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NBSIR 75-820

STUDY OF CRYOGENIC PROPELLANT SYSTEMS FOR LOADING THE SPACE SHUTTLE-

PART II, HYDROGEN SYSTEMS

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STUDY OF CRYOGENIC PROPELLANT SYSTEMS FOR LOADING THE SPACE SHUTTLE - PART II, HYDROGEN SYSTEMS*

W. G. Steward

ABSTRACT

This report covers computer simulation studies of liquid hydrogen fill and vent systems for the space shuttle. The computer programs calculate maximum and minimum permissible flow rates during cooldown as limited by thermal stress considerations, fill line cooldown time, pressure drop, flow rates, vapor content, vent line pressure drop and vent line discharge temperature. The input data for these programs are selected through graphic displays which schematically depict the part of the system being analyzed. The computed output is also displayed in the form of printed messages and graphs. Digital readouts of graph coordinates may also be obtained.

Procedures are given for operation of the graphic display unit and the associated minicomputer and timesharing computer.

Key words: Computer modeling; cooldown; cryogenic flow; stresses; two phase flow.

PREFACE

It will be noted that non-SI units appear in many of the figures of this report. The purpose of these figures is to illustrate typical displays as they appear on the screen of the graphical display terminal. These units are consistent with the current practice of KSC and are as desired by the KSC sponsor. Where dimensioned variables are mentioned in the text, dual units are given.

1. Introduction

This is a final report under NASA Contract No. CC-37171A.

This report covers a continuation of computer simulation studies of cryogenic propellant loading systems for the space shuttle. The preceding report, NBSIR 74-366, covered oxygen loading systems and the present report extends this work to the hydrogen loading and vent systems.

1.1 Objective

The objective of this study is to develop computer programs to determine thermal stress, cooldown times, and liquid hydrogen loading rates whereby loading procedures can be checked before a wet test of the actual system is conducted.

The programs of the oxygen studies which compute pressure spikes caused by water hammer or rapid vaporization during cooldown have been deleted from the hydrogen studies in favor of a more detailed analysis of the liquid loading rates and vent system. Since the pressure spikes have amplitudes which are approximately proportional to the density of the liquid, these spikes would be at least an order of magnitude smaller in hydrogen than in oxygen; therefore, they would be negligible; therefore, computation options 2, 4 and 5 were deleted from the hydrogen program. Contrarily, the effects of two phase flow during loading, vent line temperatures, and vent line pressure drop are factors of concern in the hydrogen system and were added to the present studies.

2. Graphic Display Computer Terminal

2.1 Description of Equipment

The system consists of a graphical display terminal interfaced with the KSC timeshare computer through a 8000 word storage minicomputer and MODEM. Figure 1 shows the graphical display unit and minicomputer.

Software for communication between the display unit and the KSC computer, routines for schematic displays, input-output, and graphing are programmed into the minicomputer. These routines are also stored on punched paper tape from which they may be reloaded if necessary. The programs and subroutines used in the calculations are catalogued in the KSC computer and are called as needed through the minicomputer software routines.

*This work was conducted at the National Bureau of Standards under the sponsorship of the Kennedy Space Center - National Aeronautics and Space Administration.

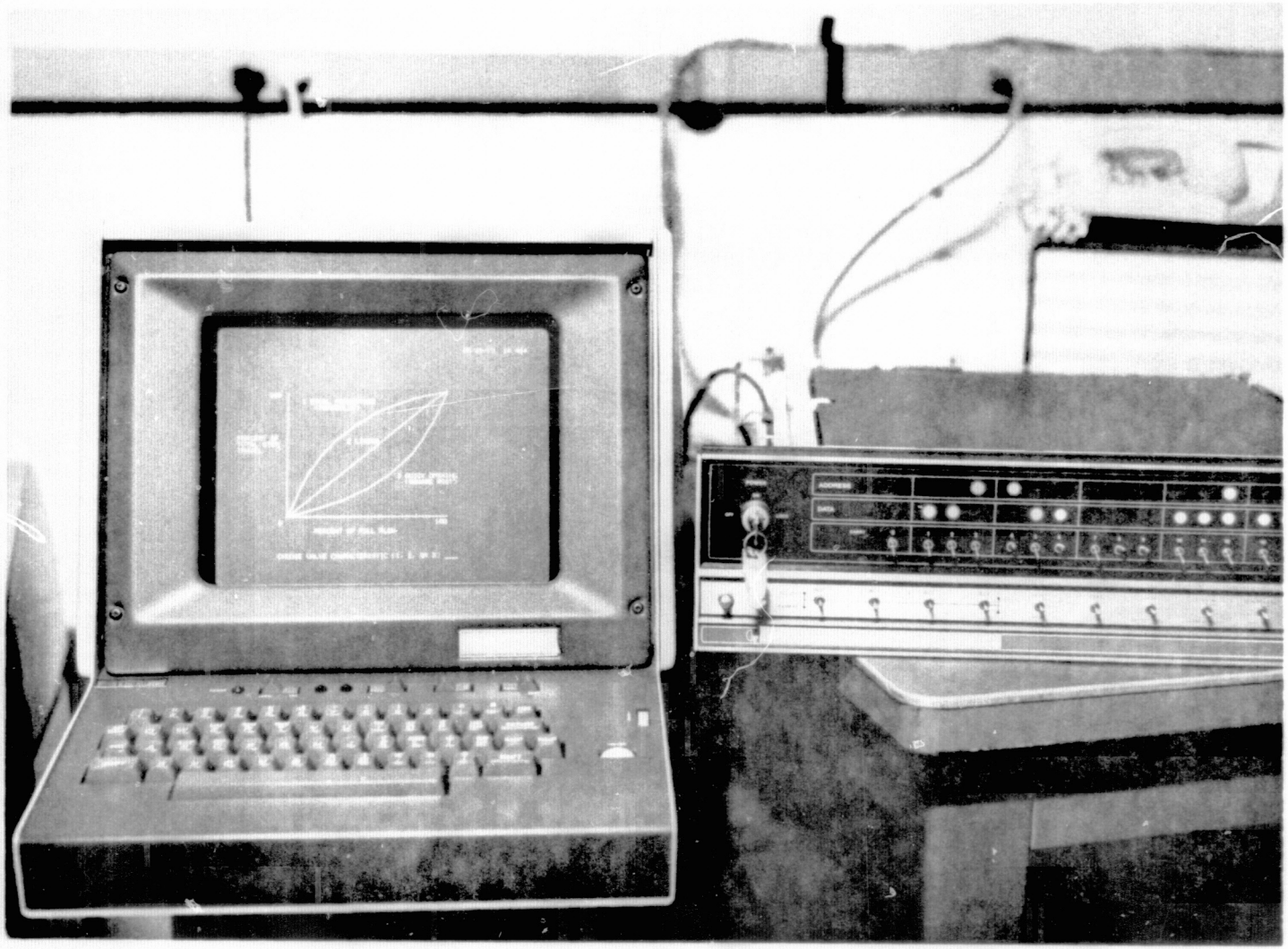


Figure 1. Graphic display terminal and minicomputer.

2.2 Description of the Minicomputer Software

The programs contained in the minicomputer control the information flow between the graphical display unit and the KSC timesharing computer. Besides the control function, the minicomputer has the input schematics with the associated input data and programs to interpret the responses received from the KSC timesharing computer (during execution of the hydrogen ground support computer program) in its memory.

The communication between the minicomputer system and the KSC computer is carried over a high speed telephone data line. The MODEM properly conditions the signals for the high speed data transmission.

Data is transmitted in various sized blocks with both horizontal and longitudinal parity. The receiving station checks for the parity errors in the incoming block of data and if the parity is correct, the transmission is accepted and an acknowledgment is returned to the sending station. If the parity of the received information is not correct, due to noise or other problems with the telephone line, the receiving station requests a retransmission. The sending station will then automatically retransmit the data. In some rare instances, the retransmission request is lost and the data must be manually retransmitted.

The minicomputer software has two basic modes of operation using the graphical display keyboard. The first mode, termed the manual mode, allows conversation with the KSC computer in a manner similar to a normal teletype except that the communication is at a high speed. The second mode of operation, termed the automatic mode, is used to run the computer programs simulating the hydrogen ground support equipment. Much of the communication between the minicomputer and the timesharing computer in the second mode is automatic, with no operator input required.

During operation in either mode, the graphical display terminal will emit an audible "beep" whenever an acknowledgment is received from the timesharing computer. This "beep" will inform the operator that a data block has been successfully sent and new information can be entered or a return can be expected from the timesharing computer. Until a successful transmission is affected, the keyboard of the graphical display unit is locked except to a control B, as explained in a later paragraph.

Operation in the manual mode allows for normal log-in procedures and the use of any subsystems on the KSC computer. Fortran, basic or the editing subsystem, may be employed in the manual mode.

Since the graphical display-minicomputer combination is connected to a terminal of the KSC timesharing system, operation in the manual mode is very similar to the general operation of the system as described in the manufacturer's manual. Log-on procedures as described in the manual are also valid for the graphic display unit.

During operation of the graphic unit, data entered on the screen of the graphics display are also entered into the memory of the minicomputer and when a carriage return is depressed, the data from the computer memory is transmitted to the timesharing computer. More than one line of data may be transmitted in a block if each line entered on the screen is terminated by a line feed and the entire block is terminated by a carriage return for transmission.

Typing errors can be corrected by using a control A which causes the cursor to be backspaced once and lowered one line. The character typed in the lower position replaces the original character in the minicomputer memory and will be transmitted when the carriage return is depressed. Since the graphics display unit is connected to a KSC timesharing terminal, other characteristics unique to that system affect the operation of the display unit. As an example, the timesharing computer counts the lines of output during its data transmission and after sufficient lines have been sent to fill the screen of the display unit, data transmission is terminated. The stop in data transmission is indicated by the ASCII code characters Λ * on the screen of the graphics unit. To receive additional data, the operator must transmit a blank line by depressing the carriage return on the keyboard.

The automatic mode of operation interacts with the specific hydrogen system simulation programs available in the Fortran subsystem of the timesharing computer. During automatic operation, the minicomputer will request a run of a specified program; send the required data when an equal sign is received; and interpret and display returning data from the timesharing computer on the graphical display unit. Usually, the returning data will be displayed

in graphical form. Since the hydrogen simulation programs are in the Fortran subsystem, the KSC computer must be in the Fortran subsystem before the automatic mode of operation is entered with the graphical display unit. The Fortran subsystem of the timesharing computer is indicated by an asterisk displayed on the screen.

Several control characters are used during normal operation of the graphic display unit to help the operator during the execution of the various programs. A control character is used during communication between the graphic display unit and the minicomputer and need not be followed by a carriage return to effect a transmission. A control character is executed by depressing and holding down the control key on the keyboard and then depressing the desired alpha-numeric key. Thus, a control D means that the control key was depressed and held, and then the letter D was depressed. The following is a description of the control characters available for use on the graphic display unit.

Control A: Control A allows the operator to correct a typing error before a block of data is sent to the timesharing computer. Any time before the carriage return is depressed, a change can be made to previously typed material. This change is made by depressing the control A an appropriate number of times until the cursor is located below the character to be changed, entering the new character and then proceding to enter subsequent characters in the line. One character is deleted each time control A is depressed.

Control B: Depressing control B will cause the minicomputer to issue a $*$ BRK command to the timeshare computer and return the minicomputer to the manual mode of operation. The function of the $*$ BRK command is described in the manufacturer's information manual. Control B can be used any time even during a transmission when the keyboard is locked to other input.

Control G: Control G causes the minicomputer to enter the automatic mode of operation. Entering the automatic mode of operation should not be attempted unless the KSC timeshare computer is operating in the Fortran subsystem and an asterisk (*) is displayed as the last received character on the graphic display unit.

Control P: Depressing the control P causes the minicomputer software to interpret data returning from the timesharing computer into graphical output. This option was supplied with the minicomputer to allow graphical output from any Fortran programs written in the manual mode. In order to graph the results of any program written in the manual mode, the output from the program must be supplied to the ASCII coded Fortran subroutine called PLOT currently available on the timesharing computer. Along with the data, labeling information can also be supplied to PLOT. The program DEMO currently loaded in the timesharing computer can be listed to obtain instructions on how to use subroutine PLOT. After writing a program for which a graphical output is expected the program is run in the manual mode, except that after all input data has been supplied and acknowledge received as indicated by a "beep"; control P should be depressed. A graph of the returning data will then appear on the graphical display unit.

2.3 Instructions for Log-In

The log-in routine for the minicomputer is accomplished in the manual mode. The procedure is to turn on the Modem (switch located inside the front cover), the minicomputer (key switch on front panel), and the graphics display unit (switch located on the front of the pedestal below the keyboard). The line-local switch on the graphics display keyboard should be set to line. After a short warm-up period, the screen on the graphics display unit will light up. The page key on the display unit should be depressed to prepare the screen for reception of messages. The starting address of the software program in the minicomputer is 00002 in octal (switch 14 on the top row of toggle switches up, all others down). After setting the top switches to the starting address, depress RESET and then START on the momentary contact control switches from the lower row of switches of the minicomputer. The timesharing computer can now be dialed on the telephone. After the computer carrier signal (a continuous tone) is confirmed, the telephone data switch can be actuated. As soon as the minicomputer software confirms the computer interconnections, the words PLEASE LOG IN will appear on the graphics display screen. If these words do not appear, a fault has developed in the minicomputer software, or the telephone interconnection was not achieved. The program should be reloaded as described in appendix C. The normal log-in procedure for the KSC timesharing system as described in the manufacturer's manual can now proceed. A carriage return should be supplied after each input to transmit the information to the timesharing computer. Figure 2 shows the appropriate log-in sequence as it would appear on the screen of the graphics display unit. Computer supplied messages are underlined.

2.4 Instructions for Initiation of Computation in the Automatic Mode

In order to perform calculations in the automatic mode using the hydrogen simulations programs, the Fortran subsystem of the timesharing computer must be available. On figure 2, the Fortran subsystem was entered by entering Fortran for the required system and new for the type of program. After an asterisk (*) appears on the screen as the last reception, control G can be depressed to enter the automatic mode of calculation. After initiation of the automatic mode, the universal figure (fig. 3) will appear on the screen of the graphics terminal. This figure is used to define the general characteristics of the piping system. Special procedures are required, however, for the use of the input display for the hydrogen programs. The necessity for, and the use of these special procedures are explained in Section 2.4.1.

2.4.1. Required Improvisations for the Hydrogen Input Displays

The data input displays are generated from programs loaded into the minicomputer from punched paper tape. Since the hydrogen programs require different input variables than the oxygen programs alternate input displays would be desirable; however, re-loading programs from paper tape each time the fluid is changed would be highly impractical. Equipment exists which could load the programs rapidly; however, purchase of additional equipment was not justifiable for this study. Therefore, it was necessary to improvise a method by which the required variables could be inserted into the hydrogen programs from the original oxygen displays. This improvisation was necessary for the "GENERAL INPUT DATA" option 3, and option 6, "COLD FLOW." The display which appears for option 1, "THERMAL STRESS" is unaltered and requires no unusual interpretation.

```
PLEASE LOG IN
$*$MD PASSWD, 26, DAC, TSS
****** CONNECT REQUEST SENT TO CP ******
KSC 635 AT CIF ON 02/06/75 AT 10.281 CHANNEL 4424


USER ID -
5ME013


PASSWORD--
XXXXXXXXXXXXXXXX
NBSH


9 BLOCKS FILE SPACE AVAILABLE

**TSS SIZE 54K CARDIN 25K

SYSTEM ?
TFOR

OLD OR NEW -
NEW

READY
*
```

Figure 2. Log-in sequence.

Figure 3 shows the "GENERAL INPUT DATA" as it will appear on the screen of the graphic display unit. Figure 3A shows the new interpretation of the numbers entered. For example, item 8 on figure 3 appears as "SUPPLY LIQUID LEVEL = 850,000 FT"; however, the hydrogen programs interpret this entry as "SUPPLY LIQUID VOLUME = 850,000 GAL". By comparison of the flow diagrams shown in figures 3 and 3A it may be seen that the pipe lengths are distributed differently in the hydrogen programs. Lengths L4 through L7 are used to represent parts of the vent line in figure 3A, whereas no vent line lengths are shown in figure 3.

In order to avoid confusion a template has been prepared which fits over the screen of the graphic display unit. The template masks the flow diagram and the wording of the oxygen display but has windows in which the entered numbers appear. The opaque portion of the template shows the new flow diagram and the appropriate wording to correspond with the hydrogen program interpretation of the entered numbers. The graphic display screen with the template in place will then appear the same as figure 3A. A similar template has been prepared for option 3 "COOLDOWN TIME", and option 6 "COLD FLOW."

2.5 Data Input

In the general input data entry 7, "SUPPLY ULLAGE PRESSURE" requires some clarification. For computation options, except option 6, there is no difference between the ullage pressure during storage and during the transfer process. For option 6, the pressure specified in the general input data is taken to be the ullage pressure during storage and it is assumed that the supply liquid becomes saturated at that pressure. The specific input data for option 6 allows a "SUPPLY ULLAGE PRESSURE DURING TRANSFER" to be selected which may be different from the supply ullage pressure during storage.

GENERAL INPUT DATA 03/14/75 8.333

1. LENGTHS: L1 = 1606 FT
   L2 = 37 FT
   L3 = 98 FT
   L4 = 24 FT
   L5 = 22 FT
   L6 = 826 FT
   L7 = 1430 FT
   L8 = 2350 FT
   L9 = 10258 FT
2. DIA FOR LENGTHS L3, L4 = 10.482 IN
   D1 = 8.33 IN
   D2 = 10.482 IN
   D5 = 8.33 IN
   D6 = 17.50 IN
   D7 = 17.50 IN
   D8 = 17.50 IN
   D9 = 393,400 IN
3. ELEVATIONS:
   H8 = 2.9 FT
   H9 = 109 FT
4. AMBIENT TEMPERATURE = 0 DEG F
5. WIND VELOCITY = 0 KNOTS
6. RELATIVE HUMIDITY = 0%
7. SUPPLY ULLAGE PRESSURE = 1.5 PSIG
8. Supply LIQUID LEVEL = 850,000 FT
9. IS THE PIPE VACUUM INSULATED
   (0 - YES, 1 - NO) ? 1
10. DOES THE LINE VENT INTO THE TANK (1)
    OR THE CATCH BASIN (2) ? 1000

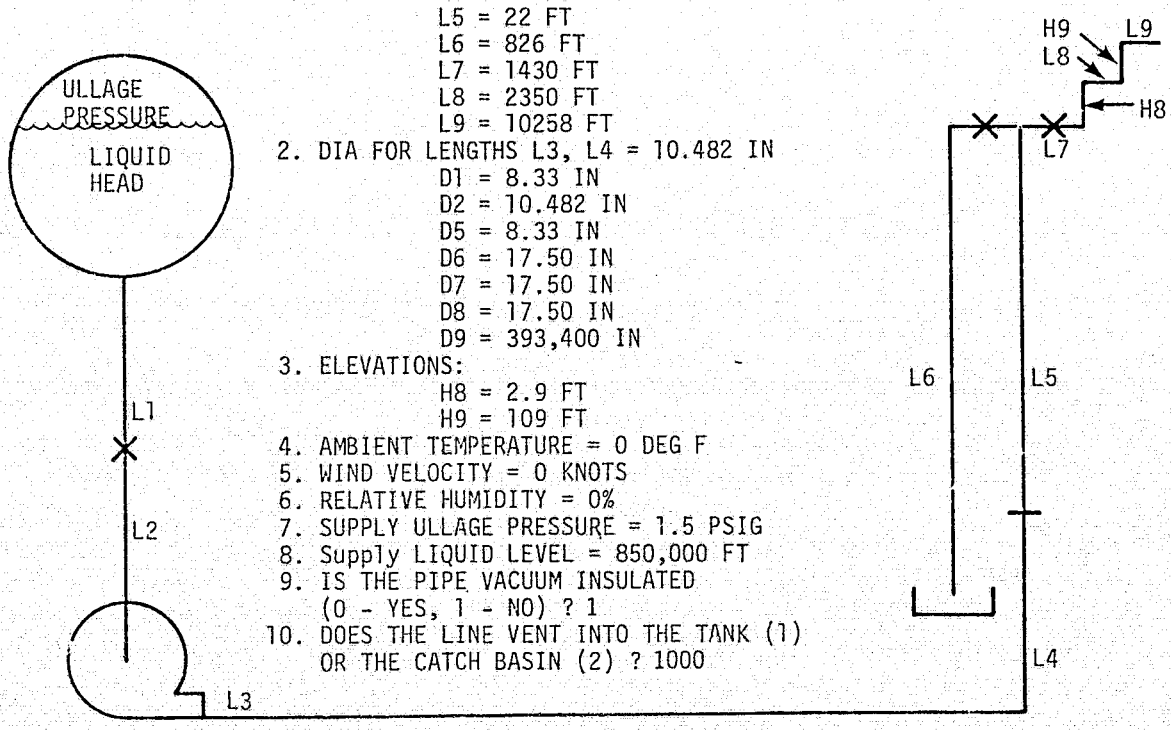


Figure 3. General input data.

