NBSIR 85-3023

CRYOGENIC PROPELLANT SCAVENGING

FINAL REPORT FOR THE PERIOD AUGUST 1, 1982 - MARCH 31, 1985

Prepared by
Chemical Engineering Science Division
National Bureau of Standards
Boulder, Colorado 80303

B. Louie
N. J. Kemp
D. E. Daney
Contract No. (T6077J)

Prepared for

National Aeronautics and Space Administration
Space Shuttle Project
Lyndon B. Johnson Space Center
Houston, Texas 77058

U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, Secretary

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Director

NBS-114A (REV. 2-80)

U.S. DEPT. OF COMM. **BIBLIOGRAPHIC DATA SHEET** (See instructions)	1. PUBLICATION OR REPORT NO. NBSIR-85/3023	2. Performing Organ. Report No. PB86 100682/AS	3. Publication Date April 1985

4. TITLE AND SUBTITLE

Cryogenic Propellant Scavenging
Final Report
August 1985 - March 1985

5. AUTHOR(S)

B. Louie, N. J. Kemp, and D. E. Daney

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

7. Contract/Grant No.

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas 77058

NBS Category No.
NBS-280

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

This report is a detailed description of a computer model that has been developed for assessing the feasibility of low g cryogen propellant scavenging from the Space Shuttle External Tank (ET). Either pump-assisted or pressure-induced propellant transfer may be selected. The receiver tank is chilled by emitting a low flowrate of single-phase cryogen through small nozzles. When two phases are present the flowrate is increased to represent transfer through the main piping. The program will accept a wide range of input variables, including the fuel to be transferred (LOX or LH_2), heat leaks, tank temperatures, and piping and equipment specifications.

The model has been parametrically analyzed to determine initial design specification for the system. Pressure-induced transfer of LH_2 can be accomplished in approximately 7 minutes with a 3-inch (0.076 m) line size. Pump-assisted scavenging of LOX can be completed in less than 4 minutes by using a 2 HP (1491.4 W) pump and a 3-inch (0.076 m) line. To maximize the quantity of LH_2 recovered, the receiver tank should be prechilled to -290 °F (94.1 K). It was determined that the LOX receiver tank does not require prechilling and can have a temperature as warm as 300 °F (421.9 K) without significant venting of fluid.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

computer model; cryogenic; fluid transfer; low-g; scavenging; thermodynamics

13. AVAILABILITY

☒ Unlimited
☐ For Official Distribution. Do Not Release to NTIS
☐ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.
☒ Order From National Technical Information Service (NTIS), Springfield, VA. 22161

14. NO. OF PRINTED PAGES

124

15. Price

$16.95

USCOMM-DC 6043-P80

CONTENTS

FIGURES

TABLES

Cryogenic Propellant Scavenging
Final Report
August 1982 - March 1985

B. Louie, N. J. Kemp, and D. E. Daney

Chemical Engineering Science Division
National Bureau of Standards
Boulder, Colorado 80303

This report is a detailed description of a computer model that has been developed for assessing the feasibility of low g cryogen propellant scavenging from the Space Shuttle External Tank (ET). Either pump-assisted or pressure-induced propellant transfer may be selected. The receiver tank is chilled by emitting a low flowrate of single-phase cryogen through small nozzles. When two phases are present the flowrate is increased to represent transfer through the main piping. The program will accept a wide range of input variables, including the fuel to be transferred (LOX or LH_2), heat leaks, tank temperatures, and piping and equipment specifications.

The model has been parametrically analyzed to determine initial design specification for the system. Pressure-induced transfer of LH_2 can be accomplished in approximately 7 minutes with a 3-inch (0.076 m) line size. Pump-assisted scavenging of LOX can be completed in less than 4 minutes by using a 2 HP (1491.4 W) pump and a 3-inch (0.076 m) line. To maximize the quantity of LH_2 recovered, the receiver tank should be prechilled to -290 °F (94.1 K). It was determined that the LOX receiver tank does not require prechilling and can have a temperature as warm as 300 °F (421.9 K) without significant venting of fluid.

Key words: computer model; cryogenic; fluid transfer; low-g; scavenging; thermodynamics.

1. INTRODUCTION

The continuing success of the frequent Space Shuttle flights has encouraged interest in suborbital scavenging of propellants. Currently, the surplus liquid hydrogen (LH_2) and oxygen (LOX) are jettisoned with the external tank (ET) or vented to space after the main-engine cutoff (MECO). Nearly 10,000 pounds* (4535.9 kg) of fuel remain after MECO, which can be compared to the full payload of 65,000 pounds (29483.4 kg). Significant savings can be realized immediately with the proposed scavenging. Accomplishment of this task would support the longer range concepts of tethered vessel storage or orbiting space station operations.

Brux and Stefan [1] have studied the physical phenomenon of cryogenic propellant transfer and discuss the logistics of the task, including receiver tank configuration and location, various heat fluxes, and the duration of a mated coast period after MECO required to meet settling thrust requirements for the ET. They find the concept feasible, provided a positive acceleration of 1×10^{-4} g's or greater is continued for a period of five to twenty minutes. A period of twenty minutes is required for the worst-case transfer of both fluids. The transfer of liquid oxygen requires a 2 to 7.5-inch (5 to 19 cm) line size and a boost pump. Liquid hydrogen transfer can be accomplished using a 4-inch (10 cm) line size with no pump. Simulation of the transfer incorporates a receiver tank cooldown period, during which a low flowrate of cryogen is circulated.

*This report does not conform with NBS policy on SI units. At the request of the sponsoring agency, NASA-JSC, English units are used for the input and output of data.

The present investigation was undertaken to determine the possibility of propellant scavenging and to evaluate the conditions required for successful ET residual transfer. A computer model written in FORTRAN IV (FORTRAN 66) is based on a thorough thermodynamic analysis of the shuttle receiver vessel, including cooldown of the vessel interior, and heat fluxes to the ET and shuttle tank. The model is analyzed parametrically in order to provide information to be used in the design of such a system.

This report summarizes our development of a computer model for cryogenic propellant transfer at the National Bureau of Standards. Fundamental equations, system description, and assumptions are presented in section 2 entitled PROGRAM DEVELOPMENT. Program logic and descriptions of parameters, subprograms, and numerical methods are discussed in section 3 entitled PROGRAM DESCRIPTION. The effect on the overall time of transfer and other operational characteristics is analyzed using parametric variations. Factors that are considered include heat leaks, vessel prechilling, and cooldown requirements. These topics are discussed in section 4 entitled RESULTS AND DISCUSSION.

2. PROGRAM DEVELOPMENT

The physical situation described by the computer model is the transfer of cryogenic propellant between two tanks in a low-gravity environment. A simplified schematic of the propellant scavenging system is shown in Figure 1. The points labeled 1 and 2 respectively denote the main fill line into and vent line from the receiver tank.

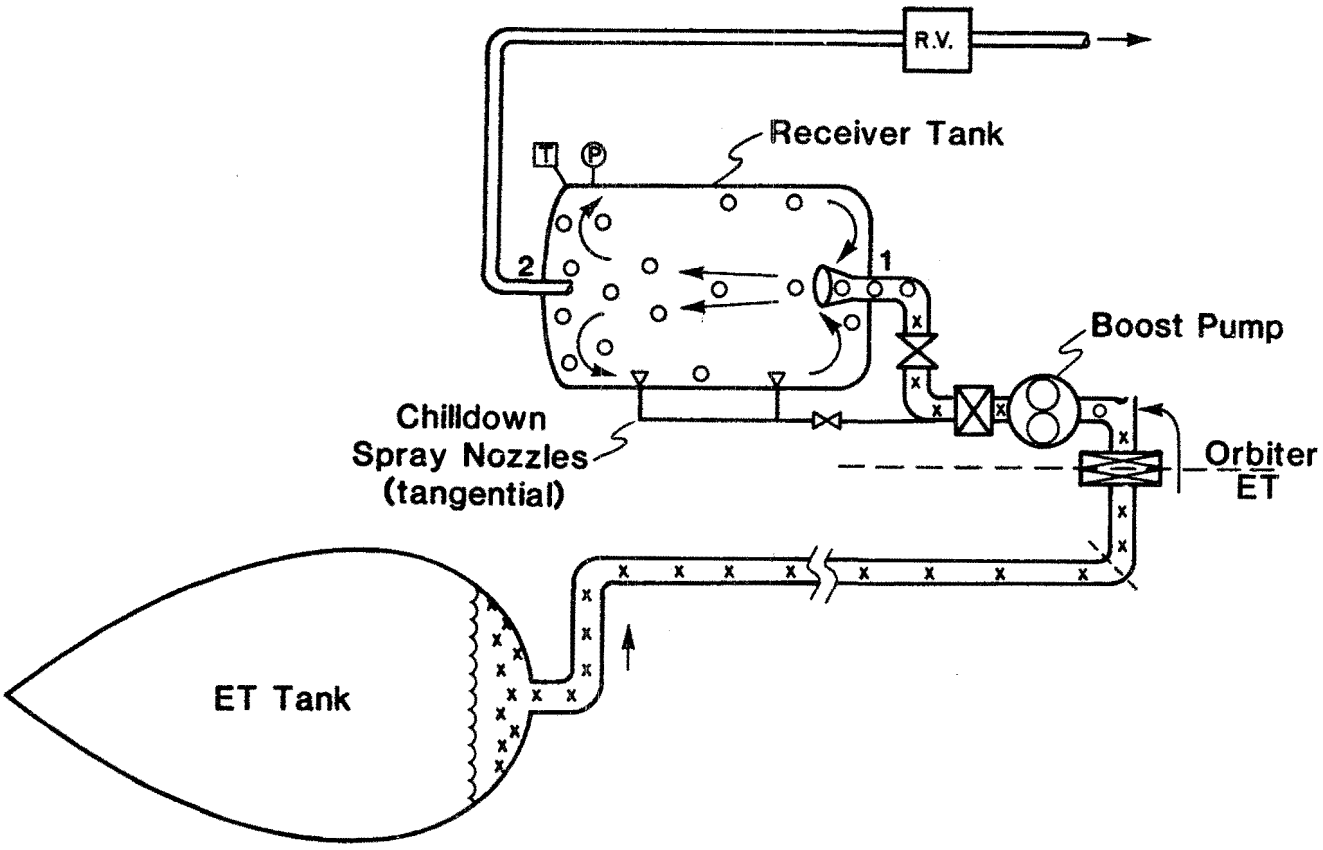


Figure 1. Flow schematic for cryogenic propellant scavenging

The process begins with a cooldown of the receiver tank by spraying the tank walls with cryogen. This is accomplished by emitting a low flowrate of cryogen through tangential spray nozzles while the main fill line is closed. Following the cooldown period the cryogen is transferred through the main fill line by utilizing ullage pressure in the supply tank or by pumping. The transfer is complete when the receiver tank is full, when the supply tank is empty, or when the back pressure in the receiver tank becomes too large.

The model is developed from the differential mass and energy balances applied to the receiver and external (ET) tanks. There are two separate thermodynamic conditions which must be considered for the receiver tank. During the cooldown period, there is only vapor in the tank. Following this single-phase process, a two-phase transfer into the tank by the cryogen must be described. Allowances for pressure relief are made to cover those instances where the tank pressure becomes too great and venting of the vapor to space results. The receiver tank derivation is based on the following assumptions:

(1) Heat leaks into receiver and supply tanks (dQ and dQ_s) are independent of tank temperature and pressure.

(2) The enthalpy of the vented fluid (h_2) is equal to the receiver tank vapor enthalpy (h_v).

(3) Receiver tank vent pressure is independent of tank temperature.

(4) There is sufficient settling so that only liquid is drained from the supply tank, and only vapor is vented from the receiver tank.

A complete derivation of the single-phase receiver tank equations is given in Appendix A. Although the equations are derived for a differential mass, dm, they are equally valid when dm is considered a flowrate. Figure 2

shows the thermodynamic properties for the receiver tank associated with the fluid in the inlet, vent and tank. The equations are summarized as follows (definitions for the equation variables are found in the table of nomenclature):

Mass balance -

$$d\rho = \frac{dm_1}{V} + \frac{dm_2}{V} \tag{1}$$

Energy balance -

$$dU = dQ + h_1 dm_1 + h_2 dm_2 \tag{2}$$

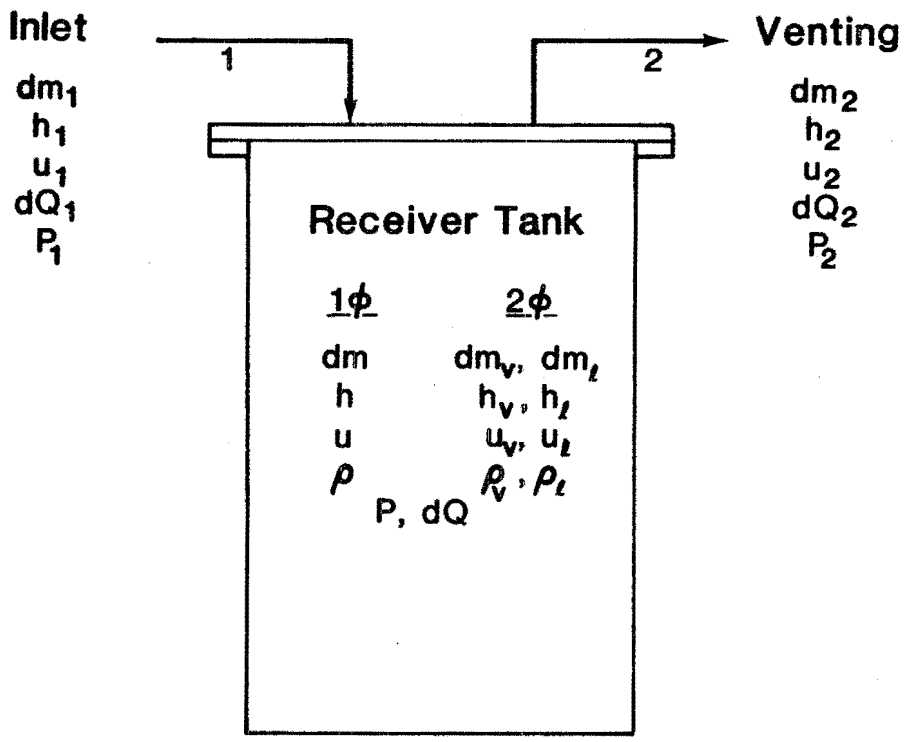


Figure 2. Flow schematic for the receiver tank

Differential temperature equation -

$$dT = \frac{\phi T dm + \frac{(h_1 - h)}{C_v} dm_1 + \frac{dQ}{C_v}}{\rho V + \frac{m_w C_w}{C_v}} \tag{3}$$

Differential pressure equation -

for $P <$ vent pressure:

$$dP = \frac{\phi[\theta dm + (h_1 - h)dm + dQ - m_w C_w dT]}{V} \tag{4}$$

$$dm = dm_1 \text{ and } dm_2 = 0$$

for $P \geq$ vent pressure:

$$dP = 0$$

$$dm = \frac{(h - h_1)dm_1 - dQ + m_w C_w dT]}{\theta} \tag{5}$$

$$dm_2 = dm - dm_1 \tag{6}$$

A complete derivation of the two-phase receiver tank equations is given in Appendix B. These equations are summarized as follows:

Mass balance -

$$dm_1 + dm_2 = dm_v + dm_\ell \tag{7}$$

Energy balance -

$$dU = dQ + h_1 dm_1 + h_2 dm_2 \tag{8}$$

Constant volume -

$$V = v_\ell\, m_\ell + v_v\, m_v \tag{9}$$
$$0 = v_\ell dm_\ell + m_\ell dv_\ell + v_v\, dm_v + m_v dv.$$

The density, ρ_ℓ or ρ_v, is substituted for the specific volume. Solving for the change in the mass of the liquid yields the following equation:

$$dm_\ell = \frac{-\frac{\rho_\ell}{\rho_v}(dm_1 + dm_2) - \rho_\ell\left[m_\ell \frac{\partial v}{\partial P}_\ell + m_v \frac{\partial v}{\partial P}_v\right]dP}{1 - \frac{\rho_\ell}{\rho_v}} \tag{10}$$

If the pressure is less than the vent pressure, the change in the pressure is given by:

$$dP = \frac{\left[h_1 - u_v + \frac{\rho_\ell}{\rho_v}(u_\ell - h_1)\right] dm_1 + (dQ)\left(1 - \frac{\rho_\ell}{\rho_v}\right)}{F(P)} \tag{11a}$$

where

$$F(P) = m_\ell\left[\left(\frac{\partial u}{\partial P}\right)_\ell \left(1 - \frac{\rho_\ell}{\rho_v}\right) + \rho_\ell\left(\frac{\partial v}{\partial P}\right)_\ell (u_v - u_\ell)\right]$$
$$+ m_v\left[\left(\frac{\partial u}{\partial P}\right)_v \left(1 - \frac{\rho_\ell}{\rho_v}\right) + \rho_v\left(\frac{\partial v}{\partial P}\right)_v (u_v - u_\ell)\right] \tag{11b}$$
$$- m_w C_w \left(\frac{\partial T}{\partial P}\right)_{sat}\left(1 - \frac{\rho_\ell}{\rho_v}\right)$$

and $dm_2 = 0.$

If the pressure is the same as or exceeds the vent pressure, the tank pressure is constant. The differential pressure and mass flow through the vent are as follows:

$$dP = 0$$

$$dm_2 = \frac{\left[u_\ell \left(\frac{v_v}{v\ell}\right) - u_v + h_1\left(1 - \frac{v_v}{v\ell}\right)\right] dm_1 + dQ\left(1 - \frac{v_v}{v\ell}\right)}{(h_v - h_\ell)\ \frac{v_v}{v_\ell}} \qquad (12)$$

The ET model is based on the assumption of non-equilibrium (thermal stratification) between the liquid and vapor phases remaining in the supply tank. This assumption is valid because the prechilled supply tanks contain subcooled liquids and the nominal amounts of fuel remaining after MECO are extremely small. Thus, no significant mass transfer can take place between the phases unless the temperature increases enough to vaporize the liquid. When this occurs, the transfer of fuel stops since severe pump cavitation conditions are present.

The following set of equations describes the supply tank at any time:

Energy balance -

vapor phase: $$dh_v = \frac{dQ_v}{m_v} + v_v dP \qquad (13a)$$

liquid phase: $$dh_\ell = \frac{dQ_\ell}{m_\ell} + v_\ell dP \qquad (13b)$$

Pressure equation -

$$dP = \frac{\frac{dm_\ell}{m_\ell} + \frac{v_v dQ_v}{m_\ell v_v \theta_v} + \frac{dQ_\ell}{\theta_\ell m_\ell}}{\frac{v_\ell}{\theta_\ell \phi_\ell} + \frac{m_v v_v^2}{m_\ell v_\ell \theta_v \phi_v}} \qquad (14)$$

Temperature equation -

$$dT = \frac{1}{C_p}\left(\frac{dQ_\ell}{m_\ell} + \nu_\ell \alpha_\ell dP\right) \tag{15}$$

Derivations of the above equations can be found in Appendix E.

Once the supply tank liquid enthalpy is determined, the enthalpy of the fluid entering the receiver tank can be calculated by:

$$h_1 = h_s + \frac{dQ_1}{dm_1} + \frac{W}{dm}_1 \tag{16}$$

and

$$dh_s = dQ_s$$

3. PROGRAM DESCRIPTION

3.1 Overview of the Computer Model

Figure 3 shows the components of the computer simulation program and the communication paths as indicated by the direction of the arrows.

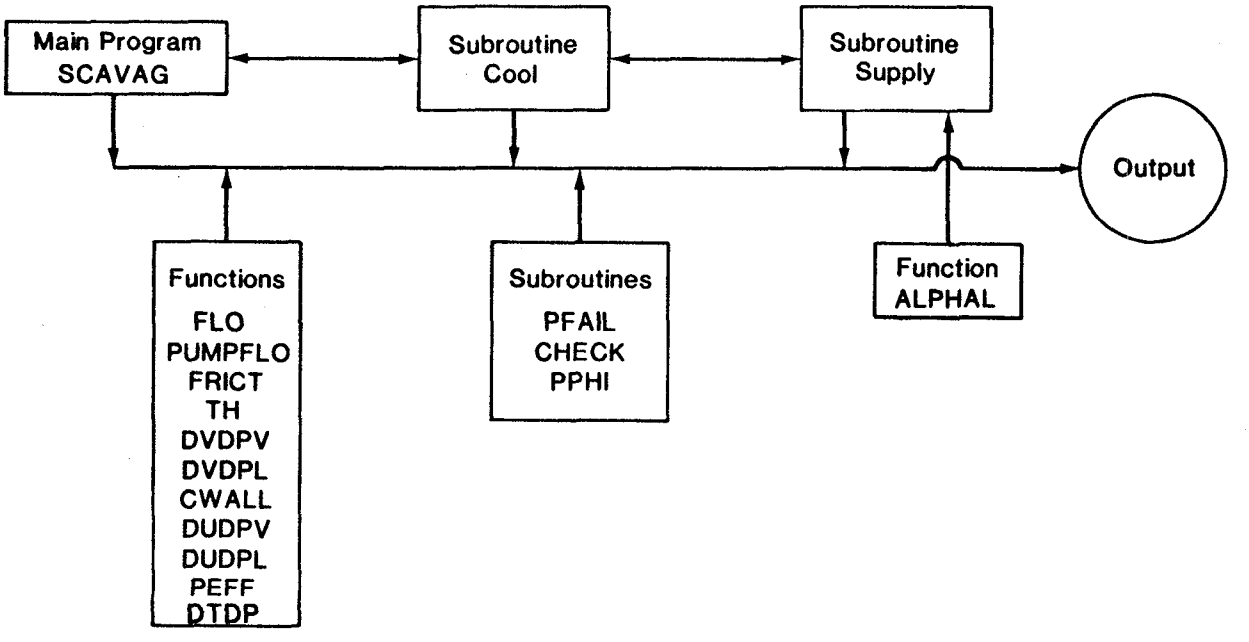


Figure 3. Components of the computer model

The program is written in FORTRAN IV and uses program subsections called subroutines and functions. The four major program sections are the main program SCAVAG and the subroutines COOL, SUPPLY and PFAIL. SCAVAG performs three distinct operations in modeling the scavenging of cryogenic propellant:

1) it serves to initialize the system parameters and direct the program flow; 2) it transfers the calculations of the single-phase receiver tank and the external tank to subroutines; and 3) it performs the calculations of the two-phase receiver tank. COOL and SUPPLY perform the thermodynamic state calculations of the single-phase receiver tank and external tank, respectively. PFAIL sets up plotting arrays and prints messages signifying which completion procedure is chosen in the program.

Provision is made at the start of the main program to select the propellant for the simulation. The namelist option is used to select the propellant. The program default value is NGAS=1, which signifies that LH_2 has been chosen. By using the namelist FUEL and setting NGAS=2, LOX can be selected.

The default values for the parameters for the entire system are initialized according to the propellant chosen. Many of these values are the same as those used by Brux and Stefan [1]. The parameters and their default values are given in Table 1. A namelist option called NAME is used to change any of the initialized values.

COMMON statements are used to pass the same value for a parameter between different portions of the program. For instance, the calculations in the main program and subroutines are dependent on the elapsed time or the quantity of propellant. Table 2 gives a general description of the parameters associated with each of the COMMON statements.

Propellant selection is important in determining the correct fluid thermodynamic properties. The properties data are part of the Fluids Pack computer programs [2] which use routines based on real fluid properties for oxygen and parahydrogen to calculate various thermodynamic properties [3, 4, 5]. The thermodynamic properties, such as saturation pressure, density,

Table 1. System Parameter Descriptions and Initialization Values*

Location	Parameter Name	Description	Value LOX	Value LH_2
Supply Tank	PET	Pressure	20 (0.138)	32 (0.221)
	TET	Temperature	-315 (80.2)	-425 (19.1)
	QET	Heat leak	0 (0)	90000 (26376.3)
	VET	Volume	19786 (560260.4)	53518 (1515415.7)
	TOTAL	Mass of propellant to be transferred	6270 (2844.0)	3098 (1405.2)
Receiver Tank	PRESS	Pressure	1 (0.007)	18 (0.124)
	TEMP	Temperature	60 (288.6)	-290 (94.1)
	Q	Heat leak	0 (0)	0 (0)
	VOL	Volume	300 (8494.8)	780 (22086.5)
	MWALL	Mass of tank wall	350 (158.8)	975 (442.4)
	PVENT	Vent pressure	30 (0.207)	30 (0.207)
Transfer Piping	DIAM	Pipe diameter	4 (10.16)	5 (12.70)
	LENGTH	Length of straight pipe	100 (30.48)	70 (21.34)
	NELBOW	Number of elbow fittings	20	10
	NGATE	Number of gate valves	0	0
	NGLOBE	Number of globe valves	2	2
	NANGLE	Number of angle valves	1	0
	NBUTT	Number of butterly valves	0	0
	METER	Number of flow meters	1	1
	QPIPE	Heat leak	104400 (30596.5)	50400 (14770.7)
	POWER	Pump power	4 (2982.8)	0 (0)
Cooldown Piping	CDLENG	Length of straight pipe	20 (6.10)	20 (6.10)
	NNOZ	Number of nozzles	6	6
	NOZDIA	Nozzle diameter	0.25 (6.4×10^{-3})	0.500 (1.3×10^{-2})
	HEADIA	Header diameter	1.000 (2.5×10^{-2})	2.000 (5.1×10^{-2})
	CONST	1./orifice constant	1.639	1.639

*Units used to initialize parameters: pressure - psia (MPa), temperature - °F (K), heat leak - Btu/hr (W), volume - cubic feet (liters), mass - pounds (kg), power - horsepower (W), length - feet (m), diameter - inches (cm).

and thermal conductivity, are found by using subroutines and functions built into Fluids Pack. When LOX or LH_2 is chosen, the subroutines DATA 02 or DATA PH2 are called.

The distinction between propellants is considered at other points in the computer code. The plotting and numerical integration routines are dependent on the propellant chosen. PFAIL writes the propellant name into a data file which is used in producing the output plots. The time step in each numerical integration is based on the values of the flowrate into the receiver tank and which propellant is used. Also, since the receiver tank construction materials are different for LOX and LH_2, the heat capacity calculation for the tank wall in FUNCTION CWALL requires this distinction.

Table 2. Description of Parameters in the COMMON Statements

Name	Description of parameters
PARAM	initialized, constant values
SUB	time dependent
FLOW	time dependent and transfer piping
NOZZLE	cool-down piping
PUMP	pump values
NGAS	choice of propellant
ETANK	supply tank
PROB	programmed exit designation

After the parameters have been initialized, they are converted to SI units. This is done to ensure compatibility with the thermodynamic data required from the Fluids Pack routines. All subsequent calculations are performed in SI units, with the exception of those in the plotting routine.

Before the transfer of fluid begins, the equivalent length of pipe between the supply and receiver tanks is calculated. Data for equivalent lengths of various pipe fittings are taken from Bennett and Meyers [6]. The equivalent length of each fitting is linearly proportional to the pipe diameter as given by

$$L_{eq} = C_I D + C_{II} \tag{17}$$

The constants are shown in Table 3. The total equivalent length is calculated by summing all the individual equivalent lengths. The equivalent length is then used by FUNCTION FLO and FUNCTION PUMPFLO to calculate a flowrate between supply and receiver tanks.

Table 3. Calculated Constants for Equivalent Length

	C_I	C_{II}
90° elbow	2.53	0.414
Gate valve	0.571	-0.0125
Globe valve	38.1	0.107
Angle valve	14.2	-1.18
Butterfly valve	1.79	-0.147

After parameter initialization and unit conversion has been accomplished, the thermodynamic condition of the supply tank is established. This procedure involves determining the quantity of ullage vapor in the tank. The initial flowrate between the tanks is calculated using the pressure difference between the tanks and the pressure drop through the piping with FUNCTION FLO. If the flow is aided by a pump, the increased flowrate as calculated in FUNCTION PUMPFLO is used.

3.2 Description of Program Sections

SCAVAG

The main program SCAVAG directs the sequence of calculations in the simulation. Following parameter initialization and unit conversion, the cool-down of the receiver tank takes place by calling SUBROUTINE COOL. When the receiver tank is cooled, there are two phases present and a return is made to SCAVAG. It is assumed that the transfer piping is simultaneously chilled.

The remaining propellant is transferred in two phases. First, the enthalpy of the fluid entering the receiver tank is computed by using an energy balance on the transfer piping. The density and enthalpy of the liquid and vapor are found with Fluids Pack functions. These values are used in the first law of thermodynamics to find the internal energy of both phases in the receiver tank. Next, the integration of the differential pressure and mass equations, Eq. (10)-(12), is carried out over an incremental time step (forward Euler method) and incorporates the thermodynamic values above. A check is made to see if the pressure in the receiver tank exceeds the vent pressure; the mass of propellant in the tank is adjusted accordingly. Following this, the supply tank properties are updated by calling SUBROUTINE SUPPLY. Finally, the values for the pressure, flowrate, and propellant vapor and liquid quantities are stored in arrays for plotting.

This calculation procedure is repeated within a loop until the receiver tank is full, until all the propellant has been transferred, or until another condition has been encountered which causes the program to be terminated. For instance, should the pressure in the tank exceed that of the entering stream, the transfer stops. If the simulation proceeds normally, SCAVAG calls SUBROUTINE PFAIL to prepare the data for graphic display.

SUBROUTINE COOL

The single-phase cool-down of the receiver tank is performed by SUBROUTINE COOL until the receiver is at the correct pressure and temperature for a two-phase propellant. Contained in the call and subroutine statements are three parameters that are needed to transfer into and return from COOL. SCAVAG provides values for the mass of vapor in the tank and the mass of vented vapor. COOL returns to SCAVAG the differential pressure and the current values of the mass of vapor in the tank and the quantity vented. A calculation procedure similar to that in SCAVAG is followed to solve Eq.(1)-(6).

Several thermodynamic quantities are needed to solve the single-phase differential equations. COOL calls SUBROUTINE PPHI which calculates the Grüneisen parameter for the single-phase (vapor) propellant in the receiver tank. A heat balance analysis on the transfer pipe affords the enthalpy for the entering stream. The Fluids Pack functions are used to find the density, enthalpy, and specific heat of the fluid in the receiver tank. When all of these thermodynamic values are known, the equations are solved incrementally, with the appropriate checks for venting and back pressure. If all the propellant has been transferred before any liquid is present in the receiver tank, a call is made to PFAIL to prepare the plotting data and terminate the program. Again, the supply tank fluid properties are updated by calling SUPPLY.

To determine when two phases are present in the receiver tank, saturation and actual gas densities are compared. If the gas saturation density at the receiver tank pressure is greater than the actual tank density, the receiver tank is two-phase. SUBROUTINE COOL returns to the main program following this determination.

SUBROUTINE SUPPLY

When updated supply tank conditions are required in either the main program or SUBROUTINE COOL, SUBROUTINE SUPPLY is accessed to perform the necessary thermodynamic calculations. The fraction of the supply tank occupied by either phase is determined first so that the heat flux to the tank can be proportioned accordingly. The vapor phase is assumed to be at the tank pressure and slightly above the saturation temperature, thereby ensuring that condensation will not occur. Next, the Fluids Pack routines are called upon to provide thermodynamic values for the vapor and liquid phases. The Grüneisen parameter and heat of expulsion for both phases are calculated by using SUBROUTINE PPHI and FUNCTION TH, respectively. Finally, the incremental changes in the tank pressure and liquid temperature and enthalpy are found by using Equations (14), (15) and (13b) and the appropriate time step.

SUBROUTINE PFAIL

SUBROUTINE PFAIL, with ENTRY FULL and ENTRY DONE, terminates the program and sets up the data and parameters to be plotted. The different entry points are accessed by unique call statements. PFAIL is called when: 1) the flow between tanks has stopped due to back pressure from the receiver tank; 2) when receiver and supply tank pressures are equal and a pump is not used; or 3) when there is excessive pressure in the receiver tank and a pump is used. PFAIL writes a message indicating why the simulation stopped and what the final conditions are. The other entries into PFAIL address other conditions and bypass inappropriate operations. ENTRY FULL is called when the main program or SUBROUTINE COOL determines that the receiver tank is full of propel-

lant. When all the fluid has been emptied out of the supply tank, ENTRY DONE is called. ENTRY PDATA is called when a programmed exit has been executed.

Each entry into the subroutine follows a similar computational procedure. Initially, the units for the parameters to be printed in the termination message are converted to English from SI. Following this conversion, the message is printed on the output file stating the cause for program termination, the quantity of propellant transferred, and the temperature and pressure for each tank. The quantity of fluid vented from the tank is also given.

Preparation of the data and parameters for plotting involves several steps. The upper and lower limits for the plots are determined first. The descriptions for the plotting parameters are shown in Table 4. Since each of the plots depicts a parameter as a function of time, the lower value is set to zero and the upper value is either 10 or a multiple of 50 minutes. Should the total time required for transfer be more than 10 minutes, the greater value will be used.

The lower limit for the receiver tank temperature is based on the initial temperature in the supply tank, and the upper limit depends on the initial receiver tank temperature. Both values are multiples of 100 and in units of Fahrenheit.

The limits on the receiver tank pressure are zero and 50 psia (0.345 MPa), unless a value in the pressure array exceeds the upper limit. When this is the case, the value is incremented by 50 psia (0.345 MPa) iteratively until the maximum pressure data point is less than the newly set limit. The upper limit for the transfer flowrate is 2000 lb/min (907.2 kg/min) for LH_2 or 10,000 lb/min (4535.9 kg/min) for LOX.

Table 4. Variables Used to Plot System Parameters

Simulation variable	Units	Array	Location of low, high bounds
TIME	Minutes	X	OPLOT(1), OPLOT(2)
TEMP	°F	Y1	OPLOT(3), OPLOT(4)
PRESS	psia	Y2	OPLOT(5), OPLOT(6)
FLOW1	Pounds/min	Y3	OPLOT(7), OPLOT(8)
MVAP	Pounds	Y4	OPLOT(9), OPLOT(10)
MLIQ	Pounds	Y5	OPLOT(11), OPLOT(12)
TOTAL	Pounds	Y6	OPLOT(13), OPLOT(14)
ETQ	Dimensionless	Y7	OPLOT(15), OPLOT(16)
TANK	Dimensionless	Y8	OPLOT(17), OPLOT(18)

The quantity of propellant in the receiver tank is graphically displayed by plotting the vapor, liquid, and combined amounts over time. All these limits are dependent on the initial quantity of propellant (TOTAL) to be transferred. The upper limit for the vapor quantity is initially set to 500 lbs (226.8 kg), but it is increased iteratively by 500 lbs (226.8 kg) if one-tenth of TOTAL is larger than the limit. The upper limits for the liquid and combined quantities are 10 times the value determined for the vapor quantity. The quality of the propellant in the supply tank and entering the receiver tank is stored in the array as percent vapor. The upper limit for the quality is 100% vapor and the lower limit is 100 percent liquid.

