REPRINT
IN-20
NMF/ISS ACC.
372 745
p. 21

AIAA-98-4032
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34th AIAA/ASME/SAE/ASEE
Joint Propulsion Conference & Exhibit
July 13-15, 1998 / Cleveland, OH

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ABSTRACT

The X-34 program is a joint industry/government program to develop, test, and operate a small, fully-reusable hypersonic flight vehicle, utilizing technologies and operating concepts applicable to future Reusable Launch Vehicle (RLV) systems. The vehicle will be capable of Mach 8 flight to 250,000 feet altitude and will demonstrate an all composite structure, composite RP-1 tank, the Marshall Space Flight Center (MSFC) developed Fastrac engine, and the operability of an advanced thermal protection systems. The vehicle will also be capable of carrying flight experiments. MSFC is supporting the X-34 program in three ways: Program Management, the Fastrac engine as Government Furnished Equipment (GFE), and the design of the Main Propulsion System (MPS). The MPS Product Development Team (PDT) at MSFC is responsible for supplying the MPS design, analysis, and drawings to Orbital. The MPS consists of the LOX and RP-1 Fill, Drain, Feed, Vent, & Dump systems and the Helium & Nitrogen Purge, Pressurization, and Pneumatics systems. The Reaction Control System (RCS) design was done by Orbital. Orbital is the prime contractor and has responsibility for integration, procurement, and construction of all subsystems. The paper also discusses the design, operation, management, requirements, trades studies, schedule, and lessons learned with the MPS and RCS designs.

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INTRODUCTION

The X-34 program is managed by Marshall Space Flight Center (MSFC) under Code R. The Orbital lead team consists of various industry partners and 6 NASA centers. The NASA centers that are involved with the project are MSFC, Kennedy Space Center (KSC), Dryden Flight Research Center (DFRC), White Sands Test Facility (WSTF), Ames Research Center (ARC), and Langley Research Center (LaRC)[1]. Holloman Air Force Base and White Sands Missile Range (WSMR) will support ground and flight testing (Figure 1). MSFC has three separate functions in the X-34 program: 1) as program management, 2) as supplier of the Fastrac engine, and 3) as Main Propulsion System (MPS) design supplier to Orbital. The relationship between Orbital and the MPS supplier will be discussed in this paper.

VEHICLE DESCRIPTION

The X-34 vehicle is based loosely on the Pegasus launch vehicle design (Figure 2), as well as, aspects of the X-15[2]. Pegasus is a winged, expendable, solid propulsion launch vehicle capable of placing ~500 lbm of payload in low earth orbit. The Pegasus is launched from the underside of the Orbital L-1011 at an altitude of 38,000 ft. The X-15 was a piloted, hypersonic, liquid propulsion, aircraft. The X-15 was powered by the XLR-99 liquid oxygen (LOX)/ Ammonia (NH3) engine and carried aloft by a B-52 prior to release. The

X-34 is a single stage LOX/rocket propellant 1 (RP-1) fueled launch vehicle. The X-34 is approximately 58 feet long with a wing span of nearly 28 feet[3]. Unlike conventional launch vehicles, the X-34 is carried for up to 2.5 hours in a horizontal captive carry mode. This is done without resupply of propellant. The X-15 used uninsulated tanks and was refueled from the B-52. The X-34 Vehicle uses the Orbital L-1011 as the first stage to carry it to launch altitude of 38,000 ft (Figure 3). The Fastrac engine ignites at 7 seconds after it is released from the L-1011. The delay in igniting the engine is to ensure that the X-34 achieves a safe distance from the L-1011. The vehicle then transitions to a vertical orientation to exit the atmosphere. After engine shutdown, the vehicle becomes a glider for reentry and aircraft style landing. In the event of an aborted engine ignition, the vehicle must dump the propellant to achieve landing weight.

The vehicle structure is all composite material. The bulkheads and side panels are composite with an internal aluminum honeycomb structure. The side panels, bulkheads and longerons tie the structure together to distribute the thrust, captive carry, and flight loads. The propellant tank attach rings are slotted on the forward end and pinned on the aft end to prevent airframe structural loading of the tanks.

The propellant is stored in three tanks (Figure 4). The single, 190 ft^3, RP-1 tank is made of composite material and has metal manhole covers. The LOX tanks are made of aluminum and have a combined volume of 304 ft^3. All three tanks have internal compartments that are used to control sloshing and to prevent an adverse center of gravity (cg) shift in an abort situation. The tanks have internal siphons, vent tubes, compartment check valves and the LOX tanks have liquid level sensing instrumentation.

The main thrust for the vehicle is provided by the MSFC developed Fastrac engine. It generates 60,000 lbf with 310 seconds of specific impulse. The engine has a single shaft pump, ablative composite nozzle and a 600 psi chamber pressure.[4] The net positive suction pressure (NPSP) requirements for the pump inlets are 28 psi at nominal flowrates of 144 and 66 lbm/s for LOX and RP-1, respectively.

The MPS includes the LOX and RP-1 Feed, Fill, Drain, Dump, Bleed, Vent, Relief, and Pressurization, Pneumatics, Purge and Pogo subsystems. The MPS functions in the loading, storing, delivery, and disposing of propellants. This is done while assuring all requirements for safety and performance are met during all operational phases of the mission including ground operations. The interaction of the MPS subsystems, Engine and RCS are shown in Figure 5.

The X-34 RCS is designed to provide the vehicle with directional control when the vehicle's control surfaces cannot respond to atmospheric disturbances or meet the requirements of commanded maneuvers. The RCS provides directional control through torque, that is generated by thrusters, fired alone or in combinations, whose lines of force do not pass through the vehicle cg.

REQUIREMENTS

The requirements define what the system must be capable of accomplishing. The overall vehicle requirements were defined by the X-34 Program Office. Orbital was tasked to provide a vehicle that was capable of flying Mach 8, to 250,000 feet altitude, 25 times a year. The vehicle is a test bed for RLV technologies including: thermal protection system, quick turnaround operations, reusability, autonomous flight and landing, composite airframe structure and tankage design, flush air data system and low cost propulsion.

From these, requirements were derived and imposed on the MPS. Of these, the most challenging to achieve were the weight allocation (excluding engine, tanks, or RCS) of 976 lbm, dumping of propellant within 300 seconds for safe landing, two fault tolerance to loss of crew or L-1011. Additionally, requirements for reusability, automated landing, two fault tolerance, and a design reliability of .99 had broad ramifications to the MPS design. The impact of these requirements will be discussed in detail later. All MPS requirements are documented in the Level III MPS Requirements Specification.

The performance requirements for the RCS are driven primarily by the guidance, navigation, and control (GN&C) parameters. Since the vehicle is not deploying a payload, no significant attitude maneuvers are required. Instead, the system is designed to react to small disturbances that the vehicle will encounter as it travels through the upper atmosphere.

The Loads and Design Criteria[5] document provided the thermal, loads, natural, dynamic, and static environments design requirements for the MPS and structure. The design adheres to MIL-STD-1522[6].

The Level III requirements were "flowed-down" to the MPS PDT at MSFC through the Level IV

Requirements and Verification document. This document is the instrument that the PDT uses to verify that the design meets the intent of the Level III requirements.

The MPS-to-Vehicle Interface Control Document (ICD) is a co-signed document between Orbital and the MSFC MPS team. It is used to document the interface requirements between the MPS and other systems on the vehicle. Changes to the design which impact the ICD must be documented here and in the Level III requirements so that configuration control is maintained.

The Engine-to-Vehicle ICD is a co-signed document between the Fastrac engine team and Orbital. This document is referenced in the MPS-Vehicle ICD for engine interface requirements.

The design is verified using the requirements and verification database system. This is an electronic database that allows the designers and analysts to coordinate their efforts and assure that the final design meets the requirements.

DESIGN

Approach

Orbital is the design lead and has responsibility for the oversight of the design, procurement of the hardware, and testing of the vehicle. The Marshall MPS PDT serves as a support contractor to Orbital. MSFC is responsible for the delivery of manufacturing, assembly, and installation drawings, component specifications, and analyses which support the requirements.

These analyses computational fluid dynamics (CFD), thermal, fluids systems, two fault tolerance, operations, and assembly. In addition, the PDT is responsible for the creation of the ICD and Level IV requirements document.

The design of the X-34 MPS had several features that are the result of the unconventional launch and landing requirements dictated by the fully reusable aspect of the vehicle. Each subsystem is described below.

Propellant Tanks

The design of the propellant tanks required that they minimize sloshing of liquid. However, they must still perform the function of propellant delivery to the engine and allow for tank pressurization. This resulted in the use of check valves that allow propellant to flow aft and the ullage gas to flow forward as shown in Figure 6. This design also impacted the way that the tanks were filled. Filling the tanks from the aft end through the dump line requires that each compartment be filled to the top before propellant spills over to the next compartment. This required that the LOX tanks be properly chilled prior to spill over. Testing performed on the LOX qualification tank using Liquid Nitrogen (LN2) demonstrated this procedure. The qualification tank is shown in Figures 7 & 8.

Between the two LOX tanks, it was necessary to design a system that would not trap an ullage pocket in the forward compartment of the aft tank. This was accomplished by adding check valves to the ullage and liquid transfer lines as shown in Figure 9.

