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PRESSURIZATION, PNEUMATIC, AND VENT SUBSYSTEMS OF THE X-34 MAIN PROPULSION SYSTEM

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ABSTRACT

In pressurization systems, regulators and orifices are use to control the flow of the pressurant. For the X-34 Main Propulsion System, three pressurization subsystem design configuration options were considered. In the first option, regulators were used while in the other options, orifices were considered. In each design option, the vent/relief system must be capable of relieving the pressurant flow without allowing the tank pressure to rise above proof, therefore, impacts on the propellant tank vent system were investigated and a trade study of the pressurization system was conducted. The analysis indicated that design option using regulators poses least risk. Then, a detailed transient thermal/fluid analysis of the recommended pressurization system was performed. Helium usage, thermodynamic conditions, and overpressurization of each propellant tank were evaluated. The pneumatic and purge subsystem is used for pneumatic valve actuation, Inter-Propellant Seal purges, Engine Spin Start, and engine purges at the required interface pressures. A transient analysis of the pneumatic and purge subsystem provided helium usage and flow rates to Inter-Propellant Seal and engine interfaces. Fill analysis of the helium bottles of pressurization and pneumatic subsystems during ground operation was performed. The required fill time and the stored helium mass for each subsystem were computed.

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INTRODUCTION

The X-34 technology development program is a joint industry/government project to develop, test, and operate a small, fully-reusable hypersonic flight vehicle demonstrating technologies and operating concepts applicable to future Reusable Launch Vehicle (RLV) systems. The X-34 Main Propulsion System (MPS) stores and delivers Rocket Propellant 1 (RP-1) fuel and Liquid Oxygen (LOX) oxidizer as required by NASA-MSFC Fastrac engine. The MPS consists of the Tank Pressurization Subsystem, Pneumatic and Purge Subsystem, Propellant Feedline Subsystems, and Fill/Drain/Dump Subsystems. An overview description of the X-34 MPS is given by Sgarlata and Winters[1]. The detailed descriptions of feed subsystem and propellant management are provided by McDonald et. al[2] and Brown et. at[3], respectively.

Stored-gas pressurization systems are used to transfer propellants from the tanks to the turbopump at the needed flow rates and pressures. The gas is stored in bottles at an initial pressure then it is supplied to the propellant tanks at limited flowrates using valves regulators or orifices. In addition, solenoid valves control the pressurization of the LOX and RP-1 tanks within the allowable pressure range.

The helium pressurant is stored initially at 5000 psia and 530 °R. The allowable pressure range for the LOX and RP-1 tanks are 55-61 psia and 47-53 psia, respectively. A closed loop control circuit uses tank pressure sensor output to control opening/closing of the flow control solenoid valves, thus monitoring tank pressure within the above control band as propellant is expelled from the tanks.

A pressurization system failure can result in propellant tank overpressurization and possibly structural failure of the tanks. To prevent the overpressurization, the vent/relief system must be capable of relieving the pressurant flow without allowing the tank pressure to rise above proof. For the proper operation of the pressurization system and to avoid propellant tanks overpressurization, the tank pressure rise rates and the vent/relief valve response time requirements for each design option should be determined. A transient analysis of the pressurization process for the most suited design candidate provides the helium usage and its thermodynamic conditions within the allowable operational range.

The Pneumatic and Purge (P&P) subsystem is used for valve actuation, Inter-Propellant Seal (IPS) purges, engine Spin Start and engine purges. The P&P System helium bottles are stored initially at 5000 psia and 530°R. The helium pressure is regulated to turbopump Spin Start and IPS and shutdown purges prior to its use as a working fluid. A transient analysis predicts helium expenditure and required flow rates at the IPS and Spin Start interfaces.

The pressurization and pneumatic bottles are filled during ground operations. In the process of filling, the temperature of the stored helium increases. Due to the free convection between the stored helium and the bottles, the bottle wall temperature also increases. There are limitations on the parameters such as the bottles wall temperature and stored helium pressure, so as these parameters reach their maximum allowable values, helium flow is stopped and bottles are allowed to cool down. Therefore, the fill procedure occurs as a step-wise process. The fill analysis provides the fill time, stored helium mass, and thermodynamic conditions of stored helium and the bottles.

PRESSURIZATION SUBSYSTEMS

Trade Study of Three Design Options

Solenoid valve operation provides the required helium to each propellant tank within the specified pressure range. Vent/relief systems prevent tank overpressurization which may lead to structural damage and a catastrophic event. The original pressurization concept utilized regulators to control the system operating pressure. However, due to operational and reliability concerns, two additional pressurization system concepts utilizing orifices to control flow rates were proposed. Three design options were as follows: 1) Pressurization system using regulators, 2) Pressurization system using a single orifice for each propellant tank, and 3) Pressurization system using multiple orifices for the LOX and single orifice for RP-1 tank. Schematics of the described design options are depicted in Figures 1-3.

