              304 STAINLESS STEEL
C         103              CARBON STEEL
C         104              6063 ALUMINUM
C         201              FOAM GLASS
C         202              SILICA
C         203              POLYURETHANE
C         204              POLYSTYRENE
C         205              FOAM RUBBER
C         301              FIBER GLASS
C         302              PERLITE
C
C         THE VALUES OF THERMAL CONDUCTIVITY WERE OBTAINED
C         FROM "CRYOGENIC SYSTEMS", 2ND ED., RANDALL F. BARRON,
C         OXFORD UNIVERSITY PRESS, 1985.
C
C           ---------------------------------------------
C
C         ---------------------------------------------
C         CALCULATE CONDUCTION HEAT TRANSFER PARAMETERS
C           ---------------------------------------------
C
          DO 60 I = 1,NUM
             DR1 = (EPOD(K) - EPID(K))/2.0
             COND1 = (DR1/TK(1,K))/((2.0*PI*EXLEN(K)*DR1)/
     *       (ALOG(EPOD(K)/EPID(K))))
        IF (INSUL(I) .LE. 1) GO TO 90
C
          R1 = EPOD(K)/2.0
          R2 = EPOD(K)/2.0 + ETI1(K)
          R3 = R2 + ETI2(K)
          R4 = R3 + ETI3(K)
C
  81      DR2 = R2 - R1
          COND2 = (DR2/TK(2,K))/((2.0*PI*EXLEN(K)*DR2)/
     *         (ALOG(R2/R1)))
          IF (INSUL(I) .LE. 2)   GO TO 80
  82      DR3 = R3 - R2
          COND3 = (DR3/TK(3,K))/((2.0*PI*EXLEN(K)*DR3)/
     *         (ALOG(R3/R2)))
          IF (INSUL(I) .LE. 3)   GO TO 80
  83      DR4 = R4 - R3
          COND4 = (DR4/TK(4,K))/((2.0*PI*EXLEN(K)*DR4)/
     *         (ALOG(R4/R3)))
C
C
  80      CONTINUE
          CONINS   COND2 + COND3 + COND4
  90      CONTINUE
          CONTOT     COND1 + CONINS
          PAMB       14.7
          TFL        EXT(K)
C               ---------------------
C         CALL SUBROUTINES FOR CALCULATION OF CONVECTIVE
C         HEAT TRANSFER COEFFICIENTS
C           --------------------------------
C
          CALL INHCO(X1,TFL,P, VELI(I),EXLEN(K),EPID(K),HIN(I))
          CALL OUTHCO(TAMB,PAMB,AIRV,EXLEN(K),EPOD(K),HOUT(I))
```

```
      HEATI     = 1.0/(PI*EPID(K)*EXLEN(K)*HIN(I))
      HEATO     = 1.0/(PI*EPOD(K)*EXLEN(K)*HOUT(I))
      UINV      = HEATI + CONTOT + HEATO
      U(I)      = 1.0/UINV
      QFLX(I)   = U(I)*(TAMB-TFL)
      QL(I)     = QFLX(I)/EXLEN(K)
      QFLA      = QFLX(I)
      QLA       = QL(I)
C
C     ----------------------------------------------------------
C     QFLX = HEAT TRANSFER, BTU/HR
C     QL   = HEAT TRANSFER, BTU/HR-FT
C     HIN  = INSIDE HEAT TRANSFER COEFFICIENT,BTU/HR-FT**2-R
C     HOUT = OUTSIDE HEAT TRANSFER COEFFICIENT,BTU/HR-FT**2-R
C     U    = OVERALL HEAT TRANSFER COEFFICIENT
C     COND1= CONDUCTION THRU PIPE = (RO-RI)/K-A,LM
C     COND2= CONDUCTION THRU INSULATION MATERIAL 1
C     COND3= CONDUCTION THRU INSULATION MATERIAL 2
C     COND4= CONDUCTION THRU INSULATION MATERIAL 3
C     ----------------------------------------------------------
C
C     ----------------------------------------------------------
C     WRITE OUTPUT FOR INDIVIDUAL VARIABLES
C     ----------------------------------------------------------
C
C       WRITE(10,910)
C910    FORMAT(/'
C    *  ---------------------------------------')
C       WRITE(10,911) K, EPID(K), EPOD(K), EXLEN(K)
C       WRITE(10,920) FLOV,AIRV,TAMB,TFL
C       WRITE(10,921) RHOL,RHOS,MDOT,VELI(I)
C       WRITE(10,912) INSUL(I), NXMAT(1,K),NXMAT(2,K),NXMAT(3,K),
C    * NXMAT(4,K)
C       WRITE(10,913) TK(1,K),TK(2,K),TK(3,K),TK(4,K)
C       WRITE(10,914) R1,R2,R3,R4
C       WRITE(10,915) COND1,COND2,COND3,COND4
C       WRITE(10,916) HIN(I),HOUT(I),U(I),QFLX(I)
C911    FORMAT(/' ELEM = ',I5,2X,' ID = ',F8.4,2X,'OD = ',F8.4,
C    * 2X,'LENGTH = ',F8.3)
C920    FORMAT(/' FLOW = ',F8.3,2X,'VAIR = ',F8.4,2X,'TAMB = ',
C    * F7.2,2X,'TFLUID = ',F7.2)
C921    FORMAT(/' RHOL = ',F7.4,2X,' RHOS = ',F7.4,2X,' MDOT =',
C    * F8.3,2X,' VFLUID = ',F8.4)
C912    FORMAT(/' NINS = ',I4,2X,' PIPE =',I5,2X,'MAT2 = ',I5,2X,
C    * 'MAT3 = ',I5,2X,'MAT4 =',I5)
C913    FORMAT(/' K1 = ',F9.4,2X,'K2 = ',F8.5,2X,'K3 = ',
C    * F8.5,2X,' K4 = ',F8.5)
C914    FORMAT(/' R1 = ',F8.4,2X,'R2 = ',F8.4,2X,'R3 = ',F8.4,2X,
C    * 'R4 = ',F8.4)
C915    FORMAT(/' CON1 =',1PE14.7,2X,' CON2 = ',0PF8.5,2X,
C    * ' CON3 = ',F8.4,2X,' CON4 = ',F8.4)
C916    FORMAT(/' HI = ',F8.4,2X,'HO = ',F8.4,2X,' U = ',F8.5,
C    *  2X,' QFLX = ',F12.4)
C
C     ----------------------------------------------------------
C     CALCULATE HEAT TRANSFER FOR A NEW ELEMENT
C     ----------------------------------------------------------
C
      CONINS = 0.0
      COND1  = 0.0
```

```
          COND2  = 0.0
          COND3  = 0.0
          COND4  = 0.0
C
   60     CONTINUE
          RETURN
          END
C
C
      SUBROUTINE INHCO(X,T,P,V,XLEN,DIA,HIN)
C
C     SUBROUTINE TO CALCULATE INSIDE HEAT TRANSFER COEFFICIENTS
C
      CALL HYDRO(X,T,P,CP,TK,RHO,VIS)
C
C     X      SOLID FRACTION
C     T    = FLUID TEMPERATURE, R
C     P    = AVERAGE FLUID PRESSURE, PSI
C     V    = FLUID VELOCITY, FT/SEC
C     XLEN= FLOW LENGTH, FT
C     DIA = FLOW DIAMETER, FT
C     CP  = SPECIFIC HEAT, BTU/LB-R
C     TK  = THERMAL CONDUCTIVITY, BTU/FT-SEC-R
C     RHO = SLUSH DENSITY, LB/CU.FT.
