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PROPELLANT FEED SUBSYSTEM FOR THE X-34 MAIN PROPULSION SYSTEM

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ABSTRACT

The Orbital Sciences Corporation X-34 vehicle demonstrates technologies and operations key to future reusable launch vehicles. The general flight performance goal of this unmanned rocket plane is Mach 8 flight at an altitude of 250,000 feet. The Main Propulsion System supplies liquid propellants to the main engine, which provides the primary thrust for attaining mission goals. Major MPS design and operational goals are aircraft-like ground operations, quick turnaround between missions, and low initial/operational costs. This paper reviews major design and analysis aspects of the X-34 propellant feed subsystem of the X-34 Main Propulsion System. Topics include system requirements, system design, the integration of flight and feed system performance, propellant acquisition at engine start, and propellant tank terminal drain.

INTRODUCTION

The X-34 program seeks to demonstrate operations, propulsion and structural technologies key to future reusable launch vehicles. Program goals are aircraft-like ground operations, quick turnaround between missions, and low acquisition and operating costs. An X-34 mission includes captive carry to an altitude of 38,000 feet, engine start in a horizontal orientation after separation from the carry vehicle, powered flight, and glide back to a runway landing. Thrust comes from a nominal 60,000 lbf thrust version of the MSFC Fastrac engine[1], which burns Rocket Propellant 1 (RP-1) grade kerosene fuel with liquid oxygen (LOX) oxidizer. The X-34 is also designed for abort scenarios where the engine either completely fails to operate or shuts down prematurely. More comprehensive reviews of the X-34 program and propulsion systems are provided by Sgarlata and Winters[2] and Sullivan and Winters[3]. The National Aeronautics and Space Administration (NASA)/Marshall Space Flight Center (MSFC) and the Sverdrup Technology/MSFC Group provide the analysis and design support for the X-34 Main Propulsion System (MPS). The MPS consists of several subsystems. Hedayat et al.[4] reviews the propellant tank pressurization, pneumatic, and tank vent subsystems. Brown et al.[5] reviews the system for propellant storage, conditioning, and dumping. This paper reviews major requirements, design features, and analyses related to the X-34 LOX and RP-1 feed systems.

FEED SYSTEM REQUIREMENTS

The feed systems transfer LOX and RP-1 propellants to the Fastrac engine interface at nominal mass flow rates of 143 and 65.5 lbm/s for LOX and RP-1, respectively. The maximum expected operating pressure (MEOP) is limited by storage tank pressure to 75 and 100 psig for the LOX and RP-1

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systems, respectively. Flow pressure losses must be small enough to maintain net positive suction pressure (NPSP) requirements at the turbopump inlets, thus preventing cavitation damage to the engine turbopumps. The design of a temporal propellant tank pressurization profile to meet these requirements is discussed in more detail later in this paper. Propellant temperature requirements for engine operation are discussed in the work by Brown et al.[5]

The X-34 vehicle requires thrust vectoring to maintain control during flight, and the feed system design must allow the engine to gimbal within an envelope of +10/-8 degrees in pitch and ±3 degrees in yaw. Also, during flight, the X-34 flight computer requires knowledge of the vehicle mass center location for control. The vehicle mass center shifts rearward as propellant is consumed, and the fully compartmentalized propellant storage tanks allow one to easily know its location as of function of the remaining propellant mass. The flight computer integrates flow meter data from the LOX and RP-1 feedlines to track the remaining propellant mass and, thus, mass center location.

Upon release from the carry vehicle, the X-34 executes a negative "g" maneuver to quickly distance itself from the carry vehicle prior to engine start. The combination of this maneuver and feed system design must not result in the ingestion of gaseous ullage from the propellant storage tanks into the feed system. Such a gas pocket, from either the LOX or RP-1 systems, entering a main engine turbopump will result in turbopump damage and possibly catastrophic loss of the X-34 vehicle. Computational fluid dynamic (CFD) simulations of this ullage motion provide assurance that ullage will not be ingested into either feed system at engine start. A similar ullage ingestion issue exists during the terminal drain phase for either the LOX or RP-1 propellant tanks. Thus, CFD simulations of propellant tank terminal drain were also performed to help determine the appropriate time for engine shutdown.

FEED SYSTEM DESIGN

Figure 1 illustrates an elevation view of the X-34 MPS and a schematic representation of the LOX and RP-1 feed systems alone. The RP-1 feed system begins at the tank outlet manifold and ends at an interface flange immediately upstream of the engine turbopumps. The LOX feed system is similar in scope, but also includes an inter-tank connection for propellant transfer between the forward and aft LOX