In option 1, helium is supplied to the propellant tanks through two regulators. During the pressurization process, the second regulator is considered to be completely open while the passage of the first regulator is adjusted such that the pressure at the exit is maintained at 350 psia. The Generalized Fluid System Simulation Program (GFSSP)[3] was utilized to develop three different models of the described configurations. The GFSSP is a general purpose fluid network analysis code developed by Sverdrup Technology//MSFC Group. GFSSP assumes a Newtonian, non-reacting and one dimensional flow in the fluid circuit. The flow could be either laminar or turbulent, incompressible or compressible, with or without heat transfer, change phase/or mixing. The following assumptions were made in the analysis:

1. Helium initial temperature and pressure are 70 °F and 5000 psia.
2. LOX tank temperature and pressure are -297 °F and 58 psia with a ± 3 psia control range.
3. RP-1 tank temperature and pressure are 70 °F and 50 psia with a ±3 psi control range.
4. Densities of LOX and RP-1 at described conditions are 71.5 lbm/ft^3 and 50.5 lbm/ft^3, respectively.
5. Volume of LOX and RP-1 tanks are 300.6 ft^3 and 188.5 ft^3, respectively.
6. Engine flow rates of LOX and RP-1 requirements are 144 lbm/s and 66 lbm/s, respectively.
7. Total volume of the helium bottles is 25.2 ft^3.
8. In option 2 design, orifice diameters of LOX and RP-1 supply lines are 0.26 in and 0.13 in, respectively.
9. In option 3 design, orifice diameters of LOX and RP-1 supply lines are 0.18 in and 0.14 in, respectively.

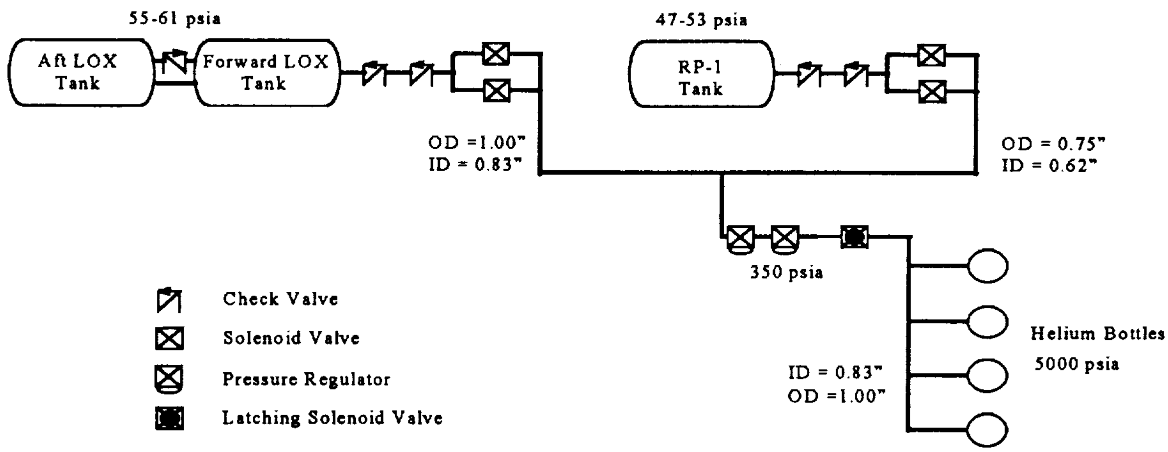

Figure 1. Schematic for Option 1 (Using Regulators).