C     VIS = VISCOSITY, LB/FT-SEC
C     RE  = REYNOLD'S NUMBER
C     PR  = PRANDTL NUMBER
C     HIN = INSIDE HEAT TRANSFER COEFFICIENT, BTU/HR-SQ.FT.-R
C
      RE  = DIA*RHO*V/VIS
      PR  = CP*VIS/TK
      IF (RE .LT. 2100.) GO TO 10
         GO TO 20
 10   HINS = 1.86*(TK/XLEN)*(RE*PR*DIA/XLEN)**0.333
      GO TO 30
 20   HINS = 0.023*(TK/XLEN)*(RE**0.8)*(PR**0.333)
 30   HIN  = HINS*3600.
      RETURN
      END
C
C
      SUBROUTINE OUTHCO(T,P,V,XLEN,DIA,HOUT)
C
C     SUBROUTINE TO CALCULATE OUTSIDE HEAT TRANSFER COEFFICIENTS
C
      CALL AIR(T,P,CP,TK,RHO,VIS,BETA)
C
C     T      AIR TEMPERATURE, R
C     P      AVERAGE AIR PRESSURE, PSI
C     V      AIR VELOCITY, FT/SEC
C     XLEN   FLOW LENGTH, FT
C     DIA    FLOW DIAMETER, FT
C     CP     SPECIFIC HEAT, BTU/LB R
C     TK     THERMAL CONDUCTIVITY, BTU/FT SEC R
C     RHO    AIR DENSITY, LB/CU.FT.
C     VIS    AIR VISCOSITY, LB/FT SEC
C     RE     REYNOLDS NUMBER
C     PR     PRANDTL NUMBER
C     GR   = GRASHOF NUMBER
C     HOUT-  OUTSIDE HEAT TRANSFER COEFFICIENT, BTU/HR-SQ.FT.-R
```

```
C
      G    = 32.2
      RE   = DIA*RHOMIX*V/VIS
      PR   = CP*VIS/TK
      GR   = XLEN**3*RHO**2*G*BETA*(T)/(VIS**2)
C
C     NOTE: THE APPROXIMATION FOR BETA IS 1/TAVG = 1/T
C
      IF (V .LT. 0.1) GO TO 15
        IF (RE .LT. 2100.) GO TO 10
          GO TO 20
15    CB      0.333
      CA      0.140
      HOUTS = (TK/XLEN)*CA*(GR*PR)**CB
      GO TO 30
10    HOUTS   1.86*(TK/XLEN)*(RE*PR*DIA/XLEN)**0.333
      GO TO 30
20    HOUTS = 0.023*(TK/XLEN)*(RE**0.8)*(PR**0.333)
30    HOUT  = HOUTS*3600.
      RETURN
      END
C
C
      SUBROUTINE AIR(T,P,CP,TK,RHO,VIS,BETA)
C
C     DATA ON AIR OBTAINED FROM GASPLUS
C
      DATA ID/'AIR'/
      CP      CPVPC(T,P,ID)
      TK      TCNVPC(T,P,ID)
      RHO     DENVPC(T,P,ID)
      VIS     VISVPC(T,P,ID)
      BETA    1.0/T
C
      RETURN
      END
C
C
      SUBROUTINE HYDRO(X,T,P,CP,TK,RHO,VIS)
C
C     DATA ON HYDROGEN OBTAINED FROM GASPLUS
C
      DATA ID/'PH2'/
      CP      CPLPC(T,P,ID)
      TK      TCNLPC(T,P,ID)
      RHOL    DENLPC(T,P,ID)
      VIS     VISLPC(T,P,ID)
      RHOS    DNSOPC(T,P,ID)
      RHO     X*RHOS + (1. X)*RHOL
C

      RETURN
      END
```

APPENDIX C

NOTES FOR NASA LEWIS VAX USERS

The following steps are required to use the FLUSH code on the NASA Lewis VAX system:

(1) Create a file called FLUSH.INP as described in the users guide. Several points could be of help in producing this file:

• Namelists must always start in column 2 of your file. Therefore, the statements $PARAMS and $SEND must start in column 2.

• The element variable ELE in the element description section is I4 format. Therefore, single-digit integers need to be in column 4; two-digit variables need to start in column 3. TYPE is A4 format and can be placed in columns 5 to 8. Because the remaining variables (DIA, LENGTH, TEMP Q, K, and HT) have F10.2 format, they need to be placed in lines 9 to 18, 19 to 28, etc.

• The line with the descriptors ELE, DIA, etc., is required for the code to work, but because this is A80 format, the user can vary the actual names of the descriptors, if desired.

• If the radiation heat transfer parameters are to be defined, a blank line is required between the element description section and the radiation heat transfer parameter section.

(2) To run the code, issue the statement

RUN [SPTLH.FLUSH]FLUSH

(3) Output will be set to unit 9, in a file called FOR009.DAT, for the final output conditions or the individual node output. The longer, individual variable output will be sent to unit 8 if LONG is greater than 0.

(4) Note that to run FLUSH the user needs access to the GASPLUS properties code. To do this, simply add the following line to the file LOGIN.COM;

ASSIGN NASA$SPID:[SPANK.GASPLUS]GASPLUS.OLB LNK$LIBRARY

REFERENCES

1. Sindt, C.F.; and Ludtke, P.R.: Slush Hydrogen Flow Characteristics and Solid Fraction Upgrading. Advances in Cryogenic Engineering, Vol. 15., K.D. Timmerhaus, ed., Plenum Press, New York, 1970, pp. 382-390.

2. Sindt, C.F.; Ludtke, P.R.; and Daney, D.E.: Slush Hydrogen Fluid Characterization and Instrumentation. NBS Technical Note 377, Feb. 1969.

3. Ewart, R.O.; and Dergance, R.H.: Cryogenic Propellant Densification Study. (MCR-78-586, Martin Marietta Crop.; NASA Contract NAS3-21014) NASA CR-159438, 1978.