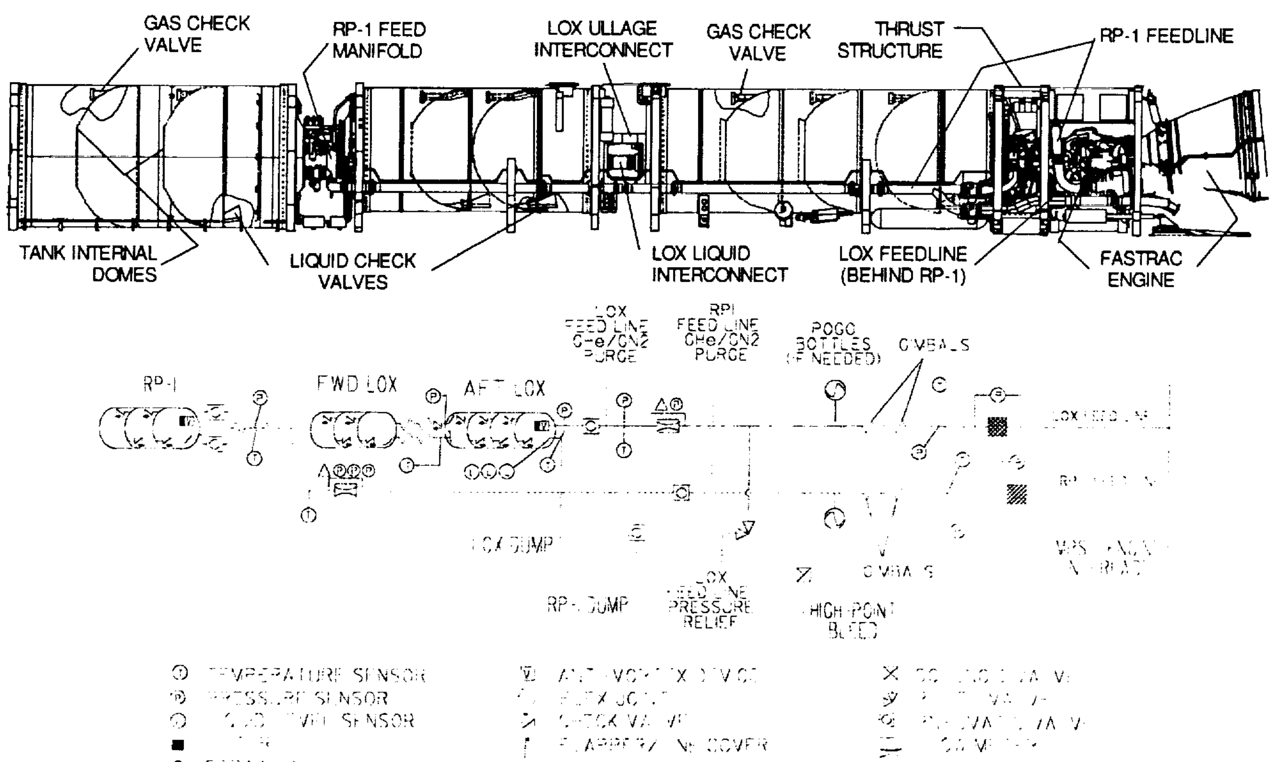


Figure 1: X-34 MPS Layout and Feed System Schematic.

tanks. The propellant tanks are compartmentalized by interior domes to minimize changes in vehicle mass center during flight. Each interior dome has a pair of check valves allowing flow as indicated in the Figure 1 schematic. The feed systems are designed around the pre-existing propellant tanks and vehicle structure. Feed system tank penetrations are allowed only through the manways at either end of the propellant tanks. The feed systems are packaged within a very limited spatial envelope and routed around existing vehicle structure to the engine interface. Both the LOX and RP-1 systems include several components for the control/monitoring of propellant flow.

LOX Feed System

The LOX feed system begins at the tank liquid interconnect between the forward and aft LOX tanks and ends at the engine interface flange. A wraparound design in the engine aft bay best accomodates the numerous flow control and monitoring components, as well as engine gimballing requirements.

Tank Interconnect

The presence of wing structural members in this region required the use of dual LOX tanks in the vehicle design. Figure 2 illustrates the interconnect design. A fixed position pickup tube extends into the forward tank to transfer LOX into the rear tank, and an ullage line allows ullage to pass into the forward LOX tank. A check valve prevents pressurant gas leakage through the ullage interconnect, thus ensuring that the aft compartment of the forward LOX tank empties completely during both dump and feed operations. The flapper on the liquid interconnect ensures that the forward compartment of the aft LOX tank is filled completely during fill operations. The forward tank pickup terminus represents a compromise between forward tank LOX residual mass for a dump scenario, where the LOX rests at the bottom of the tank, and a full performance mission, where engine thrust forces LOX rearward in the tank. A pair of flexible bellows in each line allows relative motion between the forward and aft tanks due to flight loads/vibrations.

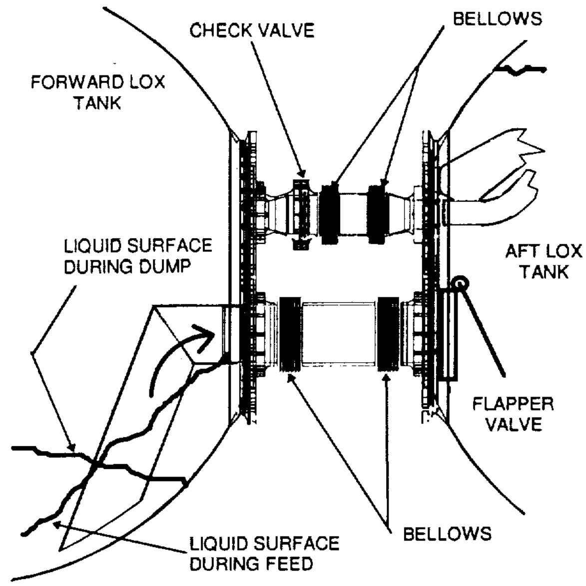


Figure 2: Liquid Oxygen Tank Interconnect Design.

