NUMERICAL MODELING OF HELIUM PRESSURIZATION SYSTEM OF PROPULSION TEST ARTICLE (PTA)

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ABSTRACT

A transient model of the Propulsion Test Article (PTA) Helium Pressurization System was developed using the Generalized Fluid System Simulation Program (GFSSP). The model included feed lines from the facility interface to the engine purge interface and Liquid Oxygen (LOX) and Rocket Propellant 1 (RP-1) tanks, the propellant tanks themselves including ullage space and propellant feed lines to their respective pump interfaces. GFSSP's capability was extended to model a control valve to maintain ullage pressure within a specified limit and pressurization processes such as heat transfer between ullage gas, propellant and the tank wall. The purpose of the model is to predict the flow system characteristics in the entire pressurization system during 80 seconds of lower feed system priming, 420 seconds of fuel and LOX pump priming and 150 seconds of engine firing. Subsequent to the work presented here, the PTA model has been updated to include the LOX and RP-1 pumps, while the pressurization option itself has been modified to include the effects of mass transfer. This updated model will be compared with PTA test data as it becomes available.

INTRODUCTION

The Propulsion Test Article (PTA) provides a test bed environment to evaluate low cost solutions to booster technology. PTA consists of Liquid Oxygen (LOX) and Rocket Propellant 1 (RP-1) tanks with a total useable propellant load of 44000 lbs. The pressurization system is one of the major PTA subsystems. This system provides helium to the propellant tanks for pressurization, to valves for actuation, and to the engine for purges. A model was built to verify by analysis that the Main Propulsion System (MPS)/engine helium system requirements are met.

The pressurization system of PTA consists of a LOX tank and an RP-1 tank that are both pressurized by helium. A mathematical model was required to predict the ullage and propellant conditions for PTA during pressurization for lower feed system priming, pump priming, and engine firing. The model prediction will ensure that the helium system can provide adequate helium flow to both propellant tanks and the engine, the temperature levels inside the tanks remain within acceptable limits, and the propellant interface pressure satisfies the Net Positive Suction Pressure (NPSP) requirements of its respective pump. The pressurization of a propellant tank is a complex thermodynamic process with heat and mass transfer in a stratified environment. Ring[1] described the physical processes and heat transfer correlation in his monograph. Epstein and Anderson[2] developed an equation for the prediction of cryogenic pressurant requirements for axisymmetric propellant tanks. Recently, Van Dresar[3] improved the accuracy of Epstein and Anderson's correlation for liquid hydrogen tanks. A computer program[4] was also developed for Marshall Space Flight Center to simulate pressurization sequencing for the LOX and hydrogen tanks in the Technology Test Bed. This program employs a single node thermodynamic ullage model to calculate the ullage pressure based on ideal gas law, heat transfer and mixing. McRight[5] estimated the helium requirement and sized the flow control orifices based on choked flow assumptions for the PTA Helium Pressurization System.

The objective of the present work is to develop an integrated mathematical model from the facility helium supply interface to the PTA/engine interfaces to model pressurization prior to and during engine operation. The model has four primary functions. They are:

a. To verify by analysis that the MPS/engine requirements are met.
b. To predict the flow rate and pressure distribution of the helium supply line feeding both the LOX and RP-1 tanks,
c. To predict the ullage conditions considering heat and mass transfer between the ullage, propellant and the tank wall,
d. To predict the propellant conditions leaving the tank.

The Generalized Fluid System Simulation Program (GFSSP) [6] has been used to develop this model. GFSSP is a general purpose fluid flow simulation program for modeling steady state and transient flow distribution in a fluid network. The transient capability of GFSSP has recently been extended[7] to model the pressurization process in a propellant tank. A simple 5-node model was developed to test the numerical stability and physical sensitivity of the formulation. The predicted pressurant requirement was also verified by comparing with Epstein and Anderson's[2] correlation.

This paper describes an integrated GFSSP model of the Helium Pressurization System of PTA. The model extends from facility interface to engine purge and pump interfaces. It includes all piping, fittings, orifices and valves. Both RP-1 and LOX tanks are included in the model. Each propellant tank has a diffuser and control system. Pressure and temperature are specified at the interfaces. The purpose of the model is to predict the pressure and flow rate distribution in the entire system. GFSSP predictions of helium requirements have also been compared with McRight's[5] analysis.

GFSSP MODEL

An integrated GFSSP model of the Helium Pressurization System of PTA is shown in Figure 1. The model consists of 61 nodes and 60 branches. The model contains six boundary nodes, which are listed along with the interface they represent in Table 1.

Table 1. PTA Boundary Node Locations

Boundary Node	Interface
1	Facility
61	Engine (Purge)
53	Ullage-propellant (LOX Tank)
55	LOX Pump
30	Ullage-propellant (RP-1 Tank)
32	RP-1 Pump

It may be noted that the nodes representing the ullage-propellant interface (Node 53 and 30) are pseudo-boundary nodes. The code uses the calculated ullage pressure at the previous time step instead of pressures provided by the user through history files. Helium enters into the system from the facility interface through 1.5 inch outside diameter (OD) tubing. From this main line, helium is distributed into three parallel branches. The first branching takes place after 128 inches of tubing. This branch supplies helium to the engine for engine purges through 0.75 inch OD tubing. The second branching takes place 305 inches downstream of the first branch. This branch supplies helium to the LOX tank using 1.0-inch OD tubing. The remainder of the helium line is routed to pressurize the RP-1 tank using 0.75-inch OD tubing. All tubing sizes have a wall thickness of 0.109 inches. The lines leading to the LOX and RP-1 tanks each have two parallel legs, one of which remains closed during a given operation. The left leg of the circuit is used to pressurize the tank during lower feed system priming and pump priming operations while the right leg of the circuit is used to pressurize the tank just prior to and during engine firing. In the model discussed in this paper, setting a high resistance in the appropriate branches eliminated the flow to the leg not being used for that particular run.