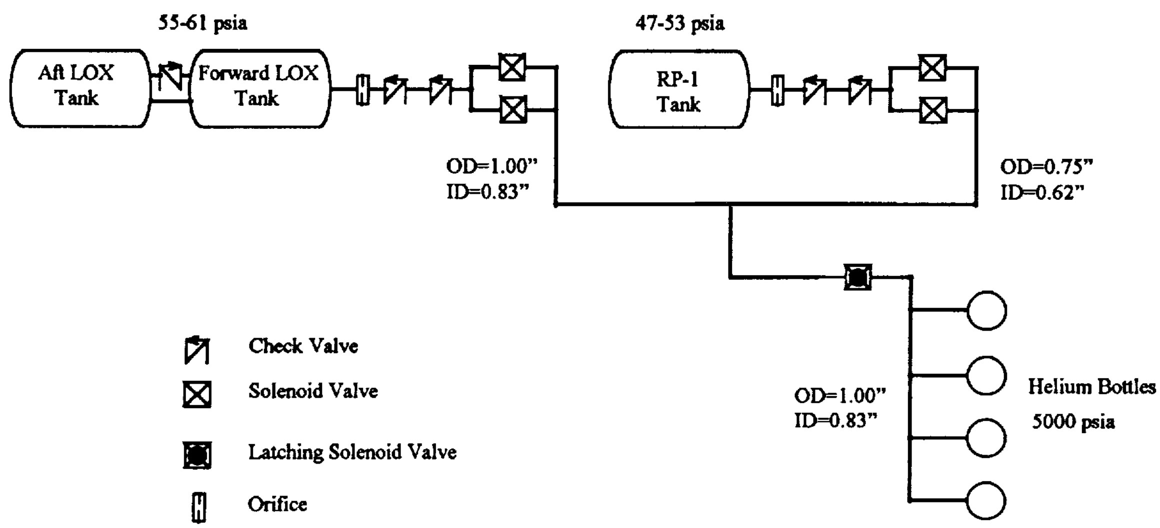

Figure 2. Schematic for Option 2 (Using Single Orifice).

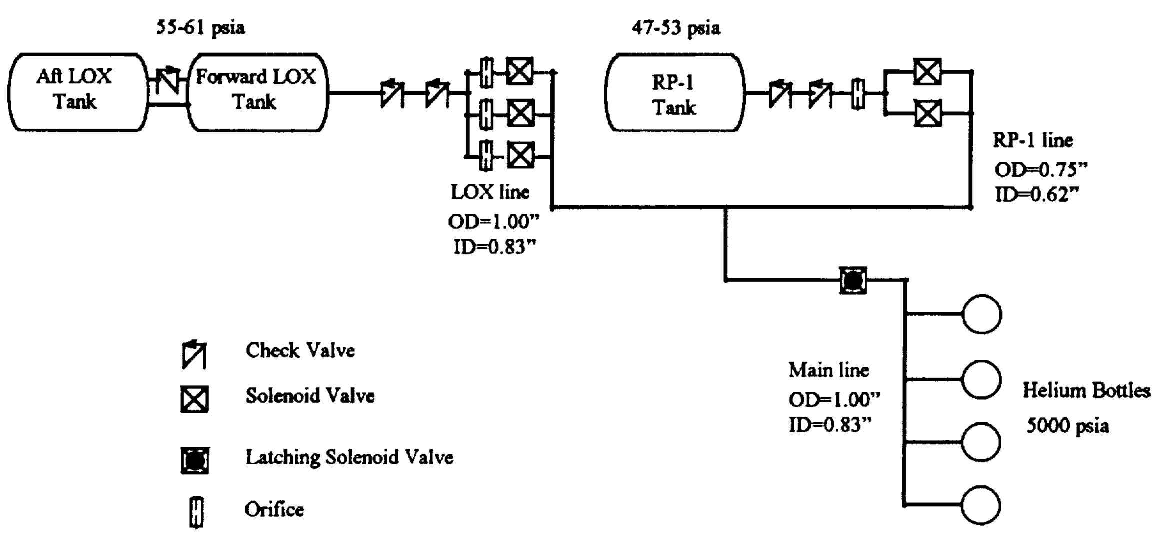

Figure 3. Schematic for Option 3 (Using Multiple Orifices).

The vent lines must be capable of relieving the entire steady state pressurant flow while the tank pressure is below proof. In addition, the vent/relief valves must be capable of opening fast enough to establish the steady relief flow prior to the tank pressure reaching proof. Vent/relief system performance was simulated by the GFSSP. The LOX vent/relief design was made up of 2.25" ID tubing and a 2.5" vent/relief valve. An orifice was included at the vent exit to restrict the flow at altitude and limit the GOX flow velocities within the lines and valve. No orifice was required for the RP-1 vent/relief system because high flow velocities within this system were not a safety concern.

Analysis indicated that a regulators based pressurization system failure would introduce worst case flow rates of 0.35 lbm/s @ -74 °F and 0.10 lbm/s @ -97 °F to the LOX and RP-1 tanks, respectively. Vent/relief subsystem performance simulations indicated that for the option 1 configuration design, the vent/relief subsystem could relieve these worst case flow rates while the tank pressures were below proof of 112.5 psia.

Analysis of the orifice based pressurization systems indicated that worst case flows of 1.39 lbm/s @ -63 °F and 0.38 lbm/s @ -66 °F to the LOX and RP-1 tanks, respectively. Vent/relief system performance simulations indicated that the orifice based pressurization systems could relieve these worst case flow rates while the tank pressures were below proof. However, the exit orifice of the LOX vent/relief system should be enlarged or removed entirely. Removal of the exit orifice would result in high (sonic) Gseous Oxygen (GOX) velocities within the vent/relief system during normal controlled vent procedures. High GOX velocities create safety concerns. If the flow velocities are high enough, the impact of entrained particles with walls may release enough energy to initiate an oxidation reaction. Since the LOX vent design requires aluminum tubing and an aluminum valve, under these flow conditions aluminum may actually burn, creating a fire that could spread to other systems. Thus, the use of an orifice based pressurization system will likely involve a complete redesign of the LOX vent system including possible materials changes.