Aft LOX Tank Outlet

The aft LOX tank aft manway, depicted in Figure 3, utilizes completely separate dump and feed lines. The aft LOX tank feed outlet consists of a sump, anti-vortex baffles, and wire mesh "rock-catcher" screen over the anti-vortex baffles. Limited space precludes the use of a non-dropout contour outlet. Furthermore, the thrust structure, which transfers engine thrust loads to the fuselage, limits the sump to only 5.75 inches inside diameter by 7 inches deep. A larger sump is desirable to minimize residual LOX residual mass due to dropout during tank terminal drain, but the present sump design meets X-34 usable LOX requirements as discussed in

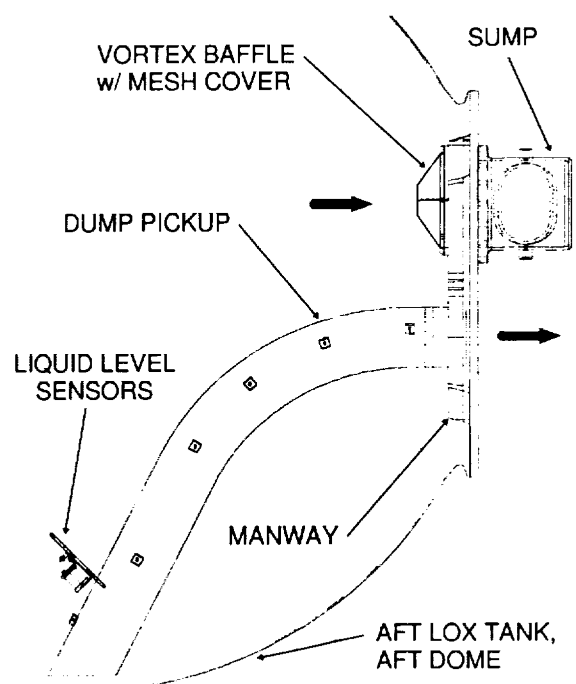


Figure 3: Aft LOX Tank Feed Outlet.

a later section. Triple redundant liquid level sensors mounted on the LOX dump pickup trigger a timer which determines the moment of engine shutdown in a full performance mission. The same sensors immediately shut off the supply of helium pressurant to the LOX tanks in an abort scenario.

Engine Bay Assembly

Figure 4 illustrates the LOX feed line assembly from the aft LOX tank outlet to the engine interface flange. This section packages the sensors, instrumentation, gimbal hardware, and auxiliary lines required for proper functioning of the LOX feed system.

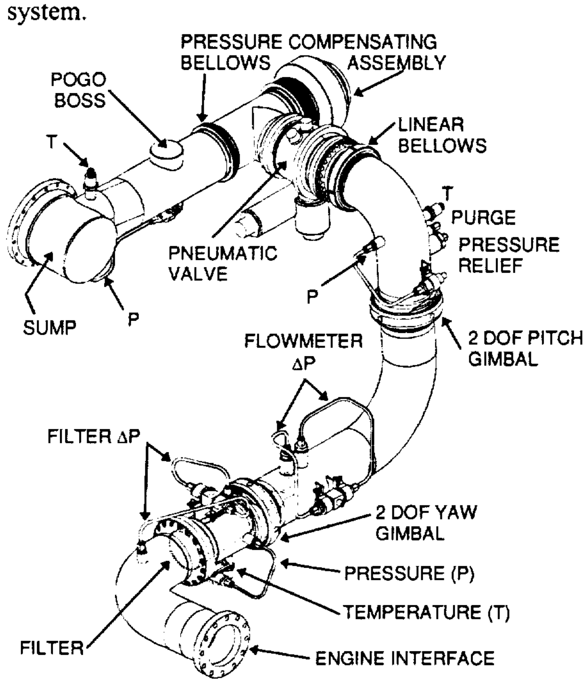


Figure 4: LOX Feedline Engine Bay Assembly.

The feedline exits the sump outlet at a right angle passing in front of the vehicle thrust structure. Absolute pressure and temperature measurements near the sump exit verify tank outlet conditions. The pogo boss provides an attach point for a pogo suppression bottle in the event static fire testing reveals a need for pogo suppression. A pressure compensating bellows removes mechanical/thermal loads upstream of the pneumatic engine pre-valve. A linear bellows immediately downstream of the pre-valve takes up loads induced by the use a 2 gimbal system to accommodate combined pitch and yaw motion. A second set of absolute pressure and temperature sensors in the downward leg verify proper pneumatic valve opening. The purge line allows removal of LOX from the feedline/engine prior to engine removal. The pressure relief line guards against over pressurization due to heat load in the event LOX is locked up between the pre-valve and engine. The next component is the pitch gimbal. This 2 degree of freedom (DOF) gimbal, centered with respect to the engine gimbal point, allows for movement of the engine in the vehicle pitch plane. A pressure differential flow meter monitors propellant mass flow rate during engine operation, thus providing information on changes in vehicle center of gravity due to propellant depletion. An 800 micron filter prevents large particles, resulting from failure of an upstream component and/or procedure, from passing into the engine turbopumps. The pressure differential measurement across this filter provides knowledge of such a failure during engine operation. Final absolute pressure and temperature measurements are made near the filter entrance to verify LOX condition requirements are being met. The MPS LOX feed system ends at the engine interface flange immediately upstream of the main engine turbopumps.