MODEL RESULTS

The GFSSP model shown in Figure 1 was broken into six separate runs that covered a period of 650 seconds, beginning at -500 seconds before engine start and continuing to +150 seconds after engine start using a time step of 0.1 second. The first three runs represent the lower feed system priming, the next two runs represent the pump priming and the final run represents the engine firing. The model was broken into multiple runs to accurately model the various propellant flow rates required at different stages of operation. These flow rates were achieved by altering the orifice sizes in branches 1054 and 1031 of Figure 1 until GFSSP predicted the calculated flow rate for that particular period of operation.

The first run is a steady state analysis, which is used exclusively to obtain an initial solution for use in the first transient run. Each run thereafter uses the previous run's final time step solution as its initial condition. The second run begins at -500 seconds and runs for one second to -499 seconds. During this time there is no flow leaving either the LOX or RP-1 tank. The ullages of each tank are initially at a pressure of 14.7 psia with their respective ullage pressure control set points set to a nominal pressure of 20 psia with a plus or minus 3 psi control band. The third run lasts for 79 seconds, beginning at -499 seconds and ending at -420 seconds. The ullage pressure control remains at a set point of 20 psia while there is now a 0.12 lbm/s propellant bleed flow from the LOX tank and a 0.1 lbm/s propellant bleed flow from the RP-1 tank. During a test, the RP-1 system is primed before the LOX system, but for simplicity, both propellant systems are primed at the same time during the analysis.

The fourth run covers a 60 second duration from -420 seconds to -360 seconds. At the beginning of this run the ullage pressure control set points increase to 67 psia for the LOX tank and 50 psia for the RP-1 tank with a plus or minus 3 psi control band. The propellant bleed flow rates see an increase to 1 lbm/s for the LOX tank and 0.25 lbm/s for the RP-1 tank. At the end of this run the RP-1 bleed is closed and the system is considered primed. The fifth run encompasses the remaining 360 seconds before engine start from -360 seconds to 0 seconds. The ullage pressure control set points remain the same for the first 240 seconds of this run. At -120 seconds prepress occurs and the set points for each tank rise by 5 psi, resulting in nominal set points of 72 psia for the LOX tank and 55 psia for the RP-1 tank with a plus or minus 3 psi control band. The propellant bleed flow rate for LOX remains at 1 lbm/s and there is no RP-1 propellant bleed flow during this time.

The sixth and final run covers the 150 second engine firing period from 0 seconds to +150 seconds. Initially, the ullage pressure control set points remain at their prepress values, but after 3 seconds they drop 5 psi to the run pressure of 67 psia for the LOX tank and 50 psia for the RP-1 tank with a plus or minus 3 psi control band. Propellant flow to the engine is 139 lbm/s for LOX and 64 lbm/s for RP-1.

PRESSURE

Figure 2 shows the predicted pressure history of the RP-1 ullage, RP-1 tank bottom, LOX ullage and LOX tank bottom pressures. The difference in pressure between the tank bottom and ullage is the gravitational head, which slowly reduces as propellant is drained from the tank. The saw tooth nature of the pressure profiles is due to the control valves that are set to close or open as the ullage pressures rise above or fall below the prescribed control band. This is especially evident in the LOX pressure predictions, where the propellant bleed flow and the ullage thermal characteristics cause enough pressure drop in the tank to cycle the control valve repeatedly. On the other hand the RP-1 propellant bleed flow is low enough that once the control valve closes there is not enough subsequent pressure drop in the tank to open the valve again until the next change in the ullage pressure control set point. Thus, the RP-1 pressure predictions appear as a series of straight lines prior to engine start.

Valve cycling is quite pronounced in both the LOX and RP-1 tank pressure predictions once the engine starts. The pressure predictions show that during engine firing the maximum tank bottom pressure in the RP-1 tank is 61.5 psia while the LOX tank bottom pressure achieves a maximum value of 83.5 psia. These maximum values are seen during the first three seconds of engine firing when the ullage pressure control set points are still at their prepress levels. It is also observed that the frequency of pressure oscillation is larger in the LOX tank than the RP-1 tank. This observation is attributable to the higher volumetric flow rates and the ullage thermal collapse associated with the LOX tank as compared to those required for the RP-1 tank.

TEMPERATURE

Figure 3 shows the predicted ullage temperature history in the RP-1 tank. Initially wall and propellant temperatures were assumed equal at 70 °F. Heat transfer between the ullage gas and wall is not very significant in the RP-1 tank and as a result the tank wall temperature remains approximately constant over the 500 seconds before engine start and rises only two degrees during the 150 second engine firing. Ullage temperature, on the other hand, experiences two significant temperature spikes in the 500 seconds before engine start. These spikes are associated with increases in the ullage pressure set points (-493 sec, -416 sec) and the assumption that the helium enters at 120 °F. The second, and largest, spike peaks at 96 °F but ullage temperature drops down to 71 °F before engine start. During engine firing, ullage temperature increases by about 28 °F due to mixing and pressurization. Ullage temperature diminishes slightly during the period of valve closure. This is due to heat transfer from the ullage gas to the wall.