The requirement to keep the total landing weight below 17,500 lbm and the vehicle dry weight set the maximum propellant residuals limits to 5% of the initial propellant mass. During propellant dump, the vehicle is in a roughly horizontal orientation. This meant that siphons were needed in all of the tanks to assure the optimum amount of propellant was removed for the given vehicle trajectories. However, during main engine burn the vehicle transitions from the horizontal to a vertical orientation. This meant that with the siphons, the usable propellant would be reduced below the requirement of 27,500 lbm. As a result, the cover plates of the RP-1 and aft LOX tanks have two outlets; one for the dump/abort case and one for the flight case. The outlets are shown in Figure 10. Extensive CFD modeling, using FLOW-3D[7], was used to simulate the drop, engine start, and tank depletion (burn and dump) transients to determine the optimum "cut" angles for the siphons and the location of low level cutoff sensors.[8]

LOX Feed Subsystem

The LOX and RP-1 Feed subsystems are designed to transfer propellants from the tanks to the engine in either the horizontal or vertical orientation of the vehicle. The engine has a gimbal requirement of +10/-8 deg in Pitch and +/- 3 deg in Yaw. This motion, along with movement of the thrust structure and engine under thrust, and the translation of the aft LOX tank dome due to cryogenic shrinkage, combines to add significant design requirement on the feedsystem.

The resulting LOX Feed subsystem design is a 4.5" Inconel tube with two dual axis gimbals, a z-axis pinned gimbal, and a pressure compensating elbow. Due to volume constraints, the outlet from the LOX tank required a sump to minimize the flow losses in turning the flow 90 degrees to avoid the engine thrust mount. The line also has a prevalve, flowmeter, and filter as shown in Figure 11. The prevalves used in the LOX system are 4" pneumatic ball valves designed by Ketema. The same prevalve is used in the RP-1 system. Due to geometric consideration the valve has two actuator configurations. The feedline has one hanging support located on the down stream side of the prevalve.

LOX Fill and Dump Subsystem

The LOX Fill and Dump subsystem provides for transfer of propellants overboard when the vehicle is in a roughly horizontal orientation during flight and provides a means by which to fill the tanks during ground operations. The line must provide sufficient flow for filling the LOX tanks in no greater than 60 minutes and dumping within the required 300 second trajectory window. This line exits the aft LOX tank aft manhole cover, is routed down the starboard side of the vehicle, and exits through the aft bulkhead.

The fill and dump line is a 4" Inconel tube with a universal bellows, a flowmeter, the same 4" Ketema control valve, and has a quick disconnect GSE fitting 4" outside of the aft bulkhead. The LOX dump line is supported by one fore-aft sliding bracket.

RP-1 Feed, Fill, and Dump Subsystem

The RP-1 system uses the same trunk line for the feed, fill, and dump functions. This configuration was necessary due to weight and packaging concerns. The aft end of the trunk branches and has one valve for feed and one for dump & fill. As with the LOX feedline, the aft portion of the RP-1 line must accommodate the same vehicle structural deflections and engine gimballing while providing propellant flow to the engine. The gimballing section of the RP-1 feedline is a 4" Inconel tube with the same component layout as the LOX feedline. The feed and dump lines are routed to avoid the thrust structure and engine mounting bulkhead. The aft section of the RP-1 line is shown in Figure 12.

The forward end of the subsystem has two isolation valves; one for feed and one for dump. To accommodate the motion of the RP-1 tank, the bulkheads, and fuselage, the main trunk has a pressure compensating elbow at the forward end and four bellows along the line at the bulkheads. The feedline is supported at the bulkheads by a combination of sliding and fixed supports. The forward section is shown in Figure 13. The bulkhead locations can be seen in Figure 6.

The RP-1 dump system is also used to fill the RP-1 tank and is required to support filling in no greater than 45 minutes and dumping within the required 300 second trajectory window. A quick disconnect GSE fitting attaches to the dump lines 4" outside of the aft bulkhead. The RP-1 and LOX tanks are filled serially with the vent valves open.

Vent Subsystems

The vent subsystems provide tank over-pressure relief, propellant conditioning during captive carry, and venting during filling. The tank vent subsystems for both the LOX and RP-1 use a common design, 2.5" Ketema vent/relief valve. The vent systems have tubes, internal to the tanks, that will allow ullage pickup in the vehicle vertical and horizontal orientation.

The LOX internal vent tube has a liquid level sensor on the end to determine when the tank is full (Figure 14). A bypass relief valve is required to meet the two-fault tolerance requirement, due to the self pressurization capability of cryogens. The RP-1 tank is filled until it spills into the vent line and then a ground support equipment (GSE) flowmeter is used to adjust the level appropriately. Figure 15 shows the internal vent line for the RP-1 system.

Pressurization

The functions of the pressurization system are to maintain the propellant pressure at the engine inlet during flight and to force the propellants out of the tanks during a dump, while not exceeding the tank operating pressures of 75 psi for LOX and 100 psi for RP-1. The Pressurization subsystem helium storage is accomplished by four Structural Composite Industries (SCI) bottles with 6.2 ft^3 storage each at 5000 psi pressure (Figure 16). The pressurization subsystem has 48.5 lbm of usable Helium and 76 lbm total stored in the bottles. The 5000 psi gas is regulated to 350 psi. Then solenoid valves, controlled by the avionics which senses the tank pressure, are used to meter gas flow to the propellant tanks to maintain the proper pressure. Check valves are used in the lines to prevent any mixing of propellants and on the LOX side to keep the cryogens from damaging the solenoids. The pressurant is introduced into the tanks through a diffuser, which is designed to operate when submerged or dry.

The pressurant tanks are connected by a 1" manifold. Downstream of the regulators, the RP-1 and LOX lines branch to ¾" and 1" lines respectively. The RP-1 pressurization system has two solenoid valves in parallel, two check valves in series, an orifice, and is completed by the tank diffuser. The LOX leg is the same with the addition of a third check valve. The additional check valve was needed to make the solenoids two fault tolerant to seeing LOX or GOX; the solenoids are not qualified for Oxygen service. The parallel solenoids on the pressurization legs are the only functional redundant components in the MPS. Failure of one of the pressurization solenoids would prevent a normal flight and also prevent the dumping of propellants. Knowing this, it was deemed prudent to provide this redundancy for mission assurance.

A full transient analysis of the system[9], including pressurant collapse in the cryogens, was performed to determine the pressurant mass requirement A steady state model was used to determine if the vent system could respond in time to prevent a tank rupture.[10] Trade studies were performed on the design of the pressurization system. The studies evaluated the benefits between regulators, single orifice, and multiple orifices in an attempt to simplify the system and still comply with the two fault tolerant requirement[9].

Pneumatics, Purge, and Pogo

The pneumatic and purge subsystems provide Helium (flight) and Nitrogen (ground operations) gases for actuation of the MPS and engine pneumatic valves, Helium for the engine turbopump spinstart, engine start purge, engine shutdown purges, and Inter-Propellant Seal (IPS) purge, and Helium and Nitrogen for post flight safeing operations. This subsystem also provides for ground purges of the feedlines to prevent contamination during engine removal

The pneumatic purge subystem uses 1 SCI bottle in the front pressurization bay and 2 Lincoln Composite bottles located in the aft end of the vehicle, under the aft LOX tank (Figure 17). The pneumatics subsystem stores 25.5 lbm of Helium with 16 lbm of the gas usable. Most of the pneumatics purge helium is required during engine startup for the spinstart (0.5 lbm/s for 2 seconds) and startup purges (0.51 lbm/s for 2 seconds). This 1.1 lbm/s flow is the driving requirement for sizing many of the components and lines. A ½" trunk line feeds the aft two bottles from the front and then a 1" manifold is routed to the ¾" line for the spinstart and IPS. The pneumatic and purge subsystem contains 2 - ¾" regulators, 2 - ¼" latching solenoid valves, 2 - 1" latching solenoid valves, 3 - ¾" solenoid valves, 2 - ¾" blanking valves, 8 - 3-way solenoid valves, 4 - ¾" check valves, and 2 - ¼" filters

Transient analysis of the complete system was done to determine reaction times, volume requirements, regulator set pressures, and flowrates.[9]

The Pogo subsystem is ground charged and sealed for flight. Testing to determine the requirements for the Pogo subsystem will be completed at Stennis Space Center later this year..

Reaction Control System

A cold gas system was chosen for the RCS because of its simplicity and operability. The choices for propellants were limited to gaseous Helium (GHe) and gaseous Nitrogen (GN2); since both gases were already being used on the vehicle in other systems. Helium provides better performance than Nitrogen on a mass basis, but it provides less performance on a volumetric basis. The amount of propellant storage available was limited by the size of the pressurant tanks and the dimensions of the vehicle. Thus Nitrogen was chosen for the X-34 RCS application.

A schematic for the RCS is shown in Figure 18. The system is operated in three modes: load, active, and safe. The Nitrogen is loaded through a ground support connection isolated by a manual valve. Since the vehicle will be operated out of WSMR, the GN2 is filtered to minimize system contamination during the fill process. The nitrogen is stored in two high pressure composite bottles. The bottles are isolated from the rest of the system by a latching piloted solenoid valve. The latching feature of this valve is included so that a continuous voltage is not required on the valve to keep the system operational. Once actuated, the pilot valve is latched and the main valve remains open as long as there is pressure on the up stream side of the valve.

