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SHUTTLE LOX LOADING TRANSIENT STUDY

TASK II MILESTONE REPORT

NATIONAL SPACE AND TECHNOLOGY LABORATORIES (NSTL) LOX LOADING FACILITY ANALYSES

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PREPARED FOR

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HUNTSVILLE, ALABAMA

NATIONAL SPACE AND TECHNOLOGY LABORATORIES
(NSTL) LOX LOADING FACILITY ANALYSIS

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ACKNOWLEDGEMENTS

Contributions to the National Space and Technology Laboratories (NSTL) facility and Main Propulsion Test Article (MPTA) system configuration and operational input data for the NSTL facility analyses were made by the following personnel:

Dwight Garrison (Global Associates)
Boyce Mix (NASA, NSTL)
Tom Winstead (NASA, MSFC)

Contributions to modifications of the Transient Cryogen Transfer Program (TCTP) and documentation of the NSTL facility analyses were made by the following Boeing personnel:

John R. Colson
James S. Richards
Ray Torstenson
Charlotte Wiser

Any questions concerning this document should be directed to the responsible Project Supervisor.

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JD-13
895-2650

1.0 INTRODUCTION

Transient thermodynamic analyses have been made for the National Space and Technology Laboratories (NSTL) LOX loading system proposed for the Space Shuttle Main Propulsion Test Article (MPTA). This system, shown in Figure 1-1, is made up of a LOX replenish system and a main LOX line which include the barge tank, the lines, pumps and valves between the barge and the Orbiter (ORB)/Ground Service Equipment (GSE) interface, the MPTA fill system, the Space Shuttle Main Engine (SSME) childown bleed system, and the GSE vent system. System analyses include predictions of system performance sensitivity to operating sequence and LOX flowrate, temperature, and quality at the ORB/GSE interface. The transient thermodynamic conditions at the SSME feed line entrance, ET entrance (tank bottom) and the SSME bleed/GSE vent TEE are also included. The SSME feed line entrance and the SSME bleed/GSE vent TEE pressures may be used to determine whether the vent pressure will cut off SSME bleed flow. The analyses are based on continuous SSME bleed flow during GSE facility childown. Also, after main LOX line childown, the flow will be switched from the main line/GSE vent to the MPTA at the same time the replenish system flow approaches the two percent level in the ET. The results of these predictions may be used as a technical basis for further development of the system configuration or operating sequence.

Several modifications and improvements of the Transient Cryogen Transfer Program (TCTP) were required for simulation of the NSTL systems and operations proposed for the MPTA. These TCTP improvements provide a more generalized capability to perform transient analyses of various cryogenic transfer system configurations and operations with various known boundary conditions.

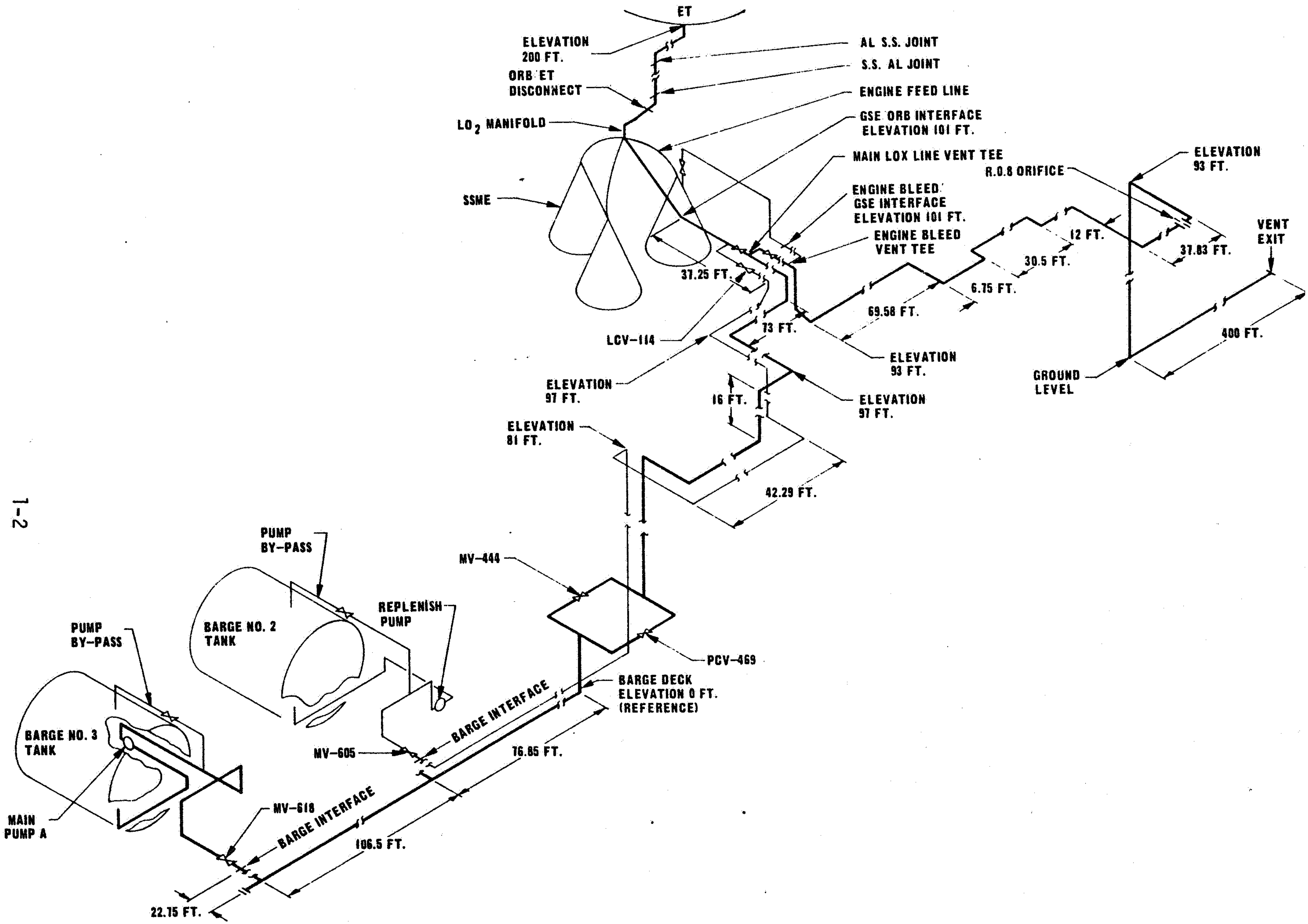


FIGURE 1-1   NSTL LOX LOADING/MPTA SYSTEM

2.0 NSTL LOX REPLENISH SYSTEM ANALYSES

Transient analyses of the NSTL LOX replenish system chill-down were performed. These analyses include both the Main Propulsion Test Article (MPTA) LOX fill system to the External Tank (ET) and simulated engine bleed flow. The replenish system chill-down analyses include the initial tank head flow period followed by a pump flow period until 100 percent liquid flow is approached at the ET entrance. The primary objective of these analyses is to predict the sensitivity of system performance to operating sequence, and LOX flowrate, temperature, and quality at the simulated orbiter interface. Further objectives are to predict the chill-down time required to approach liquid flow at the ET, transient conditions at the ET entrance, and the pressure as a function of time at the engine feed line entrance.

The NSTL LOX replenish system combined with the Space Shuttle MPTA is shown schematically in Figure 2-1. More detailed configuration input data for these analyses are presented in the Appendix, Table A-I. The NSTL facility data were derived from References 1 through 5. The Space Shuttle MPTA configuration, heat capacitance, and maximum external heat load data were derived from drawings and information provided by Mr. Tom Winstead (MSFC). Pipe friction factors for clean commercial steel as a function of Reynolds Number from Reference 6 were input to the system simulation. Equivalent length-to-diameter ratio data for the system components were derived from data provided by Mr. Dwight Garrison (Global Associates) and Mr. Tom Winstead (MSFC) as well as from References 6, 7, 8 and 9. The replenish (250 GPM) LOX pump performance data used in the system simulation are presented in the Appendix, Figure A-1. These data were derived from Byron Jackson pump data given in Rèference 10. The steady state external heat flux input for the vacuum jacketed replenish line was estimated to be 37.1 $BTU/FT^2 \cdot HR$ based upon Skylab LOX loading system analyses. The NSTL LOX replenish system is vacuum jacketed from the replenish pump discharge to the barge interface and from the 3 X 2-1/2 inch reducer on the dock to the main

2.0 (Continued)

LOX line TEE. The external heat flux input used for uninsulated GSE lines was 465 $BTU/FT^2 \cdot HR$ as suggested by References 7 and 8. The external heat flux input data used for the MPTA were 694 $BTU/FT^2 \cdot HR$ for the GN_2 purged orbiter feed lines and 35 $BTU/FT^2 \cdot HR$ for the insulated 17 inch duct to the ET. Steady state heat transfer rates for the NSTL LOX replenish and MPTA system are presented in the Appendix, Table A-II. The heat capacity of the pipe walls (inner wall for vacuum jacketed lines) was determined by assuming specific heats of 0.091 and 0.208 $BTU/LB_M \cdot °R$ for stainless steel and aluminum and densities of 501 and 169 LB_M/FT^3 for stainless steel and aluminum. The initial LOX loading system exit (ET entrance) pressure was assumed to be 16 PSIA. The initial LOX pump discharge temperature was assumed to be -295°F.

2.1 NSTL LOX REPLENISH SYSTEM TANK HEAD FLOW ANALYSIS

Results of the NSTL replenish system tank head flow analysis are shown in Figures 2-2 through 2-6. Steady state conditions are approached at the flow control valve (LCV-114) about four minutes after tank head flow initiation. Preliminary analyses indicated that neither 100 percent liquid flow at LCV-114 nor significantly lower Shuttle duct wall temperatures could be obtained by extending the tank head flow period. Therefore, the tank head flow simulation was terminated and the pump start simulation initiated at four minutes after tank head flow initiation. Figures 2-2 and 2-3 show that the system pressures and flow rates become relatively stable during the four minute tank head flow period. The maximum gas flow rate into the ET during this period is 3.0 LB_M/SEC. The entire system approaches steady flow conditions and the replenish pump NPSH stabilizes at 88.36 feet. Figure 2-4 shows that the fluid qualities at LCV-114 and the ORB/GSE interface approach constant values during the tank head flow period. Figure 2-5 shows the transient fluid temperature at the ORB/GSE interface, ORB/ET disconnect, and ET entrance. Figure 2-6 indicates that the Shuttle hardware will approach minimum temperatures for tank head

2.1 (Continued)

flow during this four minute period. Preliminary analyses for this system indicated that Shuttle hardware cooling rates would decrease with an extended tank head flow period. This is due to an increasing system hydrostatic head which decreases the system flow rates.

This system tank head flow analysis is based upon assumed constant values of 40 PSIG barge tank ullage pressure, -295°F pump discharge temperature, and 16 PSIA at the Shuttle ET entrance. A valve opening time of 8 seconds was assumed for the barge No. 2 interface valve (MV-605) to initiate flow to the LOX replenish system. The current analytical model includes by-pass flow to the barge storage tank which occurs when the pump discharge pressure exceeds 63 PSIA.

2.2 NSTL LOX REPLENISH SYSTEM PUMP FLOW ANALYSIS

For the NSTL LOX replenish system pump flow chill-down analysis, the 250 GPM pump was assumed to start four minutes after tank head flow initiation. The pump RPM was assumed to follow a straight line ramp from windmilling RPM to 3550 RPM within 15 seconds from pump start. For the initial computer simulations, the automatically controlled valve (LCV-114) operation was simulated as follows:

(1) LCV-114 approaches a closed position within four seconds after pump start due to the low (windmilling) pump RPM and low discharge pressure.

(2) LCV-114 remains closed until 100 percent liquid flow reaches the valve. At this time, the valve pressure drop causes the pump discharge pressure to exceed the pre-determined control value of 238.69 PSIA. This pressure value was calculated to provide rated flow of 250 GPM to the replenish system with 50 GPM by-pass flow.

2.2 (Continued)

(3) LCV-114 approaches the position for the estimated equivalent $(\frac{L}{D})$ required to maintain the pre-set pump discharge control pressure for rated system flow with the pump by-pass valve open.

Initial computer simulations showed that as LCV-114 opens to maintain the control pressure, the increased system flow rate results in choked two-phase flow downstream of LCV-114. The limited flow rate due to choking downstream of the valve will increase the pump discharge pressure above the control valve regardless of valve operation. This choked flow condition was simulated by limiting the flow rate with the flow control valve such that acoustic velocity downstream of the valve was not exceeded. The computer program was modified to determine each node exit acoustic velocity as a function of time. The velocities used to calculate pressure change due to expansion or compression were then limited to the corresponding acoustic velocity.

Several iterative computer simulations were made to establish the valve operation required to either simulate choked flow or maintain the control pressure for rated flow in periods of unchoked flow. For these iterative simulations, LCV-114 was operated as shown in Table 2-I. The final simulation indicated that choked flow will persist for approximately 1-1/2 minutes after 100 percent liquid flow has reached the flow control valve (24 to 108 seconds after pump start). At this time, the flow becomes 100 percent liquid downstream of the valve, and the valve will then regulate the pump discharge pressure to the pre-set value required for rated flow to the replenish system. After the pump discharge pressure stabilized at the control value, subsequent computer simulations were made with the pump by-pass valve closed. LCV-114 was operated as required to maintain the pre-determined pump discharge control pressure as the system hydrostatic head increased.

2.2 (Continued)

Results of the NSTL LOX replenish system pump flow chill-down analysis are shown in Figures 2-7 through 2-11. Figures 2-7 and 2-8 show the transient pump discharge pressure and system flowrates. Figure 2-7 shows a sharp increase in pump discharge pressure at 24 seconds after pump start. At this time, 100 percent liquid reaches LCV-114, as may be seen in Figure 2-9, choked flow occurs downstream of LCV-114, and the pump discharge pressure exceeds the pre-determined control pressure (238.69 PSIA). This choked flow condition persists until liquid flow is obtained downstream of LCV-114 at 108 seconds after pump start. At this time, the pump discharge pressure stabilizes, the pump by-pass valve is closed, and the flow rate to the system increases as shown at 112 seconds in Figure 2-8. The maximum gas flowrate to the ET during this period is 5.0 LB_M/SEC. Figure 2-8 shows total and gas flowrates at the ORB/GSE interface and ET entrance. Liquid flowrates at these locations may be determined by subtracting the gas flowrate from total flowrate. Figure 2-9 shows that 100 percent liquid flow is obtained at LCV-114 20 seconds after pump start, at the ORB/GSE interface 116 seconds after pump start, and at the Aluminum/Stainless Steel 17 inch duct joint (10 feet below the ET) at 988 seconds after pump start. The vapor volume fraction at the ET entrance decreases to 0.62 at 1000 seconds after pump start. Results of an extended simulation (to 1500 seconds after pump start) indicate that steady state conditions are approached at the ET entrance at 1000 seconds after pump start, and that no further significant decrease in vapor volume fraction will occur. Figure 2-10 shows the system pressures at the ORB/GSE interface and the Shuttle Orbiter engine feed line entrance (orbiter LO_2 manifold). Figure 2-11 shows the Shuttle transient fluid temperatures. Figure 2-12 shows the duct wall temperatures at the Orbiter fill and drain line exit and at the 17 inch duct exit.

2.2 (Continued)

This system pump flow analysis is based upon an assumed constant value of 40 PSIG barge tank ullage pressure and -296°F pump discharge temperature. The LOX fill system exit (ET entrance) pressure is assumed to increase from 16 PSIA initially to 17.46 PSIA at 1000 seconds due to hydrostatic head in the ET.

TABLE 2-I FLOW CONTROL ADJUSTMENTS FOR RATED OR CHOKED FLOW SIMULATION

CASE	V_N	P_1	VALVE POSITION
1	$< V_N^*$	$< P_{CON}$	DECREASE FOR RATED FLOW AT P_{CON}
2	$< V_N^*$	$> P_{CON}$	INCREASE FOR RATED FLOW AT P_{CON} OR APPROXIMATE CHOKED FLOW
3	$> V_N^*$	$> P_{CON}$	DECREASE TO APPROXIMATE CHOKED FLOW
4	$> V_N^*$	$< P_{CON}$	DECREASE TO APPROXIMATE CHOKED FLOW OR RATED FLOW AT P_{CON}