GENERAL INPUT DATA

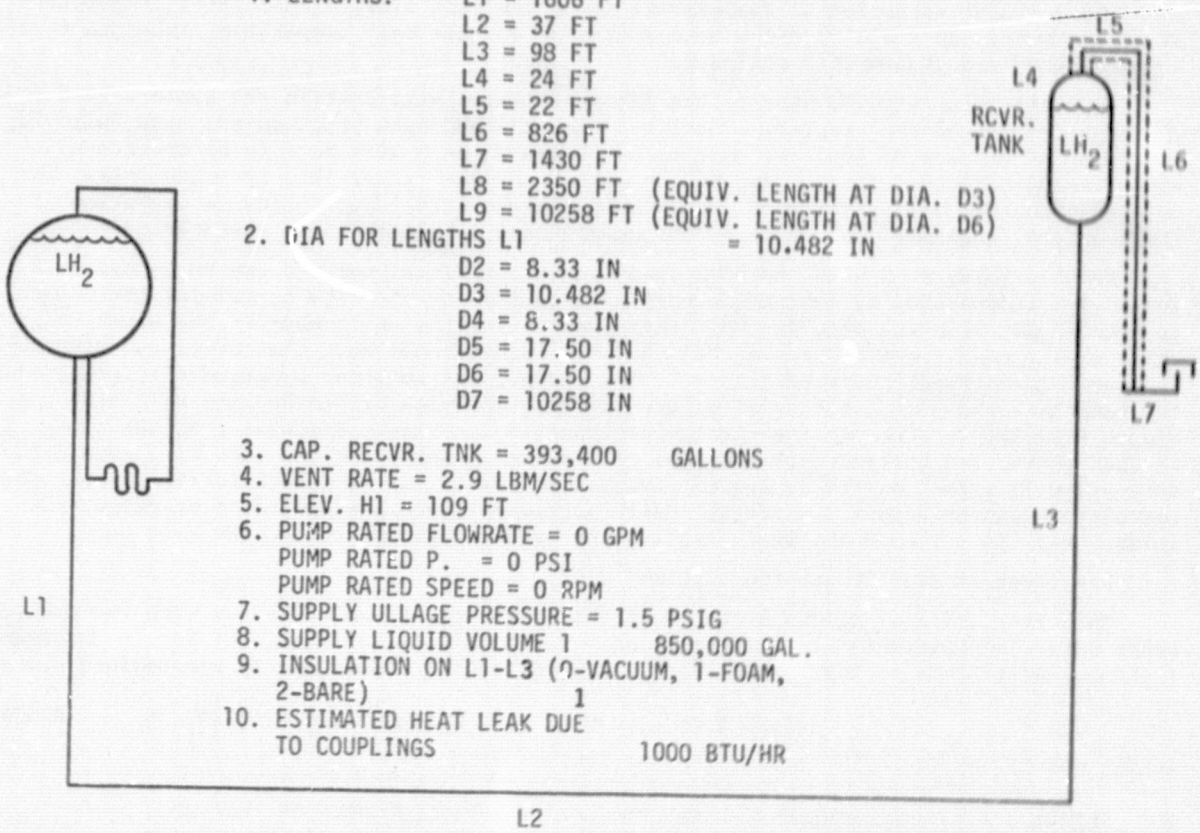


Figure 3A. Hydrogen general input data.

It will be noted that in figure 3A there are two lengths, L8 and L9, which are listed but which are not shown in the schematic flow diagram. L8 is an equivalent length of pipe of diameter D3 to represent pressure losses due to valves, fittings, flex hose, filters, etc. in addition to the actual lengths L1 through L3 in the fill line. L9 is a similar equivalent length of pipe of diameter D6 to represent additional pressure losses in the vent line.

Since the flow in the fill line is considered incompressible a standard method of determining the equivalent length as given by most manufacturers of valves and fittings may be used. When the pressure drop element is located in a pipe having a diameter other than D3 the following equation may be used:

$$L8 = L_p(D3/D_p)^4,$$

where L_p is the equivalent length as given by the manufacturer and D_p is the diameter of the pipe in which the valve or fitting is installed.

In the vent line variations in gas density must be considered as well as changes in diameter when assigning a value to equivalent length L9. This density change is due to changes in absolute temperature to a much greater extent than to changes in absolute pressure. Since the pressure drop for a given mass flow rate is inversely proportional to

density and density is approximately inversely proportional to the absolute temperature:

$$L9 = L_p(T_p/T_6)(D6/D_p)^4,$$

where T_p is the temperature at the location of the pressure drop element and T_6 is the temperature at the discharge end of length L6. These temperatures may be estimated by assuming a linear variation of temperature along the vent line, a vent inlet temperature of approximately 20 K (36°R) and a vent discharge (bubble cap) temperature obtained from a preliminary run of computer option 6.

When the input figures appear, the input variables will contain the numbers used in the previous run of the program. The first time the hydrogen programs are used following operation of the oxygen programs most of the hydrogen data will have to be re-entered since the data in the minicomputer memory will be oxygen rather than hydrogen data. The reverse situation will exist when oxygen programs are first used following operation of the hydrogen programs; i.e., most of the oxygen data will have to be re-entered.

On succeeding runs with the same fluid any or all input numbers may be changed. A change is accomplished by moving the horizontal cursor to the line containing the number to be changed, pressing the "RUB OUT" key, then typing the new number in the blank space which will appear. After pressing "RETURN" the operator may move the cursor and make further changes. Even though the schematic will not change, the computer programs will accept zero for lengths 2 and 3 (L2, L3) to eliminate the vertical rise if desired and will accept a single pipe length equal to the total pipe length and a single diameter. At the upper right on the figure, the current date and time will appear. This date and time will remain the same and will appear on all subsequent figures to be used as an identification number to correlate hardcopy output. After all input parameters have been adjusted to acceptable values, and the ALT MODE key is depressed, the system will proceed to the next page.

2.6 Selection of Computation Option

This page (fig. 4) allows a choice of the computer program to be run with the previous input data. (As was noted earlier, options 2, 4, and 5 are not available for the hydrogen system). After this choice is made by placing the option number in the appropriate blank

SELECTION OF COMPUTATION OPTIONS Ø3/Ø7/75 9.618

SELECT ONE OF THE FOLLOWING COMPUTATION OPTIONS:

1. OPTION 1 - THERMAL STRESSES. STRESSES DUE TO RAPID COOLDOWN OF FLANGES, OR BOWING OF PIPELINE DUE TO STRATIFICATION IN THE CASE OF LOW FLOW RATES.

2. OPTION 2 - VALVE OPENING SURGES. SURGES DUE TO RAPID VAPORIZATION WHEN A VALVE IS OPENED PRECEDING A FREE WHEELING PUMP. ALSO CALCULATED IS THE PRESSURE PEAK DUE TO WATER HAMMER AS THE LIQUID IMPINGES ON A FREE WHEELING PUMP.

3. OPTION 3 - COOLDOWN TIME. CALCULATES LENGTH COOLED DOWN, FLOW RATE, AND PRESSURE DROP ACROSS THE PUMP VERSUS TIME.

4. OPTION 4 - PUMP START UP COOLDOWN SURGES. CALCULATES SURGES DUE TO RAPID VAPORIZATION WHEN A PUMP IS STARTED UPSTREAM FROM A WARM LINE.

5. OPTION 5 - WATER HAMMER. PRESSURE SPIKES DUE TO WATER HAMMER WHEN VALVES ARE CLOSED IN A FLOWING LIQUID STREAM.

6. OPTION 6 - COLD FLOW. STEADY FLOW OPERATION AND TRANSIENT RESPONSE TO CHANGES IN OPERATING CONDITIONS.

7. OPTION 7 - RETURN TO MONITOR.

OPTION SELECTED IS 1

Figure 4. Selection of computation options.

and depressing ALT MODE, the terminal will display the first page of that option. The first page of each option, plus as many as two more pages will appear, allowing for more specialized input data. Typical display figures are shown in the following sections. After the input data has been adjusted as previously described and ALT MODE depressed for each input figure, the output of each option will appear after a short period of time. During this time interval, several "beeps" will be heard as input data is supplied to the timesharing computer. In some instances, when multiple output is expected, a choice of output curves will be made available. Each output curve will fill the entire screen. When the output curve appears, it will be possible to digitize any point on the curve by placing the vertical cursor on the desired point and depressing the space bar, and a hard copy may be obtained by depressing control D.

Restarting with the input display is accomplished by depressing ALT MODE. At this time the operator may choose another computation option with the previous input values, he may change the input, or he may terminate computation by selecting option 7 from the second page (RETURN TO MONITOR). Of course, if the operator chooses to start calculations on a new system, a new date and time will appear on all figures, allowing him to maintain correlation between the input and the output figures.

2.7 Reloading the Minicomputer Programs

Several paper tapes have been supplied with the system. Some of the tapes were supplied by the manufacturer of the minicomputer and can be used to debug the hardwired functions of the minicomputer. The function of the manufacturer's supplied tapes are described in accompanying literature. Other paper tapes can be used to reload the existing minicomputer program. The paper tape loading procedure using an appropriate teletype unit, is described in Appendix C.

3. Computation Options

3.1 Option 1 - Thermal Stresses

Calculates stresses due to rapid cooldown of flanges, or bowing of pipeline due to stratification in the case of low flow rates.

3.1.1 Application

This computation determines low and high limits of flow rates during cooldown from the standpoint of the resulting stresses in the piping system and flanged joints. For very high flow rates and rapid cooling excessive thermal stresses may be created in flanges due to the large radial temperature gradients. On the other hand very low flow rates might result in stratified flow with liquid lying along the bottom of the pipe. The resulting circumferential temperature gradients could cause a pipeline to bow significantly. These stress-limited cooldown flow rates are calculated according to the method of Novak [1970].

3.1.2 Input Data Entries

Section 2.3 describes the general log-in procedure for the graphic display system. After the initial log-in has been accomplished, and option 1 has been selected, a display similar to figure 5 appears. The input required for this option in addition to the general

```
                                                    Ø3/Ø7/75      9.618

                    OPTION 1 - THERMAL STRESSES

1.   OUTSIDE DIAMETER OF PIPE FLANGE IS 18 IN

2.   OUTSIDE DIAMETER OF PIPELINE IS 14 IN

3.   INSIDE DIAMETER OF PIPELINE.IS 1Ø.482 IN

4.   PIPELINE MATERIAL IS NUMBER 2
     CHOICE OF PIPELINE MATERIAL:
     1 ALUMINUM
     2 3Ø4 STAINLESS STEEL
```

Figure 5. Option 1 - thermal stresses input display.

input data of figure 3 is shown in figure 5. These are the outside diameter of the pipe flange, the outside and inside diameters of the pipeline and the material of the pipeline.

3.1.3 Output

The output for this calculation is alpha numeric only but will be displayed on the screen just as other output data. The values given will be the maximum cooldown flow rate which will allow the stress in the flanges to remain below the yield point, and the minimum flow rate which will prevent stratified flow from occurring with the given input conditions.

3.2 Option 3 - Cooldown Time - length cooled down and flow rate versus time.

3.2.1 Application

As a cryogenic liquid flows or is pumped from a reservoir into a warm pipeline, vapor forms at the leading end of the liquid stream. Frictional resistance to the flow of this vapor is the principle limiting factor in the rate of cooling pipelines of large length-to-diameter ratios. The slow moving liquid is evaporated and vapor is warmed to near the initial temperature of the pipe in a short distance relative to the length of pipe. When the pipeline is uninsulated, the heat transfer to the cold part of the pipe adds to the vaporization rate and thus further retards the progress of the liquid. The cooldown model based on this cold front concept and listing of the computer subroutine (CDT) are discussed in Supplement A (1974). The heat-mass transfer correlations are discussed in Appendix A of NBSIR 74-366 (Voth, et al. 1974).

3.2.2 Input Data Entries

Section 2.3 describes the log-in procedure for the graphic display system. After the initial log-in has been accomplished and option 3 "Cooldown Time" has been selected, a display similar to Figure 6 appears. As discussed in section 2.4 this display is a part of the minicomputer program designed for the oxygen system. It is apparent from Figure 6 that the input display accommodates six different pipe sections, three wall materials and three thicknesses. Since it was necessary to limit the number of hydrogen fill line sizes to three (L1, L2, and L3), the three extra material and thickness variables had to be eliminated. Figure 6A shows the resulting interpretation of the hydrogen input data for the cooldown time program. It can be seen that entries 3 through 8 remain unchanged.

If desired, input variables pertinent to the cooldown time computation may be viewed and changed on this display as explained in Section 2.4. The variables in figure 6A apply only to option 3 and are in addition to those of the general input data of figure 3. Concentrated masses such as valves, pumps, and fittings should be compensated for by specifying additional pipe wall thickness provided the calculated cooldown time desired is to include the time needed to completely cool these concentrated masses.

3.2.3 Output

The outputs of the computation are: (1) length cooled down versus time, (2) flow rate of liquid hydrogen versus time, and (3) pressure drop across the pump (if a pump exists) versus time. Typical examples are shown in figures 7 and 8. The x and y values shown in figure 7 and subsequent output graphs are the result of digitizing. In figure 7 x corresponds to time and y corresponds to length cooled.

3.3 Option 6 - Cold Flow - steady flow operation and transient response to changes in operating conditions.

3.3.1 Application

This computation applies after the transfer line has reached operating temperature. It deals with response to changes in operating conditions but does not deal with cooldown transients. The latter are treated separately in option 3. The flow rate and receiver tank liquid temperature (or two phase quality) are calculated as functions of the supply ullage pressure and pipe geometry. The accumulated liquid, change in supply liquid level, and vent bubble cap temperature are also computed. Supply ullage pressure and valve settings are allowed to vary with time. Details of the computation and computer program listing are given in Supplement A (1974), and Appendix D of this report.

```
                    OPTION 3 - COOLDOWN TIME          Ø3/1Ø/75     15.Ø66

PIPE WALL DATA:              MATERIALS - ENTER          FOR
                                          1        STAINLESS STEEL
                                          2        ALUMINUM
                                          3        INVAR

        1.   MATERIAL OF PIPE FOR LENGTHS
             L1, L2, L3, L4 IS 3
                 FOR L5 IS 3
                 FOR L6 IS 3
                 FOR L7 IS Ø
                 FOR L8 IS Ø
                 FOR L9 IS Ø
        2.   WALL THICKNESS FOR LENGTHS
             L1, L2, L3, L4 IS .134 IN
                 FOR L5 IS .134 IN
                 FOR L6 IS .134 IN
                 FOR L7 IS Ø IN
                 FOR L8 IS Ø IN
                 FOR L9 IS Ø IN
        3.   LENGTH OF LINE TO BE COOLED IS 4Ø9Ø FT
        4.   IS A PUMP PRESENT IN THE SYSTEM
             (Ø - NO, 1 - YES)? Ø
        5.   IF THERE IS A PUMP, DOES IT FREEWHEEL
             DURING COOLDOWN (Ø) OR IS IT STARTED
             AFTER A SPECIFIED TIME (1)? 1
        6.   IF THE PUMP IS STARTED, HOW LONG AFTER
             COOLDOWN IS IT STARTED?  35 MIN
        7.   IF THE PUMP IS STARTED, AT WHAT SPEED
             DOES IT RUN?  1ØØØ RPM
        8.   OUTPUT DESIRED IS 1
             (1) LENGTH COOLED DOWN VS. TIME
             (2) FLOW RATE OF LOX VS. TIME
             (3) PRESSURE DROP ACROSS PUMP VS. TIME
```

Figure 6. Option 3 - cooldown time input display.

```
                    OPTION 3 - COOLDOWN TIME

PIPE WALL DATA:              MATERIALS - ENTER          FOR
                                          1        STAINLESS STEEL
                                          2        ALUMINUM
                                          3        INVAR

        1.   MATERIAL OF PIPE FOR LENGTHS
                 L1 IS 3
                 L2 IS 3
                 L3 IS 3
        2.   WALL THICKNESS FOR LENGTHS
                 L1 IS .134 IN
                 L2 IS .134 IN
                 L3 IS .134 IN
        3.   LENGTH OF LINE TO BE COOLED IS 4Ø9Ø FT
        4.   IS A PUMP PRESENT IN THE SYSTEM
             (Ø - NO, 1 - YES)? Ø
        5.   IF THERE IS A PUMP, DOES IT FREEWHEEL
             DURING COOLDOWN (Ø) OR IS IT STARTED
             AFTER A SPECIFIED TIME (1)? 1
        6.   IF THE PUMP IS STARTED, HOW LONG AFTER
             COOLDOWN IS IT STARTED?  35 MIN
        7.   IF THE PUMP IS STARTED, AT WHAT SPEED
             DOES IT RUN?  1ØØØ RPM
        8.   OUTPUT DESIRED IS 1
             (1) LENGTH COOLED DOWN VS. TIME
             (2) FLOW RATE OF LOX VS. TIME
             (3) PRESSURE DROP ACROSS PUMP VS. TIME
```


Figure 6A. Option 3 - cooldown time hydrogen input display.

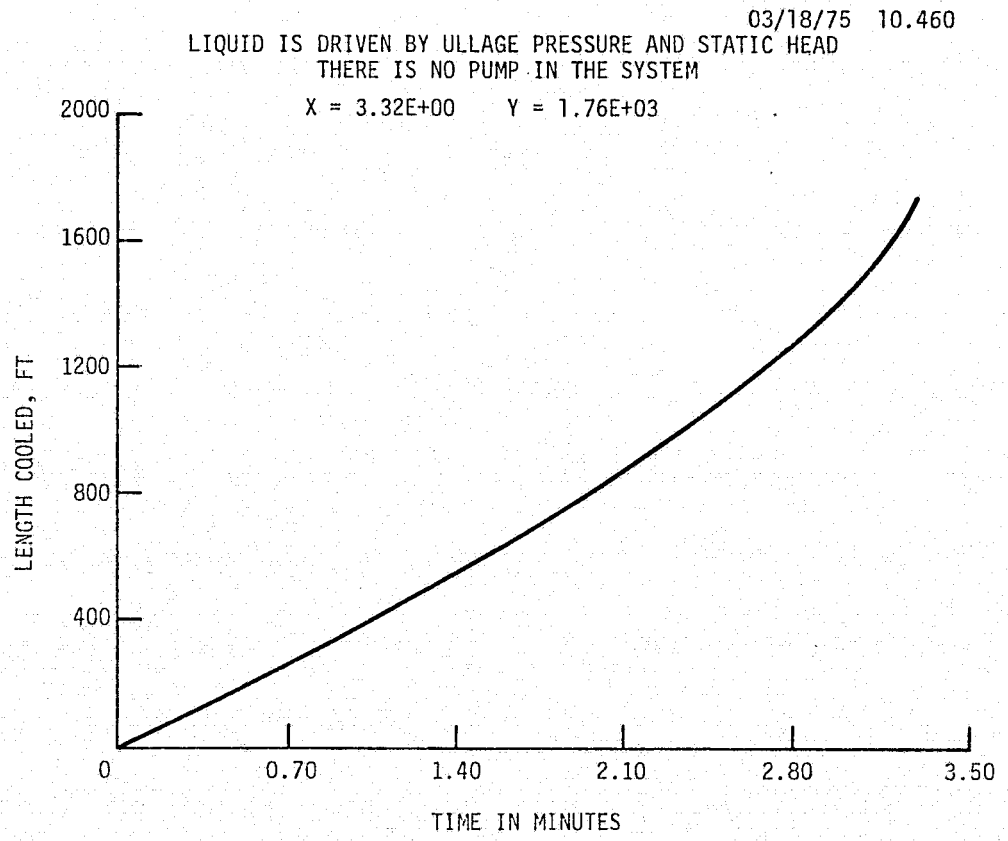


Figure 7. Option 3 - output.

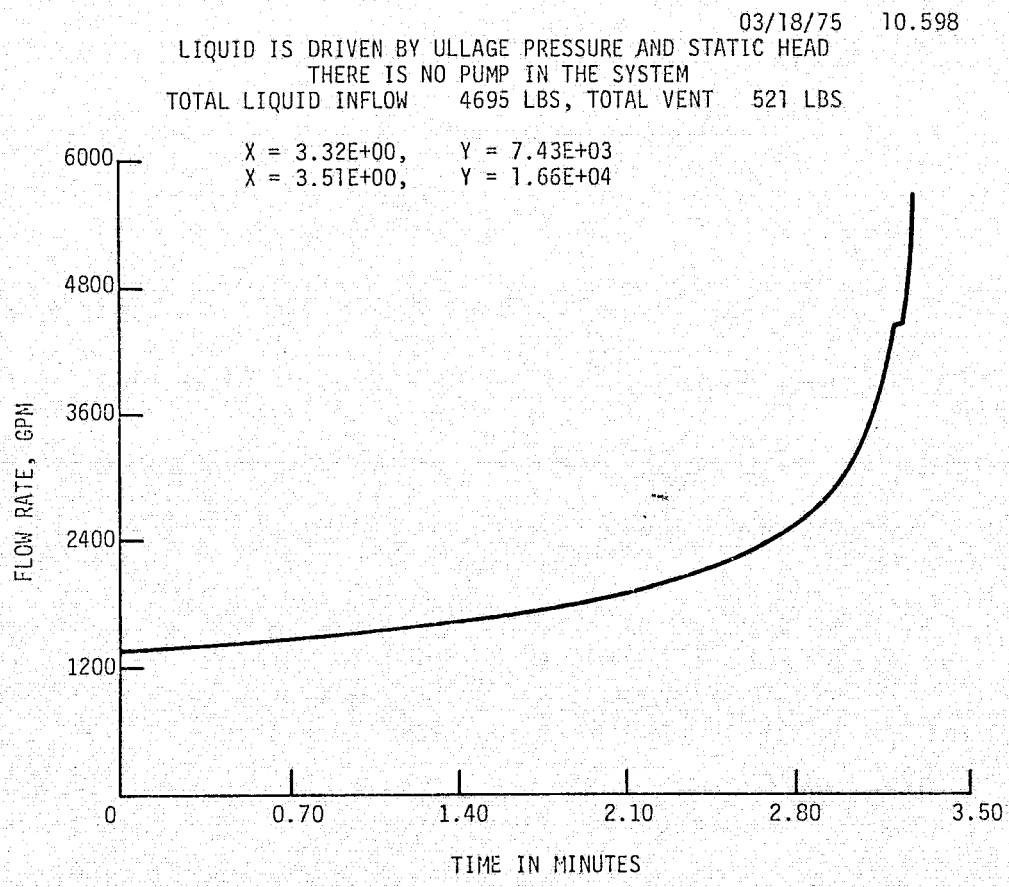


Figure 8. Option 3 - output (continued).

3.3.2 Input Data Entries

Section 2.3 describes the general log-in procedure for the graphic display system. After the option 6 is selected, a display similar to figure 9 and 10 will appear. Figure 9, as with all the input data displays, is contained in the minicomputer memory and was designed for the oxygen system. Several changes were desired for the hydrogen programs:

1. Under item 3, the output options "RECEIVER LIQUID TEMPERATURE" to replace "PUMP DISCHARGE PRESSURE" as output option 3.
2. "BUBBLE CAP TEMPERATURE" to replace "LINE PRESSURE AHEAD OF DISCHARGE VALVE" as output option 4.
3. Under item 4, the schedule of changes in operating conditions, the variable "PUMP RPM" is to be replaced by "SUPPLY ULLAGE PRESSURE".