3.3 Descriptions of Other Subroutines

SUBROUTINE PPHI

The thermodynamic quantity called the Grüneisen parameter, ϕ, appears frequently in single-phase flow [7]. It is found in the equations describing the single-phase cooldown of the receiver tank (Eq. (3)-(4)) and the subcooled

liquid propellant in the supply tank (Eq. (14)) in the present study. Both subroutines COOL and SUPPLY call PPHI during their computational procedures for values of ϕ.

The dimensionless Grüneisen parameter is given by

$$\phi = \frac{1}{\rho}\left(\frac{\partial P}{\partial u}\right)_{\rho} \tag{18}$$

or

$$\phi = \left(\frac{\partial P}{\partial T}\right)_{\rho} \left(\frac{1}{\rho C_v}\right) \tag{19}$$

When the second form of ϕ is used, the Fluids Pack subroutine DPDT can be used to find the partial derivative and the constant volume specific heat of the fluid. The density and temperature are passed from either COOL or SUPPLY to PPHI which returns a value for ϕ.

SUBROUTINE CHECK

Calls to this subroutine are routinely made to determine the quality of propellant. Both SCAVAG and COOL call CHECK to find the quality of the fluid entering the receiver tank. SCAVAG, COOL, and SUPPLY utilize CHECK to find the amount of vapor in the supply tank fluid. Because pump cavitation can be severe with a small quantity of vapor, the run will be terminated with this determination. A message is printed which states the percentage of vapor in the fluid.

For inputs of pressure, temperature and enthalpy, SUBROUTINE CHECK determines if the fluid is single-phase or two-phase and the mole fraction in each phase. First, the liquid saturation enthalpy is obtained from Fluids Pack using the input pressure. Next, if the input enthalpy is less than liquid saturation enthalpy, the stream is subcooled, and CHECK returns an indication

that no vapor is present (i.e. $x = 0$). If the input enthalpy is greater than the liquid saturation enthalpy, the proportion of fuel in the liquid and vapor phases is determined by:

$$h = h_{\ell,sat}(1-x) + h_{v,sat}(x)$$

or rearranging,

$$x = (h_{\ell,sat} - h)/(h_{\ell,sat} - h_{v,sat}) \qquad (20)$$

Since the flow equations were developed for an incompressible fluid, there may be significant error if the fraction of vapor is much greater than zero.

3.4 Descriptions of Functions

Several thermodynamic quantities in the form of partial derivatives are required in the two-phase calculations in SCAVAG. While Fluids Pack directly calculates some partial derivatives such as DPDT (which is used in determining ϕ), other partial derivatives must be calculated using an iterative approximation. The approximation is written so that thermodynamic properties from Fluids Pack may be utilized.

FUNCTIONS DVDPV and DVDPL

FUNCTION DVDPV and FUNCTION DVDPL calculate the partial derivative of specific volume with respect to pressure for saturated vapor and liquid respectively. The pressure is the required parameter in the function statement.

These partial derivatives are required by Eq. (10) for the two-phase integration. The partial derivative is approximated by the equation:

$$\left(\frac{\partial v}{\partial P}\right)_{sat} = \frac{v_{sat}(P + \Delta P) - v_{sat}(P - \Delta P)}{2\Delta P} \tag{21}$$

The values for the specific volume at saturation conditions are the inverse of the density computed by Fluids Pack at the same temperature and pressure. The pressure increment ΔP is initially set at 0.05 atm (0.005 MPa) and decreased until the partial derivative changes insignificantly.

FUNCTIONS DUDPV and DUDPL

FUNCTION DUDPV and FUNCTION DUDPL, given the pressure as an input, determine the partial derivative of internal energy with respect to pressure for saturated vapor and liquid, respectively, as required by Equation (11b). The partial derivative is approximated in a similar manner to DVDPV and DVDPL by:

$$\left(\frac{\partial u}{\partial P}\right)_{sat} = \frac{u_{sat}\ (P + \Delta P) - u_{sat}\ (P - \Delta P)}{2\Delta P} \tag{22}$$

The internal energy, u_{sat}, is calculated using enthalpy values from Fluids Pack at the saturation temperature and pressure and the (First Law) energy relationship as given by:

$$u = h - (Pv)$$

or

$$u = h - (P/\rho) \tag{23}$$

Again, ΔP is initially 0.05 atm (0.005 MPa) and decreased until the desired accuracy is obtained.

FUNCTION DTDP

This function determines the partial derivative of temperature with respect to pressure for the saturated fluid (liquid and vapor). The partial derivative is approximated by the expression

$$\left(\frac{\partial T}{\partial P}\right)_{sat} = \frac{T_{sat}(P + \Delta P) - T_{sat}(P - \Delta P)}{2\Delta P} . \tag{24}$$

Pressure is required as an input for the function and is subsequently used in the Fluids Pack function FINDTV to obtain the saturated temperature. The temperature is found at a pressure that is a small increment above and below the input. The increment, ΔP, is decreased from an initial value of 0.05 atm (0.005 MPa) until the convergence criterium is met.

FUNCTION ALPHAL

The temperature equation in SUPPLY contains the term for the liquid phase bulk expansivity, α_ℓ, which is defined as (7):

$$\alpha_\ell = - \frac{T}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p \tag{25}$$

FUNCTION ALPHAL calculates this value by approximating the partial derivative in an iterative manner. This approximation is given by:

$$\left(\frac{\partial \rho}{\partial T}\right)_p = \frac{\rho(T+\Delta T) - \rho(T-\Delta T)}{2\Delta T} \tag{26}$$

A temperature increment ΔT is used to find values of the density at temperatures slightly above or below the liquid temperature. The temperature increment ΔT is initially set at 0.05 K and decreased until the partial derivative changes insignificantly from one iteration to the next.

FUNCTIONS FLO, FRICT, PUMPFLO, and PEFF

The functions used to calculate the transfer flowrate are dependent on the pressure in the receiver tank and are themselves interdependent. These functions are used to calculate the flowrate of propellant between the supply and receiver tanks. FLO and PUMPFLO are accessed from SCAVAG and COOL. FRICT is used in FLO and PUMPFLO, and PEFF is used in PUMPFLO only. A description of each follows.

FUNCTION FLO

FUNCTION FLO calculates the flowrate between tanks for a given pressure drop. This function is used to initialize the flowrate, and the value it provides is an input for FUNCTION PUMPFLO. SCAVAG passes the receiver tank pressure through the function statement.

The flowrate between the tanks is related to the pressure drop in the system. The overall pressure drop can be stated as the sum of the individual pressure drops as follows:

$$\Delta P_{system} = \Delta P_{main}(dm^2) + \Delta P_{meter} + \Delta P_{cooldown}(dm^2), \qquad (27)$$

where (dm^2) is the functional dependence, not the multiplier. The overall pressure drop is the difference between the pressures in ET and receiver tank. The pressure drop in the meter is five percent of the overall pressure drop. The remaining terms in Eq. (27) are functions of the flowrate. The pressure drop through the main transfer line and the cooldown line are given by:

$$\Delta P_{main} = \frac{32 C f_{main} L_{main} (dm)^2}{\rho \pi^2 D_{main}^5} \quad . \qquad (28)$$

and

$$\Delta P_{cool} = \frac{32 C f_{cool} L_{cool} (dm)^2}{\rho \pi^2 D_{cool}^5} \quad . \tag{29}$$

(For the derivation of C, see Appendix D.)

The pressure drop in the cool down nozzles can be expressed as

$$\Delta P_{nozzle} = \left(\frac{dm}{C' D_o^2 C_d}\right)^2 \left(\frac{\rho}{g_c}\right)\left[1 - \left(\frac{D_o}{D_{cool}}\right)\right]^4 \tag{30}$$

When Eq. (27) is solved for the flowrate dm by substituting into it Eq. (28) - (30), the following expression is obtained:

$$dm^2 = \frac{P_s - P_{RT} - \Delta P_{meter}}{C_{main} f_{main} + C_{cool} f_{cool} + C_{nozzle}} \quad , \tag{31}$$

where $C_i = C_{main}$, C_{cool}, or C_{nozzle} refers to the right hand side of the individual equations without the flowrate term.

Since the Fanning friction factors in Eq. (28) and (29) also are functions of the flowrate, an iterative procedure is used to calculate f_{main} and f_{cool}. The friction factors are initially set to 0.005 and used to compute the flowrate. The flowrate is used as the input parameter to FUNCTIO FRICT, which computes new values for the friction factors. The new values fo f_{main} and f_{cool} are used to recalculate the flowrate. This continues until the friction factors change by less than 0.1 percent.

After the receiver tank has been chilled to allow two phases of the propellant to be present, the nozzle constant, C_d, and the length of the cool down piping, L_{cool}, are set to zero. The contribution of the cooldown line and nozzles to Eq. (27) and (31) is negated. This simulates the switching of a three-way valve to the closed position in the cooldown line.

FUNCTION FRICT

FUNCTION FRICT calculates the Fanning friction factor corresponding to flow through a pipe. Input variables are the flowrate, temperature, density, and pipe diameter.

The Fanning friction factor is related to the Reynolds number and pipe diameter. While a variety of functions are available [8], the following relationship was chosen:

$$f = \left\{ -4 \log_{10} \left(\frac{\varepsilon/D}{3.7} - \frac{5.02}{N_{Re}} \log_{10} \left(\frac{\varepsilon/D}{3.7} + \frac{14.5}{N_{Re}} \right) \right) \right\}^{-2} \qquad (32)$$

The pipe roughness ε is assumed to be 0.00015 ft (0.004572 cm), the value for commercial steel pipe [6]. The Reynolds number is calculated from the equation:

$$N_{Re} = Du_b \rho/\mu$$

or

$$N_{Re} = \frac{4(dm)M}{\pi D \mu} \qquad (33)$$

The viscosity as a function of pressure and temperature for hydrogen cannot be calculated with the Fluids Pack thermophysical properties computer programs. However, since relatively small changes in hydrogen viscosity do not significantly change the friction factor, an average viscosity is used. This value is 1.8×10^{-4} g/(cm·s) [3] and produces less than 0.5% error in the friction factor.

FUNCTION PUMPFLO

FUNCTION PUMPFLO calculates the flowrate between the ET and receiver tank and accounts for the use of a pump in the transfer. The overall pressure drop can be expressed as

$$\Delta P_{system} = \Delta P_{line}(dm^2) + \Delta P_{meter} + \Delta P_{cool}(dm^2) - \Delta P_{pump}\left(\frac{1}{dm}\right). \quad (34)$$

See the previous discussion in the section on FUNCTION FLO for descriptions of the terms ΔP_{system}, ΔP_{line}, ΔP_{meter}, and ΔP_{cool}. The term ΔP_{pump} is a function of the inverse flowrate, 1/dm, and is given by

$$\Delta P_{pump} = \frac{bp\ \rho\ \eta}{dm} . \quad (35)$$

The effect of ΔP_{pump} is opposite that of the other terms in Eq. (34); hence, the opposite sign.

An initial guess for the flowrate is used to calculate the theoretical pressure drop or rise. The flowrate dm is iterated by using a modified Newton method [9] which is found to be stable for this application:

$$dm_{n+1} = dm_n - \frac{(\Delta P - \Delta P_n)(dm_n - dm_{n-1})}{(\Delta P_{n-1} - \Delta P_n)} \quad (36)$$

The iteration ceases when calculated and actual pressure drops differ by less than 0.01%.

FUNCTION PEFF

The pump efficiency is calculated for an input of the flowrate from FUNCTION PUMPFLO. Two different sizes of pumps are used to transfer the LOX and LH_2 propellant. A linear least squares fit of data for the pump efficiency versus flowrate [10,11] is used to provide a five-coefficient, fourth order equation for each pump.

The equation for the pump efficiency for LH_2 is:

$$\eta = 0.39213 + 0.096620(dm) + 2.7793 \times 10^{-5}(dm)^2 - 8.1723 \times 10^{-8}(dm)^3 + 2.5008 \times 10^{-11}(dm)^4. \quad (37a)$$

The equation for the pump efficiency for LOX is:

$$\eta = 0.32031 + 0.48261(dm) - 1.6223 \times 10^{-3}\ (dm)^2 + 3.9836 \times 10^{-6}\ (dm)^3 - 4.8853 \times 10^{-9}\ (dm)^4. \quad (37b)$$

FUNCTION TH

SUBROUTINE COOL uses FUNCTION TH to calculate a value for the heat of expulsion for the vapor phase calculations. This thermodynamic value is defined as:

$$\theta = v \left(\frac{\partial h}{\partial v}\right)_p \quad (38a)$$

or

$$\theta = C_p \rho \frac{\left(\frac{\partial p}{\partial \rho}\right)_T}{\left(\frac{\partial p}{\partial T}\right)_\rho} . \quad (38b)$$

The Fluids Pack subroutines DPDD and DPPT are used to find the partial derivatives in the numerator and denominator, respectively, and Fluids Pack functions are used for the specific heat and density.

FUNCTION CWALL

FUNCTION CWALL returns the heat capacity of the receiver tank wall at a particular temperature. It is assumed that the oxygen tank is constructed using Inconel X-750* and the hydrogen tank is constructed using aluminum. The heat capacity-temperature data for these materials are of the form:

$$C_w = \frac{\exp(C_1 + C_2/T + C_3/T^2)}{1000} \qquad (39)$$

The constants C_1, C_2 and C_3 were determined by taking heat capacity-temperature data and applying a least-squares technique to the above equation. These values are shown in Table 5. The data used are found in Appendix C [12,13].

Table 5. Tank Wall Heat Capacity Constants

	Inconel	Aluminum
C_1	6.482	7.293
C_2	-106.3	-121.9
C_3	329.1	347.9

3.5 Program Termination

SUBROUTINE PFAIL is the normal route for program termination. ENTRY DONE is used when the supply tank is empty, i.e., when all the propellant has been

*Such identification does not imply recommendation or endorsement by the National Bureau of Standards.

transferred. ENTRY FULL is used when the receiver tank is full. This condition occurs if the receiver tank volume is too small, if the quantity of propellant is increased with the tank volume remaining the same, or if the mass balance on the fluid in tank is wrong. The main entry PFAIL is used to indicate a high backpressure condition. This can happen when the receiver tank pressure is greater than the supply tank pressure and a pump is not used, or when the flowrate is very small. The program will terminate if there is improper venting, i.e., when there is a measured flow through the vent, but the receiver tank pressure is less than the set vent pressure.

ENTRY PDATA in SUBROUTINE PFAIL is used when a programmed stop is executed. This exit is used in several locations in the main program and cool down subroutine, and it is also used by functions DVDPV, DVDPL, DUDPL, DTDP, ALPHAL, FLO, and PUMPFLO and subroutine SUPPLY. The COMMON parameter DUMP normally has a value of zero until a cause for termination is reached in one of the previously listed program sections. DUMP is reset to a value of 1.0. When the condition for termination occurs in a function, the program flow is returned to either SCAVAG or COOL. The run continues to the end of the present integration loop, when the parameter DUMP is evaluated. If DUMP equals 1.0, ENTRY PDATA is called, and the output files are replaced prior to termination.

Several subprograms use convergence criteria to obtain specific thermodynamic conditions. SUBROUTINE COOL checks for the condition when the density in the tank is greater than the saturation density, i.e. both liquid and vapor are present in the tank, and the calculations return to the main program. If two phases are not obtained within the array size limit, the program prints an error message and stops.

Functions DVDPV, DVDPL, DUDPV, DUDPL, DTDP, and ALPHAL use derivative approximations that depend on the change in thermodynamic properties about a small interval. The first five functions listed above evaluate the specific

volume, internal energy, or temperature about a small pressure interval, while ALPHAL evaluates the density about a small temperature interval. In all cases, the program will terminate should the convergence of the properties about the specified interval not be reached within 100 iterations. The message, "KOUNT exceeds 100," noting the particular function, will be printed.

FUNCTION FLO uses the Fanning friction factor calculated in FUNCTION FRICT as its convergence criterion. The flowrate found in FLO is an input for FRICT, which in turn determines the friction factor used in the flowrate calculation. The convergence of the successive values should occur within 100 iterations, or the message, "KOUNT exceeds 100 for FLO," is printed on program termination.

FUNCTION PUMPFLO checks the convergence of the actual pressure difference between the tanks and the calculated pressure drop through the piping using a pump. If the convergence between the two does not happen within 100 iterations, a message is printed and the program is stopped.

The supply tank thermodynamics are checked for errors in calculation or intolerable operating conditions in SUBROUTINE SUPPLY. When the calculated liquid enthalpy is significantly different from the enthalpy found in Fluids Pack, the program terminates with the message, "ENTHALPY DISPARITY," and prints the two values in disagreement. If the quality of the fluid is greater than one part in one million, there exists the possibility for cavitation. The program terminates with this condition and an error message, "ET LIQ BOILING. STOP TRANSFER."

3.6 Programming Information

A brief description will be given for a typical run of the program. The information provided in this section is based on procedures used with the CDC

Cyber 750 Computer System and the NOS Version 1 operating system on location at NBS in Boulder. The program is written in FORTRAN IV. These procedures should be transferable to the computer system at NASA-JSC with minor modifications. See Appendix G for program listings.

File Manipulation

All computer programs, data, and control procedures for running PROGRAM SCAVAG are stored in files. At NBS, SCAVAG is stored in filename COMBO; the input data are stored in filenames DATAIN or FUEL; output data are located in filenames PSDATA and PSOUT; and the control procedure is stored in filename SUBCOM.

Before running PROGRAM SCAVAG, the operator must prepare the control procedure and the input files. The control procedure that NBS has used, SUBCOM, retrieves COMBO, DATAIN, and BOXB (containing Fluids Pack) from permanent storage and places them into a local or usable state. SUBCOM compiles COMBO and, if the compilation is free of errors, loads and executes the compiled version.

The operator enters the following command on a time-sharing terminal to run the program:

SUBMIT, SUBCOM

This statement is a batch command which means the operator cannot interact, alter, or stop the execution of the program or job. To determine when the program has stopped, the operator can check the status of the job, or a file named DAYF. This file is created by SUBCOM to record the real time sequence of control procedures performed by the computer during program execution.

Input

The program operator must determine which propellant and values for the initialized parameters are to be used. If LOX is the desired propellant, the namelist FUEL must be modified to the following form:

```
$FUEL
 NGAS=2,
$
```

If LH_2 is chosen, FUEL should have either of the following forms:

```
$FUEL
$
```

or

```
$FUEL
 NGAS=1,
$
```

Namelist FUEL is contained in a file named FUEL. No decimal point is used since NGAS is an integer.

To change values for the initialized variables, similar steps are used with namelist NAME. NAME is contained in a file called DATAIN. Any number of changes can be made for the parameters listed in Table 1. For instance, to change the initial supply tank temperature and pressure, the quantity of propellant to be transferred, the pump power, and the length of straight pipe for the LH_2 system, one would alter NAME to the following form:

```
$NAME
 TET = -400.,
 PET = 25.,
 TOTAL = 5000.,
 POWER = 2.,
 LENGTH = 100.,
$
```

Since all the chosen variables are real, the values must have decimal points. All values are entered in English units. If no changes are desired, NAME must have the following form:

```
$NAME
$
```

The program statement defines TAPE5 and TAPE7 for use during the program. SUBCOM, which directs the sequence of operating steps for running the program, sets TAPE5 equal to filename DATAIN, or namelist NAME, and TAPE7 equal to filename FUEL, or namelist FUEL. These files must exist in order to run the program.

Output

The output from program SCAVAG is directed to two locations. While SCAVAG is running, the graphic display data is written to TAPE8 and stored in filename PSDATA. When SCAVAG terminates, the termination message and initialized parameters are written to TAPE6 and stored in filename PSOUT. See Table 6 for sample output for LH_2. The operator can access PSOUT at a later point for further evaluation.

Two FORTRAN programs utilize the data in PSDATA to produce plots describing the transfer. The first program is called PLOT. At NBS PLOT is attached to the job by the control procedure SUBCOM and run after SCAVAG has terminated. The plots that are drawn use the computer systems mathematics library (called STARPAC at NBS in Boulder) and are written to TAPE6, following the output described above. The entire contents of TAPE6 are stored in PSOUT. (Further explanation is given in Appendix F.)

The second program which uses PSDATA is called DEMO. The graphics package called DISSPLA (15) is utilized to produce plots which are more refined than those generated through PLOT. (Additional details about DEMO can be found in Appendix F.) The plots are directed to one of three output devices by selecting the appropriate CALL statement in DEMO. For the computer system at NBS CALL HP7221 accesses a multiple pen plotter; CALL TK4010(960) accesses

Table 6. Sample Output for Hydrogen

Supply tank initial conditions:

Pressure	32.000	psia	(0.221 MPa)
Temperature	-425.000	F	(19.1 K)
Hydrogen Mass	3098.00	Pounds	(1405.2 kg)
Heat Leak	90000.000	Btu/hr	(26376.3 W)

Receiver tank initial conditions:

Pressure	18.000	psia	(0.124 MPa)
Temperature	-290.000	F	(94.1 K)
Vent Pressure	30.000	psia	(0.207 MPa)
Tank Volume	780.000	Cubic Feet	(22086.5 kg)
Tank Wall Mass	975.000	Pounds	(442.2 kg)
Heat Leak	0.000	Btu/hr	(0.0 W)

Transfer Parameters:

Pipe Diameter	5.000	Inches	(12.7 cm)
Length of Straight Pipe	70.000	Feet	(21.34 m)
10 Elbow(s)			
0 Gate Valve(s)			
2 Globe Valve(s)			
0 Angle Valve(s)			
0 Butterfly Valve(s)			
1 Flow Meter (s)			
Heat Leak Into Piping	50400.000	Btu/hr	(14770.7 W)
Pump Power	0.0	HP	(0.0 W)

Cool-Down Parameters:

Length of Piping	20.000	Feet	(6.10 m)
Number of Nozzles	6		
Nozzle Diameter	0.500	Inches	(1.3×10^{-2} m)
Header Diameter	2.000	Inches	(5.1×10^{-2} m)

Cool-Down Time 0.1754 minutes

At 2.344 minutes from start of propellant transfer the supply tank is empty.

At this time the, receiver tank is at -422.89 °F (20.3 K), 16.23 psia (0.112 MPa), and contains 3098.00 pounds (1405.2 kg).

During the simulation 0.00 pounds (0.0 kg) were vented.

Supply tank is at -424.9907 °F (19.1 K), 31.55 psia (0.218 MPa).

a graphics terminal; CALL FR80(0.0) accesses microfilm. The running of program DEMO is separate from running SCAVAG and PLOT. Examples of plots from program DEMO are found in Appendix G.

4. RESULTS AND DISCUSSION

The feasibility of low-g propellant transfer is analyzed parametrically with the computer model. Particular emphasis is placed on the thermodynamic changes to the system caused by varying the temperature, pressure, or heat leak at any point. The principal parameter in this investigation is the overall time of transfer, since the transfer is to take place during a mated coast period after MECO. Other parameters of interest in the design of such a system are the pump size and piping requirements.

Nozzles are used during the cooldown of the receiver tank to induce a flowrate of propellant lower than the flowrate during the main part of the transfer. The sizes of the associated piping and nozzles, which are simply small orifices situated around the header, have been parametrically determined to accomplish a low flowrate without causing an excessive pressure drop. This specification holds except in those cases where the transition from the main piping to the cooldown piping is great. (Further explanation is provided later.) When two phases occur in the tank, the nozzles are shut off; the transfer via the main line resumes for the remainder of the simulation.

Because the transfer can require a pump, the liquid from the ET must be subcooled to prevent cavitation. This is most notably the case for LOX which has insufficient ullage pressure to accomplish a complete pressurized transfer. Single-phase flow from the supply tank also requires sufficient thrust to settle the liquid against the outlet port. We assume such a thrust for the purposes of this modelling effort.

When the program is run with the default parameters, the time required to complete the transfer of either propellant is relatively short. Transfer of LOX with a moderately sized booster pump takes 1.94 minutes; pressurized transfer of LH_2 requires 2.34 minutes. If the MECO mated coast period is

scheduled to continue to 20 minutes, the scavenging of both cyrogenic propellants can be completed in less than 12 percent of the alloted time. The final system conditions are shown in Table 7. Plots of the transfer are found in Appendix G.

Table 7. Final Conditions Using Default Values

	O_2		H_2	
Time of Transfer, min	1.936		2.344	
Receiver Tank				
Temperature, °F (K)	-312.35	(81.69)	-422.89	(20.28)
Pressure, psia (MPa)	6.72	(0.046)	16.23	(0.112)
Mass in Tank, lb (kg)	6270.	(2846.6)	3098.	(1405.2)
Mass Vented, lb (kg)	0.		0.	
Supply Tank				
Temperature, °F (K)	-314.9998	(80.22)	-424.9907	(19.12)
Pressure, psia (MPa)	19.88	(0.137)	31.55	(0.217)

4.1 Heat Leaks to the System

The conditions in the ET are governed by two opposing influences: outflow and heat leak. In the absence of heat leak, outflow gives an adiabatic expansion of the vapor and a resulting decay in temperature. In the absence of outflow, heat leak gives an increase in temperature and pressure. Figures 4 and 5 show the expected results of varying the amount of heat to the ET. Figure 4 shows that a large rate of heat flow into the LOX ET must be present for a significant change in the system parameters to occur.

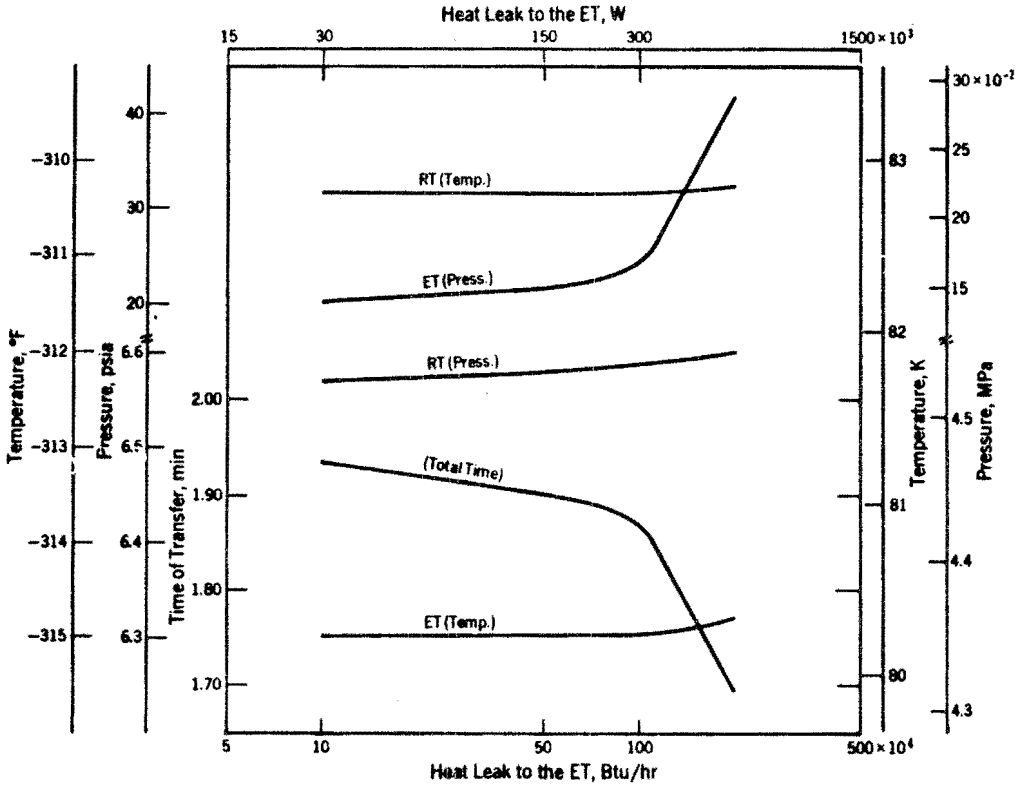


Figure 4a. Effect of varying the heat leak to the ET, LOX (default: 0 Btu/hr (0W))

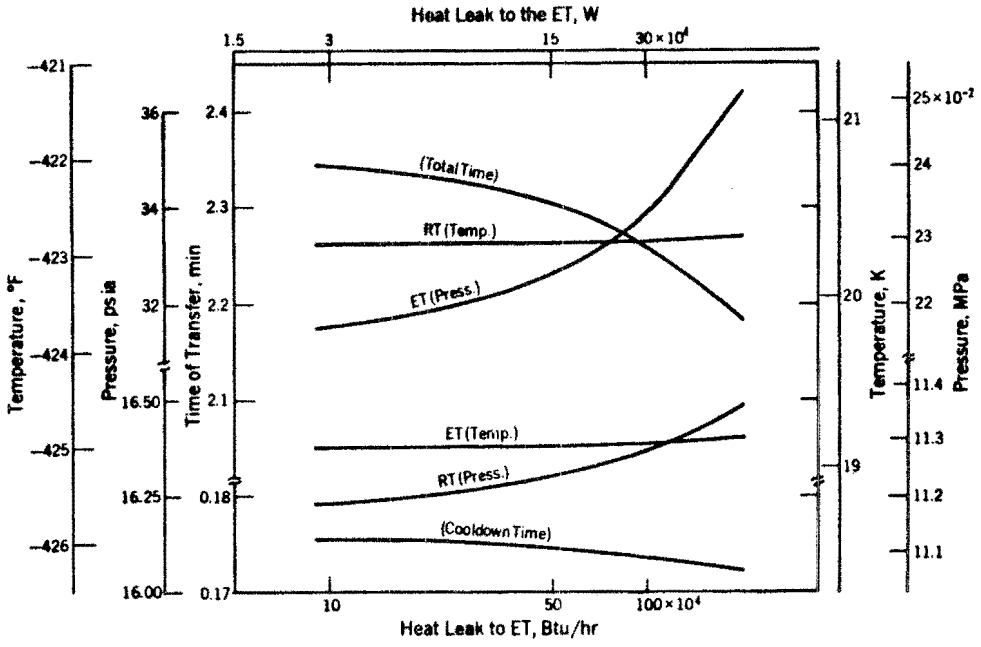


Figure 4b. Effect of varying the heat leak to the ET, LH_2 (default: 90,000 Btu/hr (2.6×10^4 W))

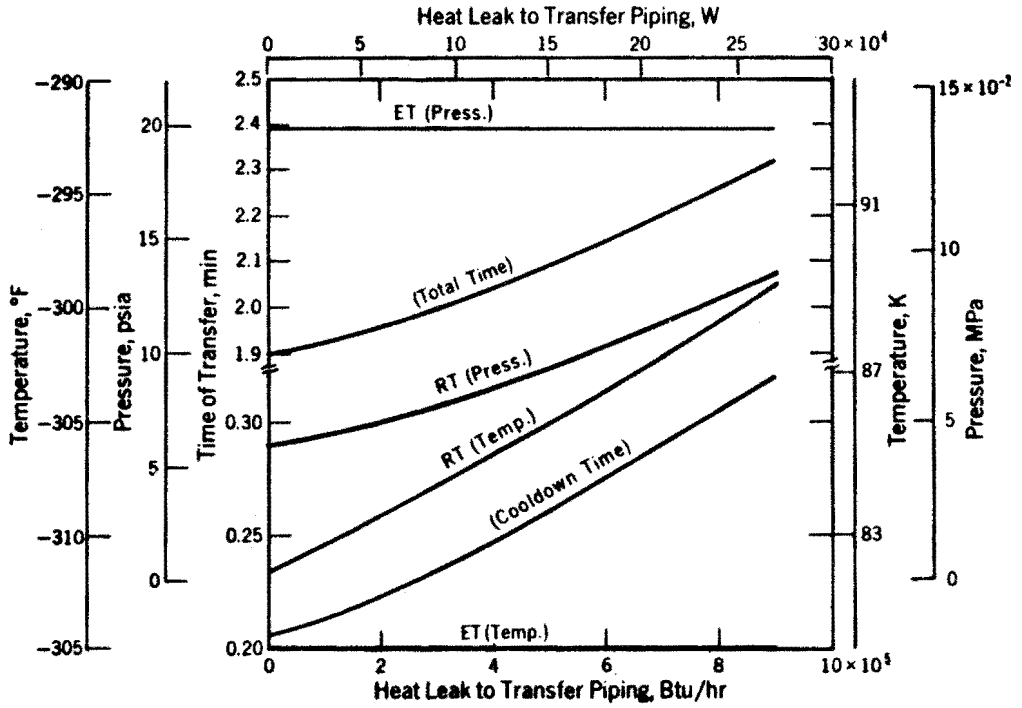


Figure 5a. Effect of varying the heat leak to the transfer piping, LOX (defualt: 104,400 Btu/hr (3.0×10^4 W))

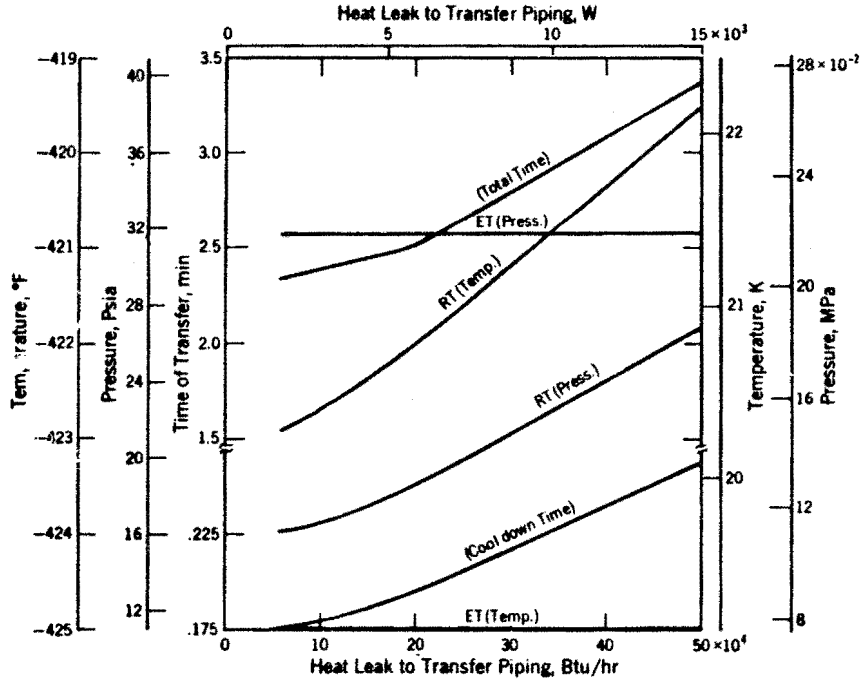


Figure 5b. Effect of varying the heat leak to the transfer piping, LH_2 (default: 50,400 Btu/hr (1.5×10^4 W))

The value at which this occurs is on the order of 10^6 Btu/hr (2.9×10^5 W). The pressures in both tanks undergo rapid increases, while the temperatures show slight increases.