The predicted ullage temperature history in the LOX tank is shown in Figure 4. The LOX ullage temperature is assumed to be initially at -260 °F while the tank wall temperature is assumed to be initially at -300 °F. The tank wall temperature rise is more pronounced in the LOX tank than the RP-1 tank, rising 43 °F over the course of the 650-second run. Unlike RP-1, LOX ullage temperature fluctuates throughout the 500 seconds before engine start due to valve cycling. During this time, temperature spikes similar to those discussed with RP-1, which are associated with increase in the ullage pressure set points (-494 sec, -417 sec), are evident. The largest LOX ullage temperature spike peaks at a value of -88 °F but drops back to -255 °F at engine start. During engine firing, the temperature rise is 173 °F. The higher temperature rise in the LOX tank is primarily due to the fact that the LOX ullage is initially assumed to be at -260 °F and mixes with helium at 120 °F. On the other hand, the initial temperature difference between the RP-1 ullage and the helium pressurant is much smaller. The other contributing factor is the higher helium flow rate into the LOX tank.

MASS FLOW RATE

Figure 5 shows the helium flow rates. Helium flow rate varies over time due to the opening and closing of the control valves. The flow from the facility interface is distributed to three branches. A nearly constant flow rate (about 0.4 lbm/sec) is predicted to the engine purge interface for engine purges. The maximum flow rates to the LOX and RP-1 tanks are about 0.34 lbm/sec and 0.085 lbm/sec, respectively. Table 2 shows a comparison of GFSSP helium flow predictions with McRight's[3] pressurization analysis model.

Table 2. Comparison between GFSSP and McRight's[3] Helium Flow Rates

GFSSP (lbm/sec)				**McRight (lbm/sec)**			
Facility	**LOX**	**RP-1**	**Purge**	**Facility**	**LOX**	**RP-1**	**Purge**
0.825	**0.34**	**0.085**	**0.4**	**1.00**	**0.35**	**0.1**	**0.55**

The comparison shown in Table 2 appears reasonable considering that McRight's analysis did not consider pressure loss in lines and fittings and choked flow rate through the orifice was calculated based on a facility pressure of 765 psia. GFSSP calculates pressure drop through the line, therefore the choked flow rate at lower pressure is evidently less than McRight's prediction.

The propellant flow rates from RP-1 and LOX tanks are shown in Figure 6. Figure 7 shows the RP-1 and LOX propellant flow rates in the period prior to engine start. All flow rates were achieved by altering the restrictions downstream of the LOX and RP-1 tanks to match the flow rates required at that point in time. This was done because of a lack of proper flow geometry information downstream of the propellant tanks. The observed oscillation in flow rate is due to the ullage pressure control band. It should be noted that this model is based on prescribed pressures at inlet and outlet boundary. This oscillating flow prediction can be eliminated by extending the model further downstream to include the pumps and appropriate resistances the pumps must overcome in the system.

SUMMARY OF RESULTS

The GFSSP model of the PTA pressurization system predicts the following flow system characteristics during the 150-second engine operation period of the run except where noted.

Average LOX ullage pressure = 67.2 psia
Average LOX tank bottom pressure = 73.0 psia
LOX temperature = 160 R
Average LOX flow rate to the engine = 139.0 lbm/sec
Total LOX supply in the complete 650 second run = 324 ft^3
LOX ullage temperature rise in the complete 650 second run =173 R

Average RP-1 ullage pressure = 50.1 psia
Average RP-1 tank bottom pressure = 52.6 psia
RP-1 temperature = 530 R
Average RP-1 flow rate to the engine = 62.4 lbm/sec
Total RP-1 supply in the complete 650 second run = 198 ft^3
RP-1 ullage temperature rise in the complete 650 second run = 29 R

Maximum Helium flow rate to LOX tank = 0.34 lbm/sec
Maximum Helium flow rate to RP-1 tank = 0.085 lbm/sec
Average Helium flow rate to Engine Interface = 0.4 lbm/sec
Maximum Helium flow rate from Facility Interface = 0.825 lbm/sec

CONCLUSIONS

A detailed numerical model of a pressurization system consisting of LOX and RP-1 tanks was developed using the Generalized Fluid System Simulation Program. GFSSP's pressurization capability was further extended by developing a numerical model for simulating a control system for maintaining ullage pressure within a specified limit. GFSSP's predicted pressure history shows the evidence of opening and closing of valves during the draining of propellant from the tank. The model also predicts the variation of valve cycling frequency due to changes in the flow rate, ullage volume and heat transfer. Future work will include adding the LOX and RP-1 pumps to the model for a more realistic prediction of system characteristics as well as modifying the pressurization option to account for the effects of mass transfer from propellant to the ullage. Model predictions will be compared with measured data from PTA tests.