V_N = NODE EXIT VELOCITY

P_1 = PUMP DISCHARGE PRESSURE

V_N^* = NODE EXIT ACOUSTIC VELOCITY

P_{CON} = PREDETERMINED PUMP DISCHARGE CONTROL PRESSURE

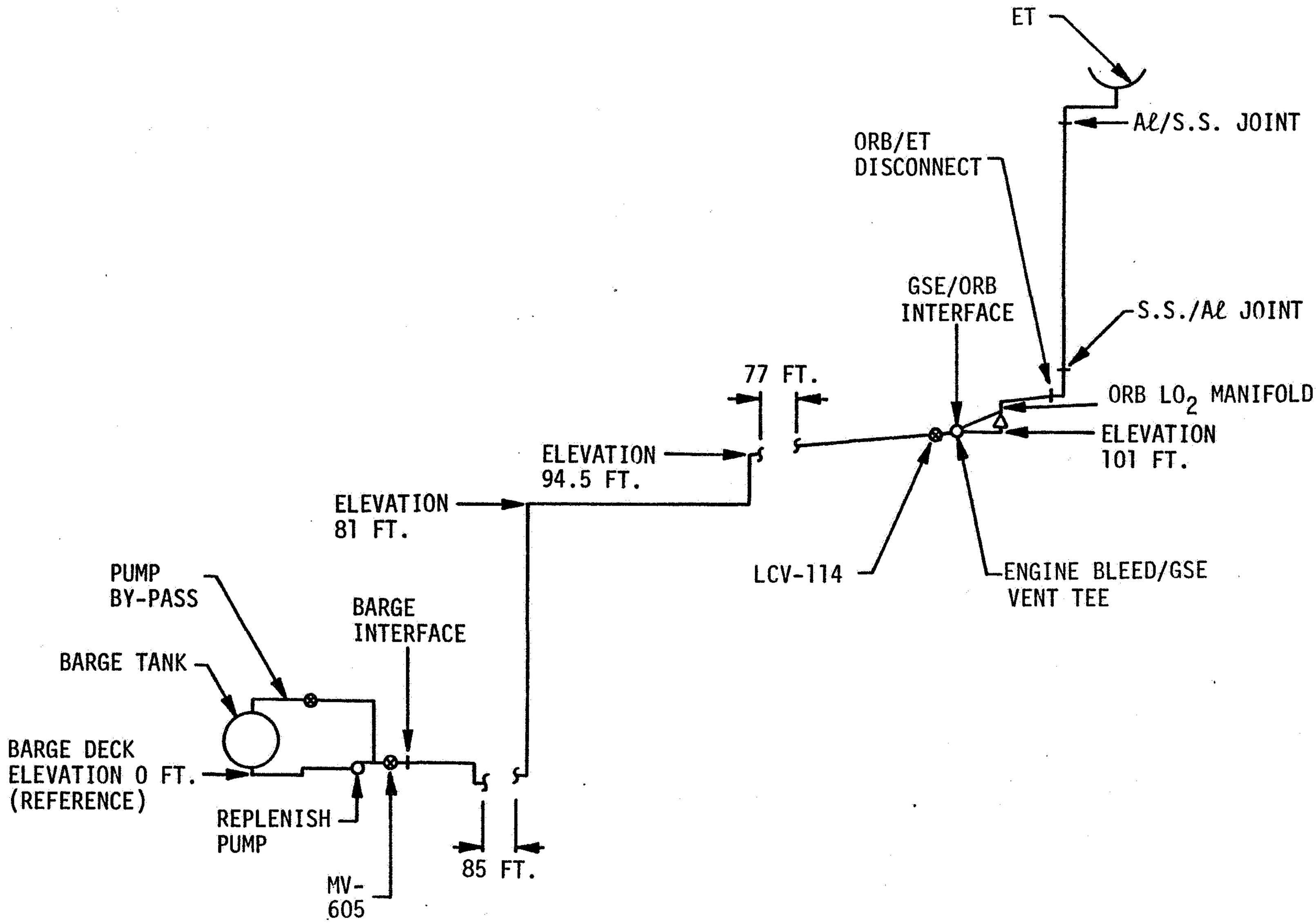


FIGURE 2-1 NSTL LOX REPLENISH AND MPTA SYSTEM

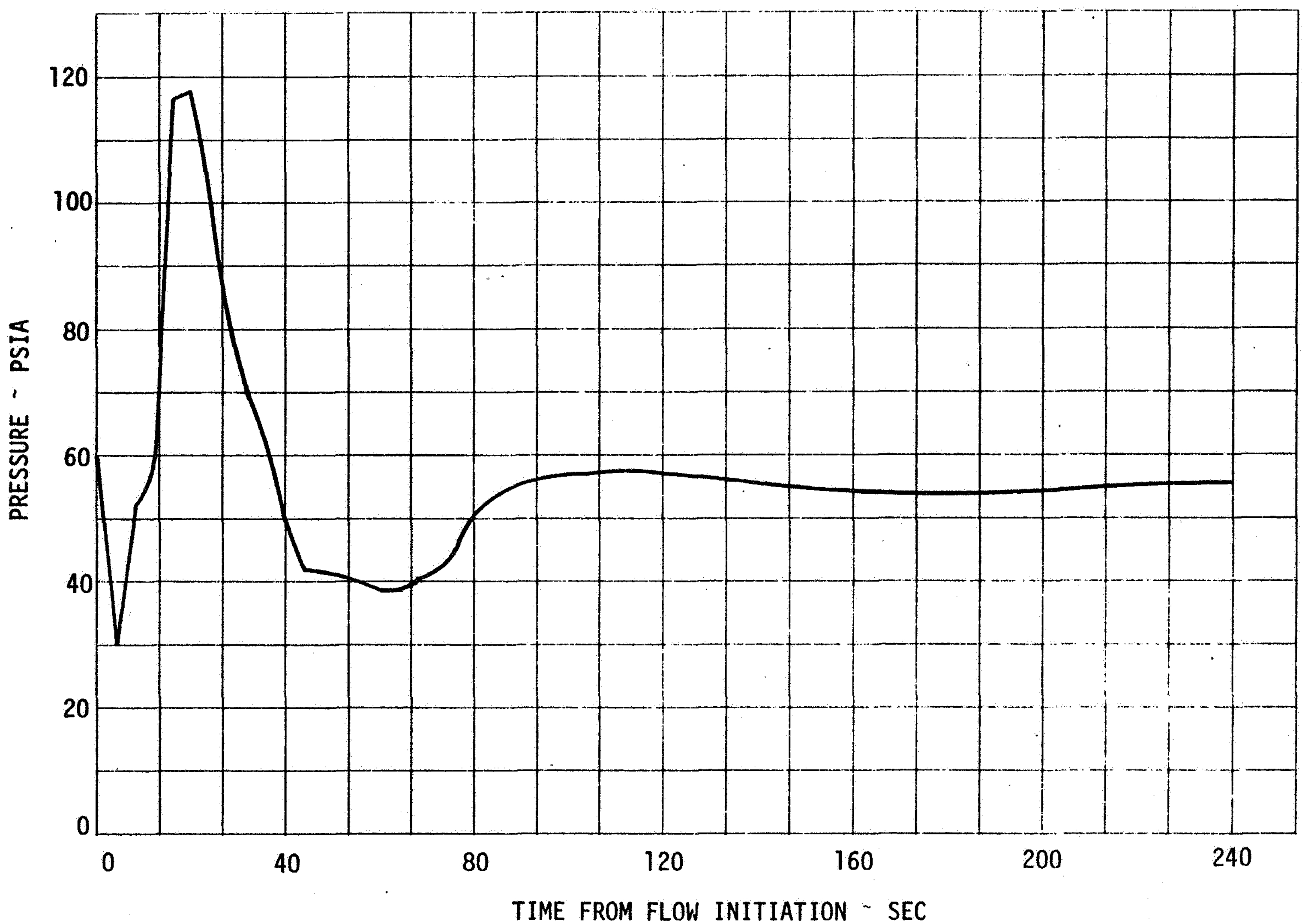


FIGURE 2-2 BARGE NO. 2 INTERFACE TRANSIENT PRESSURE FOR NSTL LOX REPLENISH SYSTEM TANK HEAD FLOW CHILL-DOWN

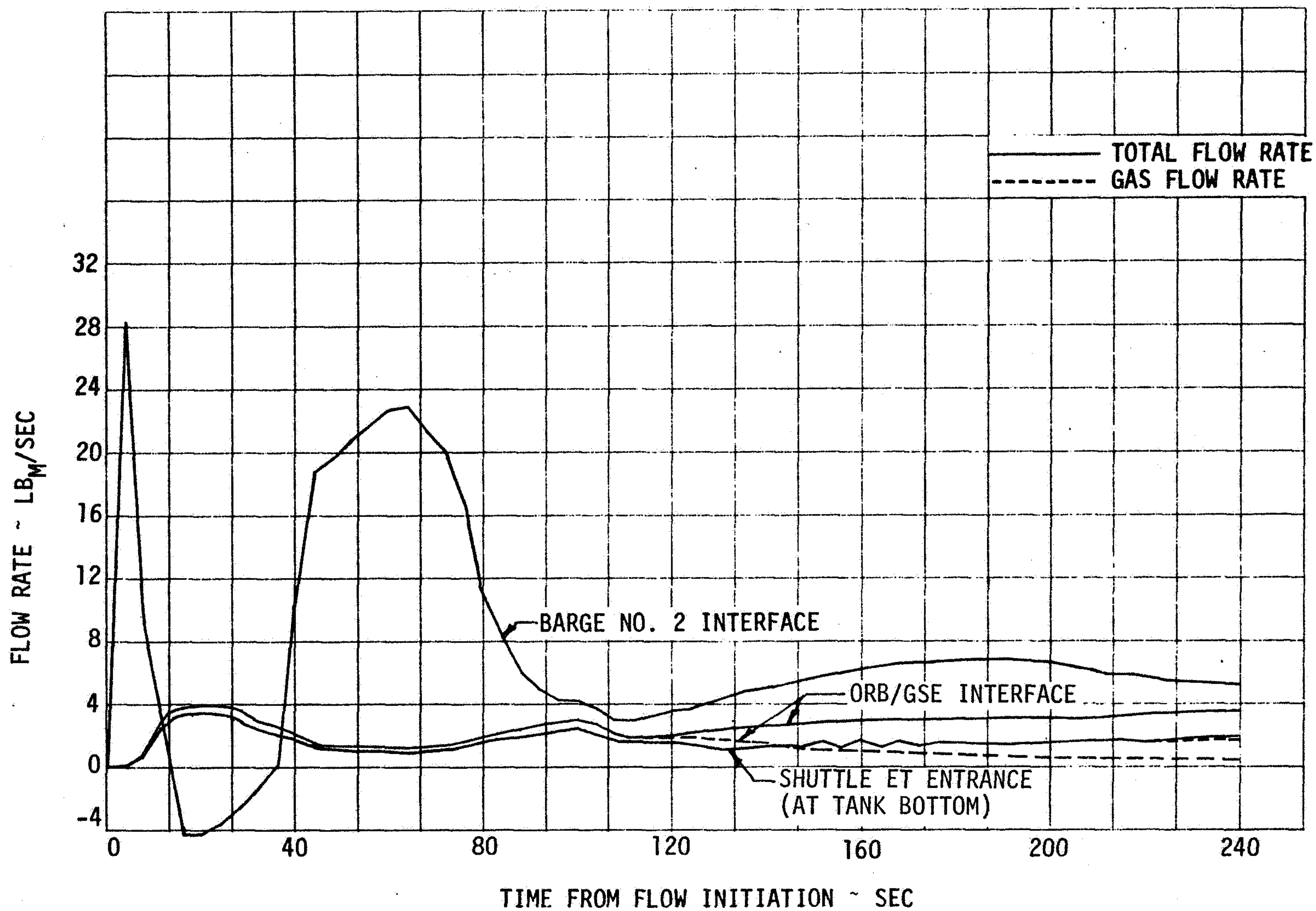


FIGURE 2-3 TRANSIENT FLOW RATES FOR NSTL LOX REPLENISH SYSTEM TANK HEAD FLOW CHILL-DOWN

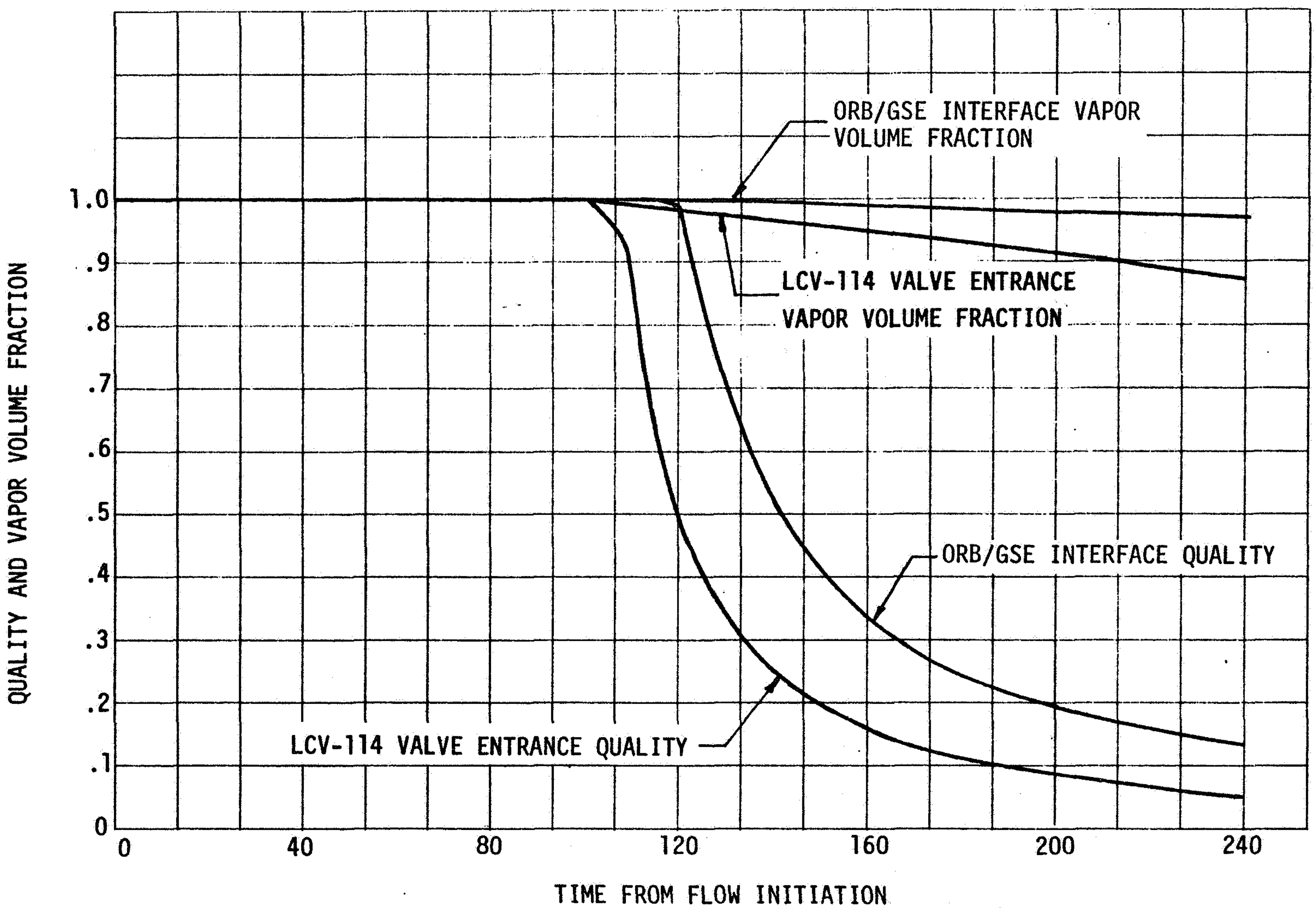


FIGURE 2-4 TRANSIENT QUALITY AND VAPOR VOLUME FRACTIONS FOR NSTL LOX REPLENISH SYSTEM TANK HEAD FLOW CHILL-DOWN

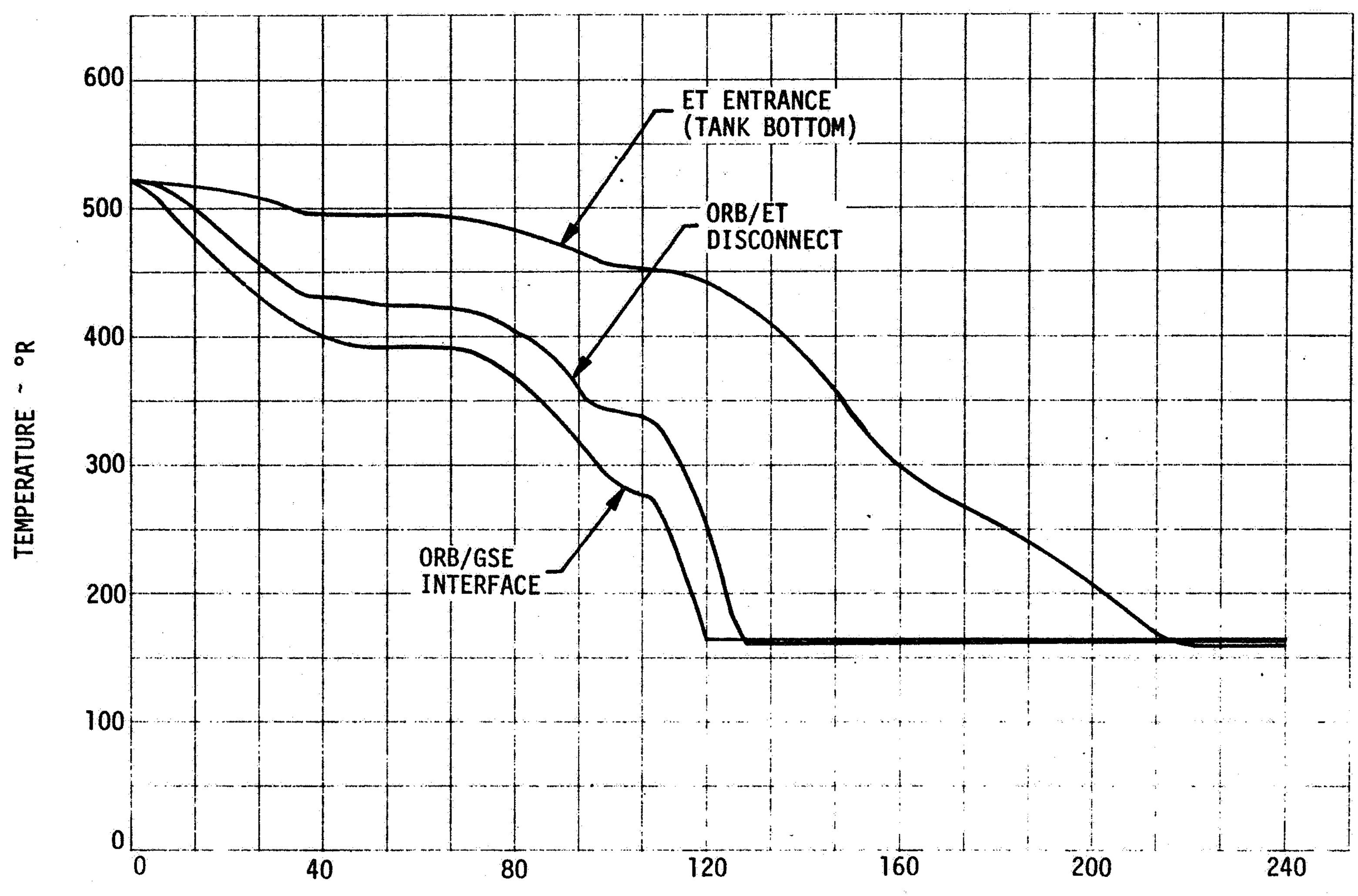


FIGURE 2-5 TRANSIENT TEMPERATURES FOR NSTL LOX REPLENISH SYSTEM TANK HEAD FLOW CHILL-DOWN

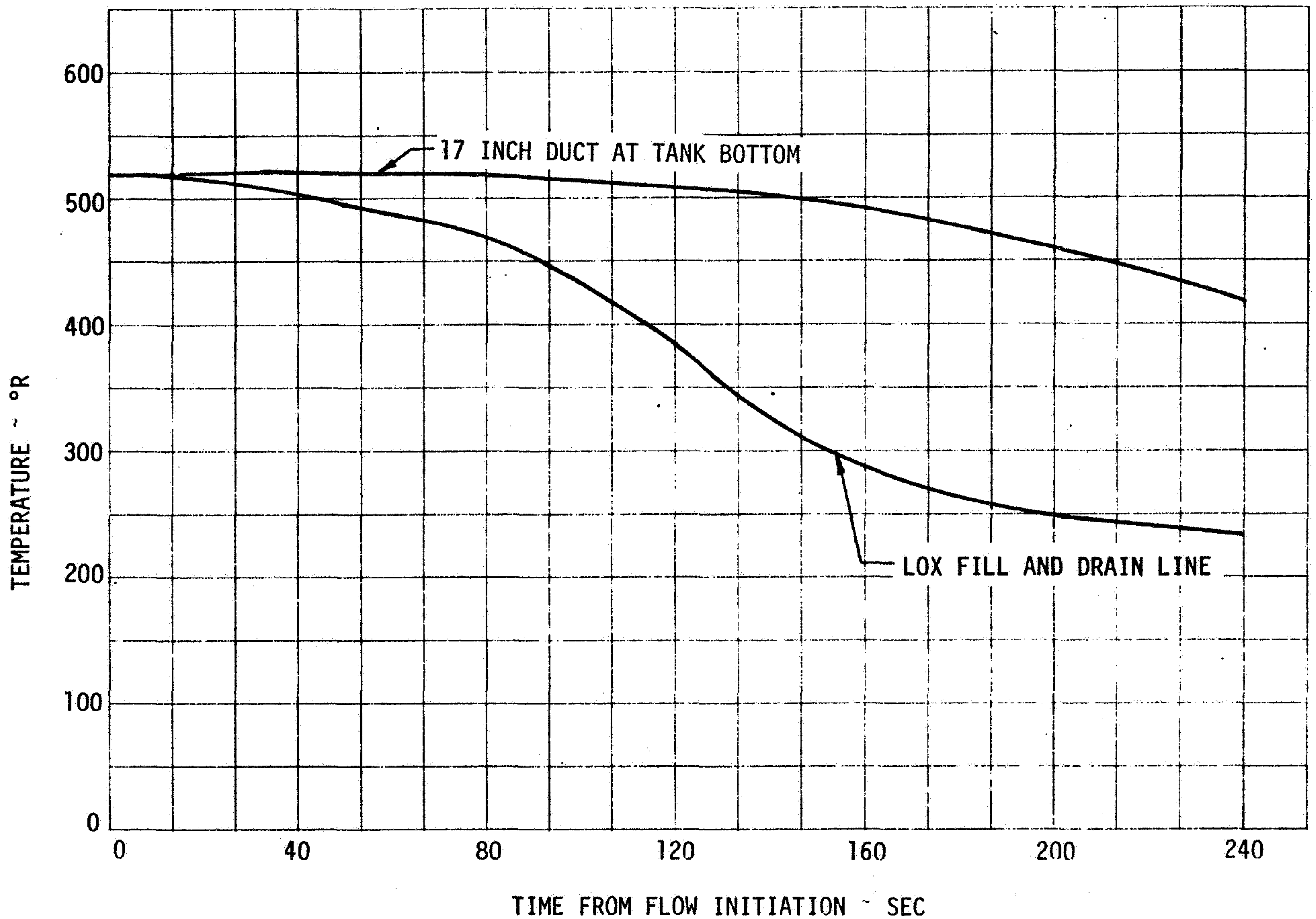