Once the system is activated by opening the isolation valve, the nitrogen flows toward a thruster manifold through a high pressure regulator. The high pressure regulator reduces the pressure of the gas from 5000 psi to 1100 psi. The outlet pressure of the regulator is slightly higher than what is required at the thruster inlet, thus accounting for pressure losses during flow from the regulator to the inlet of the thrusters. The pressure regulator maintains a constant inlet pressure to the thruster inlets; this in turn provides constant thrust during operation. The regulator can operate in a full-open position if the pressure in the propellant tank drops below the regulator set point. This is not a desired method of operation but is accounted for in the usable propellant analysis. Operating the RCS in this manner will generate a decreasing thrust level until the Nitrogen is completely depleted from the bottles.

The RCS consists of thruster nozzles, pressurant bottles, and a feed system. The feed system consists of a regulator, solenoid valves, and high pressure tubing.

The baseline RCS nozzles chosen were simple conical divergent sections. This type of nozzle is typically used to provide a shock free expansion of propellants. In addition, they are simple to manufacture. The RCS nozzles, used on the X-34, experience some losses due to non-axial flow and weak expansion waves emanating from the nozzles under near-vacuum conditions.

A pair of high pressure vessels designed and currently in production by SCI and Lincoln Composites were selected to meet the storage requirement of 7.1 ft^3. The total combined volume of the SCI (6.27 ft^3) and Lincoln Composites (1.10 ft^3) bottles is 7.37 ft^3. This volume is sufficient to meet the storage requirements with some margin.

The feed system consists of high pressure tubing that directs the high pressure Nitrogen from the storage bottles located in the front end of the vehicle, through a single 1" tube, to each of the 10 thruster assemblies. The thruster assemblies are made up of two pilot operated solenoid valves in series which are connected to nozzles customized for the X-34. The solenoid valves are arranged in a nominally open and a nominally closed configuration. The tube routing and placement of components in the system were designed to assure that pressure drops are nearly equal at each nozzle. This consistent pressure drop provides consistent levels of thrust from each thruster. The constant level of thrust in turn will allow for a simpler control system.

Most of the tubing assemblies in the manifold are welded to minimize potential leak paths. However, components such as valves are installed with separable fittings to minimize replacement time for failed units. Each set of thruster assemblies are mounted directly to a vehicle side panel. These panels can be removed for engine maintenance. Each panel is removed from the vehicle by disconnecting one flexhose and one avionics umbilical connector. This design allows for simple and rapid access to the engine compartment for maintenance between flights. The design also simplifies repair work of the RCS thruster assemblies by allowing repair work to be performed on a bench versus the limited workspace in the vehicle.

SYSTEM INTEGRATION

A major portion of the PDT effort was focused on ensuring that each of the MPS subsystems were integrated with each other and the rest of the vehicle. The MSFC Systems Analysis and Integration Laboratory was responsible for the Mass Properties Report, Configuration Management Plan and Implementation, Interface Control Document, Requirements Verification Document, Verification Tracking/Closure, Instrumentation List, and Electrical Power Report. Computer Aided Design (CAD) file conversion became a critical element in the design process in assuring the design was functional.

SAFETY AND MISSION ASSURANCE

The requirement for two fault tolerance and a design reliability of .99 had some significant impacts on the design as well as the component selections. To understand the two-fault tolerance requirement, a Fault Propagation Logic model was employed using the MSFC enhanced Failure Environment Analysis System[11] (FEAS-M). This model depicts, in a logic format similar to a fault tree, how any credible failure would propagate through the system resulting in either a catastrophic or critical failure of the vehicle, and the associated mitigators and pivotal events. Catastrophic failure was defined, for this program, as loss of crew or damage to the L-1011. Critical failure was defined as loss of the X-34 flight vehicle. The two-fault tolerance requirement applies only to catastrophic events. Two fault tolerance means that the design has three (3) inhibits or controls in place where the loss of two will still be sufficient to prevent the undesired event from occurring. The results of the FEAS-M analysis fed into the Integrated Risk Assessment (IRA). The IRA is a combination of a traditional hazard analysis and a Failure Modes and Effects Analysis (FEMA). The IRA was used to determine the failure causes, probability, and corrective actions to prevent the potential failures. The results revealed 6 Criticality-1 (catastrophic) failures that the MPS is not designed to mitigate. These were weighted against the probability of occurrence and have been forwarded to Orbital to have waivers generated for the range at HAFB.

The design reliability study for the components was performed using mean time between failure (MTBF) data from the Department of Defense Reliability Analysis Center Non-electronic Parts Reliability Database (NPRD), MSFC SSME data, and Rocketdyne J-2 engine data. The NPRD provides a multitude of aerospace industry component data and was deemed most appropriate for application to the off the shelf components of the MPS. For the engine, the reliability analysis was performed using the combined MSFC SSME and J-2 developed with adjustments made for cycle, pressure, thrust, temperatures, part count and other parameters. The combined engine and MPS single mission design reliability was .997, which exceeds the goal of .995.

OPERATIONS

The requirements for a 24 hour turnaround to flight and the 25 flights per year drove the need for an MPS operations timeline to define all of the activities that take place from servicing, loading, preflight, captive carry, engine conditioning, drop, ignition, flight, shutdown, reentry, landing, post flight, and safeing. A valve sequence was also developed which provides all of the commands that are needed to operate the MPS through a normal and aborted mission. A separate document is also provided for the engine operation during a mission.

SYSTEM ANALYSIS

The systems analysis performed for the X-34 MPS is discussed in more detail in the papers presented by McDonald et al.[8], Hedayat et al.[9], and Brown et al[10]. The major activities are described here. Refer to the above papers for details.

The majority of the fluid flow analysis (dump, pressurization, pneumatic, and vent) and a portion of the heat transfer analysis using 1D and 2D models was conducted using a combination of the computer programs Generalized Fluid System Simulation Program (GFSSP)[12] and Rocket Engine Transient Simulation (ROCETS)[13]. These codes allowed for full transient, steady state, and trade study modeling.

The feedsystem performance and propellant inventory analysis was performed using an in-house tool that incorporates the vehicle trajectory, engine performance, ullage pressure profile, and varying tank geometry.[8] A CFD analysis was performed on the LOX and RP-1 feedsystems to determine what the pressure profile looked like at the pump inlets and also to confirm the previous analysis.

Propellant conditioning analysis during loading and captive carry was performed using a combination of closed form 1D and 2D models in combination with finite difference models. These were used to determine the effectiveness of the MPS thermal protection system, impact of the captive carry environment and what the usable propellant would be after the 2.5 hour captive carry. The environments used were provided by the Orbital thermal analysis group.

A combination of g vector analysis and CFD using Flow3D was used for determination of Propellant Orientation. These efforts were to determine the location of the ullage and propellant and their temporal proximity to the propellant tank outlets and dump pickup lines.

The stress analysis was performed using the PC based piping analyzes tool CAESAR II[14]. CAESAR II has the capability of modeling and analyzing the full range of static, dynamic and thermal loads which may be imposed on the system. Bends, valves and rigid joints were defined using elements contained in CAESAR II. Stress intensity factors for each piping element were calculated by CASEAR II per the B31.3 piping code. The expansion joint assemblies were modeled using the CASEAR II Expansion Joint Modeler. By defining the axial stiffness, transverse stiffness, and bellows diameter in the element spreadsheet an expansion joint or gimbal was created. The 3-D piping models were then plotted to scale to show volumes and visuals of the input information. Vehicle deflections, random vibrations, accelerations, pressures and thermal environments were then applied as boundary conditions or loads on the model. Stress, deflection and force data could then be recovered at any location in the model.

The two primary feedlines were designed to accommodate significant motion due to engine gimbal, as well as, structural deflections of the fuel tanks and thrust structure bulkheads. Because of the premium on space around the Fastrac engine, these lines could not deflect significantly under the intense loading conditions. Inverse kinematics analysis was performed by the X-34 team on the six degree of freedom feedlines using Deneb Robotics, Inc.'s Envision software[15]. The analysis was performed by the team to quantify range of motion of the various gimbals and bellows, as well as, check for interference with the X-34 structure and Fastrac three-dimensional envelope. Use of the robotics

CAD package also provided useful visualization of the active portion of the MPS for the team.

MANAGEMENT

A PDT was established with the required disciplines from MSFC to perform the design of the MPS in the most efficient manner. The PDT consisted of Civil Service and engineer support contractor and subcontract personnel from Design, Loads, Stress, Materials, Instrumentation, Dynamics, Kinematics, Reliability, Quality, Integration, Mass Properties, Configuration Management, CFD, Thermal, and Fluids analysis disciplines. All PDT efforts were planned and tracked using electronic Gantt charts and expedited through weekly team meetings with action item lists and approximately monthly technical interchange meetings with Orbital.

The Authority to Proceed (ATP) for the X-34 Program was issued in August 1996. The MPS PDT was involved in the conceptual design of the vehicle subsystems. The MPS PDT did not fully staff until late February 1997. At this point, the analysis of the MPS design was the primary concern. The design team was concurrently working conceptual layouts and updates based on results of the structural model and other analyses. The two-fault tolerance analysis, operations analyses, and component specifications were initiated during this time to assure requirements were properly impacted on the design and to assure the design was centered around off the shelf hardware.