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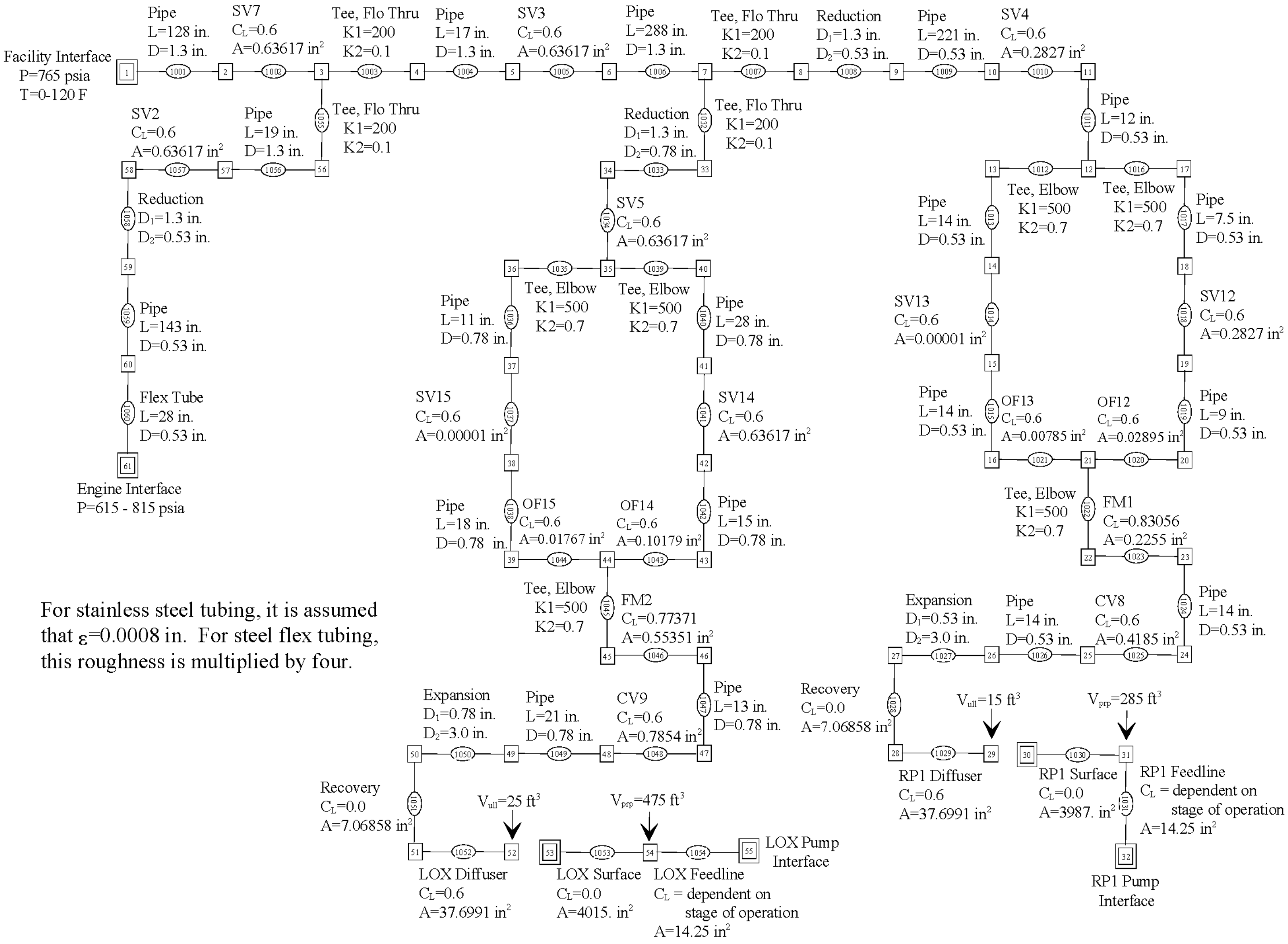

For stainless steel tubing, it is assumed that ε=0.0008 in. For steel flex tubing, this roughness is multiplied by four.