RP-1 Feed System

The RP-1 feed system contains many of the same components as the LOX feed system. The following sections relate some important differences between the LOX and RP-1 feed systems. The discussion is functional in nature, and the reader should refer to Figure 1 for reference to system components. The engine bay section is not discussed, as it is functionally similar to that for the LOX feed system.

Tank Outlet

Dual outlets are required to meet both the dump and the feed propellant residual requirements. To reduce system mass, these outlets merge into a single dump/feed line at a manifold section behind the RP-1 tank before traveling to the vehicle rear. A pair of pneumatic valves mounted to the RP-1 tank manway isolate the dump and feed functions at the tank. Space limitations between the RP-1 tank and the forward LOX tank prevents the use of either a non-dropout contour or sump outlet from the RP-1 tank. The outlet consists of a 3.5 inch inside diameter manway penetration, which is the same diameter as the feedline itself. The RP-1 tank outlet is covered by anti-vortex baffles and screens similar to those depicted in Figure 3 for the aft LOX tank.

LOX Tank Bays

The section of dump/feed line passing through the LOX tank bays must withstand temperature extremes from 340 to 560 °R during a mission. Line insulation and resistance heaters on flanges prevent the freezing of RP-1 in this section of line. To minimize insulation and heater requirements, this line is completely drained of RP-1 after tank fill, and the release of RP-1, for either jettison or engine feed, is timed to meet system temperature requirements.

The single dump/feed line passing through the LOX tank bays splits at a bifurcation in the aft end of the aft LOX bay as depicted in Figure 1. Again, two pneumatic valves isolate dump and feed functions at this end of the RP-1 feed system. The line bifurcation and the pneumatic valves and their solenoid actuators are enclosed in boxes and receive purge nitrogen from the warmer engine bay to prevent the freezing of either valves or RP-1.

FEED SYSTEM ANALYSES

Figure 5 illustrates the X-34 vehicle coordinate system. This coordinate system provides a common reference frame for analysis and design tasks. All axis references in the following sections refer to Figure 5.

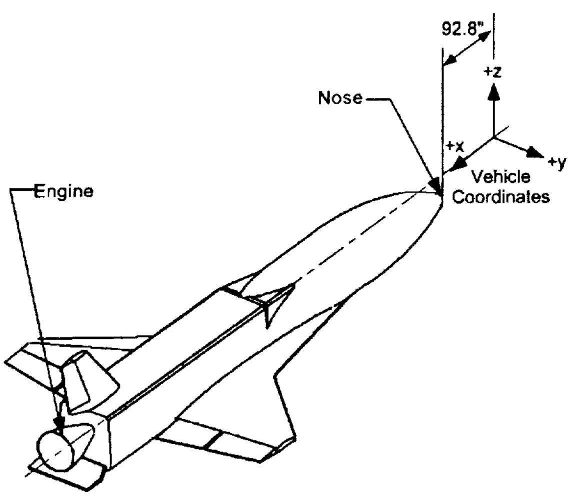


Figure 5. X-34 Vehicle Coordinate System.

The first analysis iterates between temporal flight acceleration and propellant tank ullage pressure to find an ullage pressure profile satisfying both MPS and engine requirements. The other two analyses concern the possible ingestion of ullage gas into the feed system either between release of the X-34 from its carry vehicle and engine start or during the propellant tank terminal drain phase at the end of engine operation. Ullage gas ingestion into the feed system at any time during flight damages the engine turbopumps and may result in catastrophic loss of the X-34 vehicle.

Ullage Pressurization Profile

The ullage pressurization profile must meet both engine flow and net positive suction pressure (NPSP) requirements, without exceeding the LOX and RP-1 tank maximum expected operating pressure (MEOP). The final ullage pressurization profiles for the LOX and RP-1 tanks must also consider the available pressurant mass[4].

A one dimensional fluid flow model of the feed system is used to calculate the maximum tank bottom pressure and engine interface static pressure. The propellant remaining in each tank and vehicle body accelerations during flight determine the contribution of liquid head to the above pressures. The effect of temperature on LOX vapor pressure is treated parametrically by considering the nominal (160 °R) and anticipated bounding (157 °R and 163 °R) LOX temperature from Brown et al.[5] With constant propellant flow rates and essentially constant feed system geometries, both the rate of propellant depletion and the pressure losses due to flow are known. The only remaining variables are vehicle body accelerations and ullage pressure. Thus, an iterative process begins by selecting a trial temporal ullage pressurization profile based on propellant flow rate requirements, minimum NPSP requirements, and system flow losses. This trial profile is input into a trajectory simulation to return new temporal vehicle body accelerations, which are then fed back into the one dimensional feed system model. Iteration terminates when the trajectory and feed system flow models converge to a solution. The temporal ullage profile is then modified as necessary to avoid over pressurization of the propellant tanks, and iteration continues until all engine requirements are met.

LOX Feed System

Figure 6 illustrates the LOX tank pressurization profile, along with resultant tank bottom and engine interface pressures. The nominal ullage pressure curve is bracketed by dashed curves representing a ±3 psia control band. The tank bottom pressure curve corresponds to the ullage pressure upper limit, while the pump inlet total pressure curve corresponds to the ullage pressure lower limit.

