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7 Feed System Design for a Reduced Pressure Tank

7.1 Summary

7.1.1 Design Objective

To devise a suitable fuel feed system for a tri-propellant single stage shuttle which complies with all start-up and steady-state conditions and reduces the weight of the vehicle.

7.1.2 Abstract

Three designs were considered to satisfy the design objective. These designs were the current design, a Land Based Pressurized Feed System, and a fuel recirculation system. A computer code was developed to analyze the current feed system and assist in the analysis of the two experimental systems. After comparing the three concepts, the Land Based Pressurized Feed System seemed to be the most promising new development. This design coupled with the piping configuration described in the report provides a justifiable fuel feed system which satisfies all the necessary requirements.

7.2 Glossary

LOX	- Liquid oxygen
LBPFS	- Land Based Pressurized Fuel System
LH2	- Liquid hydrogen
RP-1	- Kerosene
SSTO	- Single Stage to Orbit Vehicle

7.3 Background for SSTO Feed System

One of the main programs currently studied at NASA is the single stage rocket design. This concept would abandon the use of solid fuels due to their lack of throttle control and concentrate on liquid propellants. Because of NASA's recent trend toward international collaboration, the feed system used would be adapted from a system used by the Russian space program. This tri-propellant system burns both liquid hydrogen and RP-1, a form of kerosene, with liquid oxygen.

The current feed system considered by NASA requires high pressures in the shuttle fuel tanks to meet the engine's required mass flow rates. The high pressures, along with turbo pumps in the feedlines, rapidly increase the fuel flow, enabling the engine to receive the fuel at the more rigorous start-up conditions.

Because of the high back pressures, the fuel tank walls must be thick enough to withstand the stresses created. If the pressure in the fuel tanks can be reduced, then the fuel tank wall thickness can be decreased, resulting in thinner, lighter tanks. Since the fuel tanks make up a significant fraction of the total weight of the vehicle, reducing the tank weights would satisfy the desired objective of weight reduction.

The shuttle engine receives fuel in two stages. The first stage makes up the initial fuel requirement conditions. These conditions, which are known as start-up, are the more difficult to meet because the engine needs extremely high mass flow rates. The second stage makes up the steady state conditions. These are the conditions in which the shuttle reaches equilibrium, then lifts off. The mass flow rates during this stage are not as demanding as start-up, and high pressures in the fuel tanks are not needed to push the fuels. Therefore, a reduction in fuel tank pressure could be achieved if the start-up conditions could be met by a means other than pressurizing the tanks.

7.4 The Design Concept

The conceptual design was broken down into three phases. The first phase consisted of the development of a basic internal feed system for all three fuels. This phase includes pipe configuration, diameter and other properties of the pipes. In conjunction with this approach a computer model was developed to determine how this feed system would act. The second phase consisted of the development of a system using low pressure turbo pumps in a recirculating feed system. This system would allow the fuel to recirculate in the feedlines until the proper start-up conditions were attained. The third approach was the development of an external land based pressurized fuel system. This system would supply the shuttle engines with the necessary initial fuel requirements needed for start-up. This system would eliminate the high pressure constraints in the internal tank system.

7.4.1 Feed System Modeling

7.4.1.1 Feed System Design

7.4.1.1.1 Feed System Introduction

The feed system configurations for the Liquid Oxygen (LOX), Liquid Hydrogen (LH2), and the Kerosene (RP-1) fuels are explained in this section of the report. This sections consists of the schematic of the three feed systems, the description of each piping section, the assumptions made about the feed system configurations, and the errors which are present in the feed system configurations.

7.4.1.1.2 LOX Feed System Configuration

A diagram labeling each part of the LOX feed system, is shown in Figure 7.1. The entire system is approximately 1100 inches in length. The system starts with two tank outlets, located at the bottom of the LOX tank, feeding 20 inch trunk lines. These trunk lines are routed around the RP-1 tank, LH2 tank, and the cargo bay. At the end of the lines a manifold is present which directs fuel to the inner and outer engines.

The crossover lines attached to the trunk line manifold provide fuel to the center engine and aid in circulating the fuel. The crossover line manifold connects the two crossover lines and directs fuel towards the center engine. Attached to the crossover manifold is a prevalve which monitors fuel entering the center engine feedline. The center engine feedline is connected directly to the engine and contains three gimbals to allow for thermal movement and misalignment. A screen is located at the end of the feedline.

Located just below the trunk lines are out-board manifolds. Each of these manifolds directs fuel to two of the out-board engines. A prevalve is attached to both exits of the out board manifold to monitor fuel flow. Attached to these prevalves are the out board engine feedlines which contain three gimbals to allow for thermal movement and misalignment. Located at the end of each feedline is a screen.