The vent/relief valves must be capable of opening fast enough to establish a steady relief flow prior to the tank pressures reaching proof. Tank pressure rise rates are a function of inlet flow rate, ullage volume, and pressurant temperature. Figure 4 presents response time requirement analysis results. The vertical shaded region represents the probable vent/releif valve response time range. The times presented for each system represent the pressure rise time from 75 psia to the tank proof pressure.

Three ullage volume cases were considered for the LOX tanks. The minimum ullage case (4.7 ft^3) corresponds to tank conditions between the end of LOX tank topping and controlled vent at altitude. During controlled vent procedures, the LOX is conditioned to 160 °R, boiling off mass to remove the excess heat. The 19 ft^3 ullage case corresponds to tank conditions after the maximum boil-off had occurred. A minimum expected boil-off ullage condition (10 ft^3) was also considered. Normal pressurization system operation would not be required at times when the tanks are at the minimum (4.7 ft^3) ullage condition.

Figure 4 indicates that the regulator based system was marginal for the minimum ullage, hot pressurant case. All other systems overpressurized the propellant tanks before the vent/relief valve could open to relieve the flow. However, because the pressurization system would not be in use during the

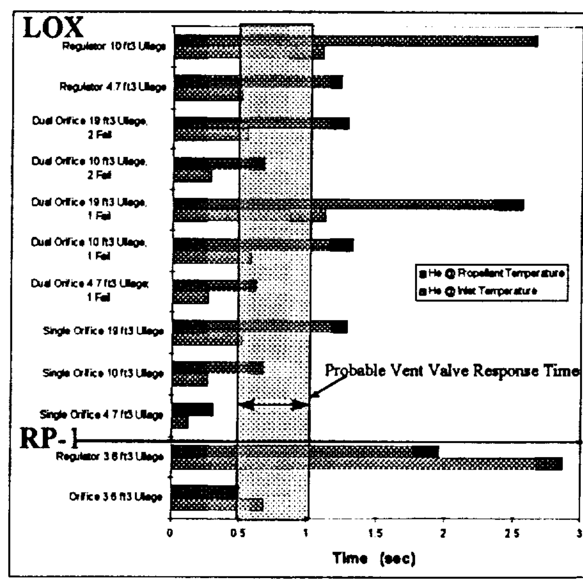

Figure 4. Tank Pressure Rise Time to Proof.

period of minimum ullage, it might be possible to inhibit the latching solenoid valve reducing the risk of a pressurization system failure at that time. Assuming the pressurization system was inhibited during the low ullage period, only the maximum and minimum boil-off cases should be considered.

The regulator based system was the only one that avoids the chance of overpressurization for both high ullage conditions. The multiple orifice system avoided overpressurization only for the maximum boil-off case and requierd the latching solenoid valve be used as the final mtigator for the second control valve failure. The multiple orifice system avoided overpressurization at both the high ullage cases if the propellant tanks are allowed to nearly reach a burst pressure. Pressurizing the tanks to such a level is likely to cause structural damage. Vent system analysis indicates that the regulator based pressurization system poses the least risk of overpressurizing the propellant tanks in the event of a component failure, therefore, option1 design configuration was chosen.

Pressurization System Transient Analysis

To simulate the transient operation of the option 1 pressurization system design, a model was developed using the ROCket Engine Transition Simulation (ROCETS)[4] program. Also, the model contained vehicle internal environment variations during the mission, heat transfer models for the heat exchange within the system and different components with the surroundings, and values of the solenoid valve lag times. As the design matured, the following requirements modifications were made:

1. LOX tank ullage pressure is 65 psia with a ±3 psia control range.
2. Initial RP-1 tank temperature is 530 °R. The RP-1 tank ullage pressure is 50 psia with a ±3 psia control range until the RP-1 tank contains 7.58 lbm of helium. Then, the helium mass is kept constant and the ullage pressure is allowed to drop until the end of Engine Mainstage Burn.
3. Addition of another check valve to the LOX line.
4. The RP-1 tank helium supply line Inside Diameter (ID) changed to 0.65 in.

In the analyses, the design requirements and proper operational conditions of the pressurization system were evaluated. The delay from the instant tank ullage pressure reaches the specified set-point until a signal reaches the solenoid valve is considered to be 0.04 seconds. The additional delay due to the valve response to a signal is assumed to be 0.05 seconds. The valve closing/opening area variation is modeled linearly.

For each system the following heat transfer mechanisms were considered:

1. Free/forced convection between the inner surface and the adjacent fluid.
2. Conduction through the wall.
3. Free convection between the outer surface and the surroundings.