Figure 9A incorporates these changes and illustrates the way in which the hydrogen programs interpret the input data entries. A template has been prepared which, when placed over the screen of the graphic display unit, shows the correct meanings of the input display entries with respect to the hydrogen version of "COLD FLOW."

If desired, input variables may be examined and changed in the display by the procedure explained in Section 2.4 except in the table of numbers showing time, valve opening, and pump speed, where the vertical and horizontal cursors must be positioned before depressing the space bar.

Entry 1 allows a supply ullage pressure during transfer to be selected which may or may not be different from the ullage pressure during storage. (The storage pressure is taken as that pressure which was selected previously under General Input Data.) Entry 1 along with entry 2 relates to the subcooling of the inlet liquid. This subcooling enters into the calculation of discharge liquid temperature, or fraction of vapor being discharged. Entry 4 allows for the selection of a schedule of changes in operating conditions. That is, the supply ullage pressure or the discharge valve setting may be specified at six times. Supply ullage pressure and valve setting change linearly from one specified time to the next. The program carries out the computation to ten seconds beyond the last entry in the schedule.

The third entry under Cold Flow allows the selection of computed quantities to be displayed. The desired quantities are selected as numbers 1 through 6. Striking ALT MODE initiates the calculation, and the next display is the selected output graph.

3.3.3 Output

Typical output graphs are shown in figures 11 through 16. The following variables may be plotted as functions of time:

Fig. 11 Flow rate

Fig. 12 Total accumulated liquid discharged into the receiver after subtracting off the quantity vaporized

Fig. 13 Receiver liquid temperature

Fig. 14 Bubble cap temperature

Fig. 15 Final vapor fraction

Fig. 16 Remaining liquid volume.

OPTION 6 - COLD FLOW Ø3/31/75 8.319

STEADY OPERATION AND TRANSIENT RESPONSE TO CHANGE IN OPERATING CONDITIONS

1. SUPPLY ULLAGE PRESSURE DURING TRANSFER IS 1.5 PSIG
(SUPPLY ULLAGE PRESSURE DURING STORAGE WAS SELECTED PREVIOUSLY)

2. INLET LIQUID WILL BE SATURATED AT CONDITION 1
1 - SATURATED AT STORAGE PRESSURE
2 - SATURATED AT TRANSFER PRESSURE

3. THE OUTPUT, FROM AMONG THE FOLLOWING, TO BE GRAPHED IS 1
1 - FLOW RATE VERSUS TIME
2 - TOTAL LIQUID DISCHARGED FROM THE PIPELINE VERSUS TIME
3 - PUMP DISCHARGE PRESSURE VERSUS TIME
4 - LINE PRESSURE AHEAD OF THE DISCHARGE VALVE VERSUS TIME
5 - OUTLET QUALITY VERSUS TIME
6 - FLUID DISCHARGE TEMPERATURE VERSUS TIME

4. THE SCHEDULE OF CHANGES IN OPERATING CONDITIONS:

TIME, MINUTES	DISCHARGE VALVE FRACTION OPEN	PUMP RPM
Ø	Ø.ØØ4	1.5
16	Ø.ØØ4	1.5
27	Ø.Ø15	1.5
3Ø	Ø.Ø15	1.5
32	1.ØØØ	77.5
65	1.ØØØ	77.5

Figure 9. Option 6 - cold flow input display.

OPTION 6 - COLD FLOW Ø3/31/75 9.884

STEADY OPERATION AND TRANSIENT RESPONSE TO CHANGE IN OPERATING CONDITIONS

1. SUPPLY ULLAGE PRESSURE DURING TRANSFER IS 1.5 PSIG
(SUPPLY ULLAGE PRESSURE DURING STORAGE WAS SELECTED PREVIOUSLY)

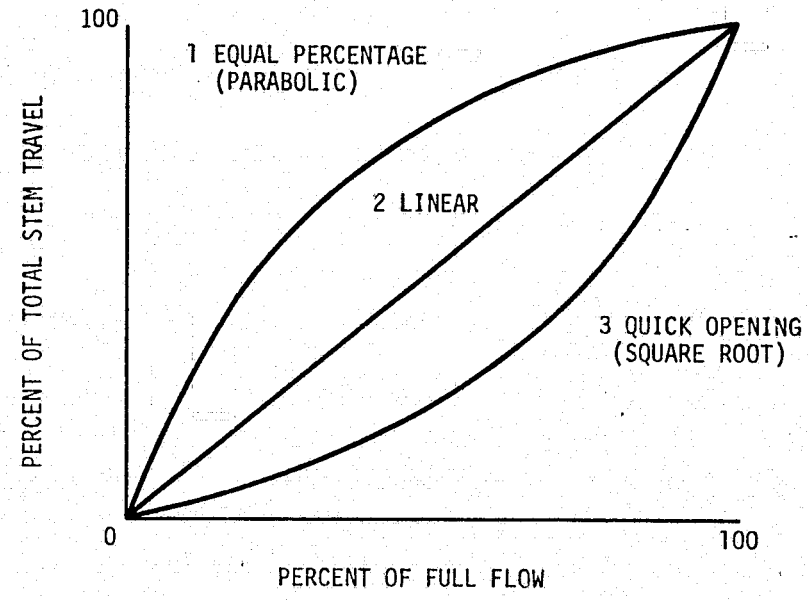
2. INLET LIQUID WILL BE SATURATED AT CONDITION 1
1 - SATURATED AT STORAGE PRESSURE
2 - SATURATED AT TRANSFER PRESSURE

3. THE OUTPUT, FROM AMONG THE FOLLOWING, TO BE GRAPHED IS 1
1 - FLOW RATE VERSUS TIME
2 - TOTAL LIQUID DISCHARGED FROM THE PIPELINE VERSUS TIME
3 - RECEIVER LIQUID TEMPERATURE
4 - BUBBLE CAP TEMPERATURE
5 - OUTLET QUALITY VERSUS TIME
6 - REMAINING LIQUID VOLUME VERSUS TIME

4. THE SCHEDULE OF CHANGES IN OPERATING CONDITIONS:

TIME, MINUTES	DISCHARGE VALVE FRACTION OPEN	TRANSFER PRESSURE PSIG
Ø	Ø.ØØ4	1.5
16	Ø.ØØ4	1.5
27	Ø.Ø15	1.5
3Ø	Ø.Ø15	1.5
32	1.ØØØ	77.5
65	1.ØØØ	77.5

Figure 9A. Option 6 - cold flow hydrogen input display.



CHOOSE VALVE CHARACTERISTIC (1, 2, OR 3) 3

Figure 10. Option 6 - cold flow input display (continued).

03/31/75 9.884

STEADY OPERATION AND TRANSIENT RESPONSE
TO CHANGES IN OPERATING CONDITIONS
DISCHARGE TEMP AT A FLOW OF 12997 GPM WAS 36 R

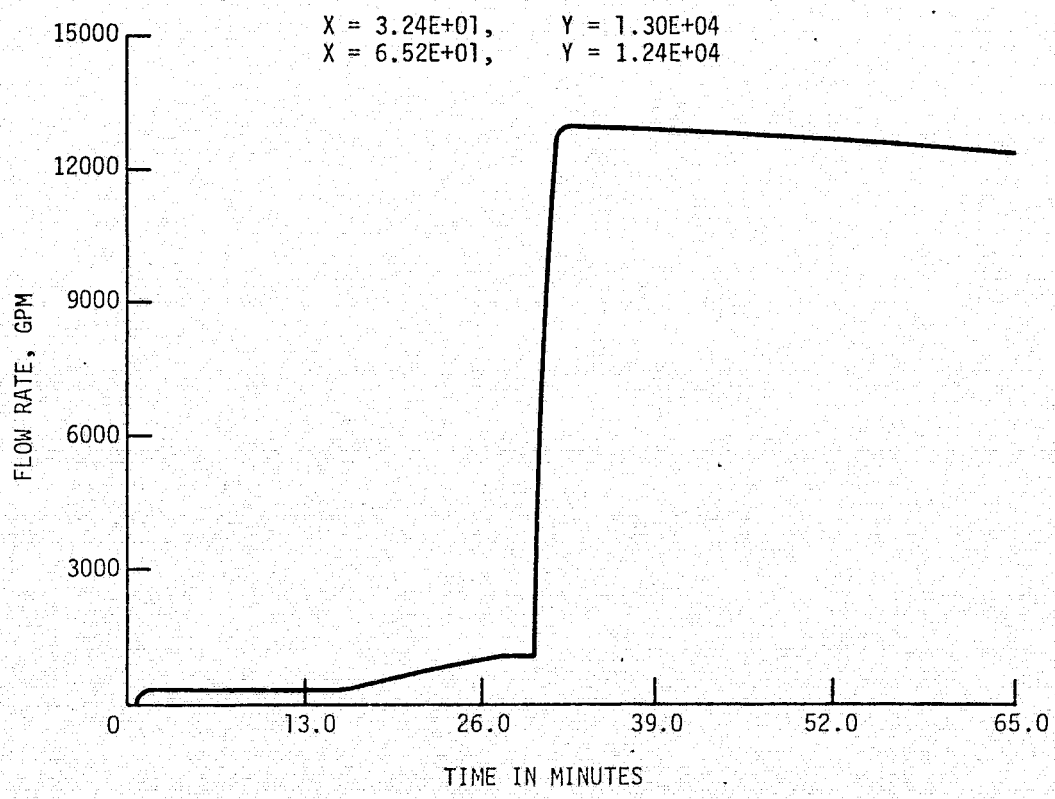


Figure 11. Option 6 - output.

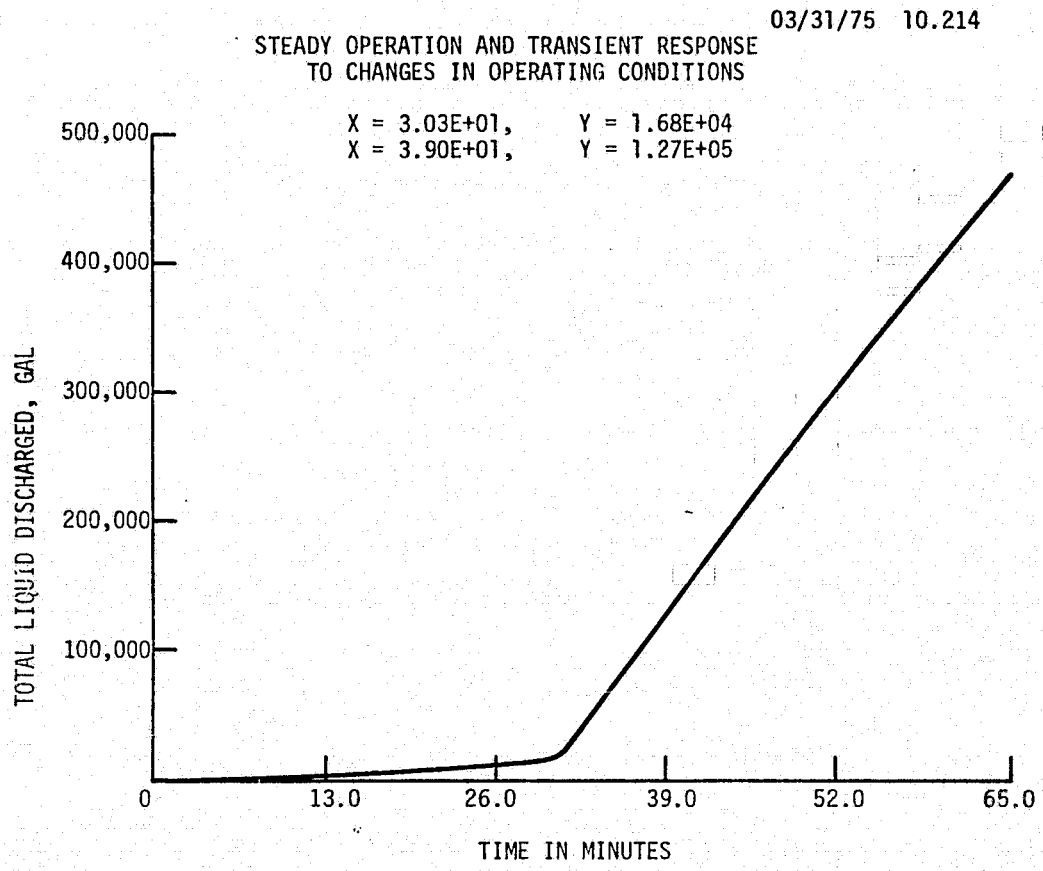


Figure 12. Option 6 - output (continued).

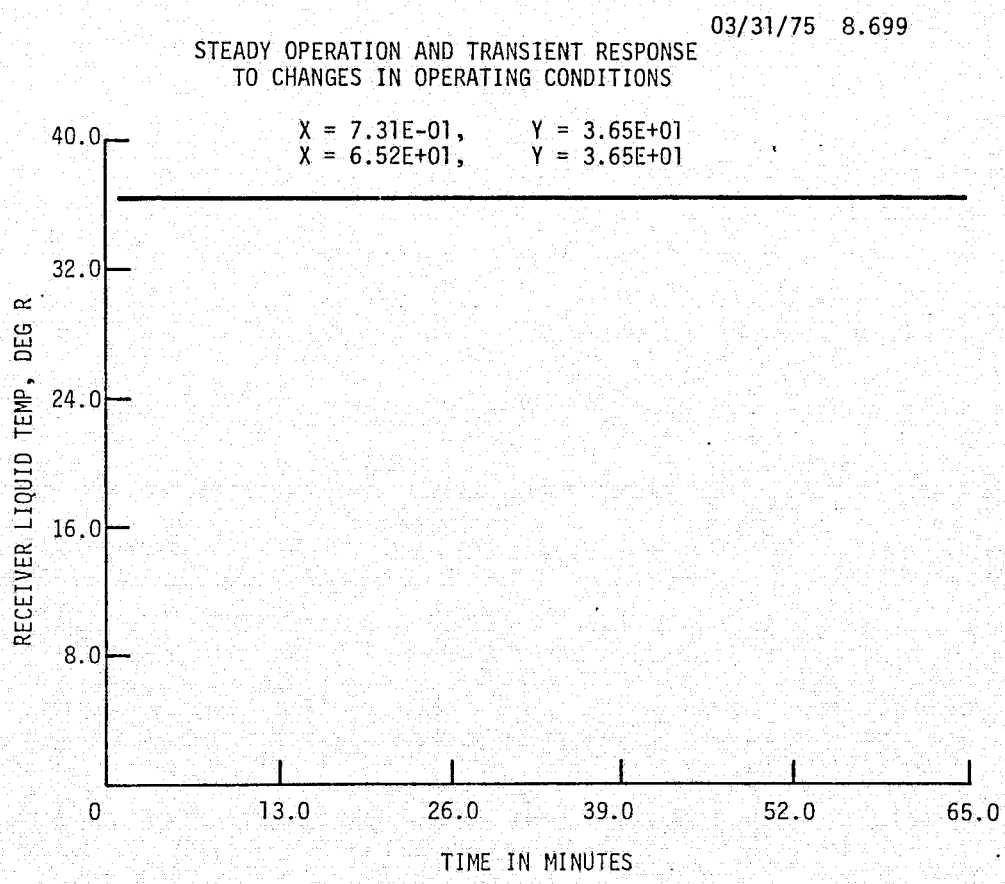


Figure 13. Option 6 - output (continued).

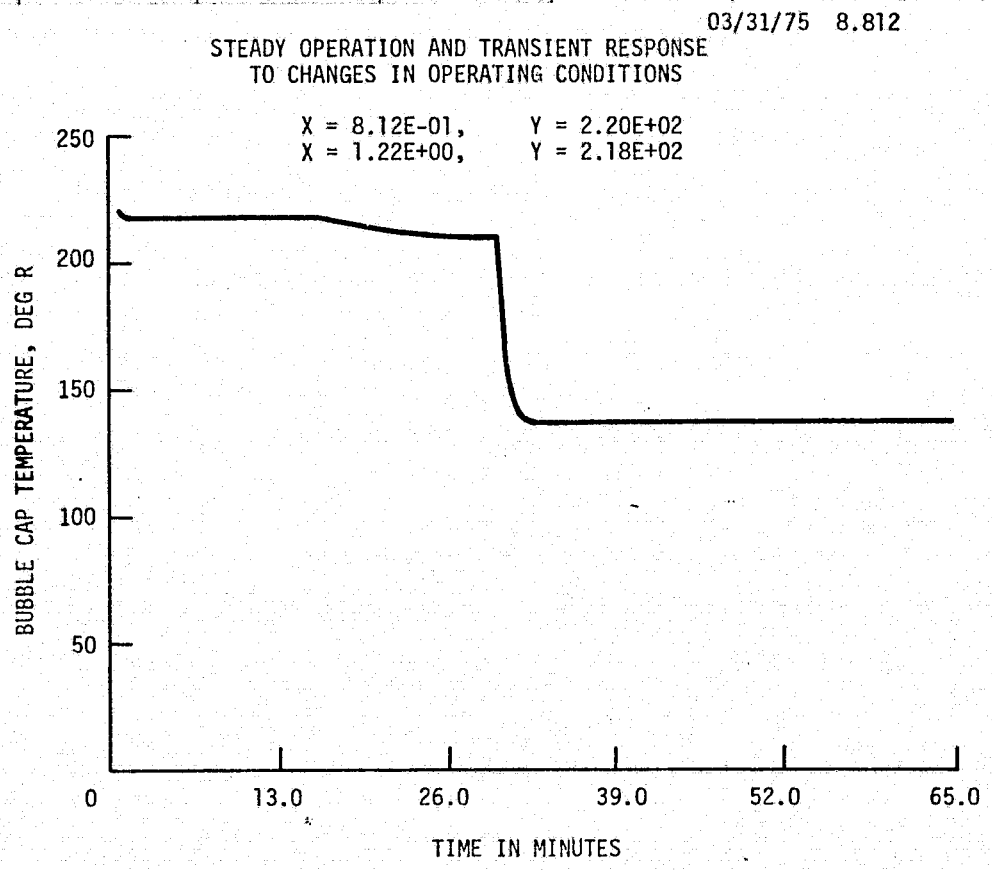


Figure 14. Option 6 - output (continued).

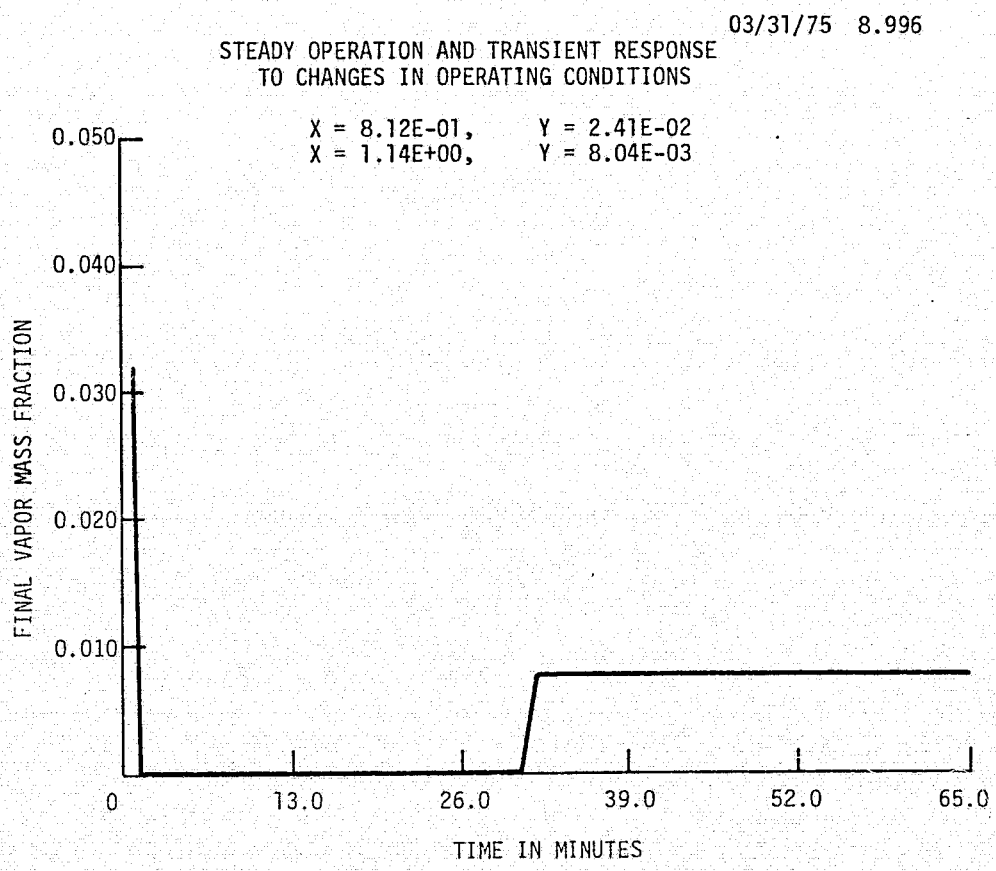


Figure 15. Option 6 - output (continued).