Figure 1. GFSSP Model of the PTA Pressurization System

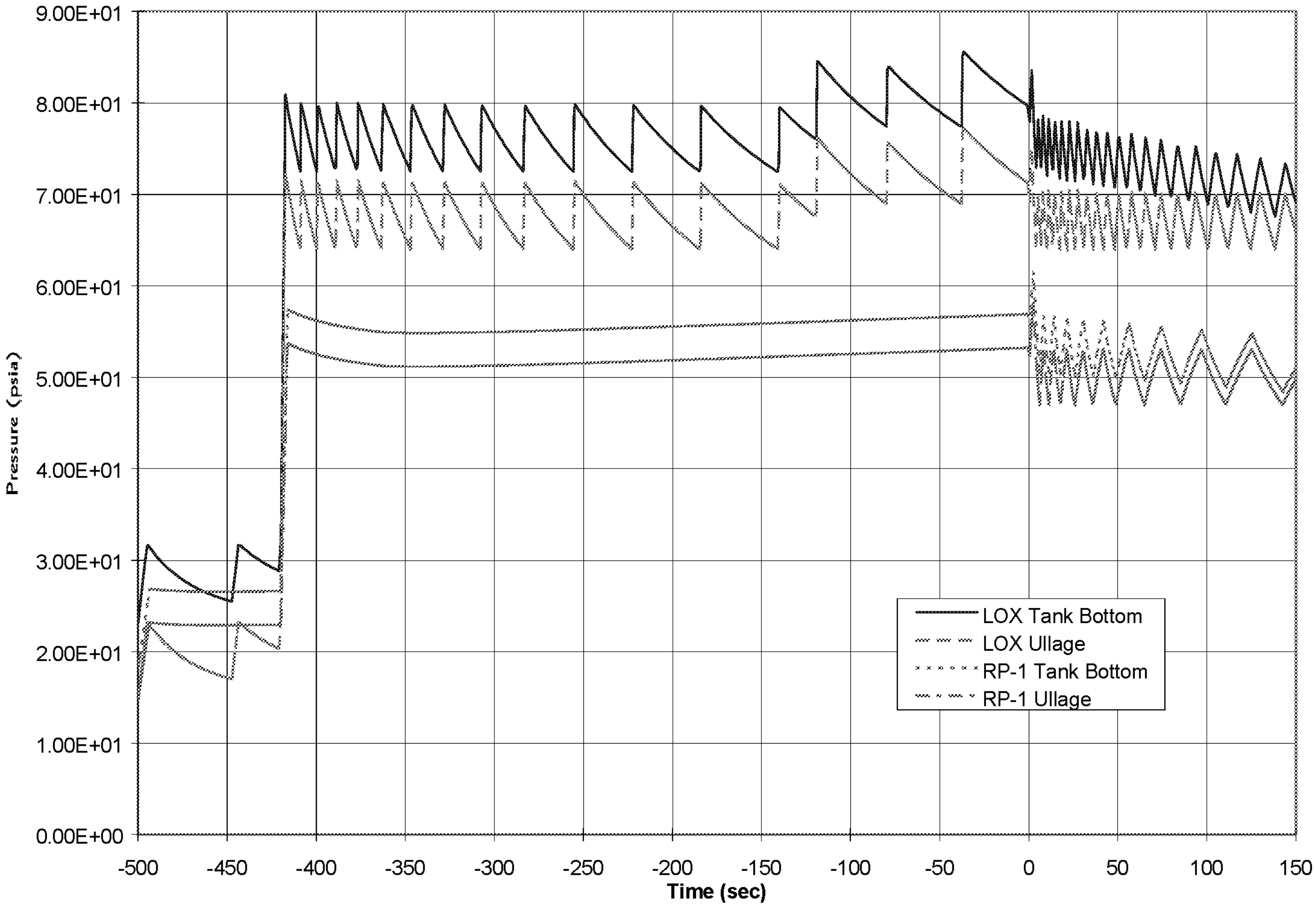

Figure 2. Propellant Tank Pressure History