4. Fowler, J.R.: GASPLUS User's Manual. NASP CR-1012, Mar. 1988.

5. Barron, R.F.: Cryogenic Systems. 2nd ed., Oxford University Press, Oxford, 1985.

6. Ludtke, P.R.; and Voth, R.O.: A Study of LC-39 Cryogenic Systems. (NBS Report 10705, National Bureau of Standards, NASA CR-126386, 1971.

7. Flow of Fluids Through Valves, Fittings, and Pipe. Crane Co., Hydro-Aire Division, Chicago, IL, TP-410, 1965.

8. Siegel, R.; and Howell, J.R.: Thermal Radiation Heat Transfer. 2nd ed., McGraw-Hill, New York, 1981.

9. Harnum, N.P.: Technology Issues Associated With Fueling The National Aerospace Plane With Slush Hydrogen. NASA TM-101386, 1988.

10. Sindt, C.: A Summary of the Characterization Study of Slush Hydrogen. Cryogenics, vol. 10, no. 5, Oct., 1970, pp. 372-380.

11. Voth, R.O., et al: On Process Design Criteria, Data and Methodology Related to Slush Hydrogen Technology. NASP TM-1006, 1987.

TABLE 1. - ELEMENT TYPE FOR USE IN INPUT FILE

Type	Corresponding element
PI	Straight pipe
BE	Bellows
BA	Bayonet fitting
FX	Flexible tubing
EL	90° Elbow
E4	45° Elbow
YV	Y-pattern globe valve
VA	Standard globe valve
AV	Angle valve
GV	Gate valve
BV	Ball valve
PP	Pump, ΔP specified
PH	Pump, horsepower specified

TABLE 2. - EXAMPLE FLUSH CODE INPUT FILE

[Analysis of a 100-ft-long, 1.5-in.-diameter Schedule 5S Line.]

```
$PARAMS
     FLOMIN=10.0, FLOMAX=100.0, FLOINC=5.0, E = 0.00015,
     P = 35., X1 = 0.5,
     ZIN=25., NUM=18, OUT=1.,
     LONG=-1., XPUT=1.,FRICT=+1.0, HEAT=+1.0,
     TAMB=540.,VAC=0.0,XRS=10.,NOJAC=0.
$END
```

ELE	TYPE	DIA,in.	LENGTH,ft	TEMP.,R.	Q	K=fL/D	HT.,ft
1	PI	1.770	1.000	25.20	0.633	0.0	25.0
2	VA	1.770	0.500	25.20	27.30	7.58	25.0
3	PI	1.770	19.00	25.20	0.633	0.0	25.0
4	BE	1.770	1.000	25.20	1.899	0.0	25.0
5	BA	1.770	0.790	25.20	14.78	0.0	25.0
6	PI	1.770	19.00	25.20	0.633	0.0	25.0
7	BE	1.770	1.000	25.20	1.899	0.0	25.0
8	BA	1.770	0.790	25.20	14.78	0.0	25.0
9	PI	1.770	19.00	25.20	0.633	0.0	25.0
10	BE	1.770	1.000	25.20	1.899	0.0	25.0
11	BA	1.770	0.790	25.20	14.78	0.0	25.0
12	PI	1.770	19.00	25.20	0.633	0.0	25.0
13	BE	1.770	1.000	25.20	1.899	0.0	25.0
14	BA	1.770	0.790	25.20	14.78	0.0	25.0
15	PI	1.770	19.00	25.20	0.633	0.0	25.0
16	BE	1.770	1.000	25.20	1.899	0.0	25.0
17	VA	1.770	0.500	25.20	27.30	7.58	25.0
18	PI	1.770	1.000	25.20	0.633	0.0	25.0

TABLE 3. - HEAT LEAK ESTIMATES FOR PIPES CARRYING LIQUID HYDROGEN

[Estimates from CVI, Inc.]

Pipe diameter, in.	Rigid pipe	Flexible pipe heat leak, Btu/hr ft
0.75	0.462	1.293
1	.515	1.545
1.5	.633	1.899
2	.854	2.562
3	1.080	3.240
4	1.407	4.221
6	1.835	5.505

TABLE 4. - HEAT LEAK AND FLOW COEFFICIENT ESTIMATES FOR LIQUID HYDROGEN VALVES AND FITTINGS

[Estimates from Cryogenic Energy Co.]

Pipe diameter, in.	Valve heat leak, Btu/hr ft	Flow coefficient, C_v		Bayonet fitting heat leak, Btu/hr ft
		Y	Globe	
0.50	8.90	9.0	6.6	7.27
.75	14.10	12.0	8.0	7.27
1	21.80	22.0	14.0	10.02
1.5	27.30	47.0	34.0	14.78
2	27.30	96.0	50.0	23.19

TABLE 5. - EXAMPLE FLUSH CODE SHORT OUTPUT FILE

[Node conditions not listed.]

****

Input Parameters

Element	Type	Dia., in.	Length, ft	Temp., R	Q, Btu/hr-ft	K=f L/D
1	PI	1.770	1.000	25.20	0.633	0.000
2	VA	1.770	0.500	25.20	27.300	7.580
3	PI	1.770	19.000	25.20	0.633	0.000
4	BE	1.770	1.000	25.20	1.899	0.000
5	BA	1.770	0.790	25.20	14.780	0.000
6	PI	1.770	19.000	25.20	0.633	0.000
7	BE	1.770	1.000	25.20	1.899	0.000
8	BA	1.770	0.790	25.20	14.780	0.000
9	PI	1.770	19.000	25.20	0.633	0.000
10	BE	1.770	1.000	25.20	1.899	0.000
11	BA	1.770	0.790	25.20	14.780	0.000
12	PI	1.770	19.000	25.20	0.633	0.000
13	BE	1.770	1.000	25.20	1.899	0.000
14	BA	1.770	0.790	25.20	14.780	0.000
15	PI	1.770	19.000	25.20	0.633	0.000
16	BE	1.770	1.000	25.20	1.899	0.000
17	VA	1.770	0.500	25.20	27.300	7.580
18	PI	1.770	1.000	25.20	0.633	0.000

****

TABLE 5. - Concluded.