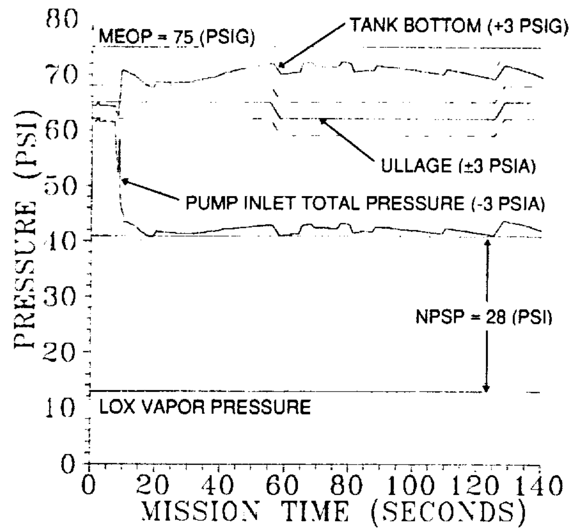


Figure 6. LOX Feed System Pressurization Profiles.

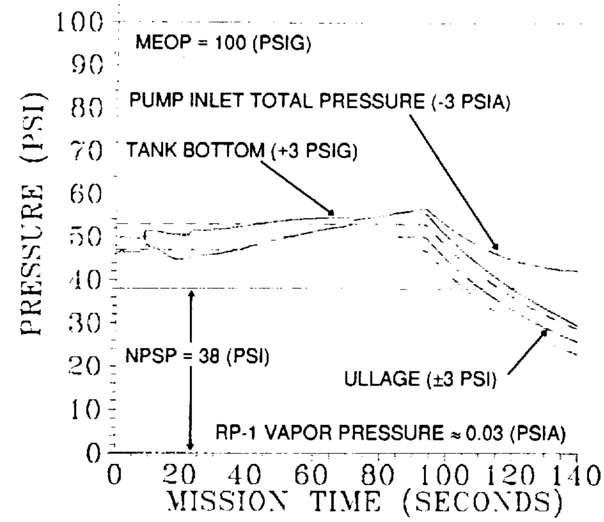


Figure 7. RP-1 Feed System Pressurization Profiles.

Mission time equal to 0 seconds corresponds to the moment of X-34 drop from the carry vehicle. Propellant flow initiates at 6.8 seconds to support the engine start command at 7 seconds. The increasing propellant flow causes a rapid decrease in the pump inlet total pressure due to system flow losses. A pump inlet total pressure minima at 18 seconds requires an initial ullage pressure setting of 65 psia to meet the 28 psi LOX turbopump NPSP requirement. The tank bottom pressure steadily increases after 18 seconds, due mainly to increasing flight acceleration, and a 3 psi drop in the ullage pressure set point is required at 55 seconds to avoid exceeding tank MEOP. Towards the end of powered flight, the decreasing LOX liquid height relative to the engine interface requires an ullage pressure increase back to 65 psia to avoid violating the NPSP requirement.

RP-1 Feed System

Figure 7 illustrates the RP-1 tank pressurization profile, along with resultant tank bottom and engine interface pressures. The nominal ullage pressure curve is bracketed by dashed curves representing a ±3 psia control band. The tank bottom pressure curve corresponds to the ullage pressure upper limit, while the pump inlet total pressure curve corresponds to the ullage pressure lower limit.

At 100 psig, the RP-1 tank MEOP is well above the maximum tank bottom pressure throughout engine operation. The pump inlet total pressure curve increases in direct proportion to increasing vehicle acceleration acting on a roughly 330 inch liquid head height from the RP-1 tank outlet to the engine interface. Therefore, meeting NPSP requirements poses no problem. With such a generous head contribution to the pump inlet total pressure, pressurant flow to the RP-1 tank is shut off at 93 seconds to conserve helium pressurant. The 93 second point leaves enough residual pressurant mass in the tank to expel the remaining RP-1 and still comfortably meet NPSP at the mission end.

Drop Transient Ullage Motion

Immediately after drop from the L-1011 carry vehicle, the X-34 executes a negative "g" maneuver to achieve a safe distance from the L-1011 prior to engine start. The gaseous volume in the LOX and RP-1 tanks, known as ullage, moves towards the tank bottom as a result of the body accelerations generated by the separation maneuver. The 3-dimensional computational fluid dynamic (CFD) code Flow3D[6] was used to simulate the drop transient ullage motion and determine whether candidate drop trajectories result in ullage ingestion by either the LOX or RP-1 feed systems.

The drop transient CFD simulations require time varying body acceleration data along the vehicle X axis (AXB) and Z axis (AZB) as boundary condition inputs. Temporal values for AXB and AZB come from simulations of candidate separation trajectories performed by the Orbital Guidance, Navigation, and Control (GNC) group. The trajectory simulations consider off-nominal body accelerations due to reasonable variations in flight/control parameters, thus accounting for anticipated drop-to-drop variations. The trajectory simulations calculate the pitch axis body acceleration also, but it was negligible and not considered in the following CFD analyses.

RP-1 Tank

Figure 8 illustrates temporal AXB and AZB dispersions calculated at the volume center of the aft most compartment of the RP-1 tank. Mission time equal to 0 seconds corresponds to the moment of release from the carry vehicle. The shaded region in Figure 8 represents the aforementioned off-nominal dispersion of trajectory simulation results. The solid and dashed lines in Figure 8 represent the drop trajectories exhibiting the least and greatest variation, respectively, in AXB and AZB.