The helium temperature within the helium bottles, along the helium lines, and within the propellant tanks could be found by applying energy balance as following:

$$M_{He}\, c_{pHe}\, dT_{He}/dt = \Sigma q + \Sigma m_{in} H_{in} - \Sigma m_{out} H_{out}$$

In the above equation, M_{He}, C_{pHe}, and T_{He} represent mass, heat capacity at constant pressure, and temperature of the helium. q, m_{in}, and m_{out} donate heat exchange, incoming, and outgoing mass flow rates, respectively. Also, H_{in} and H_{out} represent the incoming and outgoing specific enthalpies, respectively. Helium temperature can be computed as following:

$$T_{He}^{new} = T_{He}^{old} + (\Delta t / M_{He}\, c_{pHe})\, (\Sigma q + \Sigma m_{in} H_{in} - \Sigma m_{out} H_{out})$$

$$q = \Delta T / \Sigma R$$

where R is the thermal resistance which depends on the geometry and heat transfer mode.

To transport propellants to the engine at the required flowrates, propellant tanks should be pressurized within the prescribed range. To achieve the prescribed pressure range, sufficient helium must be provided to each propellant tank. The total initial stored helium mass is 76 lbm at 530 °R and 5000 psia. Prior to engine start up, due to vehicle internal environment temperature reduction during ground operations and captive carry periods, stored helium temperature and pressure drop to 485 °R and 4580 psia. Figure 5 depicts the stored helium mass history during the pressurization. The residual helium mass at the end of the pressurization process is approximately 27 lbm.

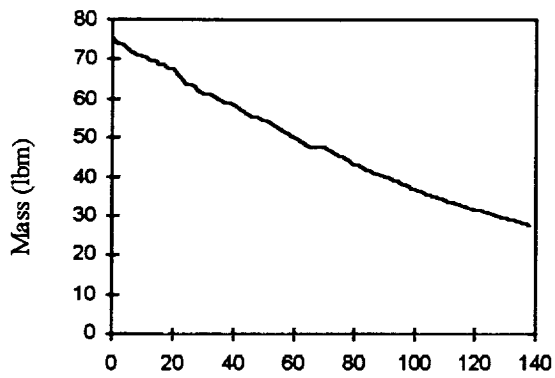

Figure 5. Stored Helium Mass During Pressurization.

The pressure history of the stored helium is shown in Figure 6. At the end of the process, helium pressure is approximately 740 psia.

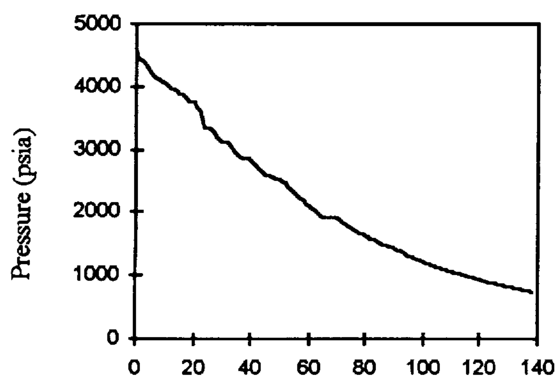

Figure 6. Pressure History of Helium Bottles During Pressurization.

The temperature history of the stored helium is illustrated in Figure 7. At the end of the pressurization, helium temperature in the storage bottles is approximately 240 °R.

The LOX ullage pressure history is shown in Figure 8. The LOX tank was maintained at 65 psia with a ±3 psia control range. The LOX ullage pressure reaches a maximum of 70 psia after 6 seconds.

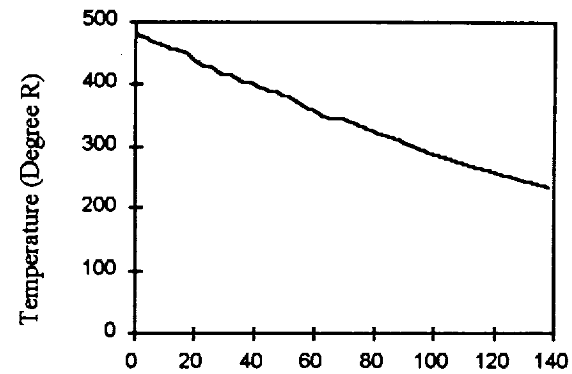

Figure 7. Stored Helium Temperature History During Pressurization.

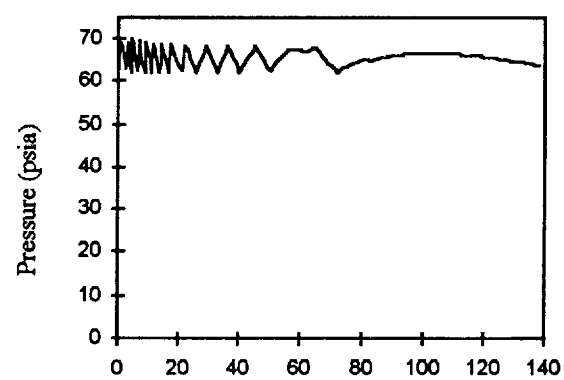

Figure 8. LOX Tank Pressure History During Pressurization.