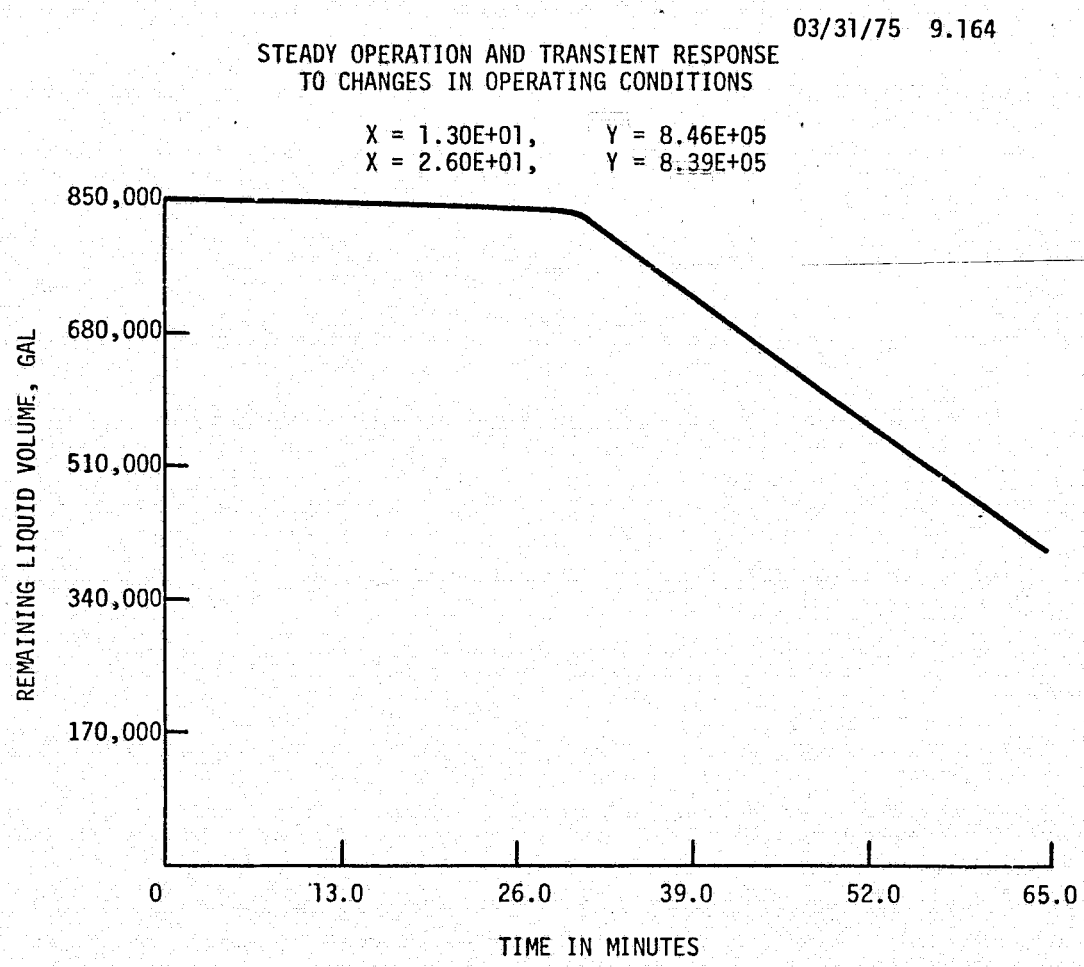


Figure 16. Option 6 - output (continued).

4. Nomenclature

D = diameter.

D_e = external diameter of vent line.

D_i = internal diameter of vent line.

$d\ell$ = differential length of vent line.

dQ = heat flux to the hydrogen vent line in the length $d\ell$.

$f_{T\ell}$ = Fanning friction factor calculated as though the total flow were liquid.

f_{tv} = Fanning friction factor calculated as though the total flow were vapor.

G_ℓ = liquid mass flow rate per unit cross sectional area.

G_{tp} = two phase mass flow rate per unit cross sectional area.

h_e = heat transfer coefficient between the outside of the vent line and the atmosphere.

h_i = heat transfer coefficient between the inside of the vent line and the vent gas.

h_1 = average heat transfer coefficient for the double walled section of the vent line.

h_2 = average heat transfer coefficient for the single walled section of the vent line.

k = heat transfer factor as defined by equation A_6.

k_1 = k for the double walled section of the vent line.

k_2 = k for the single walled section of the vent line.

L_1 = length of the double walled section of the vent line.

L_2 = length of the single walled section of the vent line.

$\dot{m}$ = mass flow rate.

p = absolute pressure.

$(\Delta P/\Delta x)_\ell$ = liquid pressure drop per unit length in the fill line.

$(\Delta P/\Delta x)_{tp}$ = two phase pressure drop per unit length in the fill line.

R_G = ratio of two phase to liquid flow rates.

R_{GL} = value of R_G at the discharge end of the fill line.

T = absolute temperature.

T_a = ambient absolute temperature.

T_{in} = absolute temperature at the inlet of a section of vent line.

T_{out} = absolute temperature at the outlet of a section of vent line.

T_w = pipe wall absolute temperature.

Y = Quality, mass of vapor divided by total mass of the mixture.

β = two phase flow properties parameter as defined by equation B4.

θ = two phase pressure drop parameter.

μ_ℓ = liquid absolute viscosity.

μ_v = vapor absolute viscosity.

ρ_ℓ = liquid density.

ρ_v = vapor density.

5. References

Boeing Company, Vehicle Vent Subsystem, Liquid Hydrogen Subsystem Launch Complex 39A NASA P/N 75M05753, Test Report TR-520-D, Boeing Company (March 1, 1967).

Martinelli, R. C., and Nelson, D. B., Prediction of pressure drop during forced circulation boiling of water, ASME Transactions, 70, pp. 695-716 (1948).

Novak, J. K., Cooldown flow rate limits imposed by thermal stresses in liquid hydrogen or nitrogen pipelines, Advances in Cryogenic Engineering, 15, Ed. K. D. Timmerhaus, pp. 346-353, (Plenum Press, New York, N.Y., 1970).

Supplement A. Oxygen Loading Simulation Computer Programs (1974). Available on request.

Voth, R. O., Steward, W. G., and Hall, W. J., Study of Cryogenic Propellant Systems for Loading the Space Shuttle, Nat. Bur. Stand. (U.S.) NBSIR 74-366 (April 1974).

APPENDIX A

Vent Gas Temperature

The heat flux from the atmosphere to a differential length, $d\ell$, of a cryogenic ventline is

$$dQ = h_e(T_a - T_w)\ \pi\ D_e d\ell\ . \tag{A1}$$

The heat flux from the wall to the vent gas, assuming no temperature gradient through the wall, is

$$dQ = h_i(T_w - T)\ \pi\ D_i d\ell\ . \tag{A2}$$

(Symbols are defined in the nomenclature of this report.)

The vent gas temperature rise due to dQ, neglecting axial heat conduction, is

$$dT = \frac{1}{\dot{m}c_p}\ dQ. \tag{A3}$$

Elimination of dQ and T_w from equations (A1), (A2), and (A3) yields,

$$\frac{dT}{T_a - T} = \frac{\pi h_e D_e d\ell}{\dot{m}c_p\left(\frac{h_e D_e}{h_i D_i} + 1\right)} \tag{A4}$$

If h_e and h_i are taken to be constant average values over the length L, integration of (A4) yields,

$$T_a - T_{out} = (T_a - T_{in})\ \exp\ (-k\ \frac{D_e L}{\dot{m}}\ ) \tag{A5}$$

where

$$k = \frac{\pi h_e}{\dot{m}c_p\left(\frac{h_e D_e}{h_i D_i} + 1\right)}\ . \tag{A6}$$

In the calculation of vent line temperature it is assumed that the heat transfer from the environment to the vent line will have two characteristic coefficients. For the double walled length, L_1, of the vent line starting at the vehicle $h = h_1$ and $k = k_1$; for the uninsulated length, L_2, extending from the end of L_1 to the burn pond, $h = h_2$ and $k = k_2$. Then, from (A5),

$$T_a - T_1 = (T_a - T_o)\ \exp\ (\frac{-k_1 D_1 L_1}{\dot{m}}\ ), \tag{A6}$$

and

$$T_a - T_2 = (T_a - T_1)\ \exp\ (\frac{-k_2 D_2 L_2}{\dot{m}}\ ). \tag{A7}$$

T_o = Temperature at vehicle tank

T_1 = Temperature at the connection of L_1 and L_2

T_2 - Bubble cap temperature.

The exponents k_1 and k_2 were evaluated from the following experimental data (Boeing Company [1967], Fig. 4-5):

T_o = 75 K (135°R)

T_1 = 84.4 K (152°R)

L_1 = 281 m (923 ft.)

D_1 = 43.8 cm (17.25 in.)

T_2 = 144 K (260°R)

L_2 = 344 m (1130 ft)

D_2 = 43.8 cm (17.25 in)

T_a = 300 K (540°R)

$\dot{m}$ = 1211 g/s (2.67 lb/s)

$k_1 = 1.475\ (10)^{-5}$

$k_2 = 4.468\ (10)^{-5}$.

Constant k_1, k_2 are used with equations (A6) and (A7) to compute the vent gas discharge temperature (bubble cap temperature).

APPENDIX B

Two Phase Flow

In computation option 6, "COLD FLOW", heat leak into the liquid and pressure drop along the fill line can result in vapor formation and two phase flow. The presence of even a small fraction of vapor in the fluid stream can cause a significant increase in the friction pressure drop for a given mass flow rate. The correlation of Martinelli and Nelson [1948] has been used to predict two phase flow pressure drop with good results for all cryogenic fluids. An adaptation of that correlation has been used in this study to predict the effect of the presence of vapor on liquid hydrogen flow rates. The modified form of the Martinelli-Nelson correlation, given in equation B1, has the advantage of reducing properly to the usual single phase expression for liquid or gas.

$$\left(\frac{\Delta P}{\Delta X}\right)_{tp} = \theta\left[\frac{f_{tv}\,Y^{1.8}}{\rho_v} + \frac{f_{t\ell}\,(1-Y)^{1.8}}{\rho_\ell}\right]\frac{G_{tp}^2}{2D}\ , \tag{B1}$$

where the symbols are defined in the nomenclature of this paper. The two phase flow factor, θ is a function of liquid and vapor properties and quality (mass fraction of vapor),

$$\theta = \theta(\beta)$$

$$\beta = \frac{1}{1 + \left(\frac{\mu_\ell}{\mu_v}\right)^{0.056}\left(\frac{\rho_v}{\rho_\ell}\right)^{0.28}\left(\frac{1-Y}{Y}\right)^{0.5}}\ . \tag{B2}$$

The experimentally derived relationship between θ and β is shown graphically in figure B1.

The following equation, B3, fits the experimental curve $\theta(\beta)$ to within 5% of the experimental θ.

$$\theta = 0.8560 + 7.944e^{-16.33(\beta-0.5)^2} \quad \text{for } 0 \leq \beta \leq 1\ . \tag{B3}$$

The value of β for hydrogen near 1 atm pressure is

$$\beta = \frac{1}{1 + 0.380\left(\frac{1-Y}{Y}\right)^{0.5}}\ . \tag{B4}$$

For single phase liquid flow ($Y = 0$, $\theta = 1$) equation B1 becomes,

$$\left(\frac{\Delta P}{\Delta X}\right)_\ell = \frac{f_{t\ell}}{\rho_\ell}\ \frac{G_\ell^2}{2D}\ . \tag{B5}$$

The ratio of two phase-to-liquid mass flow rates for a given pressure drop per unit length and given pipe size is then obtained from equation (B1) and (B5):

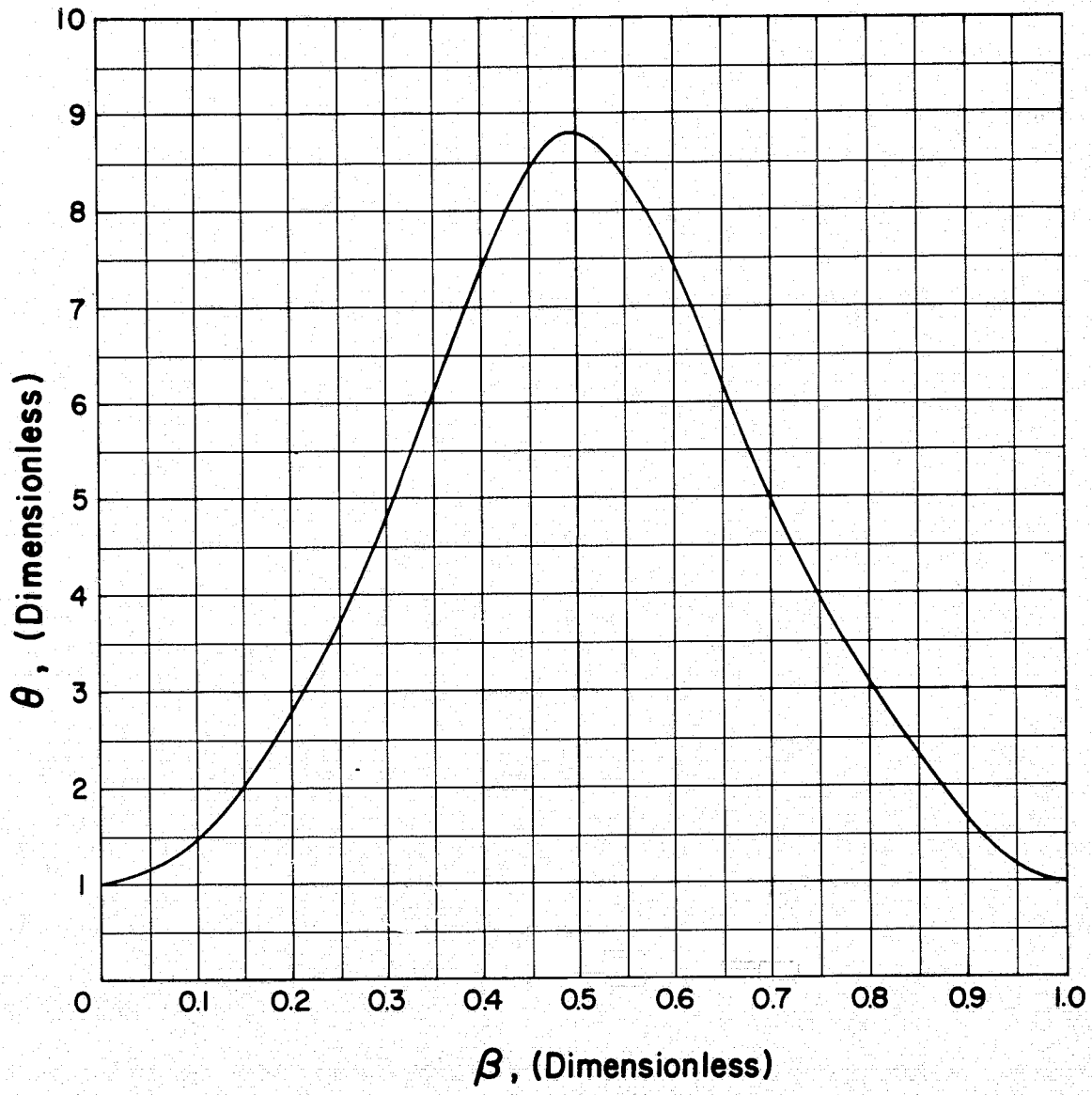


Figure B1. Modified Martinelli-Nelson two phase flow factor.

$$R_G = \frac{G_{tp}}{G_\ell} = \frac{\dot{m}_{tp}}{\dot{m}_\ell} = \left[\theta\left(\frac{\rho_\ell}{\rho_v} \quad \frac{f_{tv}}{f_{t\ell}} \quad Y^{1.8} + (1 - Y)^{1.8}\right)\right]^{-1/2} . \tag{B6}$$

In general single phase liquid flow will exist up to some point, L_s, in the fill line. Beyond L_s the amount of vapor in the fluid stream will increase from 0 at L_s to a maximum at the pipe discharge. If we let the average value of R_G be defined as

$$\bar{R}_G = \frac{1}{L} \int_o^L R_G dx, \tag{B7}$$

and assume a linear variation of R_G with X from L_s to L, we obtain

$$\bar{R}_G = \frac{1}{2}\left[R_{GL}\left(1 - \frac{L_s}{L}\right) + \left(1 + \frac{L_s}{L}\right)\right] . \tag{B8}$$

The enthalpy of the liquid increases with distance along the pipe due to heat addition and the saturation enthalpy (or saturation temperature) decreases due to pressure drop. The point at which saturation enthalpy equals the fluid enthalpy determines the saturation point L_s which is required in equation (B8). We obtain,

$$\frac{L_s}{L} = \frac{E_{is} - E_{in}}{E_{is} - E_{in} + E_{out} - E_{os}} . \tag{B9}$$

All of the enthalpys on the right side of equation (B9) are calculated in the cold flow program. These enthalpys, however, are a function of the flow rate which in turn varies with the exit quality. Therefore, an iterative solution becomes necessary for the two phase flow ratio:

1. From the initial (assumed single phase liquid flow rate) the enthalpys are calculated for equation (B9).
2. $\bar{R}_G$ from equation (B8).
3. $\dot{m}_{tp}$ from (B6).

The calculation returns to step 1 and steps 1 through 3 are repeated until the final calculated $\dot{m}_{tp}$ is within 0.1% of the assumed value.

APPENDIX C.

Loading of the Minicomputer

The method of loading programs into the minicomputer is described in Section 3.3 of the instruction manual. This appendix is an elaboration of the procedure described there.

The Binary Loader

The binary loader is usually in the minicomputer and is not destroyed by any of the programs. For that reason, following the procedure below should be sufficient to load any program in the minicomputer.

However, occasionally a sharp spike on the power lines or a malfunction of the memory in the computer can cause the binary loader to be destroyed. If this should happen, the "Bootstrapping" procedure must be performed first.

1. Preparing the Teletype

The minicomputer and CRT display must be turned on but not running and the CRT display LOCAL/LINE switch set to LOCAL. The teletype is plugged into the back of the CRT display. Turn the teletype power switch, LINE/OFF/LOCAL, to LINE. With the teletype reader switch in OFF position, place the paper tape containing the program in the reader with the tape coming out toward the front of the teletype and the narrower side from the sprocket holes in the tape toward the outside of the teletype. Position the tape so that unpunched tape is over the read position. Set the reader switch to ON.

2. Loading the Program

On the minicomputer, the upper row of switches is called the Switch Register, and are labeled 0 through 15. The lower row of switches are all momentary switches used for control and their functions are listed on the panel.

Set the Switch Register 0, 1, 2 down and 3 through 15 up. Press control switch RESET and then START. The teletype should start reading paper tape. At the end of each binary block on the tape, the printer mechanism should receive some null character and, thus, cycle or "chuckle". Should it fail to do this, back up to the beginning of the paper tape and try again. Should it still fail it may be necessary to follow the "Bootstrapping" procedure and then try again. If the program loads correctly, it may self start or it may halt the computer. If the computer halts, set all the Switch Register switches down except 14, which must be up, and press START. If subsequent operations are to be between the minicomputer and the CRT display, the LOCAL/LINE switch on the CRT should be set to LINE before pressing START, and the teletype turned to OFF.

If the computer halts in the middle of the tape reading, the teletype has made an error while reading the tape. It is not necessary to start the tape over completely. Merely back the tape up at least one block and start the computer again. The beginning of a block is fairly easy to recognize. It consists of two frames with no punches in the tape except the sprocket hole followed by a frame with at least the four top most positions punched followed by a frame with all positions punched. Reposition the tape on one of the two unpunched positions, set the teletype reader to ON and push START on the minicomputer. If the teletype fails to start "Chuckling", the tape should be restarted at the beginning.

Bootstrapping

It may occasionally be necessary to restart the minicomputer from a completely obliterated condition. To do this, turn on the minicomputer and the CRT display. Set the CRT display LOCAL/LINE switch to LOCAL. Prepare the teletype with the tape marked "CHUCKLING LOADER" in the reader just as you would for any other program tape. Next, follow the instructions in TABLE C-1. After the last line of the table has been executed the computer should read the tape and stop at the end. It will not "chuckle" the teletype. If it does not read the tape, the computer or teletype is likely in need of repair. If it does read the tape correctly, proceed to load program as described in the section, Binary Loader.