FIGURE 2-6 SHUTTLE LOX FILL SYSTEM TRANSIENT WALL TEMPERATURES FOR NSTL LOX REPLENISH SYSTEM TANK HEAD FLOW CHILL-DOWN

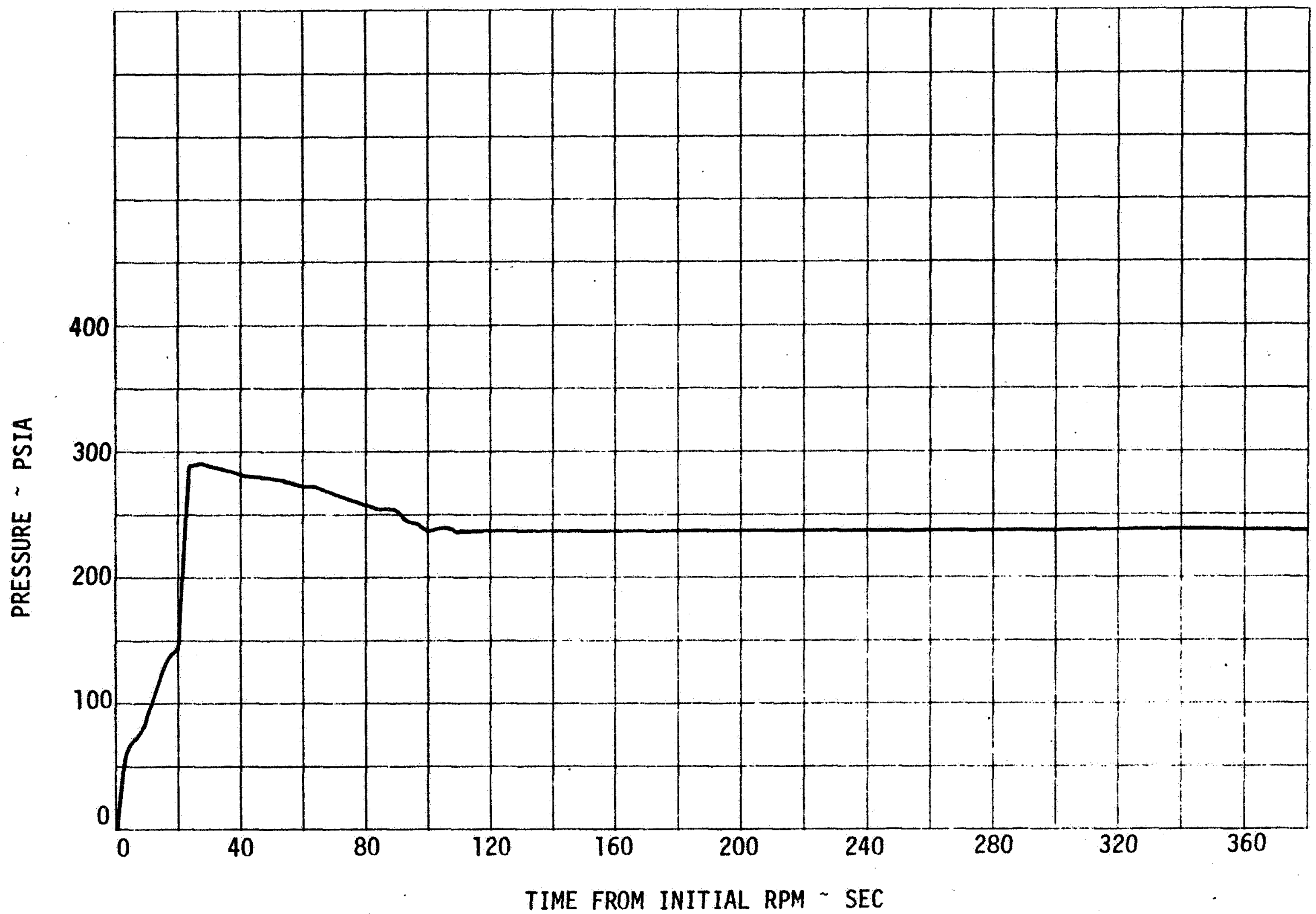


FIGURE 2-7 REPLENISH PUMP TRANSIENT DISCHARGE PRESSURE FOR NSTL LOX REPLENISH SYSTEM PUMP FLOW CHILL-DOWN

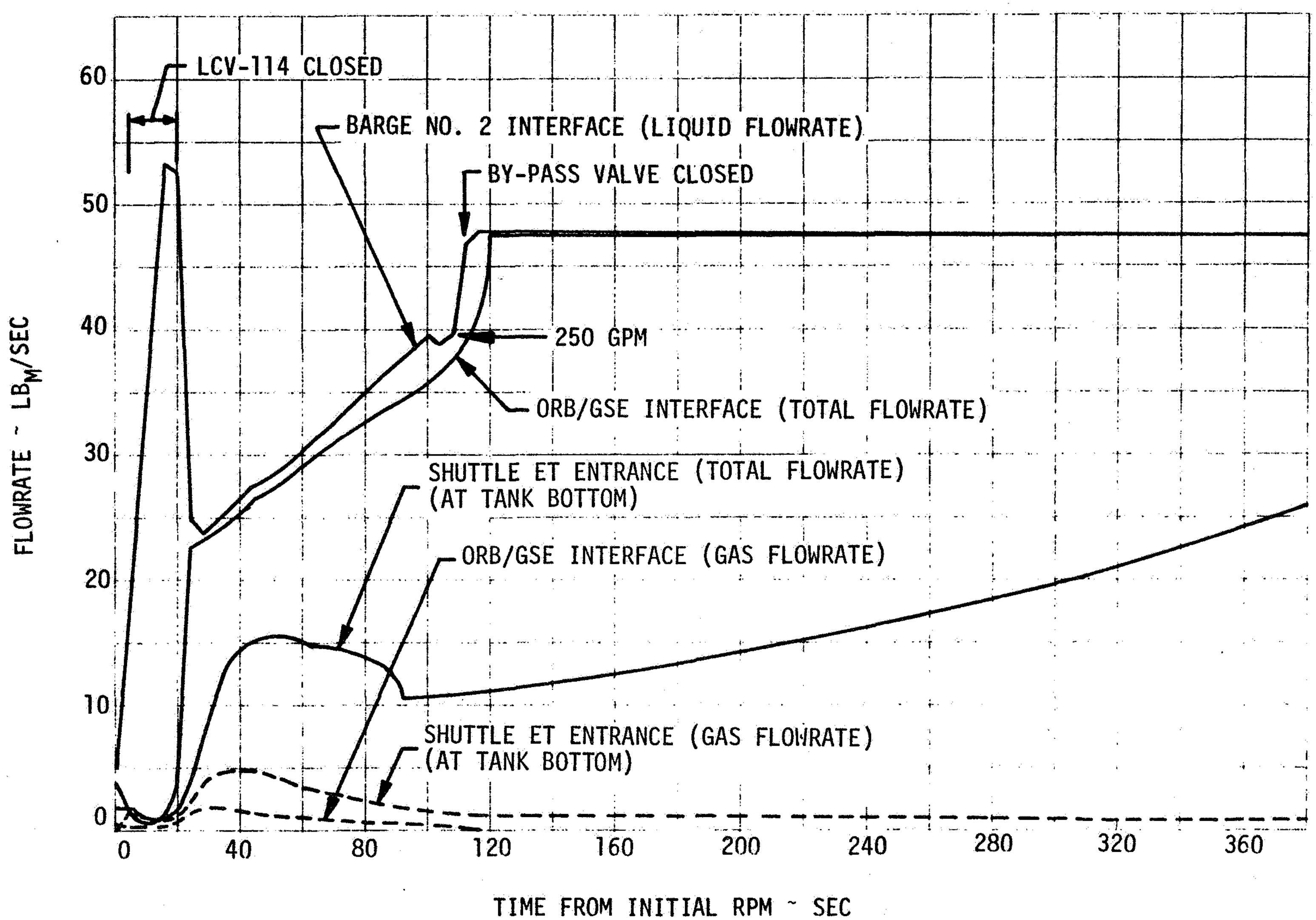


FIGURE 2-8 TRANSIENT FLOWRATES FOR NSTL LOX REPLENISH SYSTEM PUMP FLOW CHILL-DOWN

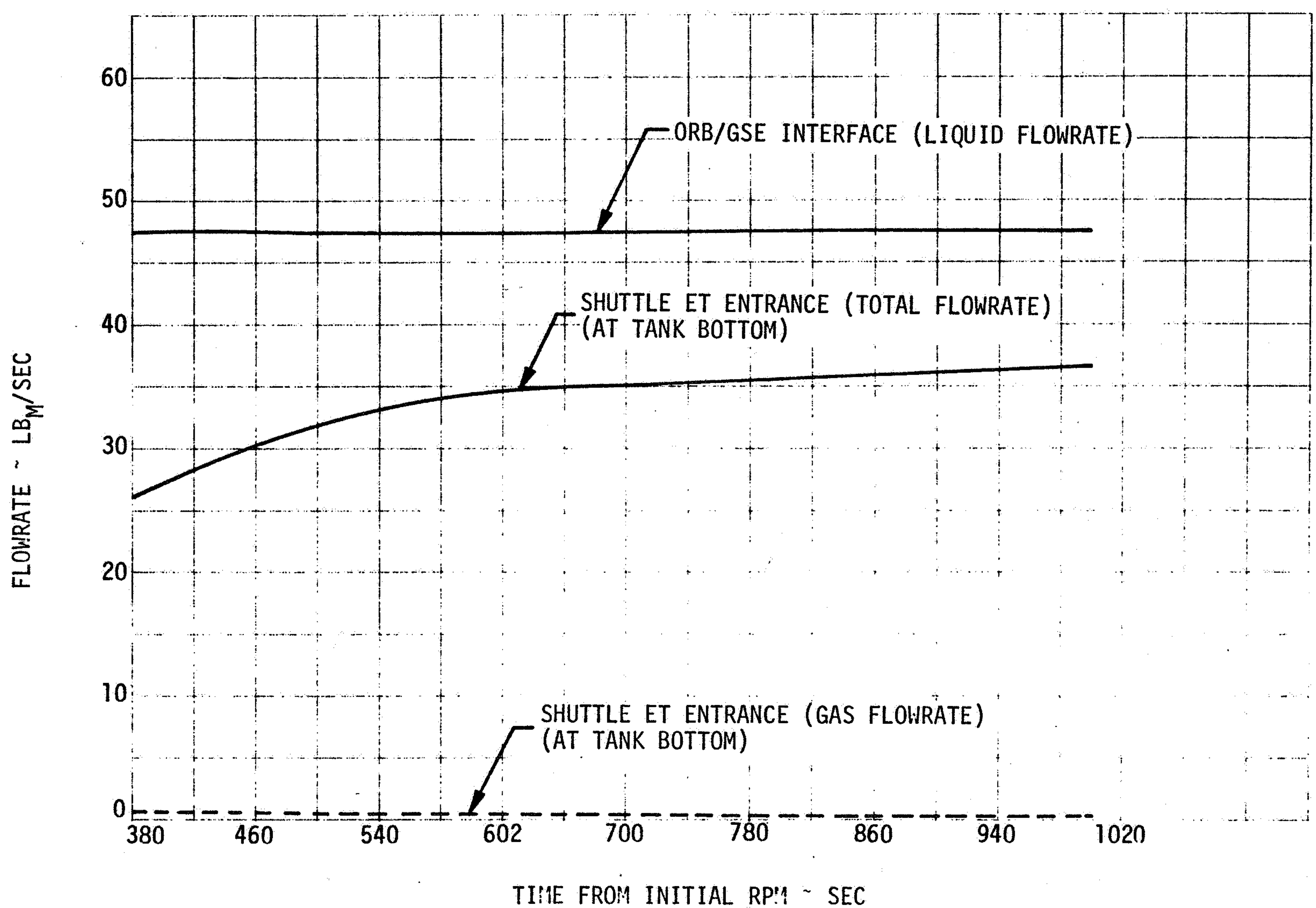


FIGURE 2-8 TRANSIENT FLOWRATES FOR NSTL LOX REPLENISH SYSTEM PUMP FLOW CHILL-DOWN (CONTINUED)

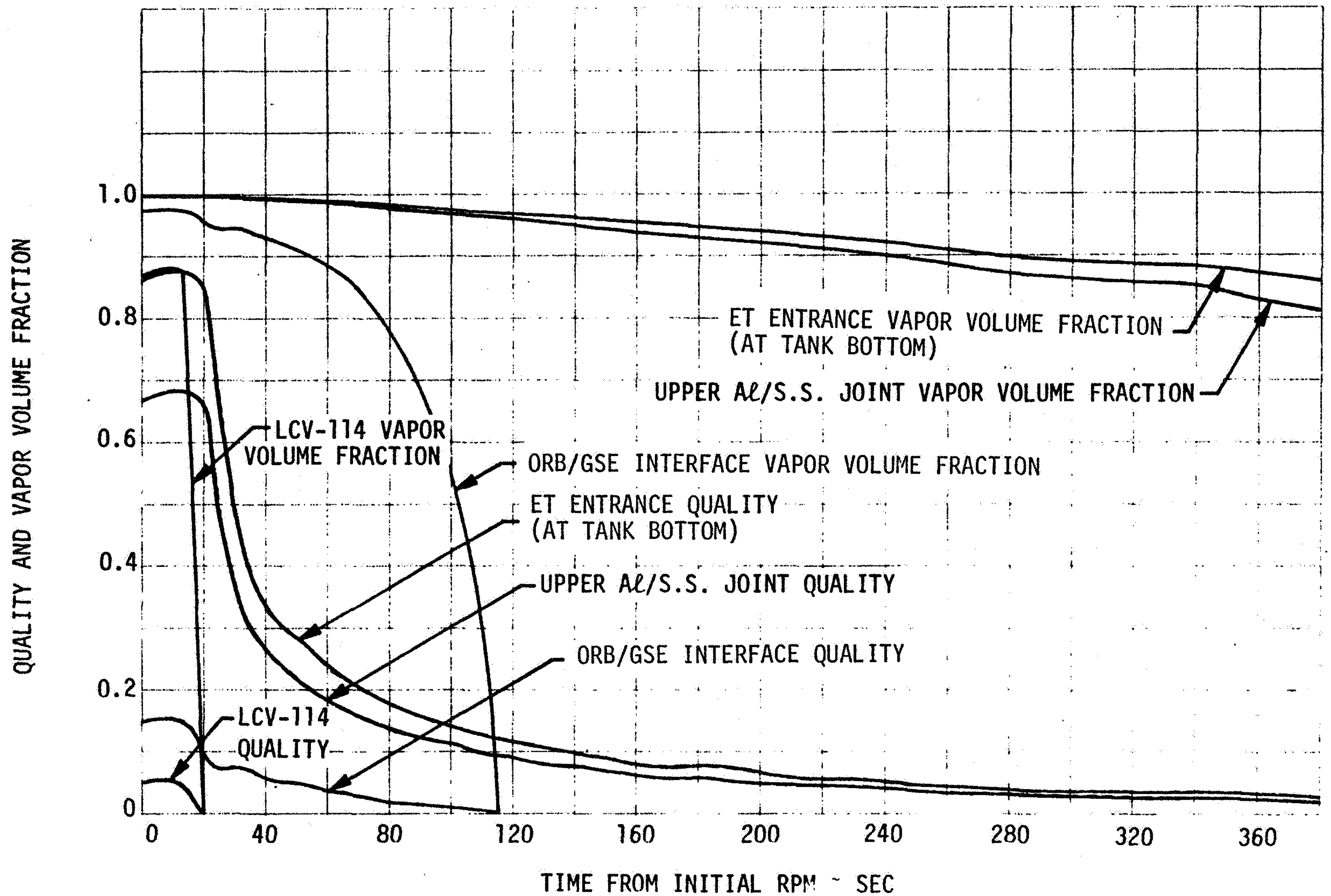


FIGURE 2-9 TRANSIENT QUALITY AND VAPOR VOLUME FRACTIONS FOR NSTL LOX REPLENISH SYSTEM PUMP FLOW CHILL-DOWN

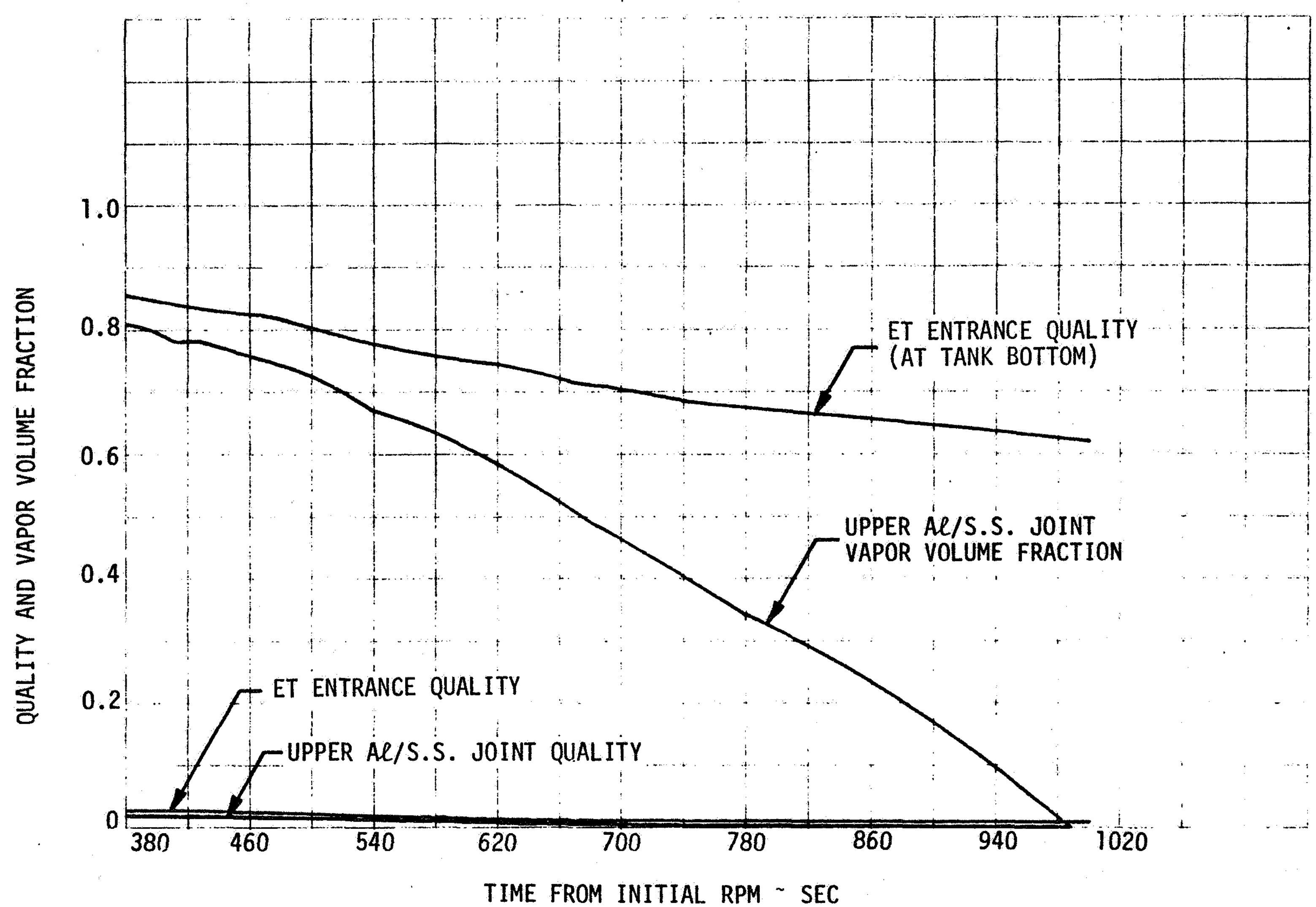


FIGURE 2-9 TRANSIENT QUALITY AND VAPOR VOLUME FRACTIONS FOR NSTL LOX REPLENISH SYSTEM PUMP FLOW CHILL-DOWN (CONTINUED)