The changes in temperature and pressure that the LH_2 system experiences are less abrupt than those of the LOX system. They do show the same trends, however. As the heat leak to the ET is increased, the pressures and temperatures show gradual increases.

As the heat leak to the transfer piping is increased, the final conditions in the receiver tanks for both propellants show a corresponding rise greater than the results for a heat leak to the ET. The results are presented in Figure 5. Venting occurs for LOX when the heat input is increased to 5×10^6 Btu/hr (1.5×10^6 W); approximately 28% of the propellant is vented. The LOX temperature of -284.29 °F (97.28 K) at the vent pressure is located at the liquid-vapor boundary. The pressure history for this transfer is shown in Figure 6.

Similar observations can be stated for the case of LH_2. When the heat leak to the transfer piping is increased to 10^6 Btu/hr (2.9×10^5 W), a small amount of fuel is vented. This occurs at the end of the transfer, as the fluid reaches the liquid-vapor boundary.

Conditions in the ET do not vary with an increased heat leak to the piping. This is due to the flow of cryogen from the tank which directs any potential effects to the receiver tank. The overall time of transfer increases linearly for both LOX and LH_2. The time required to transfer LOX remains quite brief, but the transfer requires an additional minute when 5×10^5 Btu/hr (1.5×10^5 W) leaks into the LH_2 piping.

The effect of heat leak into the receiver tank is similar to that into the transfer piping. For LH_2 the transfer time is increased by nearly a minute for a heat rate of 4×10^5 Btu/hr (1.2×10^5 W). Increasing the heat

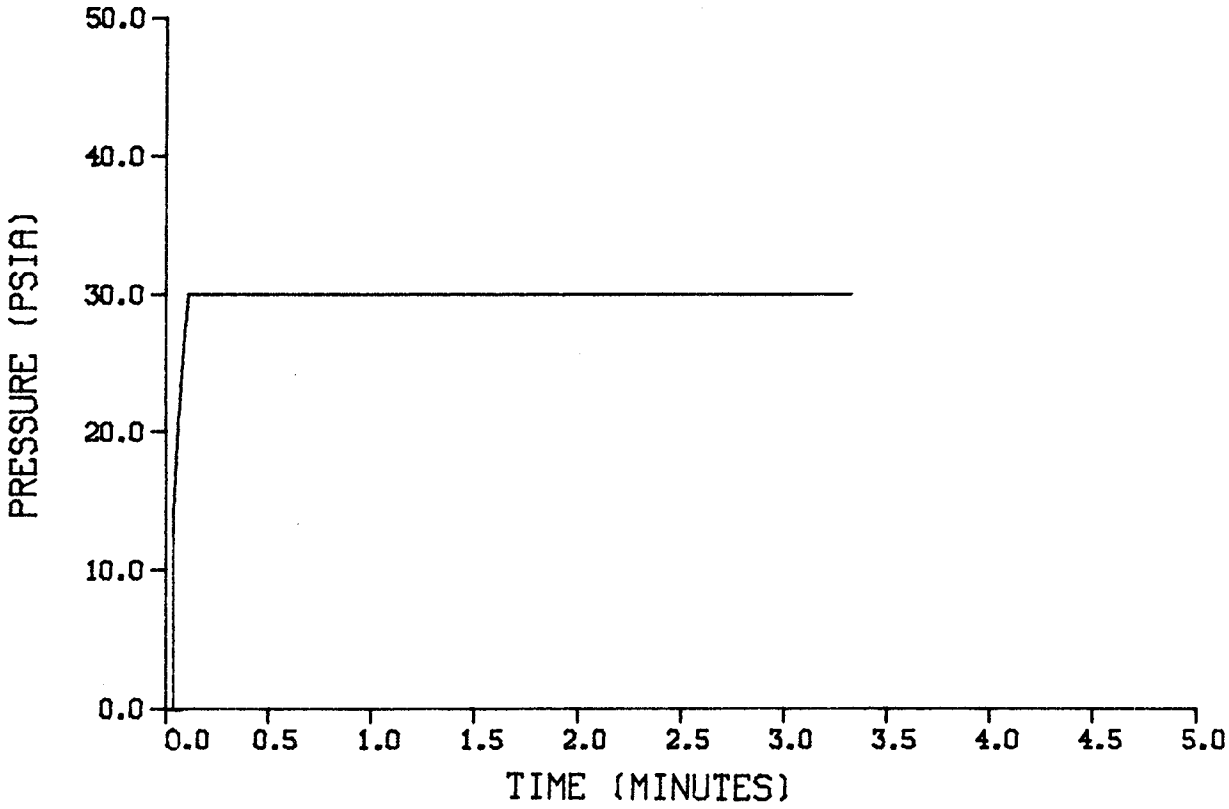


Figure 6. Pressure history of LOX transfer for a heat leak of 2×10^6 Btu/hr (5.8×10^5 W) to the transfer piping

leak to the receiver tank at the rate of 10^6 Btu/hr (2.9×10^5 W) causes LH_2 to vent. The transfer time for LOX rises smoothly with increased heat input; an additional minute is required to transfer LOX at a heat leak of 1.2×10^6 Btu/hr (3.5×10^5 W). Also, venting takes place at this rate of heat addition. These results are shown in Figure 7.

4.2 Receiver Tank Temperature

Since the temperature for the LOX receiver tank is unspecified in the study by Brux and Stefan [1], the effects of several temperatures were examined in this study. The results are shown in Figure 8. It can be assumed that the receiver tank will receive some soakback heat leak from the insulation as well as radiation prior to MECO. Thus, temperatures higher than cryogenic are realistic and allow examination of the chilldown process. A wide range of initial temperatures neither significantly alters the time required to transfer the oxygen nor the final receiver tank temperature. The coolest temperature input of -100 °F (199.7 K) would require the vessel to be prechilled on the ground. For temperatures above 120° F (321.8 K) a small amount of venting (less than 1 percent) takes place at the beginning of transfer. This rapid increase of the RT pressure to the vent pressure is shown in Figure 9.

The study by Brux and Stefan [1] recommends that the LH_2 receiver tank be prechilled to -290 °F (94.1 K) to prevent venting during the transfer after MECO. They state that at higher temperatures, a large amount of venting would be required to achieve chilldown of the receiver tank. We find that only minor venting at the start of the transfer takes place when given an initial temperature between -250° F (116.3 K) and -50 °F (227.4 K). For all cases, the overall time of transfer is less than 2.80 minutes.

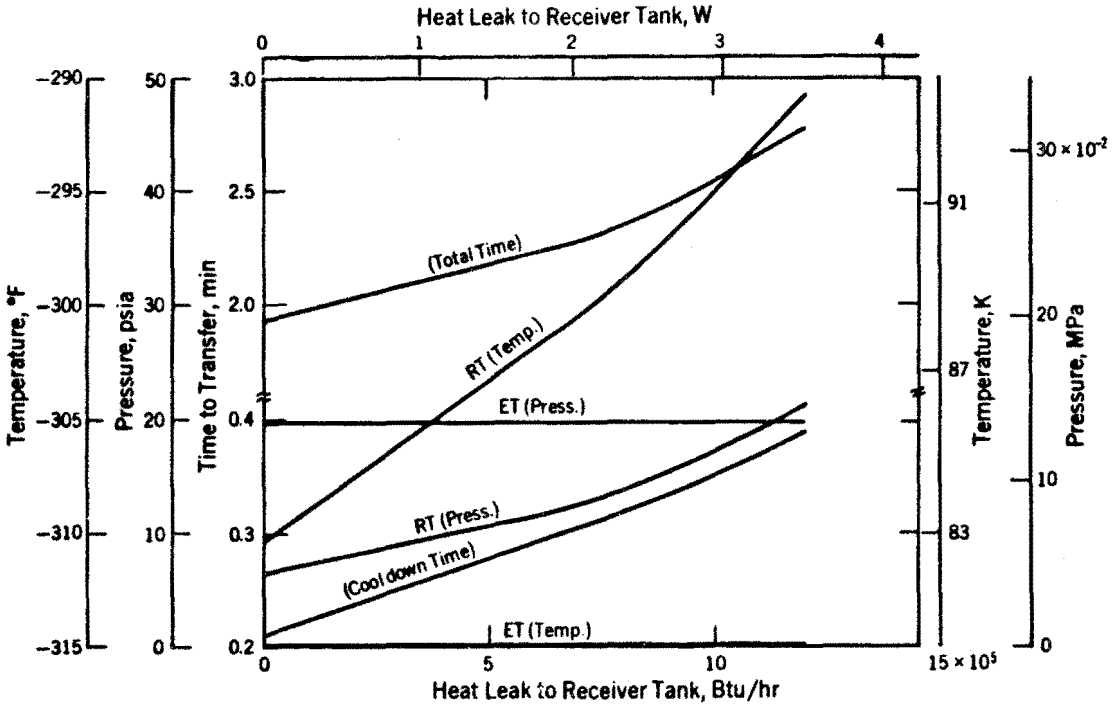


Figure 7a. Effect of varying the heat leak to the receiver tank, LOX (default: 0 Btu/hr (0 W))

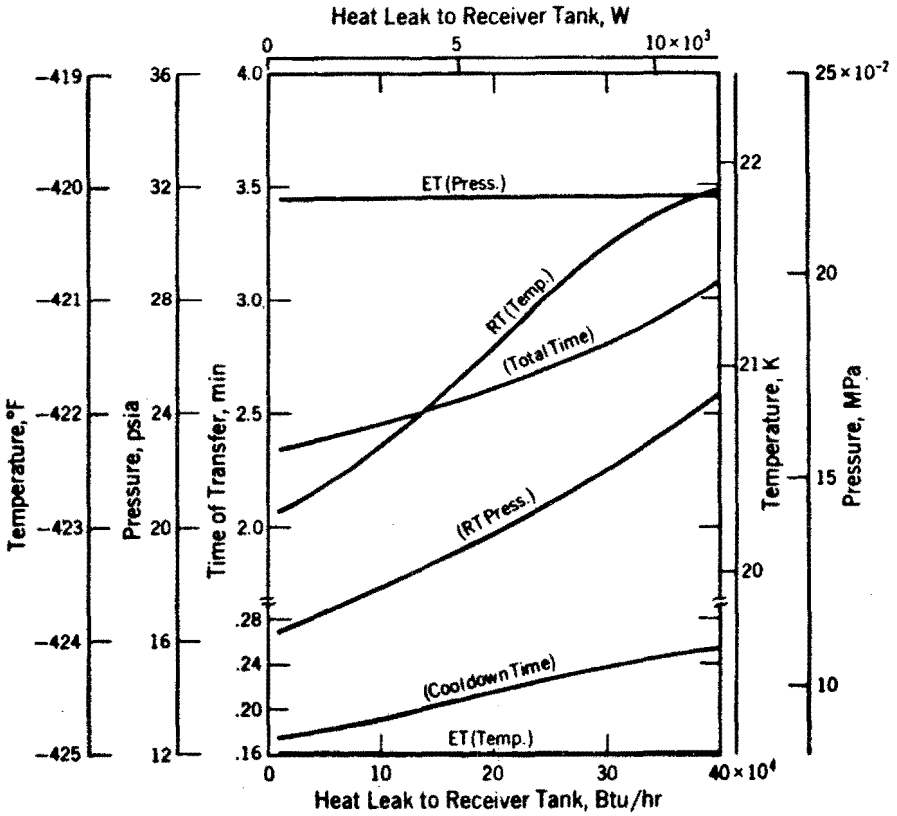


Figure 7b. Effect of varying the heat leak to the receiver tank, LH_2 (default: 0 Btu/hr (0 W))

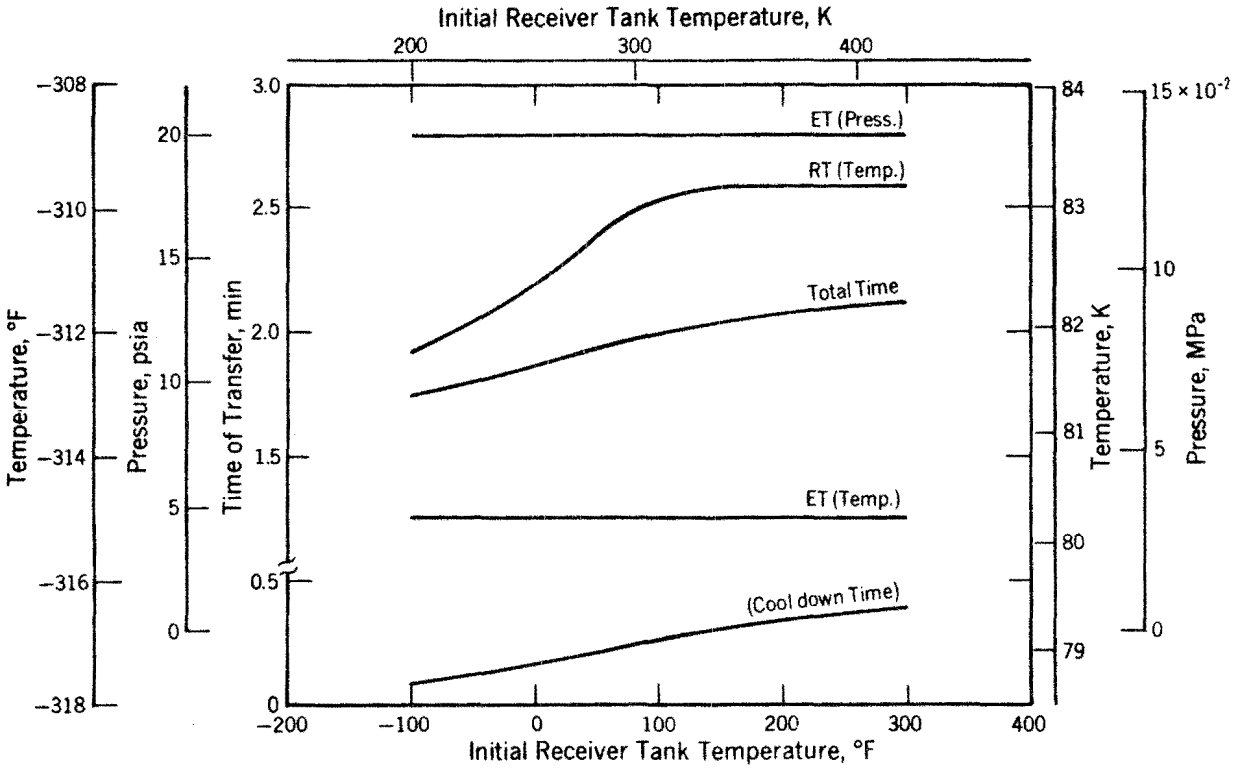


Figure 8a. Effect of varying the initial receiver tank temperature, LOX (default: 60°F (288.6 K))

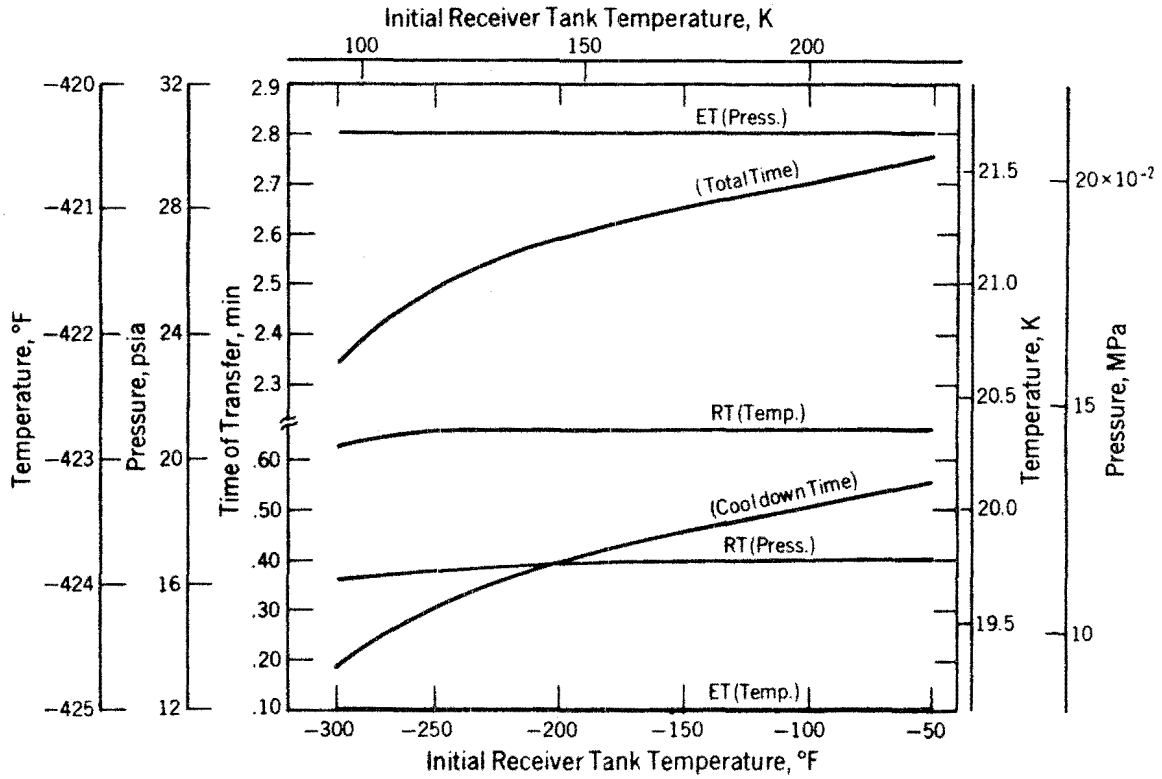


Figure 8b. Effect of varying the initial receiver tank temperature, LH_2 (default: -290°F (94.1 K))

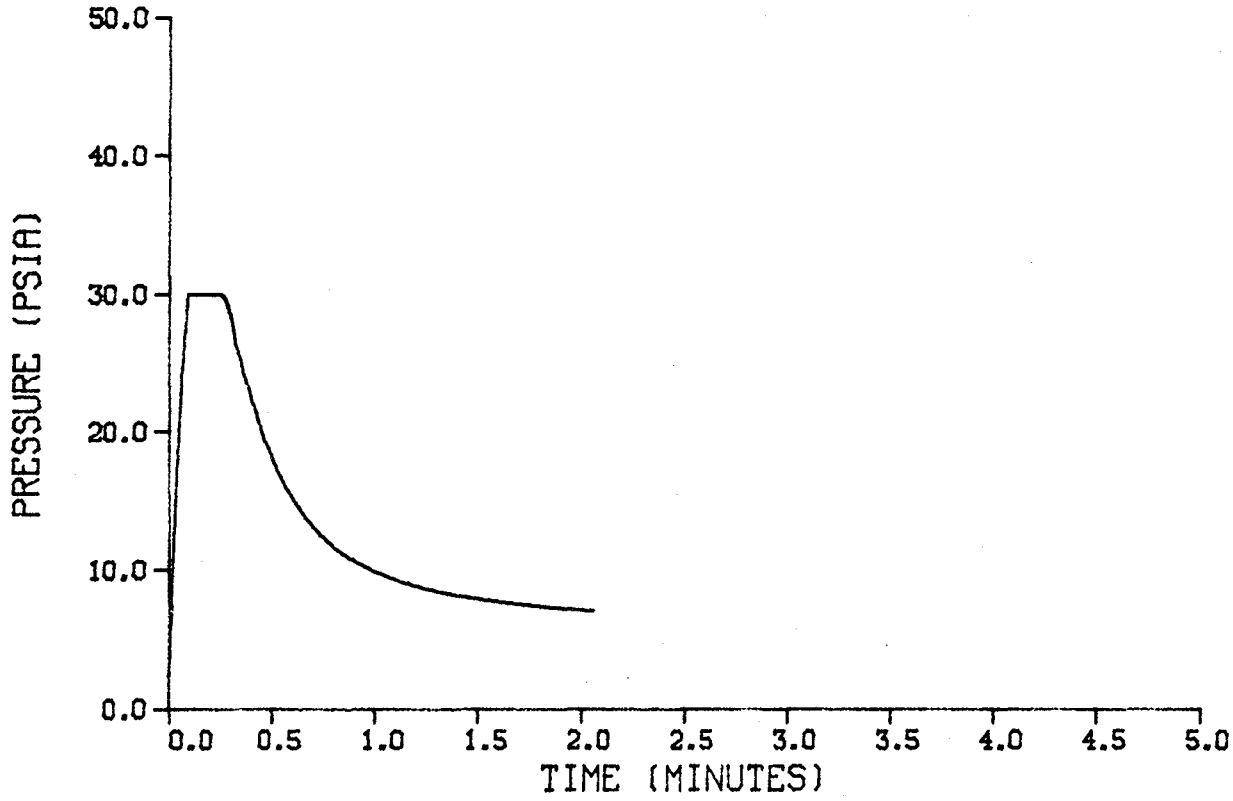


Figure 9. Pressure history of LOX transfer for an initial receiver tank temperature of 200 °F (366.3 K)

4.3 ET Temperature

Since the previous study [1] indicates the ET fluid is subcooled, the default initial temperatures in this study were between the melting line and the liquid-vapor boundary [3,4,5]. Increasing the ET initial temperatures cause longer transfer times, while additional cooling accomplishes the transfer faster. As the melting line temperature of either propellant is approached, failure of the Fluids Pack [2] routine occurs. When the temperature reaches the vapor-liquid boundary, the simulation stops due to vapor induced cavitation. Because the transfer of LH_2 is pressure induced, the transfer times are significantly affected by warmer ET temperatures. Additional cooling time is required before the switch to the transfer mode through the main piping.

4.4 Pipe Size and Pump Requirement

When the values for line size and pump power suggested by Brux and Stefan [1] are used in the model, the time required to transfer the nominal quantity of either propellant is less than 3 minutes. Because the mated coast period after MECO probably will be somewhat longer than this, transfer times of approximately 8 minutes or less appear reasonable. Such transfer times are obtained with a number of cases where the transfer pipe diameter or the pump size is changed. Figure 10 illustrates these changes.

If the LOX default pump size remains unchanged at 4 HP (2982.8 W) while the line size is reduced to 2 inches (5.1 cm), the transfer time is slightly less than 7 minutes. When the pump size is reduced by half, the transfer time is less than 4 minutes for a 3-inch (7.6 cm) diameter pipe. Line sizes of

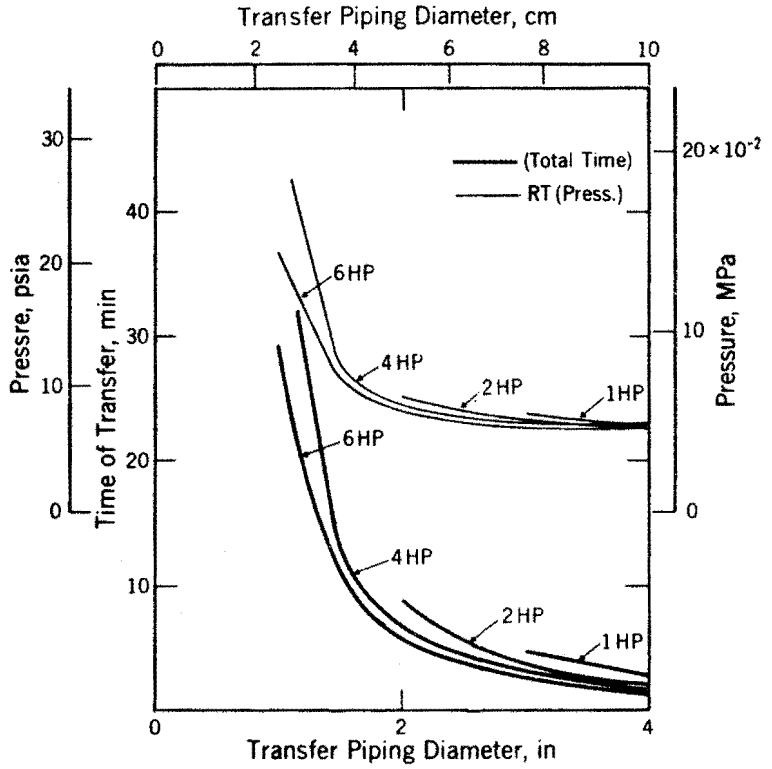


Figure 10a. Effect of varying the pump or transfer line sizes, LOX (default: 4 HP (2982.8 W), 4 in (10.2 cm))

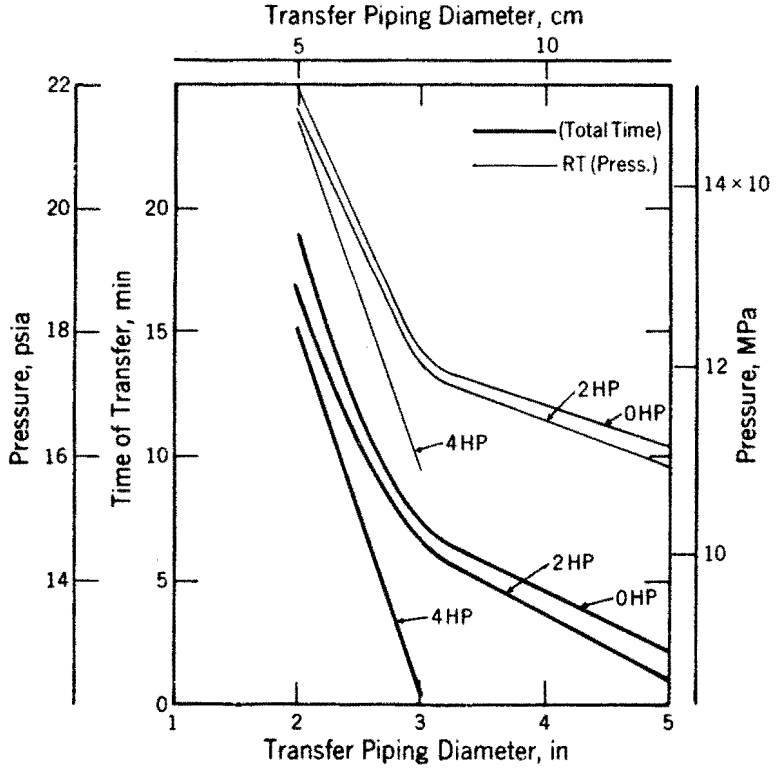


Figure 10b. Effect of varying the pump or transfer line sizes, LH_2 (default: 0HP (0W), 5 in (12.7 cm))

approximately 1 inch (2.5 cm) appear to restrict the flow too much and cause venting in the receiver tank and extremely long transfer times. A 6-inch (15.2 cm) line size promotes a fast transfer of the remaining LOX propellant, but it also is heavy; no further study of this line size was done. Since the smaller line sizes would be lighter, easier to design around the existing equipment, and less costly, reducing the line size from the default value of 4 inches (10.1 cm) to 3 inches (7.6 cm) is a reasonable exchange for the increase in transfer time. A pump size of 2 HP (14914.4 W) would not tax the energy requirements in the system.

Similar results are seen for LH_2 scavenging. A reasonable transfer time of slightly more than 7 minutes is obtained when a 3-inch (7.6 cm) line size is used without pump assist. However, there appears to be too much flow resistance in smaller line sizes, even with the assistance of a pump. Hence, longer transfer times are seen for these cases, even when a large pump is used. When a 2 HP (14914.4 W) pump is used with 3-inch (7.6 cm) piping, the time is reduced to slightly less than 6.5 minutes. Reducing the line size to 3 or 4 inches (7.6 or 10.1 cm) and pressurized transfer of LH_2 is an optimum combination for the system.

4.5 Limitations

Accuracy for the results is limited by the size of the time step used in program. When a very small step is used, the amount of computer time required is large and consequently quite costly. Thus, the time steps used in the previously discussed analyses are large enough to allow speedy computation, yet small enough to yield reasonable accuracy. When the time step is reduced by a factor of seven in SUBROUTINE COOL and by a factor of thirteen

in SCAVAG, the total time required to transfer LOX propellant changes by less than 1.5 percent. However, the computer time required for this run increases by a factor of 80.

5. SUMMARY

We have developed a computer model to investigate the scavenging of cryogenic propellant from the ET to shuttle mounted receiver tanks in the cargo bay. Based on the requirement that sufficient thrust exists to settle the liquid in the ET, the model predicts the successful transfer of liquid oxygen and hydrogen in short periods of time, typically less than 2.5 minutes for both LOX and LH_2 using the default parameters in the program. A parametric analysis was performed to evaluate the effects of heat fluxes to various system components, prechilling the receiver tank, and line and pump size variations.

Moderate to large heat fluxes affect the pressurized transfer of LH_2 more than the pump-assisted transfer of oxygen. Heat leaks to the ET increase the pressure, and thus speed up the transfer of LH_2. Heat leaks to the piping or receiver tank slow down the transfer of both propellants due to additional receiver tank chilling demands, and cause venting at sufficiently high fluxes.

Prechilling the receiver tank for LH_2 is a critical requirement. The LH_2 receiver tank must be approximately -290 °F (94.1 K) in order to transfer the fluid without venting. The LOX receiver tank can be close to 300 °F (421.9 K) without the significant venting of fluid.

Line and pump size selection are dependent on the time allowed, the piping design constraints and energy demands of the transfer system.

Pump-assisted transfer in the LOX scavenging is needed, and by using a 2 HP (1491.4 W) pump and a 3-inch pipe diameter, a relatively lightweight, fast system can be used. Liquid hydrogen can be transferred by pressure difference in a 3-inch line. The smaller line and pump sizes allow the transfer to be completed in less than 8 minutes.