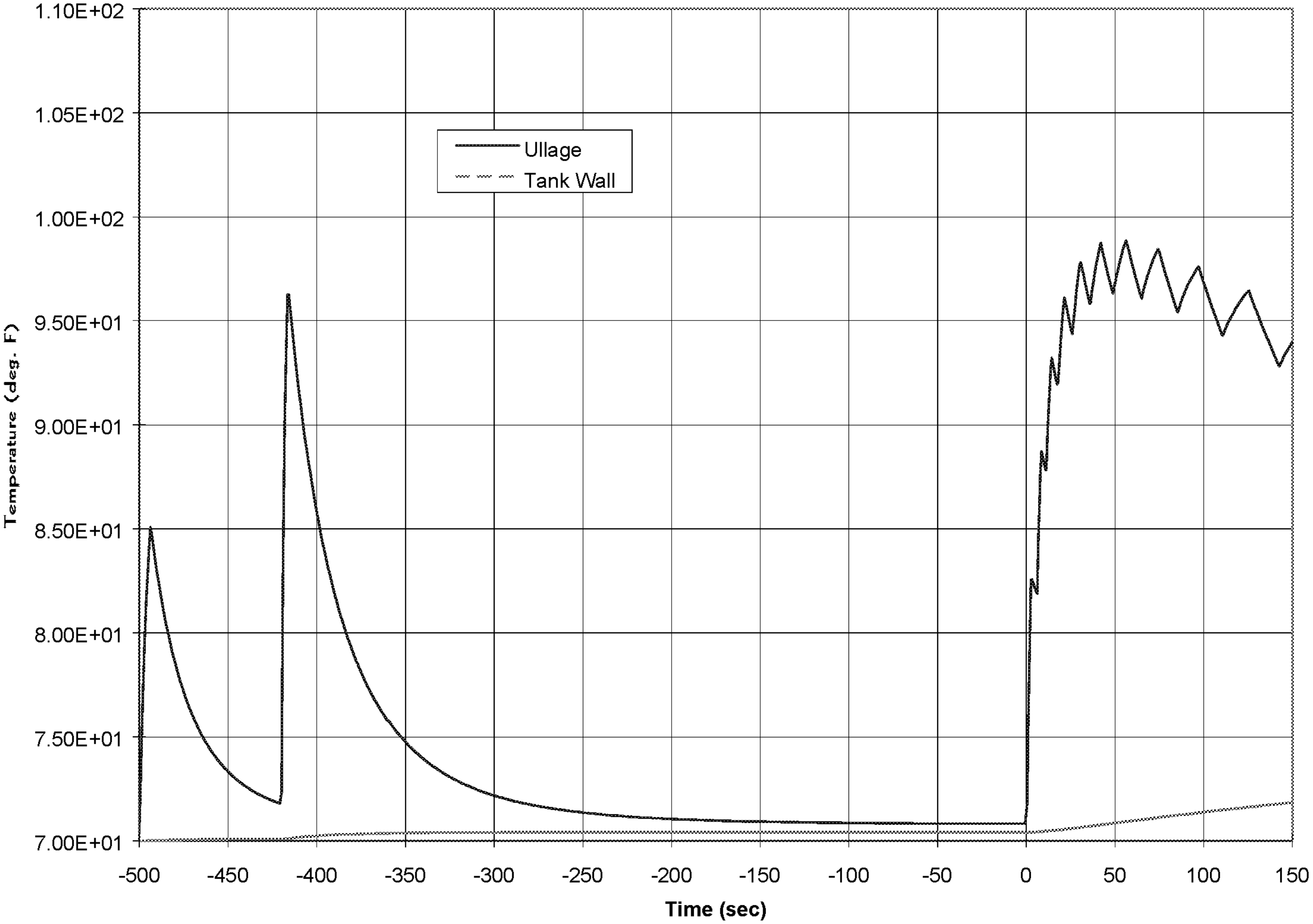

Figure 3. RP-1 Temperature History

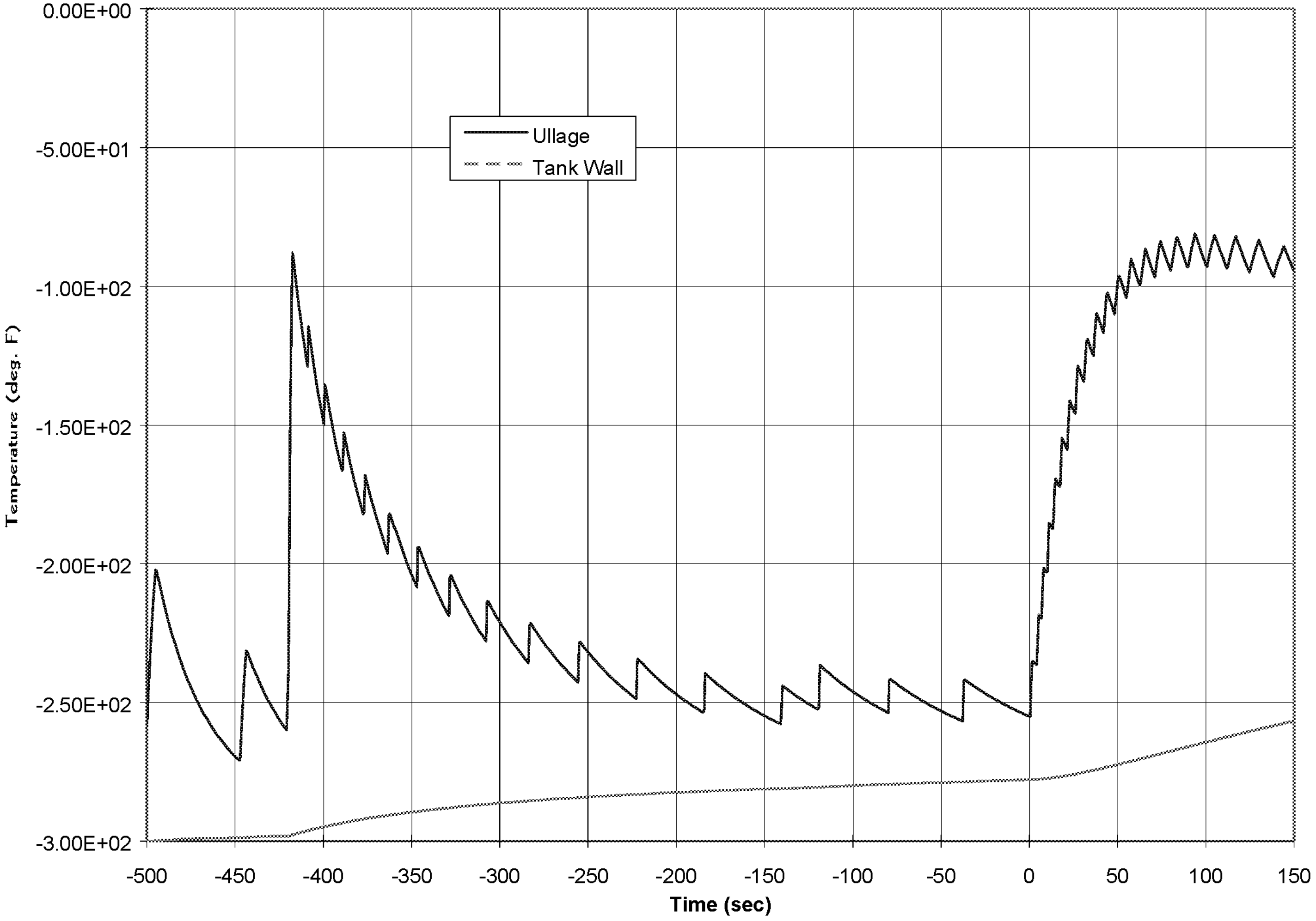