The LOX tank ullage expenditure history is depicted in Figure 9. This figure indicates that at the end of pressurization process, the LOX tank is filled with 41 lbm of helium.

Figure 10 illustrates the pressure history of ullage within the RP-1 tank. At the beginning, the ullage pressure was considered to be 53 psia. The ullage reaches a maximum of 58 psia after 8 seconds. After 82 seconds, as depicted in Figure 11, the RP-1 tank is filled with 7.58 lbm of helium. At this point, the solenoid valve is closed and the ullage mass is kept constant until the end of the engine burn. At the end of the pressurization process, the RP-1 tank ullage pressure is 26 psia.

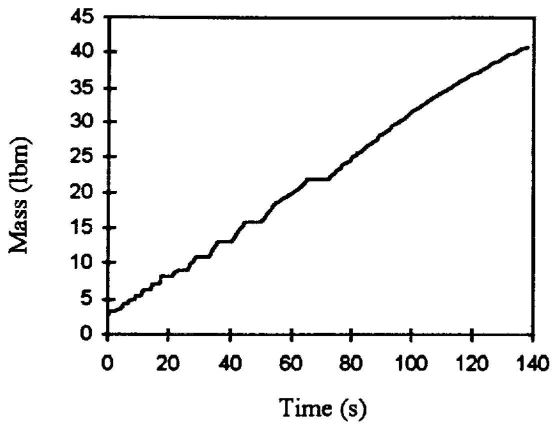

Figure 9. LOX Tank Helium Mass During Pressurization.

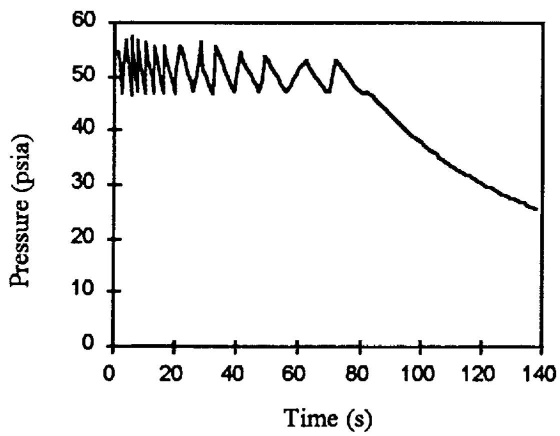

Figure 10. RP-1 Tank Pressure History During Pressurization.

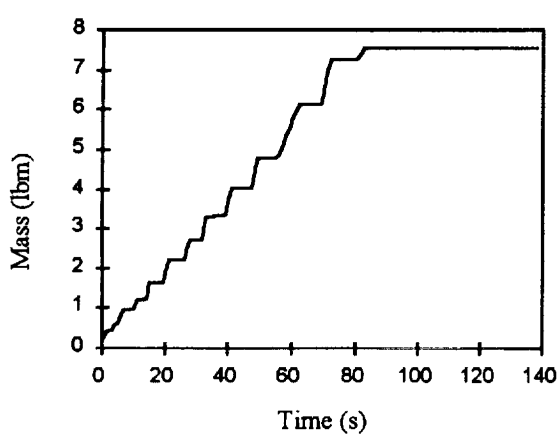

Figure 11. Helium Mass Within RP-1 Tank During Pressurization.

PNEUMATIC AND PURGE SUBSYSTEM

The pneumatic and purge (P&P) subsystem provides gaseous helium for the engine purges and Spin Start. A main engine IPS purge is required whenever propellants are provided to the engine to assure separation of RP-1 and LOX in the single shaft pump of the Fastrac engine. Also, the engine Spin Start process requires a high flow of helium through the turbine to drive the pumps during the initial period of pump operation. A schematic of pneumatic and purge subsystem is shown in Figure 12. The combination of forward and aft bottles provides approximately 25.5 lbm of helium initially at 5000 psia and 530 °R. The volumes of forward and combined aft bottles are 6.2 ft^3 and 2.2 ft^3, respectively. The helium lines to IPS and Spin Start interface have OD of 0.75 in and ID of and 0.65 in, respectively. The regulator in the IPS line reduces the pressure to 900 psia while the regulator in the Spin Start side provides a pressure of 750 psia at the regulator exit.

To evaluate the IPS and Spin Start interface conditions, a transient ROCETS model for P&P was developed. The model contained heat transfer from the surroundings environment to the helium bottles, heat transfer from the surroundings to helium lines, and valve timeline provided by the vendor.