FLUSH Code Output

Pipe Diameter = 1.77 in.   Flow = 10.00 gpm

Total Pipe Length = 106.16 ft   Initial Solid Fraction = 0.500

Pipe Roughness = 0.000150   Initial Temperature = 25.20 R

Flow, gpm	Flow, lb/s	Final Solid Fraction	Change in x	Pressure Drop, psi
10.000	0.114	0.4858	0.0142	0.0300
15.000	0.171	0.4904	0.0096	0.0659
20.000	0.227	0.4926	0.0074	0.1155
25.000	0.284	0.4938	0.0062	0.1788
30.000	0.341	0.4946	0.0054	0.2558
35.000	0.398	0.4950	0.0050	0.3465
40.000	0.455	0.4952	0.0048	0.4509
45.000	0.512	0.4953	0.0047	0.5690
50.000	0.569	0.4952	0.0048	0.7007
55.000	0.626	0.4951	0.0049	0.8462
60.000	0.682	0.4949	0.0051	1.0053
65.000	0.739	0.4946	0.0054	1.1782
70.000	0.796	0.4942	0.0058	1.3647
75.000	0.853	0.4938	0.0062	1.5649
80.000	0.910	0.4933	0.0067	1.7789
85.000	0.967	0.4928	0.0072	2.0065
90.000	1.024	0.4923	0.0077	2.2479
95.000	1.081	0.4916	0.0084	2.5029
100.000	1.137	0.4910	0.0090	2.7717

TABLE 6. - EXAMPLE FLUSH CODE OUTPUT FOR NODE CONDITIONS LISTED

Pipe Diameter = 1.77 in. Flow = 10.00 gpm

Total Pipe Length = 106.16 ft Initial Solid Fraction = 0.500

Pipe Roughness = 0.000150 Initial Temperature = 25.20 R

Node	Pressure Drop, psi	Flow, lb/s	Final Solid Fraction	Change in x	Pressure, psi
1	0.00000	0.1137	0.5000	0.0000	35.0000
2	0.00015	0.1137	0.4999	0.0001	34.9999
3	0.00725	0.1137	0.4986	0.0014	34.9928
4	0.01010	0.1137	0.4974	0.0026	34.9899
5	0.01025	0.1137	0.4972	0.0028	34.9898
6	0.01037	0.1137	0.4961	0.0039	34.9896
7	0.01323	0.1137	0.4949	0.0051	34.9868
8	0.01338	0.1137	0.4947	0.0053	34.9866
9	0.01350	0.1137	0.4936	0.0064	34.9865
10	0.01635	0.1137	0.4924	0.0076	34.9837
11	0.01650	0.1137	0.4922	0.0078	34.9835
12	0.01662	0.1137	0.4911	0.0089	34.9834
13	0.01948	0.1137	0.4899	0.0101	34.9805
14	0.01963	0.1137	0.4897	0.0103	34.9804
15	0.01975	0.1137	0.4886	0.0114	34.9803
16	0.02261	0.1137	0.4874	0.0126	34.9774
17	0.02276	0.1137	0.4872	0.0128	34.9773
18	0.02986	0.1137	0.4858	0.0142	34.9701
19	0.03001	0.1137	0.4858	0.0142	34.9700

TABLE 6. - Concluded.

FLUSH Code Output

Pipe Diameter = 1.77 in.	Flow = 15.00 gpm
Total Pipe Length = 106.16 ft	Initial Solid Fraction = 0.500
Pipe Roughness = 0.000150	Initial Temperature = 25.20 R

Node	Pressure Drop, psi	Flow, lb/s	Final Solid Fraction	Change in x	Pressure, psi
1	0.00000	0.1706	0.5000	0.0000	35.0000
2	0.00032	0.1706	0.5000	0.0000	34.9997
3	0.01629	0.1706	0.4990	0.0010	34.9837
4	0.02242	0.1706	0.4982	0.0018	34.9776
5	0.02274	0.1706	0.4981	0.0019	34.9773
6	0.02300	0.1706	0.4973	0.0027	34.9770
7	0.02913	0.1706	0.4965	0.0035	34.9709
8	0.02945	0.1706	0.4964	0.0036	34.9705
9	0.02970	0.1706	0.4957	0.0043	34.9703
10	0.03584	0.1706	0.4949	0.0051	34.9642
11	0.03616	0.1706	0.4947	0.0053	34.9638
12	0.03641	0.1706	0.4940	0.0060	34.9636
13	0.04255	0.1706	0.4932	0.0068	34.9574
14	0.04287	0.1706	0.4930	0.0070	34.9571
15	0.04312	0.1706	0.4923	0.0077	34.9569
16	0.04926	0.1706	0.4915	0.0085	34.9507
17	0.04958	0.1706	0.4914	0.0086	34.9504
18	0.06556	0.1706	0.4904	0.0096	34.9344
19	0.06589	0.1706	0.4904	0.0096	34.9341

TABLE 7. - EXAMPLE FLUSH CODE INPUT FILE FOR HEAT LEAK CALCULATIONS ON ELEMENTS 1 AND 9

```
$PARAMS
     FLOMIN=10.0, FLOMAX=100.0, FLOINC=5.0, E = 0.00015,
     P = 35., X1 = 0.5,
     ZIN=25., NUM=18, OUT=-1.,
     LONG=-1., XPUT=1.,FRICT=+1.0, HEAT=+1.0,
     TAMB=540.,VAC=2.0,XRS=10.,NOJAC=0.
$END
```

ELE	TYPE	DIA,in.	LENGTH,ft	TEMP.,R.	Q	K=fL/D	HT.,ft
1	PI	1.770	1.000	25.20	-1.00	0.0	25.0
2	VA	1.770	0.500	25.20	27.30	7.58	25.0
3	PI	1.770	19.00	25.20	0.633	0.0	25.0
4	BE	1.770	1.000	25.20	1.899	0.0	25.0
5	BA	1.770	0.790	25.20	14.78	0.0	25.0
6	PI	1.770	19.00	25.20	0.633	0.0	25.0
7	BE	1.770	1.000	25.20	1.899	0.0	25.0
8	BA	1.770	0.790	25.20	14.78	0.0	25.0
9	PI	1.770	19.00	25.20	-1.00	0.0	25.0
10	BE	1.770	1.000	25.20	1.899	0.0	25.0
11	BA	1.770	0.790	25.20	14.78	0.0	25.0
12	PI	1.770	19.00	25.20	0.633	0.0	25.0
13	BE	1.770	1.000	25.20	1.899	0.0	25.0
14	BA	1.770	0.790	25.20	14.78	0.0	25.0
15	PI	1.770	19.00	25.20	0.633	0.0	25.0
16	BE	1.770	1.000	25.20	1.899	0.0	25.0
17	VA	1.770	0.500	25.20	27.30	7.58	25.0
18	PI	1.770	1.000	25.20	0.633	0.0	25.0

Radiation Heat Transfer Parameters

ELE	O.D.	I.D.	Ei	Eo
1	1.900	3.334	0.30	0.30
9	1.900	3.334	0.30	0.30

TABLE 8. - SCHEDULE 5S STAINLESS STEEL PIPE DATA

Nominal size, in.	Inner diameter, in.	Outer diameter, in.