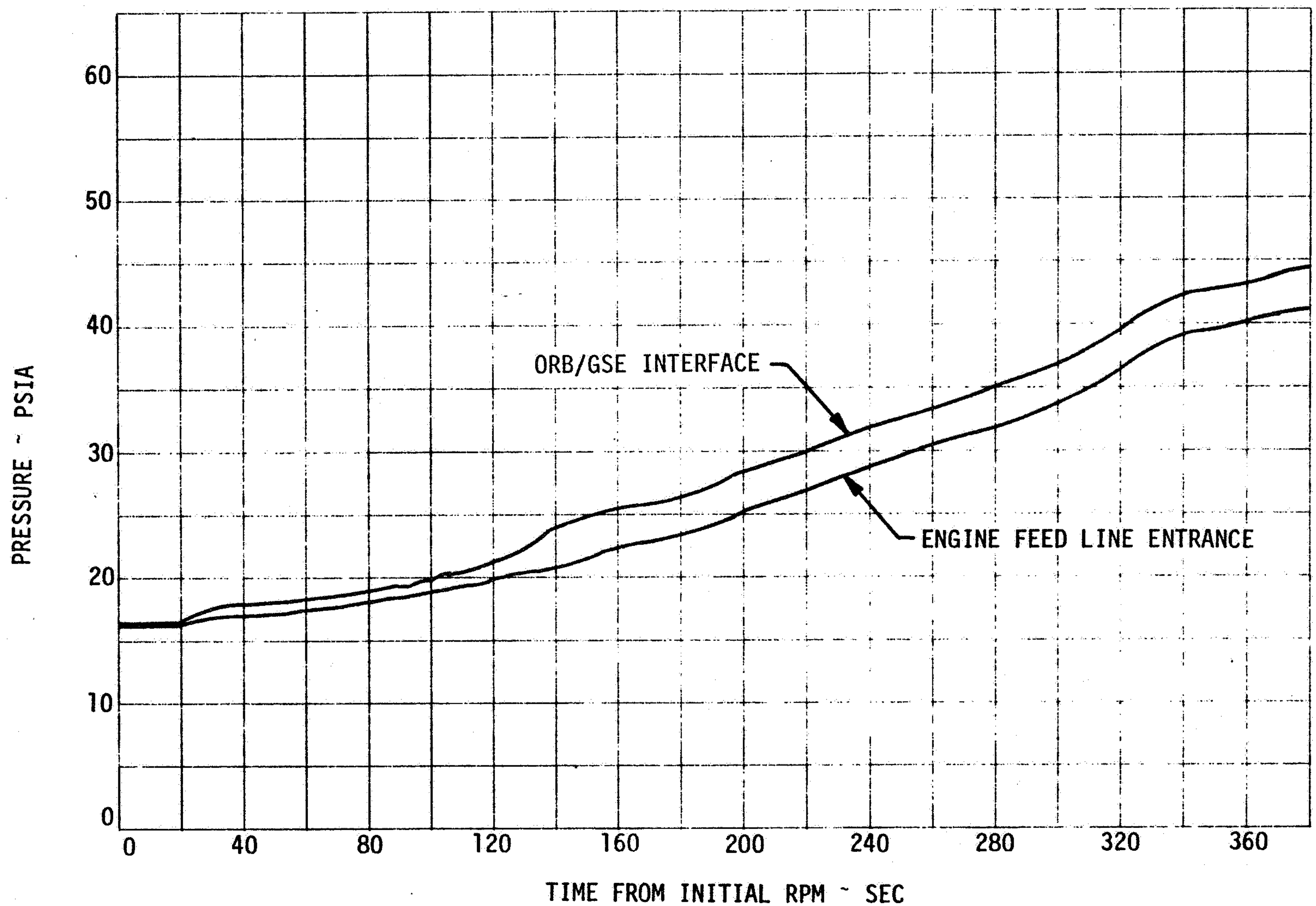


FIGURE 2-10 TRANSIENT PRESSURES FOR NSTL LOX REPLENISH SYSTEM PUMP FLOW CHILL-DOWN

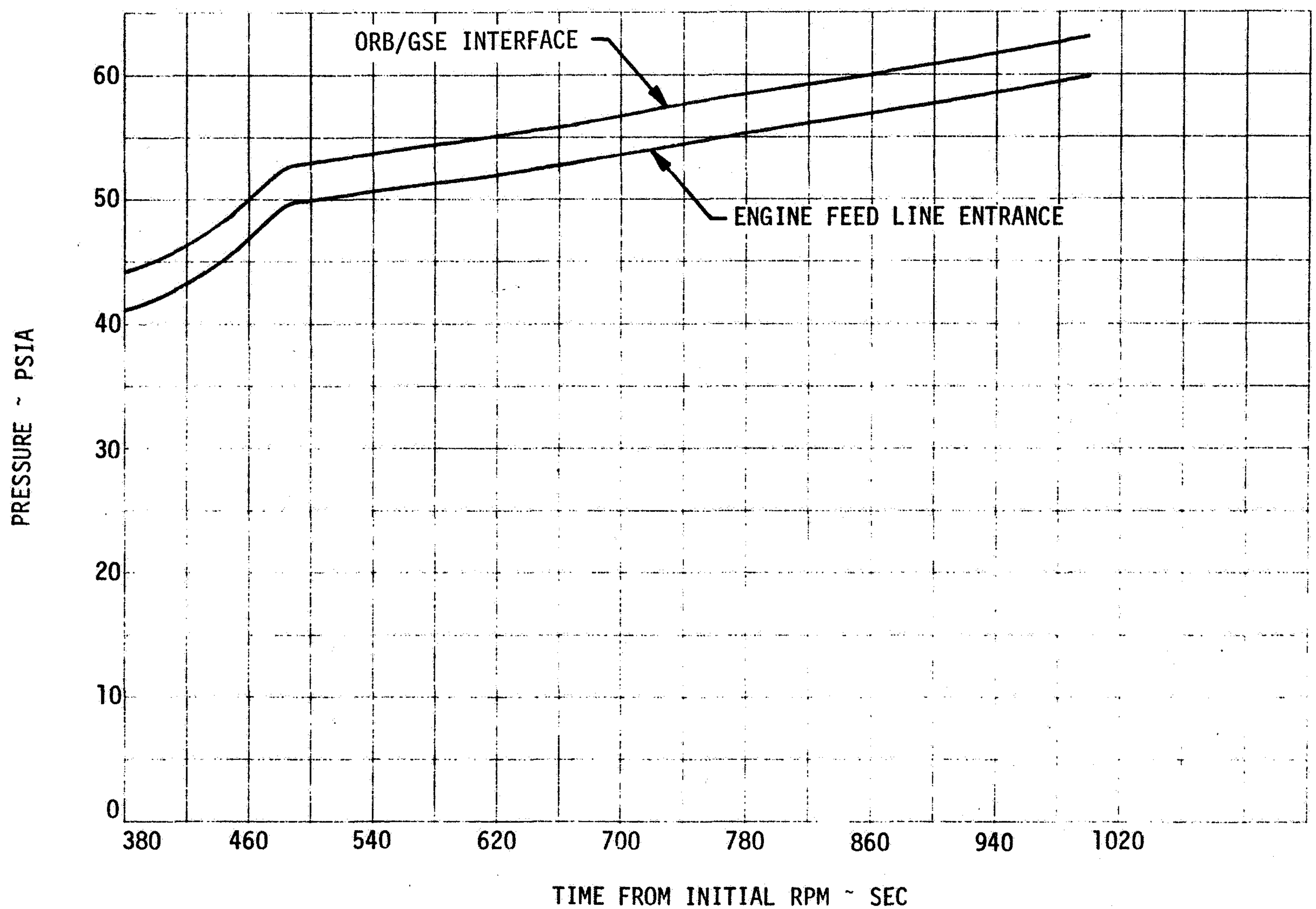


FIGURE 2-10 TRANSIENT PRESSURES FOR NSTL LOX REPLENISH SYSTEM PUMP FLOW CHILL-DOWN (CONTINUED)

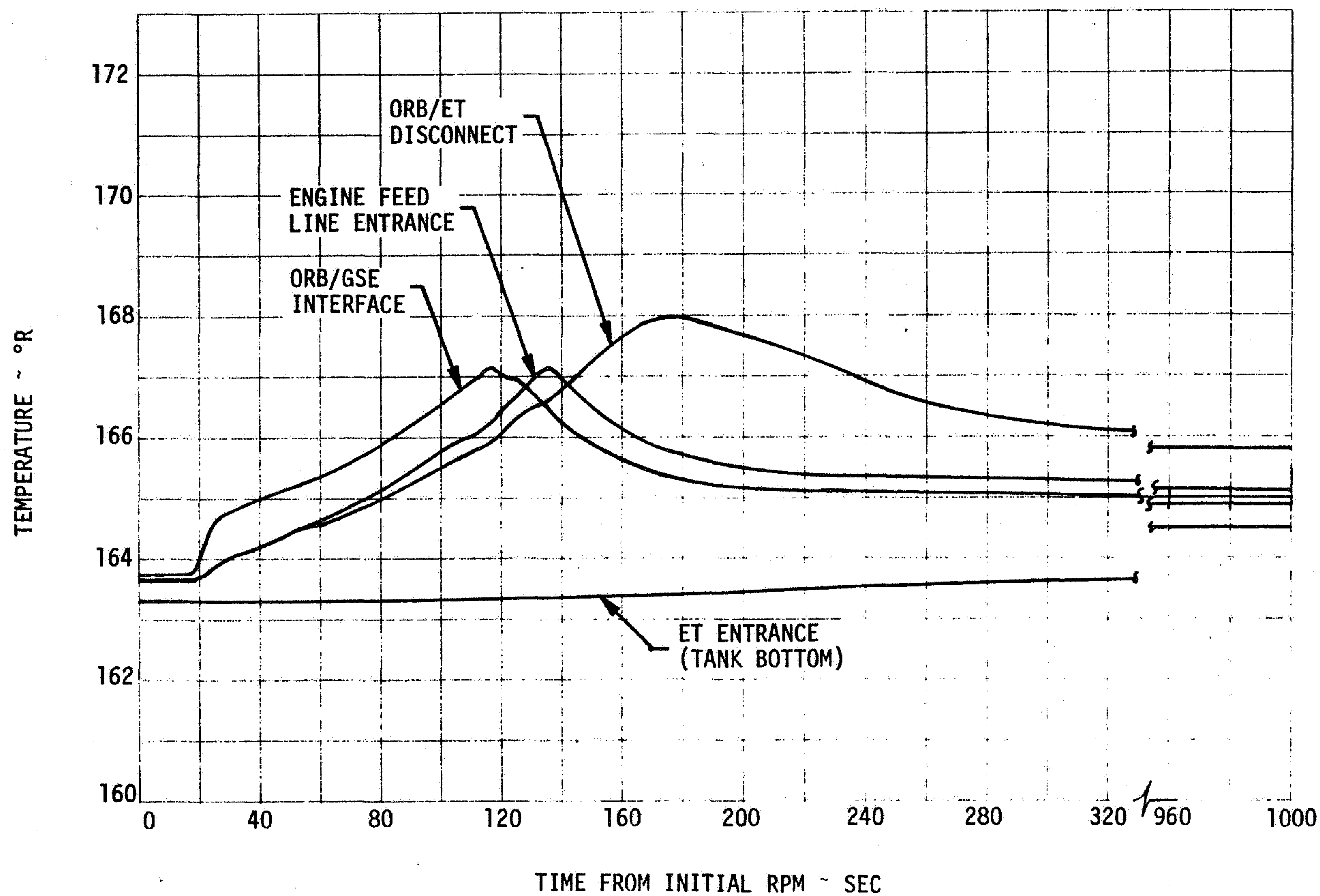


FIGURE 2-11 TRANSIENT TEMPERATURES FOR NSTL LOX REPLENISH SYSTEM PUMP FLOW CHILL-DOWN

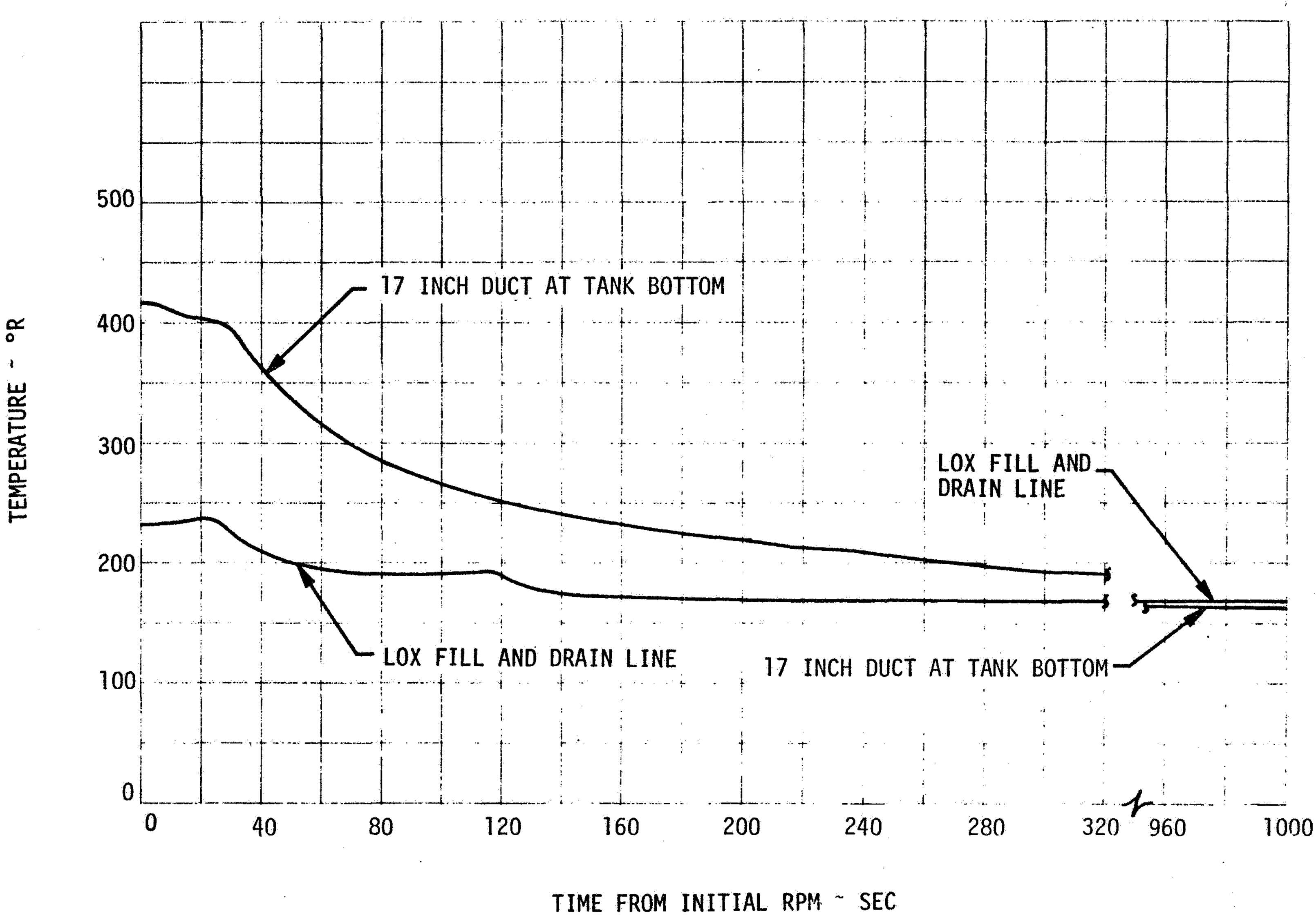


FIGURE 2-12 SHUTTLE LOX FILL SYSTEM TRANSIENT WALL TEMPERATURES FOR NSTL REPLENISH SYSTEM PUMP FLOW CHILL-DOWN

3.0 NSTL MAIN LOX LINE ANALYSES

Transient analyses of the NSTL main LOX line chill-down were performed. These analyses include the initial tank head flow chill-down period followed by a pump flow period until 100 percent liquid flow has reached the main line/GSE vent TEE. Specific objectives of these analyses are to predict the chill-down time required to achieve liquid flow at the main line/GSE vent TEE and to predict the pressure as a function of time at the engine bleed/GSE vent TEE.

The NSTL main LOX line and GSE vent system is shown schematically in Figure 3-1. More detailed configuration input data for these analyses are presented in the Appendix, Table A-III. The main LOX line configuration and pressure drop input data were derived as indicated in Paragraph 2.0 for the replenish system. The main (1250 GPM) LOX pump performance data used in the system simulation are presented in the Appendix, Figure A-II. These data were derived from Byron Jackson pump data given in Reference 10. The steady state external heat flux input for the uninsulated main LOX line and vent line was estimated to be 465 $BTU/FT^2 \cdot HR$ as suggested by References 7 and 8. The main LOX line is uninsulated to the 81 FT. elevation shown in Figure 2-1. The main LOX line will be insulated from the 81 FT. elevation to the vent TEE by the Svedrup and Parcel system modification. The steady state external heat flux for this portion of line is estimated to be 34.8 $BTU/FT^2 \cdot HR$ based on insulation conductivity data obtained from Mr. Dwight Garrison (Global Associates) on September 23, 1974. Steady state heat transfer rates for the NSTL main LOX line/GSE vent system are presented in the Appendix, Table A-IV. The heat capacity of the pipe walls was determined by assuming a specific heat of 0.091 $BTU/LB_M \cdot °R$ and density of 501 LB_M/FT^3 for stainless steel. The initial main LOX pump discharge temperature was assumed to be -295°F.

3.1 NSTL MAIN LOX LINE TANK HEAD FLOW ANALYSIS

The main LOX line chill-down was initially analyzed with a four minute tank head flow period followed by the pump start-up. For this tank head flow period, 100 percent liquid flow was not achieved at the system flow control (PCV-469) valve. The subsequent pump flow analysis indicated that a large step increase in pressures from PCV-469 to the pump discharge would occur when liquid reached the valve. The tank head flow period was extended to 12.7 minutes until liquid flow reached the valve to prevent this pressure step increase after pump start.

Results of the NSTL main LOX line tank head flow analysis are shown in Figures 3-2 through 3-5. The transient pump discharge pressure and flowrate are shown in Figures 3-2 and 3-3. Figure 3-3 also shows the mixture flowrate at the main line/GSE vent TEE. The initial pump discharge pressure oscillation remains below the pressure required for by-pass flow. Figure 3-4 shows the predicted transient vapor volume fraction and quality at PCV-469 and at the main LOX line/GSE vent TEE. These results indicate that liquid flow will be obtained at PCV-469 at 12.7 minutes after initiation of tank head flow. Figure 3-5 shows the GSE vent system pressure at the engine bleed TEE. The LOX pump NPSH is 86.45 feet at the end of this tank head flow period (just prior to pump start).

This main LOX line tank head flow chill-down analysis is based upon assumed constant values of 40 PSIG barge tank ullage pressure, -295°F pump discharge temperature, and 15 PSIA at the vent system exit. A valve opening time of 8 seconds was assumed for the barge No. 3 interface valve (MV-618) to initiate flow to the main LOX line.

3.2 NSTL MAIN LOX LINE PUMP FLOW ANALYSIS

The 1,250 GPM pump was assumed to start 13 minutes after tank head flow initiation for the NSTL main LOX line pump flow chill-down analysis. The

3.2 (Continued)

pump RPM was assumed to follow a straight line ramp from the windmilling RPM to 3550 RPM within 15 seconds from pump start. The parallel flow valve (MV-444) was assumed to be manually closed over a four second period prior to pump start. The automatically controlled PCV-469 operation was simulated as follows:

(1) PCV-469 closes within 4 seconds after pump start due to the low (windmilling) pump RPM and discharge pressure.

(2) PCV-469 remains closed until a pre-determined time (12 seconds from pump start for the assumed RPM ramp). This time allows pump discharge control pressure to reach the pre-determined value (261.4 psia) which will provide rated flow (1250 GPM) to the main line with 225 GPM by-pass flow.

(3) PCV-469 opens within 4 seconds to the position required for the estimated equivalent (L/D) required to maintain the pump discharge control pressure with by-pass flow.

Initial computer simulations verified the pre-determined pump discharge control pressure for 1250 GPM flow to the system with 225 GPM by-pass flow and the time required to reach the control pressure. Three iterative computer simulations were required to establish the control valve opening time and equivalent L/D (200,675) required to maintain the pump discharge control pressure with by-pass flow. Two subsequent computer simulations were made to close the by-pass valve after the pump discharge pressure stabilized and to re-adjust PCV-469 $(L/D)_e$ to an estimated value required to maintain the pump discharge control pressure without by-pass flow.

Results of the NSTL main LOX line pump flow chill-down analysis are shown in Figures 3-6 through 3-10. Figures 3-6 and 3-7 show the transient pump discharge pressure and mainline entrance flowrate during the pump start

3.2 (Continued)

ramp and the following pump flow chill-down period. Figure 3-7 also shows the mixture flowrate at the main LOX line/GSE vent TEE. Although the system is filled with liquid to the vent TEE at 104 seconds, and vent TEE flowrate is slightly lower than mainline entrance flowrate due to increasing liquid densities with decreasing system temperatures. Figure 3-8 shows that liquid flow is obtained at the vent TEE 104 seconds after pump start. Figure 3-9 shows the transient fluid temperature at the main LOX line/GSE vent TEE. Figure 3-10 shows the GSE vent system pressure at the engine bleed TEE.

This main LOX line pump flow chill-down analysis is based upon assumed constant values of 40 PSIG barge tank ullage pressure, -296°F pump discharge temperature, and 15 PSIA at the vent system exit.