APPENDIX A

Derivation of single-phase receiver tank equations:

First Law

$$dU = dQ_{total} + h_1 dm_1 + h_2 dm_2$$

Mass Balance $\quad dm = dm_1 + dm_2$

By applying the mass balance to the system and assuming $h = h_2$, the first law may be expressed as:

$$mdu + udm = dQ_{total} + h_1 dm_1 - h(dm_1 - dm)$$

$$du = \frac{dQ_{total}}{m} + \frac{h_1 dm_1}{m} - \frac{h(dm_1 - dm)}{m} - \frac{udm}{m}$$

$$du = \frac{dQ_{total}}{m} + \frac{dm_1}{m}(h_1 - h) + \frac{dmPv}{m} . \qquad (A.1)$$

Because we wish to find temperature as a function of mass flow we next expand du. The total differential energy equation with respect to temperature and density is given by

$$du = \left(\frac{\partial u}{\partial T}\right)_\rho dT + \rho \left(\frac{\partial u}{\partial \rho}\right)_T \frac{d\rho}{\rho}$$

$$du = C_v dT - v \left(\frac{\partial u}{\partial v}\right)_T \frac{d\rho}{\rho} . \qquad (A.2)$$

By using the thermodynamic relationship

$$du = Tds - Pdv$$

we can obtain

$$v \left(\frac{\partial u}{\partial v}\right)_T = Tv \left(\frac{\partial s}{\partial v}\right)_T - Pv .$$

The definitions for C_v and the Grüneisen parameter ϕ are

$$C_v = T\left(\frac{\partial s}{\partial T}\right)_v$$

$$\phi = \frac{\rho}{T}\left(\frac{\partial T}{\partial \rho}\right)_s$$

and the chain rule gives

$$v\left(\frac{\partial u}{\partial v}\right)_T = \phi T C_v - \frac{P}{\rho} .$$

Equation (2) then becomes

$$du = C_v dT - (\phi T C_v - \frac{P}{\rho}) \frac{dm}{m} . \qquad (A.3)$$

Combining Equations (1) and (3) and solving for dT yields:

$$C_v dT - (\phi T C_v - \frac{P}{\rho}) \frac{dm}{m} = \frac{dQ_{total}}{m} + \frac{dm_1}{m} (h_1 - h) + \frac{dm\ Pv}{m}$$

or

$$dT = \frac{1}{m} \left\{ (\phi T dm + \frac{(h_1 - h)}{C_v}) dm_1 + \frac{dQ_{total}}{C_v} \right\}. \qquad (A.4)$$

The heat flux is the sum of the heat leak through the tank and the heat in the wall of the tank,

$$dQ_{total} = dQ + dQ_w$$

$$dQ_w = - m_w C_{p_w} dT \quad .$$

Substituting these expressions into the temperature equation yields the following expression:

$$dT + \frac{m_w C_{p_w}}{C_v m} dT = \frac{1}{m} \left(\phi T dm + \frac{(h_1 - h)}{C_v} dm_1 + \frac{dQ}{C_v} \right) .$$

Upon rearrangement the following relationship is obtained:

$$dT = \frac{\phi T dm + (h_1 - h) dm_1 / C_v + dQ / C_v}{m + m_w C_{p_w} / C_v} . \qquad (A.5,3)$$

We next wish to find pressure as a function of mass flow. The total differential energy equation with respect to pressure and density is given by

$$du = \left(\frac{1}{\rho}\right) \rho \left(\frac{\partial u}{\partial P}\right)_\rho dP + \rho \left(\frac{\partial u}{\partial \rho}\right)_P \frac{d\rho}{\rho} .$$

The first term on the right-hand side contains the Grüneisen parameter which is also defined as

$$\phi = \frac{1}{\rho}\left(\frac{\partial P}{\partial u}\right)_{\rho} .$$

The second term on the right-hand side may be expressed with the heat of expulsion

$$\theta = - \rho \left(\frac{\partial h}{\partial \rho}\right)_{P} \tag{A.6}$$

and by using the definition of enthalpy to give

$$\rho\left(\frac{\partial u}{\partial \rho}\right)_{P} = \rho\left(\frac{\partial h}{\partial \rho}\right)_{P} + \frac{P}{\rho} .$$

The differential energy equation may then be written as

$$du = \frac{1}{\rho\phi}\, dP - \left(\theta - \frac{P}{\rho}\right)\, \frac{d\rho}{\rho} . \tag{A.7}$$

Combining Equations (A.1) and (A.6) and solving for dP when $dm_1 = dm$ yields the following expression:

$$dP = \frac{1}{V}\left(\phi\, [\theta + h_1 - h]\, dm + \phi(dQ - m_w C_w dT)\right). \tag{A.8}$$

When dm_1 is not equal to dm, there is flow through the vent. Thus, dP = 0 and

$$dm = \frac{[(h - h_1)dm_1 - dQ + m_w C_w dT]}{\theta} \tag{A.9,5}$$

Appendix B

Derivation of two-phase receiver tank equations:

First Law

$$dU = dQ - dW + \Sigma\, h_1 dm_1$$

Since there is no work done, the first law may be expressed as:

$$m_\ell du_\ell + m_v du_v + u_\ell dm_\ell + u_v dm_v = dQ_{total} + h_1 dm_1 + h_2 dm_2 \quad (B.1)$$

Continuity

$$dm_\ell + dm_v = dm_1 + dm_2 \quad (B.2,7)$$

Constant volume

$$v_\ell dm_\ell + m_\ell dv_\ell + v_v dm_v + m_v dv_v = 0 \; . \quad (B.3,9)$$

Solving for dm_ℓ

$$dm_\ell = - \frac{v_v}{v_\ell} dm_v - \frac{1}{v_\ell} (m_\ell dv_\ell + m_v dv_v)$$

Let

$$dv_{sat} = \left(\frac{\partial v}{\partial p} \right)_{sat} dp \quad .$$

The equation for the differential mass of the liquid in the tank is:

$$dm_\ell = - \frac{v_v}{v_\ell} dm_v - \frac{1}{v_\ell} \left[m_\ell \left(\frac{\partial v}{\partial p} \right)_\ell + m_v \left(\frac{\partial v}{\partial p} \right)_v \right] dP \quad . \quad (B.4)$$

Substituting Equation (B.4) into Equation (B.2) produces the following expression:

$$- \frac{v_v}{v_\ell} dm_v + dm_v - \frac{1}{v_\ell} \left[m_\ell \left(\frac{\partial v}{\partial p} \right)_\ell + m_v \left(\frac{\partial v}{\partial p} \right)_v \right] dP = dm_1 + dm_2 \quad .$$

Solving for the differential mass of the vapor:

$$dm_v = \frac{dm_1 + dm_2 + \frac{1}{v_\ell}\left[m_\ell\left(\frac{\partial v}{\partial p}\right)_\ell + m_v\left(\frac{\partial v}{\partial p}\right)_v\right]dP}{(1 - v_v/v_\ell)} \quad . \qquad (B.5)$$

Substituting Equation (B.5) into Equation (B.4), we obtain the following equation for dm_ℓ

$$dm_\ell = \frac{-(v_v/v_\ell)(dm_1 + dm_2) - \frac{1}{v_\ell}\left[m_\ell\left(\frac{\partial v}{\partial p}\right)_\ell + m_v\left(\frac{\partial v}{\partial P}\right)_v\right]dP}{(1 - v_v/v_\ell)} \quad . \qquad (B.6,10)$$

Combining Equations (B.1), (B.5) and (B.6), we obtain

$$m_\ell\left(\frac{\partial u}{\partial P}\right)_\ell dP + m_v\left(\frac{\partial u}{\partial p}\right)_v dP - u_\ell\left\{\frac{v_v}{v_\ell}\ \frac{dm_1 + dm_2}{(1 - v_v/v_\ell)}\right.$$

$$\left. + \frac{\frac{1}{v_\ell}\ m_\ell\left(\frac{\partial v}{\partial p}\right)_\ell + m_v\left(\frac{\partial v}{\partial P}\right)_v\ dP}{(1 - v_v/v_\ell)}\right\} + \left\{u_v\ \frac{dm_1 + dm_2}{(1 - v_v/v_\ell)}\right.$$

$$\left. + \frac{\frac{1}{v_\ell}\ m_\ell\left(\frac{\partial v}{\partial p}\right)_\ell + m_v\left(\frac{\partial v}{\partial p}\right)_v\ dP}{(1 - v_v/v_\ell)}\right\} = dQ_{total} + h_1 dm_1 + h_2 dm_2 \quad . \qquad (B.7)$$

We can solve Equation (B.7) for the differential pressure when there is no venting:

$$dP = \frac{\left[h_1 - u_v + \frac{v_v}{v_\ell}(u_\ell - h_1)\right]dm_1 + dQ_{total}(1 - v_v/v_\ell)}{F(p)} \quad . \qquad (B.8,11a)$$

where

$$F(p) = m_\ell \left[\left(\frac{\partial u}{\partial P}\right)_\ell \left(1 - \frac{v_v}{v_\ell}\right) + \frac{1}{v_\ell} \left(\frac{\partial v}{\partial P}\right)_\ell (u_v - u_\ell) \right]$$

$$+ m_v \left[\left(\frac{\partial u}{\partial P}\right)_v \left(1 - \frac{v_v}{v_\ell}\right) + \frac{1}{v_\ell} \left(\frac{\partial v}{\partial P}\right)_v (u_v - u_\ell) \right] \qquad \text{(B.9,11b)}$$

$$- m_w C_w \left(\frac{\partial T}{\partial P}\right)_{sat} \left(1 - \frac{v_v}{v_\ell}\right) .$$

When there is venting, the pressure is constant. Since dP = 0, the following equation is obtained when Equation (B.7) is solved:

$$0 = u_\ell \left(\frac{v_v}{v_\ell} \frac{dm_1 + dm_2}{(1 - v_v/v_\ell)} \right) - \left(u_v \frac{dm_1 + dm_2}{(1 - v_v/v_\ell)} \right)$$

$$+ dQ - m_w C_w dT + h_1 dm_1 + h_2 dm_2 .$$

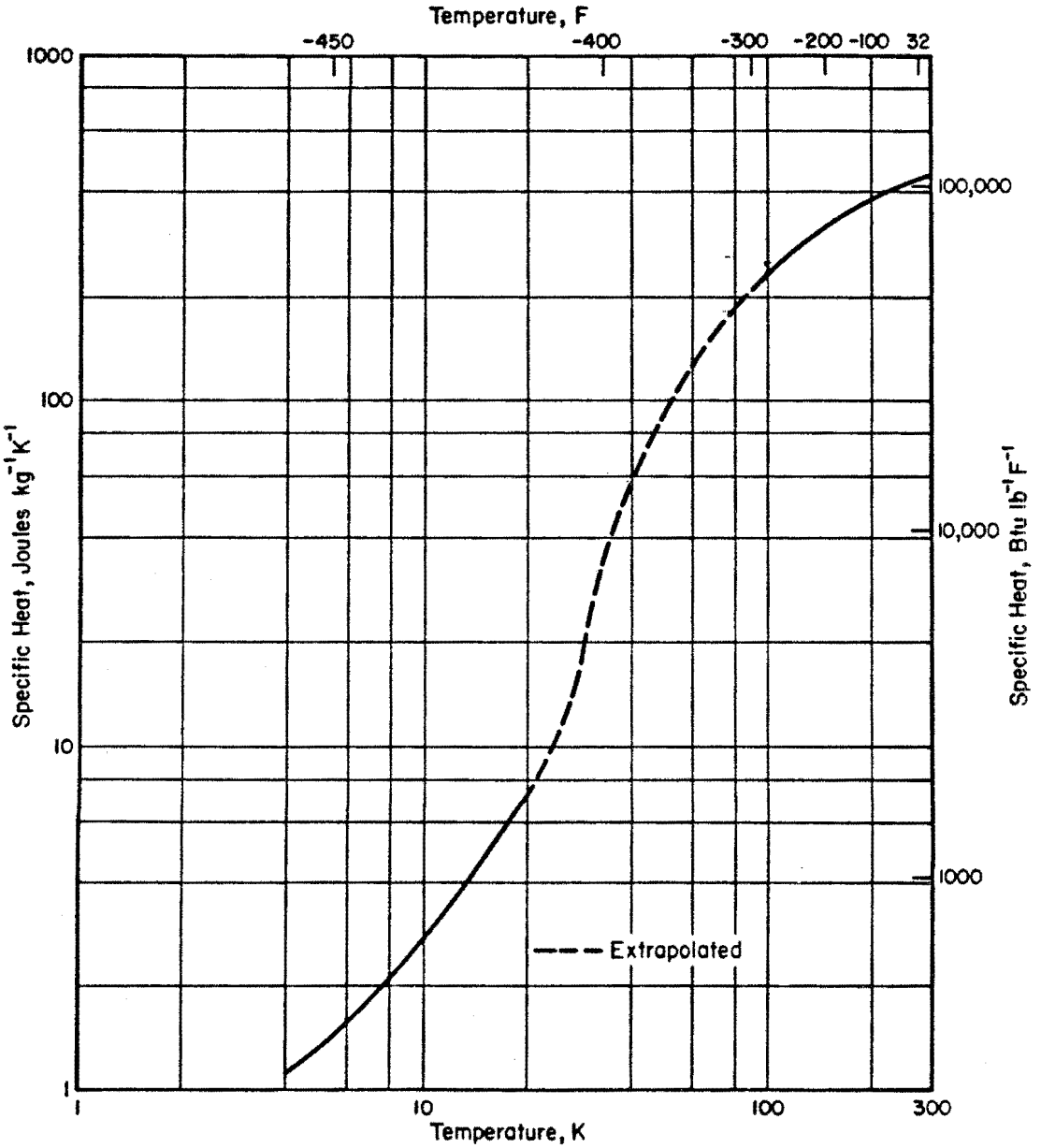
Finally, an expression for the differential mass through the vent is obtained:

$$dm_2 = \frac{\left[u_\ell \frac{v_v}{v_\ell} - u_v + h_1 \left(1 - \frac{v_v}{v_\ell}\right) \right] dm_1 + dQ \left(1 - \frac{v_v}{v_\ell}\right)}{(h_v - h_\ell) \frac{v_v}{v_\ell}} \qquad \text{(B.10,12)}$$

Appendix C

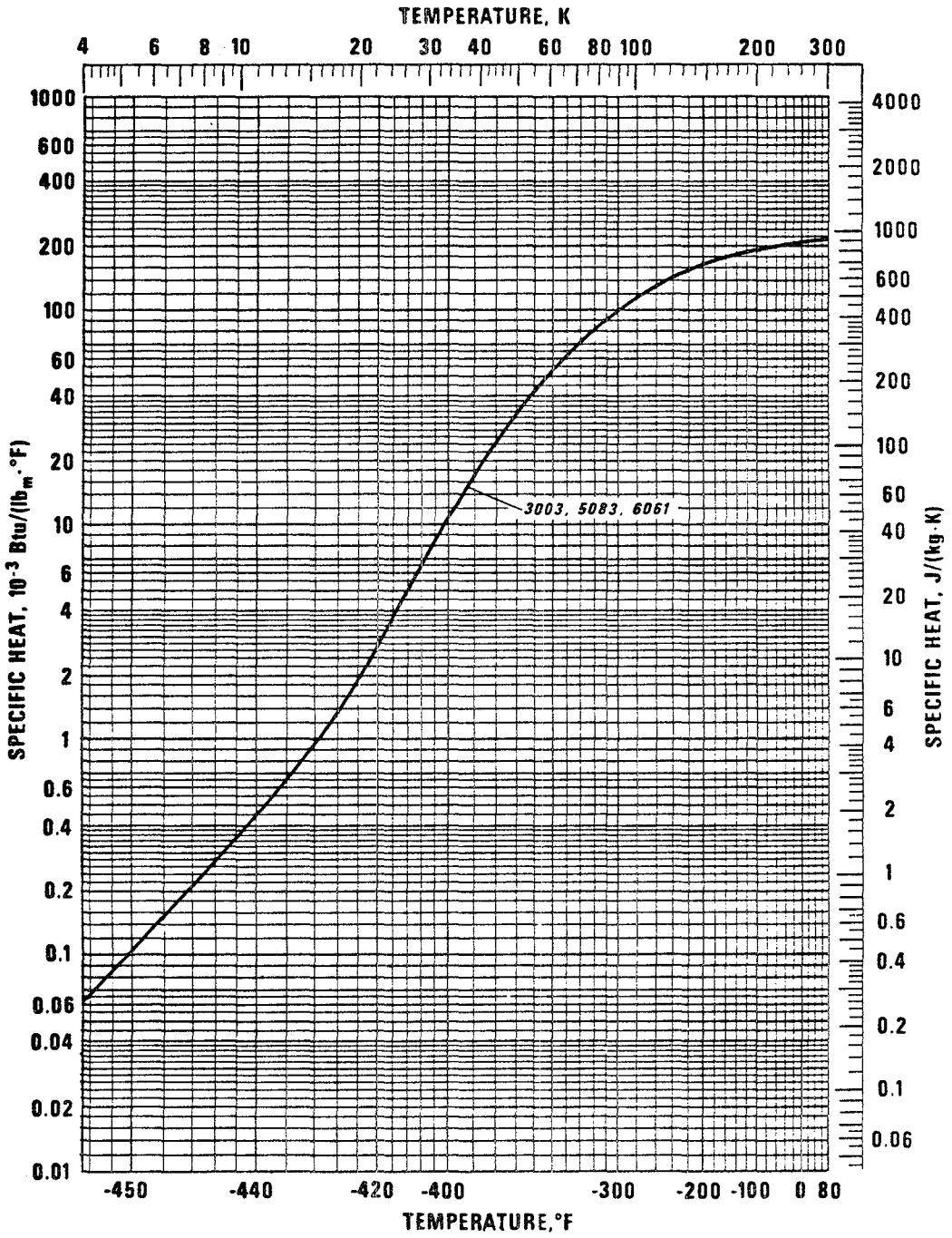
Tank Material Physical Data

INCONEL*[12]



*Such recommendation does not imply recommendation or endorsement by the National Bureau of Standards.

ALUMINUM [13]


TEMPERATURE, K
4 6 8 10 20 30 40 60 80 100 200 300
1000 600 400 200 100 60 40 20 10 6 4 2 1 0.6 0.4 0.2 0.1 0.06 0.04 0.02 0.01
SPECIFIC HEAT, 10⁻³ Btu/(lbm·°F)
4000 2000 1000 600 400 200 100 60 40 20 10 6 4 2 1 0.6 0.4 0.2 0.1 0.06
SPECIFIC HEAT, J/(kg·K)
3003, 5083, 6061
-450 -440 -420 -400 -300 -200 -100 0 80
TEMPERATURE, °F

Appendix D

Conversion factor calculation

The conversion factor C for Equation (26) may be derived as follows:

$$32\ C = \frac{\Delta P\ \rho\pi^2\ D^5}{fL(dm)^2M}$$

where ΔP = atm

ρ = gmol/ℓ

D = cm

L = m

M = g/gmol

Therefore,

$$32C = \frac{(atm)(gmol/\ell)(cm^5)}{(m)(gmol/s)^2(g/gmol)} \left(\frac{1m}{100\ cm}\right)^5 \left(\frac{1\ \ell}{0.001\ m^3}\right)^2 \left(\frac{1\ kg\ m2}{J\ s^2}\right)$$

$$\times \left(\frac{1000\ g}{1\ kg}\right)\left(\frac{101.325\ J}{1\ \ell\ atm}\right)$$

$$32C = 3.158\ \frac{(atm)(s^2)(cm^5)}{(m)(\ell)(g)}$$

Appendix E

Derivation of the supply tank equations:

First Law

$$dU = dQ - dW + \Sigma h_i m_i$$

The first law can be written for both phases, and when the mass of vapor is held constant we have the following expression:

vapor phase $\quad m_v du_v = dQ_v - P(m_v dv_v)$

Since $\quad m_v h_v = m_v u_v + P m_v v_v$

then $\quad dh_v - v_v dP = du_v + P dv_v$.

Upon substitution and rearrangement, the vapor phase enthalpy equation becomes:

$$dh_v = \frac{dQ_v}{m_v} + v_v dP \quad . \qquad \text{(E.1,13a)}$$

For the liquid the first law may be expressed as

liquid phase $\quad m_\ell du_\ell + u_\ell dm_\ell = dQ_\ell - P m_\ell dv_\ell - P v_\ell dm_\ell + h_\ell dm_\ell$.

By using the previous substitution and rearrangement, the liquid phase enthalpy equation can be written as

$$dh_\ell = \frac{dQ_\ell}{m_\ell} + v_\ell dP \ . \qquad \text{(E.2,13b)}$$

Volume

Since the ET volume is constant the following expression is used:

$$V = \text{constant} = v_\ell m_\ell + v_v m_v \ .$$

Upon rearrangement,

$$v_\ell dm_\ell = - (m_\ell dv_\ell + m_v dv_v) \ . \tag{E.3}$$

The total derivative for volume with respect to pressure and enthalpy is expressed as

$$dv = \left(\frac{\partial v}{\partial h}\right)_P dh + \left(\frac{\partial v}{\partial P}\right)_h dP \ . \tag{E.4}$$

We recall the definition for the heat of expulsion θ and substitute it for the first term in the total volume derivative as follows:

$$\theta = -\rho \left(\frac{\partial h}{\partial \rho}\right)_P = v \left(\frac{\partial h}{\partial v}\right)_P$$

$$\left(\frac{\partial v}{\partial h}\right)_P dh = \frac{v}{\theta} dh \ .$$

To elucidate the thermodynamic nature of the second partial derivative, the following thermodynamic identity is used:

$$\left(\frac{\partial v}{\partial P}\right)_h \left(\frac{\partial h}{\partial v}\right)_P \left(\frac{\partial P}{\partial h}\right)_v = - 1 \ .$$

The term $\left(\frac{\partial v}{\partial P}\right)_h$ can be expressed in terms of θ

$$\left(\frac{\partial v}{\partial P}\right)_h = -\left(\frac{\partial v}{\partial h}\right)_P \left(\frac{\partial v}{\partial P}\right)_v = - \frac{v}{\theta} \left(\frac{\partial h}{\partial P}\right)_v .$$

The definition for the Grüneisen parameter can be used with the first law to eliminate the remaining partial derivative. The Grüneisen parameter is:

$$\phi = \frac{1}{\rho}\left(\frac{\partial P}{\partial u}\right)_\rho = v\left(\frac{\partial P}{\partial u}\right)_v \ .$$

By writing the first law in terms of derivatives with respect to pressure at constant volume, we can make the following substitutions:

$$\left(\frac{\partial h}{\partial P}\right)_v = \left(\frac{\partial u}{\partial P}\right)_v + v$$

$$= \frac{v}{\phi} + v$$

$$= v\left(\frac{\phi + 1}{\phi}\right).$$

The second term in Equation (E.4) can be expressed as:

$$\left(\frac{\partial v}{\partial P}\right)_h = -\frac{v}{\theta}\left(\frac{v(\phi + 1)}{\phi}\right).$$

Equation (E.4) can now be expressed by the following relationship

$$dv = \frac{v}{\theta}\, dh - \frac{v^2(\phi + 1)}{\theta\phi}\, dP \ . \qquad (E.5)$$

We can substitute Equation (E.5) into (E.3) to obtain the following relationship:

$$\frac{dm_\ell}{m_\ell} = -\frac{dh_\ell}{\theta_\ell} - \frac{m_v v_v}{m_\ell v_\ell}\frac{dh_v}{\theta_v} + \frac{v_\ell}{\theta_\ell}\left(\frac{\phi + 1}{\phi}\right)_\ell$$

$$+ \frac{m_v v_v^2}{m_\ell v_\ell \theta_v}\left(\frac{\phi + 1}{\phi}\right)_v dP \ . \qquad (E.6)$$

By solving Equations (E.1), (E.2), and (E.3) simultaneously, a relationship for the ET pressure is found:

$$dP = \frac{\dfrac{dm_\ell}{m_\ell} + \dfrac{v_v dQ_v}{m_\ell v_\ell \theta_v} + \dfrac{1}{\theta_\ell}\dfrac{dQ_\ell}{m_\ell}}{\dfrac{v_\ell}{\theta_\ell \phi_\ell} + \dfrac{m_v v_v^2}{m_\ell v_\ell \theta_v \phi_v}} \ . \qquad (E.7,14)$$

An expression for the temperature of the liquid can be obtained by using the liquid enthalpy equation (E.2) and the total enthalpy derivative.

The total enthalpy derivative with respect to temperature and pressure is given by:

$$dh = \left(\frac{\partial h}{\partial P}\right)_T dP + \left(\frac{\partial h}{\partial T}\right)_P dT \ . \qquad (E.8)$$

The second partial derivative in Equation (E.8) is the definition of the constant pressure heat capacity C_p. The first partial can be expressed as [14]

$$\left(\frac{\partial h}{\partial P}\right)_T = v - T\left(\frac{\partial v}{\partial T}\right)_P \ .$$

The definition for the bulk thermal expansivity α of a fluid is given by [7]

$$\alpha = - \frac{T\left(\frac{\partial \rho}{\partial T}\right)_P}{\rho} = \frac{T}{v}\left(\frac{\partial v}{\partial T}\right)_P \ .$$

The partial derivative may be expressed as

$$\left(\frac{\partial h}{\partial P}\right)_T = v\ (1 - \alpha) \ .$$

By substituting for the partial derivatives as discussed, Equation (E.8) may be written as follows for the ET liquid phase

$$dh_\ell = v\ (1 - \alpha_\ell)\ dP + C_p dT \ .$$

By substituting Equation (E.2) for dh_ℓ in the previous equation and solving for dT, the temperature equation is given by the relationship

$$dT = \frac{1}{C_p}\ \frac{dQ_\ell}{m_\ell} + v_\ell \alpha_\ell\ dP \ . \qquad (E.9,15)$$

Appendix F

Plotting routines

The data which describe the transfer of fluid are stored in file PSDATA (see printout of file in Appendix C). These data are used in two plotting programs called PROGRAM PLOT and PROGRAM DEMO. Both programs are written in FORTRAN IV and are fully described below. The data file is described first.

FILE PSDATA/TAPE8

The first four lines of the file are data points for identifying and initializing the plots for either PROGRAM PLOT or DEMO. The first line of data contains four identifying parameters -- the transfer line size, pump size, and the initial receiver tank temperature and pressure. The second line contains the alphanumeric name of the propellant, HYDROGEN or OXYGEN. The total number of data lines, N, is written on the third line. Finally, the fourth line holds the lower and upper limits for each of the plots to be drawn. The order of these pairs of values is the time, receiver tank temperature and pressure, the flowrate, the mass of vapor, mass of liquid, total mass of fluid transferred, the quality of fluid in the ET, and the quality of fluid entering the receiver tank.

Following these lines are the N lines of data. Each entry holds the data describing the transfer for each increment of time. The values in each line are the elapsed time, the receiver tank temperature, receiver tank pressure, the flowrate, the mass of vapor, liquid, and total mass of propellant transferred, the ET fluid quality, and the quality of fluid entering the receiver tank.

PROGRAM PLOT

The NBS computer system in Boulder has a mathematics library called STARPAC from which subroutines may be called to perform assigned tasks. For program PLOT the SUBROUTINE PPC is used to produce four plots and is accessed by the statement CALL PPC(A1, A2, A3, A4, A5, A6, A7, A8, A9, A10). Each parameter is described as follows:

A1	Array containing the value to be plotted on the vertical axis.
A2	Array containing the values for the elapsed time during the transfer to be plotted on the horizontal axis.
A3	The number of lines of data to be read.
A4,A5,A6	Parameters describing whether the plot is to be logarithmic, the size of the plot is to be altered, or the plot is to be reprinted. All are set equal to zero.
A7,A8	Lower and upper values for the vertical axis.
A9,A10	Lower and upper values for the horizontal (time) axis.

PLOT first assigns single array dimension sizes for the time, temperature, pressure, flowrate, mass of vapor, and mass of liquid. Second, the first four lines of data are read into appropriate variable names. Following these assignments the data points are read into the dimension arrays.

The first call to PPC enables a plot to be drawn of the receiver tank temperature as a function of time. The second call to PPC is for a plot of the receiver tank pressure as a function of time. The third call plots the mass of propellant in the vapor phase as a function of time. The fourth call to PPC produces a plot of the mass of liquid phase propellant as a function of time. Each plot has an appropriate heading. There are 10 vertical and horizontal axis divisions for each plot.

When batch control procedure SUBCOM is used, the plots are located after the output from program SCAVAG and all output subsequently are written to

TAPE6 and PSOUT. Should the operator choose to have the output separated, two other batch control procedures are used. First, SCAVAG is run with NOPLOT, in the same manner as has been described in the main text for SUBCOM. Output is written to TAPE6/PSOUT and PSDATA as before. To generate the plots for the transfer with program PLOT, control procedure LIBPLOT is used. Output is directed to TAPE6 and stored in filename TRACE. (See Appendix G for the program, data, control procedure listings, and sample plots.)

PROGRAM DEMO

The DISSPLA graphics package [15] is available at NBS in Boulder and at NASA-JSC. Since it produces high quality plots and is quite versatile, DISSPLA was chosen for graphic display of some of the results of this study. It is used by program DEMO to produce seven plots. Two plots, each allowed half of a standard page, are placed on the first three pages, and the remaining plot is located on the upper half of the fourth page.

DEMO assigns dimension sizes and variable names in a manner very similar to that of program PLOT. However, additional arrays and variable names are required for the parameters used in the DISSPLA subroutine calls. After the lower and upper bounds for each of the plots are read from PSDATA, DEMO calculates the division size for the axes of each plot. After the data points are read into their respective arrays, the program is fully initiated and proceeds with a succession of DISSPLA subroutine calls which set up and plot the curves. A full description of each subroutine can be found in the DISSPLA user's manual. (The program listing and sample plots are located in Appendix G.)

Several items are unique to program DEMO. Whereas PLOT reads the first line of data into four dummy variables, DEMO uses these data as identifiers located in the corner of the first plot. The name of the propellant is not used in PLOT, but in DEMO it is used in the heading for each page. In

addition to the four plots which are generated by both PLOT and DEMO, DEMO also plots the total mass of propellant transferred, the flowrate into the receiver tank, and the percent of vapor and liquid phases in the receiver tank, as a function of time.

DEMO is run interactively by the operator. Instead of storing the output in files which are accessed at a later time (i.e., batch operation, SCAVAG with control procedures SUBCOM or NOPLOT, and PLOT with control procedures SUBCOM or LIBPLOT), output is generated immediately at the terminal or other output device. To run DEMO at NBS, the operator types in at the terminal

```
GET, DEMO
DEMO
```

or `BEGIN, DEMO, DEMO`

The first line instructs the computer system to retrieve program DEMO from storage and place it in the local mode and ready for use. When DEMO is typed, the procedure for running the program is activated. The alternative command identically performs both statements. The procedure is located in the lines prior to the program statement and uses a sequence of control statements similar to those contained in the batch control procedures SUBCOM, NOPLOT, or LIBPLOT.

Output is generated at the terminal screen when the appropriate call is made and graphics capabilities are available. Other output options are a multiple pen plotter or microfilm. The first page, or two plots, are drawn automatically. The operator types

```
COPYBR, Z
```

to have each subsequent page drawn at the terminal or the pen plotter. All plots are automatically drawn on microfilm.