The MPS Preliminary Design Review (PDR) was held in March 1997. The System Design Freeze (SDF) was held in May 1997. One result of the SDF was that a contract modification was made to add a nonpowered flight to the program. This delayed the first powered flight and extended the MPS design from September 1997 to May 1998. The MPS Critical Design Review (CDR) was held in December 1997. At this time the design was 80% complete. Following the CDR, the Review Item Discrepancies (RID's) were collected and resolved.

In March 1998, a manufacturing review was held with the feedsystem hardware vendor, Orbital, and MSFC. This resulted in some design changes to better match the manufactures capabilities, reduce cost, reduce weight, improve operability, and assembly time. The baseline design was delivered complete and on time in May 1998 per contract. The MPS PDT will continue at a significantly reduced level of effort in a sustaining engineering and design maintenance role until the hardware is delivered. At that time the PDT will participate in the buildup and testing of the MPS.

LESSONS LEARNED

Several observations can be made about the partnership between industry and government in low cost vehicle design efforts.

One observation can be made about the timing of starting the MPS detail design effort. The MPS design team got into full swing in January 1997. At that time trade studies were still ongoing with the placement of various subsystems and structure within the vehicle. Having the MPS designers onboard early did help in the allocation of space for the MPS but added to the rework that was required as the trades reached conclusion. The MPS PDT should not have been brought up to full staff until the SDF was completed.

Another observation was with the generation of component specifications and vendor selection. Specifications were generated and detail design began based on these at the completion of SDF. These specs had been used to secure rough order of magnitude (ROM) bids from vendors. However, final selection, negotiations and contracts on the specifications did not occur until several months later. This allows for the rethinking of components once the firm cost and capabilities of the components were made available. The result was that a significant number of components were changed. This also added significant rework by the designers and analysts.

The firm definition of component requirements as well as selection and involvement of the component manufacturers early on in the design cycle is critical. The initial drawings that were created were not vendor specific. Once the vendors were onboard after CDR and a manufacturing review was conducted, it became obvious that changes would have to be made to reduce cost and improve delivery time. The vendors should be under contract soon after SDF in order to better influence the design in a timely manner.

The use of a common CAD system is a requirement for a program such as this, where there are numerous interface concerns between 2 organizations. The program attempted this from the start, but budget constraints and schedule delays (due to retraining) necessitated separate systems between Orbital and MSFC. Although successful translators were developed, the process is still labor intensive. This resulted in the Orbital and MSFC CAD models always being out of sync by a few weeks.

The suppliers of the design and analysis should have formal notification and acknowledgment on all changes to specifications, interface drawings, and other engineering change notices that impact their subsystem. Without this communication, the supplier inevitably will get out of sync with the prime contractor.

Finally, with these points said, it should be understood that in a experimental flight program, with a compressed schedule and concurrent engineering, changes are inevitable. The teams that survive are the ones that learn how to adjust to this pace and environment.

ACKNOWLEDGMENTS

The author acknowledges and thanks the Product Development Team for their expertise, hard work, and dedication of the MPS efforts, without which, this project would not have been possible. Thanks to the Orbital team members for their leadership. Thanks to Intergraph for the development and maintenance of our web page and drawing database. Special thanks to the Sverdrup Technology team members for their support in analysis, design, operations, component specifications, and requirements development. Special thanks also to the Chief Engineer, Lab leads, and Sverdrup leads for making it happen: Jimmy Lee, Bob Vaughan, Ralph Arnold, Tony Harrison, Tom Owens, Ed Trentham & Kyle Daniel, Bill White, Karl Knight, and Richard Sheller.

REFERENCES

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

2. Wiswell, R., "X-15 Propulsion System," 334d AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Seattle, WA, July 1997.

3. Sgarlata, P. and Winters, B., "X-34 Propulsion System Design," 33 rd AIAA/ ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Seattle, WA, July 1997.

4. 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.

5. "X-34 Loads and Design Criteria", OSC X10001, Rev A, Orbital, Dulles, VA May 1997.

6. "Standard General Requirements for Safe Design and Operation of Pressurized Systems", MIL-STD-1522.

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

8. McDonald, J.P., Minor, R.B., Knight, K.C., Champion, R.H., Jr. (1998), "Propellant Feed Subsystem for the X-34 Main Propulsion System," AIAA Paper No. 98-3517.

9. 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.

10. 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.

11. Knight, K., and Christenson, R., "Failure Environment Analysis System -MSFC, An Enhanced Tool for Hardware Reliability in Design," AIAA, ASQC, IEEE, IES, IIE, SAE, SOLE, SRE, SSS Annual Reliability and Maintainability Symposium Computer Aided Engineering Workshop, Las Vegas, Nevada, 1996.

12. Majumdar, A. P., "A Generalized Fluid System Simulation Program In Fluid Networks," Report No. 331-96-003, Sverdrup Technology, Inc, / MSFC Group, Huntsville, AL, October 1996.

13. "ROCETS User's Manual," Pratt & Whitney, West Palm Beach, FL, January 1995.

14. <u>CAESAR II version 3.24d</u>, COADE Engineering Software, Houston, Texas (www.coade.com).

15. <u>Envision Version 4.0</u>, Deneb Robotics, Inc.'s, Troy, Michigan (www.deneb.com).