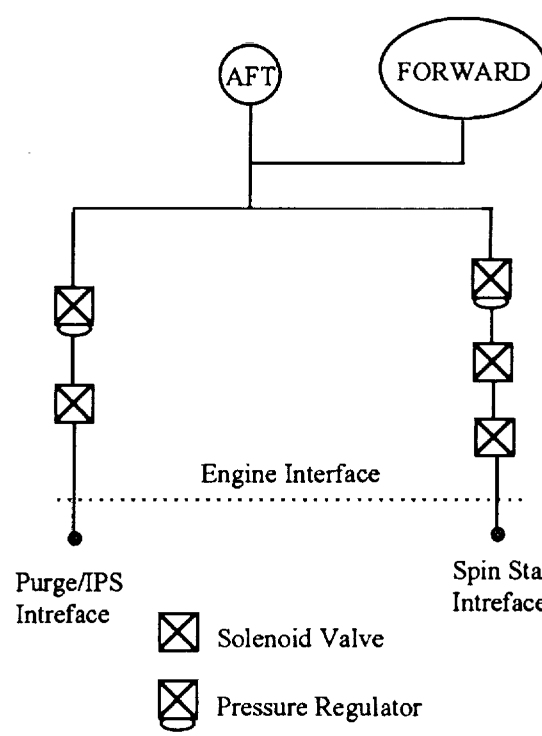

Figure 12. Pneumatic System Schematic.

Figure 13 depicts the helium usage history. The IPS helium usage is relatively linear except during the begining of engine burn period which has a jump. By the end of engine burn, approximately 15 lbm of helium is supplied to the IPS. Helium used by the Spin Start is about 1 lbm which is supplied very fast at the beginning of the engine burn .

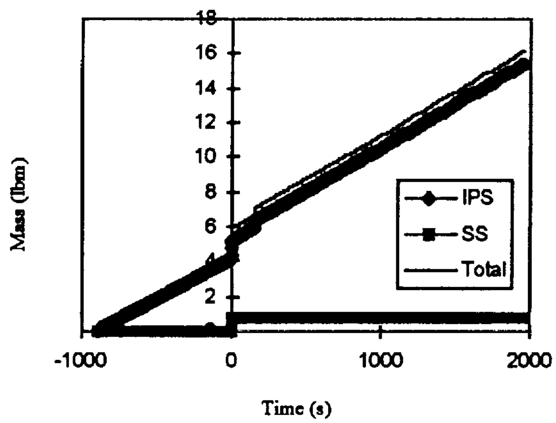

Figure 13. Helium Usage History.

Figure 14 illustrates the pressure histories at the IPS and Spin Start interfaces. The Spin Start pressure has a spike of about 800 psia at the beginning of the engine burn. The IPS pressure remains a constant value of 730 psia. The Spin Start interface pressure goes up to 800 psia at engine start when the Spin Start solenoid valve is opened.

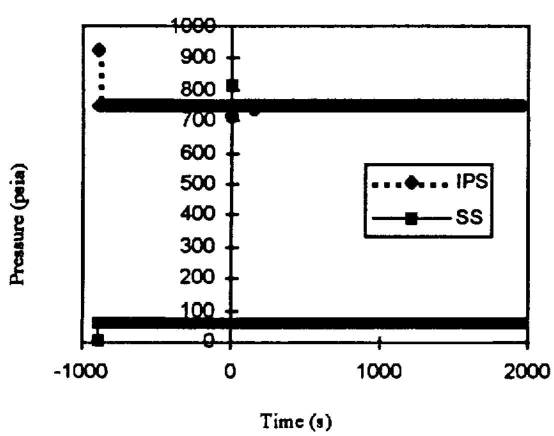

Figure 14. Pressure History at Inter-Propellant Seal and Spin Start Interfaces.

HELIUM BOTTLES FILL ANALYSIS

During ground operations, the helium bottles of the pressurization and pneumatic systems are loaded at specified conditions. Helium is transported from the supply source to the bottles through a transfer line. The flow of the helium to the bottles is controlled by a valve. A schematic of each system is shown in Figures 15 and 16.

The ROCETS Program is used to simulate the fill procedure during the ground operations. The ROCETS models of the fill procedures, for both pressurization and pneumatic systems, are based on the maximum operational helium pressure, maximum wall temperature, and maximum stored

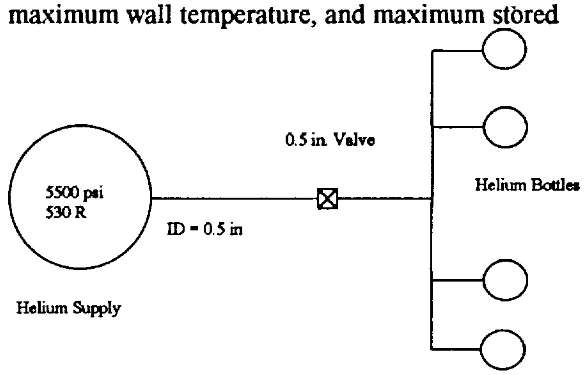

Figure 15. Pressurization System Fill Schematic.