To aid in passive fuel conditioning all of the feedlines are sloped at least 15 degree from horizontal. To maintain proper fuel temperatures and aid in circulation all of the feedlines except those containing gimbals are insulated.

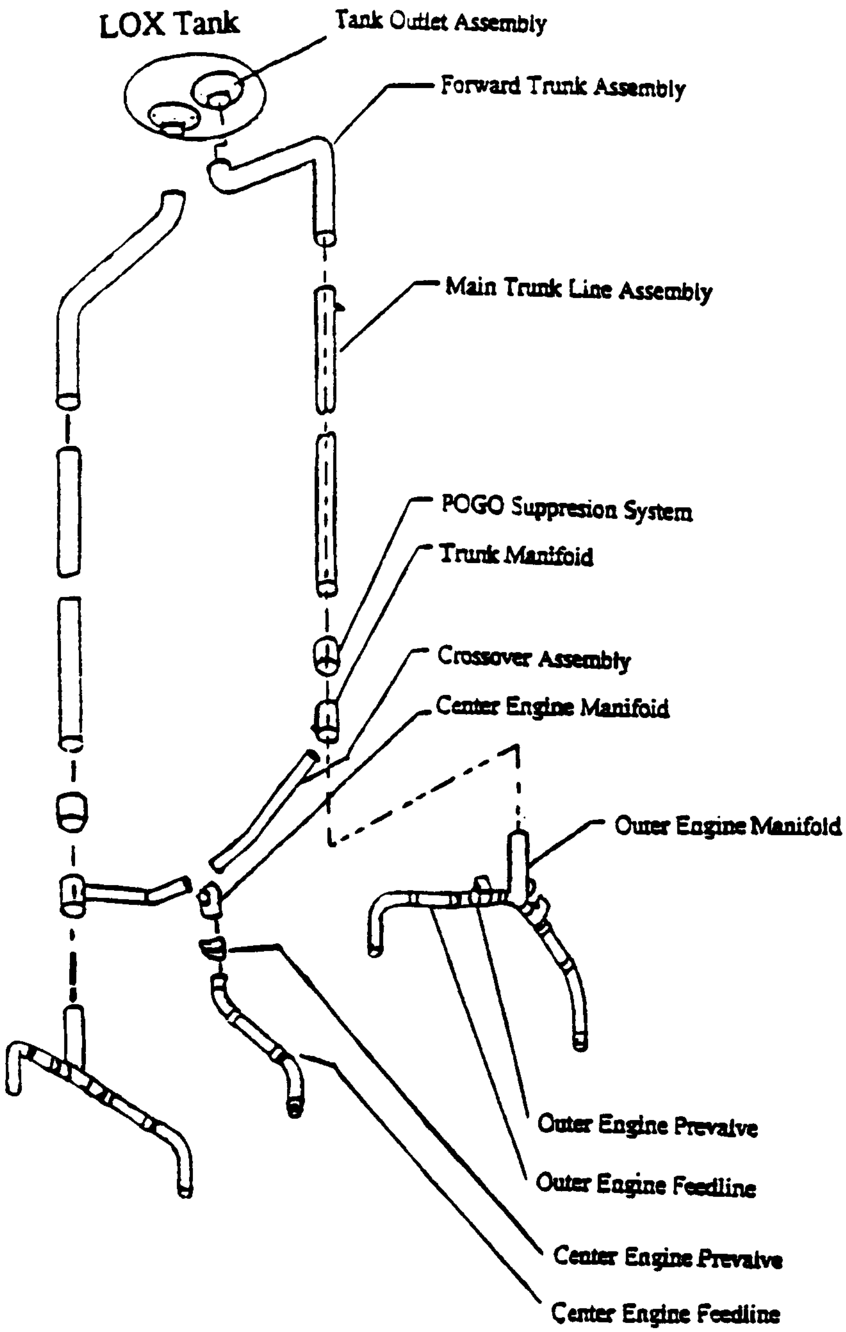

Figure 7.1--LOX Feed System Configuration

7.4.1.1.3 LOX Piping Descriptions

The LOX Tank Outlet Assembly- These two outlets allow fuel to leave the LOX tank and enter the feed system fuel lines. At the bottom of these outlets, screens are placed which help reduce impurities flowing through the feedlines. The Outlets are made of stainless steel and have been computer analyzed to minimize flow restrictions.

Qty: 2 Flow Coefficient: 1.08[1] Diameter: N/A

The Forward LOX Trunk Assembly- These sections direct the fuel around the RP-1 tanks to the outer shell of the vehicle. The forward trunk line assembly contains two elbows, a straight section and three BSTRA gimbals. The straight section and the elbows are insulated, the gimbals are not. The trunk lines are made of stainless steel.