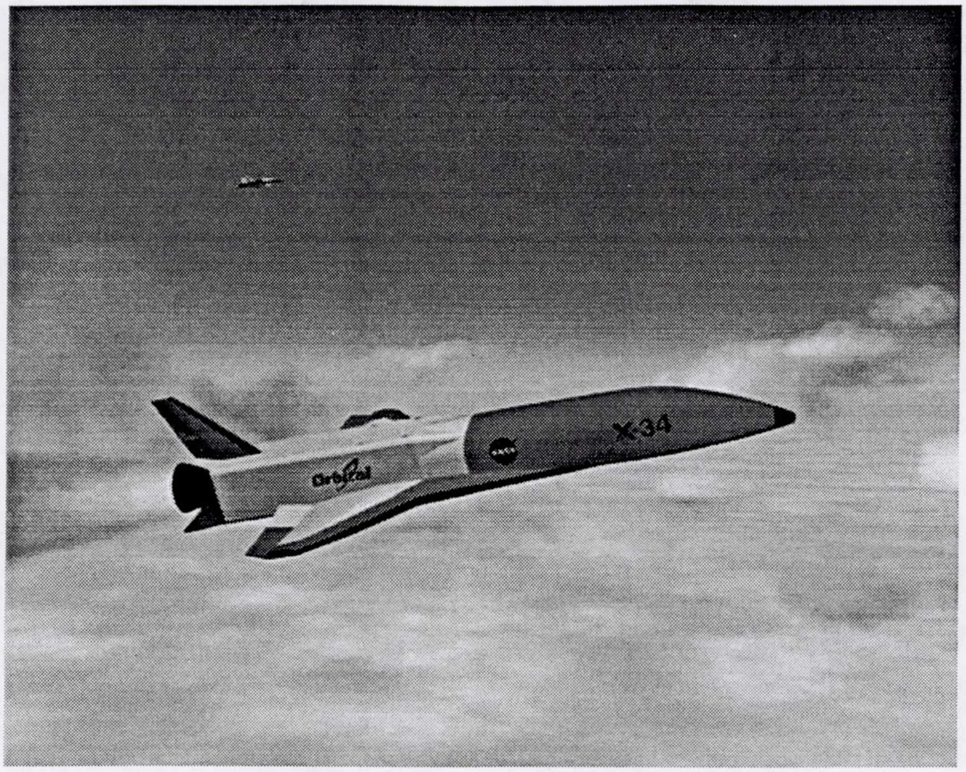


Figure 2 X-34 Vehicle

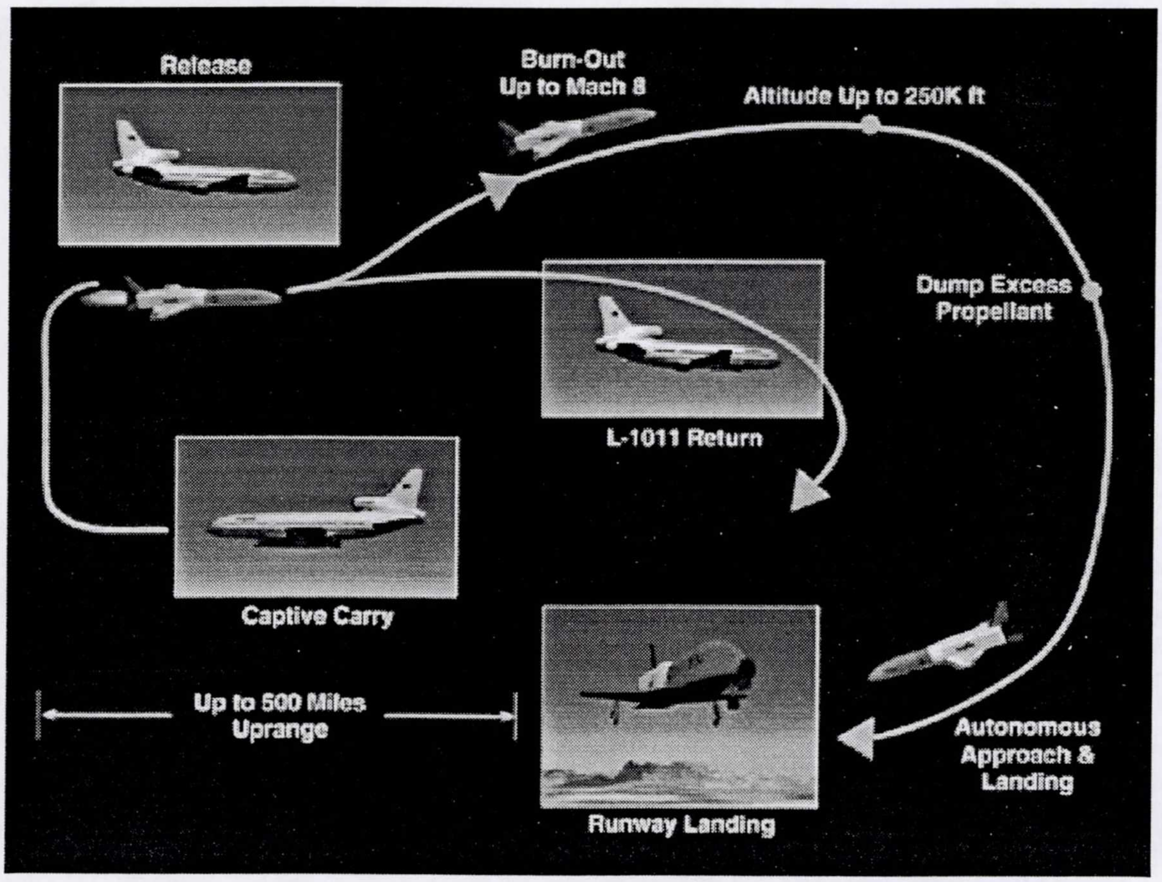
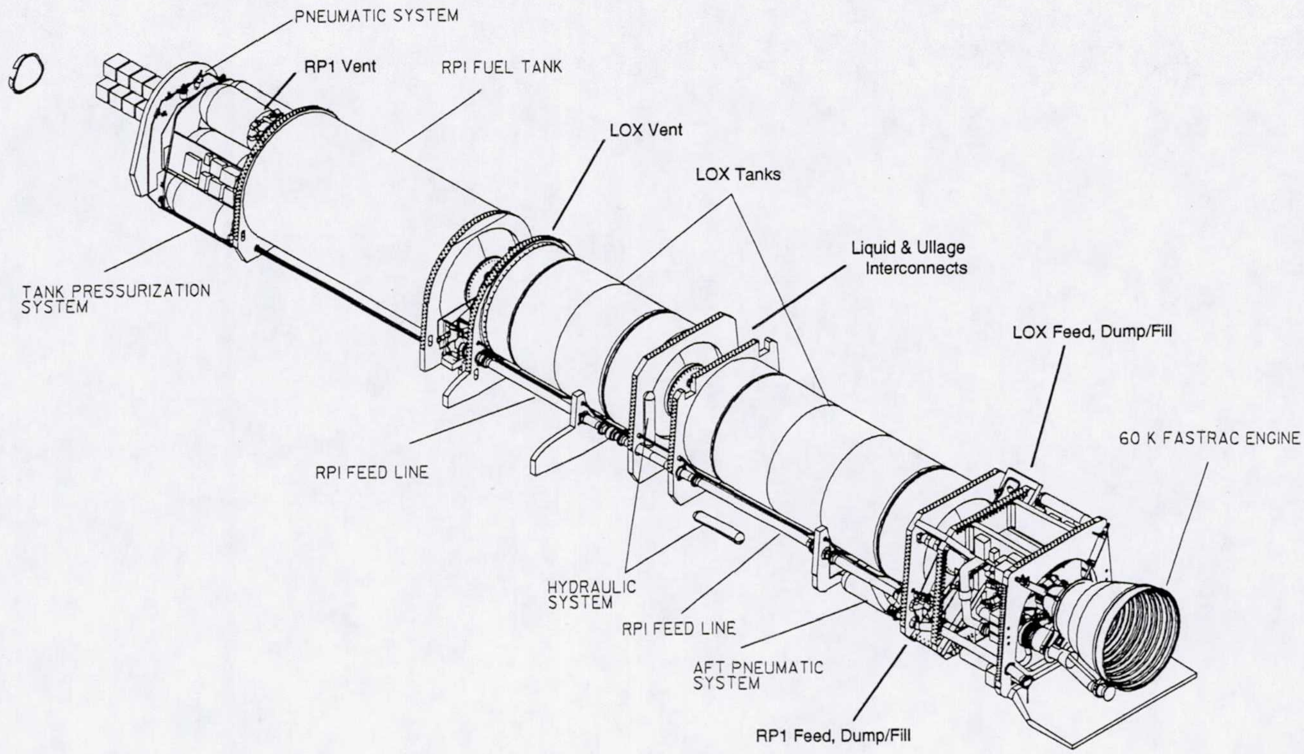


Figure 3 X-34 Flight Profiel



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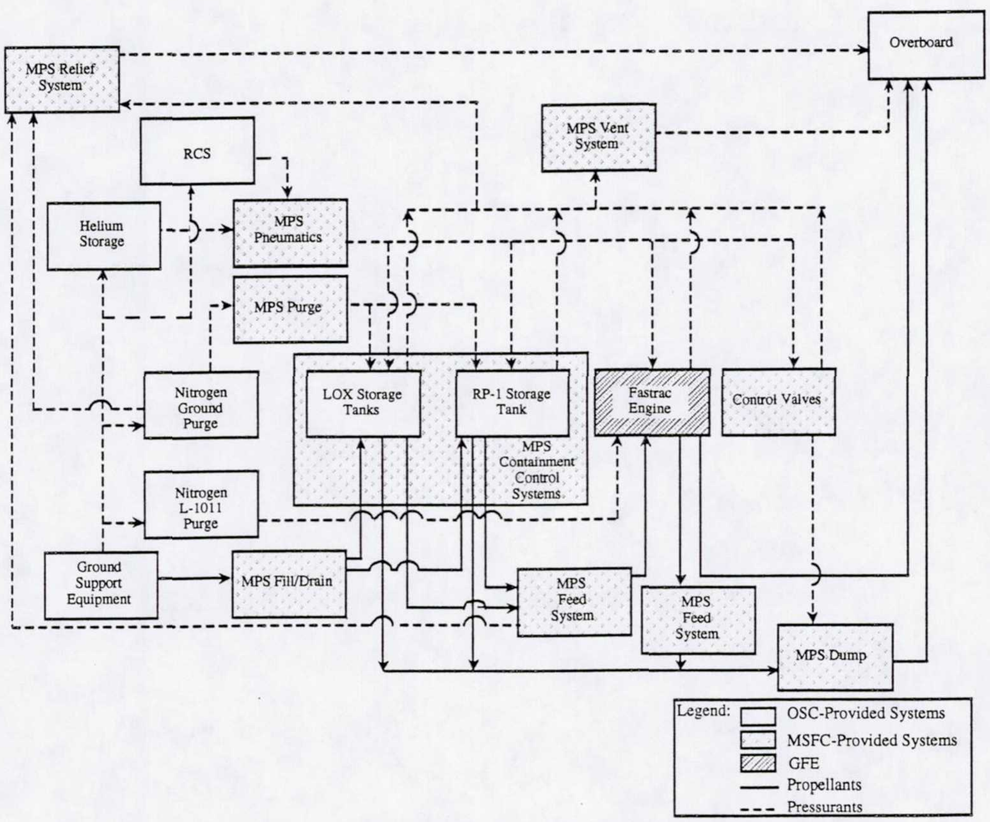

Figure 5 MPS System Interaction

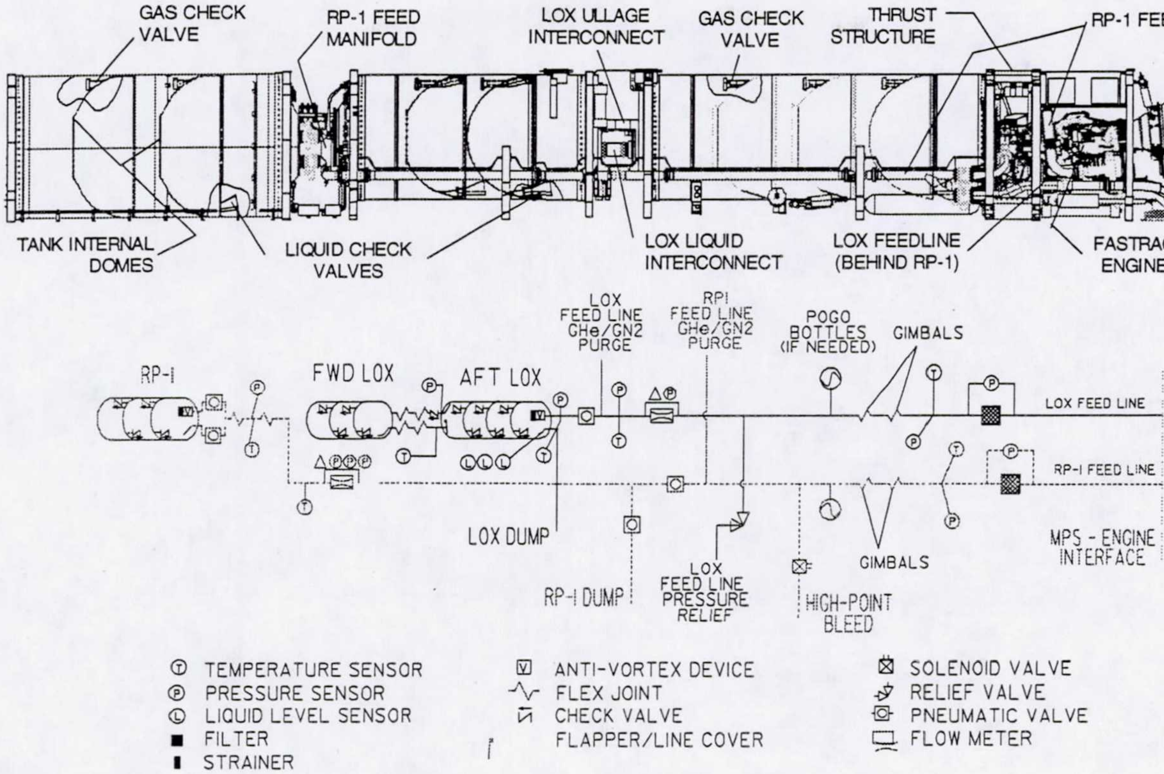

Figure 6 X-34 MPS Layout and Feed System Schematic.