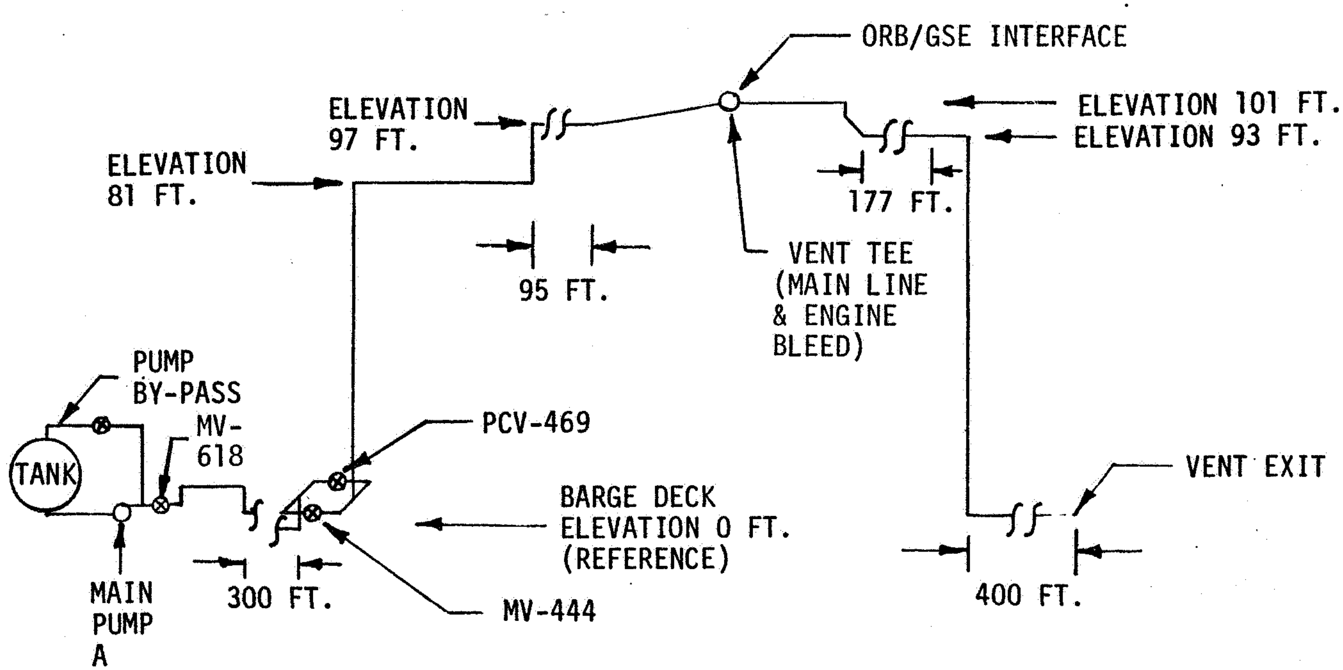


FIGURE 3-1   NSTL MAIN LOX LINE AND VENT SYSTEM

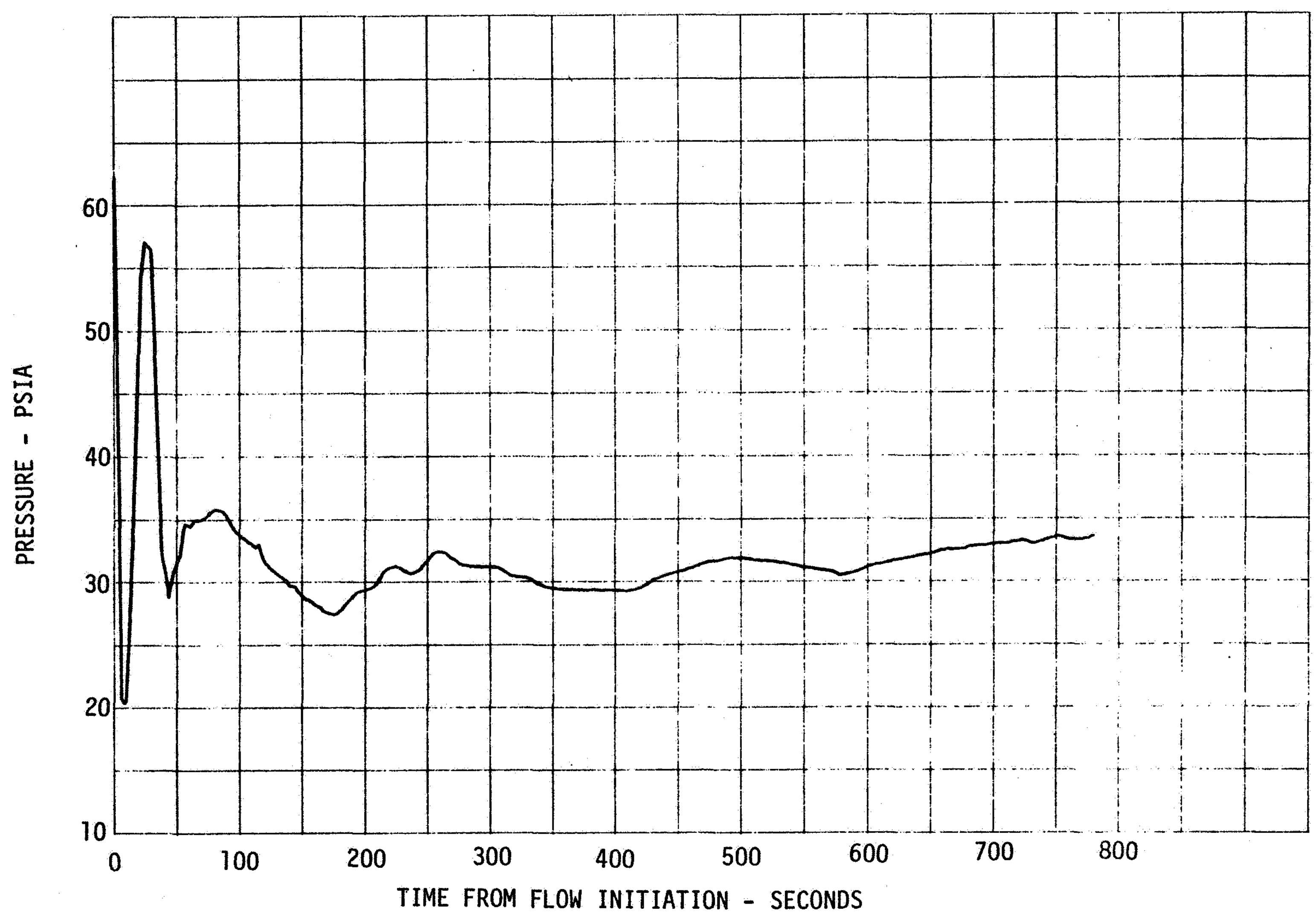


FIGURE 3-2 BARGE NO. 3 PUMP A TRANSIENT DISCHARGE PRESSURE FOR NSTL MAIN LOX LINE TANK HEAD FLOW CHILL-DOWN

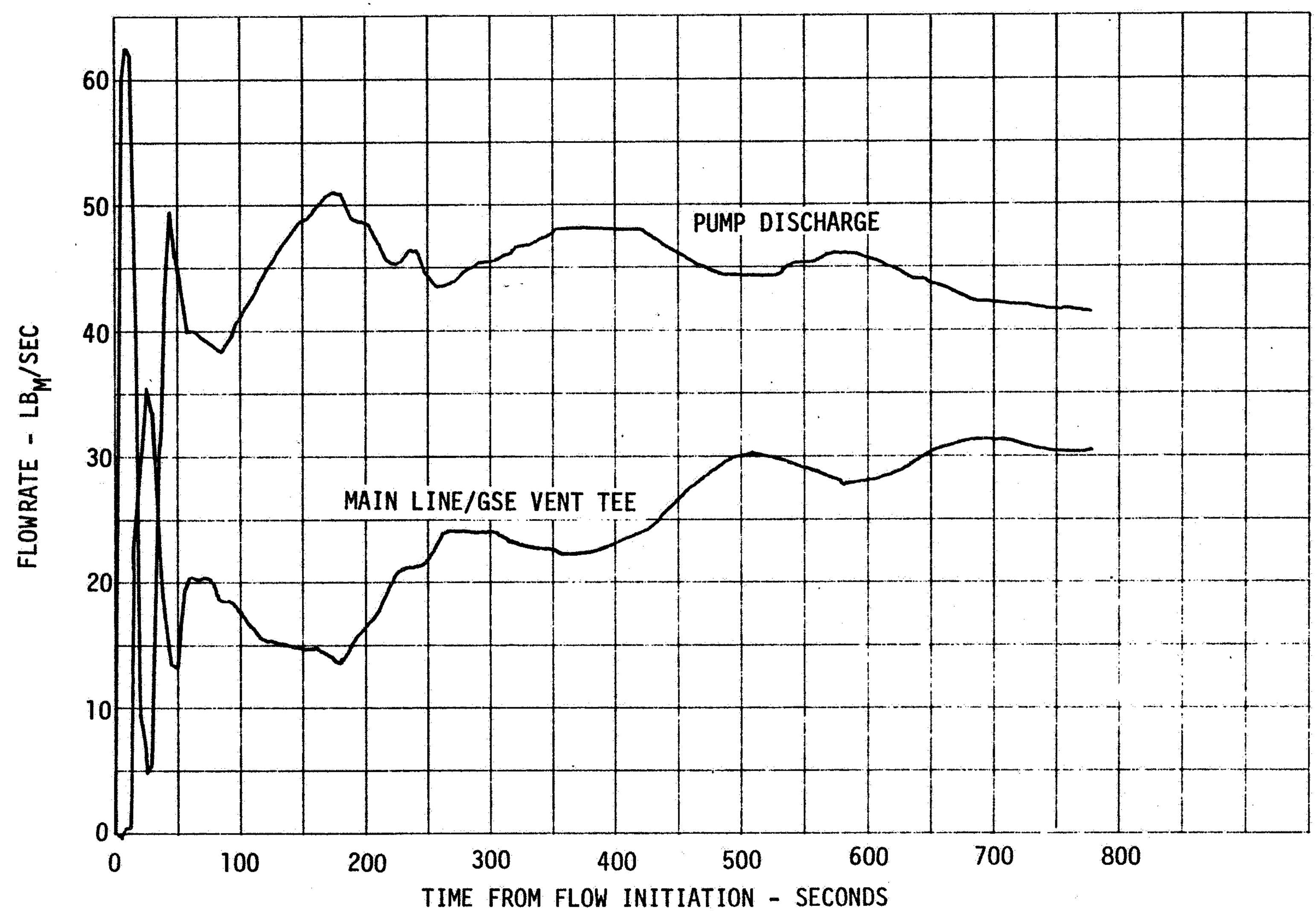


FIGURE 3-3 TRANSIENT FLOW RATES FOR NSTL MAIN LOX LINE TANK HEAD FLOW CHILL-DOWN

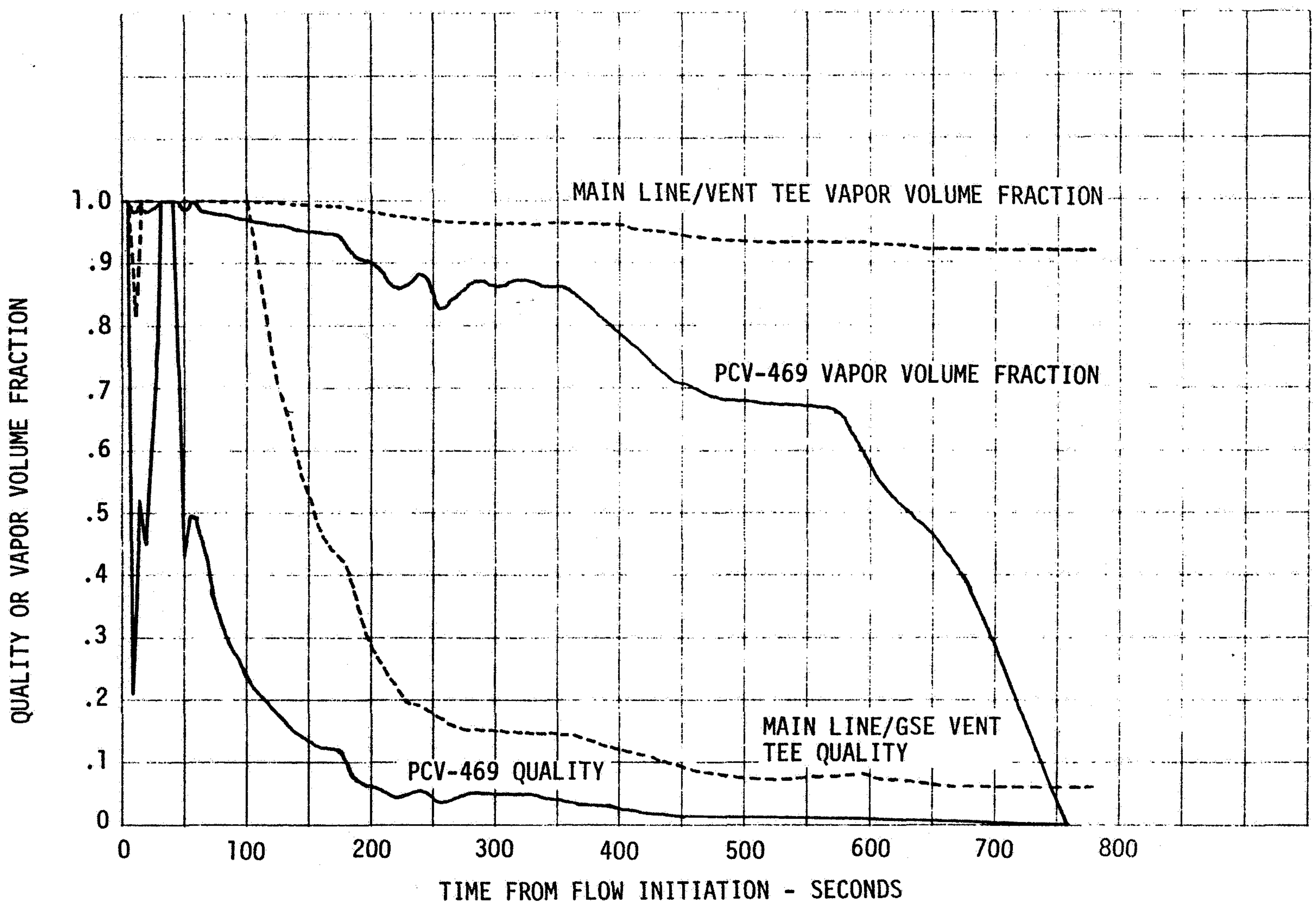


FIGURE 3-4 TRANSIENT QUALITIES AND VAPOR VOLUME FRACTIONS FOR NSTL MAIN LOX LINE TANK HEAD FLOW CHILL-DOWN

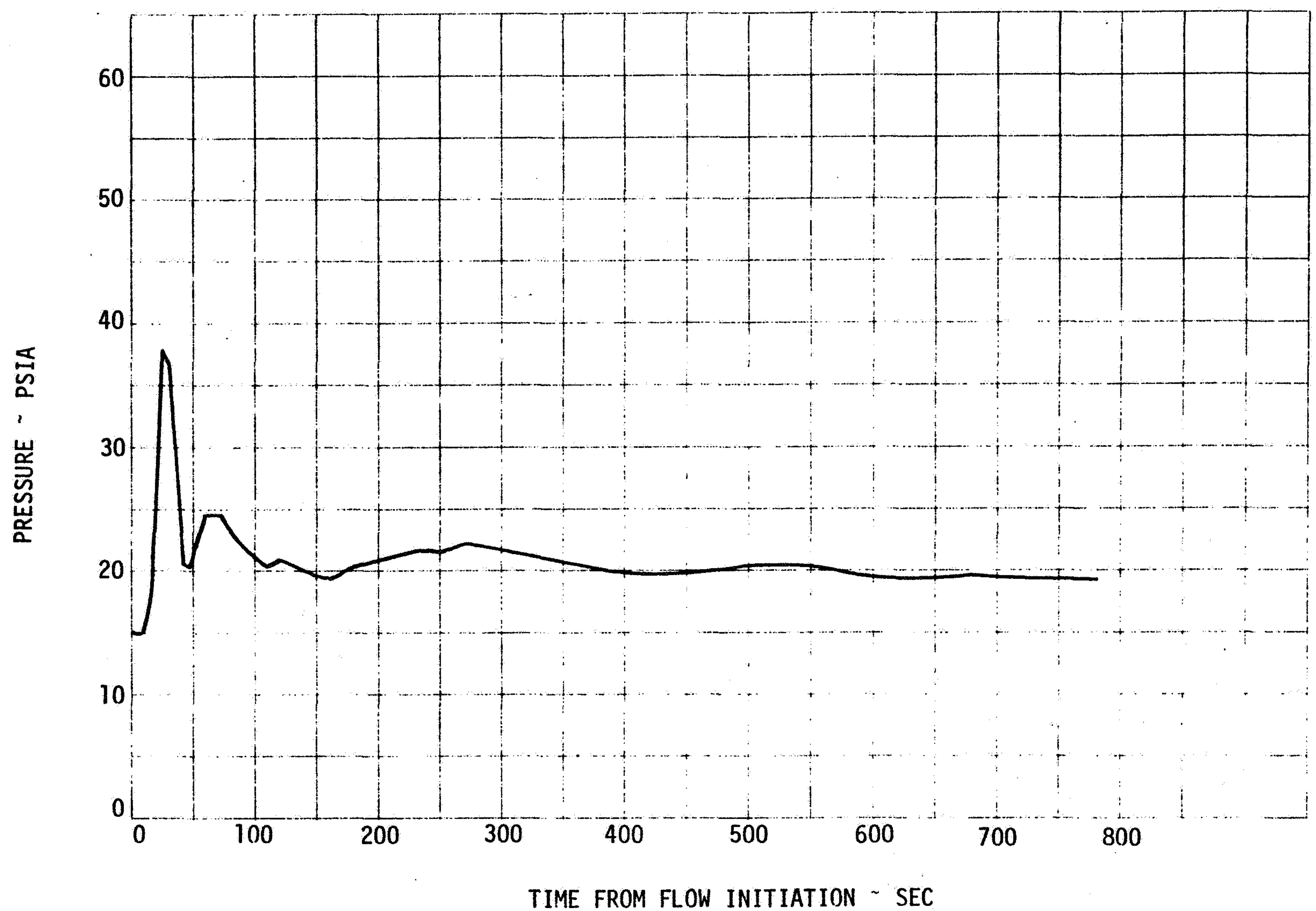


FIGURE 3-5 TRANSIENT ENGINE BLEED/GSE VENT TEE PRESSURE FOR NSTL MAIN LOX LINE TANK HEAD FLOW CHILL-DOWN

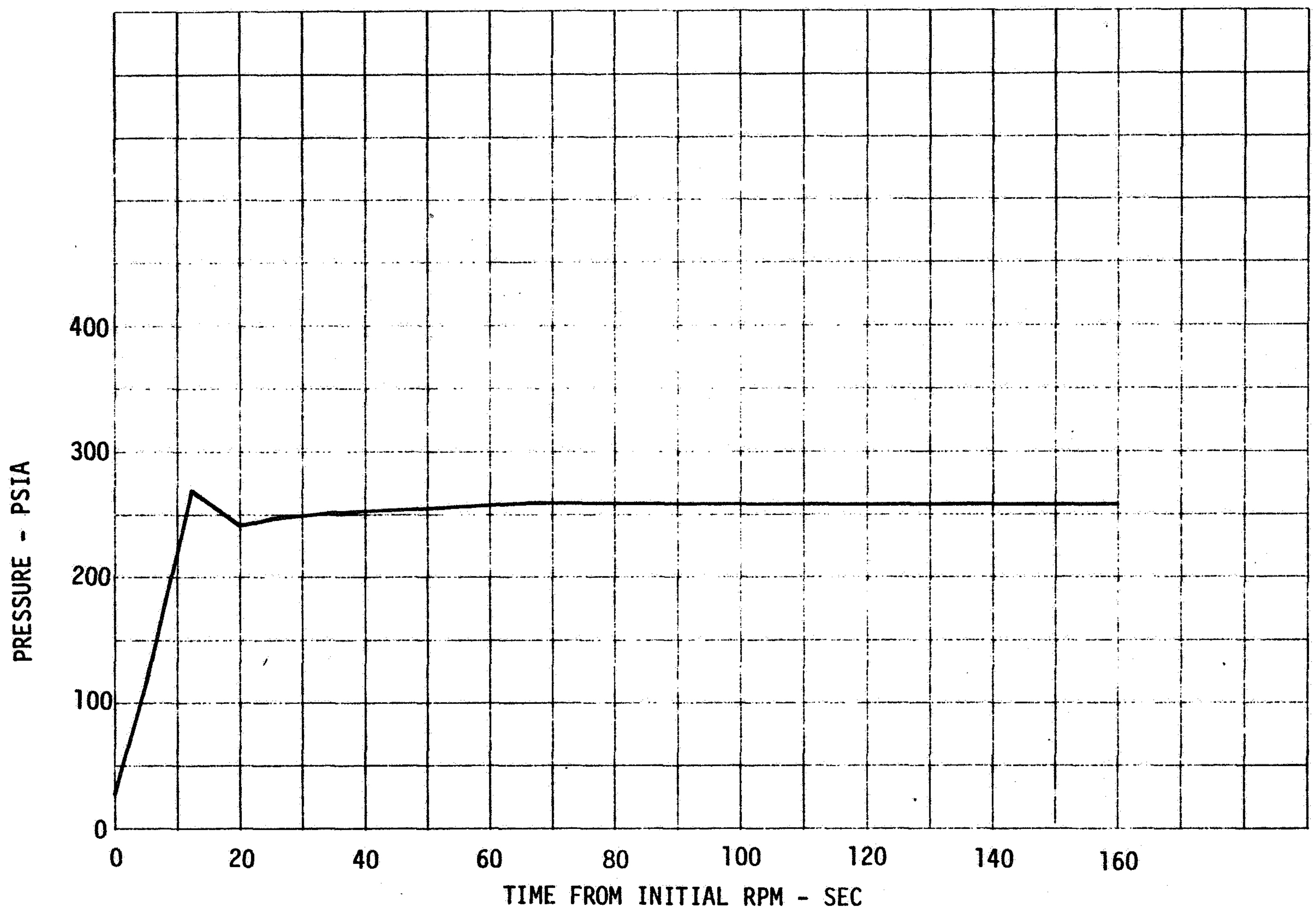


FIGURE 3-6 PUMP A TRANSIENT DISCHARGE PRESSURE FOR NSTL MAIN LOX LINE PUMP FLOW CHILL-DOWN

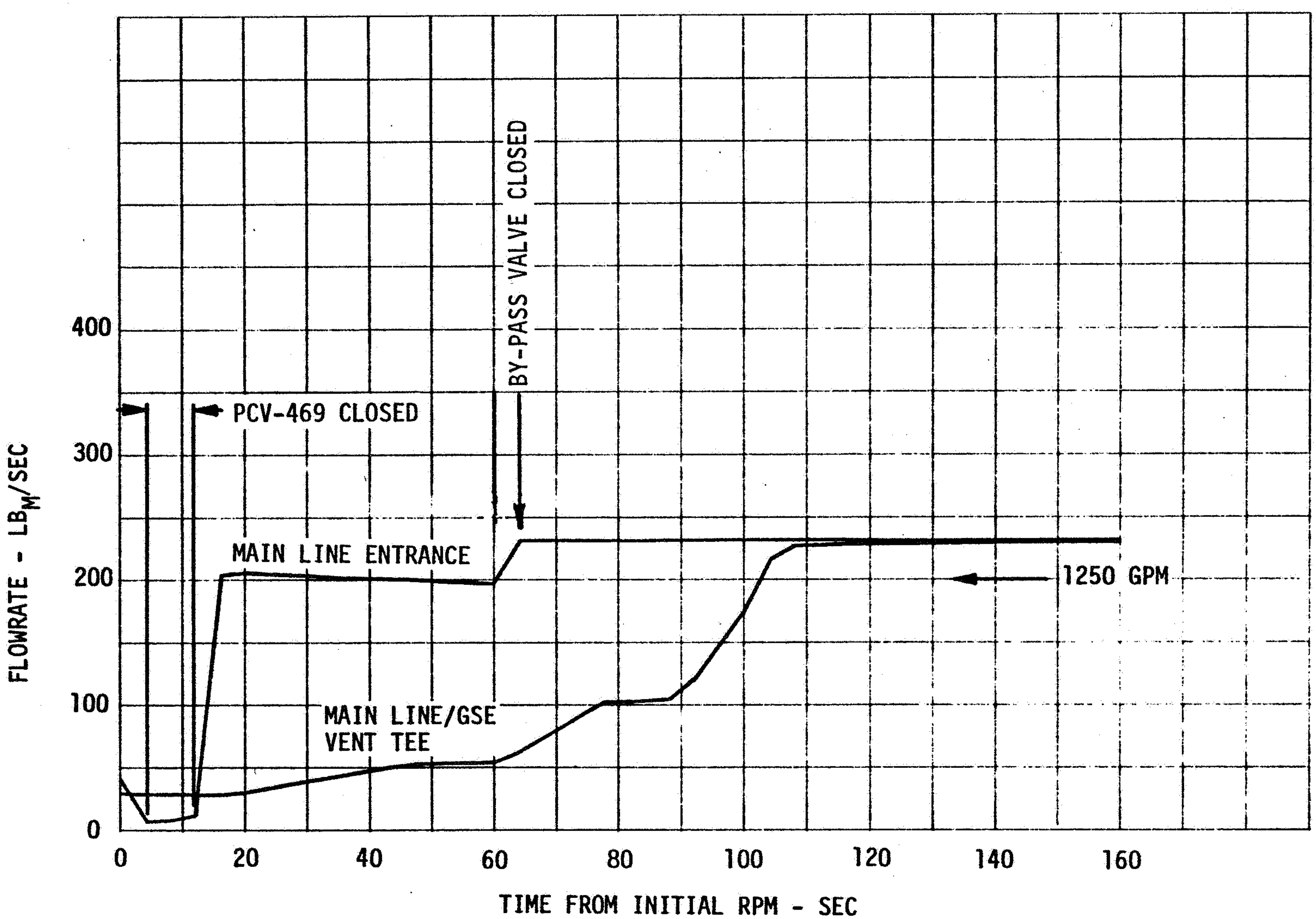


FIGURE 3-7 TRANSIENT FLOWRATES FOR NSTL MAIN LOX LINE PUMP FLOW CHILL- DOWN

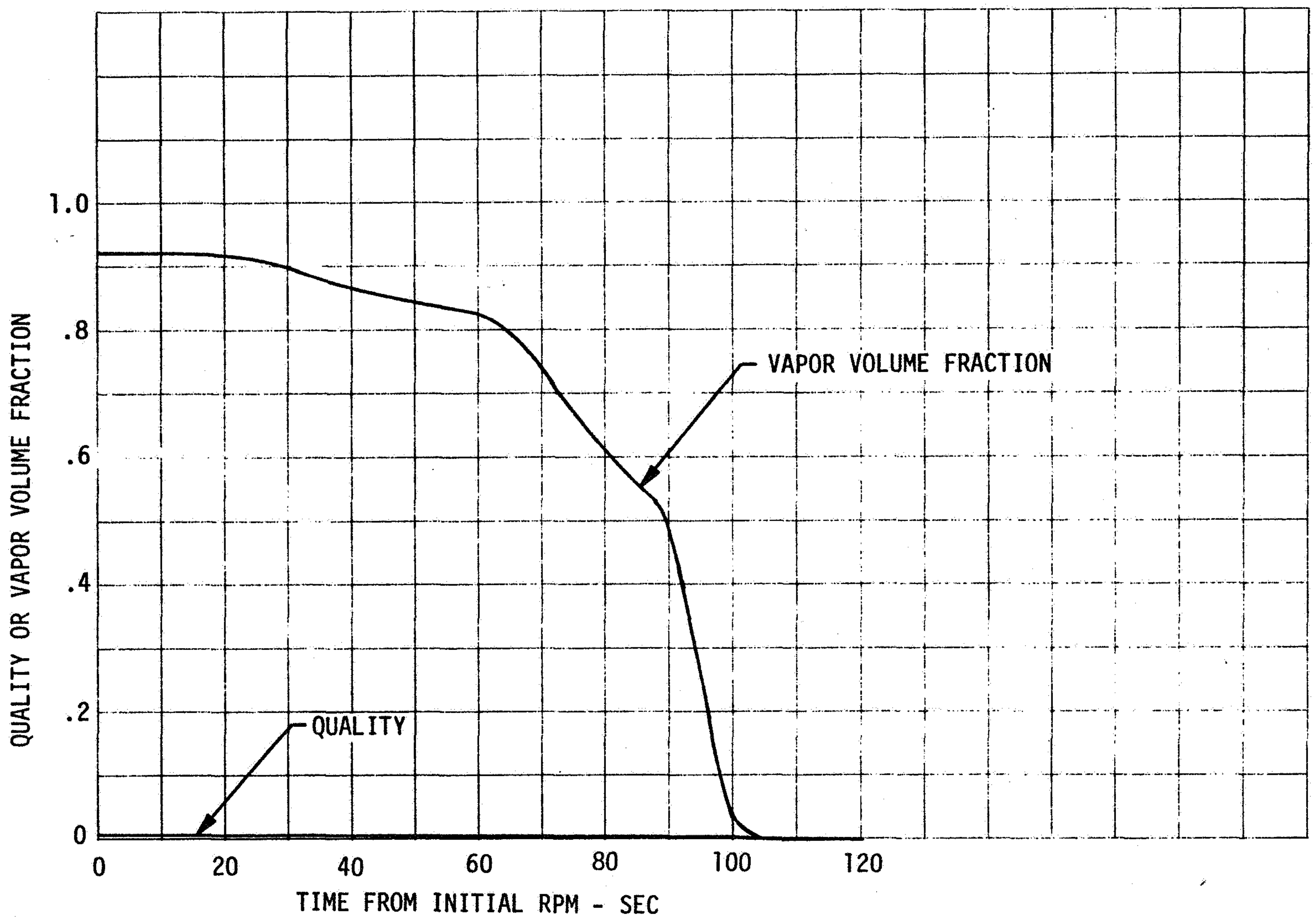


FIGURE 3-8 TRANSIENT MAIN LINE/GSE VENT TEE QUALITIES AND VAPOR VOLUME FRACTIONS FOR NSTL MAIN LOX LINE PUMP FLOW CHILL-DOWN

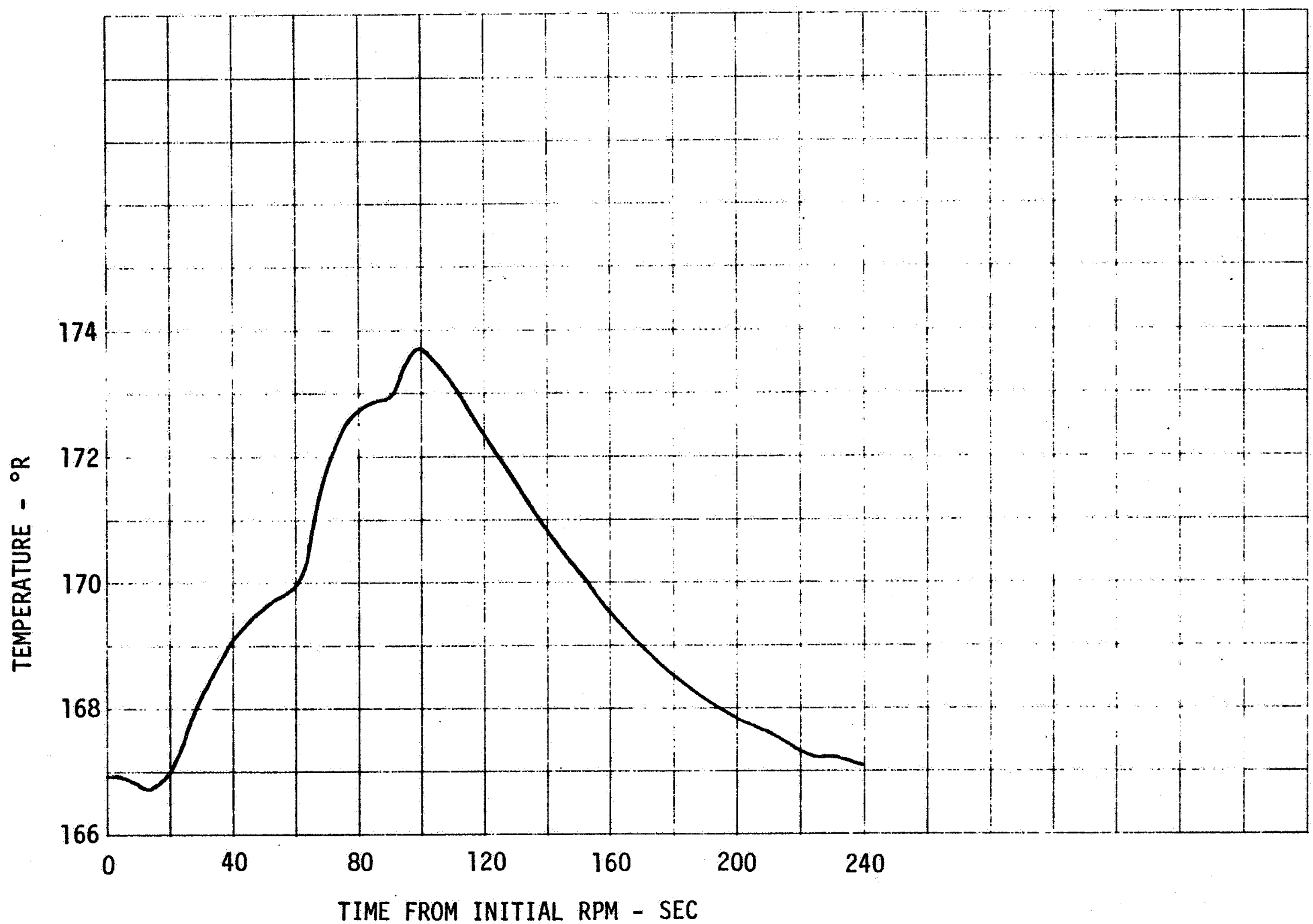


FIGURE 3-9 TRANSIENT MAIN LINE/GSE VENT TEE FLUID TEMPERATURE FOR NSTL MAIN LOX LINE PUMP FLOW CHILL-DOWN

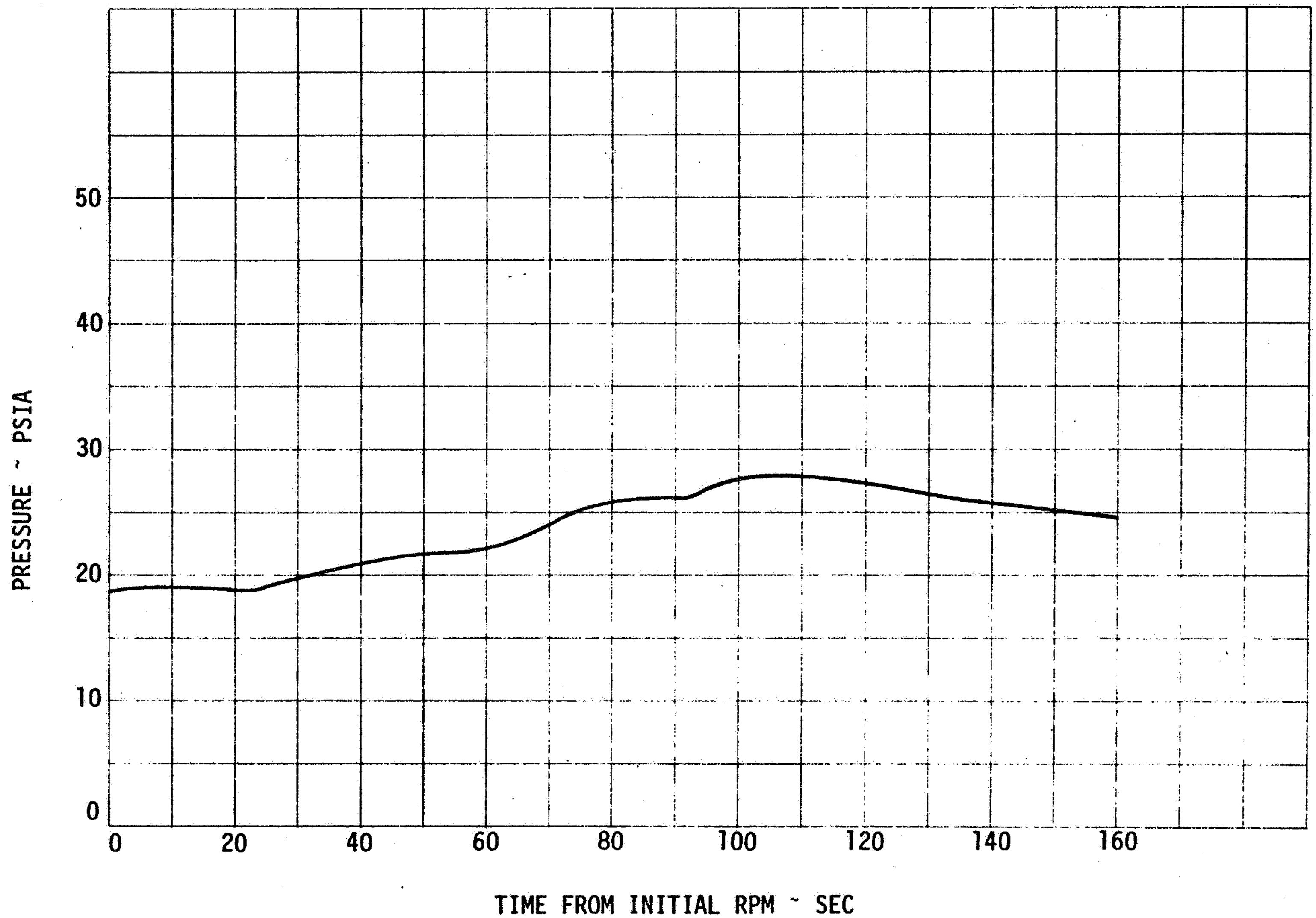


FIGURE 3-10 TRANSIENT ENGINE BLEED/GSE VENT PRESSURE FOR NSTL MAIN LOX LINE PUMP FLOW CHILL-DOWN

4.0 COMPUTER PROGRAM MODIFICATIONS

Several modifications and improvements to the Transient Cryogen Transfer Program (TCTP) Reference 11, were required to simulate the proposed NSTL system configurations and operations. These program improvements include the following capabilities:

(1) Throttlable flow control valves.

(2) Storage tank bottom pressure as a function of storage tank ullage pressure, liquid level, and suction line flow rate.

(3) Pump inlet pressure and NPSH as a function of storage tank bottom pressure and suction line flowrate.