Table C-1

Set Switch Register Switch Position: (U = up; D = down) Then Press

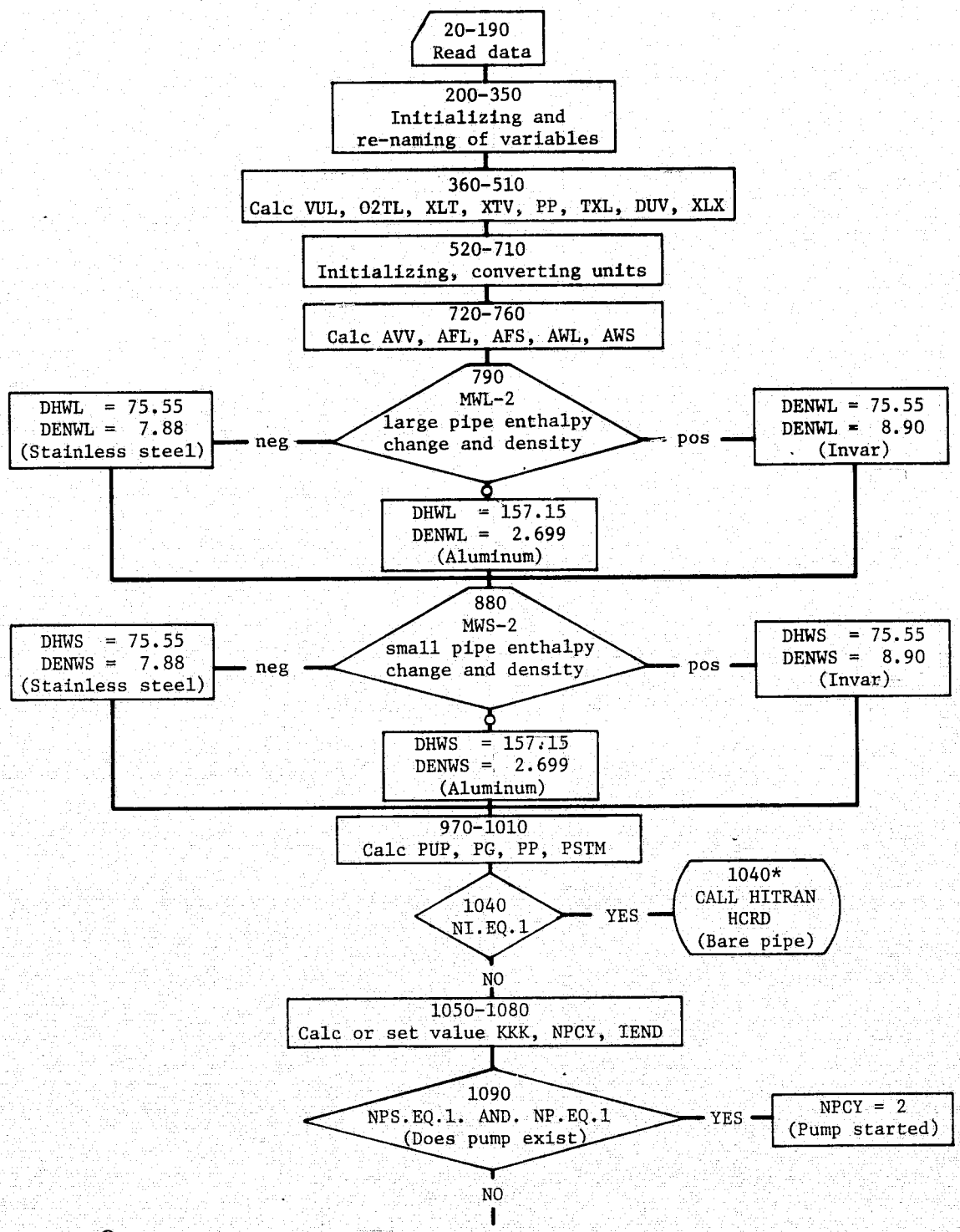
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
D	D	D	U	U	U	U	U	U	U	U	D	U	U	U	U	EXAMINE
U	D	U	D	U	U	D	U	D	D	U	D	D	D	D	D	DEPOSIT
D	U	U	D	D	U	U	U	U	D	D	D	U	D	D	D	DEPOSIT NEXT
D	D	D	D	D	D	D	U	U	U	U	U	U	U	U	U	" "
D	U	U	D	D	D	D	U	D	U	D	D	U	D	D	D	" "
U	D	U	D	U	U	U	D	D	U	D	D	D	D	D	D	" "
U	D	U	D	U	U	U	D	D	U	D	D	D	D	D	D	" "
U	D	D	D	U	U	U	D	D	D	D	D	D	D	U	U	" "
D	D	D	D	D	D	D	U	U	U	U	U	U	D	U	D	" "
D	D	D	D	D	D	U	U	D	D	D	D	D	D	D	D	" "
D	U	U	D	D	D	D	D	D	U	D	D	U	D	D	D	DEPOSIT NEXT
D	D	D	D	U	D	D	U	U	U	U	U	D	U	U	D	" "
D	U	D	D	U	D	D	U	D	D	D	D	D	D	U	D	" "
D	D	D	D	U	D	D	U	U	U	U	U	D	U	D	D	" "
D	D	D	U	U	U	U	U	U	U	U	U	U	D	D	D	START

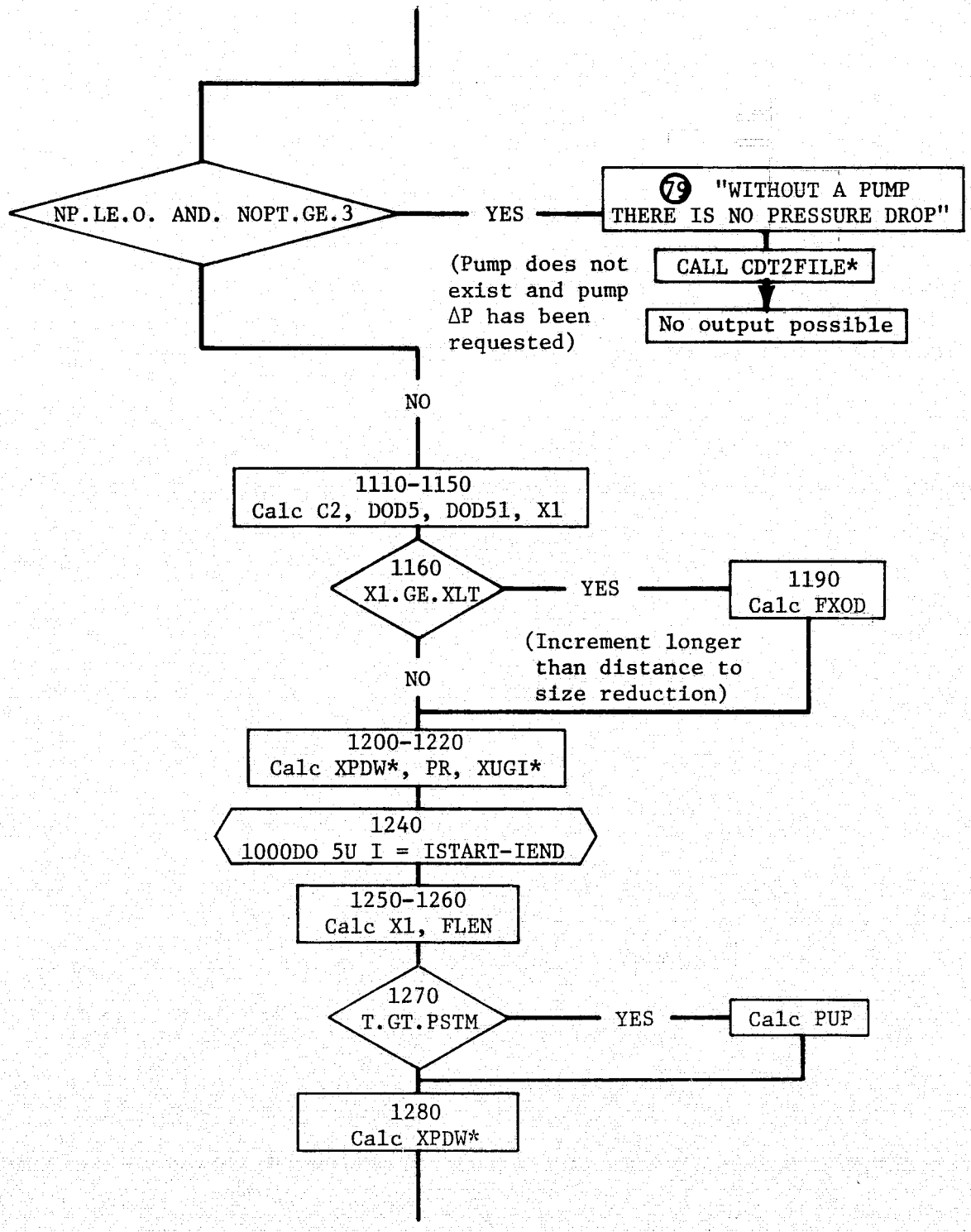
APPENDIX D

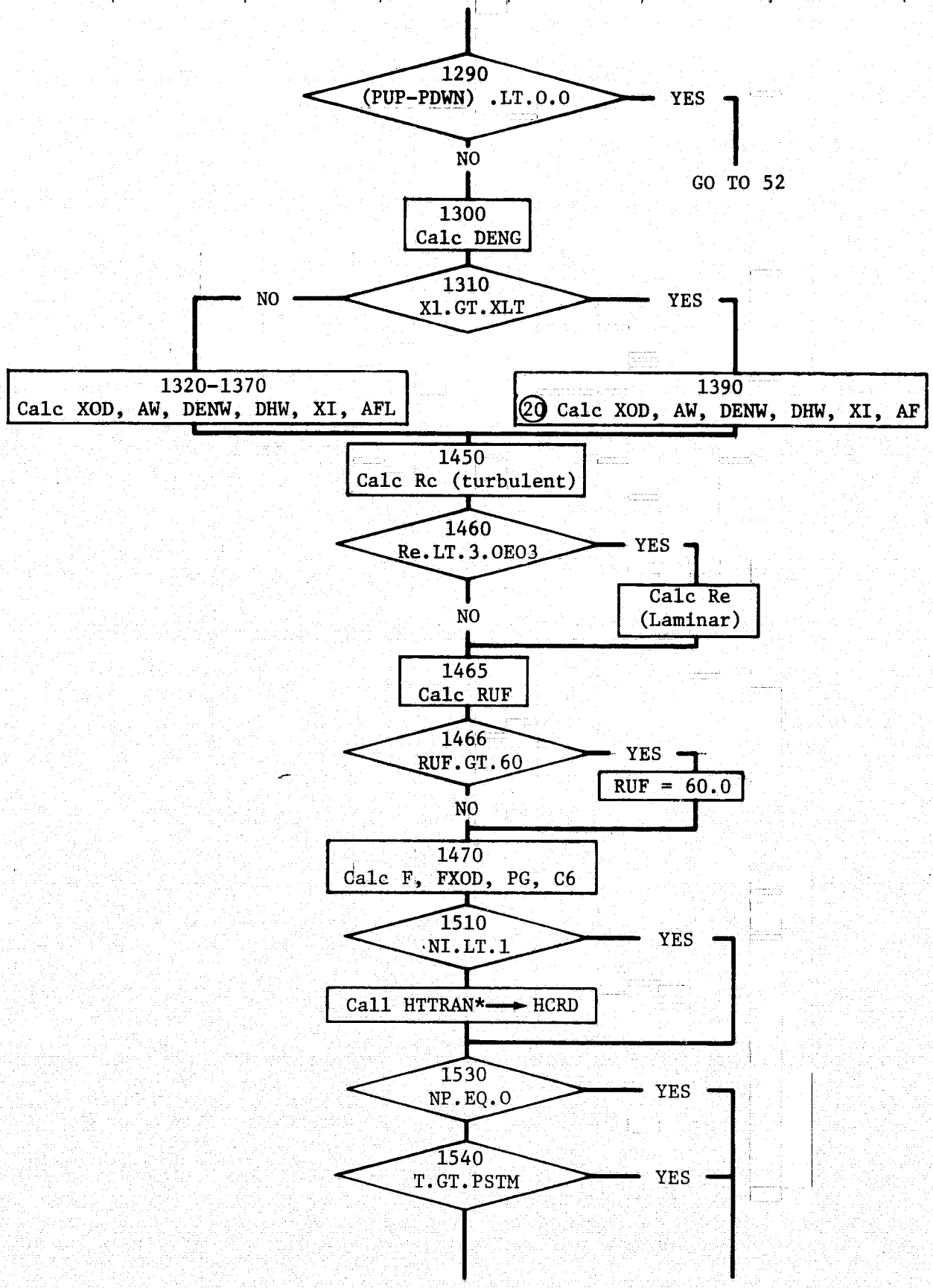
Hydrogen Computer Programs

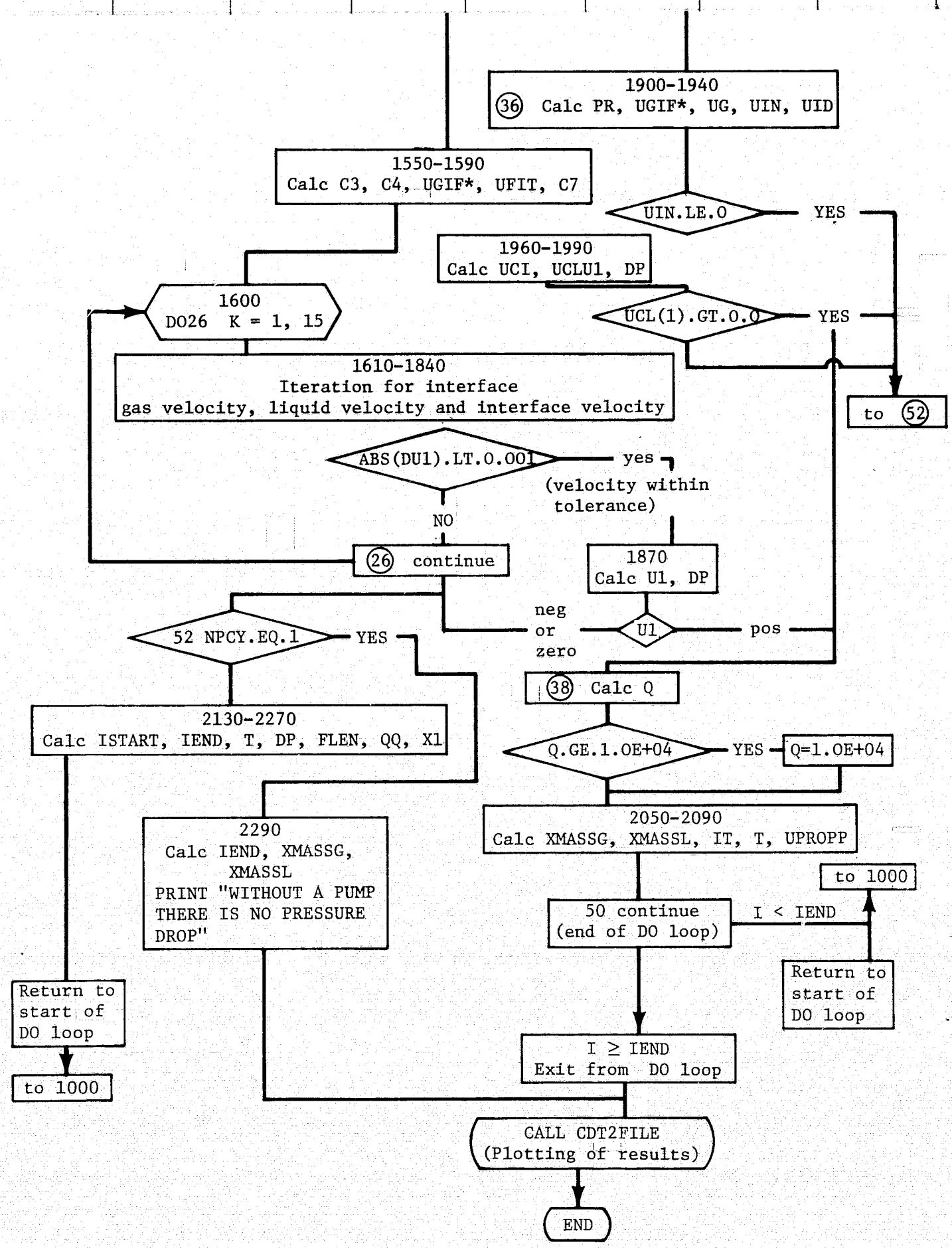
Program CDT
Option 3. Cooldown Time

Due to the length and complexity of the program, a computer flow diagram and list of computer symbols are included.




NP.LE.O. AND. NOPT.GE.3
YES
79 "WITHOUT A PUMP THERE IS NO PRESSURE DROP"
CALL CDT2FILE*
No output possible
(Pump does not exist and pump ΔP has been requested)
NO
1110-1150
Calc C2, DOD5, DOD51, X1
1160
X1.GE.XLT
YES
1190
Calc FXOD
(Increment longer than distance to size reduction)
NO
1200-1220
Calc XPDW*, PR, XUGI*
1240
1000DO 5U I = ISTART-IEND
1250-1260
Calc X1, FLEN
1270
T.GT.PSTM
YES
Calc PUP
1280
Calc XPDW*


1290
(PUP-PDWN) .LT.0.0
YES
GO TO 52
NO
1300
Calc DENG
1310
X1.GT.XLT
NO
YES
1320-1370
Calc XOD, AW, DENW, DHW, XI, AFL
1390
20 Calc XOD, AW, DENW, DHW, XI, AF
1450
Calc Rc (turbulent)
1460
Re.LT.3.0E03
YES
Calc Re
(Laminar)
NO
1465
Calc RUF
1466
RUF.GT.60
YES
RUF = 60.0
NO
1470
Calc F, FXOD, PG, C6
1510
NI.LT.1
YES
Call HTTRAN* → HCRD
1530
NP.EQ.0
YES
1540
T.GT.PSTM
YES


1900-1940
36 Calc PR, UGIF*, UG, UIN, UID
1550-1590
Calc C3, C4, UGIF*, UFIT, C7
UIN.LE.0
YES
1960-1990
Calc UCI, UCLU1, DP
1600
DO26 K = 1, 15
UCL(1).GT.0.0
YES
1610-1840
Iteration for interface
gas velocity, liquid velocity and interface velocity
to 52
ABS(DU1).LT.0.001
yes
(velocity within tolerance)
NO
26 continue
1870
Calc U1, DP
neg or zero
U1
pos
52 NPCY.EQ.1
YES
38 Calc Q
2130-2270
Calc ISTART, IEND, T, DP, FLEN, QQ, X1
Q.GE.1.0E+04
YES
Q=1.0E+04
2290
Calc IEND, XMASSG, XMASSL
PRINT "WITHOUT A PUMP THERE IS NO PRESSURE DROP"
2050-2090
Calc XMASSG, XMASSL, IT, T, UPROPP
to 1000
50 continue
(end of DO loop)
I < IEND
Return to start of DO loop
Return to start of DO loop
to 1000
I ≥ IEND
Exit from DO loop
CALL CDT2FILE
(Plotting of results)
END

CDT - Computer Listing Symbols

AF	Flow cross section area, cm^2
AFL	Flow cross section area, large pipe, cm^2
AFS	Flow cross section area, small pipe, cm^2
AW	Cross section area of the wall at the current liquid-gas interface location, cm^2
AWL	Cross section area of the wall, large pipe, cm^2
AWS	Cross section area of the wall, small pipe, cm^2
C1	Constant used to convert liquid velocity to pressure drop due to the pump
C4	Total heat transferred through uninsulated line to liquid, watts
C6	Same as C7 except reciprocal
C7	AF/AFL-used to correct velocity calculation for area
DENG	Density of the gas at the liquid-gas interface, gm/cm^3
DENL	Density of the liquid, gm/cm^3
DENW	Density of the wall material at the current liquid-gas interface, gm/cm^3
DENWL	Density of wall material, large pipe, gm/cm^3
DENWS	Density of wall material, small pipe, gm/cm^3
DHL	Change in enthalpy from liquid to ambient temperature gas, Joules/gm
DHW	Change in enthalpy at the current liquid-gas interface location, Joules/gm
DHWL	Change in enthalpy, large pipe, Joules/gm
DHWS	Change in enthalpy, small pipe, Joules/gm
DIAIL	Large diameter before reduction, in-cm
DIAIS	Small diameter after transition, in-cm
DIAOL	Outer diameter of the large pipe, cm
DIAOS	Outer diameter of the small pipe, cm
DOD5	$(DIAIS/DIAIL)^5$
DP	Pressure drop across the pump at a particular time during cooldown, psi
DPP	Reference pressure, psi
DU1	Constants used during an iteration calculation; difference between a trial velocity and a calculated velocity, cm/sec
DU2	Same as DU1
DX	Length increment, cm

2. CDT

F	Friction factor
FLEN	Total length of line cooled, cm
FLOW	Flow rate, gpm
FXOD	Friction factor times the gas column length divided by an effective diameter
H	Surface heat transfer coefficient, watts/cm^2
HMAX	Maximum length cooled without running the pump, cm
IEND	Number of DX increments required to traverse entire length of pipe to be cooled
II	Used to count number of DX lengths calculated
MU	Wall material for a uniform pipe size
MWL	Wall material before transition
MWS	Wall material after transition
O2TL	Supply liquid level, ft
NI	Existence of vacuum insulation, 0-yes, 1-no
NOPT	
NP	Existence of pump, 0-no, 1-yes
NPCY	Indicates whether pump has started, 1-no, 2-yes
NPS	Pump free wheeling-0, started after PSTM-1
NV	No. of the discharge valve which is open
NVR	Existence of vertical rise, 0-yes, 1-no
PG	First value of pressure in iteration, psi
PG1	Supply pressure, psi
PMAXL	Maximum length cooled when pump is running, cm
PMAXP	Maximum liquid driving pressure when the pump is running, psia
PP	Reference pressure, psi
PR	Pressure ratio across the gas column in the pipe
PSTM	Pump start-up time, min
PUP	Upstream pressure acting to push liquid into pipeline, psia
PDWF	An external function used to calculate a pressure due to a head vise
PDWN	Pressure at the liquid-gas interface; is equal to upstream pressure minus a head due to any vertical rise

3. CDT

Q	Flow, gal/min
QPP	Print out of initial flow rate, gal/min
RE	Reynolds number
RELHU	Relative humidity, percent
RPM	Pump speed after it is started, RPM
T	Time in interation loop, sec
TAMB	Ambient temperature, deg F
TIP	Print time, sec
U	Liquid-gas interface velocity as it moves down the pipe, cm/sec
UCI	Velocity of liquid vapor interface, ft/sec
UCL	Velocity of liquid determined by boil-off gas, ft/sec
UFIT	A constant to fit the gas velocity versus pressure ratio
UGI	Gas velocity at the interface, cm/sec
UID	Denominator in expression for UCl
UIN	Numerator in expression for UCl
UL	Liquid velocity in pipe due to pump pressure drop, cm/sec
ULLP	Ullage pressure, psig
UPI	Uniform pipe inside diameter, in-cm
UPWT	Uniform pipe wall thickness
WIND	Wind velocity, knots
WTL	Wall thickness before transition, in
WTS	Wall thickness after transition, in
XCL	Length of line to be cooled, ft
XFINAL	Final length, cm
XL	Total length of line, ft
XLT	Length before size reduction, ft

4. CDT

XLV	Length to vertical rise, ft
XOD	Gas column length divided by an effective diameter
XTV	Length of pipe before vertical rise, ft
X1	Liquid column length, cm

Function Subroutines

CDS	
CDXMAX	Maximum cooldown length, ft
HTTRAN	Return heat transfer coefficient, Btu/lb°F
PDWF	Return liquid-vapor interface pressure
UGIF	Used to calculate gas velocity in the gas column supplied an FXOD, and a pressure ratio

Program TS

Option 1, Thermal Stresses

```
10 DIMENSION P(12)
20 DIMENSION XL(9),D(9),H(2)
30 DATA P/32.29,-0.4254,261.8,-3.104,1304.,-11.2,
40&  0.334,-0.348,2.154,-2.86,10.87,-10.731/
50 READ:PFID,POD,PFOD,MF
60 I=1
70 IF(MF.GT.1) I=7
80 TOD=(PFOD-PFID)/(2.0*PFID)
90 C1=P(I)*EXP(P(I+1)*TOD)
100 C2=P(I+2)*EXP(P(I+3)*TOD)
110 C3=P(I+4)*EXP(P(I+5)*TOD)
120 WMAX=PFID*(C1+C2+C3)
130 WMIN=0.00661442*PFID**2+0.02219435*PFID-0.01880877
140 GPML=WMAX*101.6
150 GPMS=WMIN*101.6
160 PRINT:"&"
170 DO 9 I=1,9
180 9 PRINT:" "
190 PRINT:"THE MAXIMUM FLOW PERMITTED WITHOUT CAUSING EXCESSIVE THERMAL"
200 PRINT:" "
210 PRINT:"STRESS IS ",GPML,"  GPM"
220 PRINT:" "
230 PRINT:" "
240 PRINT:" "
250 PRINT:"THE MINIMUM FLOW PERMITTED WITHOUT CAUSING EXCESSIVE THERMAL"
260 PRINT:" "
270 PRINT:"STRESS IS ",GPMS,"  GPM&"
280 END
```