Figure 9 LOX Tank Connection

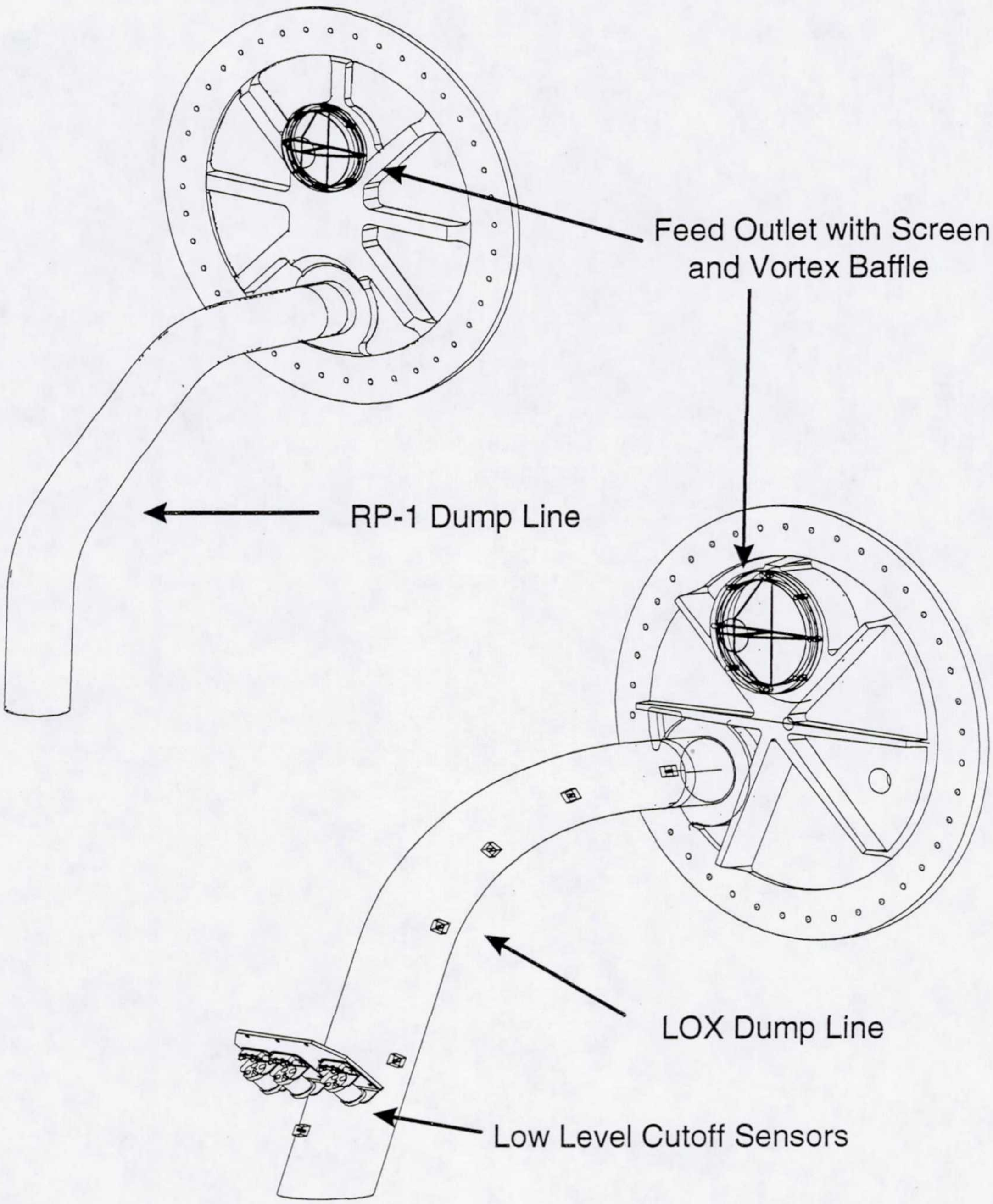

Figure 10 RP-1 and LOX Tank Outlets

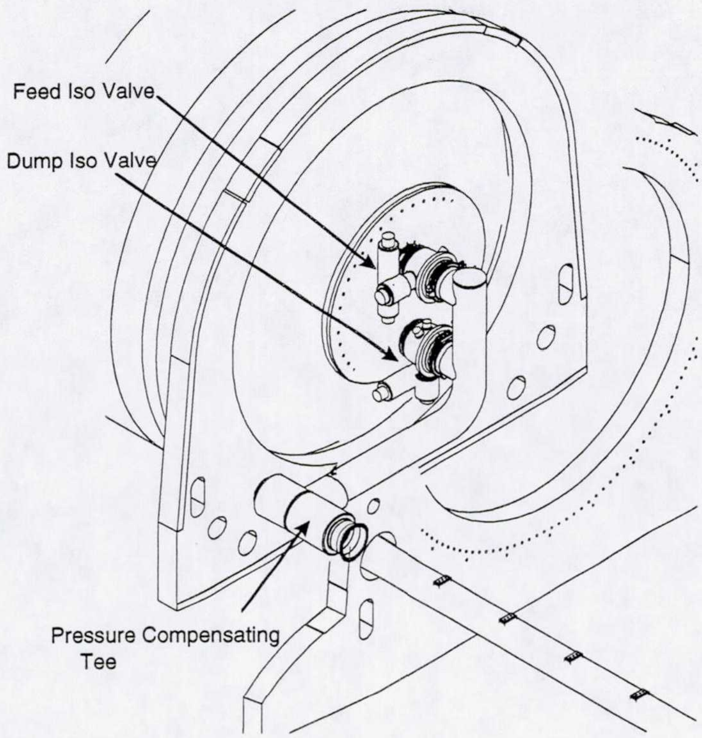

Figure 13 Forward RP-1 Feedsystem

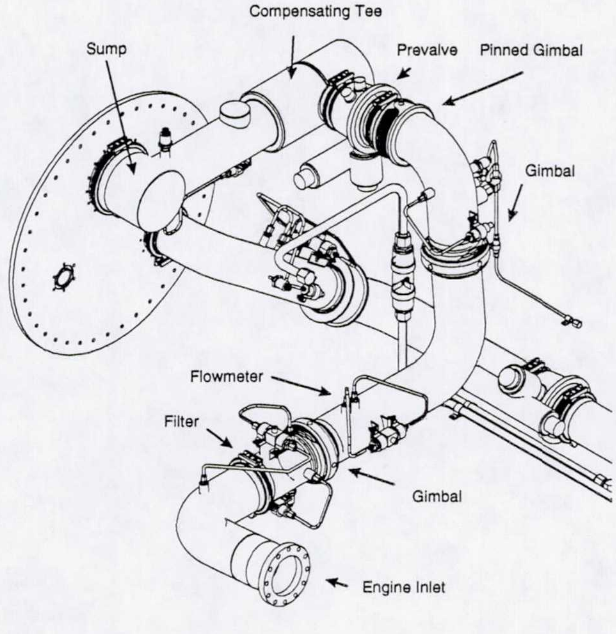

Figure 11 LOX Feedsystem

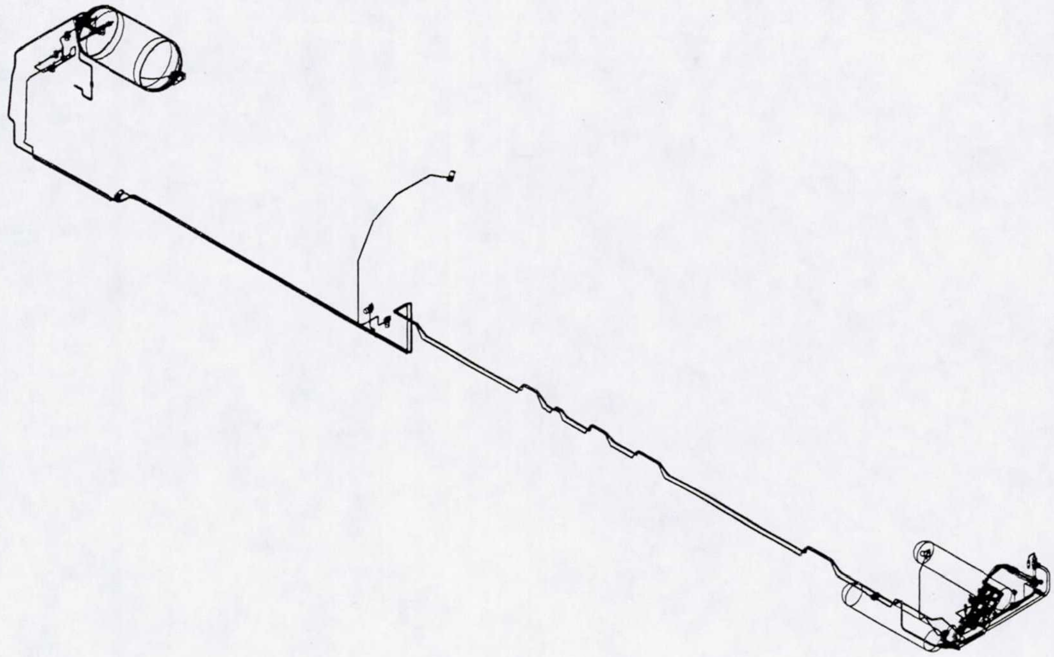