(4) Pump by-pass flow as a function of pump discharge and storage tank pressures.

These program modifications provide a more generalized capability to perform transient analyses of various system configurations and operations with various known boundary conditions. System flowrates may be simulated for known flow control valve operation. In the absence of known pump inlet or discharge boundary conditions, storage tank bottom and pump inlet boundary conditions may be computed as a function of known storage tank ullage pressure and initial liquid level. These modifications also allow improved simulation of a system between the storage tank and pump inlet. The pump by-pass flow may be subtracted from the pump discharge flow to determine the transfer system inlet flow for known by-pass system pressure drop characteristics.

Further program improvements were made to simulate tank head flow starting from zero flowrate into hot (ambient temperature) lines. Since this is a very unstable period of system operation, involving low flowrates and flow

4.0 (Continued)

reversal in portions of the system, numerical instabilities were encountered in initial attempts to simulate this transient flow condition. In order to simulate the tank head flow start condition, program modifications were included to vary the external heat input as a function of the current local temperature difference across the line insulation or vacuum jacket, and to smooth the transition from two-phase to liquid heat transfer correlations. Also, in order to obtain a numerically stable simulation, it was necessary to improve the simulation of node interface conditions when reverse flow is encountered. This TCTP modification for reverse flow includes:

(1) Trial and error determination of the weighted average interface enthalpy entering a node as a function of current interface flowrate (determined by the energy and mass balance).

(2) Determination of the density corresponding to the trial value of enthalpy.