Figure 4. LOX Temperature History

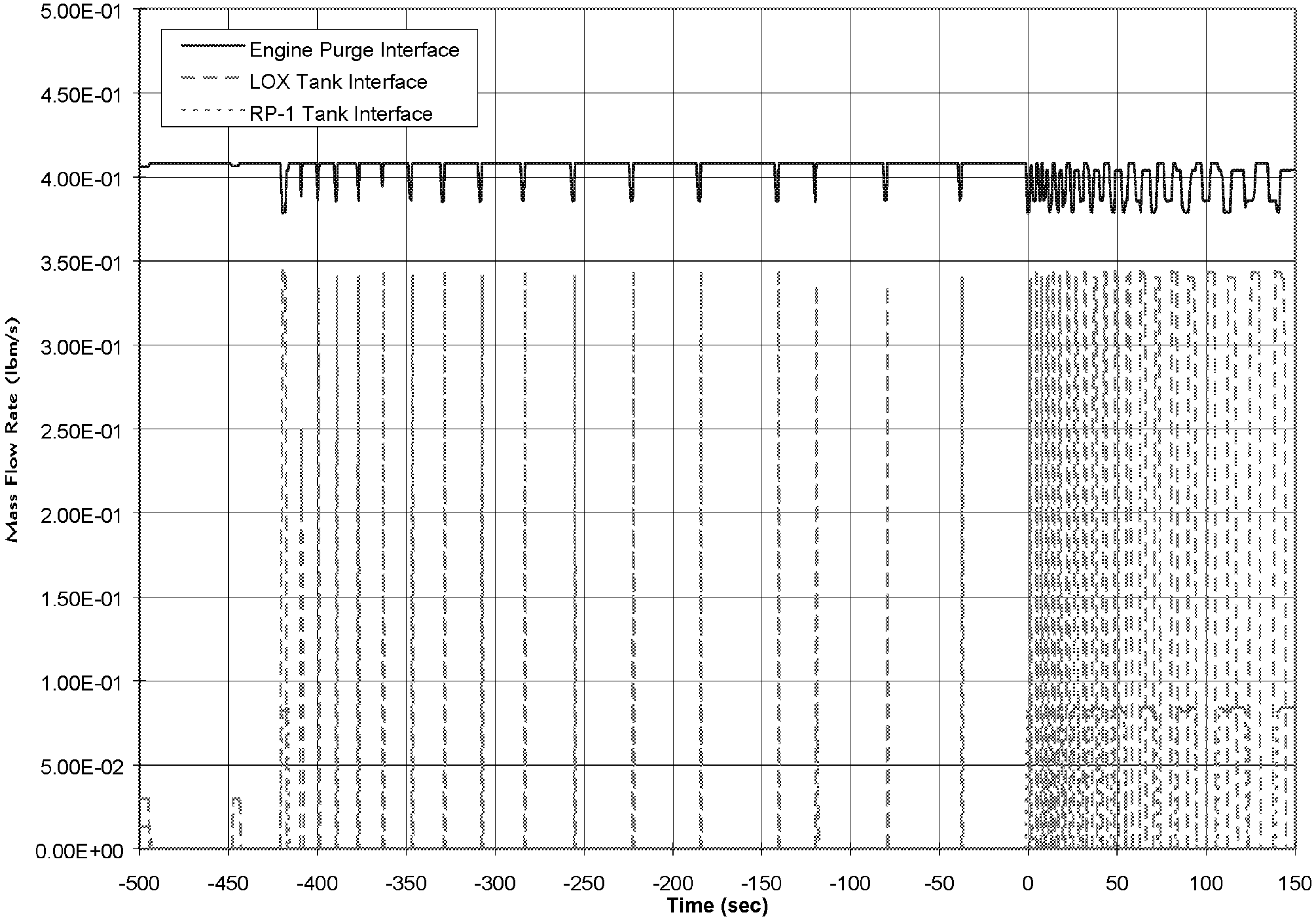

Figure 5. Helium Flow Rate History

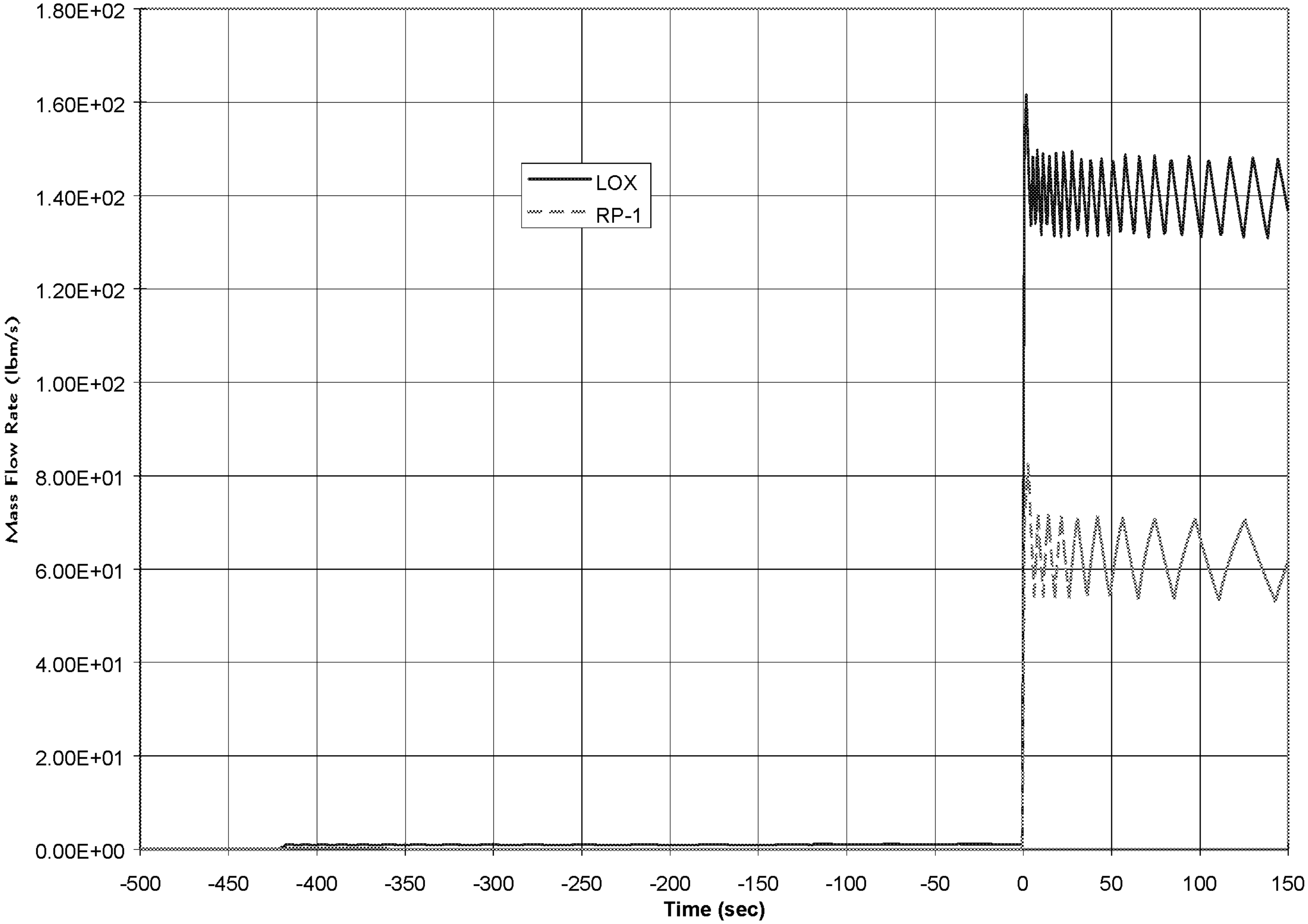