0.50	0.710	0.840
.75	.920	1.050
1	1.185	1.315
1.5	1.770	1.900
2	2.245	2.375
2.5	2.709	2.875
3	3.334	3.500
4	4.334	4.500
5	5.345	5.563
6	6.407	6.625
8	8.407	8.625
10	10.482	10.750
12	12.438	12.750

TABLE 9. - EXAMPLE FLUSH CODE OUTPUT FOR HEAT LEAK CALCULATIONS ON ELEMENTS 1 AND 9

****

Input Parameters

Element	Type	Dia., in.	Length, ft	Temp., R	Q, Btu/hr-ft	K f L/D
1	PI	1.770	1.000	25.20	0.552	0.000
2	VA	1.770	0.500	25.20	27.300	7.580
3	PI	1.770	19.000	25.20	0.633	0.000
4	BE	1.770	1.000	25.20	1.899	0.000
[illegible]	BA	1.770	0.790	25.20	14.780	0.000
6	PI	1.770	19.000	25.20	0.633	0.000
7	BE	1.770	1.000	25.20	1.899	0.000
8	BA	1.770	0.790	25.20	14.780	0.000
9	PI	1.770	19.000	25.20	0.552	0.000
10	BE	1.770	1.000	25.20	1.899	0.000
11	BA	1.770	0.790	25.20	14.780	0.000
12	PI	1.770	19.000	25.20	0.633	0.000
13	BE	1.770	1.000	25.20	1.899	0.000
14	BA	1.770	0.790	25.20	14.780	0.000
15	PI	1.770	19.000	25.20	0.633	0.000
16	BE	1.770	1.000	25.20	1.899	0.000
17	VA	1.770	0.500	25.20	27.300	7.580
18	PI	1.770	1.000	25.20	0.633	0.000

Radiation Heat Transfer Parameters

Element	Inner O.D.	Outer I.D.	Ei	Eo
1	1.900	3.334	0.30000	0.30000
9	1.900	3.334	0.30000	0.30000

TABLE 9. - Concluded.

FLUSH Code Output

Pipe Diameter =	1.77 in.	Flow =	10.00 gpm
Total Pipe Length =	106.16 ft	Initial Solid Fraction =	0.500
Pipe Roughness =	0.000150	Initial Temperature	25.20 R

Flow, gpm	Flow, lb/s	Final Solid Fraction	Change in x	Pressure Drop, psi
10.000	0.114	0.4859	0.0141	0.0300
15.000	0.171	0.4905	0.0095	0.0659
20.000	0.227	0.4927	0.0073	0.1155
25.000	0.284	0.4939	0.0061	0.1788
30.000	0.341	0.4946	0.0054	0.2558
35.000	0.398	0.4951	0.0049	0.3465
40.000	0.455	0.4953	0.0047	0.4509
45.000	0.512	0.4953	0.0047	0.5690
50.000	0.569	0.4953	0.0047	0.7007
55.000	0.626	0.4951	0.0049	0.8462
60.000	0.682	0.4949	0.0051	1.0053
65.000	0.739	0.4946	0.0054	1.1782
70.000	0.796	0.4943	0.0057	1.3647
75.000	0.853	0.4938	0.0062	1.5649
80.000	0.910	0.4934	0.0066	1.7789
85.000	0.967	0.4928	0.0072	2.0065
90.000	1.024	0.4923	0.0077	2.2479
95.000	1.081	0.4916	0.0084	2.5029
100.000	1.137	0.4910	0.0090	2.7717

TABLE 10. - EXAMPLE FLUSH CODE INPUT FOR HEAT LEAK CALCULATIONS FOR STANDARD INSULATION AND BARE PIPE ON ELEMENTS 3, 6, 12, 15, AND 18

```
$PARAMS
     FLOMIN=50.0, FLOMAX=90.0, FLOINC=10.0, E = 0.00015,
     P = 35., X1 = 0.5,
     ZIN=25., NUM=18, OUT=-1.,
     LONG=+1., XPUT=1.,FRICT=+1.0, HEAT=+1.0,
     TAMB=540.,VAC=2.0,XRS=10.,NOJAC=5
$END
```

ELE	TYPE	DIA,in.	LENGTH,ft	TEMP.,R.	Q	K-fL/D	HT.,ft
1	PI	1.770	1.000	25.20	-1.00	0.0	25.0
2	VA	1.770	0.500	25.20	27.30	7.58	25.0
3	PI	1.770	19.00	25.20	0.633	0.0	25.0
4	BE	1.770	1.000	25.20	1.899	0.0	25.0
5	BA	1.770	0.790	25.20	14.78	0.0	25.0
6	PI	1.770	19.00	25.20	0.633	0.0	25.0
7	BE	1.770	1.000	25.20	1.899	0.0	25.0
8	BA	1.770	0.790	25.20	14.78	0.0	25.0
9	PI	1.770	19.00	25.20	-1.00	0.0	25.0
10	BE	1.770	1.000	25.20	1.899	0.0	25.0
11	BA	1.770	0.790	25.20	14.78	0.0	25.0
12	PI	1.770	19.00	25.20	0.633	0.0	25.0
13	BE	1.770	1.000	25.20	1.899	0.0	25.0
14	BA	1.770	0.790	25.20	14.78	0.0	25.0
15	PI	1.770	19.00	25.20	0.633	0.0	25.0
16	BE	1.770	1.000	25.20	1.899	0.0	25.0
17	VA	1.770	0.500	25.20	27.30	7.58	25.0
18	PI	1.770	1.000	25.20	0.633	0.0	25.0

Radiation Heat Transfer Parameters

ELE	O.D.	I.D.	Ei	Eo
1	1.900	3.334	0.30	0.30
9	1.900	3.334	0.30	0.30

Conduction Heat Transfer Parameters

ELE	O.D.	T1	T2	T3
3	1.900	0.125	0.125	0.125
6	1.900			
12	1.900	0.125	0.125	0.125
15	1.900	0.125	0.125	
18	1.900	0.125		

ELE	PIPE CODE	MAT. 1 CODE	MAT. 2 CODE	MAT. 3 CODE
3	102	201	203	205
6	102			
12	101	202	204	301
15	103	201	203	
18	104	101		

TABLE 11. - MATERIAL CODES FOR USE IN STANDARD INSULATION OR BARE PIPE CALCULATIONS

Material code	Material
101	Teflon
102	304 Stainless steel
103	Carbon steel
104	6063 Aluminum
201	Foam glass
202	Silica
203	Polyurethane
204	Polystyrene
205	Foam rubber
301	Fiber glass
302	Perlite

TABLE 12. - EXAMPLE FLUSH CODE OUTPUT FOR HEAT LEAK CALCULATIONS FOR STANDARD INSULATION AND BARE PIPE ON ELEMENTS 3, 6, 12, 15, AND 18

****

Input Parameters

Element	Type	Dia., in.	Length, ft	Temp., R	Q, Btu/hr-ft	K=f L/D
1	PI	1.770	1.000	25.20	0.552	0.000
2	VA	1.770	0.500	25.20	27.300	7.580
3	PI	1.770	19.000	25.20	32.156	0.000
4	BE	1.770	1.000	25.20	1.899	0.000
5	BA	1.770	0.790	25.20	14.780	0.000
6	PI	1.770	19.000	25.20	253.611	0.000
7	BE	1.770	1.000	25.20	1.899	0.000
8	BA	1.770	0.790	25.20	14.780	0.000
9	PI	1.770	19.000	25.20	0.552	0.000
10	BE	1.770	1.000	25.20	1.899	0.000
11	BA	1.770	0.790	25.20	14.780	0.000
12	PI	1.770	19.000	25.20	35.507	0.000
13	BE	1.770	1.000	25.20	1.899	0.000
14	BA	1.770	0.790	25.20	14.780	0.000
15	PI	1.770	19.000	25.20	37.947	0.000
16	BE	1.770	1.000	25.20	1.899	0.000
17	VA	1.770	0.500	25.20	27.300	7.580
18	PI	1.770	1.000	25.20	208.666	0.000

Radiation Heat Transfer Parameters

Element	Inner O.D.	Outer I.D.	Ei	Eo
1	1.900	3.334	0.30000	0.30000
9	1.900	3.334	0.30000	0.30000

TABLE 12. - Concluded.