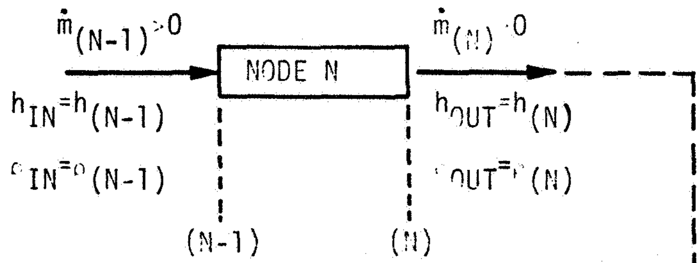
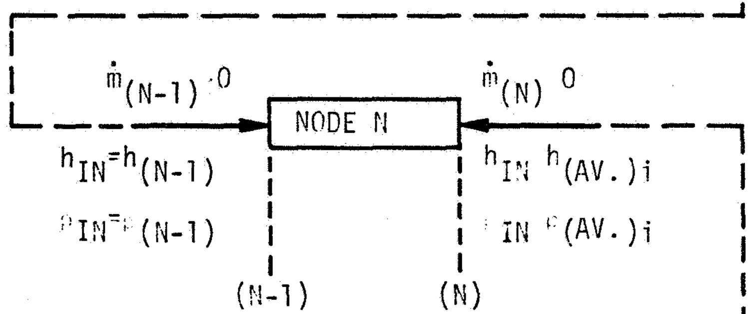
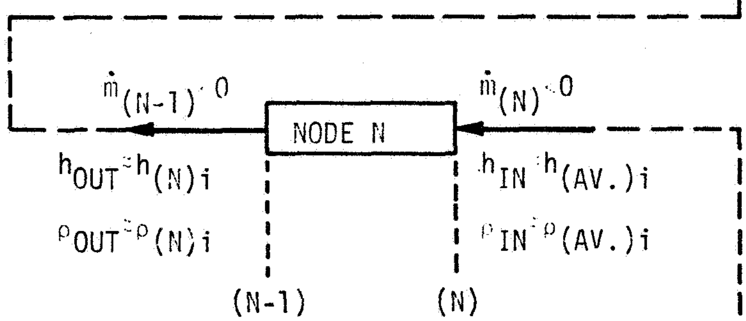
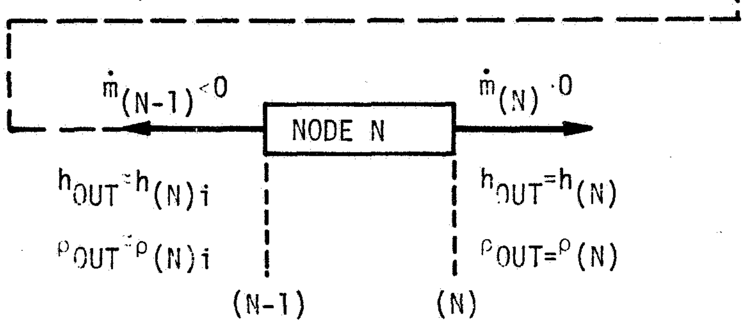
(3) Correction of the node vapor volume fraction and density used to determine frictional pressure drop for reverse flow.

(4) Correction of the kinetic energy terms entering and leaving a node for consistency with the positive (forward) flow model.

A summary of the enthalpy and density values applied in the modified energy/mass balance is shown in Table 4-I.

Details of all the computer program modifications made during the Shuttle LOX Loading Transient Study will be incorporated into an updated program user's manual. This updated manual will be attached to the study final report.

TABLE 4-I SUMMARY OF NODE INTERFACE ENTHALPY AND DENSITY

FLOW CASE	FLOW MODEL
I	
II	
III	
IV	

$h(J)$ and $\rho(J)$ designate bulk node properties leaving node (J), determined for the current time step.

$h_{(J)i}$ and $\rho_{(J)i}$ designate bulk node properties leaving node (J), determined for the previous time step.

(AV.) designates weighted average value for the total mass entering the node over the current time increment.

5.0 CONCLUSIONS

For the proposed NSTL LOX replenish system configuration and chill-down operation, steady flow conditions will be approached after four minutes of tank head flow. No further benefits can be obtained by extending the tank head flow period with the planned 40 PSIG barge tank ullage pressure. After the replenish pump start, a sudden increase in flow control valve upstream and pump discharge pressures will occur when 100 percent liquid flow reaches the flow control valve (LCV-114). At this time, the flow downstream of LCV-114 will be choked.

This sudden increase in pressures could be avoided by one or more of the following changes to the planned system configuration or operation:

(1) Increase the barge tank ullage pressure, system flowrate, and tank head flow period to achieve 100 percent liquid at LCV-114 prior to pump start.

(2) Increase the replenish pump RPM slowly with LCV-114 held open until 100 percent liquid reaches the valve at a low flowrate.

(3) Use a larger flow control valve and downstream line size.

After the replenish pump start transients have stabilized , 100 percent liquid flow will reach the Aluminum/Stainless Steel 17 inch duct joint (10 feet below the ET) at about 16.5 minutes from pump start. After this time, steady state conditions will be approached with the liquid mass flow rate approaching the total mass flow rate (low quality) at the ET entrance. However, the 2-phase fluid will be approximately 60 percent vapor by volume at the ET entrance. If it is desired to guarantee 100 percent liquid flow at the ET entrance at the end of the system chill-down, one or more of the following changes should be

5.0 (Continued)

considered for the planned system configuration or operation:

(1) Decrease the system inlet LOX temperature.

(2) Decrease the external heat load (improve the system insulation).

(3) Increase the system flow rate by adding a second replenish pump to the system after liquid is obtained at the ORB/GSE interface.

(4) Maintain a higher ullage pressure (approximately 19.5 PSIA) in the ET to increase the tank bottom pressure above saturation pressure.

For the proposed NSTL main LOX line and vent system configuration and chill-down operation, 13 minutes of tank head flow will be required to obtain liquid flow at the system flow control valve (PCV-469). An additional 1.7 minutes after pump start will be required to obtain liquid flow at the main line/GSE vent TEE.

If the main LOX line flow is switched from the GSE vent to the MPTA upon completion of chill-down for both the main line and replenish systems, the chill-down operational sequence would be as shown in Figure 5-1. For this sequence, the engine feed line entrance and engine bleed/GSE vent TEE pressures are shown in Figure 5-2. These data indicate that the engine bleed flow could be momentarily stopped due to the relatively high vent pressure at 16 to 41 and 53 to 74 seconds after main LOX line tank head flow initiation. During these periods, the time that the engine bleed flow is stopped depends upon the hydrostatic head for the engine bleed system. If the average density in the engine bleed system approaches vapor density, the flow will be stopped for the periods indicated on Figure 5-2. If the average density in the engine bleed system approaches the density at the engine feed line entrance, the flow will be stopped at 17 to 38 seconds after main LOX line tank head flow initiation.

5.0 (Continued)

The results of these NSTL facility analyses may be used as a basis for further development of the system configurations or operating procedures. Further development and investigations of the NSTL facility and operations will be included in the study final report.

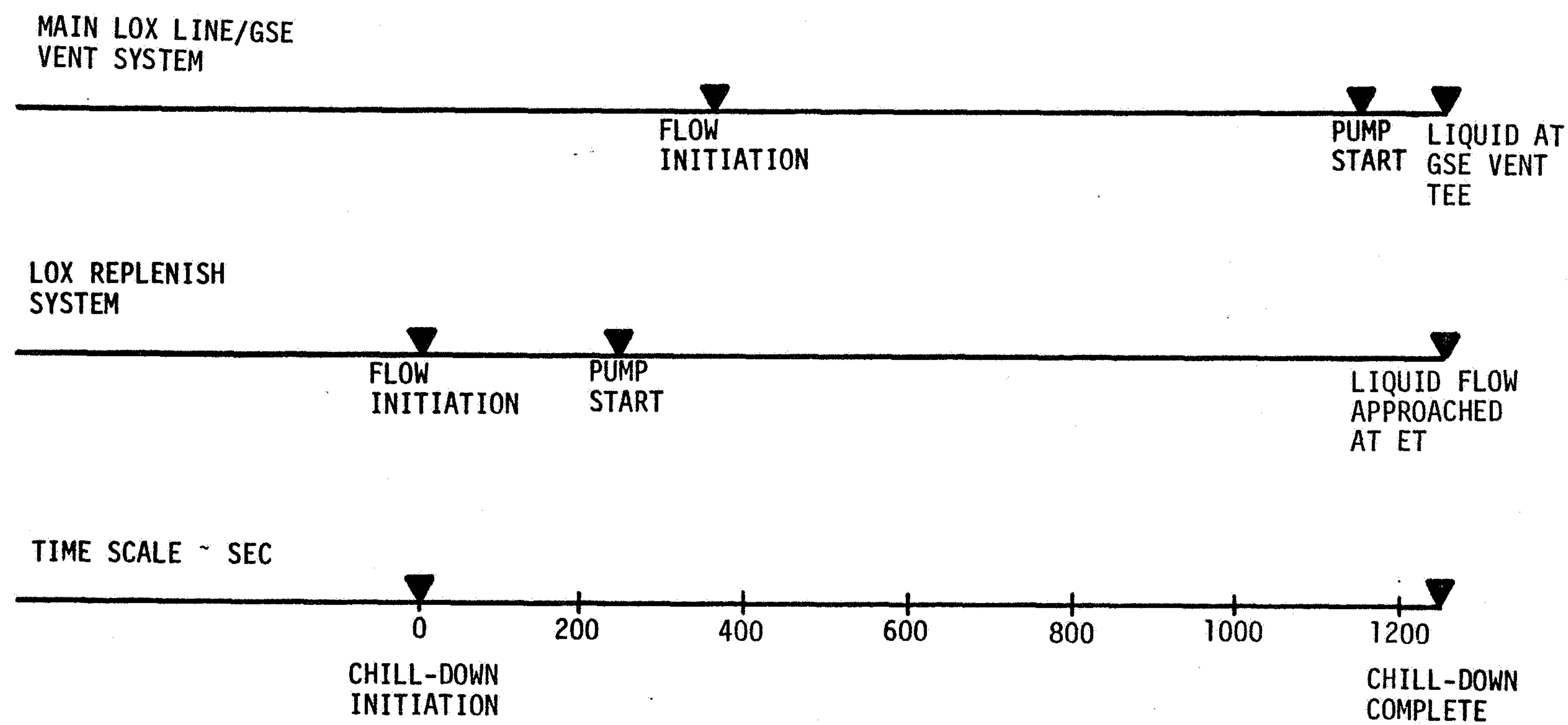


FIGURE 5-1 NSTL FACILITY CHILL-DOWN SEQUENCE

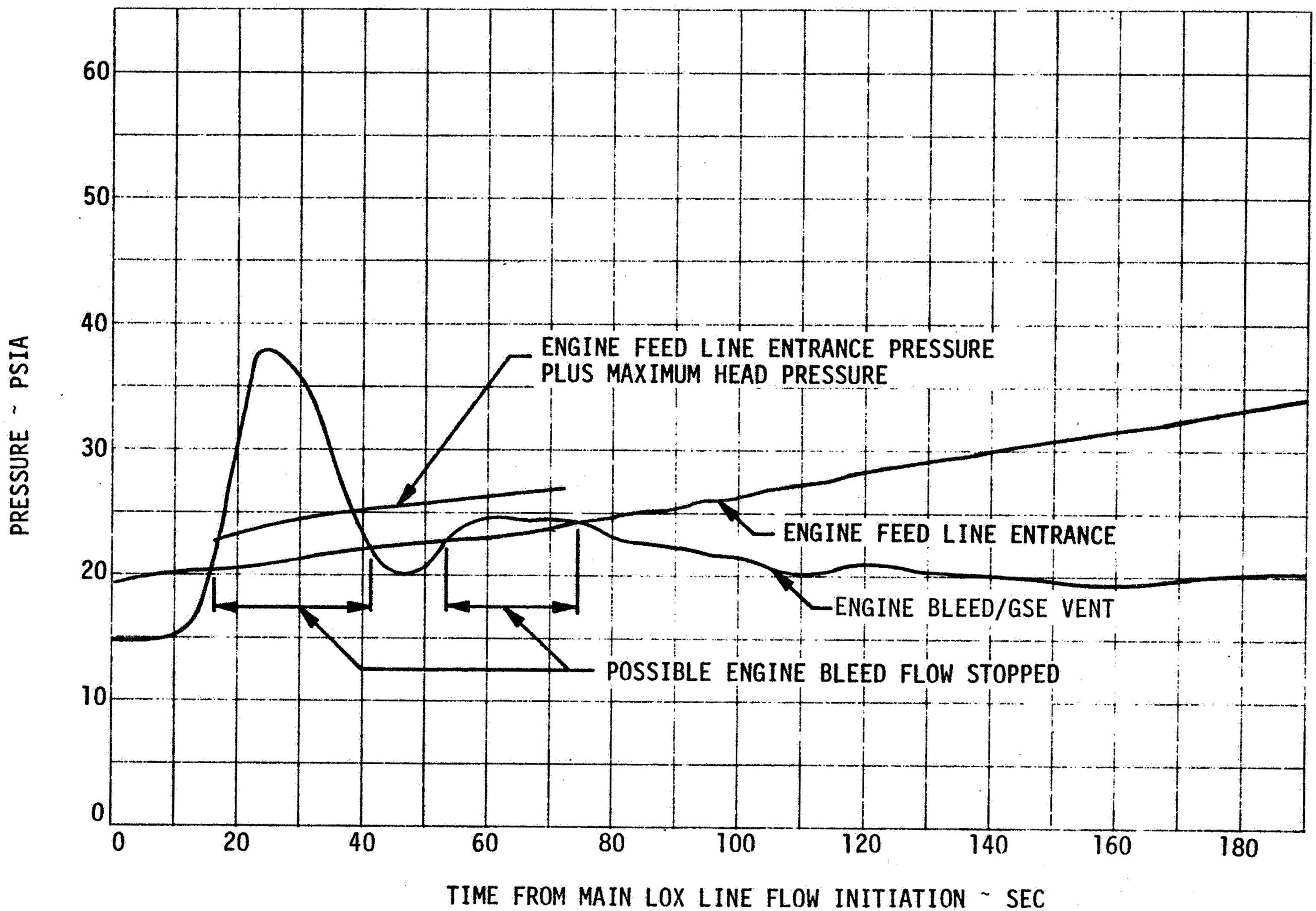


FIGURE 5-2 TRANSIENT ENGINE BLEED PRESSURES FOR NSTL MAIN LOX LINE TANK HEAD FLOW CHILL-DOWN INITIATION 116 SECONDS AFTER REPLENISH PUMP START

6.0 REFERENCES

1. Global Associates Drawing No. SK-701, "LOX Barge Vessel Fill & Drain," dated May 7, 1974.

2. Global Associates Drawing No. SK-702, "S-IC, B2 Position LOX Fill, Drain & Vent System," dated May 7, 1974.

3. General Electric Drawing No. 31B00-P001, "Marine Equipment LOX Barges LOX Piping Schematic," revised October 16, 1970.

4. General Electric Drawing No. 11BH0-P001, "Oxygen, Liquid S-IC LOX Dock Piping Schematic," revised September 18, 1969.

5. General Electric Drawing No. 11BHF-P001, "Oxygen, Liquid S-IC Stand B-2 Position Piping Schematic," revised July 21, 1969.

6. Crane Technical Paper No. 410, "Flow of Fluids Through Valves, Fittings, and Pipe," dated 1972.

7. Boeing Report, SK-DD-MDD-43/507, "Space Shuttle LOX System Servicing Study - LC39 A&B," dated April 26, 1974.

8. Boeing Report, SK/DD-MDD-43/508, "Space Shuttle LOX System MLP Valve Complex Design Proposal," dated April 26, 1974.

9. Southwest Research Institute Report, NASA-CR-124376, "Bellows Flow - Induced Vibrations and Pressure Loss," by C. R. Gerlach, E. C. Schroeder, R. L. Bass III, and J. L. Holster, dated April 13, 1973.

10. Global Associates Drawing No. 54B00-GK00, "Pump, Cryogenic 2X3 & 4X6," issued January 16, 1974.

11. Boeing Letter Report 5-9030-HT-158, "Cryogen Transfer Computer Program Development and Verification," dated September 3, 1974.

APPENDIX

PROGRAM INPUT DATA

Tabulated input for the NSTL LOX Facility Analyses are presented in this Appendix.

TABLE A-I NODAL INPUT DATA FOR NSTL LOX REPLENISH AND MPTA SYSTEMS

NODE NO.	DESCRIPTION	LENGTH (FT)	INTERNAL DIAMETER (EQUIV~FT)	NODE EXIT ELEVATION* (FT)	INCLUDED COMPONENTS	EQUIVALENT (L/D)	DUCT WALL MASS (LB_M)
IN	Barge Tank Bottom to Pump Inlet	111.0**	0.2717	3.17	(1) 8" 90° EL (1) VA-609 8" VALVE (1) EJ-6A01 8" Ex. Joint (1) EJ-7 8" Ex. Joint (1) 8X8X6" "T" (RUN) 14.25 FT. 8" LINE 18.00 FT. 3" LINE (1) 8X8X3" "T" (BRANCH) (2) 3" 90° EL (1) MV-602 3" VALVE (1) EJ-2 3" Ex. Joint (1) SC-20 3" SCREEN	0.33 0.60 0.20 0.18 0.47 0.48 66.25 60.00 28.00 263.88 24.36 83.20	265.23
1	Pump	N.A.	0.2717	3.17	N.A.	N.A.	N.A.
N.A.	Pump By-Pass	N.A.	0.1798	20.00	N.A.	1191.35	N.A.
10	Pump to Barge No. 2 Interface	14.0	0.2717	3.73	(1) CHV-612 3" CHECK VALVE (2) 3" 90° EL 14 FT. 3" LINE	141.23 28.00 51.53	62.09
20	Barge No. 2 Interface to Dock 3X2-1/2" Reducer	20.0	0.2717	3.73	(1) MV-605 3" VALVE (1) SC-23 3" SCREEN 20 FT. 3" FLEX HOSE	263.88 166.39 562.90	88.70

*ELEVATIONS ABOVE LOX SUPPLY BARGE DECK
**EQUIVALENT LENGTH TO SIMULATE VOLUME AND MASS

TABLE A-I NODAL INPUT DATA FOR NSTL LOX REPLENISH AND MPTA SYSTEMS (Cont'd)

NODE NO.	DESCRIPTION	LENGTH (FT)	INTERNAL DIAMETER (EQUIV~FT)	NODE EXIT ELEVATION* (FT)	INCLUDED COMPONENTS	EQUIVALENT (L/D)	DUCT WALL MASS (LB_M)
30	3X2-1/2" Reducer to Barge No. 1 "T"	55.0	0.3612	-1.22	(1) 3X2-1/2" REDUCER (1) VA-422 2.5" VALVE (1) 2.5" 90° EL (1) 2.5X4" INCREASER (1) EJ-5 4" Ex. Joint 55 FT. 4" LINE	22.05 1187.53 102.47 167.90 18.32 152.27	220.57
40	Barge No. 1 "T" to Verticle Rise	30.0	0.3612	0.80	(1) 4" "T" (RUN) (1) SC-52 4" SCREEN (1) EJ-7 4" Ex. Joint (1) 4" 270° BEND (3) 4" 90° EL 30 FT. 4" LINE	20.00 129.80 14.70 87.70 42.00 83.00	120.30
50	Verticle Rise to 4X3" Reducer	80.0	0.3612	80.80	(1) 4" 90° EL 80 FT. 4" LINE	14.00 221.48	320.83
60	Horizontal at 80.8 Ft. Elevation	63.79	0.2717	80.80	(1) 4X3" REDUCER (4) 3" 90° EL 63.79 FT. 3" LINE	9.29 56.00 234.78	282.90
70	Verticle Rise to 94.49 Ft. Elevation	13.69	0.2717	94.49	(1) 3" 90° EL 13.69 FT. 3" LINE	14.00 64.39	60.71
80	94.49 Ft. Elevation to FE-114 Flow Meter	76.66	0.2717	96.52	(2) 3" 90° EL (8) 3" 45° EL 76.66 FT. 3" LINE	28.00 56.00 282.15	339.98

*ELEVATIONS ABOVE LOX SUPPLY BARGE DECK

TABLE A-I NODAL INPUT DATA FOR NSTL LOX REPLENISH AND MPTA SYSTEMS (Cont'd)