Program CDT

Option 3, Cooldown Time

```
10SUSE CDTSUB;PLOT;CDT2FILE
20 COMMON DHL,TAMB,RELHU,DIAIL,DIAIS,DIAOL,DIAOS,AFS,AFL,TXL,XCL,XLT
30 COMMON XLV,XTV,WIND,KKK,H,DVV,AVV
40 COMMON XL(9),D(9),HH(2),NTOB,XMASSL,XMASSG,PSTM
50 COMMON FLEN(105),T(105),O(105),DP(105),NP,NPS,NOPT,IEND
60 DIMENSION HL(2),HCL(2)
70 DIMENSION XXL(9),DD(7)
80 READ:(XXL(I),I=1,5)
90 READ:(XXL(I),I=6,9),DD(1)
100 READ:(DD(I),I=2,6)
110 READ:DD(7),GALR,VHT,H1,GPM
120 DO 200 J=1,7
130 200 IF(DD(J).LE.0.1)DD(J)=0.1
140 READ:PUMP,SPD,ULLP,SVOL,HI
150 READ:OX
160 READ:MWL,MWS,MW6,MW7,MW8
170 READ:MW9,WTL,WTS,WT6,WT7
180 READ:WTR,WTO,XCL,NP,NPS
190 READ:PSTM,RPM,NOPT
200 DIAIL=DD(1)
210 DO 201 J=1,3
220 D(J)=DD(1)
230 201 XL(J)=XXL(1)/3.
240 D(3)=DD(2)
250 D(4)=D(3)
260 XL(4)=XXL(2)
270 DO 202 J=5,9
```

```
280 D(J)=DD(3)
290 202 XL(J)=XXL(3)/6.
300 HH(1)=XXL(3)/6.
310 HH(2)=XXL(3)/6.
320 TAMB=85.0
330 WIND=10.
340 RELHU=80.
350 CAP=900000.
360 RSPH=0.62035*CAP**0.33333
370 VUL=CAP-SVOL
380 O2TL=2.*RSPH-0.477465*VUL/(RSPH*RSPH)
390 NTOB=1
400 XLT=XL(1)+XL(2)+XL(3)+XL(4)
410 XTV=XLT-XL(4)
420 PP=(-3.782475+0.012881335*RPM+0.2610459E-3*RPM*RPM)*0.494401
430 IF(NTOB.GT.2)GO TO 40
440 TXL=XLT+XL(5)+XL(7)+XL(8)+XL(9)+HH(1)+HH(2)
450 DVV=(D(7)+D(8)+D(9))/3.0
460 XLX=XL(7)+XL(8)+XL(9)+HH(1)+HH(2)
470 GO TO 41
480 40 TXL=XLT+XL(5)+XL(6)
490 DVV=D(6)
500 XLX=XL(6)
510 41 CONTINUE
520 DIAIS=D(5)
530 XMASSG=0.0
540 XMASSL=0.0
550 PI=3.141592654
560 DENL=0.07080
570 TXL=TXL*30.48
580 XCL=XCL*30.48
590 XLX=XLX*30.48
600 XLT=XLT*30.48
610 IF(XCL.GT.TXL) XCL=TXL
620 ISTART=1
630 FLEN(1)=0.0
640 TFINAL=0.0
650 XFINAL=0.0
660 DVV=DVV*2.54
670 DIAIL=DIAIL*2.54
680 DIAIS=DIAIS*2.54
690 IF(DVV.GT.DIAIS) DVV=DIAIS
700 DIAOL=DIAIL+5.08*WTL
710 DIAOS=DIAIS+5.08*WTS
720 AVV=PI/4.0*DVV*DVV
730 AFL=PI/4.0*DIAIL*DIAIL
740 AFS=PI/4.0*DIAIS*DIAIS
750 AWL=PI/4.0*(DIAOL**2-DIAIL**2)
760 AWS=PI/4.0*(DIAOS**2-DIAIS**2)
770 C1=11584.0
780 DHL=4456.1
790 IF(HWL-2) 5,6,7
800 5 DHWL=75.55
810 DENWL=7.88
820 GO TO 8
830 6 DHWL=157.15
840 DENWL=2.699
850 GO TO 8
860 7 DHWL=75.55
870 DENWL=8.90
880 8 IF(HWS-2)9,10,11
890 9 DHWS=75.55
900 DENWS=7.88
```

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```
910 GO TO 12
920 10 DHWS=157.15
930 DENWS=2.699
940 GO TO 12
950 11 DHWS=75.55
960 DENWS=8.90
970 12 PUP=O2TL*0.03069+ULLP+14.696
980 PG=PUP
990 PG1=PUP
1000 PP=PP+PG1
1010 IF (NP.EQ.0.OR.NPS.EQ.0) PSTM=1.E10
1020 H=0.0
1030 KKK=1
1040 IF(NI.EQ.1) CALL HTTRAN(60.0)
1050 KKK=2
1060 NPCY=1
1070 DX=XCL/97
1080 IEND=98
1090 IF(NPS.EQ.1.AND.NP.EQ.1) NPCY=2
1100 IF((NP.LE.0).AND.(NOPT.GE.3)) GO TO 79
1110 56 C2=3.0086E-03/(TAMB+460.0)
1120 T(1)=0.0
1130 DOD5=(DVV/DIAIL)**5.0
1140 DOD51=(DVV/DIAIS)**5.0
1150 X1=DX/2.0
1160 IF(X1.GE.XLT) GO TO 14
1170 FXOD=((XLT-X1)*DOD5+(TXL-XLT-XLX)*DOD51+XLX)*0.02/DVV
1180 GO TO 15
1190 14 FXOD=0.02*((TXL-X1)*DOD51+XLX)/DVV
1200 15 CALL XPDW(X1,PDWF)
1210 PR=(PUP-PDWF)/14.696
1220 CALL XUGI(PR,FXOD,UGI)
1230 X1=-DX
1240 1000 DO 50 I=ISTART,IEND
1250 X1=X1+DX
1260 FLEN(I+1)=FLEN(I)+DX/30.48
1270 IF(T(I).GT.PSTM) PUP=PP-5.960636E-8*QPP*OPP
1280 CALL XPDW(X1,PDWN)
1290 IF((PUP-PDWN).LT.0.0) GO TO 52
1300 DENG=(PUP-PDWN)*C2
1310 IF(X1.GE.XLT) GO TO 20
1320 XOD=((XLT-X1)*DOD5+(TXL-XLT-XLX)*DOD51+XLX)/DVV
1330 AW=AWL
1340 DENW=DENWL
1350 DHW=DHWL
1360 XI=PI*DIAOL*X1
1370 AF=AFL
1380 GO TO 22
1390 20 XOD=((TXL-X1-XLX)*DOD51+XLX)/DVV
1400 AW=AWS
1410 DENW=DENWS
1420 DHW=DHWS
1430 XI=PI*((DIAOL*XLT)+(X1-XLT)*DIAOS)
1440 AF=AFS
1450 22 RE=11161.*DENG*UGI*DIAIS
1460 IF(RE.LT.3.0E3) RE=3.0E3
1465 RUF=101.6/DIAIS
1466 IF(RUF.GT . 60.) RUF=60.
1470  F=0.0055*(1.0+(RUF+1.E6/RE)**0.33333)
1480 FXOD=XOD*F
1490 PG=-0.02
1500 C6=AVV/AF
1510 IF(NI.LT.1) GO TO 24
```

```
1520 CALL HTTRAN(T(I)*60.0)
1530 24 IF (NP.EQ.0) GO TO 36
1540 IF(T(I).GT.PSTM) GO TO 36
1550 C3=AF*DHL
1560 C4=H*XI
1570 CALL XUGI(1.1,FXOD,UGIF)
1580 UFIT=UGIF*C6/0.1
1590 C7=AF/AFL
1600 DO 26 K=1,15
1610 KK=K
1620 DO 71 IK=1,2
1630 IF(PUP-PDWN-PG) 28,28,30
1640 28 PG=PUP-PDWN
1650 UL(IK)=0.0
1660 GO TO 33
1670 30 UL(IK)=SQRT(C1*(PUP-PDWN-PG))
1680 33 DENG=PG*C2
1690 PR=PG/14.696
1700 IF(PR.GT.1.1) GO TO 72
1710 UG=UFIT*PR-UFIT
1720 GO TO 73
1730 72 CALL XUGI(PR,FXOD,UGIF)
1740 UG=UGIF*C6
1750 73 IF(PR.LT.0.0) UG=0.0
1760 UCI=((UG*DENG*C3)-C4)/(C5+(DENG*C3))
1770 UCL(IK)=(UCI+DENG/DENL*(UG-UCI))*C7
1780 PG=PG-0.01
1790 71 CONTINUE
1800 DU1=UL(1)-UCL(1)
1810 DU2=UL(2)-UCL(2)
1820 IF(ABS(DU1).LT.0.001) GO TO 34
1830 PG=PG+0.02-DU1*0.01/(DU1-DU2)
1840 UGI=UG
1850 26 CONTINUE
1860 GO TO 52
1870 34 U1=1.0/UCI
1880 DP(I)=PUP-PDWN-PG
1890 IF(U1) 52,52,38
1900 36 PR=(PUP-PDWN)/14.696
1910 CALL XUGI(PR,FXOD,UGIF)
1920 UG=UGIF*C6
1930 UIN=(UG*DENG*AF*DHL)-(H*XI)
1940 UID=(DENW*AW*DHW)+(DENG*AF*DHL)
1950 IF(UIN.LE.0.0) GO TO 52
1960 UCI=UIN/UID
1970 UCL(1)=(UCI+DENG*(UG-UCI))*AF/AFL
1980 U1=UID/UIN
1990 DP(I)=PG1-PUP
2000 IF(UCL(1).GT.0.0) GO TO 38
2010 GO TO 52
2020 38 Q(I)=AFL*60.0*UCL(1)/4546.1
2030 IF(Q(I).GT.1.E+4) Q(I)=1.E+4
2040 XMASSG=XMASSG+DENG*AF*UG*U1*DX
2050 XMASSL=XMASSL+DENL*AF*UCL(1)*U1*DX
2060 II=I
2070 T(I+1)=T(I)+U1*DX/60.0
2080 UPR=U1
2090 OPP=Q(1)
2100 50 CONTINUE
2110 GO TO 100
2120 52 IF(NPCY.EQ.1) GO TO 100
2130 ISTART=II+3
2140 IEND=IEND+3
```

```
2150 T(II+1)=T(II)+0.001
2160 T(II+2)=PSTM-0.001
2170 T(II+3)=PSTM+0.001
2180 DP(II+1)=0.0
2190 DP(II+2)=0.0
2200 FLEN(II+1)=FLEN(II)
2210 FLEN(II+2)=FLEN(II)
2220 FLEN(II+3)=FLEN(II)
2230 Q(II+1)=XI*H/(DHL*DENL*75.76833)
2240 Q(II+2)=Q(II+1)
2250 X1=X1-DX
2260 NPCY=1
2270 GO TO 1000
2280 100 CONTINUE
2290 IEND=II
2300 XMASSG=XMASSG/453.59
2310 XMASSL=XMASSL/453.59
2320 79 PRINT:"WITHOUT A PUMP THERE IS NO PRESSURE DROP#"
2330 CALL CDT2FILE
2340 END
```

Subroutine CDT2FILE

Graph Headings and Labels for CDT

```
10 SUBROUTINE CDT2FILE
20 COMMON DHL,TAMB,RELHH,DIAIL,DIAIS,DIAOL,DIAOS,AFS,AFL,TXL,XCL,XLT
30 COMMON XLV,XTV,WIND,KKK,H,DVV,AVV
40 COMMON XL(9),D(9),HH(2),NTOB,XMASSL,XMASSG,PSTM
50 COMMON FLEN(105),T(105),Q(105),DP(105),NP,NPS,NOPT,IEND
60 ASCII A1(42),A2(14),A3(14),B1(14),CC1(7)
70 T(IEND+1)=T(IEND)
80 T(IEND+2)=0.0
90 ENCODE(B1,75)
100 75 FORMAT(20X,"TIME IN MINUTES",21X)
110 ENCODE (A3,55)
120 55 FORMAT(56X)
130 IF (NP-1) 61,62,62
140 61 ENCODE (A2,77)
150 77 FORMAT(13X,"THERE IS NO PUMP IN THE SYSTEM",13X)
160 GO TO 56
170 62 IF (NPS-1) 63,64,64
180 63 ENCODE (A2,79)
190 79 FORMAT(4X,"THRU A FREEWHEELING PUMP DURING THE ENTIRE PERIOD",3X)
200 GO TO 56
210 64 IPSTM=PSTM
220 ENCODE (A2,76) IPSTM
230 76 FORMAT(11X,"UNTIL PUMP STARTS AT",I6," MINUTES",11X)
240 56 CONTINUE
250 IML=XMASSL
260 IMG=XMASSG
270 IF (NOPT.EQ.2) ENCODE (A3,65) IML,IMG
280 65 FORMAT("  TOTAL LIQUID INFLOW",I8," LBS, TOTAL VENT",I6," LBS ")
290 ENCODE (A1,2) A2,A3
300 2 FORMAT("   LIQUID IS DRIVEN BY ULLAGE PRESSURE AND STATIC HEAD  "
310 IF (NOPT-2) 81,82,83
320 81 FLEN(IEND+1)=FLEN(IEND)
330 FLEN(IEND+2)=0.0
340 ENCODE(CC1,74)
350 74 FORMAT(6X,"LENGTH COOLED FT",6X)
```

```
360 CALL GRAPH(A1,B1,CC1,IEND,T,FLEN)
370 GO TO 85
380 82 IEND=IEND-2
390 T(IEND+1)=T(IEND)
400 T(IEND+2)=0.0
410 Q(IEND+1)=Q(IEND)
420 Q(IEND+2)=0.0
430 ENCODE(CC1,78)
440 78 FORMAT(7X,"FLOW RATE GPM",8X)
450 CALL GRAPH (A1,B1,CC1,IEND,T,Q)
460 GO TO 85
470 83 DP(IEND+1)=DP(IEND)
480 ENCODE(CC1,48)
490 48 FORMAT(6X,"PUMP DELTA P PSI",6X)
500 DP(IEND+2)=0.0
510 CALL GRAPH (A1,B1,CC1,IEND,T,DP)
520 85 CONTINUE
530 RETURN
540 END
```


Heat Transfer and Pressure Drop Subroutines for CDT