Appendix G

Program listings and sample plots

```
      PROGRAM SCAVAG(INPUT,TAPE5,TAPE6,TAPE7,OUTPUT=TAPE6,TAPE8)
C     THIS PROGRAM SIMULATES THE FILLING OF A RECEIVER TANK IN LOW G
C     USING A SUPPLY/EXTERNAL TANK.
C
      COMMON/PARAM/ MW,MWALL,Q,VOL,QPIPE,QET,TOTAL,PVENT
      COMMON/SUB/ FLOW1,FLOW2,PRESS,TEMP,TIME,HET
      COMMON/FLOW/ DIAM,DET,TET,PET,LENGTH,PMETER
      COMMON/NOZZLE/CDIAM,NOZDIA,HEADIA,NNOZ,CONST,CDLENG
      COMMON/PUMP/ POWER,EFF
      COMMON/PLOT/ NPLOT,X,Y1,Y2,Y3,Y4,Y5,Y6,Y7,Y8
      COMMON/PROP/NGAS
      COMMON/ETANK/ETLIQ,ETVAP,VET,ETQ
      COMMON/PROB/DUMP
      REAL MVAP,MLIQ,MW,MWALL,LENGTH,NOZDIA
      REAL X(600),Y1(600),Y2(600),Y3(600),Y4(600),Y5(600),Y6(600)
     + ,Y7(600),Y8(600)
C
C     THE NAMELIST "NAME" CONTAINS ALL PARAMETERS THAT CAN BE VARIED
C     FROM DEFAULT VALUES.
C
      NAMELIST/NAME/PET,TET,QET,TOTAL,DIAM,NELBOW,NANGLE,NGATE,
     + NGLOBE,NBUTT,LENGTH,METER,QPIPE,POWER,VOL,MWALL,TEMP,PRESS,
     + PVENT,Q,CDLENG,HEADIA,NNOZ,NOZDIA,VET,CONST
C
C     NGAS = 1 FOR HYDROGEN AND 2 FOR OXYGEN  CHANGE IN NAMELIST "FUEL"
      NAMELIST/FUEL/NGAS
C
      NGAS = 1
C
      READ(7,FUEL)
C
C
C    INITIALIZE FLUID PROPERTIES WITH FLUIDS PACK SUBROUTINE.
      IF(NGAS.EQ.2)GO TO 1
      CALL DATA P H2
C
C    INITIALIZE MOLECULAR WEIGHT
C
      MW = 2.01594
C
C    SET DEFAULT VALUES FOR THE SIMULATION.
C
C     INPUT PARAMETERS FOR SUPPLY TANK:
C       PET = TANK PRESSURE, PSIA
C       TET = TANK TEMPERATURE, DEG. F
C       QET = HEAT FLUX INTO SUPPLY TANK, BTU/HR
C       TOTAL = TOTAL PROPELLANT IN SUPPLY TANK, POUNDS
C       VET = TANK VOLUME, CUBIC FEET
C
      PET = 32.
      TET = -425.
      QET = 90000.
      TOTAL = 3098.
      VET = 53518.
C
C     INPUT PARAMETERS FOR PIPING BETWEEN TANKS:
C       DIAM = PIPE DIAMETER, INCHES
C       NELBOW = NUMBER OF RIGHT-ANGLE ELBOWS
C       NGATE = NUMBER OF GATE VALVES
C       NGLOBE = NUMBER OF GLOBE VALVES
C       NANGLE = NUMBER OF ANGLE VALVES
C       NBUTT = NUMBER OF BUTTERFLY VALVES
C       LENGTH = LENGTH OF STRAIGHT PIPE, FEET
C       METER = NUMBER OF FLOW METERS
```

```
C       QPIPE = HEAT FLUX INTO PIPE, BTU/HR
C       POWER = PUMP POWER, HP
C
        DIAM = 5.
        NELBOW = 10
        NGATE = 0
        NGLOBE = 2
        NANGLE = 0
        NBUTT = 0
        LENGTH = 70.
        METER = 1
        QPIPE = 50400.
        POWER = 0.
C
C     INPUT PARAMETERS FOR RECEIVER TANK:
C       VOL = TANK VOLUME, CUBIC FEET
C       MWALL = TANK WALL MASS, POUNDS
C       TEMP = INITIAL RECEIVER TANK TEMPERATURE, DEG F
C       PRESS = INITIAL RECEIVER PRESSURE, PSIA
C       PVENT = RELIEF VALVE VENT PRESSURE, PSIA
C       Q = HEAT FLUX INTO TANK, BTU/HR
C
        VOL = 780.
        MWALL = 975.
        TEMP = -290.
        PRESS = 18.
        PVENT = 30.
        Q = 0.
C
C     INPUT PARAMETERS FOR FLOW SIMULATION AND COOL-DOWN PIPING:
C     CDLENG = LENGTH OF COLL-DOWN PIPING + HEADER
C     NNOZ   = NUMBER OF NOZZLES
C     NOZDIA = DIAMETER OF ORIFICE/NOZZLE,FEET
C     HEADIA = DIAMETER OF HEADER AND COOL-DOWN PIPING, INCHES
C     CONST  = 1/ORIFICE CONSTANT.  ORIFICE CONSTANT = 0.61
C
        CDLENG = 20.
        NNOZ = 6
        CONST = 1.639
        NOZDIA = 0.5
        HEADIA = 2.0
C
        GO TO 2
C
    1   CALL DATA O2
C
        MW = 31.9988
        PET = 20.
        TET = -315.
        QFT = 0.
        VET = 19786.
        TOTAL = 6270.
        DIAM = 4.
        NELBOW = 20
        NGATE = 0
        NGLOBE = 2
        NANGLE = 1
        NBUTT = 0
        LENGTH = 100.
        METER = 1
        QPIPE = 104400.
        POWER = 4.
        VOL = 300.
        MWALL = 350.
```

```
      TEMP = 60.
      PRESS = 1.
      PVENT = 30.
      Q = 0.
      CDLENG = 20.
      NNOZ = 6
      CONST = 1.639
      NOZDIA = 0.25
      HEADIA = 1.0
C
   2  CONTINUE
C
C     READ IN VALUES OF SIMULATION PARAMETERS THAT ARE TO BE DIFFERENT
C     FROM THE DEFAULT VALUES.
      READ(5,NAME)
C
C      WRITE SOME SIMULATION PARAMETERS TO BE WRITTEN ON DISSPLA PLOTS
C      FOR SIMULATION IDENTIFICATION.
C
      WRITE(8,*) DIAM,POWER,TEMP,PRESS
C
C     WRITE SIMULATION PARAMETERS ON OUTPUT.
      IF(NGAS.EQ.2)GO TO 4449
      WRITE(6,4400)
 4400 FORMAT(1H1,*HYDROGEN TRANSFER*)
      GO TO 4499
 4449 WRITE(6,4450)
 4450 FORMAT(1H1,*OXYGEN TRANSFER*)
C
 4499 WRITE(6,4500) PET,TET,TOTAL,QET
 4500 FORMAT(1H1,*SUPPLY TANK INITIAL CONDITIONS:*/,5X,*PRESSURE = *
     + ,F10.3,* PSIA*/,5X,*TEMPERATURE = *,F10.3,* F*/,5X,
     + *MASS = *,F10.2,* POUNDS*/,5X,*HEAT LEAK = *,
     + F12.3,* BTU/HR*)
      WRITE(6,4600) PRESS,TEMP,PVENT,VOL,MWALL,Q
 4600 FORMAT(* RECEIVER TANK INITIAL CONDITIONS:*/,5X,
     + *PRESSURE = *,F10.3,* PSIA*/,5X,*TEMPERATURE = *,F10.3,
     + * F*/,5X,*VENT PRESSURE = *,F10.3,* PSIA*/,5X,
     + *TANK VOLUME = *,F10.3,* CUBIC FEET*/,5X,
     + *TANK WALL MASS = *,F10.3,* POUNDS*/,5X,*HEAT LEAK = *,
     + F12.3,* BTU/HR*)
      WRITE(6,4700) DIAM,LENGTH,NELBOW,NGATE,NGLOBE,NANGLE,NBUTT,
     + METER,QPIPE,POWER
 4700 FORMAT(* TRANSFER PARAMETERS:*/,5X,*PIPE DIAMETER = *,
     + F8.3,* INCHES*/,5X,*LENGTH OF STRAIGHT PIPE = *,F8.3,
     + * FEET*/,5X,I3,* ELBOW(S)*/,5X,I3,* GATE VALVE(S)*/,5X,I3,
     + * GLOBE VALVE(S)*/,5X,I3,* ANGLE VALVE(S)*/,5X,I3,
     + * BUTTERFLY VALVE(S)*/,5X,I3,* FLOW METER(S)*/,5X,
     + *HEAT LEAK INTO PIPING = *,F12.3,* BTU/HR*/,5X,
     + *PUMP POWER = *,F5.1,* HP*)
      WRITE(6,4800)CDLENG,NNOZ,NOZDIA,HEADIA
 4800 FORMAT(* COOL-DOWN PARAMETERS:*/,5X,*LENGTH OF PIPING = *
     1,F8.3,* FEET*/,5X,*NUMBER OF NOZZLES = *,I4,
     1/,5X,*NOZZLE DIAMETER = *,F8.4,* INCHES*,
     1/5X,*HEADER DIAMETER = *,F8.4,* INCHES*)
C
C     CALCULATE EQUIVALENT LENGTH OF PIPING.
C
      LENGTH = LENGTH + FLOAT(NELBOW)*(2.52738*DIAM+.414286)
     + + FLOAT(NGATE)*(.57083*DIAM-.0125)+FLOAT(NGLOBE)*
     + (38.0595*DIAM+.10714)+(FLOAT(NANGLE)+FLOAT(NBUTT)/8.)*
     + (14.3452*DIAM-1.17857)
C
C    CONVERT ALL PARAMETERS AND VARIABLES FROM ENGLISH UNITS INTO
```

```
C     SI UNITS:  PRESSURE - ATM, TEMPERATURE - DEGREES KELVIN, HEAT LEAKS -
C                JOULES/SEC, MASS - GRAM-MOLES, PIPE DIAMETER - CM, PIPE
C                LENGTH - METERS, PUMP POWER - JOULES/SEC, VOLUME - LITERS,
C                TIME - SEC.
C
      PET = PET/14.696
      TET = (TET+460.)*5./9.
      QET = QET*1054.35/3600.
      VET = VET*28.317
      TOTAL = TOTAL*454./MW
      DIAM = DIAM*2.54
      LENGTH = LENGTH * .3048
      PMETER = FLOAT(METER)/14.696
      QPIPE = QPIPE*1054.35/3600.
      POWER = POWER*746.
      VOL = VOL*28.317
      MWALL = MWALL*453.59
      TEMP = (TEMP+460.)*5./9.
      PRESS = PRESS/14.696
      PVENT = PVENT/14.696
      Q = Q*1054.35/3600.
      CDLENG = CDLENG*0.3048
      CDIAM = HEADIA*2.54
C
C
C    INITIALIZE THE FLUID PROPERTIES
      DET = FIND D(PET,TET)
      HET = ENTHAL(PET,DET,TET)
C
C
C
      FRACT = TOTAL/VET/DET
C
C
      TETSAT = FINDTV(PET)
      ETVAP = FINDD(PET,TETSAT+1.E-3)*VET*(1.-FRACT)
C     OBTAIN QUALITY OF SUPPLY TANK FLUID
C
      CALL CHECK(HET,PET,TET,ETQ)
C
C     INITIALIZE TIME
C
      TIME = 0.
C
C   INITIALIZE COOL-DOWN NOZZLE PRESSURE DROP
C
C   INITIALIZE FLOWRATE.  THE FLOW IS DUE TO PRESSURE DROP BETWEEN THE TANKS
C
      FGUESS = FLO(PRESS)
      FLOW1 = PUMPFLO(PRESS,FGUESS)
C
C     INITIALIZE VENT FLOWRATE
C
      FLOW2 = 0.
C
C     INITIALIZE TOTAL AMOUNT OF MATERIAL VENTED AND AMOUNT OF VAPOR
C     PRESENT IN THE RECEIVER TANK.
C
      XVENT = 0.
      MVAP = 0.
C
C     INITIALIZE COUNTER FOR OUTPUT TO GO TO PLOTTING ROUTINE.
C
      NPLOT = 0
```

```
C
C    INITIALIZE VENT FLAG TO INDICATE THAT THE RECEIVER TANK VENT
C    IS CLOSED.
C
       NVENT = 0
C
C    INITIALIZE PROGRAMMED STOP PARAMETER
C
       DUMP = 0.
C
C
C     CALL SUBROUTINE THAT MODELS THE COOL-DOWN OF THE RECEIVER TANK UNTIL
C     TWO PHASES ARE PRESENT IN THE RECEIVER TANK.
C
       CALL COOL(MVAP,XVENT,DPRESS)
       NPRT = 0
C
C     CALCULATE THE ENTHALPY OF THE FLUID ENTERING THE RECEIVER TANK
C     AND CHECK THE QUALITY OF THE FLUID.
C
       H1 = HET+QPIPE/FLOW1 + POWER/FLOW1
       CALL CHECK(H1,PRESS,TEMP,TANKQ)
C
C     SET THE TIME STEP FOR THE SIMULATION.  NOTE:  DTIME = 2000./FLOW1
C     FOR LH2 AND 300./FLOW1 FOR LOX ON NASA-JSC COMPUTER
C
       DTIME = VOL/FLOW1/500.
       IF(NGAS .EQ. 2)DTIME = DTIME/2.
       IF(NGAS .EQ. 1)DTIME = DTIME*2.
       DTIME = DTIME*50.
C.       DTIME = DTIME/3.14159
C    INITIALIZE THE AMOUNT OF LIQUID PRESENT IN THE RECEIVER TANK.
C
       MLIQ = 0.
C
C
       DLIQ = FIND D(PRESS+1.E-3,TEMP)
       DVAP = FIND D(PRESS-1.E-5,TEMP)
C
C   LOOP FOR TWO-PHASE SIMULATION.
       I = 0
 1000 CONTINUE
       I = I+1
C
C     OBTAIN VAPOR AND LIQUID ENTHALPY (J/GMOL)AND INTERNAL ENERGY (J/GMOL)
C
       HVAP = ENTHAL(PRESS-1.E-5,DVAP,TEMP)
       HLIQ = ENTHAL(PRESS+1.E-5,DLIQ,TEMP)
       UVAP = HVAP-PRESS*101.327/DVAP
       ULIQ = HLIQ-PRESS*101.327/DLIQ
C     CALCULATE FUNCTION FOR DELTA P.
C
       FP = MLIQ*((1.-DLIQ/DVAP)*DUDPL(PRESS)+DLIQ*DVDPL(PRESS)
      + *(UVAP-ULIQ))+MVAP*((1.-DLIQ/DVAP)*DUDPV(PRESS)
      + +DLIQ*DVDPV(PRESS)*(UVAP-ULIQ))
       FPP = FP+MWALL*CWALL(TEMP)*DTDP(PRESS)*
      + (1.-DLIQ/DVAP)
       DELTAT = DTDP(PRESS)*DPRESS
C
C   CALCULATE DELTA P
C
       DPRESS = ((H1-UVAP+DLIQ/DVAP*(ULIQ-H1))*FLOW1+(Q)*
      + (1.-DLIQ/DVAP))/FPP
   32  CONTINUE
```

```
C
C     CALCULATE NEW PRESSURE AND OBTAIN NEW TEMPERATURE.
C
      PRESS = PRESS + DPRESS*DTIME
      TEMP = FINDTV(PRESS)
C
C   RECALCULATE THE FLOWRATE
      FL = FLOW1*MW*.13216
      FLOW = FLOW1
      FLOW1 = PUMPFLO(PRESS,FLOW)
      FL = FLOW1*MW*.13216
   17 CONTINUE
C    CHECK FOR RELIEF VALVE OPENING
C
      FLOW2 = 0.
  179 CONTINUE
      IF (PRESS+DPRESS*DTIME .LT. PVENT*.999) GO TO 15
      IF (NVENT .EQ. 0 .AND. PRESS+DPRESS*DTIME .LT. PVENT*1.002)
     + GO TO 15
C     CALCULATE THE VENT FLOWRATE
      FLOW2 = (0*(1.-DLIQ/DVAP)-(UVAP-H1-DLIQ/DVAP*(ULIQ-H1))
     + *FLOW1)/(DLIQ/DVAP*(HVAP-HLIQ))
C
C     CHECK TO SEE IF THE SYSTEM IS VENTING PROPERLY.
C
      IF (FLOW2 .LT. 0.) GO TO 40
      GO TO 14
   40 DPRESS = 0.
      PRESS = PVENT
C
C     SET FLAG TO INDICATE THAT THE RECEIVER TANK IS VENTING AND
C     CALCULATE TOTAL MOLES VENTED.
C
      NVENT = 2
      XVENT = XVENT-FLOW2*DTIME
      GO TO 15
   14 FLOW2 = 0.
      NVENT = 0
C
   15 CONTINUE
C
C     CALCULATE NEW VAPOR AND LIQUID DENSITIES
C
      DLIQN = FIND D(PRESS+1.E-2,TEMP)
      DVAP = FIND D(PRESS-1.E-5,TEMP)
      IF(DLIQ/DLIQN .GT. 10.)GO TO 231
      DLIQ = DLIQN
  231 CONTINUE
C
C   CALCULATE CHANGE IN LIQUID MOLES AND ACTUAL NUMBER OF MOLES
C     IN LIQUID AND VAPOR PHASES AT T = TIME.
      DMLIQ = -DLIQ/DVAP*(FLOW1+FLOW2)/(1.-DLIQ/DVAP)-DLIQ*
     + (MLIQ*DVDPL(PRESS)+MVAP*DVDPV(PRESS))*DPRESS/
     + (1.-DLIQ/DVAP)
      MLIQ = MLIQ+DMLIQ*DTIME
C
      MVAP = (VOL-MLIQ/DLIQ)*DVAP
C
C     CHECK TO SEE IF THE RECEIVER TANK IS FULL OR OVERFLOWING
      IF(MLIQ+MVAP+XVENT .LT. 0.95*TOTAL)GO TO 45
   46 IF(MLIQ+MVAP+XVENT .LE. TOTAL)GO TO 48
   47 MLIQ = MLIQ-DMLIQ*DTIME
      MVAP = (VOL-MLIQ/DLIQ)*DVAP
   48 DTIME1 = (TOTAL-(XVENT+MLIQ+MVAP))/DMLIQ
```

```
      IF(DTIME .LT. DTIME1)GO TO 45
   49 MLIQ = MLIQ+DMLIQ*DTIME1
      MVAP = (VOL-MLIQ/DLIQ)*DVAP
   38 IF (MVAP .GT. 0.) GO TO 35
C
C     CALL THE SUBROUTINE TO STOP THE PROGRAM.
C
      NPLOT = NPLOT + 1
      X(NPLOT) = TIME/60.
      Y1(NPLOT) = TEMP*9./5.-460.
      Y2(NPLOT) = PRESS*14.696
      Y3(NPLOT) = FLOW1*MW*.13216
      Y4(NPLOT) = MVAP*MW/454.
      Y5(NPLOT) = MLIQ*MW/454.
      Y6(NPLOT) = Y4(NPLOT)+Y5(NPLOT)
      Y7(NPLOT) = ETQ
      Y8(NPLOT) = TANKQ
      CALL FULL(MLIQ,XVENT)
C
C    CHECK TO SEE IF ALL THE FLUID HAS BEEN TRANSFERRED.
C    CALL SUBROUTINE TO STOP PROGRAM.
C
   35 NPLOT = NPLOT + 1
      X(NPLOT) = TIME/60.
      Y1(NPLOT) = TEMP*9./5.-460.
      Y2(NPLOT) = PRESS*14.696
      Y3(NPLOT) = FLOW1*MW*.13216
      Y4(NPLOT) = MVAP*MW/454.
      Y5(NPLOT) = MLIQ*MW/454.
      Y6(NPLOT) = Y5(NPLOT) + Y4(NPLOT)
      Y7(NPLOT) = ETQ
      Y8(NPLOT) = TANKQ
      CALL DONE(MLIQ+MVAP,XVENT)
C
C   UPDATE THE  SUPPLY TANK PROPERTIES .
C
   45 ETLIQ = TOTAL-MLIQ-MVAP-XVENT
      CALL CHECK(HET,PET,TET,ETQ)
      CALL SUPPLY(DTIME)
      CALL CHECK(HET,PET,TET,ETQ)
C
C    INCREMENT THE TIME
C
      TIME = TIME + DTIME
C
C    CHECK TO SEE IF FLOW HAS STOPPED DUE TO RECEIVER TANK BACK PRESSURE
C    IN THE ABSENCE OF A PUMP.
C
      IF (PRESS .GE. PET .AND. POWER .LT. .05)GO TO 63
C
C
C    CHECK THE FLOWRATE TO SEE IF BACK PRESSURE FROM THE RECEIVER HAS
C    STOPPED FLOW IN THE PRESECE OF A PUMP.
C
      IF (ABS(FLOW1) .LT. .1) GO TO 63
      GO TO 73
   63 CONTINUE
      NPLOT = NPLOT + 1
      X(NPLOT) = TIME/60.
      Y1(NPLOT) = TEMP*9./5.-460.
      Y2(NPLOT) = PRESS*14.696
      Y3(NPLOT) = FLOW1*MW*.13216
      Y4(NPLOT) = MVAP*MW/454.
      Y5(NPLOT) = MLIQ*MW/454.
```

```
      Y6(NPLOT) = Y4(NPLOT)+Y5(NPLOT)
      Y7(NPLOT) = ETQ
      Y8(NPLOT) = TANKQ
      CALL PFAIL(MVAP+MLIQ,XVENT)
C
C     CALCULATE THE ENTHALPY OF FLUID ENTERING RECEIVER TANK AND OBTAIN
C     ITS QUALITY.
C
   73 CONTINUE
      H1 = HET+QPIPE/FLOW1 + POWER/FLOW1
      CALL CHECK(H1,PRESS,TEMP,TANKQ)
C
      IF(DUMP .NE. 1.)GO TO 585
      NPLOT = NPLOT + 1
      X(NPLOT) = TIME/60.
      Y1(NPLOT) = TEMP*9./5.-460.
      Y2(NPLOT) = PRESS*14.696
      Y3(NPLOT) = FLOW1*MW*.13216
      Y4(NPLOT) = MVAP*MW/454.
      Y5(NPLOT) = MLIQ*MW/454.
      Y6(NPLOT) = Y4(NPLOT)+Y5(NPLOT)
      Y7(NPLOT) = ETQ
      Y8(NPLOT) = TANKQ
      CALL PDATA(MVAP+MLIQ,XVENT)
  585 CONTINUE
C
C     WRITE RESULTS EVERY CHOSEN TIME INCREMENT.
C
      NPRT = NPRT + 1
      IF (NPRT .NE. 1) GO TO 20
      NPRT = 0
      NPLOT = NPLOT + 1
      X(NPLOT) = TIME/60.
      Y1(NPLOT) = TEMP*9./5.-460.
      Y2(NPLOT) = PRESS*14.696
      Y3(NPLOT) = FLOW1*MW*.13216
      Y4(NPLOT) = MVAP*MW/454.
      Y5(NPLOT) = MLIQ*MW/454.
      Y6(NPLOT) = Y4(NPLOT)+Y5(NPLOT)
      Y7(NPLOT) = ETQ
      Y8(NPLOT) = TANKQ
C
C
   20 IF(NPLOT .LE. 600) GO TO 1000
      WRITE(6,153)
  153 FORMAT(/,* ARRAY LENGTH EXCEEDED*)
      CALL PDATA(MVAP+MLIQ,XVENT)
      END
C
C*************************************************************************
C
      SUBROUTINE COOL(M,XVENT,DPRESS)
C
C     THIS SUBROUTINE TAKES THE SIMULATION FROM TIME ZERO UNTIL
C    TWO PHASES ARE PRESENT IN THE RECEIVER TANK.
C
          COMMON/FLOW/ DIAM,DET,TET,PET,LENGTH,PMETER
          COMMON/PARAM/ MW,MWALL,Q,VOL,QPIPE,QET,TOTAL,PVENT
          COMMON/SUB/ FLOW1,FLOW2,PRESS,T,TIME,HET
          COMMON/NOZZLE/CDIAM,NOZDIA,HEADIA,NNOZ,CONST,CDLENG
          COMMON/PUMP/ POWER,EFF
          COMMON/PLOT/ NPLOT,X,Y1,Y2,Y3,Y4,Y5,Y6,Y7,Y8
          COMMON/ETANK/ETLIQ,ETVAP,VET,ETQ
          COMMON/PROB/DUMP
```

```
      COMMON/PROP/NGAS
      COMMON/NEG/IJK
      REAL X(600),Y1(600),Y2(600),Y3(600),Y4(600),Y5(600),Y6(600)
     + ,Y7(600),Y8(600)
      REAL MW,MWALL,M,LENGTH,CDLENG,NOZDIA
C
C     INITIALIZE PRINTOUT COUNTER, VENT FLAG AND SIMULATION LOOP COUNTER.
C
      IJK = 2
      NPRT = 0
      NVENT = 0
      KOUNT = 0
      K = 0
C
C     INITIALIZE FLOWRATE BETWEEN TANKS, PUMP EFFICIENCY AND DENSITY OF VAPO
C     IN RECEIVER TANK.
C
      EFF = PEFF(FLOW1)
      DENS = FIND D(PRESS,T)
C
C     CALCULATE THE CHANGE IN VAPOR MOLES.
      DM = FLOW1+FLOW2
      DTIME = VOL/FLOW1/800.
      IF(NGAS.EQ.2)DTIME=DTIME/2.
C.      DTIME = DTIME/7.
C
C     LOOP FOR SIMULATION
C
   10 KOUNT = KOUNT + 1
C
C     CALCULATE GRUENSIAN PARAMETER AND THE ENTHALPY OF FLUID ENTERING RECEI
C     TANK AND CHECK ITS QUALITY.
C
      CALL PPHI(DENS,T,PHII)
      GRU = PHII
      H1 = HET+QPIPE/FLOW1 + POWER/FLOW1
      CALL CHECK(H1,PRESS,T,TANKQ)
C
C     OBTAIN ENTHALPY OF VAPOR IN RECEIVER TANK (J/GMOL), HEAT CAPACITY AT
C     CONSTANT VOLUME (J/GMOL/DEG K).
C
      H = ENTHAL(PRESS,DENS,T)
      CVAP = CV(DENS,T)
C
C     CALCULATE CHANGE IN VAPOR DENSITY AND RECEIVER TANK TEMPERATURE
C     WITH RESPECT TO TIME.
C
      DDENS = DM*DTIME/VOL
      DT=(GRU*T*DM+((H1-H)*FLOW1+Q)/CVAP)/(DENS*VOL+MWALL*CWALL(T)/CVAP)
     + *DTIME
C
C     CALCULATE HEAT ABSORBED BY TANK WALL, HEAT OF EXPULSION AND CHANGE
C     OF RECEIVER TANK PRESSURE WITH RESPECT TO TIME.
C
      QWALL = -MWALL*CWALL(T)*DT/DTIME
      THETA = TH(DENS,T)
      DPRESS=GRU*(THETA*DM+(H1-H)*FLOW1+Q+QWALL)*DTIME
     + /VOL/101.327
C
C     CALCULATE NEW RECEIVER TANK DENSITY, TEMPERATURE AND PRESSURE, AND
C     INCREMENT THE SIMULATION TIME.
C
      DENS = DENS + DDENS
      T = T + DT
```

```
      TIME = TIME + DTIME
      PRESS = PRESS + DPRESS
C  RECALCULATE THE FLOWRATE
      FLOW = FLOW1
      FLOW1 = PUMPFLO(PRESS,FLOW)
      FL = FLOW1*MW*.13216
  11  CONTINUE
C
      FLOW2 = 0.
C     CHECK TO SEE IF THE RELIEF VALVE HAS OPENED.
C
      IF (PRESS .LT. PVENT*.999) GO TO 25
      IF (NVENT .EQ. 0 .AND. PRESS .LT. PVENT*1.002) GO TO 25
C
C     CALCULATE THE CHANGE OF MOLES IN RECEIVER TANK WITH VENTING.
C
      DM = ((H-H1)*FLOW1-Q-QWALL)/THETA
C
C     CHECK TO SEE IF THE SYSTEM IS VENTING PROPERLY.
C
      IF ((DM-FLOW1) .LT. 0.) GO TO 30
      IF(PRESS .LT. PVENT*1.002)GO TO 25
C
      WRITE(6,250)
 250  FORMAT(1H ,*THE SYSTEM IS NOT VENTING PROPERLY;*,
     + * CONTACT A PROGRAMMER*)
      NPLOT = NPLOT + 1
      X(NPLOT) = TIME/60.
      Y1(NPLOT) = T*9./5.-460.
      Y2(NPLOT) = PRESS*14.696
      Y3(NPLOT) = FLOW1*MW*.13216
      Y4(NPLOT) = M*MW/454.
      Y5(NPLOT) = 0.
      Y6(NPLOT) = Y4(NPLOT)+Y5(NPLOT)
      Y7(NPLOT) = ETQ
      Y8(NPLOT) = TANKQ
      CALL PDATA(M,XVENT)
C
  30  DPRESS = 0.
      PRESS = PVENT
      FLOW2 = DM-FLOW1
C
C    SET FLAG TO SHOW THE RECEIVER TANK IS VENTING AND CALCULATE TOTAL
C     AMOUNT VENTED.
C
      NVENT = 2
      XVENT = XVENT-FLOW2*DTIME
      GO TO 26
  25  CONTINUE
C
  26  DM = FLOW1+FLOW2
C
C     CALCULATE NEW NUMBER OF MOLES PRESENT IN RECEIVER TANK.
C
      M = M + DM*DTIME
C
C     CHECK TO SEE IF ALL FLUID HAS BEEN TRANSFERRED.
C
      IF(M+XVENT .LT. 0.95*TOTAL)GO TO 45
  46  IF(M+XVENT .LE. TOTAL)GO TO 48
  47  M = M-DM*DTIME
  48  DTIME1 = (TOTAL-(XVENT+M))/DM
      IF(DTIME .LT. DTIME1)GO TO 45
  49  M = M+DM*DTIME1
```

```
      CALL DONE(M,XVENT)
C
   45 CALL CHECK(HET,PET,TET,ETQ)
C
C    UPDATE THE SUPPLY TANK PROPERTIES .
C
      ETLIQ = TOTAL-M-XVENT
      CALL SUPPLY(DTIME)
C
C    IF BACK PRESSURE FROM RECEIVER TANK IN THE ABSENCE OF A PUMP STOPS
C    FLOW, CALL SUBROUTINE TO STOP PROGRAM.
C
      IF (PRESS .GT. PET .AND. POWER .LT. .05)GO TO 33
C
C     IF FLOW HAS STOPPED IN THE PRESENCE OF A PUMP DUE TO BACK PRESSURE
C    FROM THE RECEIVER, CALL A SUBROUTINE TO STOP PROGRAM.
      IF (ABS(FLOW1) .LT. .1) GO TO 33
      GO TO 23
   33 CONTINUE
      NPLOT = NPLOT + 1
      X(NPLOT) = TIME/60.
      Y1(NPLOT) = T*9./5.-460.
      Y2(NPLOT) = PRESS*14.696
      Y3(NPLOT) = FLOW1*MW*.13216
      Y4(NPLOT) = M*MW/454.
      Y5(NPLOT) = 0.
      Y6(NPLOT) = Y4(NPLOT)+Y5(NPLOT)
      Y7(NPLOT) = ETQ
      Y8(NPLOT) = TANKQ
      CALL PFAIL(M,XVENT)
   23 CONTINUE
      IF(DUMP .NE. 1.)GO TO 485
      NPLOT = NPLOT + 1
      X(NPLOT) = TIME/60.
      Y1(NPLOT) = T*9./5.-460.
      Y2(NPLOT) = PRESS*14.696
      Y3(NPLOT) = FLOW1*MW*.13216
      Y4(NPLOT) = M*MW/454.
      Y5(NPLOT) = 0.
      Y6(NPLOT) = Y4(NPLOT)+Y5(NPLOT)
      Y7(NPLOT) = ETQ
      Y8(NPLOT) = TANKQ
      CALL PDATA(M,XVENT)
  485 CONTINUE
      NPRT = NPRT + 1
C
C     WRITE SIMULATION VALUES INTO PLOT ARRAYS EVERY CHOSEN ITERATION.
C
      IF (NPRT .NE. 5) GO TO 35
      NPRT = 0
      K = 0
      NPLOT = NPLOT + 1
      X(NPLOT) = TIME/60.
      Y1(NPLOT) = T*9./5.-460.
      Y2(NPLOT) = PRESS*14.696
      Y3(NPLOT) = FLOW1*MW*.13216
      Y4(NPLOT) = M*MW/454.
      Y5(NPLOT) = 0.
      Y6(NPLOT) = Y4(NPLOT)
      Y7(NPLOT) = ETQ
      Y8(NPLOT) = TANKQ
C
C     IF RECEIVER TANK TEMPERATURE IS GREATER THAN CRITICAL TEMPERATURE,
C     DON'T BOTHER CHECKING FOR TWO PHASES IN RECEIVER TANK.
```

```
C
      IF(NGAS.EQ.2) GO TO 19
   35 IF (T .GE. 40.) GO TO 20
      GO TO 36
   19 IF(T.GE.157.)GO TO 20
C
C     OBTAIN SATURATION TEMPERATURE AT RECEIVER TANK PRESSURE, USE THIS TO
C     GET SATURATION DENSITY; COMPARE SIMULATION AND SATURATION DENSITIES
C     TO DETERMINE WHETHER OR NOT ANY LIQUID IS PRESENT IN THE RECEIVER TANI
C
   36 TSAT = FIND TV(PRESS)
      TTPRES = PRESS-1.E-5
      DSAT = FIND D(TTPRES,TSAT)
      DCALC = M/VOL
      IF (T .LT. TSAT) T = TSAT
      IF (DCALC .LE. DSAT) GO TO 20
C
C     IF TWO PHASES ARE PRESENT, BACK UP ONE ITERATION AND RETURN TO THE
C     MAIN PROGRAM.  SHUT OFF COOL-DOWN NOZZLES, RECALCULATE FLOWRATE.
C
      M = M - DM*DTIME
      DENS = DENS-DDENS
      TIME = TIME-DTIME
      PRESS = PRESS-DPRESS
      T = FIND TV(PRESS)
C
      CONST = 0.
      CDLENG = 0.
      IJK = 1
      FGUESS = FLOW1 * 5.
      IF(NGAS .EQ. 2)FGUESS = FGUESS*4.
      FLOW1 = PUMPFLO(PRESS,FGUESS)
C
      TIM = TIME/60.
      WRITE(6,58)TIM,KOUNT
   58 FORMAT(/,* COOLDOWN TIME = *,F12.4,*  KOUNT = *,I6)
      RETURN
   20 IF(NPLOT .LE. 600)GO TO 10
      WRITE(6,151)
  151 FORMAT(* ARRAY LENGTH EXCEEDED*)
      CALL PDATA(M,XVENT)
      END
C
C*******************************************************************************
C
      SUBROUTINE PPHI(DD,TT,PHII)
C
C     SUBROUTINE TO CALCULATE THE GRUENSIAN PARAMETER (PHII) AS A
C     FUNCTION OF DENSITY (GMOL/L) AND TEMPERATURE (DEG K).
C
      D = DD
      T = TT
      CALL DPDT(DT,D,T)
      CAP = CV(D,T)
      PHII = DT/D/CAP*101.325
      RETURN
      END
C
C*******************************************************************************
C
      FUNCTION TH(DENS,TEMP)
C
C     CALCULATE THE HEAT OF EXPULSION (J/GMOL) AS A FUNCTION OF
C     DENSITY (GMOL/L) AND TEMPERATURE (DEG K).
```

```
C
      CALL DPDT(DT,DENS,TEMP)
      CALL DPDD(DD,DENS,TEMP)
      TH = CP(DENS,TEMP)*DENS*DD/DT
      RETURN
      END
C
C*************************************************************************
C
      FUNCTION DVDPV(PRESS)
C
      COMMON/PROB/DUMP
C
C     CALCULATE THE PARTIAL DERIVATIVE OF SPECIFIC VOLUME WITH RESPECT TO
C     PRESSURE FOR A SATURATED VAPOR.
C
      PVAP = PRESS-1.E-5
      TEMP = FINDTV(PRESS)
      V = 1./FIND D(PVAP,TEMP)
C
C     SET AN INITIAL DELTA P
C
      DP = .05
      IF((PRESS-DP) .LT. 1.E-4)DP = DP/2.
      KOUNT = 0
   25 TEMP = FIND TV(PRESS-DP)
      VLOW = 1./FIND D(PVAP-DP,TEMP)
      TEMP = FIND TV(PRESS+DP)
      VHIGH = 1./FIND D(PVAP+DP,TEMP)
      DVDPV = (VHIGH-VLOW)/DP/2.
C
C     SEE IF THE DERIVATIVE WILL CHANGE BY MAKING DELTA P SMALLER
C
      IF (ABS((VHIGH-2.*V+VLOW)/(VHIGH-V)) .LT. 1.E-3) RETURN
      KOUNT = KOUNT + 1
C
C     IF THE SOLUTION HAS NOT CONVERGED, MAKE DELTA P SMALLER.
C
      DP = DP /2.
C
C     IF THE DERIVATIVE HAS NOT CONVERGED IN 100 ITERATIONS, WRITE AN
C     ERROR MESSAGE (THIS FUNCTION USUALLY CONVERGES WITHIN 2-3 ITERATIONS).
C
      IF (KOUNT .LE. 100) GO TO 25
      WRITE(6,125)
  125 FORMAT(1H ,*KOUNT EXCEEDS 100 FOR DVDPV. STOP PROGRAM*)
      DUMP = 1.
      RETURN
      END
C
C*************************************************************************
C
      FUNCTION DVDPL(PRESS)
C
      COMMON/PROB/DUMP
C
C     CALCULATE THE PARTIAL DERIVATIVE OF SPECIFIC VOLUME WITH RESPECT TO
C     PRESSURE FOR SATURATED LIQUID.  INPUT IS PRESSURE (ATM), OUTPUT
C     DVDPL (L/GMOL/ATM)
C
      PLIQ = PRESS+1.E-5
      TEMP = FIND TV(PRESS)
      V = 1./FIND D(PLIQ,TEMP)
      DP = .05
```

```
      IF((PRESS-DP) .LT. 1.E-4)DP = DP/2.
      KOUNT = 0
   25 TEMP = FIND TV(PRESS-DP)
      VLOW = 1./FIND D(PLIQ-DP,TEMP)
      TEMP = FIND TV(PRESS+DP)
      VHIGH = 1./FIND D(PLIQ+DP,TEMP)
      DVDPL = (VHIGH-VLOW)/DP/2.
C
C     SEE IF THE PARTIAL DERIVATIVE HAS CONVERGED.
C
      IF (ABS((VHIGH-2.*V+VLOW)/(VHIGH-V)) .LE. 1.E-3) RETURN
      KOUNT = KOUNT+ 1
C
C     IF THE SOLUTION HAS NOT CONVERGED, MAKE DELTA P SMALLER.
C
      DP = DP / 2.
C
C     THE DERIVATIVE SHOULD CONVERGE IN 100 ITERATIONS (USUALLY,
C     2-3 ITERATIONS ARE SUFFICIENT).
C
      IF (KOUNT .LE. 100) GO TO 25
      WRITE(6,125)
  125 FORMAT(1H ,*KOUNT EXCEEDS 100 FOR DVDPL. STOP PROGRAM*)
      DUMP = 1.
      RETURN
      END
C
C*************************************************************************
C
      FUNCTION DUDPV(PRESS)
C
      COMMON/PROB/DUMP
C
C     CALCULATE THE PARTIAL DERIVATIVE OF INTERNAL ENERGY WITH RESPECT
C     TO PRESSURE FOR A SATURATED VAPOR.  INPUT IS PRESSURE (ATM).
C
      TEMP = FINDTV(PRESS)
      DENS = FIND D(PRESS-1.E-5,TEMP)
C
C     SINCE INTERNAL ENERGY IS NOT RETURNED BY THE THERMODYNAMIC PROPERTIES
C     PACKAGE, U = H - PV
C
      U = ENTHAL(PRESS-1.E-5,DENS,TEMP)-PRESS*101.327/DENS
      DP = .05
      IF((PRESS-DP) .LT. 1.E-4)DP = DP/2.
      KOUNT = 0
   25 TEMP = FINDTV(PRESS-DP)
      DENS = FIND D(PRESS-DP-1.E-5,TEMP)
      ULOW = ENTHAL(PRESS-DP-1.E-5,DENS,TEMP)-(PRESS-DP)*101.327/DENS
      TEMP = FINDTV(PRESS+DP)
      DENS = FIND D(PRESS+DP-1.E-5,TEMP)
      UHIGH = ENTHAL(PRESS+DP-1.E-5,DENS,TEMP)-(PRESS+DP)*101.327/DENS
      DUDPV = (UHIGH-ULOW)/DP/2.
C
C     SEE IF THE DERIVATIVE HAS CONVERGED.
C
      IF(ABS((UHIGH-2.*U+ULOW)/(UHIGH-U)).LT. 1.E-3) RETURN
      KOUNT = KOUNT + 1
C
C     IF THE SOLUTION HAS NOT CONVERGED, MAKE DELTA P SMALLER.
C
      DP = DP /2.
      IF (KOUNT .LE. 100) GO TO 25
      WRITE(6,125)
```

```
  125 FORMAT(1H ,*KOUNT EXCEEDS 100 FOR DUDPV. STOP PROGRAM*)
      DUMP = 1.
      RETURN
      END
C
C*************************************************************************
C
      FUNCTION DUDPL(PRESS)
C
      COMMON/PROB/DUMP
C
C     CALCULATE THE PARTIAL DERIVATIVE OF INTERNAL ENERGY WITH RESPECT TO
C     PRESSURE FOR SATURATED LIQUID.  INPUT IS PRESSURE (ATM), PARTIAL
C     DERIVATVE OUTPUT (J/GMOL/ATM).
C
      TEMP = FINDTV(PRESS)
      DENS = FIND D(PRESS+1.E-5,TEMP)
      U = ENTHAL(PRESS+1.E-5,DENS,TEMP)-PRESS*101.327/DENS
      DP = .05
      IF((PRESS-DP) .LT.1.E-4)DP = DP/2.
      KOUNT = 0
   25 TEMP = FINDTV(PRESS-DP)
      DENS = FIND D(PRESS-DP+1.E-5,TEMP)
      ULOW = ENTHAL(PRESS-DP+1.E-5,DENS,TEMP)-(PRESS-DP)*101.327/DENS
      TEMP = FINDTV(PRESS+DP)
      DENS = FIND D(PRESS+DP+1.E-5,TEMP)
      UHIGH = ENTHAL(PRESS+DP+1.E-5,DENS,TEMP)-(PRESS+DP)*101.327/DENS
      DUDPL = (UHIGH-ULOW)/DP/2.
C
C     CHECK ACCURACY OF PARTIAL DERIVATIVE.
C
      IF(ABS((UHIGH-2.*U+ULOW)/(UHIGH-U)).LT. 1.E-3) RETURN
      KOUNT = KOUNT + 1
C
C     IF THE SOLUTION HAS NOT CONVERGED, MAKE DELTA P SMALLER.
C
      DP = DP /2.
C
C     CHECK TO SEE IF THE SOLUTION IS CONVERGING (CONVERGENCE USUALLY
C     OCCURS IN 2-3 ITERATIONS).
C
      IF (KOUNT .LE. 100) GO TO 25
      WRITE(6,125)
  125 FORMAT(1H ,*KOUNT EXCEEDS 100 FOR DUDPL. STOP PROGRAM*)
      DUMP = 1.
      RETURN
      END
C
C*************************************************************************
C
      FUNCTION DTDP(PRESS)
C  CALCULATE THE PARTIAL DERIVATIVE OF TEMPERTURE WITH
C  RESPECT TO PRESS FOR A SATURATED LIQUID
C
      COMMON/PROB/DUMP
C
      TEMP = FINDTV(PRESS)
      DP = 0.05
      IF(PRESS-DP .LT. 1.E-4)DP=DP/2.
      KOUNT = 0
   25 THIGH = FINDTV(PRESS+DP)
      TLOW = FINDTV(PRESS-DP)
      DTDP = (THIGH-TLOW)/DP/2.
C
```

```
C  CHECK CONVERGENCE
C
      IF(ABS((THIGH-2.*TEMP+TLOW)/(THIGH-TEMP)) .LE. 1.E-3)