Figure 17 Pneumatics System

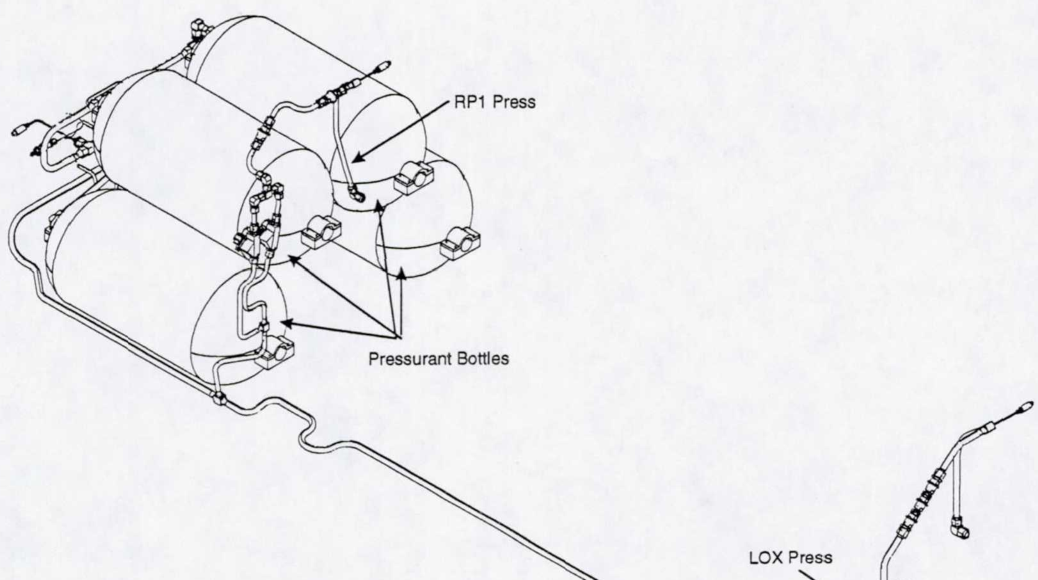

Figure 16 Pressurization System

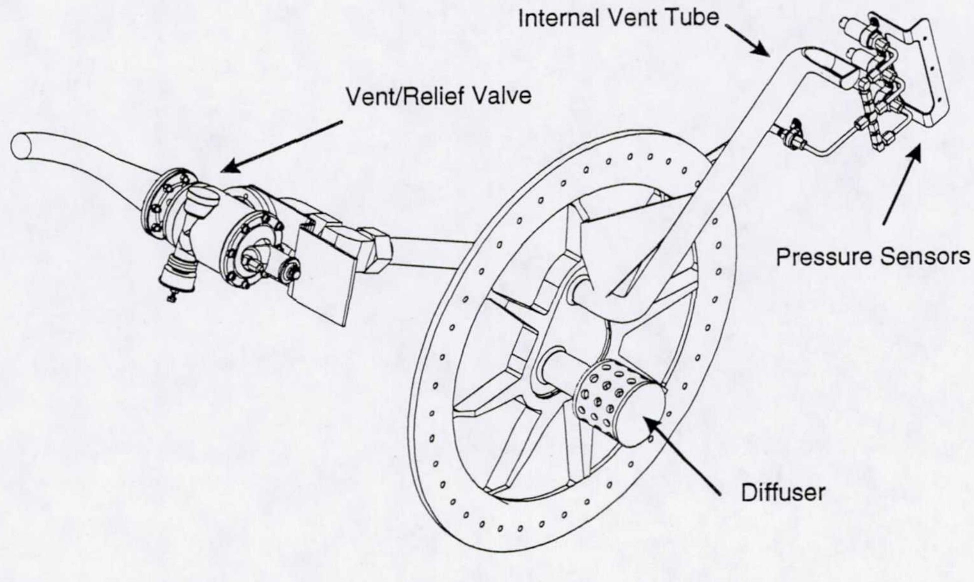

Figure 15 RP-1 Tank Vent Subsystem

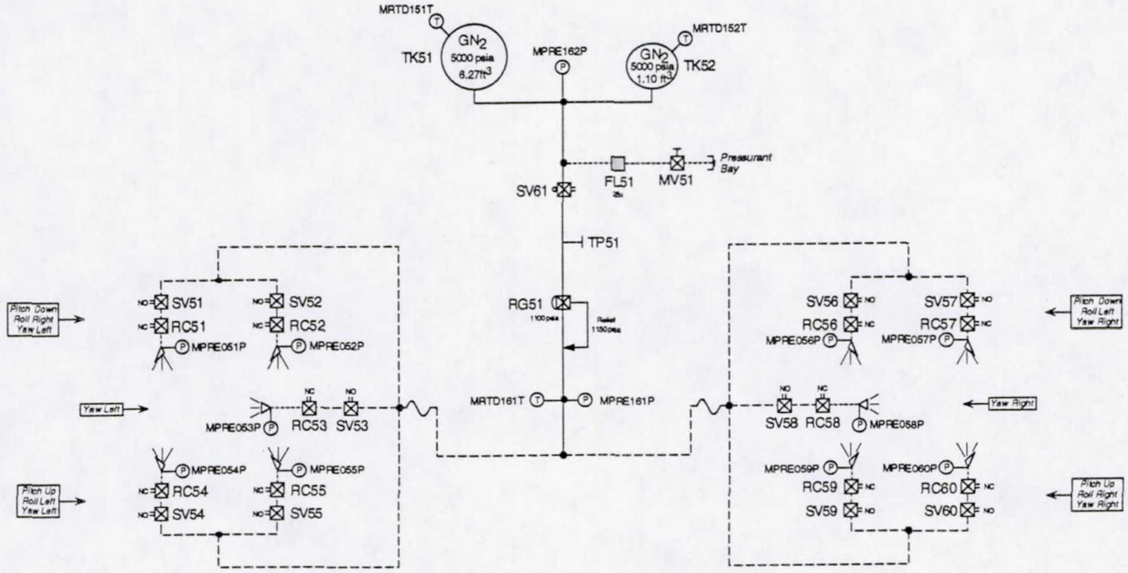

Figure 18 RCS Schematic

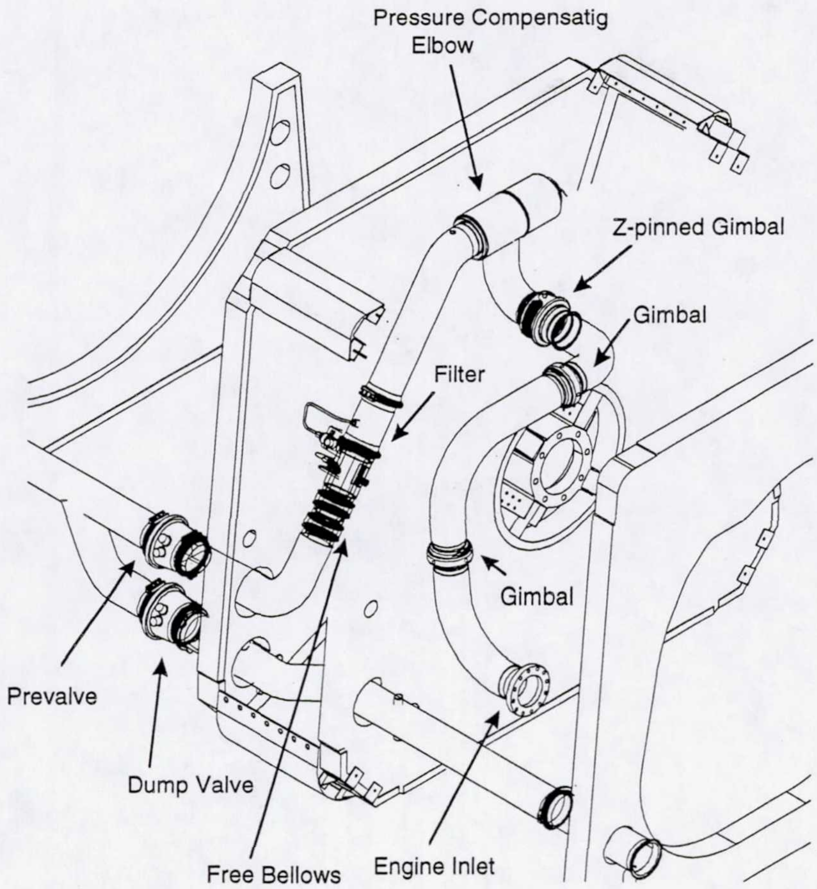

Figure 12 Aft RP-1 Feedsystem