```
5 SUBROUTINE HTTRAN (TIME)
10 COMMON DHL,TAMB,RELHU,DIAIL,DIAIS,DIAOL,DIAOS,AFS,AFL,TXL,XCL,XLT
15 COMMON XLV,XTV,WIND,KKK,HCRD,DVV,AVV
20 COMMON XL(9),D(9),HH(2),NTOB
300 DAVG=(DIAOL+DIAOS)/2.
310 HCRD=1.6846/(DAVG**0.25)
330 RETURN
335 END
340 SUBROUTINE XPDW(X1,PDWF)
345 COMMON DHL,TAMB,RELHU,DIAIL,DIAIS,DIAOL,DIAOS,AFS,AFL,TXL,XCL,XLT
350 COMMON XLV,XTV,WIND,KKK,H,DVV,AVV
355 COMMON XL(9),D(9),HH(2),NTOB
360 X=X1/30.48
365 CONV=0.030694
370 IF(X.GT.XTV) GO TO 5
375 PDWF=0.0
380 RETURN
385 5 IF(X.GT.(XTV+XL(4)+XL(5))) GO TO 10
390 PDWF=(X-XTV)*CONV
395 RETURN
400 10 IF(NTOB.EQ.2) GO TO 15
405 IF(X.GT.(XTV+XL(4)+XL(5)+XL(7))) GO TO 20
410 15 PDWF=(XL(4)+XL(5))*CONV
415 RETURN
420 20 IF(X.GT.(XTV+XL(4)+XL(5)+XL(7)+HH(1))) GO TO 25
425 PDWF=(X-XTV-XL(7))*CONV
430 RETURN
435 25 IF(X.GT.(XTV+XL(4)+XL(5)+XL(7)+HH(1)+XL(8))) GO TO 30
440 PDWF=(XL(4)+XL(5)+HH(1))*CONV
445 RETURN
450 30 IF(X.GT.(XTV+XL(4)+XL(5)+XL(7)+HH(1)+XL(8)+HH(2))) GO TO 40
455 RETURN
460 40 PDWF=XLV*CONV
465 RETURN
470 END
475 SUBROUTINE XHGI(X,FXODI,HGIF)
```

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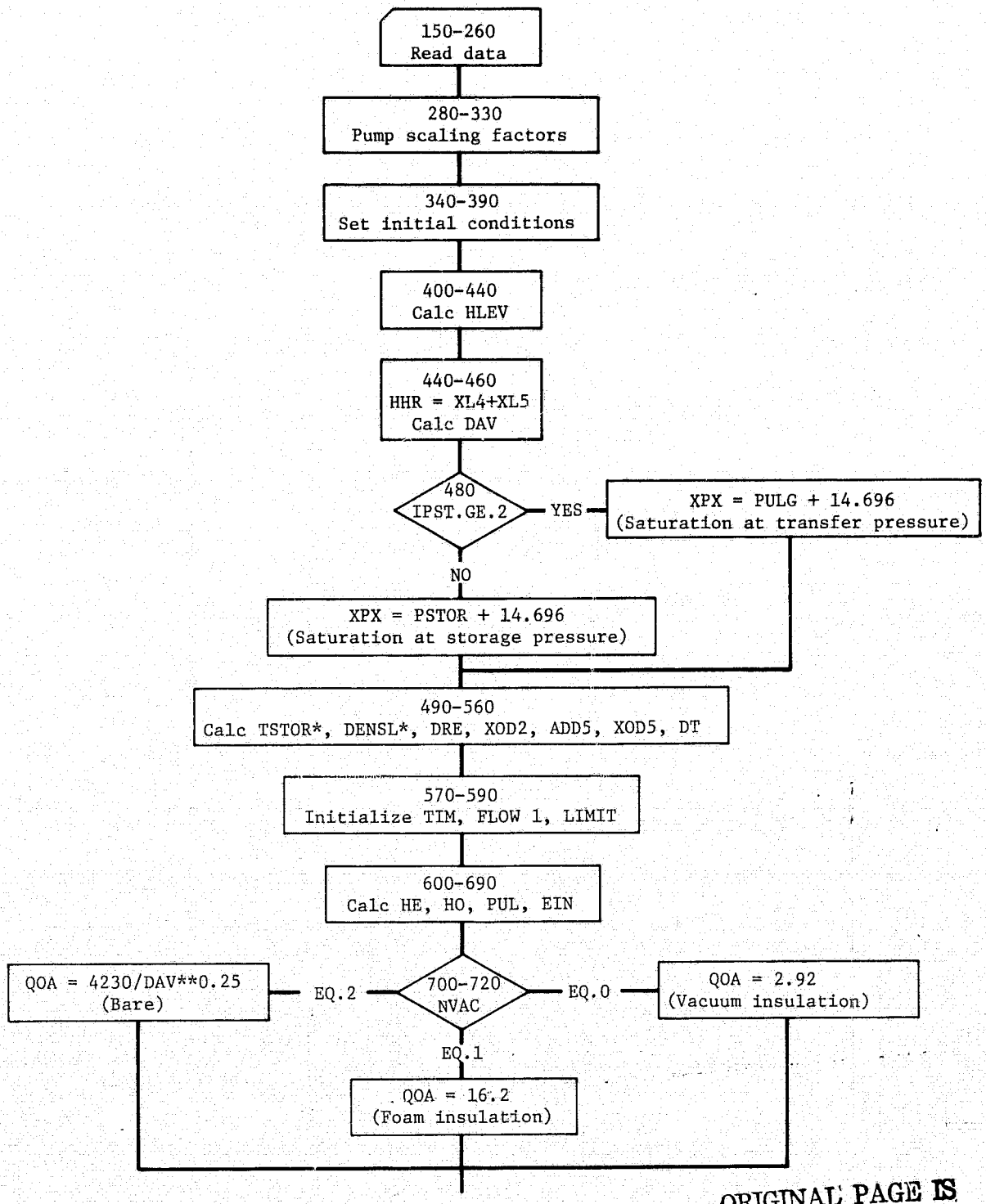
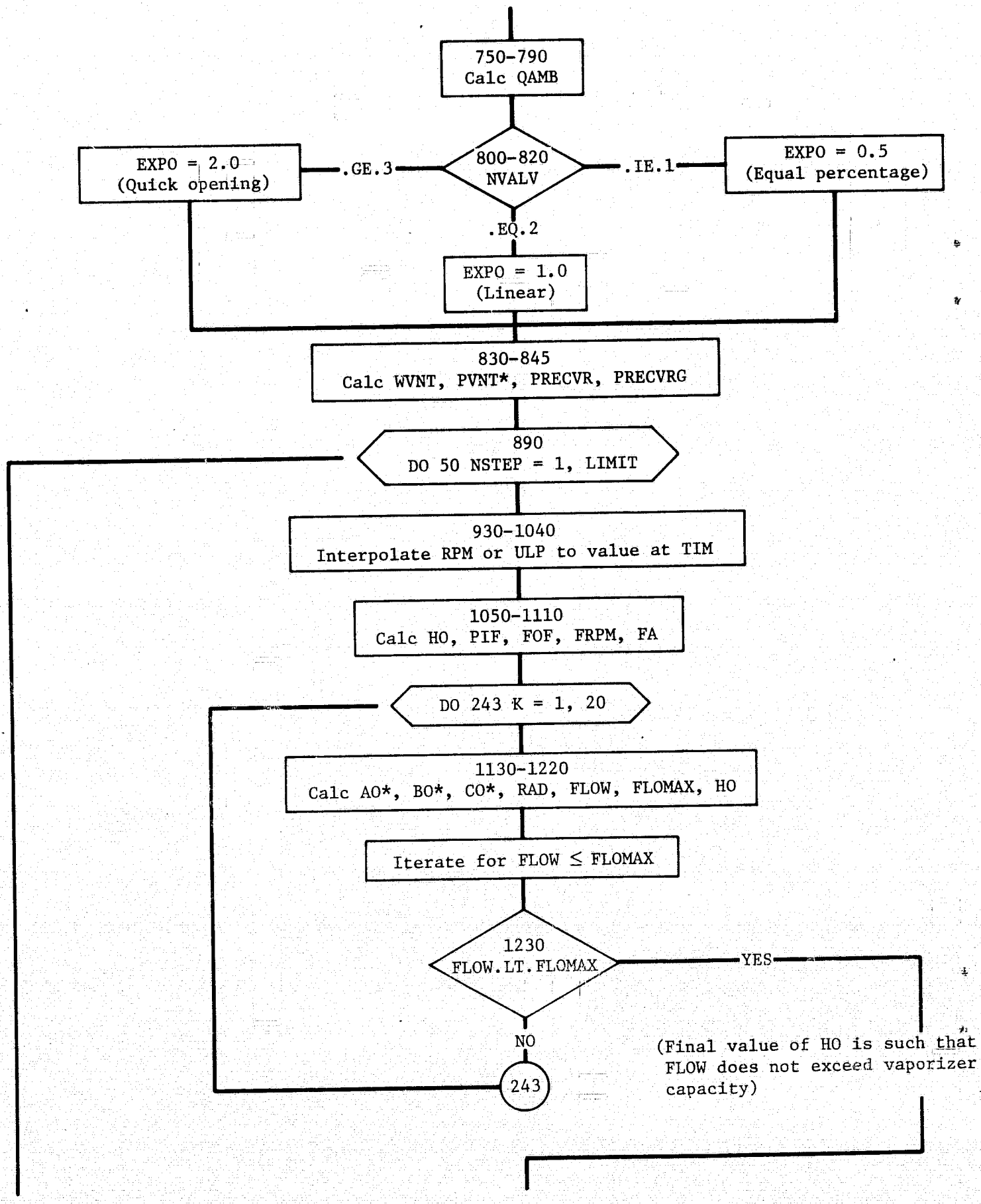
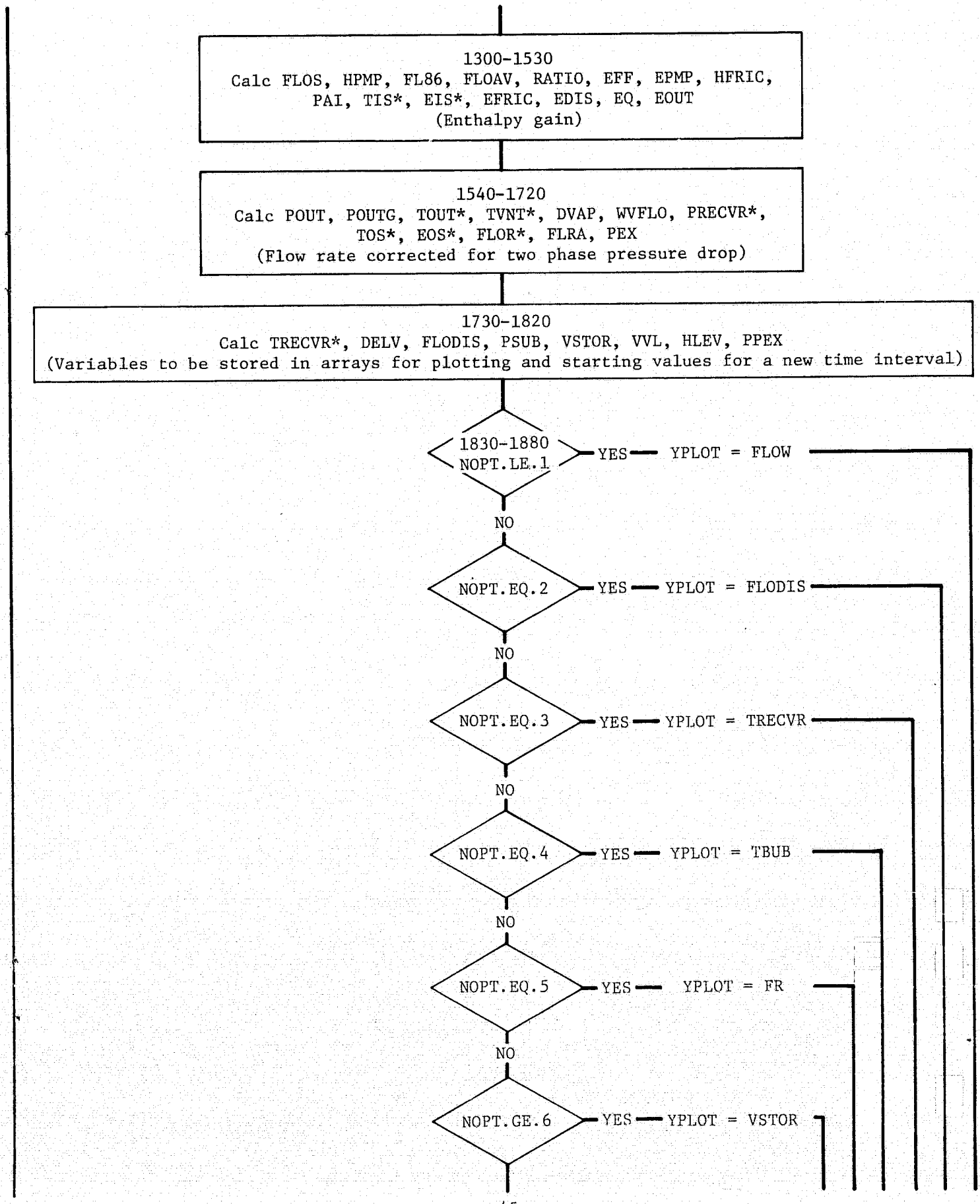
```
480 IF(X.GT.1.0.AND.FXODI.GT.0.0) GO TO 10
485 UGIF=0.0
490 IF(FXOLI.LE.0.0)UGIF=1.340E05
495 RETURN
500 10 PR=X
505 SONO2=1.340E05
510 CHN=SQRT(6.25+6.0/(PR*PR))-2.5
515 FXOD=FXODI
520 FLODCH=(1.0-CHN)/(1.4*CHN)+0.85714*ALOG(1.2*CHN/(1.0+0.2*CHN))
525 IF(FXOD.LE.0.0) FXOD=0.1E-8
530 IF(FXOD.LE.FLODCH) GO TO 45
535 GN2=0.71428*(1.0-1.0/(PR*PR))/(FXOD-0.85714*ALOG(1.0/(PR*PR)))
540 F2=1.0/GN2
545 DO 44 IITRY=1,50
550 GN3=SQRT(6.25+5.0*(PR*PR)*GN2*(1.0+0.2*GN2))-2.5
555 F3=1.0/GN3
560 FXODT=0.71428*(F2-F3)+0.85714*ALOG((F3+0.2)/(F2+0.2))
565 ERR=FXOD-FXODT
570 IF(ABS(ERR/FXOD).LT.0.001) GO TO 80
575 DF3DF2=(F2+0.4)*(F3+0.2)*F3/((F3+0.4)*(F2+0.2)*F2)
580 DER=0.71428*(1.0-DF3DF2)+0.85714*(DF3DF2/(F3+0.2)-1.0/(F2+0.2))
585 F2=F2+ERR/DER
590 GN2=1.0/F2
595 44 CONTINUE
600 PRINT:"VG1 DID NOT CONVERGE#",X,FXODI
605 GO TO 80
610 45 GM2=1.0/(0.965*(FXOD**0.5229)+1.0)
615 GN2=GM2**2
620 F2=1.0/GN2
625 F3=1.0
630 DO 70 ITRY=1,50
635 FXODT=0.71428*(F2-F3)+0.85714*ALOG((F3+0.2)/(F2+0.2))
640 ERR=FXOD-FXODT
645 IF(ABS(ERR/FXOD).LT.0.001) GO TO 80
650 DF3DF2=(F2+0.4)*(F3+0.2)*F3/((F3+0.4)*(F2+0.2)*F2)
655 DER=0.71428*(1.0-DF3DF2)+0.85714*(DF3DF2/(F3+0.2)-1.0/(F2+0.2))
660 F2=F2+ERR/DER
665 GN2=1.0/F2
670 70 CONTINUE
675 PRINT:"VG1 DID NOT CONVERGE#",X,FXODI
680 80 IF(GN2.LE.0.0) RETURN
685 VO=SQRT(GN2)
690 UGIF=VO*SONO2
695 90 RETURN
700 END
```

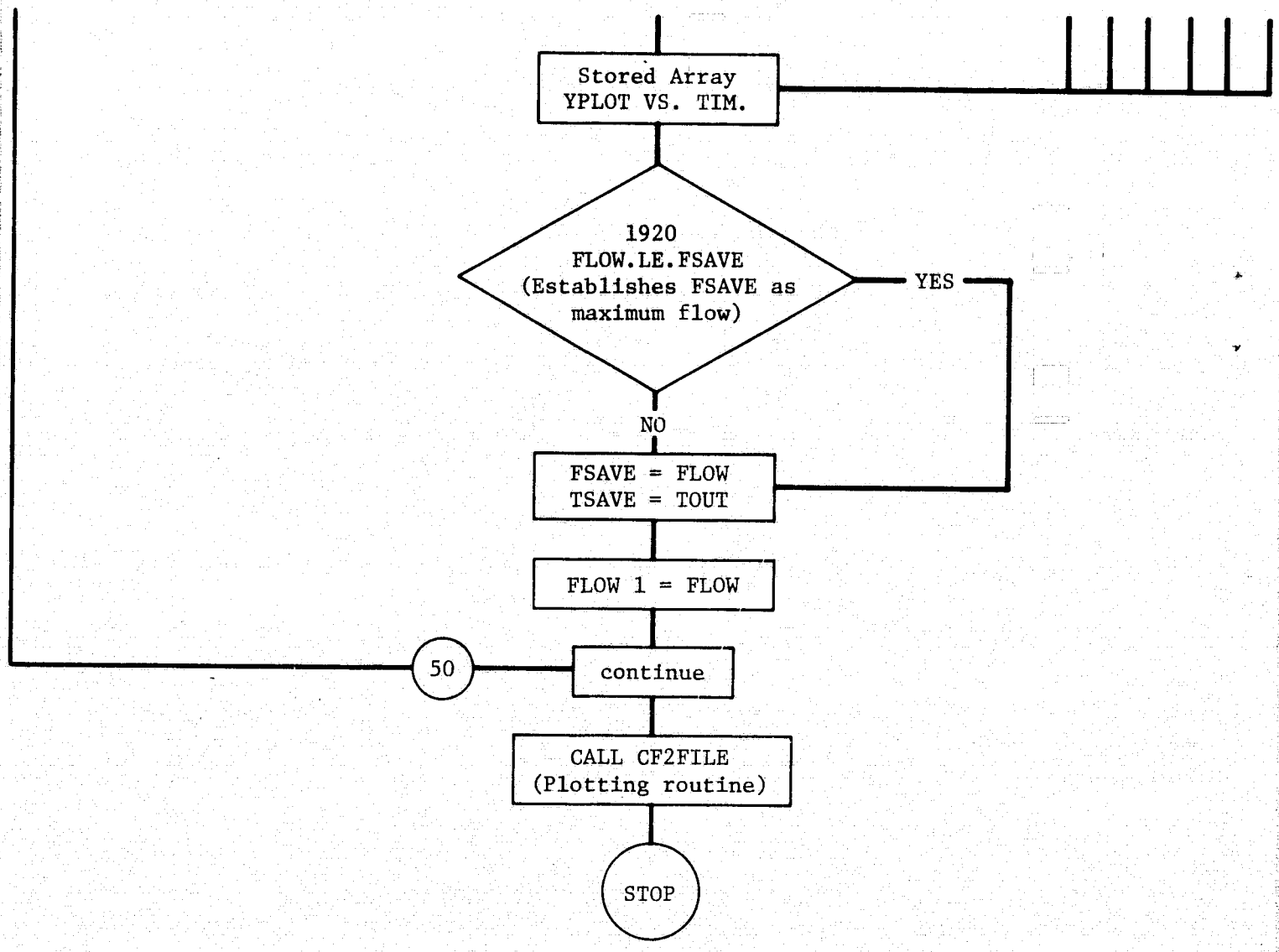
Program CF
Option 6. Cold Flow

Due to the length and complexity of this program, a computer flow diagram and a list of computer symbols are included.




750-790
Calc QAMB
800-820
NVALV
.GE.3
EXPO = 2.0
(Quick opening)
.IE.1
EXPO = 0.5
(Equal percentage)
.EQ.2
EXPO = 1.0
(Linear)
830-845
Calc WVNT, PVNT*, PRECVR, PRECVRG
890
DO 50 NSTEP = 1, LIMIT
930-1040
Interpolate RPM or ULP to value at TIM
1050-1110
Calc HO, PIF, FOF, FRPM, FA
DO 243 K = 1, 20
1130-1220
Calc AO*, BO*, CO*, RAD, FLOW, FLOMAX, HO
Iterate for FLOW ≤ FLOMAX
1230
FLOW.LT.FLOMAX
YES
NO
243
(Final value of HO is such that FLOW does not exceed vaporizer capacity)


1300-1530
Calc FLOS, HPMP, FL86, FLOAV, RATIO, EFF, EPMP, HFRIC, PAI, TIS*, EIS*, EFRIC, EDIS, EQ, EOUT
(Enthalpy gain)
1540-1720
Calc POUT, POUTG, TOUT*, TVNT*, DVAP, WVFLO, PRECVR*, TOS*, EOS*, FLOR*, FLRA, PEX
(Flow rate corrected for two phase pressure drop)
1730-1820
Calc TRECVR*, DELV, FLODIS, PSUB, VSTOR, VVL, HLEV, PPEX
(Variables to be stored in arrays for plotting and starting values for a new time interval)
1830-1880
NOPT.LE.1
YES
YPLOT = FLOW
NO
NOPT.EQ.2
YES
YPLOT = FLODIS
NO
NOPT.EQ.3
YES
YPLOT = TRECVR
NO
NOPT.EQ.4
YES
YPLOT = TBUB
NO
NOPT.EQ.5
YES
YPLOT = FR
NO
NOPT.GE.6
YES
YPLOT = VSTOR



*Calculation by subroutine in CFSUB or HPROP

CF - Computer Listing Symbols

AO	Coefficient of $FLOW^2$ terms
AQ	Heat transfer surface area, ft^2
BO	Coefficient of $FLOW^1$ terms
CO	Coefficient of $FLOW^0$ terms
COEF	Coefficient of $FLOW^2$ frictional terms only
DELV	Incremental flow out of storage in DT, gal
DENSL	Density of LH_2, lb/ft^3
DT	Time increment, sec
D1-D7	Inside diameters, in
EDIS	Dissipated energy, pump, and friction, Btu/lb
EFF	Pump efficiency
EFRIC	Energy dissipated in pipe friction only, Btu/lb
EIN	Inlet enthalpy, Btu/lb
EOS	Saturation enthalpy at outlet condition, Btu/lb
EOUT	Outlet enthalpy, Btu/lb
EPMP	Energy dissipated due to pump inefficiency, Btu/lb
EQ	Enthalpy rise due to ambient heating, Btu/lb
ERR	Error in flow iteration
EXPO	Exponent in equation for FA
FA	Correction factor for non-linear valve opening characteristic
FLDIS(I)	Array for FLODIS
FLO(J)	Array for FLO
FLOAV	Flow averaged over the time increment, gal/min
FLODIS	Accumulated flow in receiving tank after subtracting quantity evaporated, gal
FLOW	Flow rate, gal/min
FLOW1	Flow rate, at the beginning of the time increment, gal/min
FLOR	Ratio of two phase to single phase flow rates
FLRA	Average of FLOR
FL86	Factor in equation for pump efficiency

2. CF

FOF	Fractional closing if discharge valve
FOPN(I)	Array for FSET
FPREV	Temporary storage symbol
FRPM	RPM dependent terms in equation for pump head
FSET	Valve setting at time I
HE	Exit head corresponding to absolute receiver pressure, ft
HDWDT	Head developed from momentum change, ft
HHR	Vertical rise at receiver end, ft
HFRIC	Friction head, ft
HLEV	Supply liquid level, ft
HO	Head corresponding to PRECVR-PULG, ft
HOLD	Old value of HO, ft
HTRY	Trial value of HLEV at time I
HUR	Relative humidity, percent
HUS	Specific humidity, grains/lb
NSTEP	Number of the time step
NVALV	Indicates type of valve (input data)
PD	Vapor pressure corresponding to dry bulk temperature
PHSCL	Pump head scaling factor
POUT	Pressure upstream from discharge valve, psia
POUTG	Gauge pressure equivalent of POUT, psig
PPEX	Pump discharge pressure, psig
PRECVR	Receiver pressure, psig
PSSCL	Pump speed scaling factor
PSTOR	Storage pressure of the supply liquid, psig
PSUB	Pressure in excess of the vapor pressure at the discharge, psig
PULG	Supply ullage pressure, psig
PVSCL	Pump volume flow scaling factor
QOA	Convection heat flux per unit area, $Btu/hr \cdot ft^2$
QRAD	Radiation heat flux per unit area, $Btu/hr \cdot ft^2$
RADI	Radicand (temporary storage)

3.

RPM	Pump RPM
RPM1(I)	Array for RPM
RSPH	Spherical tank radius, ft
TA	Atmospheric temperature, deg F
TBUB	Bubble cap temperature, deg R
TFRA	Time for computing fractional valve opening, sec
TIM	Actual time, sec
TIME(I)	Time of I'th change in conditions, sec
TME(J)	Array for TIM
TOS	Saturation temperature at outlet pressure, deg R
TOUT	Temperature upstream from discharge valve, deg F
TPRINT	Temporary storage for TIME(I)
TR	Absolute temperature corresponding to TA, deg R
TSTOR	Saturation temperature corresponding to PSTOR, deg R
TVENT	Vent gas temperature, deg R
VSTOR	Storage volume corresponding to HLEV, gal
VNT	Vent flow rate under static conditions, lb/sec
VTRY	Trial value in iteration for VSTOR, gal
WVFLO	Vent flow rate during fill, lb/sec
XK	Coefficient in pressure drop through restrictions
XL1-XL9	Pipe lengths, ft
X3	Coefficient of $FLOW^2$ in computing pressure drop at the discharge valve
XPX	Vapor pressure at the inlet, psia
XSOL	Ratio of length of pipe containing single phase liquid to total length

Option 6, Cold Flow

```
10$USE CFSUB;HPROP;PLOT;CF2FILE
20 COMMON FLOW1,XOD2,XOD5,DAV,XK,FA,DT,HLEV,RPM,HO,HHR
30 COMMON HUS,TA,WFPS,COEF,NSTEP,POUT
40 COMMON TME(105),YPLOT(105),NOPT,ITSAVE,IFSAVE,NPTS
50 COMMON DRE,PHSCL,PSSCL,PVSCL,GPM
60 DIMENSION TIME(6),FOPN(6),RPM1(6)
150 READ:XL1,XL2,XL3,XL4,XL5
160 READ:XL6,XL7,XL8,XL9,D1
170 READ:D2,D3,D4,D5,D6
180 READ: D7,GALR,VNT,H1,GPM
190 READ: PUMP,SPD,PSTOR,SVOL,NVAC
200 READ:QX
210 READ:PULG,IPST,NOPT,TIME(2),TIME(3)
220 READ:(TIME(I),I=4,6)
230 READ:(FOPN(I),I=1,5)
240 READ:FOPN(6)
250 READ:(RPM1(I),I=1,5)
260 READ:RPM1(6),NVALV
265 XEOF=XL8
270 222 CONTINUE
280 PHSCL=PUMP/400.
290 PSSCL=SPD/1700.
300 PVSCL=GPM/10000.
310 IF(PUMP.EQ.0.) PHSCL=1.
320 IF (SPD.EQ.0.) PSSCL=1.
330 IF(GPM.EQ.0.) PVSCL=1.
340 TIME(1)=0.
350 WIND=10.
360 FSAVE=0.
370 PRECVR=0.
380 HADD=0.
390 GAL=SVOL
400 CAP=900000.
410 IF(GAL.GE.CAP) GAL=0.99*CAP
420 RSPH=0.31794*CAP**0.333
430 VUL=CAP-GAL
440 HLEV=0.477465*VUL/(RSPH*RSPH)
450 HHR=XL4+XL5
460 DAV=(XL1*D1+XL2*D2+XL3*D3)/(12.*(XL1+XL2+XL3))
470 XPX=PSTOR+14.696
480 IF(IPST.GE.2)XPX=PULG+14.696
490 TSTOR=VATEMP(XPX)
500 DENSL=DEN(TSTOR)
510 DRE=(D1+D2+D3)/3.
520 ADD2=0.0
530 XOD2=XL1/(D1*D1)+XL2/(D2*D2)+XL3/(D3*D3)+ADD2
540 ADD5=XEOF/D3**5
550 XOD5=XL1/D1**5+XL2/D2**5+XL3/D3**5+ADD5
560 DT=TIME(6)/100.0
570 TIM=0.0
580 FLOW1=0.1
590 LIMIT=100
600 HE=(PRECVR+14.7)*144.0/DENSL
610 FLODIS=0.0
620 HO=(PRECVR-PULG)*144.0/DENSL
630 PUL=PULG+14.7
640 NSTEP=1
650 XPX=PSTOR+14.696
660 IF(IPST.GE.2) XPX=PULG+14.696
670 TSTOR=VATEMP(XPX)
```