Figure 6. Propellant Flow Rate History

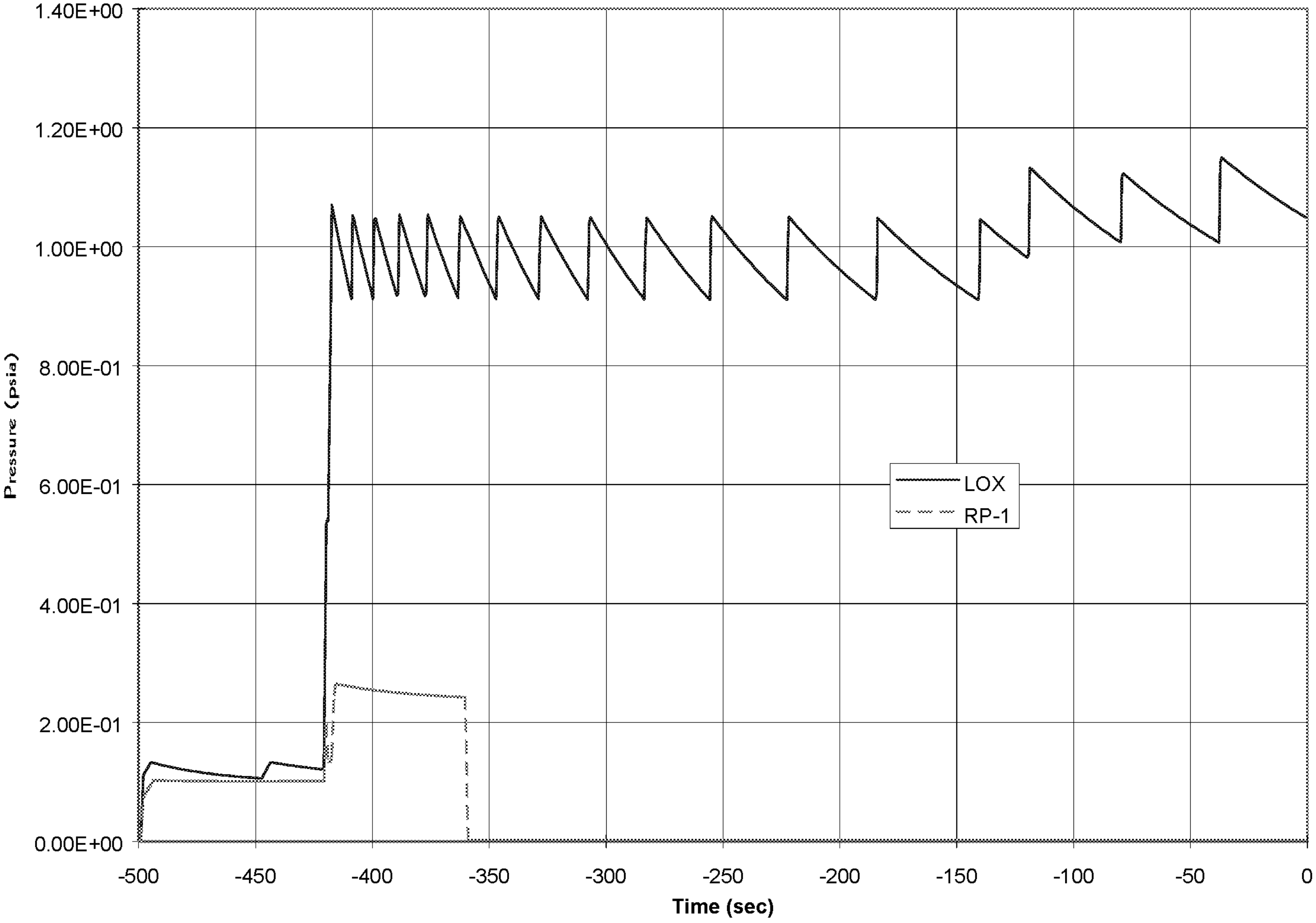

Figure 7. Propellant Bleed Flow Rate History Detail