Bare Pipe or Standard Insulation Parameters

Element	Pipe O.D.	Insulation 1 Thickness, ft	Insulation 2 Thickness, ft	Insulation 3 Thickness, ft
3	1.9000	0.1250	0.1250	0.1250
6	1.9000	0.0000	0.0000	0.0000
12	1.9000	0.1250	0.1250	0.1250
15	1.9000	0.1250	0.1250	0.0000
18	1.9000	0.1250	0.0000	0.0000

Element	Pipe Material	Insulation 1	Insulation 2	Insulation 3
3	304 St Steel	Foam Glass	Polyurethane	Foam Rubber
6	304 St Steel			
12	Teflon	Silica	Polystyrene	Fiber Glass
15	Carbon Steel	Foam Glass	Polyurethane	
18	6063 Alum.	Teflon		

FLUSH Code Output

Pipe Diameter = 1.77 in. Flow = 50.00 gpm

Total Pipe Length = 106.16 ft Initial Solid Fraction = 0.500

Pipe Roughness = 0.000150 Initial Temperature 25.20 R

Flow, gpm	Flow, lb/s	Final Solid Fraction	Change in x	Pressure Drop, psi
50.000	0.569	0.3589	0.1411	0.7080
60.000	0.682	0.3761	0.1239	1.0145
70.000	0.796	0.3884	0.1116	1.3758
80.000	0.910	0.3977	0.1023	1.7920
90.000	1.024	0.4049	0.0951	2.2630

TABLE 13. - EXAMPLE FLUSH CODE INPUT WITH PUMPS AT ELEMENTS 2 AND 4

```
$PARAMS
      FLOMIN=352.3, FLOMAX=352.3, FLOINC=10.0, E = 0.00015,
      P = 25., X1 = 0.5,
      ZIN=25., NUM=5, OUT=1.,
      LONG=+1., XPUT=1.,FRICT=+1.0, HEAT=+1.0,
      TAMB=540.,VAC=0.0,XRS=10.,NOJAC=0
$END
```

ELE	TYPE	DIA,in.	LENGTH,ft	TEMP.,R.	Q	K=fL/D	HT.,ft
1	PI	1.770	5.000	25.20	0.633	0.0	25.0
2	PH	1.770	1.000	25.20	1.690	.322	25.0
3	PI	1.770	5.000	25.20	0.633	0.0	25.0
4	PP	1.770	1.000	25.20	2.643	.322	25.0
5	PI	1.770	5.000	25.20	0.633	0.0	25.0

TABLE 14. - EXAMPLE FLUSH CODE OUTPUT WITH PUMPS AT ELEMENTS 2 AND 4

Input Parameters

Element	Type	Dia., in.	Length, ft	Temp., R	Q, Btu/hr-ft	K=f L/D
1	PI	1.770	5.000	25.20	0.633	0.000
2	PH	1.770	1.000	25.20	1.690	0.322
3	PI	1.770	5.000	25.20	0.633	0.000
4	PP	1.770	1.000	25.20	2.643	0.322
5	PI	1.770	5.000	25.20	0.633	0.000

FLUSH1 Code Output

Pipe Diameter = 1.77 in. Flow = 352.30 gpm

Total Pipe Length = 17.00 ft Initial Solid Fraction = 0.500

Pipe Roughness = 0.000150 Initial Temperature = 25.20 R

Node	Pressure Drop,psi	Flow, lb/s	Final Solid Fraction	Change in x	Pressure, psi
1	0.00000	4.0056	0.5000	0.0000	25.0000
2	0.78304	4.0056	0.4978	0.0022	24.2170
3	-1.86134	4.0056	0.4893	0.0107	26.8613
4	-1.07737	4.0056	0.4872	0.0128	26.0774
5	-3.72037	4.0056	0.4787	0.0213	28.7204
6	-2.93547	4.0056	0.4765	0.0235	27.9355

TABLE 15. - CRITICAL FLOW RATES FOR SLUSH PIPING

[Based on a critical velocity of 1.5 ft/sec; Data in the table are scaled from experimental results obtained using a 0.652-in.-i.d. pipe (ref. 2).]

Nominal diameter, in.	Critical flow rate, gpm
1	5.2
1.5	11.5
2	18.5
2.5	27.9
3	40.8
4	69.0
5	104.9
6	150.7
8	259.5
10	403.4
12	568.0

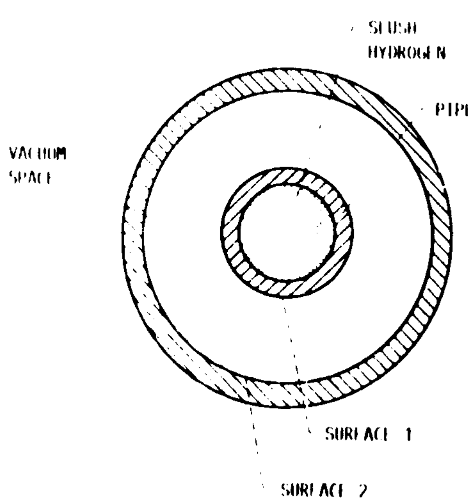


FIGURE 1. - CROSS SECTION OF VACUUM JACKETED PIPE.