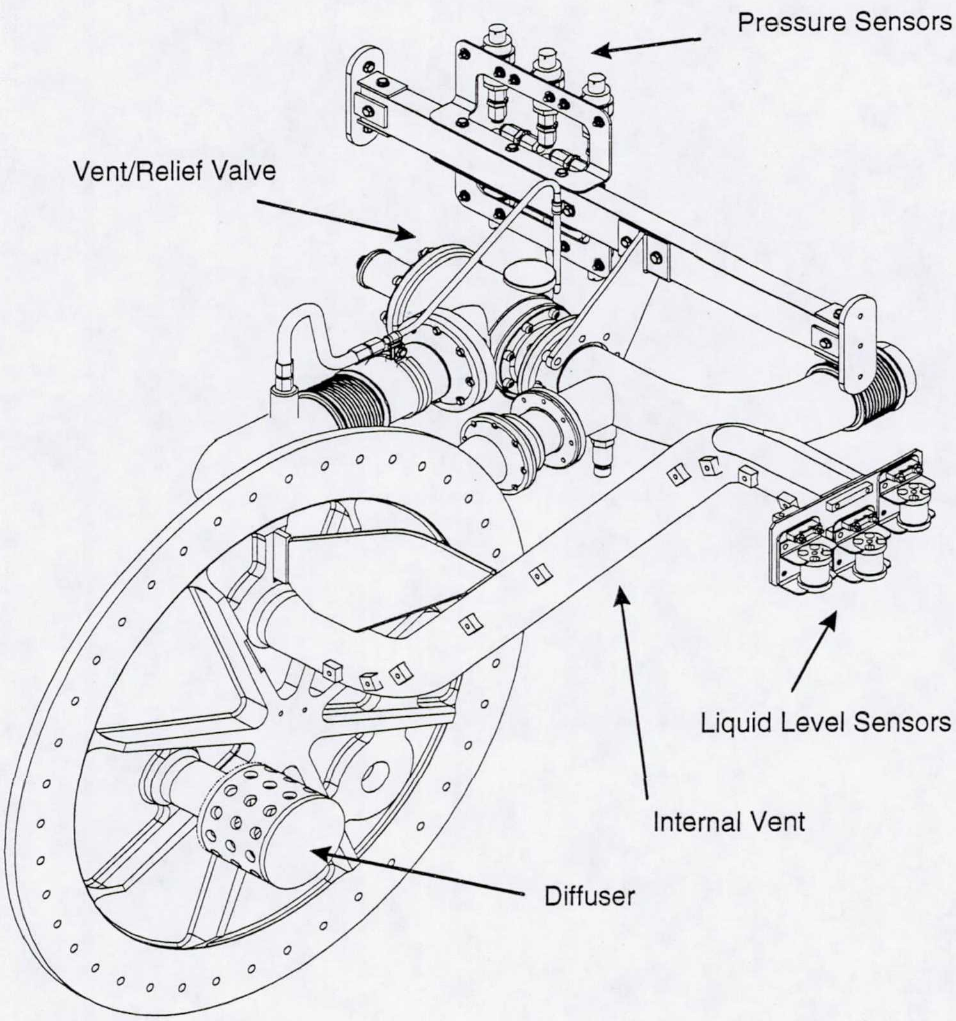

Figure 14 LOX Vent Subystem

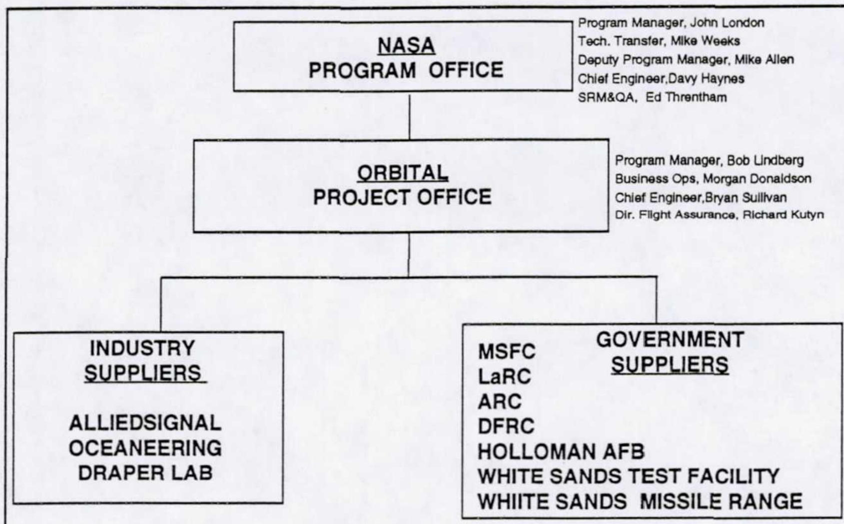

Figure 1 Program Organization

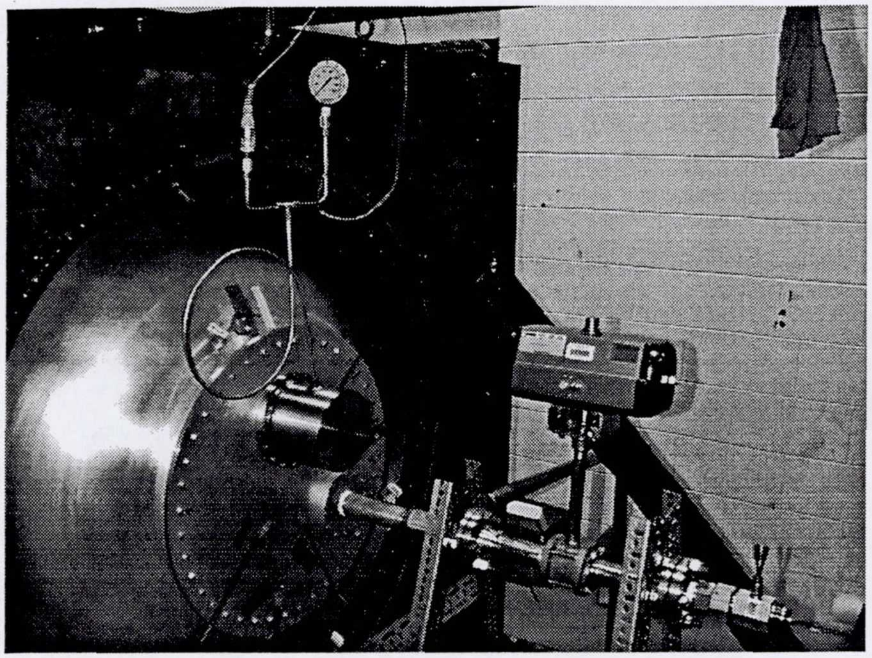

Figure 7 LOX Qual Tank, Aft

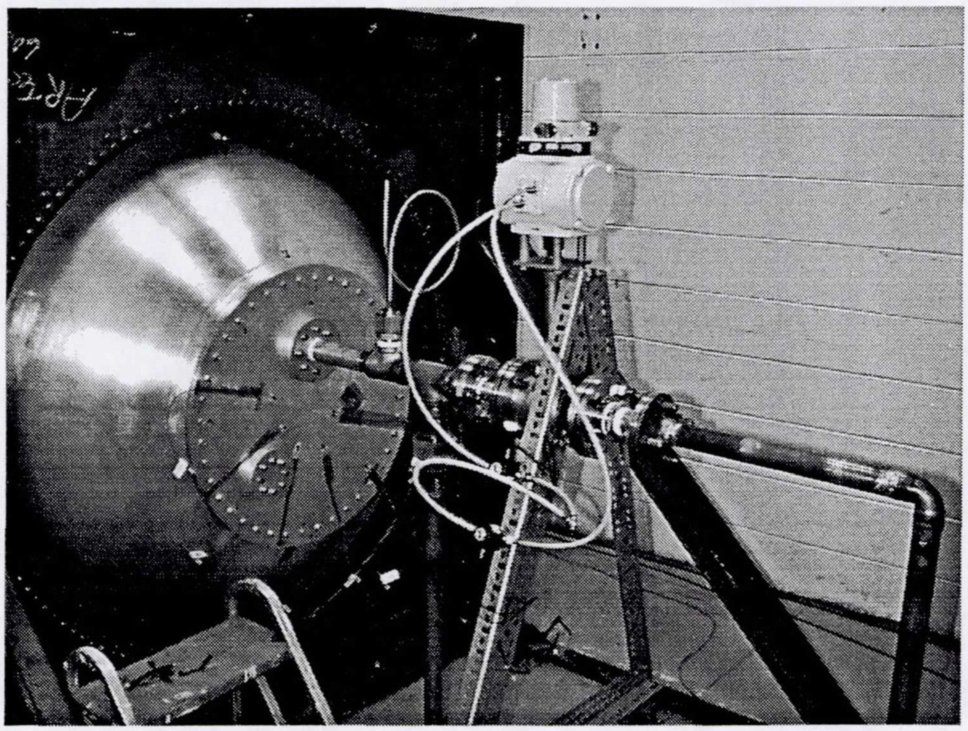

Figure 8 LOX Qual Tank, Forward