Figure 9 illustrates the CFD model initial condition for the RP-1 tank aft compartment cut in

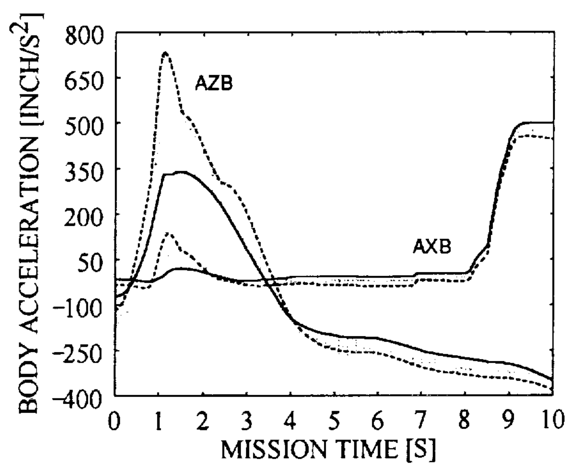


Figure 8. RP-1 Tank Body Accelerations.

the plane Y=0 at the tank centerline. Recall that upper check valves in the propellant tank intercompartment walls prevent the rearward motion of pressurant. Thus, liquid propellant is forced rearward through the lower check valves and compresses the ullage in all but the foremost compartment where pressurant enters the tank. The actual ullage volume after tank pressurization is roughly 1/2 of that depicted in Figure 9. The simulation ullage volume was increased to reduce the mesh density required to accurately track the liquid/ullage interface, thus resulting in a more reasonable problem size and slightly conservative simulation results. Figure 10 illustrates the temporal ullage bubble centroid location. The ullage bubble is fully submerged in the tanked RP-1 by 1 second. Once submerged, bubble motion depends primarily on the relative magnitude of AXB to AZB, and the bubble undergoes negligible movement towards the feed outlet. The bubble centroid moves rapidly forward and back again, as the bubble is flattened against the lower tank contour and then re-submerges after the negative "g" maneuver. The bubble is safely above the feed outlet at 6 seconds, or 1 second before engine start command at 7 seconds. Thus, the drop trajectories resulting in body accelerations within the dispersion in Figure 8 pose no problem regarding ullage ingestion into the RP-1 feed system prior to engine start.

Figure 9. RP-1 Tank Drop Simulation Initial Condition.

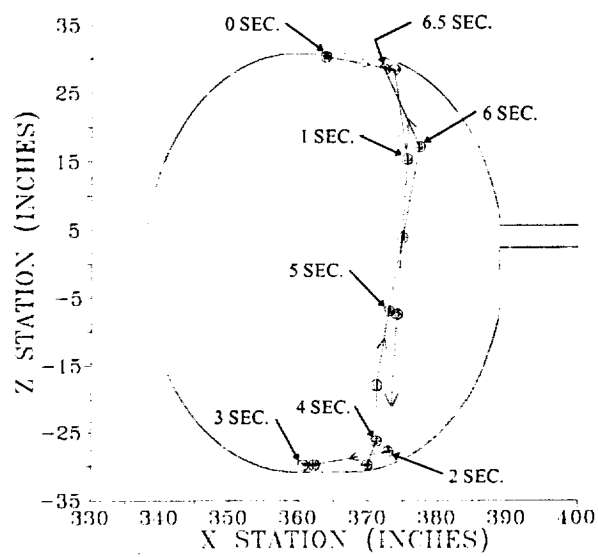


Figure 10. RP-1 Tank Drop Simulation Ullage Motion.

Aft LOX Tank

Figure 11 illustrates body acceleration dispersions calculated at the aft LOX tank aft compartment volume center. As for Figure 8, the solid and dashed curves represent the trajectories with the minimum and maximum variations, respectively.

The ullage volume in the aft LOX tank aft compartment is considerably greater than for the RP-1 tank, since some 716 lbm of LOX boils off during propellant conditioning[5]. Figure 12 illustrates the aft LOX tank aft compartment model initial condition in the plane Y=0. Figure 12 corresponds to the LOX fill level after tank pressurization and compression of the gaseous oxygen (GOX) ullage.

The large ullage volume greatly impacts ullage motion relative to that in Figure 10 for the RP-1 tank simulation. Figure 13 illustrates the ullage bubble location 1 second after X-34 drop from the carry vehicle. The ullage bubble briefly uncovers the sump outlet between 0.8 and 1.2 seconds as it descends in the tank (Fig. 13), and again between 4.4 and 4.8 seconds as it rises back to the top of the tank. Thus, the ingestion of a small volume of ullage is possible for the aft LOX tank outlet. To eliminate any risk, however small, associated with ullage ingestion, a maximum 20 second time delay is specified in the X-34 operations timeline between the final LOX conditioning vent cycle[5] and tank pressurization. This maximum delay prevents the GOX ullage, left in the aft most compartment after LOX conditioning, from rising above the oxygen saturation temperature corresponding to the initial ullage pressure set point of 62 psia. Thus, the GOX ullage collapses into a sub-cooled LOX state upon tank pressurization. This virtually eliminates ullage from all but the forward most compartment of the forward LOX tank where the pressurant enters.