     + RETURN
      KOUNT = KOUNT+1
C
C  REDUCE DP
C
      DP = DP/2.
C
C
      IF (KOUNT .LE. 100) GO TO 25
      WRITE(6,125)
  125 FORMAT(1H ,*KOUNT EXCEEDS 100 FOR DTDP. STOP PROGRAM*)
      DUMP = 1.
      RETURN
      END
C*********************************************************************
C
      FUNCTION CWALL(TEMP)
C
C    CALCULATE THE HEAT CAPACITY OF THE TANK WALL (J/G/DEG K)
C    AS A FUNCTION OF TEMPERATURE (DEG K).  WALL MATERIAL IS ALUMINUM
C    FOR LH2 AND INCONEL FOR LOX.
C
         COMMON/PROP/NGAS
      IF(NGAS.EQ.2) GO TO 1
      CWALL = EXP(7.29296-121.912/TEMP+347.918/(TEMP**2))/1000.
      GO TO 2
   1  CWALL = EXP(6.482-106.3/TEMP+321.9/(TEMP**2))/1000.
   2  RETURN
      END
C
C*********************************************************************
C
      FUNCTION FLO(PRESS)
C
C    CALCULATE THE PUMPLESS FLOWRATE (GMOL/SEC) AS A FUNCTION OF
C    SUPPLY AND RECEIVER TANK PRESSURES (ATM).  FOR THIS FUNCTION, THE
C    SUPPLY TANK PRESSURE MUST BE GREATER THAN THE RECEIVER TANK PRESSURE.
C
         COMMON/FLOW/ DIAM,DET,TET,PET,LENGTH,PMETER
         COMMON/NOZZLE/CDIAM,NOZDIA,HEADIA,NNOZ,CONST,CDLENG
         COMMON/PARAM/ MW,MWALL,Q,VOL,QPIPE,QET,TOTAL,PVENT
      COMMON/PROB/DUMP
      REAL LENGTH,MW,MWALL,NOZDIA
      PI = 3.14159
C
C    INITIALIZE THE FRICTION FACTOR.
C
      FLINE = 0.005
      FCOOL = 0.005
      PMETER = (PET-PRESS)*0.05
      KOUNT = 0
C
C    CALCULATE FLOWRATE, OBTAIN A NEW FANNING FRICTION FACTOR, THEN
C    RE-CALCULATE THE FLOWRATE.  THIS CONTINUES UNTIL THE FRICTION
C    FACTOR CHANGES SIGNIFICANTLY
C
  35  CONTINUE
C
C  CALCULATE CONSTANTS FOR INDIVIDUAL PRESSURE DROPS
C
C  MAIN TRANSFER LINE
```

```
C
      CLINE = (3.15815*MW*LENGTH)/(DET*PI**2*DIAM**5)
C
C  COOLDOWN LINE
C
      CCOOL = (3.15815*MW*CDLENG)/(DET*PI**2*CDIAM**5)
C
C  COOLDOWN NOZZLES
C
      A = CONST * 6.7162E-2 / (NOZDIA**2)
      B = 1.941E-3 * MW / DET
      C = 1. - ((NOZDIA/HEADIA)**4)
      CNOZ = ((A**2) * B * C ) / FLOAT(NNOZ) * 4.725E-4
C
C  CALCULATE FLOWRATE
C
      FLO = SQRT((PET-PRESS-PMETER)/(CLINE*FLINE+CCOOL*FCOOL+CNOZ))
C
C  CALCULATE NEW FRICTION FACTORS
C
      FLNEW = FRICT(FLO,TET,DET,DIAM)
      FCNEW = FRICT(FLO,TET,DET,CDIAM)
C
C  CONVERGENCE CHECK
C
      IF(ABS(FLNEW-FLINE)/FLINE.LT.0.01.AND.ABS(FCNEW-FCOOL)/FCOOL
     +  .LT.0.01)GO TO 80
      GO TO 81
   80 CONTINUE
C.      WRITE(6,77)FLINE,FCOOL
   77 FORMAT(* FLINE = *,E12.5,* FCOOL = *,E12.5)
      RETURN
   81 CONTINUE
C  ITERATE
C
      FLINE = FLNEW
      FCOOL = FCNEW
      KOUNT = KOUNT+1
      IF(KOUNT .LT. 100)GO TO 35
      WRITE(6,100)
  100 FORMAT(1H ,*KOUNT EXCEEDS 100 FOR FLO. STOP PROGRAM*)
  101 DUMP = 1.
      RETURN
      END
C
C*************************************************************************
C
      FUNCTION FRICT(FLO,T,D,DIAM)
C
C    CALCULATE THE FRICTION FACTOR AS A FUNCTION OF PIPE ROUGHNESS AND
C    REYNOLDS NUMBER.
C
         COMMON/PARAM/ MW,MWALL,Q,VOL,QPIPE,QET,TOTAL,PVENT
         COMMON/PROP/NGAS
      REAL MW,MWALL
      PI = 3.14159
C
C    CALCULATE THE DIMENSIONLESS REYNOLDS NUMBER
C
      IF(NGAS.EQ.2) GO TO 1
      REY = 4.*FLO*MW/(1.8367E-4*DIAM*PI)
      GO TO 2
    1 REY = 4.*FLO*MW/(VISC(D,T)*1.E-6*DIAM*PI)
C
```

```
C     THE PIPE ROUGHNESS IS ASSUMED TO BE 0.00015 INCHES
C
  2    EPSILON = .00015*30.48
       FRICT = (-4.*ALOG10(EPSILON/DIAM/3.7-5.02/REY*ALOG10(EPSILON
      + /DIAM/3.7 + 14.5/REY)))**(-2)
       RETURN
       END
C
C*************************************************************************
C
       SUBROUTINE CHECK(H1,PRESS,TEMP,QUAL)
C
C     CHECK THE QUALITY OF A STREAM OR TANK GIVEN ENTHALPY (J/GMOL),
C     PRESSURE (ATM) AND TEMPERATURE (DEG K).
C
       TSAT = FIND TV(PRESS)
       DSAT = FIND D(PRESS+1.E-5,TSAT)
       HCALC = ENTHAL(PRESS+1.E-5,DSAT,TSAT)
       IF (HCALC .LT. H1) GO TO 10
C
C     IF ACTUAL ENTHALPY IS LESS THAN LIQUID SATURATION ENTHALPY, THE
C     LIQUID IS SUBCOOLED AND THERE IS NO VAPOR PRESENT (QUAL = 0).
C
       QUAL = 0.
       RETURN
   10  DVAP = FIND D(PRESS-1.E-5,TSAT)
       HVAP = ENTHAL(PRESS-1.E-5,DVAP,TSAT)
C
C     CALCULATE THE QUALITY USING ACTUAL, LIQUID AND VAPOR ENTHALPIES.
C
       QUAL =100.*(HCALC-H1)/(HCALC-HVAP)
       RETURN
       END
C
C*************************************************************************
C
       FUNCTION PUMPFLO(PRESS,PFLO1)
C
C     CALCULATE THE FLOWRATE BETWEEN TANKS (GMOL/SEC) IN THE PRESENCE OF
C     A PUMP (J/S).  THIS ROUTINE REQUIRES AN INITIAL GUESS FOR THE
C     FLOWRATE.
C
          COMMON/FLOW/ DIAM,DET,TET,PET,LENGTH,PMETER
          COMMON/NOZZLE/CDIAM,NOZDIA,HEADIA,NNOZ,CONST,CDLENG
          COMMON/PARAM/ MW,MWALL,Q,VOL,QPIPE,QET,TOTAL,PVENT
          COMMON/PUMP/ POWER,EFF
          COMMON/PROB/DUMP
       COMMON/NEG/IJK
       REAL MW,MWALL,LENGTH,NOZDIA
       KOUNT = 0
       DP = PET-PRESS
       PMETER = DP*0.05
       PI = 3.14159
   25  EFF = PEFF(PFLO1)
C
C     CALCULATE A THEORETICAL PRESSURE DROP (OR RISE) BETWEEN TANKS.
C
C  NOZZLE PRESSURE DROP
C
       A = CONST * 6.7162E-2 / (NOZDIA**2)
       B = 1.941E-3 * MW / DET
       C = 1. - ((NOZDIA/HEADIA)**4)
       DPNOZ = ((PFLO1**2) * (A**2) * B * C) / FLOAT(NNOZ) * 4.725E-4
C
```

```
C  COOLDOWN LINE
C
      FCOOL = FRICT(PFLO1,TET,DET,CDIAM)
      DPCOOL=(PFLO1**2)*(3.15815*MW*CDLENG*FCOOL)/(DET*PI**2*CDIAM**5)
C
C  MAIN TRANSFER LINE
C
      FLINE = FRICT(PFLO1,TET,DET,DIAM)
      DPLINE = (PFLO1**2)*(3.15815*MW*LENGTH*FLINE)/(DET*PI**2*DIAM**5)
C
C  PUMP
C
      DPPUMP = (0.009868*POWER*EFF*DET)/(PFLO1)
C
C  CALCULATE PRESSURE DROP
C
      DPCALC1 = + PMETER + DPNOZ + DPCOOL + DPLINE - DPPUMP
C
C  INCREMENT FOR INTERATION
C
      KOUNT = KOUNT + 1
      IF (KOUNT .GT. 1) GO TO 10
      PFLO = PFLO1
      PFLO1 = PFLO1*1.5
      DPCALC = DPCALC1
      GO TO 25
C
C    CALCULATE A NEW FLOWRATE USING A QUASI-NEWTON METHOD.
C
C    NOMENCLATURE:
C      PUMPFLO - FLOWRATE (GMOL/S) AT N+1 ITERATION
C      PFLO1 - FLOWARATE AT N ITERATION
C      PFLO - FLOWATE AT N-1 ITERATION
C      DPCALC1 - CALCULATED PRESSURE DROP (ATM) AT N ITERATION
C      DPCALC - CALCULATED PRESSURE DROP AT N-1 ITERATION
C      DP - ACTUAL PRESSURE DROP (OR RISE) BETWEEN TANKS.
C
   10 PUMPFLO = PFLO1-(DP-DPCALC1)*(PFLO1-PFLO)/(DPCALC-DPCALC1)
C
C    CHECK TO SEE IF THE THEORETICAL AND ACTUAL TANK PRESSURE
C    DIFFERENCES ARE WITHIN 0.01% OF EACH OTHER.
C
C
C  CONVERGENCE CHECK
C
      IF(ABS((DPCALC1-DP)/DP) .LT. 1.E-4) GO TO 180
      GO TO 170
  180 CONTINUE
  160 CONTINUE
      RETURN
  170 CONTINUE
C
C    ITERATE THE FLOWRATE, CALCULATE PRESSURE DROP.
C
      DPCALC = DPCALC1
      PFLO = PFLO1
      PFLO1 = PUMPFLO
C
      IF (KOUNT .LT. 100) GO TO 25
      WRITE(6,100)
  100 FORMAT(1H ,*KOUNT EXCEEDS 100 FOR PUMPFLO. STOP PROGRAM*)
      DUMP = 1.
      RETURN
      END
```

```
C
C*************************************************************************
C
      FUNCTION PEFF(FLOW1)
C
C     CALCULATE PUMP EFFICIENCY OF A CENTAUR PUMP
C
          COMMON/FLOW/ DIAM,DET,TET,PET,LENGTH,PMETER
          COMMON/PROP/NGAS
      REAL LENGTH
C
C     CHANGE UNITS ON FLOWRATE FROM GMOL/S TO GALLONS/MIN.
C
      GPM = FLOW1*15.8502/DET
C
C     CALCULATE PUMP EFFICIENCY
C
      IF(NGAS.EQ.2) GO TO 1
      PEFF=(.39213+.09662*GPM+2.7797E-5*(GPM**2)-
     + 8.1723E-8*(GPM**3)+2.5008E-11*(GPM**4))/100.
      GO TO 2
    1 PEFF = (.32031+.48261*GPM-1.6223E-3*(GPM**2)+
     + 3.9836E-6*(GPM**3)-4.8853E-9*(GPM**4))/100.
    2 CONTINUE
      RETURN
      END
C
C*************************************************************************
C
      SUBROUTINE PFAIL(M,XVENT)
C
C     THIS SUBROUTINE FINISHES OFF THE PROGRAM.  PFAIL IS USED WHEN
C     FLOW BETWEEN TANKS STOPS DUE TO BACK PRESSURE FROM THE RECEIVER
C     TANK.
C
          COMMON/SUB/ FLOW1,FLOW2,PRESS,TEMP,TIME,HET
          COMMON/PARAM/ MW,MWALL,Q,VOL,OPIPE,QET,TOTAL,PVENT
          COMMON/FLOW/ DIAM,DET,TET,PET,LENGTH,PMETER
          COMMON/PLOT/ NPLOT,X,Y1,Y2,Y3,Y4,Y5,Y6,Y7,Y8
          COMMON/PROP/NGAS
      DIMENSION OPLOT(18)
      REAL X(600),Y1(600),Y2(600),Y3(600),Y4(600),Y5(600),Y6(600)
     + ,Y7(600),Y8(600)
      REAL M,MW,MWALL,LENGTH
C
C     CONVERT TIME FROM SECONDS TO MINUTES, PRESSURE FROM ATM TO PSI,
C     TEMPERATURE FROM DEG K TO DEG F AND QUANTITY FROM GMOL TO LB.
C
      XTIME = TIME/60.
      XPRESS = PRESS*14.696
      PET = PET*14.696
      XTEMP = TEMP*9./5.-460.
      TET = TET*9./5.-460.
      XM = M*MW/454.
      XOUT = XVENT*MW/454.
C
C     WRITE A MESSAGE STATING WHY THE SIMULATION STOPPED AND WHAT THE
C     CONDITIONS WERE AT THAT TIME.
C
      WRITE(6,100) XTIME,XTEMP,XPRESS,XM,XOUT
  100 FORMAT(//* AT *,F7.3,* MINUTES FROM START OF PROPELLANT*
     + ,* TRANSFER*/,* FLOW HAS STOPPED DUE TO BACK PRESSURE FROM*
     + ,*  THE RECEIVER TANK.*,//,*AT THIS TIME THE RECEIVER TANK*,
     + * IS AT *,F7.2,* DEG F, *,F7.2,* PSIA*/,
```

```
     + * AND CONTAINS *,F10.2,* POUNDS *,
     + //,* DURING THE SIMULATION *,F8.2,* POUNDS WERE VENTED*)
C
      WRITE(6,101)TET,PET
  101 FORMAT(/* SUPPLY TANK IS AT *F9.4,* DEG F, *F7.2,* PSIA*)
C     SKIP OVER OTHER MESSAGES AND GO TO INITIALIZATION OF PLOT DATA
C     AND PARAMETERS.
C
      GO TO 10
      ENTRY FULL
C
C     THIS ENTRY IS USED WHEN THE RECEIVER TANK IS FULL OF LIQUID.
C
C     CONVERT TIME, TEMPERATURE, PRESSURE AND QUANTITY IN RECEIVER TANK TO
C     ENGLISH UNITS.
C
      IF(M .LT. TOTAL .AND. XVENT .EQ. 0.)M = TOTAL
      IF(M+XVENT .NE. TOTAL)M = TOTAL-XVENT
      XTIME = TIME/60.
      XTEMP = TEMP*9./5.-460.
      TET = TET*9./5.-460.
      XPRESS = PRESS*14.696
      PET = PET*14.696
      XM = M*MW/454.
      XOUT = XVENT*MW/454.
C
C     WRITE OUT A MESSAGE STATING WHY THE SIMULATION STOPPED AND WHAT THE
C     CONDITIONS WERE AT THAT TIME.
C
      WRITE(6,110) XTIME,XTEMP,XPRESS,XM,XOUT
  110 FORMAT(//,* AT *,F7.3,* MINUTES FROM START OF PROPELLANT*,
     + * TRANSFER,*/,* THE RECEIVER TANK IS FULL.*//,* AT THIS TIME *
     + *THE RECEIVER TANK IS AT *,F7.2,* DEG F, *,F7.2,* PSIA,*/,
     + * AND CONTAINS *,F10.2,*POUNDS*,
     + //,* DURING THE SIMULATION *,F8.2,* POUNDS WERE VENTED*)
C
      WRITE(6,111)TET,PET
  111 FORMAT(/* SUPPLY TANK IS AT *F9.4,* DEG F, *F7.2,* PSIA*)
C     SKIP OVER UNWANTED MESSAGE.
C
      GO TO 10
      ENTRY DONE
C
C     THIS ENTRY IS USED WHEN THE SUPPLY TANK IS EMPTY.
C
      IF(M .LT. TOTAL .AND. XVENT .EQ. 0.)M = TOTAL
      IF(M+XVENT .NE. TOTAL)M = TOTAL-XVENT
C     CONVERT TO ENGLISH UNITS.
C
      XTIME = TIME/60.
      XTEMP = TEMP*9./5.-460.
      TET = TET*9./5.-460.
      XPRESS = PRESS*14.696
      PET = PET*14.696
      XM = M*MW/454.
      XOUT = XVENT*MW/454.
C
C     WRITE AN APPROPRIATE MESSAGE AND STOPPING CONDITIONS.
C
      WRITE(6,120) XTIME,XTEMP,XPRESS,XM,XOUT
  120 FORMAT(/,* AT *,F7.3,* MINUTES FROM START OF PROPELLANT*,
     + * TRANSFER*/,* THE SUPPLY TANK IS EMPTY*,/,* AT THIS TIME THE*
     + * RECEIVER TANK IS AT *,F7.2,* DEG F, *,F7.2,* PSIA,*/,
     + * AND CONTAINS *,F10.2,*POUNDS*,
```

```
     + /,* DURING THE SIMULATION *,F8.2,
     + * POUNDS WERE VENTED*)
C
      WRITE(6,121)TET,PET
  121 FORMAT(/* SUPPLY TANK IS AT *F9.4,* DEG F, *F7.2,* PSIA*)
C     IDENTIFY THE PROPELLANT  FOR THE PLOTTING ROUTINE.
C
      GO TO 10
      ENTRY PDATA
C
C  THIS ENTRY IS USED WHEN A PROGRAMMED STOP IS EXECUTED
C
C  CONVERT TO ENGLISH UNITS
C
      XTIME = TIME/60.
      XPRESS = PRESS*14.696
      PET = PET*14.696
      XTEMP = TEMP*9./5.-460.
      TET = TET*9./5.-460.
      XM = M*MW/454.
      XOUT = XVENT*MW/454.
C
C  WRITE A MESSAGE STATING THE CONDITIONS WHEN PROGRAM IS STOPPED
C
      WRITE(6,140)XTIME,XTEMP,XPRESS,XM,XOUT
  140 FORMAT(//,* AT *,F7.3,* MINUTES FROM START OF PROPELLANT*,
     + * TRANSFER*/,* A STOP IS REACHED*,//* AT THIS TIME THE*
     + * RECEIVER TANK IS AT *,F7.2,* DEG F, *,F7.2,* PSIA,*/,
     + * AND CONTAINS *,F10.2,*POUNDS*,
     + //,* DURING THE SIMULATION *,F8.2,
     + * POUNDS WERE VENTED*)
C
      WRITE(6,141)TET,PET
  141 FORMAT(//* SUPPLY TANK IS AT *F9.4,* DEG F, *F7.2,* PSIA*)
   10 CONTINUE
      IF(NGAS.EQ.2)GO TO 11
C
      WRITE(8,190)
  190 FORMAT(*HYDROGEN*)
      GO TO 12
   11 WRITE(8,191)
  191 FORMAT(*OXYGEN*)
   12 CONTINUE
C
C     WRITE THE NUMBER OF PLOT POINTS FOR USE BY THE PLOT ROUTINE.
C
      WRITE(8,200) NPLOT
  200 FORMAT(I3)
C
C     OPLOT(4) ARE BOUNDS FOR Y1, OPLOT(5) AND OPLOT(6) ARE BOUNDS
C     SET LOWER AND UPPER BOUNDARIES FOR PLOTS
C
      OPLOT(1) = 0.
      OPLOT(2) = 0.
      DO 708  I=1,4
      IF(TIME/60. .LE. 10.)OPLOT(2) = 10.
      IF(TIME/60. .LE. 5.)OPLOT(2) = 5.
      IF (TIME/60. .GT. OPLOT(2))OPLOT(2) = OPLOT(2) + 50.
  708 CONTINUE
      OPLOT(3) = -500.
      IF(NGAS.EQ.2)OPLOT(3) = -400.
      OPLOT(4) = 0.
      IF(NGAS.EQ.2)OPLOT(4) = 100.
      DO 55  J = 1,3
```

```
      IF(Y1(1) .GT. OPLOT(4)) OPLOT(4) = OPLOT(4)+100.
   55 CONTINUE
      OPLOT(5) = 0.
      OPLOT(6) = 50.
      DO 57 I=1,NPLOT
      IF((Y2(I).GT.OPLOT(6)).AND.(Y2(I).LT.(OPLOT(6)+50.)))OPLOT(6) =
     + OPLOT(6) + 50.
   57 CONTINUE
   56 OPLOT(7) = 0.
      OPLOT(8) = 2000.
      IF(NGAS.EQ.2)OPLOT(8) = 10000.
      OPLOT(9) = 0.
      OPLOT(10) = 250.
      TOTAL = TOTAL/454.*MW
      DO 1000  I=5000,65000,5000
      IF(TOTAL.LE.FLOAT(I))OPLOT(10) = FLOAT(I)*0.10
      IF(TOTAL.LE.FLOAT(I))GO TO 1001
 1000 CONTINUE
 1001 CONTINUE
      OPLOT(11) = 0.
      OPLOT(12) = OPLOT(10)*10.
      OPLOT(13) = 0.
      OPLOT(14) = OPLOT(12)
      OPLOT(15) = 0.
      OPLOT(16) = 100.
      OPLOT(17) = 0.
      OPLOT(18) = 100.
C
C     WRITE PLOT PARAMETERS FOR PLOTTING ROUTINE.
C
C      WRITE(6,*)(OPLOT(II),II=1,18)
       WRITE(8,*)(OPLOT(II),II=1,18)
C
C     WRITE ARRAYS CONTAINING SIMULATION VARIABLES.
C
C      WRITE(6,249)(X(I),Y1(I),I=1,2)
C 249 FORMAT(2F15.5)
      WRITE(8,250) (X(I),Y1(I),Y2(I),Y3(I),Y4(I),Y5(I),Y6(I),
     + Y7(I),Y8(I),I=1,NPLOT)
  250 FORMAT(F8.3,T10,F8.3,T20,F8.5,T30,F8.2,T40,F8.1,T50,F8.1,T60,F8.1
     + ,T70,F8.3,T80,F8.3)
      STOP
      END
C
C*************************************************************************
C
      SUBROUTINE SUPPLY(DTIME)
         COMMON/SUB/ FLOW1,FLOW2,PRESS,TEMP,TIME,HET
         COMMON/FLOW/ DIAM,DET,TET,PET,LENGTH,PMETER
         COMMON/PARAM/ MW,MWALL,Q,VOL,QPIPE,QET,TOTAL,PVENT
         COMMON/PROB/DUMP
         COMMON/ETANK/ETLIQ,ETVAP,VET,ETQ
      REAL MW,MWALL,LENGTH
C    THIS SUBROUTINE MONITORS THE PROPERTIES OF THE SUPPLY TANK.
C
C    INITIALIZE THE SUBROUTINE
C
C     ENTHALPY AND HEAT CAPACITY OF LIQUID IN  SUPPLY TANK.
C
      HL = HET
      CSUBP = CP(DET,TET)
C
C    FRACTION OF TANK VOLUME OCCUPIED BY LIQUID AND AMOUNT OF
C    HEAT TO EACH PHASE.
```

```
C
      FRACT = ETLIQ/VET/DET
      DQL = QET*FRACT
      DQV = QET-DQL
C
C   SPECIFIC VOLUME OF LIQUID .
C
      VETLIQ = 1./DET
C
C   SATURATION TEMP AT GIVEN PRESSURE, AND THE VAPOR DENSITY.
C
      TETSAT = FINDTV(PET)
      DETVAP = FINDD(PET,TETSAT+1.E-3)
C
C   SPECIFIC VOLUME OF VAPOR.
C
      VETVAP = 1./DETVAP
C
C
C   GRUNEISEN PARAMETER FOR VAPOR AND LIQUID.
C
      CALL PPHI(DETVAP,TETSAT+1.E-3,PHII)
      GRUVAP = PHII
      CALL PPHI(DET,TET,PHII)
      GRULIQ = PHII
C
C   HEAT OF EXPULSION FOR VAPOR AND LIQUID
C
      THETAV = TH(DETVAP,TETSAT+1.E-3)
      THETAL = TH(DET,TET)
C
C   CALCULATE THE CHANGE IN THE SUPPLY TANK PRESS WITH TIME
C
      DPET = ((-FLOW1+VETVAP/VETLIQ/THETAV*DQV+1./THETAL
     1 *DQL)/ETLIQ/(VETLIQ/THETAL/GRULIQ+ETVAP*
     2 VETVAP**2/ETLIQ/VETLIQ/THETAV/GRUVAP)/101.327)*DTIME
C
C   CALCULATE THE CHANGE IN THE SUPPLY TANK LIQUID TEMPERATURE
C   WITH TIME
C
      DTET = ((DQL/ETLIQ+VETLIQ*ALPHAL(PET,TET,DET)*DPET*101.327
     1 /DTIME)/CSUBP)*DTIME
C
C   CALCULATE THE CHANGE IN THE SUPPLY TANK LIQUID ENTHALPY WITH
C   TIME
C
      DHL = (DQL/ETLIQ+VETLIQ*DPET/DTIME*101.327)*DTIME
C
C   INCREMENT THE PRESSURE, LIQUID TEMPERATURE AND ENTHALPY
C
      PET = PET+DPET
      TET = TET+DTET
      HL = HL+DHL
C   OBTAIN NEW LIQUID DENSITY AND ENTHALPY FROM FLUIDSPACK
C   OBTAIN THE SUPPLY TANK LIQUID QUALITY
C
 501  DET = FINDD(PET,TET)
      HET = ENTHAL(PET,DET,TET)
      CALL CHECK(HET,PET,TET,ETQ)
C
C    IF QUALITY IS GREATER THAN ZERO, CAVITATION COULD OCCUR. STOP
C      TRANSFER IMMEDIATELY.
      IF(ETQ.LT.1.E-6)GO TO 99
      WRITE(6,225)ETQ
```

```
  225 FORMAT(1HO,*ET LIQ BOILING. STOP TRANSFER*,5X,*ETO = *E12.5)
      DUMP = 1.
      RETURN
C
C   COMPARE MODEL AND FLUIDSPACK ENTHALPIES.  IF THE VALUES ARE WIDELY
C   DISPARATE, THE ET MODEL IS IN ERROR.  STOP THE PROGRAM.
C   OTHERWISE USE THE MODEL VALUE.
C
   99 IF(ABS((HET-HL)/HL) .GT. 0.100)GO TO 100
      HET = HL
      RETURN
  100 WRITE(6,255)HET,HL
  255 FORMAT(1HO,* ENTHALPY DISPARITY.  HET = *E12.5,* HL = *E12.5)
C
      DUMP = 1.
      RETURN
      END
C
C*********************************************************************
C
      FUNCTION ALPHAL(PET,TET,DET)
C
      COMMON/PROB/DUMP
C
C   THIS FUNCTION CALCULATE THE BULK EXPANSIVITY FOR THE LIQUID
C
C
C   SET THE TEMPERATURE STEP AND THE LOOP COUNTER
C
      DT = 0.05
      KOUNT = 0
C
C   FIND VALUES SLIGHTLY ABOVE AND BELOW THE ACTUAL TEMPERATURE
C   FOR THE DENSITY
C
   25 DHIGH = FINDD(PET,TET-DT)
      DLOW = FINDD(PET,TET+DT)
C
C   CALCULATE THE BULK EXPANSIVITY
C
      ALPHAL = -TET/DET*(DHIGH-DLOW)/DT/2.
      IF(ABS((DHIGH-2.*DET+DLOW)/(DHIGH-DET)) .LT. 1.E-3)RETURN
      KOUNT = KOUNT + 1
C
C   IF THE VALUES ARE NOT CONVERGING, MAKE THE TEMPERATURE STEP SMALLER
C
      DT = DT/2.
      IF(KOUNT.LE.100)GO TO 25
      WRITE(6,125)
  125 FORMAT(1H1,*KOUNT EXCEEDS 100 FOR ALPHAL. STOP PROGRAM*)
      DUMP = 1.
      RETURN
      END
```

```
.PROC,DEMO.
.*
.* DEMONSTRATION PROGRAM USING DISSPLA 9.0.
.*.
EVICT,LGO,PLOT.
FTN,I=PROG,L=FAIL,R=3,PMD.
IFE,FILE(GRAFING,.NOT.AS),JO.
GET,GRAFING/UN=GRAF.
ENDIF,JO.
GET,TAPE2=PSDATA.
BEGIN,DISPLA9,GRAFING.
RETURN,PROG,LGO.
REPLACE,PLOT.
RENAME,Z=PLOT.
SKIPR,Z.
COPYBR,Z,OUTPUT,1.
REVERT.
EXIT.
REVERT,ABORT.
REPLACE,FAIL.
.DATA,PROG
      PROGRAM DEMO(INPUT,TAPE2,OUTPUT=/1000,PLOT=/1000)
      REAL LMIN,LMAX
      DIMENSION X(400),Y1(400),Y2(400),Y3(400),Y4(400),Y5(400),
     + Y6(400),Y7(400),Y8(400)
      DIMENSION XAXIS(4),HEAD(3),IPKRAY(300),L1(3),L2(3),L3(3),L4(3)
      DIMENSION NAME(2),IPK2(100)
      DATA XAXIS/10HTIME (MINU,10HTES)$      ,2*10H
      READ(2,*) DIAM,POWER,TEMP,PRESS
      READ(2,80) NAME(1),NAME(2)
   80 FORMAT(2A4)
      READ(2,*) N
      READ(2,*) TM1,TM2,TMIN,TMAX,PMIN,PMAX,FMIN,FMAX,VMIN,
     + VMAX,LMIN,LMAX,DUM1,DUM2,DUM3,DUM4,DUM5,DUM6
      DTIME = (TM2-TM1)/10.
      DTEMP = (TMAX-TMIN)/5.
      DPRESS = (PMAX-PMIN)/5.
      DFLOW = (FMAX-FMIN)/5.
      DVAP = (VMAX-VMIN)/5.
      DLIQ = (LMAX-LMIN)/5.
      DO 10 I=1,N
   10 READ(2,*) X(I),Y1(I),Y2(I),Y3(I),Y4(I),Y5(I),Y6(I),Y7(I),Y8(I)
      CALLID("  LOUIE,$",100)
C     CALL HP7221
      CALL FR80(0.0)
C     CALL TK4010(120)
C     CALL HWSPEC(4HPLOT,4HFILE)
      CALL NOBRDR
      CALL PHYSOR(1.25,6.)
      CALL AREA2D(6.,4.)
      ENCODE(30,100,HEAD) NAME(1),NAME(2)
```

```
100 FORMAT(2A4," PROPELLANT TRANSFER$")
    CALL HEADIN(HEAD,100,1.25,1)
    CALL XNAME(XAXIS,100)
    CALL YNAME("TEMPERATURE (DEG F)$",100)
    CALL YAXANG(0.)
    ENCODE(30,15,L1) DIAM
 15 FORMAT("DIAMETER: ",F4.1," IN.$")
    ENCODE(30,20,L2) POWER
 20 FORMAT("PUMP: ",F4.1," HP$")
    ENCODE(30,25,L3) TEMP
 25 FORMAT("TANK TEMP: ",F6.1," DEG F$")
    ENCODE(30,30,L4) PRESS
 30 FORMAT("TANK PRESS: ",F4.1," PSIA$")
    CALL LINES (L1,IPKRAY,1)
    CALL LINES(L2,IPKRAY,2)
    CALL LINES(L3,IPKRAY,3)
    CALL LINES(L4,IPKRAY,4)
    CALL LSTORY(IPKRAY,4,3.5,3.0)
    CALL GRAF(TM1,DTIME,TM2,TMIN,DTEMP,TMAX)
    CALL CURVE(X,Y1,N,0)
    CALL ENDGR(0)
    CALL PHYSOR(1.25,1.)
    CALL AREA2D(6.,4.)
    CALL XNAME(XAXIS,100)
    CALL YNAME("PRESSURE (PSIA)$",100)
    CALL YAXANG(0.)
    CALL GRAF(TM1,DTIME,TM2,PMIN,DPRESS,PMAX)
    CALL CURVE(X,Y2,N,0)
    CALL ENDGR(0)
    CALL ENDPL(0)
    CALL NOBRDR
    CALL YAXANG(0.)
    CALL PHYSOR(1.25,6.)
    CALL AREA2D(6.,4.)
    CALL HEADIN(HEAD,100,1.25,2)
    CALL HEADIN("(PAGE 2)$",100,1.,2)
    CALL XNAME(XAXIS,100)
    CALL YNAME("POUNDS IN VAPOR PHASE$",100)
    CALL GRAF(TM1,DTIME,TM2,VMIN,DVAP,VMAX)
    CALL CURVE(X,Y4,N,0)
    CALL ENDGR(0)
    CALL YAXANG(0.)
    CALL PHYSOR(1.25,1.)
    CALL AREA2D(6.,4.)
    CALL XNAME (XAXIS,100)
    CALL YNAME ("POUNDS IN LIQUID PHASE$",100)
    CALL GRAF(TM1,DTIME,TM2,LMIN,DLIQ,LMAX)
    CALL CURVE(X,Y5,N,0)
    CALL ENDGR(0)
    CALL ENDPL(0)
    CALL NOBRDR
    CALL YAXANG(0.)
    CALL PHYSOR(1.25,6.)
    CALL AREA2D(6.,4.)
```

```
CALL HEADIN(HEAD,100,1.25,2)
CALL HEADIN("(PAGE 3)$",100,1.,2)
CALL XNAME(XAXIS,100)
CALL YNAME("TOTAL POUNDS TRANSFERRED$",100)
CALL GRAF(TM1,DTIME,TM2,LMIN,DLIQ,LMAX)
CALL CURVE(X,Y6,N,0)
CALL ENDGR(0)
CALL YAXANG(0.)
CALL PHYSOR(1.25,1.)
CALL AREA2D(6.,4.)
CALL XNAME (XAXIS,100)
CALL YNAME ("FLOWRATE (POUNDS/MIN)$",100)
CALL GRAF(TM1,DTIME,TM2,FMIN,DFLOW,FMAX)
CALL CURVE(X,Y3,N,0)
CALL ENDPL(0)
CALL PHYSOR(1.5,6.)
CALL AREA2D(6.,4.)
CALL HEADIN(HEAD,100,1.25,2)
CALL HEADIN("(PAGE 4)$",100,1.,2)
CALL XNAME(XAXIS,100)
CALL YNAME(1H ,1)
CALL YNONUM
CALL LINES("SUPPLY$",IPK2,1)
CALL LINES("RECEIVER INLET$",IPK2,2)
CALL GRAF(TM1,DTIME,TM2,-10.,120.,110.)
CALL RLVEC(TM1-.2,0.,TM1+.2,0.,0)
CALL RLVEC(TM1-.2,100.,TM1+.2,100.,0)
X1 = XINVRS(XMESS("100% LIQ. $",100),0.)
X2 = XINVRS(XMESS("100% VAP. $",100),0.)
CALL RLMESS("100% LIQ. $",100,TM1-.2-X1,0.)
CALL RLMESS("100% VAP. $",100,TM1-.2-X2,100.)
CALL CURVE(X,Y7,N,10)
CALL CURVE(X,Y8,N,10)
CALL LEGEND(IPK2,2,3.,3.)
CALL  ENDPL(0)
CALL DONEPL
STOP
END
```

```
      PROGRAM PLOT(INPUT,TAPE6,OUTPUT=TAPE6,TAPE8=INPUT)
      REAL TIME(400),TEMP(400),PRESS(400),FLOW1(400),MVAP(400),MLIQ(400)
      REAL LLB,LUB
      READ(8,*) DUM1,DUM2,DUM3,DUM4
      READ(8,90) NAME
   90 FORMAT(A10)
      READ(8,100) N
  100 FORMAT(I3)
      READ(8,*) TLB,TUB,TEMPLB,TEMPUB,PLB,PUB,FLB,FUB,VLB,VUB,LLB,LUB,
     + TOTLB,TOTUB,Q1LB,Q1UB,Q2LB,Q2UB
      DO 10 I = 1,N
   10 READ(8,110) TIME(I),TEMP(I),PRESS(I),FLOW1(I),MVAP(I),MLIQ(I)
  110 FORMAT(F8.3,T10,F8.3,T20,F8.5,T30,F8.2,T40,F8.1,T50,F8.1)
      ILOG = 0
      ISIZE = 0
      NOUT = 0
      WRITE(6,120)
  120 FORMAT(1H1,*ORBITER TANK TEMPERATURE (DEGREES F) VS.*
     + ,* TIME (MINUTES)*)
      CALL PPC(TEMP,TIME,N,ILOG,ISIZE,NOUT,TEMPLB,TEMPUB,TLB,TUB)
      WRITE(6,130)
  130 FORMAT(1H1,*TANK PRESSURE (PSIA) VS. TIME (MINUTES)*)
      CALL PPC(PRESS,TIME,N,ILOG,ISIZE,NOUT,PLB,PUB,TLB,TUB)
      WRITE(6,140)
  140 FORMAT(1H1,*FLOWRATE (LB/MIN) VS. TIME (MINUTES)*)
      CALL PPC(FLOW1,TIME,N,ILOG,ISIZE,NOUT,FLB,FUB,TLB,TUB)
      WRITE(6,150)
  150 FORMAT(1H1,*POUNDS IN VAPOR PHASE VS. TIME (MINUTES)*)
      CALL PPC(MVAP,TIME,N,ILOG,ISIZE,NOUT,VLB,VUB,TLB,TUB)
      WRITE(6,160)
  160 FORMAT(1H1,*POUNDS IN LIQUID PHASE VS. TIME (MINUTES)*)
      CALL PPC(MLIQ,TIME,N,ILOG,ISIZE,NOUT,LLB,LUB,TLB,TUB)
      STOP
      END
```

```
4. 4. 60. 1.
OXYGEN
64
0. 5. -400. 100. 0. 50. 0. 10000. 0. 1000. 0. 10000. 0. 10000. 0. 100. 0. 100.
   .001    48.699    2.75189   3398.11       3.1       0.0       3.1     0.000     8.601
   .002    37.590    4.42648   3398.11       6.2       0.0       6.2     0.000     5.954
   .003    26.672    6.02568   3398.11       9.3       0.0       9.3     0.000     4.107
   .004    15.938    7.55134   3398.11      12.4       0.0      12.4     0.000     2.671
   .005     5.384    9.00520   3398.11      15.5       0.0      15.5     0.000     1.493
   .005    -4.998   10.38895   3398.11      18.6       0.0      18.6     0.000      .494
   .006   -15.211   11.70422   3398.11      21.7       0.0      21.7     0.000     0.000
   .007   -25.260   12.95254   3398.11      24.8       0.0      24.8     0.000     0.000
   .008   -35.151   14.13541   3398.11      27.9       0.0      27.9     0.000     0.000
   .009   -44.889   15.25425   3398.11      31.0       0.0      31.0     0.000     0.000
   .010   -54.477   16.31042   3398.11      34.1       0.0      34.1     0.000     0.000
   .011   -63.921   17.30522   3398.11      37.2       0.0      37.2     0.000     0.000
   .012   -73.224   18.23991   3398.11      40.3       0.0      40.3     0.000     0.000
   .013   -82.391   19.11569   3398.11      43.4       0.0      43.4     0.000     0.000
   .014   -91.425   19.93369   3398.11      46.5       0.0      46.5     0.000     0.000
   .015  -100.331   20.69502   3398.11      49.6       0.0      49.6     0.000     0.000
   .016  -109.113   21.40072   3398.11      52.8       0.0      52.8     0.000     0.000
   .016  -117.773   22.05177   3398.11      55.9       0.0      55.9     0.000     0.000
   .017  -126.316   22.64913   3398.11      59.0       0.0      59.0     0.000     0.000
   .018  -134.745   23.19370   3398.11      62.1       0.0      62.1     0.000     0.000
   .019  -143.064   23.68633   3398.11      65.2       0.0      65.2     0.000     0.000
   .020  -151.276   24.12782   3398.11      68.3       0.0      68.3     0.000     0.000
   .021  -159.383   24.51894   3398.11      71.4       0.0      71.4     0.000     0.000
   .022  -167.390   24.86040   3398.11      74.5       0.0      74.5     0.000     0.000
   .023  -175.299   25.15287   3398.11      77.6       0.0      77.6     0.000     0.000
   .024  -183.114   25.39698   3398.11      80.7       0.0      80.7     0.000     0.000
   .025  -190.836   25.59330   3398.11      83.8       0.0      83.8     0.000     0.000
   .026  -198.469   25.74237   3398.11      86.9       0.0      86.9     0.000     0.000
   .026  -206.015   25.84467   3398.11      90.0       0.0      90.0     0.000     0.000
   .027  -213.476   25.90064   3398.11      93.1       0.0      93.1     0.000     0.000
   .028  -220.856   25.91069   3398.11      96.2       0.0      96.2     0.000     0.000
   .029  -228.155   25.87516   3398.11      99.3       0.0      99.3     0.000     0.000
   .030  -235.376   25.79435   3398.11     102.4       0.0     102.4     0.000     0.000
   .031  -242.520   25.66852   3398.11     105.5       0.0     105.5     0.000     0.000
   .032  -249.589   25.49788   3398.11     108.6       0.0     108.6     0.000     0.000
   .033  -256.583   25.28260   3398.11     111.7       0.0     111.7     0.000     0.000
   .034  -263.502   25.02281   3398.11     114.8       0.0     114.8     0.000     0.000
   .035  -270.347   24.71859   3398.11     117.9       0.0     117.9     0.000     0.000
   .036  -277.115   24.37000   3398.11     121.0       0.0     121.0     0.000     0.000
   .037  -283.805   23.97707   3398.11     124.1       0.0     124.1     0.000     0.000
   .037  -290.413   23.53982   3398.11     127.2       0.0     127.2     0.000     0.000
   .038  -295.604   23.06581   3398.11     130.3       0.0     130.3     0.000     0.000
   .145  -291.025   21.25714   2628.10     116.0     293.3     409.3     0.000     0.000
   .253  -292.181   19.97737   2628.10     108.0     583.2     691.3     0.000     0.000
   .360  -293.033   19.07144   2628.10     102.1     871.1     973.2     0.000     0.000
   .467  -293.684   18.40162   2628.10      97.4    1157.8    1255.2     0.000     0.000
   .575  -294.195   17.88860   2628.10      93.5    1443.6    1537.1     0.000     0.000
```