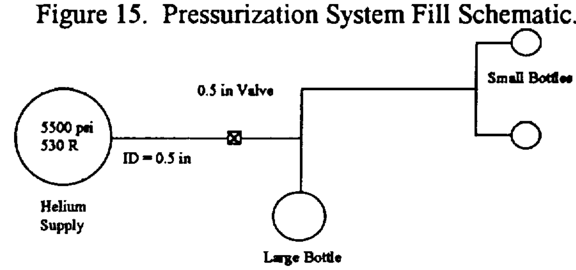

Figure 16. Pneumatic System Fill Schematic.

helium temperature of 5000 psia, 680 °R, and 800 °R, respectively. Therefore, as the helium pressure, bottle wall temperature, or helium temperature exceeds the above values, the valve is closed. While the valve is closed, the bottles are allowed to cool down until the helium temperature reaches 540 °R, at which time the valve is reopened. The following assumptions were made:

1. The supply source is at constant pressure and temperature of 5500 psia and 530 °R.
2. Maximum operational temperature of the helium bottle(s) is 680 °R .
3. Surroundings temperature is constant 530 °R
4. Helium bottles are model AC-5178 of SCI and X600045 of Technical Products Group, Inc.

During the fill procedure, due to transport of energy to the bottles, the stored helium within the bottles experiences an increase in its temperature. Then, due to the free convection heat transfer between the helium and the bottle inner wall, the wall temperature will be increased. Since there is a maximum operational temperature limit on the bottle wall, the filling procedure should be conducted such that the heat transferred from helium does not increase the wall temperature above the prescribed value. The ROCETS model for each system contains free convection between the bottles inner surface helium, conduction through the bottles wall, and free convection between the bottles outer surface and the surroundings.

Figures 17 depicts the helium mass accumulation history of the pressurization bottles. To fill the four bottles with 76 lbm of helium, approximately 7300 seconds (2.02 hours) is required. During this period the valve is opened 6 times with minimum and maximum open times of 1 second and 9 seconds. The nearly vertical lines represent mass accumulation when the valve is opened. The horizontal lines or curves indicate when the valve is closed and helium accumulates in the bottles due to bleed down of the line.

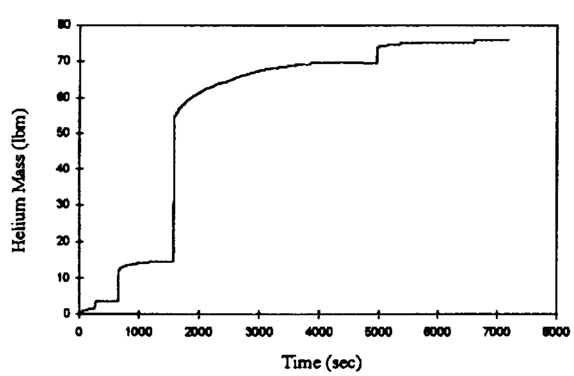

Figure 17. Helium Fill History of the Pressurization System.

Figure 18 illustrates the helium mass accumulation within the pneumatic system bottles. The fill procedure requires approximately 2.5 hours to load 25.5 lbm. The number of valve open cycles is 6 with minimum and maximum open times of 1 second and 4 seconds.

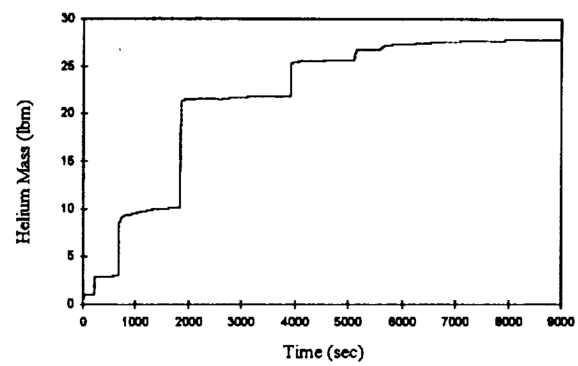

Figure 18. Pneumatic System Bottle Helium Fill History.

SUMMARY

A trade study of three pressurization subsystem configurations were performed. Pressurization using regulators was chosen because of its safest operational performance. A transient performance of the regulators based pressurization system was simulated and he required pressurant mass and its thermodynamic conditions were determined. The required helium mass for LOX and RP-1 tank were 41 lbm and 7.5 lbm, respectively. Also, computations indicated that the residual helium mass at the end of the pressurization was 27 lbm. The transient analysis of pneumatic and purge subsystem indicated that the flow rates required by the IPS and engine Spin Start were met. The helium expendture for the IPS and Spin Start were 15 lbm and 1 lbm, respectively. The helium bottles fill procedure was simulated. The results indicated that the fill times to load pressurization bottles with 76 lbm and pneumatic bottles with 25.5 lbm were 2 hours and 2.5 hours, respectively.

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