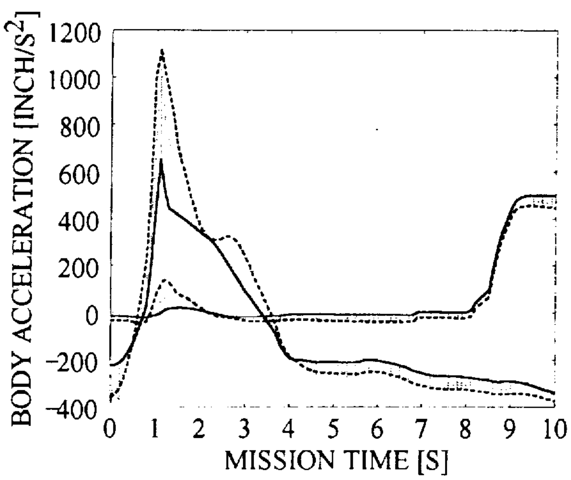


Figure 11. Aft LOX Tank Body Acceleration.

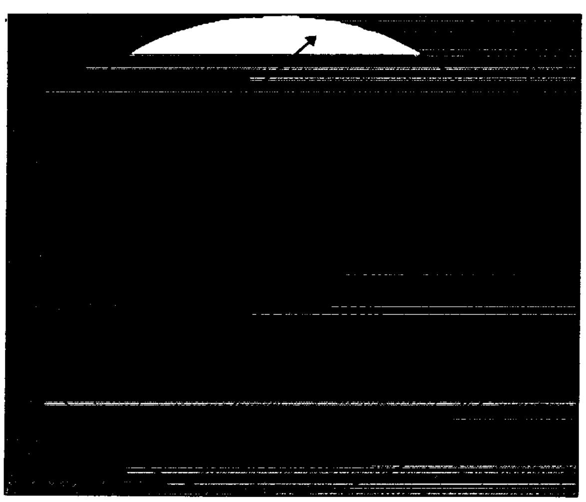


Figure 12. Aft LOX Tank Drop Simulation Initial Condition.

Figure 13. GOX Ullage Location at 1 Second.

Propellant Tank Terminal Drain

The possibility of ullage ingestion also exists when the propellant tanks are nearly empty at the end of main engine burn. At a certain liquid level height, a noticeable depression in the liquid free surface forms near the outlet of any draining tank. Under suitable conditions, this free surface depression may result in gas being entrained into the outlet flow prior to completely emptying the tank. This phenomenon, often referred to as "dropout," is very undesirable in the X-34 propellant feed system, as the entrained gas may damage the engine turbopumps.

The liquid height for dropout depends upon numerous factors including: the outlet flow rate, any generated/residual vorticity in the propellant, body accelerations experienced by the propellant during terminal drain, and the geometry of the tank/outlet combination. Designers may most readily influence the geometry variable. If possible, the tank outlet is designed to minimize dropout height, and thus residual propellant. Severe space limitations in the X-34 system prevented the design of tank outlets specifically to minimize propellant residuals. Thus, the following simulations were performed, using the same code[6] as for the ullage motion simulations, to provide working estimates for propellant residuals.

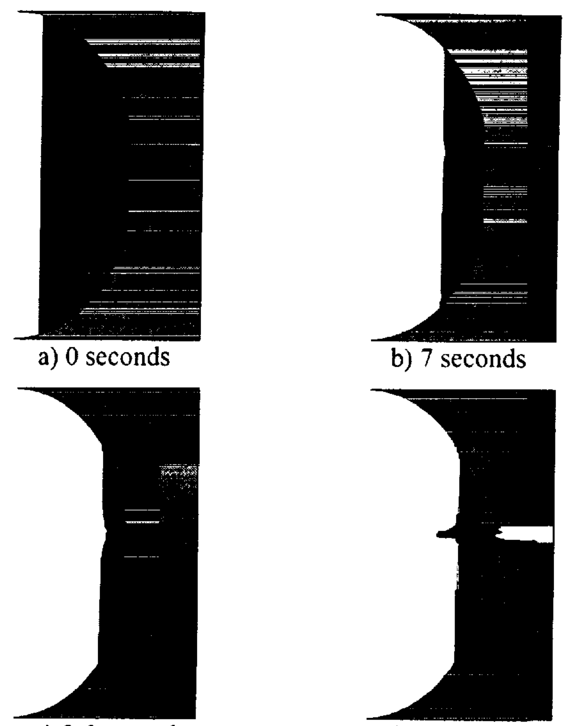
Boundary/Initial Conditions

The outlet mass flow rates are 65.5 lbm/s and 143 lbm/s for the RP-1 and aft LOX tank outlets, respectively. The necessary body accelerations are from Orbital GNC trajectory simulations of the Mach 8, 250,000 ft altitude X-34 mission, where the values of AXB and AZB are 3.4 g and -0.05 g, respectively, at the end of main engine burn. Thus, the liquid free surface orientation in the propellant tanks is roughly normal to the vehicle X-axis during terminal drain. Towards more conservative results, the anti-vortex baffles and screens, illustrated in Figure 3 for the LOX outlet, are neglected for both the RP-1 and LOX simulations.

Since fluid vorticity influences the dropout height, the following simulations artificially introduce vorticity to the tanked propellant. Each tank spins about its centerline at 0.5 radians/second for the first 1 second of simulation time. This spin rate and time combination does not correspond to a planned maneuver, and is believed to represent a conservative situation relative to actual operation.