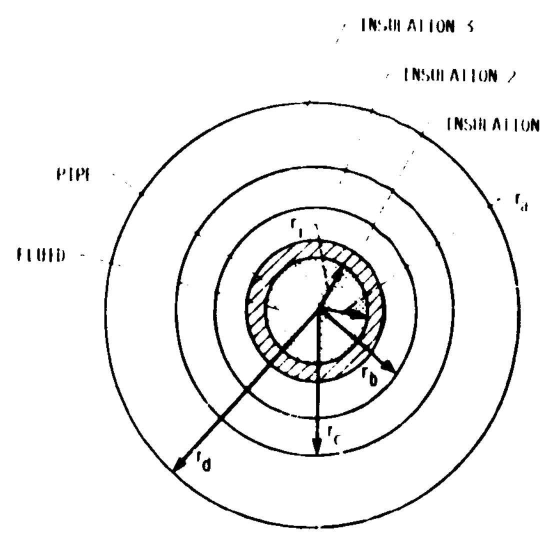


FIGURE 2. - CROSS SECTION OF PIPE WITH THREE LAYERS OF INSULATION.

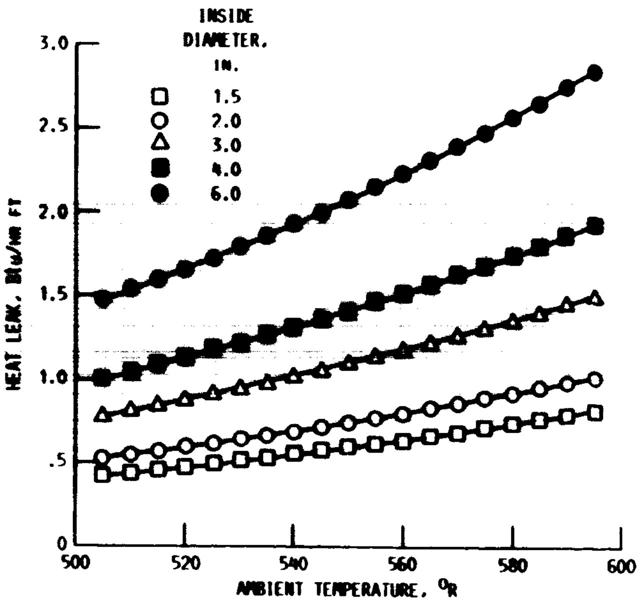


FIGURE 3. - HEAT LEAK VERSUS AMBIENT TEMPERATURE FOR SEVERAL SIZES OF VACUUM JACKETED PIPE. NUMBER OF RADIATION SHIELDS, 10; EMISSIVITY, 0.3.

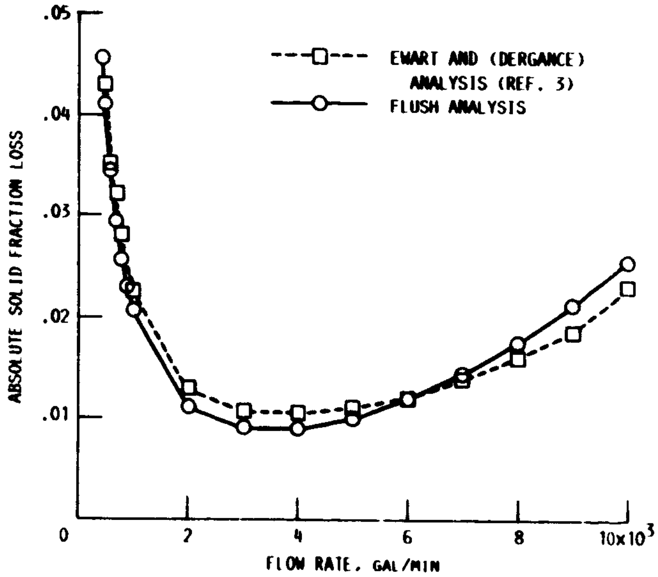
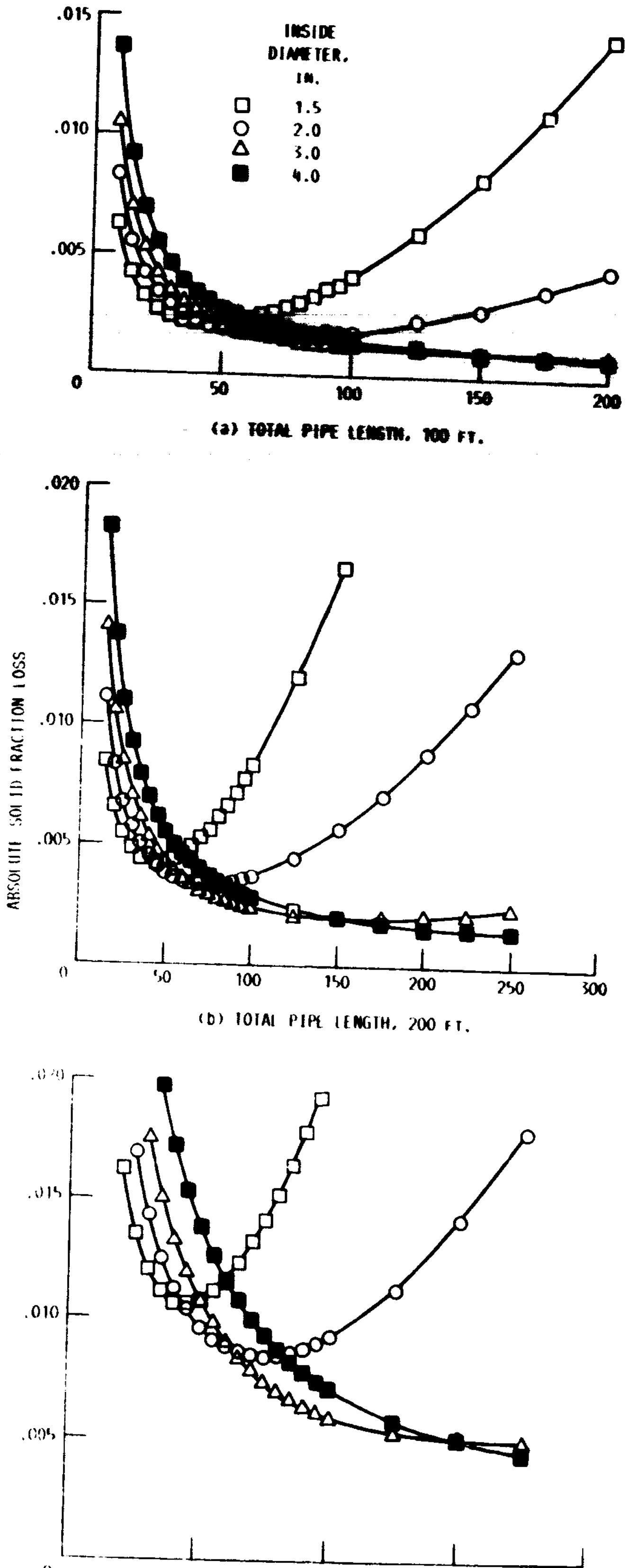


FIGURE 4. - COMPARISON OF FLUSH ANALYSIS WITH PREVIOUS SLUSH HYDROGEN ANALYSIS. PIPE 12-IN.-DIAMETER SCHEDULE 5S; HEAT LEAK INTO ELEMENT, Q, 12 Btu/HR FT; PIPE LENGTH, 1750 FT.