.682	-294.606	17.48423	2628.10	90.3	1728.8	1819.0	0.000	0.000
.789	-294.942	17.15792	2628.10	87.4	2013.5	2101.0	0.000	0.000
.896	-295.223	16.88937	2628.10	84.9	2298.0	2382.9	0.000	0.000
1.004	-295.461	16.66470	2628.10	82.6	2582.2	2664.8	0.000	0.000
1.111	-295.664	16.47408	2628.10	80.5	2866.3	2946.8	0.000	0.000
1.218	-295.840	16.31039	2628.10	78.5	3150.1	3228.7	0.000	0.000
1.325	-295.994	16.16835	2628.10	76.7	3433.9	3510.6	0.000	0.000
1.433	-296.130	16.04397	2628.10	74.9	3717.6	3792.5	0.000	0.000
1.540	-296.251	15.93416	2628.10	73.3	4001.2	4074.5	0.000	0.000
1.647	-296.358	15.83652	2628.10	71.7	4284.7	4356.4	0.000	0.000
1.755	-296.455	15.74914	2628.10	70.1	4568.2	4638.3	0.000	0.000
1.862	-296.543	15.67050	2628.10	68.6	4851.6	4920.3	0.000	0.000
1.969	-296.622	15.59936	2628.10	67.2	5135.0	5202.2	0.000	0.000
2.076	-296.694	15.53469	2628.10	65.7	5418.4	5484.1	0.000	0.000
2.184	-296.761	15.47565	2628.10	64.3	5701.7	5766.0	0.000	0.000
2.291	-296.822	15.42154	2628.10	63.0	5985.0	6048.0	0.000	0.000
2.355	-296.867	15.38141	2628.10	61.9	6211.6	6273.5	0.000	0.000

```
/JOB
/NOSEQ
COMBO(T500)
/READ,ACCOUNT
HEADING. OLOUIE
GET,COMBO,BOXB,TAPE5=DATAIN,TAPE7=FUEL.
FTN,I=COMBO,OPT=2,L=TRACE,R=3,PMD.
LDSET(PRESET=ZERO)
LOAD,BOXB.
LGO.
SKIP,PASS.
EXIT.
REWIND,TRACE.
COPYEI,TRACE,TAPE6.
ENDIF,PASS.
REWIND,TAPE8.
COPYEI,TAPE8,PSDATA.
REPLACE,PSDATA.
DAYFILE,TAPE6.
REWIND,TAPE6.
COPYEI,TAPE6,PSOUT.
REPLACE,TAPE6,PSOUT.
DAYFILE,DAYF.
REPLACE,DAYF.
/EOI
```

LIBPLOT

```
/JOB
/NOSEQ
FPLOT(T500)
/READ,ACCOUNT
GET,PSDATA,FPLOT.
ATTACH,STAR4/UN=CAMLIB,NA.
LIBRARY,STAR4.
FTN,I=FPLOT,B=B,L=0,R=3.
LOAD,B.
EXECUTE,,,,PSDATA.
/READ,SPY
```

SUBCOM

```
/JOB
/NOSEQ
COMBO(T500)
/READ,ACCOUNT
HEADING. OLOUIE
GET,COMBO,BOXB,TAPE5=DATAIN,TAPE7=FUEL.
FTN,I=COMBO,OPT=2,L=TRACE,R=3,PMD.
LDSET(PRESET=ZERO)
LOAD,BOXB.
LGO.
SKIP,PASS.
EXIT.
REWIND,TRACE.
COPYEI,TRACE,TAPE6.
ENDIF,PASS.
REWIND,TAPE8.
COPYEI,TAPE8,PSDATA.
REPLACE,PSDATA.
REWIND,TAPE8.
ATTACH,STAR4/UN=CAMLIB,NA.
LIBRARY,STAR4.
GET,FPLOT.
FIN,I=PLOT,B=B,L=LIST,R=3.
LOAD,B.
EXECUTE,,TAPE8.
SKIP,OK.
EXIT.
REWIND,LIST.
COPYEI,LIST,TAPE6.
ENDIF,OK.
DAYFILE,TAPE6.
REWIND,TAPE6.
COPYEI,TAPE6,PSOUT.
REPLACE,TAPE6,PSOUT.
DAYFILE,DAYF.
REPLACE,DAYF.
/EOI
```

DATAIN

```
$NAME
 QPIPE = 1000000.,
$
```

FUEL

```
$FUEL
 NGAS=2,
$
```

Oxygen Default Parameters

Supply tank initial conditions:

Pressure =	20.000 psia
Temperature =	-315.000 F
Oxygen Mass =	6270.00 Pounds
Heat Leak =	0.000 Btu/hr

Receiver tank initial conditions:

Pressure =	1.000 psia
Temperature =	60.000 F
Vent Pressure =	30.000 psia
Tank Volume =	300.000 Cubic Feet
Tank Wall Mass =	350.000 Pounds
Heat Leak =	0.000 Btu/hr

Transfer Parameters:

Pipe Diameter =	4.000 Inches
Length of Straight Pipe =	100.000 Feet
20 Elbow(s)	
0 Gate Valve(s)	
2 Globe Valve(s)	
1 Angle Valve(s)	
0 Butterfly Valve(s)	
1 Flow Meter (s)	
Heat Leak Into Piping =	104400.000 Btu/hr
Pump Power =	4.0 HP
Cool-Down Time =	1.000 Minutes

Cool-Down Parameters:

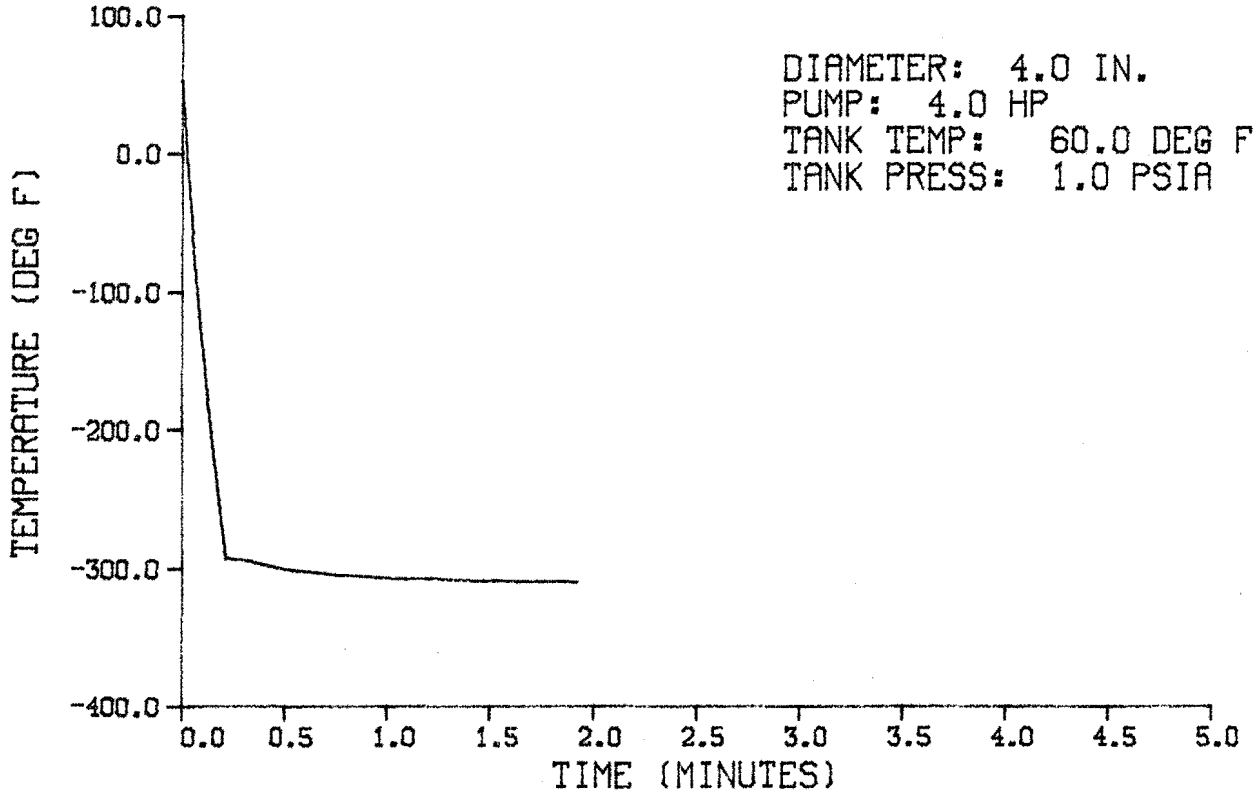
Length of Piping =	20.000 Feet
Header Diameter =	0.5000 Inches
Nozzle Diameter =	0.1250 Inches
Number of Nozzles =	6

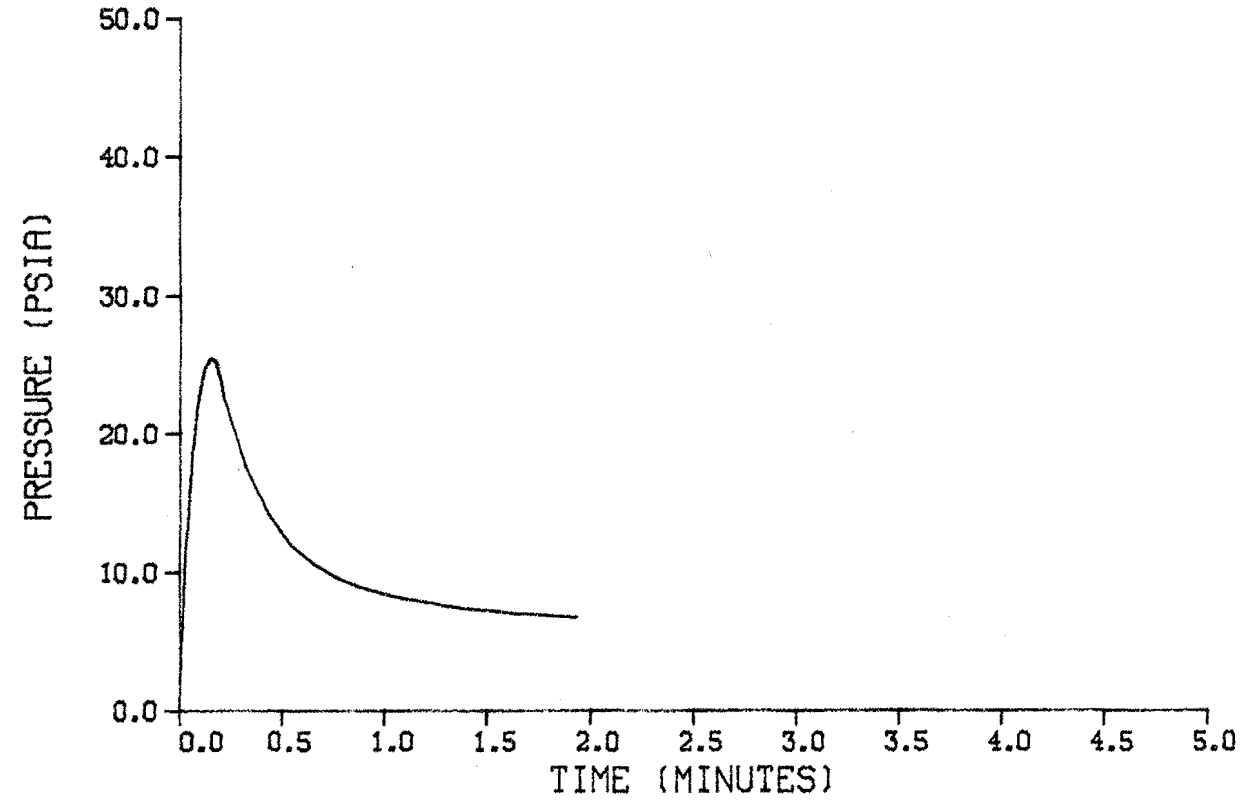
At 1.92 minutes from start of propellant transfer the supply tank is empty.

At this time the, receiver tank is at -310.17 Deg F, 6.65 psia, and contains 6270.00 pounds of oxygen.

During the simulation 0.00 pounds were vented.

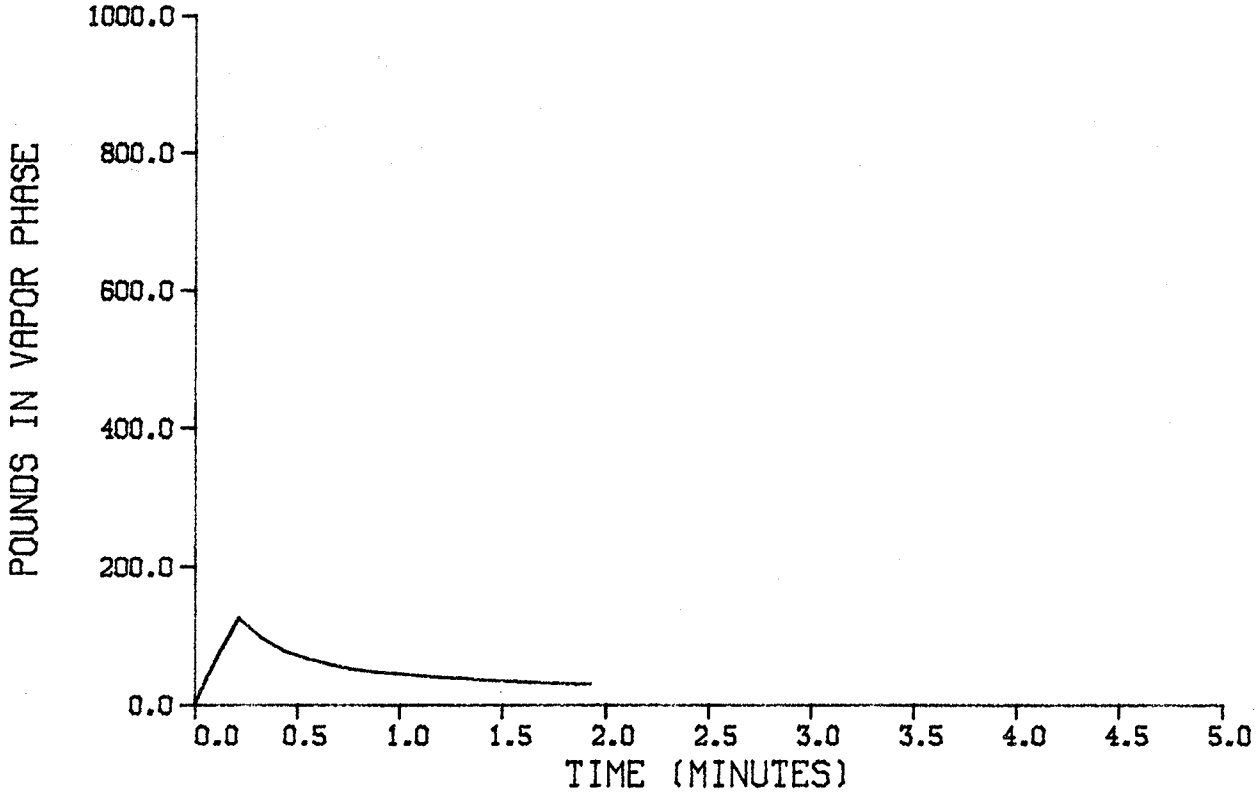
OXYGEN PROPELLANT TRANSFER*

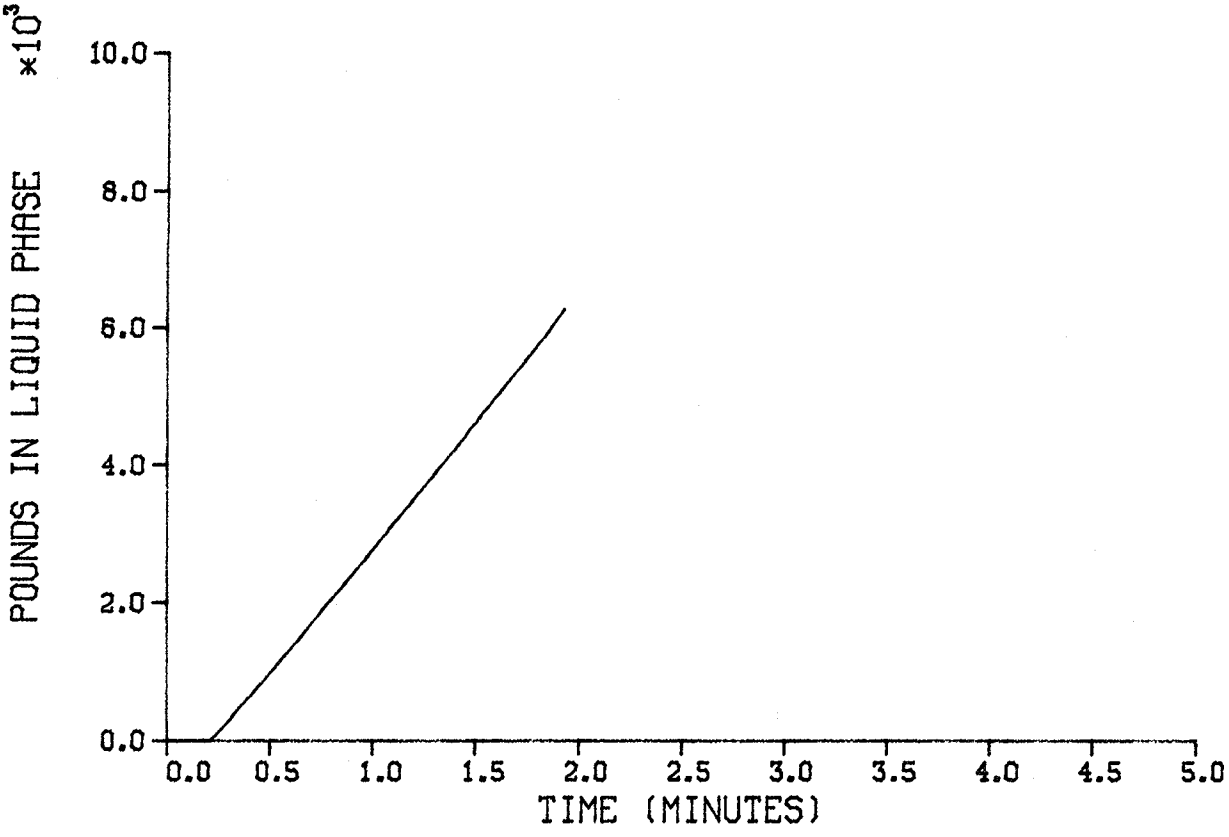




* Computer generated plots.