RP-1 Tank Simulation

Figure 14a depicts the initial condition, corresponding to a simulation time of 0 seconds, for the RP-1 tank terminal drain simulation. The initial fill height is 16 inches. Figure 14b depicts the first indication of a depression in the RP-1 surface at 7 seconds and a fluid height of 7.4 inches. The surface depression and outlet vorticity grow steadily until 8.6 seconds and a fluid height of 4.5 inches, illustrated in Figure 14c, immediately preceding dropout. Figure 14d illustrates the simulation at 8.8 seconds immediately after the ingestion of ullage gas into the feed outlet. The estimated RP-1 tank residual is 170 lbm. Though considerably larger than that attainable



a) 0 seconds b) 7 seconds

c) 8.6 seconds d) 8.8 seconds

Figure 14. RP-1 Tank Terminal Drain Results.

with non-dropout outlet designs, the current outlet design meets usable propellant goals for the X-34 MPS.

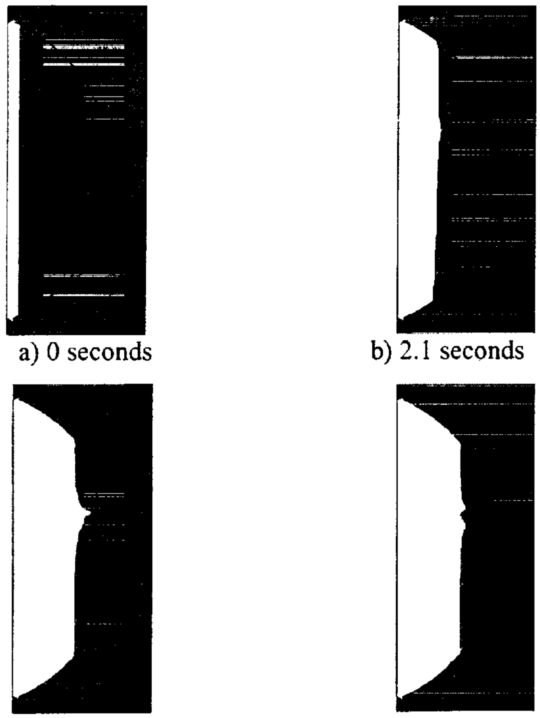
Aft LOX Tank Simulation

Figure 15a illustrates the initial condition at 0 seconds. The initial fill level is 13 inches. Figure 15b illustrates the first indication of a surface depression at 2.1 seconds and a an 8 inch fill level. Dropout occurs at roughly after 3.4 seconds and a fill height of 4.8 inches corresponding to Figure 15c. In Figure 15d, at 3.5 seconds, the small splash of LOX back into the tank indicates the passage of ullage into the feedline.

The estimated aft LOX tank residual is 180 lbm. Though not optimized to minimize residual mass, this 180 lbm LOX residual meets usable propellant requirements for the X-34 MPS.

SUMMARY

Feed systems have been designed which fulfill design requirements for the X-34 hypersonic research vehicle. The resultant feed system design supports engine propellant flow rate and turbopump Net Positive Suction Pressure (NPSP) requirements and



a) 0 seconds b) 2.1 seconds

a) 3.4 seconds b) 3.5 seconds

Figure 15. Aft LOX Tank Terminal Drain Results.

accommodates engine thrust vectoring as required for vehicle control. The LOX feed system was reviewed in greater detail than the RP-1 feed system, as it contains components related to the use of dual LOX tanks not present in the RP-1 system. The LOX and RP-1 feed systems are very similar in function/design.

Propellant tank pressurization profiles meeting both tank Maximum Expected Operating Pressure (MEOP) and main engine turbopump NPSP requirements is presented. The LOX tank pressurization profile requires a drop in ullage pressure during flight to stay within tank MEOP, while the RP-1 results allow pressurant flow to be cut off during engine operation to conserve helium pressurant.

The analyses of propellant tank ullage motion between release of the X-34 from its carry vehicle suggests there to be no problem with the ingestion of ullage gas into the RP-1 feed system at engine start. Analysis of the LOX system revealed the possibility of the ingestion of a small volume of ullage at engine start. As a result, the maximum time between the last propellant conditioning vent cycle and tank pressurization is limited to 20 seconds, which ensures the collapse of the gaseous oxygen ullage existing near the saturation curve into a sub-cooled LOX state eliminating the possibility of ullage ingestion.

The last analyses provide insight into the terminal drain characteristics of the LOX and RP-1 tanks. These terminal drain analyses result in conservative estimates of the residual propellant mass. Similar analyses may also be useful in determining the timing of engine shutdown in a full performance mission.

ACKNOWLEDGEMENTS

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REFERENCES

1. Fisher, M. and Ise, M. (1998), "Low Cost Propulsion Technology at the Marshall Space Flight Center–Fastrac Engine and The Propulsion Test Article," AIAA Paper No. AIAA-98-3365.

2. Sgarlata, P. and Winters, B. (1997), "X-34 Propulsion System Design," AIAA Paper No. AIAA-97-3304.

3. Sullivan, B. and Winters, B. (1998), "Propulsion System Overview," AIAA Paper No. AIAA-98-3516.

4. Hedayat, A., Steadman, T.E., Brown, T.M., Knight, K.C., White, C.E., Jr. and Champion, R.H., Jr. (1998), "Pressurization, Pneumatic, and Vent Subsystems of the X-34 Main Propulsion System," AIAA Paper No. AIAA-98-3519.

5. Brown, T.M., McDonald, J.P., Hedayat, A., Knight, K.C., and Champion, R.H., Jr. (1998), "Propellant Management and Conditioning Within the X-34 Main Propulsion System," AIAA Paper No. AIAA-98-3518.

6. <u>FLOW-3D Version 6.0</u>, Flow Science, Inc., Los Alamos, NM