(a) TOTAL PIPE LENGTH, 100 FT.

(b) TOTAL PIPE LENGTH, 200 FT.

(c) TOTAL PIPE LENGTH, 500 FT.

FIGURE 5. - SLUSH LOSS VERSUS FLOW RATE FOR SEVERAL SIZES OF VACUUM JACKETED PIPE.

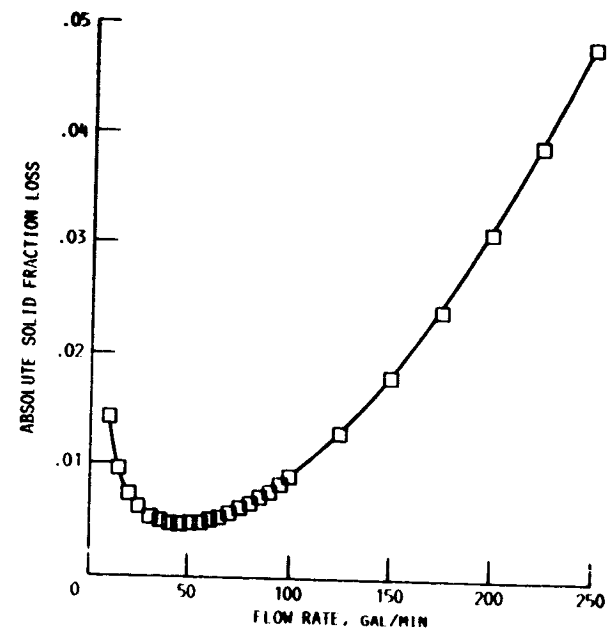


FIGURE 6. - EXPECTED SLUSH SOLID FRACTION LOSS AT K-SITE FOR 1.5-IN.-DIAMETER VACUUM-JACKETED PIPE.

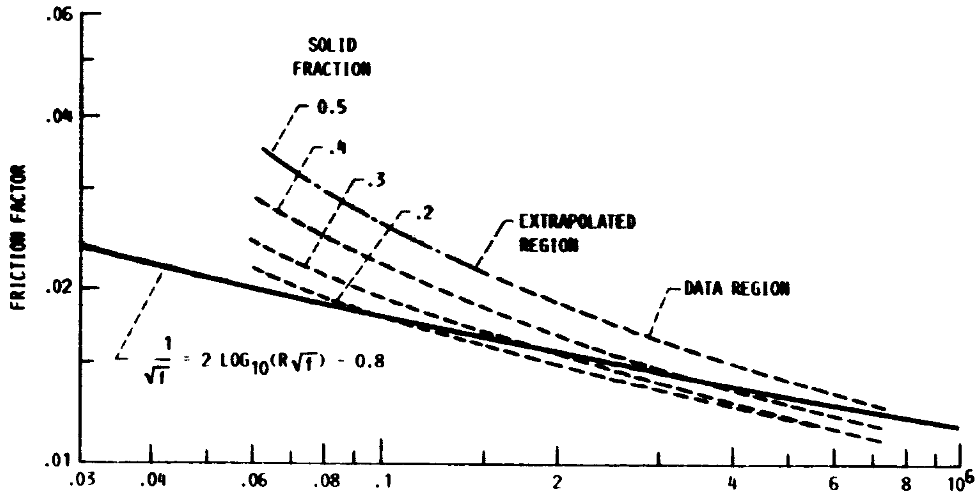


FIGURE 7. - FRICTION FACTOR VERSUS REYNOLDS NUMBER FOR SLUSH HYDROGEN. PIPE DIAMETER, D, 0.652 IN.; TRIPLE-POINT HYDROGEN VISCOSITY, $\mu = 1.73\times10^{-5}$ LBM/FT SEC. (FROM REF. 2.)

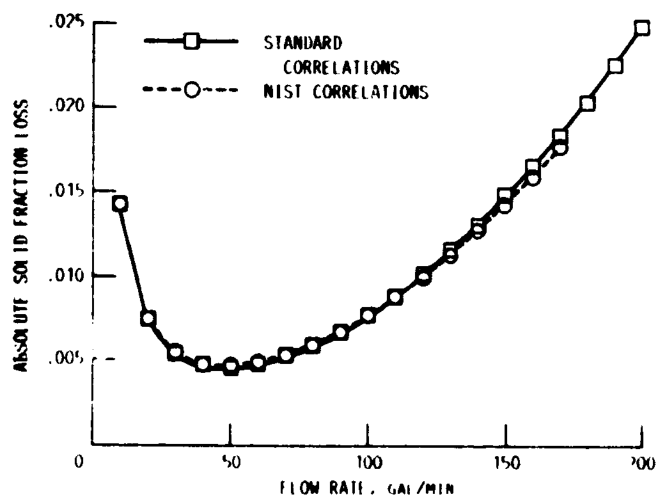


FIGURE 8. COMPARISON OF SLUSH HYDROGEN LOSS WITH VARIOUS FRICTION FACTOR CORRELATIONS. 1.5 IN.-I.D. VACUUM JACKETED PIPE; INITIAL SLUSH SOLID FRACTION, 0.5.

NASA
National Aeronautics and Space Administration

Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-102467		

4. Title and Subtitle	5. Report Date
FLUSH: A Tool for the Design of Slush Hydrogen Flow Systems	February 1990
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Terry L. Hardy	E-5255
	10. Work Unit No.
	763-01-21
9. Performing Organization Name and Address	11. Contract or Grant No.
National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191	
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, D.C. 20546-0001	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

As part of the National Aerospace Plane Project an analytical model was developed to perform calculations for in-line transfer of solid-liquid mixtures of hydrogen. This code, called FLUSH, calculates pressure drop and solid fraction loss for the flow of slush hydrogen through pipe systems. The model solves the steady-state, one-dimensional equation of energy to obtain slush loss estimates. A description of the code is provided as well as a guide for users of the program. Preliminary results are also presented showing the anticipated degradation of slush hydrogen solid content for various piping systems.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Slush hydrogen; Hydrogen; NASP; Analytical model; Computer program; Flow systems; Heat transfer; Propellant	Unclassified – Unlimited Subject Category 28

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified	70	A04

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161