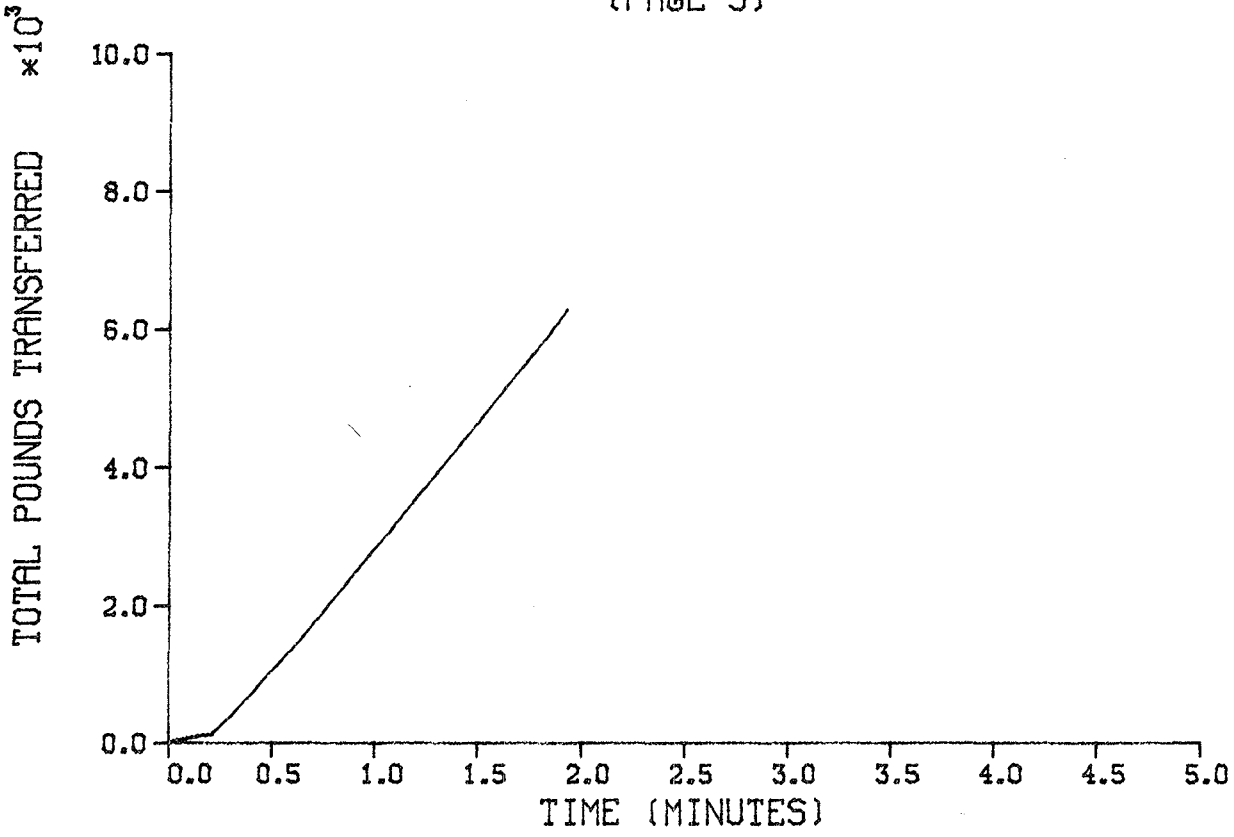
OXYGEN PROPELLANT TRANSFER
(PAGE 2)

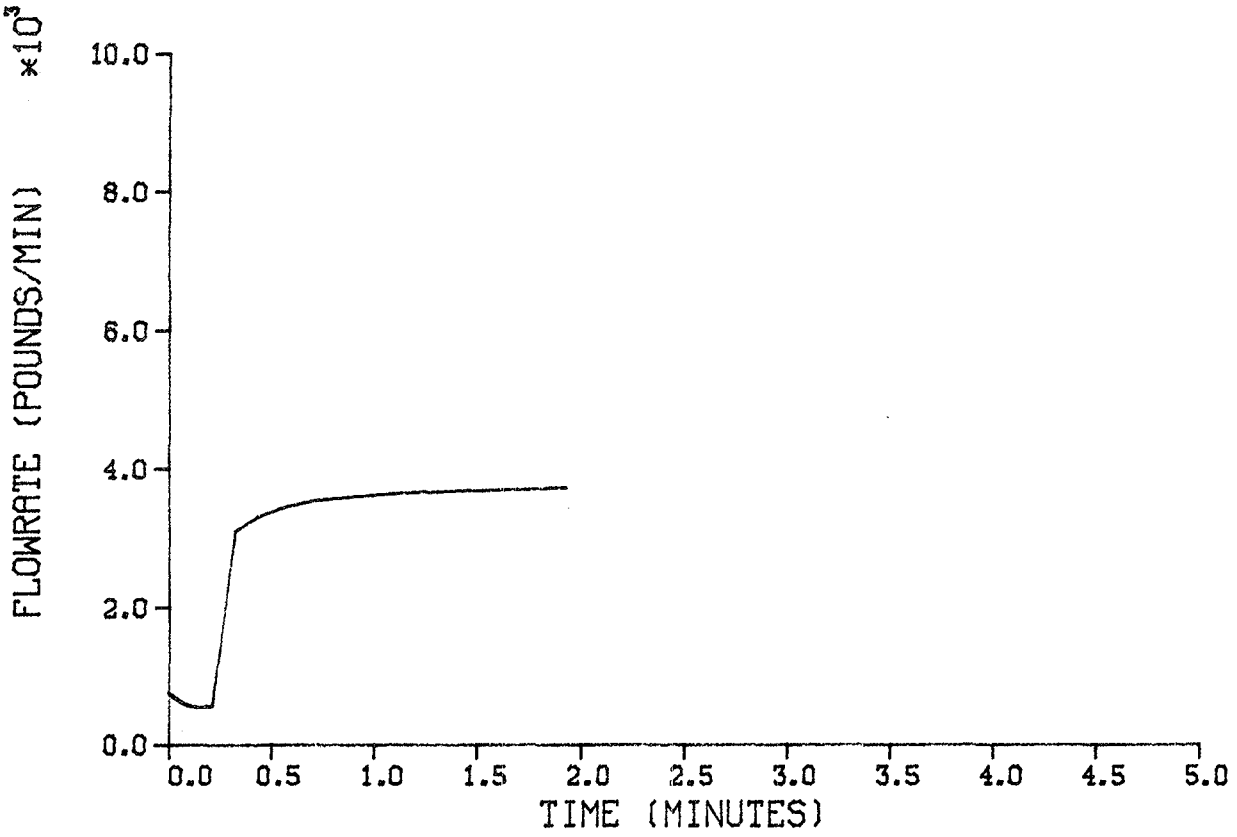




OXYGEN PROPELLANT TRANSFER

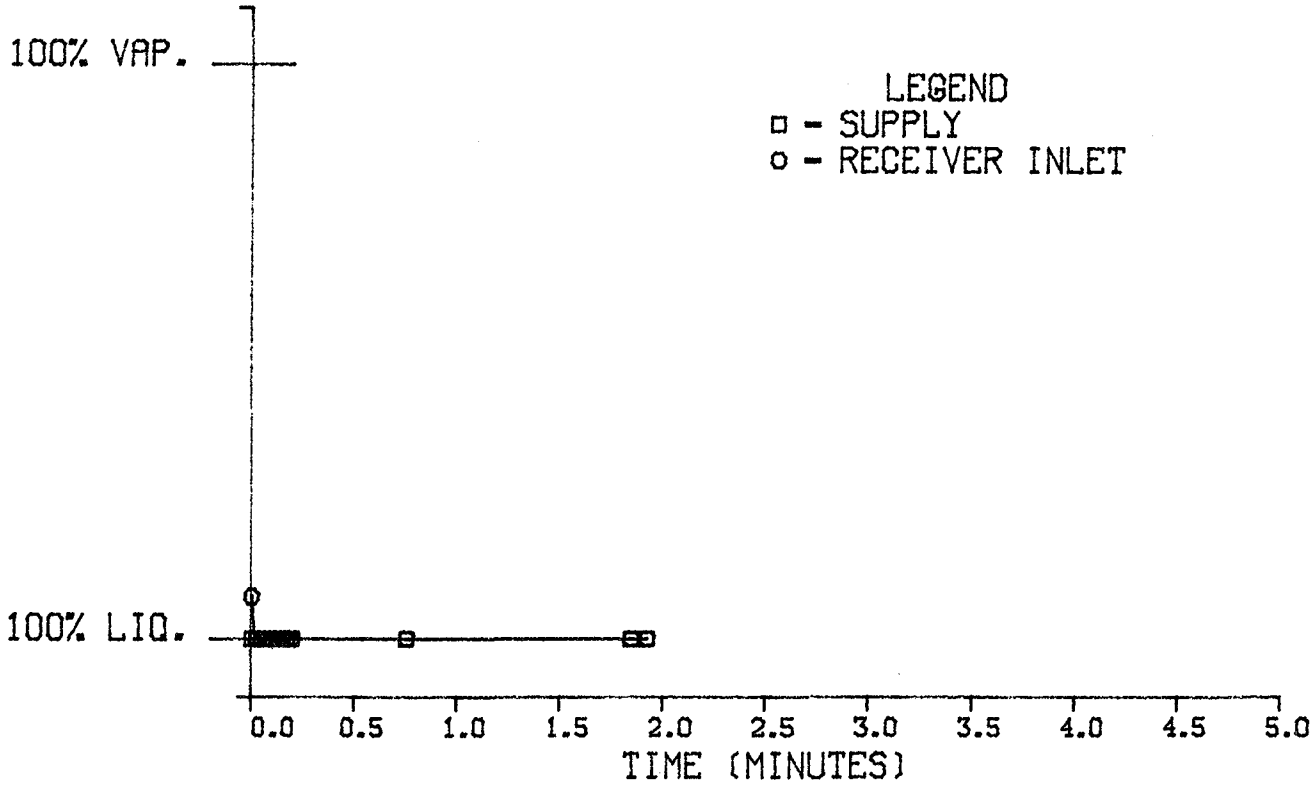
(PAGE 3)



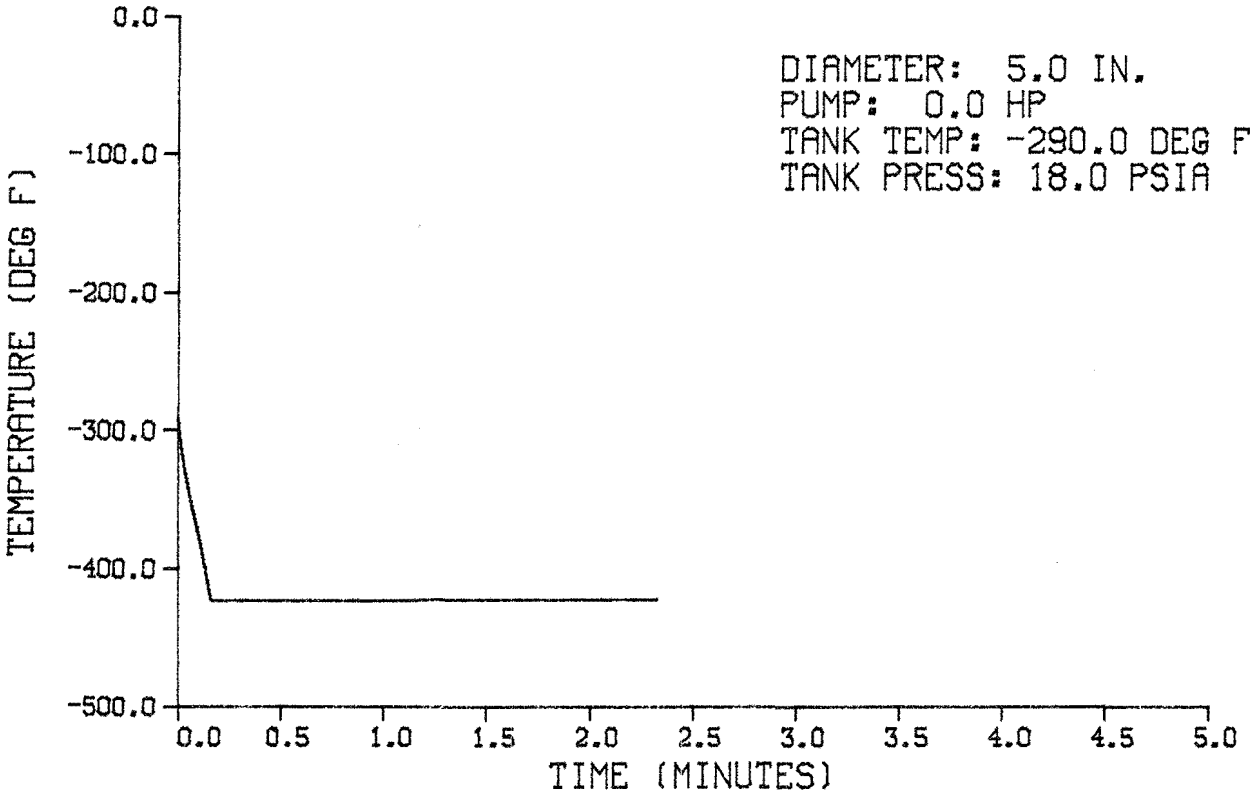


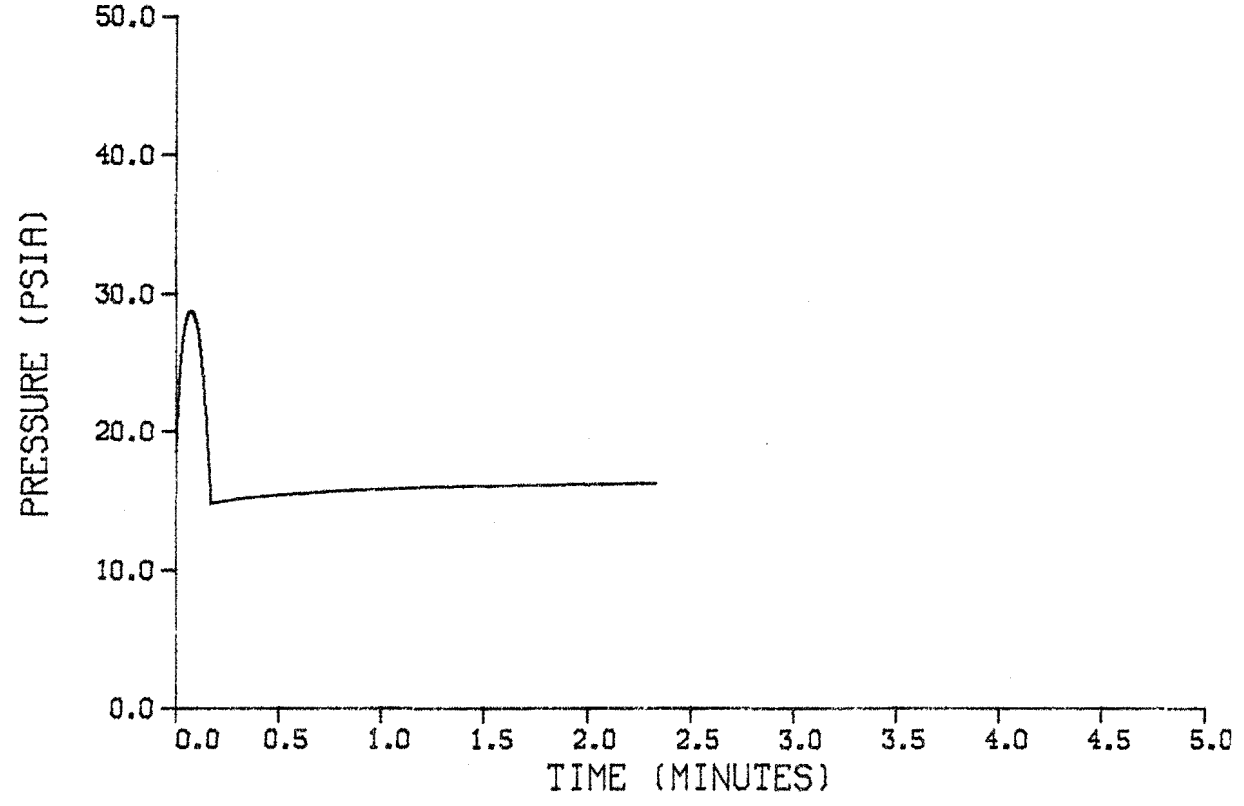
OXYGEN PROPELLANT TRANSFER

(PAGE 4)

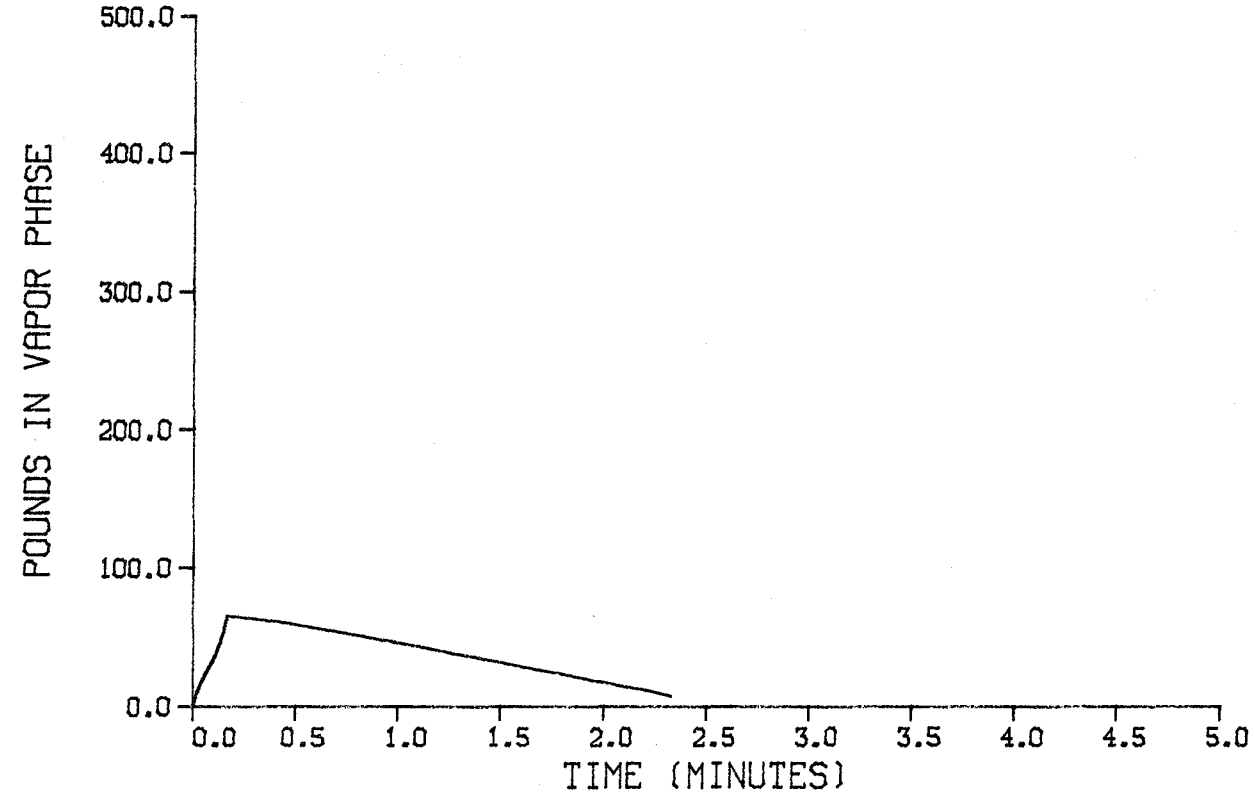


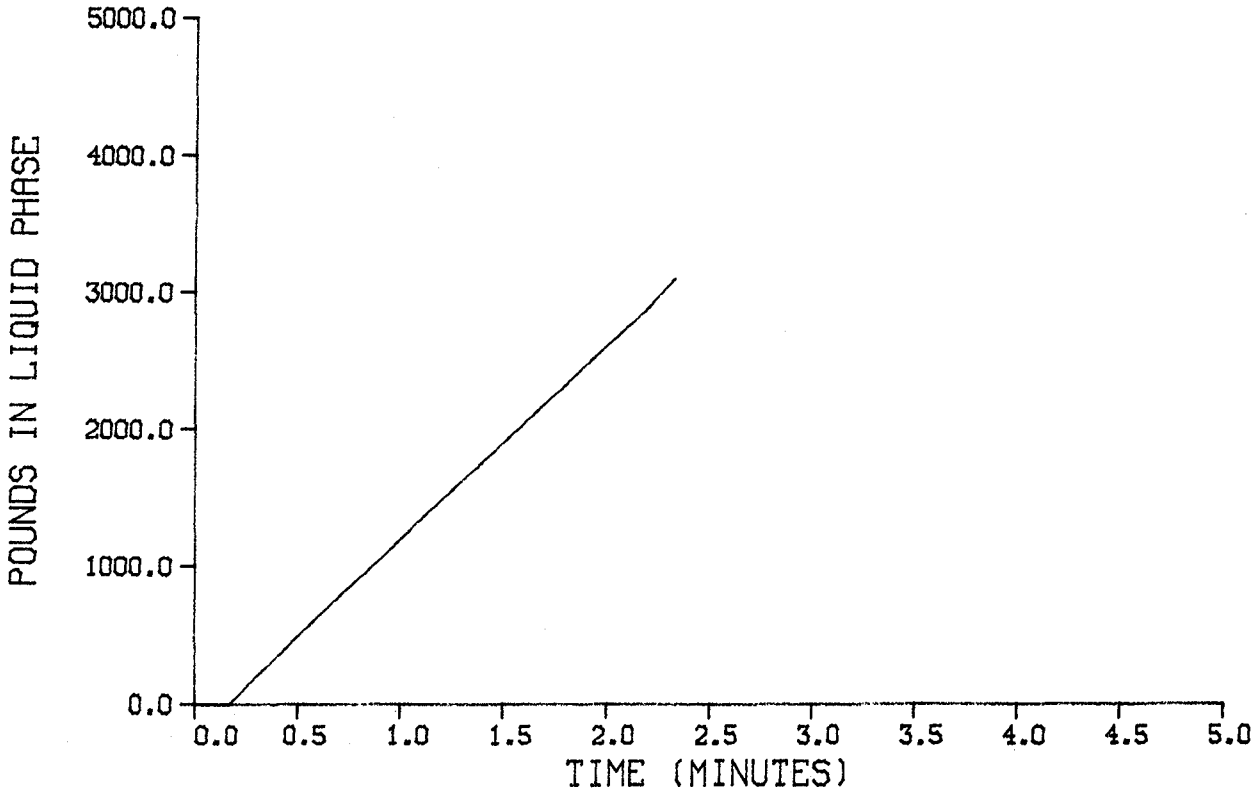
HYDROGEN PROPELLANT TRANSFER



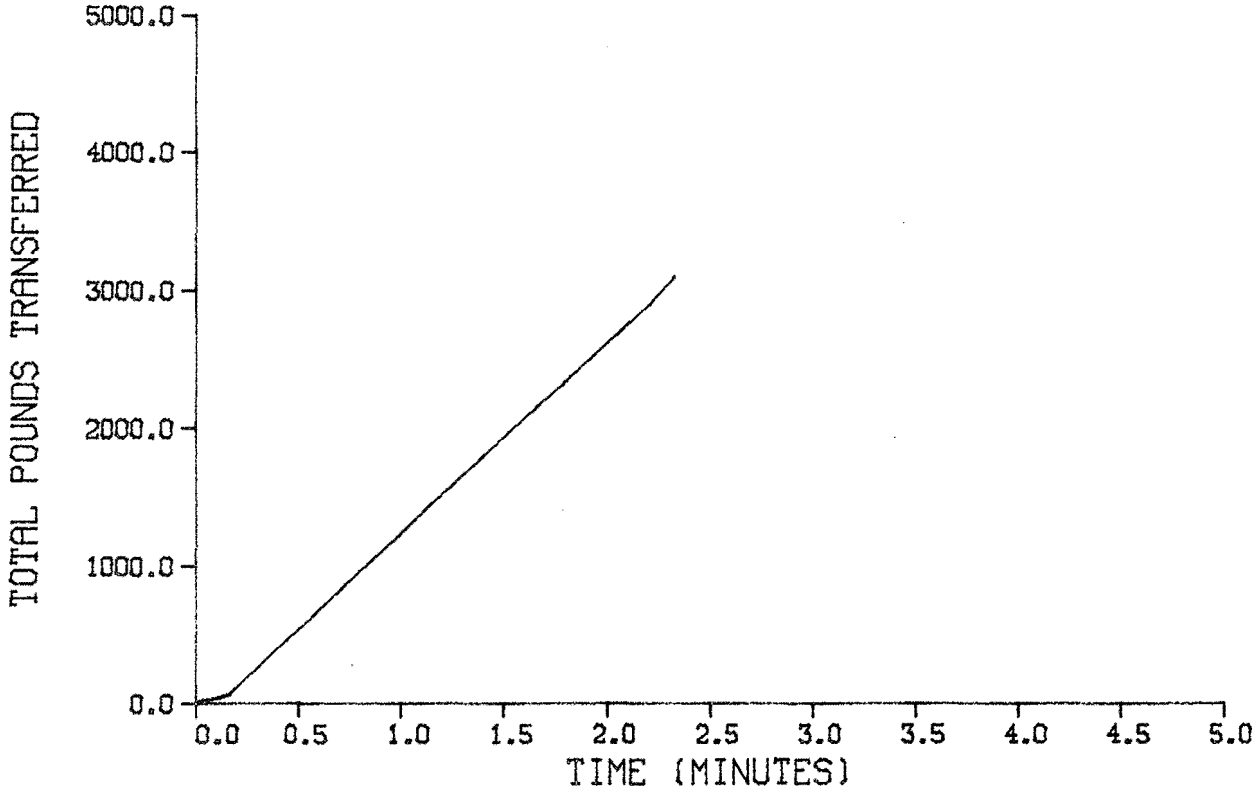


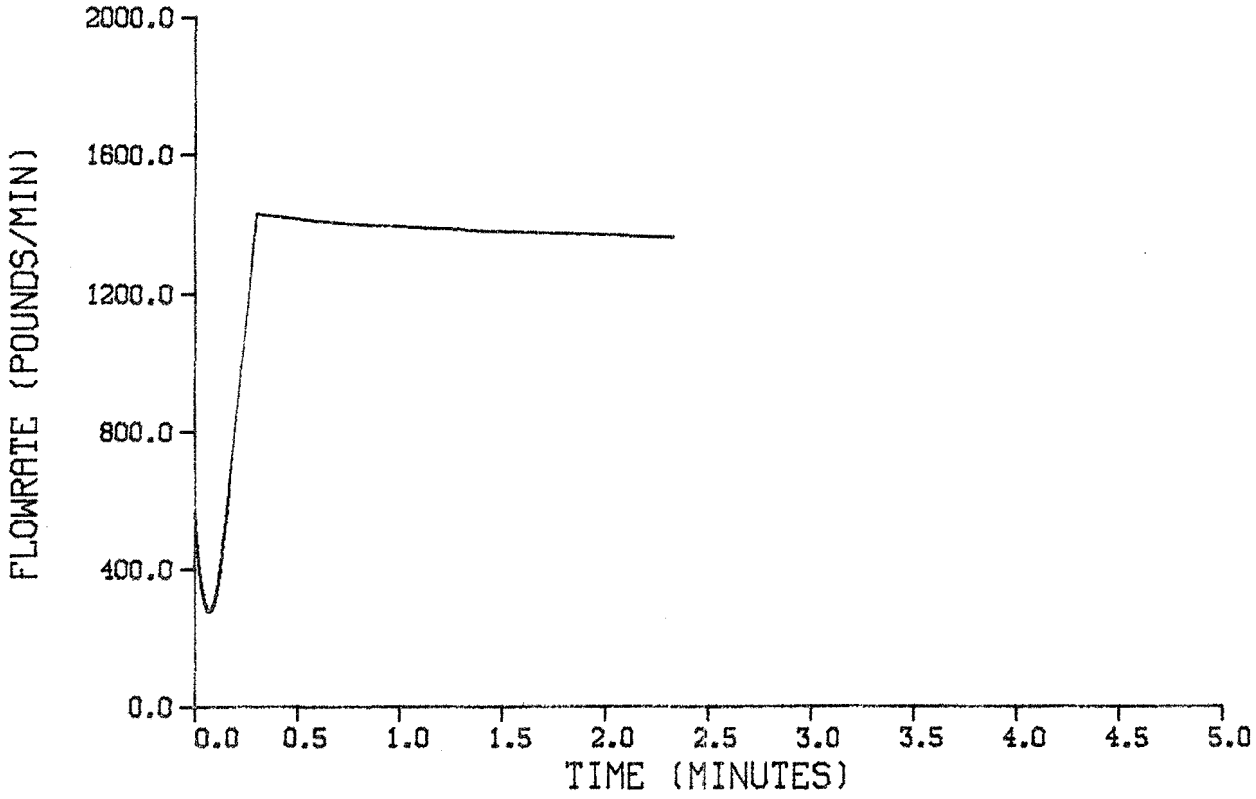
HYDROGEN PROPELLANT TRANSFER
(PAGE 2)



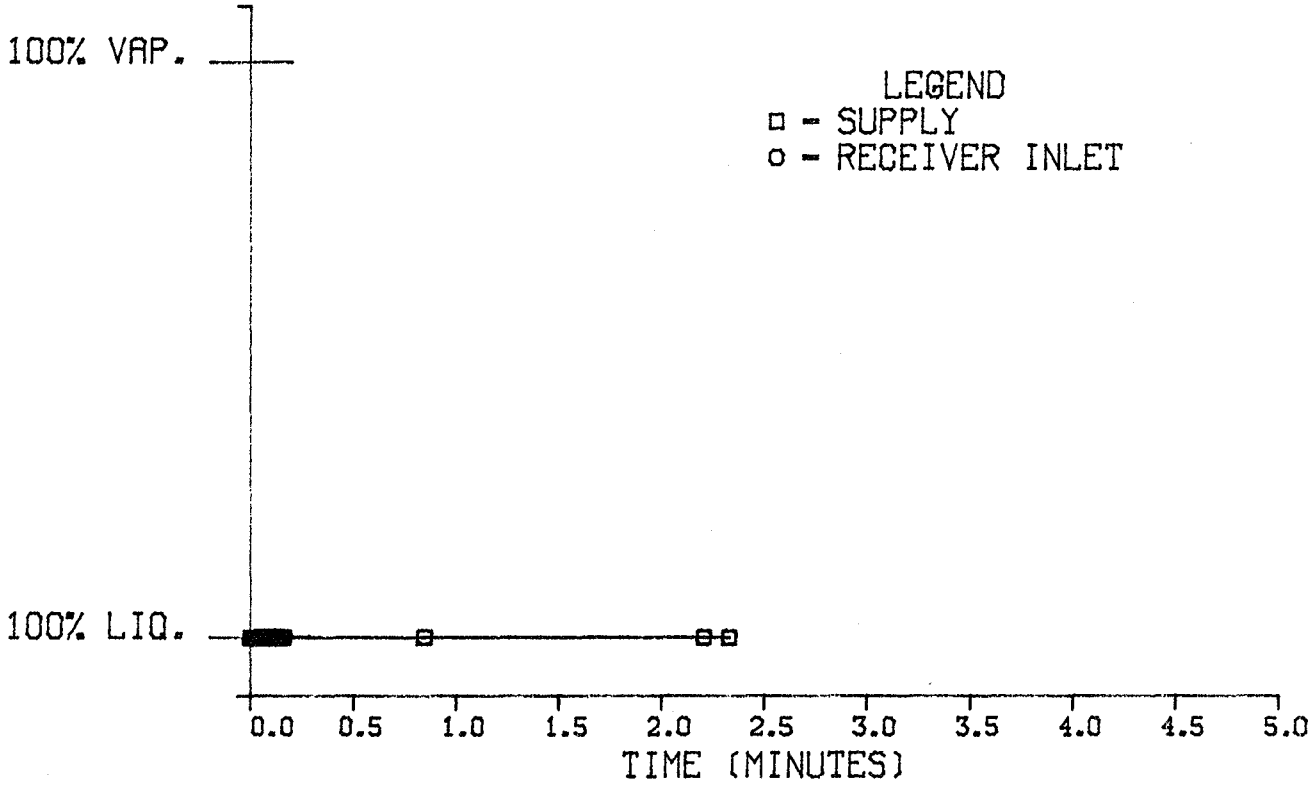


HYDROGEN PROPELLANT TRANSFER
(PAGE 3)





HYDROGEN PROPELLANT TRANSFER
(PAGE 4)



NOMENCLATURE

The units used in the computer model and derivation of equations are given first and are followed by SI units, which are enclosed in parentheses.

bp	brake horsepower for a pump, HP, (W)
C	conversion factor used in Equations (28) and (29)
C_I, C_{II}	constants used in Equation (17)
C'	constant used in Equation (30)
C_1, C_2, C_3	constants used in Equation (39)
C_p	constant pressure heat capacity, Btu/(lb·°F), (J/(gmol·K))
C_v	constant volume heat capacity, Btu/(lb·°F), (J/(gmol·K))
C_w	constant pressure heat capacity of receiver tank wall, Btu/(lb·°F), (J/(gmol·K))
D	pipe diameter, inches, (cm)
dm	differential mass or flowrate of fluid, lb/min, (gmol/s)
f	Fanning friction function factor, dimensionless
F(P)	term defined in Equation (11b)
h	specific enthalpy, Btu/lb, (J/gmol)
L	pipe length, ft, (m)
L_e	equivalent length of a pipefitting, ft, (m)
M	molecular weight, lb/mol, (g/gmol)
m_w	tank wall mass, lb, (g)
m	propellant quantity, lb, (moles)
N_{Re}	Reynolds number, dimensionless
P	pressure, atm, (MPa)
ΔP	pressure drop between supply and receiver tanks, atm, (MPa)
$\Delta P_{cooldown}$	pressure drop in the cooldown piping, atm, (MPa)
ΔP_{meter}	pressure drop across flowmeter, atm, (MPa)
Q	heat flux in the receiver tank, Btu/hr, (W)
Q_{total}	total heat flux in the system, Btu/hr, (W)
T	temperature, °F, (K)

U	total internal energy, Btu, (J)
u	specific internal energy, Btu/lb, (J/gmol)
u_b	bulk velocity, ft/s, (m/s)
V	tank volume, cu.ft, (ℓ)
v	specific volume, cu.ft/lb, (ℓ/gmol)
W	work, Btu/hr, (J/s)
x	quality of fluid, dimensionless
X	dummy variable used in Equation (15)
α	bulk thermal expansivity, $-\frac{T}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p$, dimensionless
ε	pipe roughness, ft, (m)
η	pump efficiency, dimensionless
θ	heat of expulsion, $-\rho\left(\frac{\partial h}{\partial \rho}\right)_p$, Btu/lb, (J/gmol)
μ	viscosity, lb/(ft·s), (gmol/(m·s))
ρ	density, lb/ft^3, (gmol/ℓ)
ϕ	Grüneisen parameter, $\frac{1}{\rho}\left(\frac{\partial P}{\partial u}\right)_\rho = \frac{\rho}{T}\left(\frac{\partial T}{\partial \rho}\right)_s$, dimensionless

Subscripts

ℓ	liquid
v	vapor
1	main fill line into receiver tank
2	receiver tank vent line
cool	cool down piping
i	either stream 1 or 2
main	main transfer piping
o	orifice in cooldown piping
RT	receiver tank
s	supply tank
sat	saturated conditions
w	tank wall

REFERENCES

[1] Brux, A.F.; A.J. Stefan, "Suborbital Recovery of External Tank Propellants", Rockwell International, May, 1982.

[2] McCarty, Robert D., Interactive Fortran IV Computer Programs for the Thermodynamic and Transport Properties of Selected Cryogens (Fluids Pack), NBS Technical Note 1025, National Bureau of Standards, Boulder, Colorado, 1980.

[3] McCarty, Robert D., Hydrogen Technological Survey - Thermophysical Properties, National Aeronautics and Space Administration, Washington, D.C., 1975.

[4] McCarty, Robert D.; Lloyd A. Weber, "Thermophysical Properties of Oxygen from the Freezing Liquid Line to 600 R for Pressure to 5000 Psia, NBS technical Note 384, National Bureau of Standards, Boulder, Colorado, 1971.

[5] Younglove, B. A., "Thermophysical Properties of Fluids. 1. Argon, Ethylene, Parahydrogen, Nitrogen, Nitrogen Trifluoride, and Oxygen", Journal of Physical and Chemical Reference Data, 11 (1982) Supp.1.

[6] Bennett, C.O.; J.E. Myers, Momentum, Heat, and Mass Transfer, 2nd edition, McGraw-Hill, New York, 1974.

[7] Arp, V., J.M. Persichetti and G. Chen, "The Grüneisen Parameter in Fluids," Journal of Fluids Engineering, 106 (1984) 193.

[8] Olujić, Zarko, "Compute Friction Factors Fast for Flow in Pipes", Chemical Engineering, December 14 (1981) 91.

[9] Carnahan, Brice; H. A. Luther; J. O. Wilkes, Applied Numerical Methods, John Wiley & Sons, Inc., New York, 1969.

[10] Sunstrand Aviation Mechanical Brochure No. 9006692, Cyrogenic Pump Model 044018, Sunstrand Corporation, Rockford, Illinois.

[11] Sunstrand Aviation Mechanical Brochure No. 9006592, Cyrogenic Pump Model 044015, Sunstrand Corporation, Rockford, Illinois.

[12] Handbook on Materials for Superconducting Machinery, Metals and Ceramics Information Center, Battelle, Columbus, Ohio 43201, January 1977.

[13] Mann, D. B., Ed., LNG Materials and Fluids, Cryogenics Division, National Bureau of Standards, Boulder, Colorado, 1977.

[14] Bridgman, P. W., Condensed Collection of Thermodynamic Formulas, Harvard University Press, Cambridge, Mass., 1926.

[15] DISSPLA, Version 9, Integrated Software Systems Corporation, San Diego, California, 1981.

☆U.S. GOVERNMENT PRINTING OFFICE:1985—578-700 / 25188