NODE NO.	DESCRIPTION	LENGTH (FT)	INTERNAL DIAMETER (EQUIV~FT)	NODE EXIT ELEVATION* (FT)	INCLUDED COMPONENTS	EQUIVALENT (L/D)	DUCT WALL MASS (LB_M)
90	FE-114 Flow Meter to Main Line "T"	44.34	0.2717	100.78	(1) FE-114 Flow Meter (2) 3" 45° EL (3) 3" 90° EL (1) 2" LCV-114 (1) 10X10X3" "T" (BR) 44.34 FT 3" LINE	665.55 14.00 14.00 2807.00 ← OPEN 60.00 163.20	196.64
100	Main Line "T" to ORB/GSE Interface	7.5	0.8735	100.78	(1) F2 Filter 7.5 FT 10" LINE	80.00 8.96	111.93
110	ORB Fill and Drain to LO_2 Manifold	12.72	0.667	107.10	(1) 5°18' MITRE (2) MC-284 VALVE (1) 75° BEND (2) 64.6° BEND 12.72	2.20 26.00 11.67 20.10 19.07	70.68
200	LO_2 Manifold to ORB/ET Disconnect	13.56	1.406	110.99	(3) "T" (RUN) (1) 17" 75.2° BEND (1) 17" 73.9° BEND (1) 17" 5.03° BEND 13.56 FT 17" LINE	60.00 11.70 11.50 0.78 9.64	158.17
210	ORB/ET Disconnect to S.S./Aℓ Joint	11.38	1.406	119.05	(1) 17" 90° BEND 11.38 FT 17" LINE	14.00 8.09	132.74

*ELEVATIONS ABOVE LOX SUPPLY BARGE DECK

TABLE A-I NODAL INPUT DATA FOR NSTL·LOX REPLENISH AND MPTA SYSTEMS (Cont'd)

NODE NO.	DESCRIPTION	LENGTH (FT)	INTERNAL DIAMETER (EQUIV~FT)	NODE EXIT ELEVATION* (FT)	INCLUDED COMPONENTS	EQUIVALENT (L/D)	DUCT WALL MASS (LB_M)
220	Aℓ Duct	23.59	1.406	142.64	23.59 FT 17" LINE	16.81	117.71
230	Aℓ Duct	23.59	1.406	166.23	23.59 FT 17" LINE	16.81	117.71
240	Aℓ Duct/S.S. Joint	23.60	1.406	189.83	23.60 FT 17" LINE	16.81	117.71
250	Aℓ/S.S. Joint to ET (Tank Bottom)	25.06	1.406	200.01	(2) 90° Bends 25.06 17" LINE	28.00 17.82	292.30

*ELEVATIONS ABOVE LOX SUPPLY BARGE DECK

TABLE A-II STEADY STATE HEAT TRANSFER RATES FOR NSTL LOX REPLENISH AND MPTA SYSTEM

NODE NO.	DESCRIPTION	HEAT TRANSFER RATE - BTU/HR
10	PUMP TO BARGE NO. 2 INTERFACE	443
20	BARGE NO. 2 INTERFACE TO DOCK 3 X 2-1/2" REDUCER	7928
30	3 X 2-1/2" REDUCER TO BARGE NO. 1 "T"	2314
40	BARGE NO. 1 "T" TO VERTICLE RISE	1262
50	VERTICLE RISE TO 4 X 3" REDUCER	3366
60	HORIZONTAL AT 80.8 FT. ELEVATION	2019
70	VERTICLE RISE TO 94.49 FT. ELEVATION	433
80	94.49 FT. ELEVATION TO FE-114 FLOW METER	2426
90	FE-114 FLOW METER TO MAIN LINE "T"	1403
100	MAIN LINE "T" TO ORB/GSE INTERFACE	9164
110	ORB FILL AND DRAIN TO LO_2 MANIFOLD	18519
200	LO_2 MANIFOLD TO ORB/ET DISCONNECT	41615
210	ORB/ET DISCONNECT TO S.S./Aℓ JOINT	1759
220	Aℓ DUCT	3638
230	Aℓ DUCT	3638
240	Aℓ DUCT/S.S. JOINT	3640
250	Aℓ/S.S. JOINT TO ET (TANK BOTTOM)	3873
TOTAL		107,440

TABLE A-III NODAL INPUT DATA FOR NSTL MAIN LOX LINE/GSE VENT SYSTEM

NODE NO.	DESCRIPTION	LENGTH (FT)	INTERNAL DIAMETER (EQUIV~FT)	NODE EXIT ELEVATION* (FT)	INCLUDED COMPONENTS	EQUIVALENT (L/D)	DUCT WALL MASS (LB_M)
IN	Barge Tank Bottom to Pump Inlet	27.17**	0.5298	2.42	(1) 8" 90° BEND (1) VA-609 8" VALVE (1) EJ-6A01 8" Ex. Joint (1) EJ-7 8" Ex. Joint (1) 8X8X6" "T" (BRANCH) 11.75 FT 8" LINE (1) 6" 90° BEND (1) MV-306 VALVE (1) SC-21 6" SCREEN (1) EJ-1A 6" Ex. Joint 7.0 FT 6" LINE	4.75 10.99 3.63 3.27 60.00 5.75 14.00 300.41 121.19 13.98 13.21	227.71
1	Pump	N.A.	0.5298	2.417	N.A.	N.A.	N.A.
N.A.	Pump By-Pass	N.A.	0.1798	20.00	N.A.	66.31	N.A.
10	Main LOX Pump A to Barge Interface No. 3	52.06**	0.5298	3.73	(1) FH-6A02 4" FLEX HOSE (1) 4X6" INCREASER (1) CHV-616 6" CHECK VALVE 16 FT 6" LINE (1) MV-614 6" VALVE (1) 6" 90° BEND (1) CHV-6A02 6" CHECK VALVE	134.51 110.20 141.25 30.20 300.42 14.00 158.91	436.75

*ELEVATIONS ABOVE LOX SUPPLY BARGE DECK
**EQUIVALENT LENGTH TO SIMULATE VOLUME AND MASS

TABLE A-III NODAL INPUT DATA FOR NSTL MAIN LOX LINE/GSE VENT SYSTEM (Cont'd)

NODE NO.	DESCRIPTION	LENGTH (FT)	INTERNAL DIAMETER (EQUIV~FT)	NODE EXIT ELEVATION* (FT)	INCLUDED COMPONENTS	EQUIVALENT (L/D)	DUCT WALL MASS (LB_M)
10	(Continued)				(1) EJ-9A 6" Ex. Joint (1) 8X8X6" "T" (BRANCH) 20.75 FT 8" LINE (2) 8" 90° BEND	17.04 20.37 10.16 9.50	
20	Barge No. 3 Interface to Dock "T"	22.75	0.6941	-0.94	(1) MV-618 VALVE (1) FH-53 8" FLEX HOSE (18.75 FT) (1) 8X6" REDUCER (1) VA-405 VALVE (1) 6" 90° BEND (1) 6X8" INCREASER 4 FT 8" LINE (1) 12X12X8" "T" (BR)	196.08 260.13 39.30 614.78 41.26 39.30 5.76 60.00	578.05
30	Barge Pos. No. 3 "T" to Pos. No. 2 "T"	106.5	1.0325	-0.72	(1) EJ-3 12" Ex. Joint 106.5 FT 12" LINE	7.18 103.15	2634.43
40	Barge Pos. No. 2 "T" to Pos. No. 1 "T"	54.5	1.125	-0.66	(1) 14X12" INCREASER (1) 14X14X8" "T" (RUN) (1) EJ-4 14" Ex. Joint 54.5 FT 14" LINE	3.14 20.00 10.11 48.44	2047.85
50	Barge Pos. No. 1 "T" to Branch "T"	31.0	1.125	8,38	(1) 14X14X8" "T" (RUN) (1) SC-51 14" SCREEN (1) EJ-6 14" Ex. Joint (1) 14X14X14" "T" (BR) 31 FT 14" LINE	20.00 68.48 6.59 60.00 27.55	1164.83

*ELEVATIONS ABOVE LOX SUPPLY BARGE DECK

TABLE A-III NODAL INPUT DATA FOR NSTL MAIN LOX LINE/GSE VENT SYSTEM (Cont'd)

NODE NO.	DESCRIPTION	LENGTH (FT)	INTERNAL DIAMETER (EQUIV~FT)	NODE EXIT ELEVATION* (FT)	INCLUDED COMPONENTS	EQUIVALENT (L/D)	DUCT WALL MASS (LB_M)
60	Parallel Flow Branch (2 Legs)	44.0**	1.125	8.38	(1) 14X14X14" "T" (BR) (1) 14X8" REDUCER (2) 8" 90° EL (1) MV-444 VALVE (1) 8X14" INCREASER 4 FT 14" LINE	60.00 140.58 28.00 263.39 194.25 12.44	1653.31
					(1) 14X14X14" "T" (BR) (1) 14X6" REDUCER (2) 6" 90° EL (1) PCV-469 (1) 6X14" INCREASER 4FT 14" LINE	60.00 527.10 28.00 300.41 ← OPEN 923.63 12.44	
					EQUIV. SINGLE LINE	268.11	
70	Verticle Rise to 14X10" Reducer	72.71	1.125	81.08	(1) 14X14X14" "T"((BR) 72.71 FT 14" LINE	60.00 64.76	2732.09
80	Horizontal at 81.18 Ft. Elevation	43.0	0.874	81.18	(1) 14X10" REDUCER (2) 10" 90° EL 43 FT 10" LINE	8.82 28.00 49.20	669.33
90	81.18 Ft. Elevation to 96.80 Ft. Elevation	15.0	0.874	96.80	(1) 10" 90° BEND 15 FT 10" LINE	14.00 17.16	233.49
100	Horizontal at 96.97 Ft. Elevation	95.0	0.874	96.97	(3) 10" 90° BEND (1) FE-115 FLOW METER 95 FT 10" LINE	42.00 665.55 108.69	1478.75

*ELEVATIONS ABOVE LOX SUPPLY BARGE DECK

TABLE A-III NODAL INPUT DATA FOR NSTL MAIN LOX LINE/GSE VENT SYSTEM (Cont'd)

NODE NO.	DESCRIPTION	LENGTH (FT)	INTERNAL DIAMETER (EQUIV~FT)	NODE EXIT ELEVATION* (FT)	INCLUDED COMPONENTS	EQUIVALENT (L/D)	DUCT WALL MASS (LB_M)
110	96.97 Ft. Elevation to Main Line/GSE Vent "T"	32.0	0.874	100.78	(2) 10" 90° BEND (1) MV-108 VALVE 36 FT 10" LINE	28.00 200.00 36.61	498.11
120	Vent "T" to 90° EL Down	28.0	0.874	100.78	(1) 10X10" "T" (BR) (1) 10" 90° BEND (1) MV-110 VALVE (2) "T" (RUN) 28 FT 10" LINE	60.00 14.00 200.00 40.00 32.04	435.84
130	100.78 Ft. Elevation to S&P Orifice (R.0.8)	183.45	0.874	93.03	(9) 10" 90° BEND (2) 10" 45° BEND (2) 10" Ex. Joint 183.45 FT 10" LINE	126.00 14.00 13.46 209.90	2855.55
140	S&P Orifice to 18" O.V.	9.25	0.874	93.03	(1) R.0.8 ORIFICE (1) 10" 90° BEND 9.25 FT 10" LINE (1) 10" Ex. Joint	355.67 14.00 10.58 6.73	143.98
150	18" O.V. Entrance to Ground Level	90.0	1.4583	3.03	(1) 10X18" "T" (BR) (1) 10X18" ABRUPT ENLARGEMENT 90FT 18" LINE	60.00 216.56 61.72	4365.46
160	Horizontal to Vent Exit	400.0	1.4583	3.03	400 FT 10" LINE MISCELLANEOUS	274.29 50.00	19402.03

*ELEVATIONS ABOVE LOX SUPPLY BARGE DECK

TABLE A-IV STEADY STATE HEAT TRANSFER RATES FOR NSTL MAIN LOX LINE/GSE VENT SYSTEM

NODE NO.	DESCRIPTION	HEAT TRANSFER RATE - BTU/HR
10	MAIN LOX PUMP A TO BARGE INTERFACE NO. 3	40,240
20	BARGE NO. 3 INTERFACE TO DOCK "T"	23,038
30	BARGE POSITION NO. 3 "T" TO POSITION NO. 2 "T"	160,429
40	BARGE POSITION NO. 2 "T" TO POSITION NO. 1 "T"	89,452
50	BARGE POSITION NO. 1 "T" TO BRANCH "T"	50,881
60	PARALLEL FLOW BRANCH (2 LEGS)	72,218
70	VERTICLE RISE TO 14 X 10" REDUCER	119,341
80	HORIZONTAL AT 81.18 FT. ELEVATION	4,110
90	81.18 FT. ELEVATION TO 96.80 FT. ELEVATION	1,434
100	HORIZONTAL AT 96.97 FT. ELEVATION	9,081
110	96.97 FT. ELEVATION TO MAIN LINE/GSE VENT "T"	3,059
120	VENT "T" TO 90° EL DOWN	35,704
130	100.78 FT. ELEVATION TO S&P ORIFICE (R.0.8)	233,922
140	S&P ORIFICE TO 18" O.V.	11,795
150	18" O.V. ENTRANCE TO GROUND LEVEL	191,483
160	HORIZONTAL TO VENT EXIT	851,038
TOTAL		1,897,225

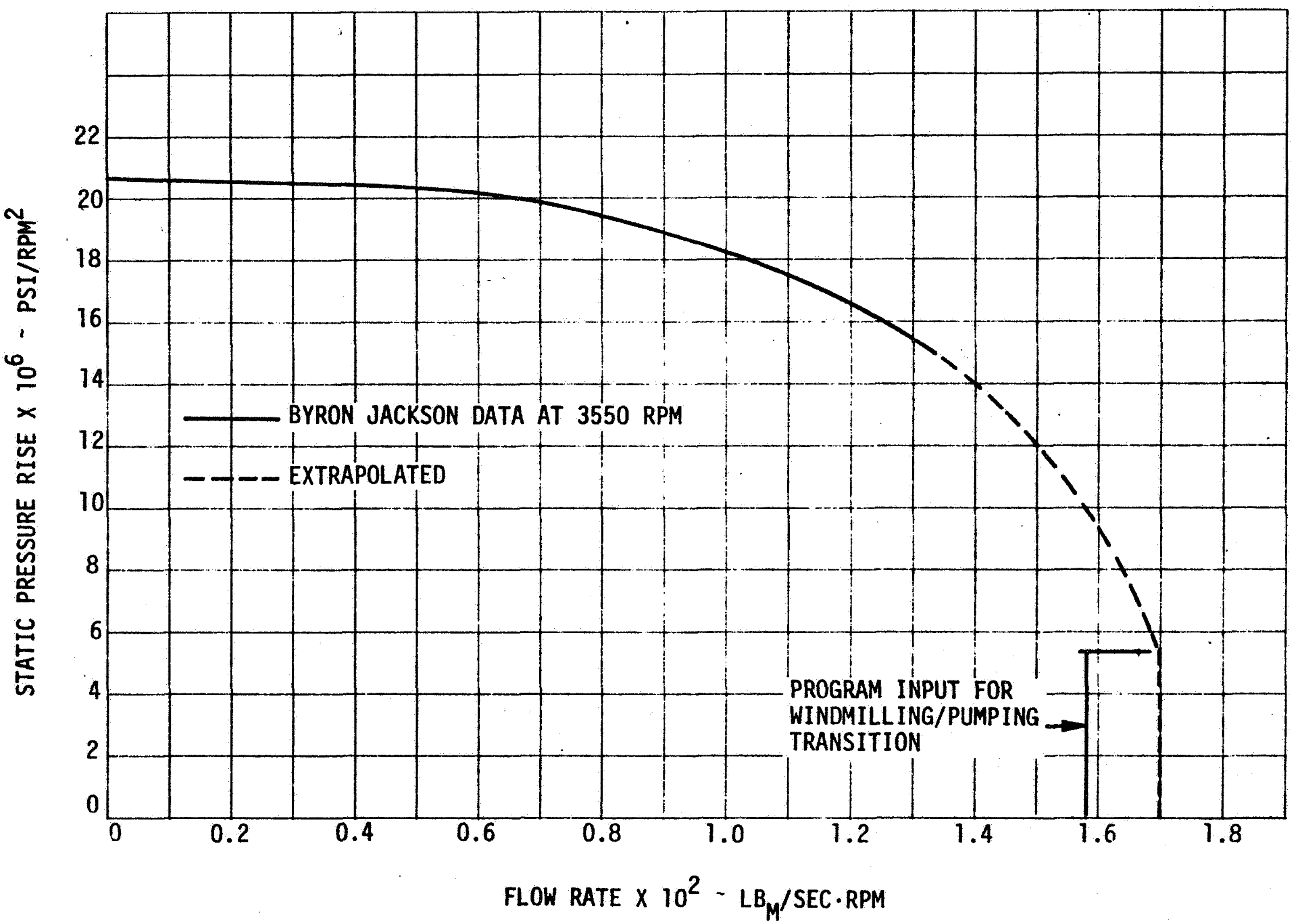


FIGURE A-1 NORMALIZED NSTL REPLENISH PUMP PERFORMANCE

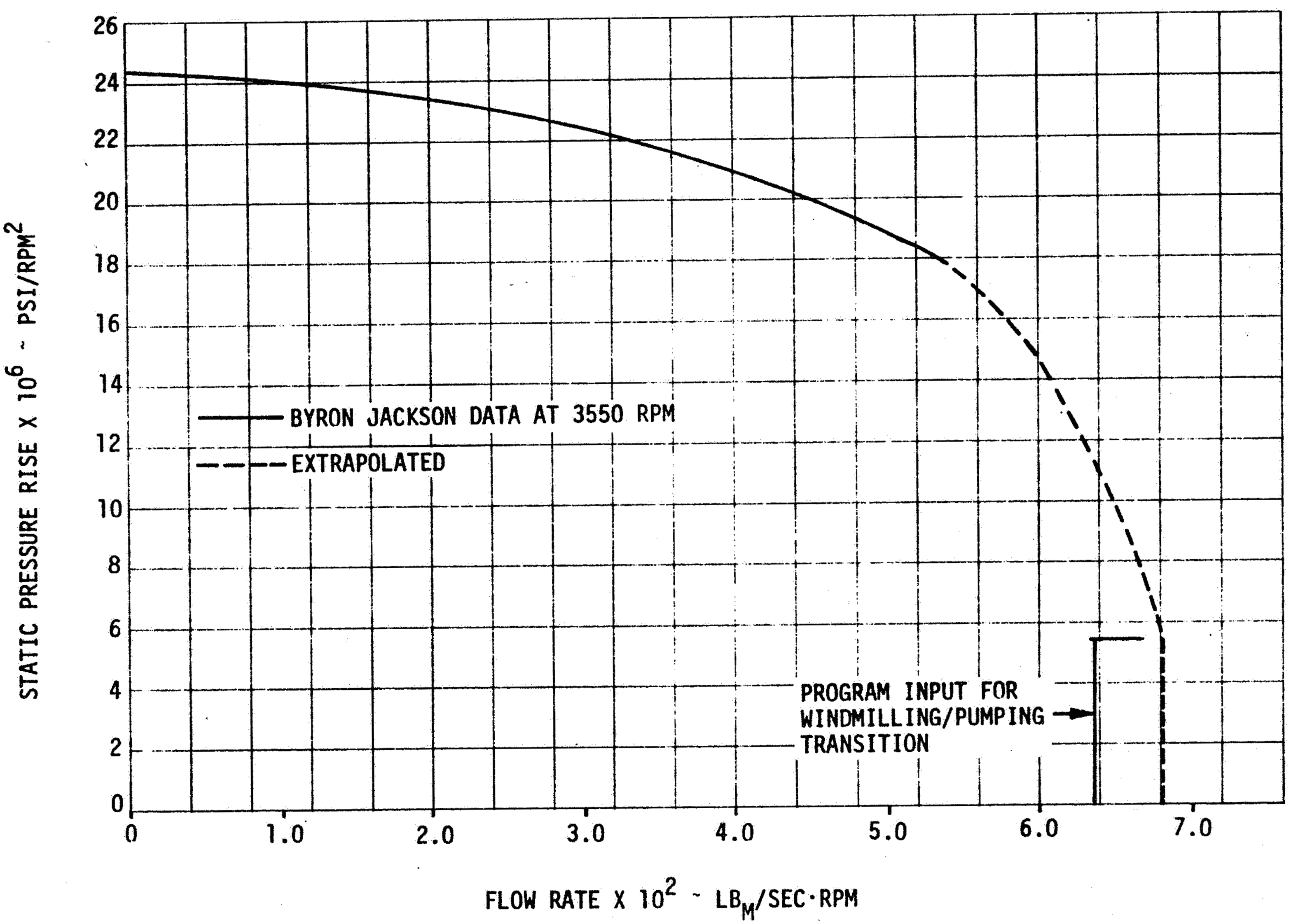


FIGURE A-2 NORMALIZED NSTL MAIN LOX PUMP PERFORMANCE