```
680 VSTOR=GAL
690 EIN=ENTH(TSTOR,PUL,IIII)
700 IF(NVAC.EQ.0) QOA=2.92
710 IF(NVAC.EQ.1) QOA=16.2
720 IF(NVAC.EQ.2) QOA=4230./DAV**0.25
730 TR=460.+TA
740 HADD=0.0
750 AO=0.2618*(D1*XL1+D2*XL2+D3*XL3)+HADD
760 OAMB=QOA*AO
770 GO TO 12
780 10 OAMB=0.0
790 12 CONTINUE
800 IF(NVALV.LE.1) EXPO=0.5
810 IF(NVALV.EQ.2) EXPO=1.0
820 IF(NVALV.GE.3)EXPO=2.0
830 WVNT=VNT
840 PRECVR=PVENT(WVNT,XL4,XL5,XL6,XL7,XL9,D4,D5,D6,D7,TBUB)
845 PRCVRG=PRECVR-14.696
890 DO 50 NSTEP=1,LIMIT
900 FLOW=FLOW1
910 TIM=TIM+DT
930 DO 20 I=2,6
940 IT=I
950 IF(TIME(I).GT.TIM) GO TO 22
960 20 CONTINUE
970 GO TO 24
980 22 DENOM=TIME(IT)-TIME(IT-1)
990 IF(DENOM.EQ.0.0)DENOM=0.001
1000 TFRA=(TIM-TIME(IT-1))/(TIME(IT)-TIME(IT-1))
1010 FSET=FOPN(IT-1)+(FOPN(IT)-FOPN(IT-1))*TFRA
1020 RPM=RPM1(IT-1)+(RPM1(IT)-RPM1(IT-1))*TFRA
1030 ULP=PULG
1040 IF(GPM.EQ.0.)ULP=RPM
1050 HO=(PRCVRG-ULP)*144./DENSL
1052 PIF=1.41E-07*FLOW**2
1055 IF(ULP.GT.30.)HO=HO+PIF*144./DENSL
1060 24 FOF=1.0-FSET
1070 RPMS=RPM*PSSCL
1080 FRPM=-3.782475+0.0162881335*RPMS+0.2610459E-3*RPMS**2
1090 IF(FOF.LE.0.0)FOF=0.0000001
1100 IF(FOF.GE.1.0)FOF=0.999
1110 FA=1.0/(1.0-FOF**EXPO)**2-1.0
1120 DO 243 K=1,20
1130 AO=AF(D1,D5)
1140 BO=BF(DT)
1150 IF(NSTEP.EQ.1)BO=0.0
1160 CO=CF(RPMS)
1170 RAD1=BO**2-4.0*AO*CO
1180 IF(RAD1.GT.0.0) GO TO 25
1190 RAD1=0.0
1200 25 FLOW=(BO-SQRT(RAD1))/(2.0*AO)
1210 FLOMAX=35746.*PUL**0.817059
1220 IF(GPM.EQ.0.)FLOMAX=99999.
1230 IF(K.EQ.1.AND.FLOW.LT.FLOMAX) GO TO 244
1240 DH=-10.
1250 IF(K.GT.1)DH=(HOLD-HO)*(FLOMAX-FLOW)/(FLOLD-FLOW)
1260 HO=HO+DH
1270 HOLD=HO
1280 FLOLD=FLOW
1290 243 CONTINUE
1300 244 FLOS=FLOW/PVSCL
1310 27 HPMP=FRPM-0.4822511E-6*FLOS*ABS(FLOS)
1320 IF(GPM.EQ.0.)HPMP=0.
```

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```
1330 IF (FLOW.GT.0.0) GO TO 30
1340 EFF=0.0
1350 EPMP=0.0
1360 FLOW=0.1
1370 GO TO 32
1380 30 FL86=2003.879+16.1913*HPMP-0.0106583*HPMP**2
1390&   +0.440906E-5*HPMP**3
1400 FLOAV=(FLOW+FLOW1)/2.
1410 RATIO=FLOW/FL86
1420 EFF=0.86-0.854997+2.312442*RATIO-2.363036*RATIO**2+0.9065751*
1430&    RATIO**3
1440 EPMP=1.2851E-3*HPMP*(1.0/EFF-1.0)
1450 32 HFRIC=COEF*FLOW**2
1460 IF(GPM.EQ.0.)HFRIC=0.
1470 PAI=PUL+(HLEV+HPMP-HFRIC)*DENSL/144.
1480 TIS=VATEMP(PAI)
1490 EIS=ENTH(TIS,PAI,IVI)
1500 EFRIC=1.2851E-3*HFRIC
1510 EDIS=EPMP+EFRIC
1520 EO=0.12466*QAMB/FLOW/DENSL
1530 EOUT=EIN+EPMP+EFRIC+EO
1540 XSOL=(EIS-EIN)/(EIS-EIN+EOUT-EOS)
1550 IF(XSOL.LT.0.)XSOL=0.
1560 IF(XSOL.GT.1.)XSOL=1.
1570 X3=7.198E-3*FA/D3**4
1580 HDWDT=0.1360195*(FLOW-FLOW1)
1590 POUT=(HE+X3*FLOW**2)*DENSL/144.
1595 IF(ULP.GT.30.)POUT=POUT+PIF
1600 POUTG=POUT-14.7
1610 TOUT=TEMP(EOUT,POUT,FR)
1620 TVNT=TEMP(EOUT,PRECVR,FRV)
1630 DVAP=0.18635*PRECVR/TVNT
1640 WVFLO=VNT+2.228E-03*FLOW*(FRV*DENSL+(1.-FRV)*DVAP)
1650 PRECVR=PVENT(WVFLO,XL4,XL5,XL6,XL7,XL9,D4,D5,D6,D7,TBUB)
1660 TOS=VATEMP(POUT)
1670 EOS=ENTH(TOS,POUT,IVO)
1680 FLRA=0.5*(FLOR(FR,TOUT,POUT)*(1.-XSOL)+1.+XSOL)
1690 IF(FLRA.LT.0.1)FLRA=0.1
1700 IF(FLRA.GT.1.0)FLRA=1.0
1710 FLOW=FLOW*FLRA
1720 PEX=PRECVR+14.7
1730 TRECVR=VATEMP(PRECVR)
1740 DELV=DT*FLOAV
1750 FLODIS=FLODIS+DELV
1760 PSUB=POUT-VAPO(TOUT)
1770 VSTOR=VSTOR-DELV
1780 IF(VSTOR.LE.0.0) GO TO 983
1790 VUL=CAP-VSTOR
1800 HLEV=2.*RSPH-0.477465*VUL/(RSPH*RSPH)
1810 PPEX=PULG+(HLEV+10.-2.2127E-8*FLOW**2+HPMP)*DENSL/144.
1820 40 THE(NSTEP)=TIM
1830 IF(NOPT.LE.1) YPLOT(NSTEP)=FLOW
1840 IF(NOPT.EQ.2) YPLOT(NSTEP)=FLODIS
1850 IF(NOPT.EQ.3) YPLOT(NSTEP)=TRECVR
1860 IF(NOPT.EQ.4) YPLOT(NSTEP)=TBUB
1870 IF(NOPT.EQ.5) YPLOT(NSTEP)=FR
1880 IF(NOPT.GE.6) YPLOT(NSTEP)=VSTOR
1895 DPO=HO*DENSL/144.0
1920 IF(FLOW.LE.FSAVE) GO TO 45
1930 FSAVE=FLOW
1940 TSAVE=TOUT
1950 45 FLOW1=FLOW
1960 NPTS=NSTEP
```

```
1970 50 CONTINUE
1980 983 TME(NPTS+1)=TIME(6)
1990 IFSAVE=FSAVE
2000 ITSAVE=TSAVE
2010 TME(NPTS+2)=0.0
2020 CALL CF2FILE
2030 999 STOP
2040 END
```

Subroutine CF2FILE

Graph Headings and Labels for CF

```
10 SUBROUTINE CF2FILE
20 COMMON FLOW1,XOD2,XOD5,DAV,XK,FA,DT,HLEV,RPM,HO,HHR
30 COMMON HUS,TA,WFPS,COEF,NSTEP,POUT
40 COMMON TME(105),YPLOT(105),NOPT,ITSAVE,IFSAVE,NPTS
50 ASCII A(42),B(14),C(7)
60 ENCODE (B,10)
70 10 FORMAT(56X)
80 GO TO (1,2,3,4,5,6),NOPT
90 1 ENCODE (C,11)
100 11 FORMAT(7X,"FLOW RATE GPM",8X)
110 ENCODE(B,17) IFSAVE,ITSAVE
120 17 FORMAT(4X,"DISCHARGE TEMP AT A FLOW OF",I6," GPM WAS",I4," R",5X)
130 GO TO 7
140 2 ENCODE (C,22)
150 22 FORMAT("TOTAL LIQUID DISCHARGED GAL ")
160 GO TO 7
170 3 ENCODE (C,33)
180 33 FORMAT("RECEIVER LIQUID TEMP DEG R  ")
190 GO TO 7
200 4 ENCODE (C,44)
210 44 FORMAT ("BUBBLE CAP TEMPERATURE DEG R")
220 GO TO 7
230 5 ENCODE (C,55)
240 55 FORMAT(" FINAL VAPOR MASS FRACTION  ")
250 GO TO 7
260 6 ENCODE (C,66)
270 66 FORMAT("REMAINING LIQUID VOLUME GAL ")
280 7 ENCODE (A,73) B
290 73 FORMAT(8X,"STEADY OPERATION AND TRANSIENT RESPONSE",20X,
300& "TO CHANGES IN OPERATING CONDITIONS",11X,14A4)
310 IF(NPTS.LT.100) ENCODE (A,75) B
320 75 FORMAT(8X,"STEADY OPERATION AND TRANSIENT RESPONSE",17X,
330& "LIQUID SUPPLY DEPLETED BEFORE FINAL TIME",8X,14A4)
340 ENCODE (B,77)
350 77 FORMAT(20X,"TIME IN MINUTES",21X)
360 YPLOT(NPTS+1)=0.0
370 YPLOT(NPTS+2)=YPLOT(1)
380 CALL GRAPH (A,B,C,NPTS,TME,YPLOT)
390 RETURN
400 END
```

Program CFSUB

Pressure Drop Functions for CF

```
10 FUNCTION AF(D1,D5)
20 COMMON FLOW1,XOD2,XOD5,DAV,XK,FA,DT,HLEV,RPM,HO,HHR,
30&HUS,TA,WFPS,COEF,NSTEP,POUT
35 COMMON TME(105),YPLOT(105),NOPT,ITSAVE,IFSAVE,NPTS
40 COMMON DRE,PHSCL,PSSCL,PVSCL,GPM
50 FPMP=PHSCL/PVSCL**2
60 IF(GPM.EQ.0.) FPMP=0.
70 IF (NSTEP.GT.1)GO TO 20
80 PDI=2.2170401E-08*FPMP
90 PC4=4.82251154E-07*FPMP
100 PDC=3.109385599E-2
110 RC=2.5911E-3
120 TC=7.198E-3
130 X10=XOD5*PDC
140 20 RE=FLOW1*15359./DRE
150 IF(RE.LT.3.0E+03) RE=3.0E+3
160 F=0.0055*(1.0+(2.77+1.E+06/RE)**0.33333)
170 X1=F*X10
180 X3=TC*FA/D5**4
190 COEF=PDI+X1+X3
200 AF=-PC4-COEF
210 RETURN
220 END
230 FUNCTION BF(X)
240 COMMON FLOW1,XOD2,XOD5,DAV,XK,FA,DT,HLEV,RPM,HO,HHR,
250&HUS,TA,WFPS,COEF,NSTEP,POUT
260 CM=2.1147E-04*XOD2
270 BF=CM/DT
280 RETURN
290 END
300 FUNCTION CF(X)
310 COMMON FLOW1,XOD2,XOD5,DAV,XK,FA,DT,HLEV,RPM,HO,HHR,
320&HUS,TA,WFPS,COEF,NSTEP,POUT
330 CM=2.1147E-04*XOD2
340 PC3=2.610459E-4
350 PC2=1.628813355E-2
360 PC1=3.782475
370 RPMSC=RPM*PSSCL
380 X1=PC2*RPMSC
390 X2=PC3*RPMSC**2
400 X3=CM*FLOW1/DT
410 IF(FLOW1.EQ.100.)X3=0.0
420 FPMP=(-PC1+X1+X2)*PHSCALE
430 CF=HLEV-PC1+X1+X2-HO-HHR+X3
440 RETURN
450 END
```

Hydrogen Properties, Vent and Two Phase Flow Functions for CF

```
10 FUNCTION VAPO(TR)
20 DIMENSION B(4)
30 DATA B/2.0062,50.09708,1.0044,.01748495/
40 T=TR/1.8
50 VALOG=B(1)-B(2)/(T+B(3))+B(4)*T
60 VATM=10.**VALOG
70 VAPO =VATM*14.696
80 RETURN
90 END
100 FUNCTION XLH(PO)
110 IF(PO.GE.187.5) XLH=0.01
120 IF(PO.LT.187.5)XLH=20.6577*(187.5-PO)**0.427612
130 RETURN
140 END
150 FUNCTION DPDTVP(T)
160 TK=T/1.8
170 PVA=VAPO(T)/14.696
180 ELOG=0.434294
190 DERIV=PVA/ELOG*(50.09708/(TK+1.0044)**2+0.01748495)
200 DPDTVP=DERIV*14.696/1.8
210 RETURN
220 END
230 FUNCTION ENTH(T,PSI,IF)
240 DIMENSION A(4)
250 TK=T/1.8
260 P=PSI/14.696
270 DATA A/-0.05720323,2.794294,-61.70376,-70.95291/
280 C=32.72-TK
290 HSAT=A(1)*C**3+A(2)*C**2+A(3)*C+A(4)
300 PSAT=VAPO(T)/14.696
310 BT1=0.00232108*TK*TK-0.0897882*TK+0.831432
320 BT2=-0.0748928*TK*TK+2.764046*TK-21.88605
330
340 PX=P-PSAT
350 HOFP=BT1*PX*PX+BT2*PX
360 ENTH=0.213377*(HSAT+HOFP)
370 IF=1
380 IF(P.GT.PSAT)RETURN
390 IF=0
400 ENTH=HSAT*0.221968
410 RETURN
420 END
430 FUNCTION VATEMP(POBS)
440 PLOG=0.43429448*ALOG(POBS/14.696)
450 C1=2.01818
460 C2=3.96617
470 C3=7.43630
480 C4=0.0349699
490 TK=(PLOG-C1+SQRT(PLOG*PLOG-C2*PLOG+C3))/C4
500 VATEMP=TK*1.8
510 RETURN
520 END
530 FUNCTION TEMP(H,P,FR)
540 5 T1=VATEMP(P)
550 H1=ENTH(T1,P,IF)
560 XL=XLH(P)
570 FR=(H-H1)/XL
580 TEMP=T1
590 IF(FR.GT.1.0) FR=1.0
600 IF (FR.GE.0.0)RETURN
610 FR=0.0
620 10 DO 40 L=1,20
630 12 T2=T1-0.001
```

```
640 14 H1=ENTH(T1,P,IF)
650 16 H2=ENTH(T2,P,IX)
652 18 A=(T1-T2)/(H1-H2)
655 ERR=(H1-H)/H
660 20 IF(ABS(ERR).LT.0.001) GO TO 42
680 22 T1=T1-(H1-H)*A
690 40 CONTINUE
700 PRINT 100
710 42 TEMP=T1
720 RETURN
730 100 FORMAT("  SUBROUTINE TEMP DID NOT CONVERGE  ")
740 END
750 FUNCTION DEN(TSTOR)
760 D0=5.343989
770 D1=-7.70289E-03
780 D2=-5.138191E-04
790 DEN=D0+D1*TSTOR+D2*TSTOR*TSTOR
800 RETURN
810 END
820 FUNCTION PVENT(WVNT,XL4,XL5,XL6,XL7,XL9,D4,D5,D6,D7,TBUB)
830 DIMENSION TAV(4),FDP(4)
835 REAL KE
840 KE=-1.475E-05
850 TU=36.
860 DO 110 J=1,4
870 GO TO (102,103,104,105),J
880 102 XL=XL4
890 D=D4
900 GO TO 106
910 103 XL=XL5
920 D=D5
930 GO TO 106
940 104 XL=XL6
950 D=D6
960 GO TO 106
970 105 XL=XL7
980 D=D7
990 KE=-4.468E-05
1000 106 TR=540.-(540.-TU)*EXP(KE*D*XL/WVNT)
1004 EXPO=EXP(KE*D*XL/WVNT)
1010 TAV(J)=(TU+TR)/2.
1020 TU=TR
1030 TK=TR/1.8
1040 VIS=-0.0960808E-07*TK**4+0.0792293E-04*TK**3-0.2562415E-02*TK*TK
1050&  +0.6147894*TK-0.4933261
1060 VISC=2.4191E-04*VIS
1070 FDP(J)=0.90199*XL*VISC**0.2*WVNT**1.8/D**4.8
1080 110 CONTINUE
1090 TBUB=TR
1100 PDN=PVENT
1110 PAV=14.696
1120 PDN=14.696
1130 DO 126 K=1,4
1140 I=5-K
1150 DO 120 J=1,20
1160 DGAS=0.18635*PAV/TAV(I)
1170 DP=FDP(I)/DGAS
1180 PNEW=PDN+0.5*DP
1190 PVENT=PDN+DP
1200 IF(ABS(PNEW-PAV)/PNEW.LT.0.0001) GO TO 126
1210 PAV=PNEW
1220 120 CONTINUE
1230 PRINT:"PVENT FAILED TO CONVERGE"
```

```
1240 PVENT=14.696
1250 GO TO 127
1260 126 CONTINUE
1270 127 RETURN
1280 END
1300 FUNCTION FLOR(FR,TOUT,POUT)
1310 IF(FR.GT.0.00001)YF=SQRT(ABS((1.-FR)/FR))
1315 IF (FR.LE.0.00001)YF=0.0
1320 BTA=1./(1.+0.37988*YF)
1330 TH=0.875988+7.9440*EXP(-16.32928*(BTA-0.5)**2)
1340 IF(TH.LE.1.0)TH=1.0
1350 DR=DEN(TOUT)*TOUT/0.18635/POUT
1360 SRTH=SQRT(ABS(TH))
1370 SRD=SQRT(ABS(0.59941*DR*FR**1.8+(1.-FR)**1.8))
1380 FLOR=1.0/SRTH/SRD
1390 RETURN
1400 END
```


Plotting Subroutine for all Programs

```
10 SUBROUTINE GRAPH (A,B,C,N,X,Y)
20 DIMENSION A(42),B(14),C(7),X(103),Y(103),S(12)
30 ASCII A,B,C,S
40 IF (N.GT.0) GO TO 7
50 PRINT 3
60 1 RETURN
70 3 FORMAT(1X,"&&")
80 7 PRINT 10,A,B,C
90 10 FORMAT(1X,"&",14A4)
100 L=N+2
110 XH=X(1)
120 XL=X(1)
130 YH=Y(1)
140 YL=Y(1)
150 DO 20 I=2,L
160 IF(X(I).GT.XH) XH=X(I)
170 IF(X(I).LT.XL) XL=X(I)
180 IF(Y(I).GT.YH) YH=Y(I)
190 IF(Y(I).LT.YL) YL=Y(I)
200 20 CONTINUE
210 CALL SCALE (XL,XH,S)
220 PRINT 11,S
230 CALL SCALE (YL,YH,S)
240 11 FORMAT(1X,"&",2A4,4X,2A4,3X,2A4,4X,2A4,3X,2A4,4X,2A4)
250 DO 22 I=1,12,2
260 22 PRINT 10,S(I),S(I+1)
270 DX=(XH-XL)/800.
280 DY=(YH-YL)/600.
290 27 FORMAT(1X,"&",2I4)
300 DO 33 I=1,N
310 IX=130.5+(X(I)-XL)/DX
320 IY=66.5+(Y(I)-YL)/DY
330 33 PRINT 27,IX,IY
340 PRINT 3
350 44 READ:IX
360 IF(IX-1) 44,1,47
370 47 XV=XL+(IX-130)*DX
380 DO 55 I=2,N
```

```
390 IF(XV.LE.X(I)) GO TO 66
400 55 CONTINUE
410 I=N
420 66 YV=(XV-X(I-1))/(X(I)-X(I-1))*(Y(I)-Y(I-1))+Y(I-1)
430 PRINT 77,XV,YV
440 77 FORMAT(1X,"&X =",1PE9.2,",    Y =",E9.2)
450 GO TO 44
460 END
470 SUBROUTINE SCALE (XL,XH,S)
480 DIMENSION S(12),T(2)
490 ASCII S,T
500 I=ALOG(XH-XL)/2.3025851
510 I=I-1
520 D=10.0**I
530 IF(XL)7,8,8
540 7 IL=XL/D-.999
550 GO TO 9
560 8 IL=XL/D
570 9 IF(XH) 11,11,12
580 11 IH=XH/D
590 GO TO 13
600 12 IH=XH/D+.999
610 13 J=(IH-IL+4)/5
620 XL=IL*D
630 XH=XL
640 IF (I) 14,17,18
650 14 IF(I+2) 16,19,15
660 15 I=4
670 GO TO 20
680 16 I=1
690 GO TO 20
700 17 I=2
710 GO TO 20
720 18 IF(I.GT.6) GO TO 16
730 I=3
740 GO TO 20
750 19 I=5
760 20 DO 30 K=1,12,2
770 GO TO (21,22,23,24,25),I
780 21 ENCODE (T,31) XH
790 GO TO 27
800 22 ENCODE (T,32) XH
810 GO TO 27
820 23 IE=XH
830 ENCODE (T,33) IE
840 GO TO 27
850 24 ENCODE (T,34) XH
860 GO TO 27
870 25 ENCODE (T,35) XH
880 27 S(K)=T(1)
890 S(K+1)=T(2)
900 30 XH=XH+J*D
910 XH=XL+5*J*D
920 RETURN
930 31 FORMAT(1PE8.1)
940 32 FORMAT(F8.1)
950 33 FORMAT(I8)
960 34 FORMAT(F8.2)
970 35 FORMAT(F8.3)
980 END
```

Program DATFILE

Prints Date and Time on Input and Output Figures

```
10 DIMENSION DATE(2)
20 CALL DATE#TIME(DATE,TIME)
30 PRINT 10, DATE, TIME
40 10 FORMAT(X,1H&,2A4,F8.3)
50 END
```

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This report covers computer simulation studies of liquid hydrogen fill and vent systems for the space shuttle. The computer programs calculate maximum and minimum permissible flow rates during cooldown as limited by thermal stress considerations, fill line cooldown time, pressure drop, flow rates, vapor content, vent line pressure drop and vent line discharge temperature. The input data for these programs are selected through graphic displays which schematically depict the part of the system being analyzed. The computed output is also displayed in the form of printed messages and graphs. Digital readouts of graph coordinates may also be obtained.

Procedures are given for operation of the graphic display unit and the associated minicomputer and timesharing computer.

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