Qty: 2 Flow Coefficient: 0.886[2] Diameter: 20"

The Main LOX Trunk Line Assembly- These sections direct the fuel along the outer shell of the vehicle. These sections are the longest of the feed system, encompassing approximately 900 inches. The main trunk line assembly is composed of four flanged sections flanged together. The entire section is insulated and made of stainless steel.

Qty: 2 Flow Coefficient: 0.68[3] Diameter: 20"

The LOX POGO Suppression System- These sections of the feed system maintain the controlled flow of the fuel. These sections contain baffles to restrict the fuel from swirling in the pipes before it reaches the engines. These baffles also help maintain the constant flow rate of the fuel. These sections are made of stainless steel and are fully insulated.

Qty: 2 Flow Coefficient: 0.0[4] Diameter: 20"

The LOX Trunk Manifold- These sections of the feed system direct the fuel into two separate paths, one leading to the center engine and the other path leading to the outer engines. The entire manifold is insulated and is made of stainless steel.

Qty: 2 Flow Coefficient: 0.27- Through Diameter: 17"- Through
0.77- Branch[5] 8.5"- Branch

The LOX Crossover Assembly- This section directs fuel to the center engine and aids in recirculating the fuel. This section is made of stainless steel and contains three BSTRA flexible mechanism which account for thermal movement and misalignment. All but the gimbals are insulated.

Qty: 2 Flow Coefficient: 0.419[6] Diameter: 8.5"

The LOX Center Engine Manifold- This section joins the two crossover lines which bring fuel to supply the center engine. The section is made of stainless steel and is insulated all around.

Qty: 1 Flow Coefficient: 0.56 Diameter: 8.5"- Inlet
12"- Outlet

The LOX Center Engine Prevalve- The prevalve allows the flow to the center engine to be cut off in case a leak is detected. The section is made of stainless steel.

Qty: 1 Flow Coefficient: 0.1[7] Diameter: 12"

The LOX Center Engine Feedline- This section delivers fuel directly to the center engine. The feedline has three BSTRA gimbals to accommodate thermal movement and misalignment. This section is made of stainless steel and all but the gimbals are insulated. A screen is located at the end of the feedline to filter out impurities in the fuel.

Qty: 1 Flow Coefficient: 1.08 Diameter: 12"

The LOX Outer Engine Manifold- This section of pipe directs the fuel into two branches, each feeding one of the outer engines. This section is made of stainless steel and is fully insulated.

Qty: 2 Flow Coefficient: 0.56[8] Diameter: 17"- Inlet
12"- Outlet

The LOX Outer Engine Prevalve- These prevalves allow flow to be cut off to the outer engines in case a leak in the feedlines is detected. This section is made of stainless steel.

Qty: 4 Flow Coefficient: 0.1 Diameter: 12"

The LOX Outer Engine Feedline- These sections of pipe deliver fuel directly to the outer engines. They are made of stainless steel and contain three BSTRA gimbals to allow for thermal movement and misalignment. All but the gimbals are insulated. A screen is present at the end of the feedline to filter out impurities present in the fuel.

Qty: 4 Flow Coefficient: 1.53[9] Diameter: 12"

7.4.1.1.4 RP-1 Feed System Configuration

A diagram showing the configuration of each part of the RP-1 feed system configuration is shown in Figure 7.2. The feed system is approximately 850 inches in length. The configuration of the RP-1 system is identical to the LOX system except that the RP-1 system uses two separate tanks each supplying one feedline.

7.4.1.1.5 RP-1 Piping Descriptions

The RP-1 Tank Outlet Assembly- One outlet assembly is located at the bottom of each of the two RP-1 tanks. These two outlets allow fuel to leave the RP-1 tank and enter the feed system fuel lines. At the bottom of these outlets are screens to help reduce impurities flowing through the feedlines. The outlets are made of stainless steel and have been computer analyzed to minimize flow restrictions.

Qty: 2 Flow Coefficient: 1.08 Diameter: N/A

The Forward RP-1 Trunk Assembly- These sections direct the fuel around the LH2 tanks and the cargo bay to the outer shell of the vehicle. The forward trunk line assembly contains two elbows, a straight section and three BSTRA gimbals. The straight section and the elbows are insulated; the gimbals are not. The trunk lines are made of stainless steel.

Qty: 2 Flow Coefficient: 0.886 Diameter: 20"

The Main RP-1 Trunk Line Assembly- These sections direct the fuel along the outer shell of the vehicle. These sections are the longest of the RP-1 feed system, encompassing approximately 650 inches.

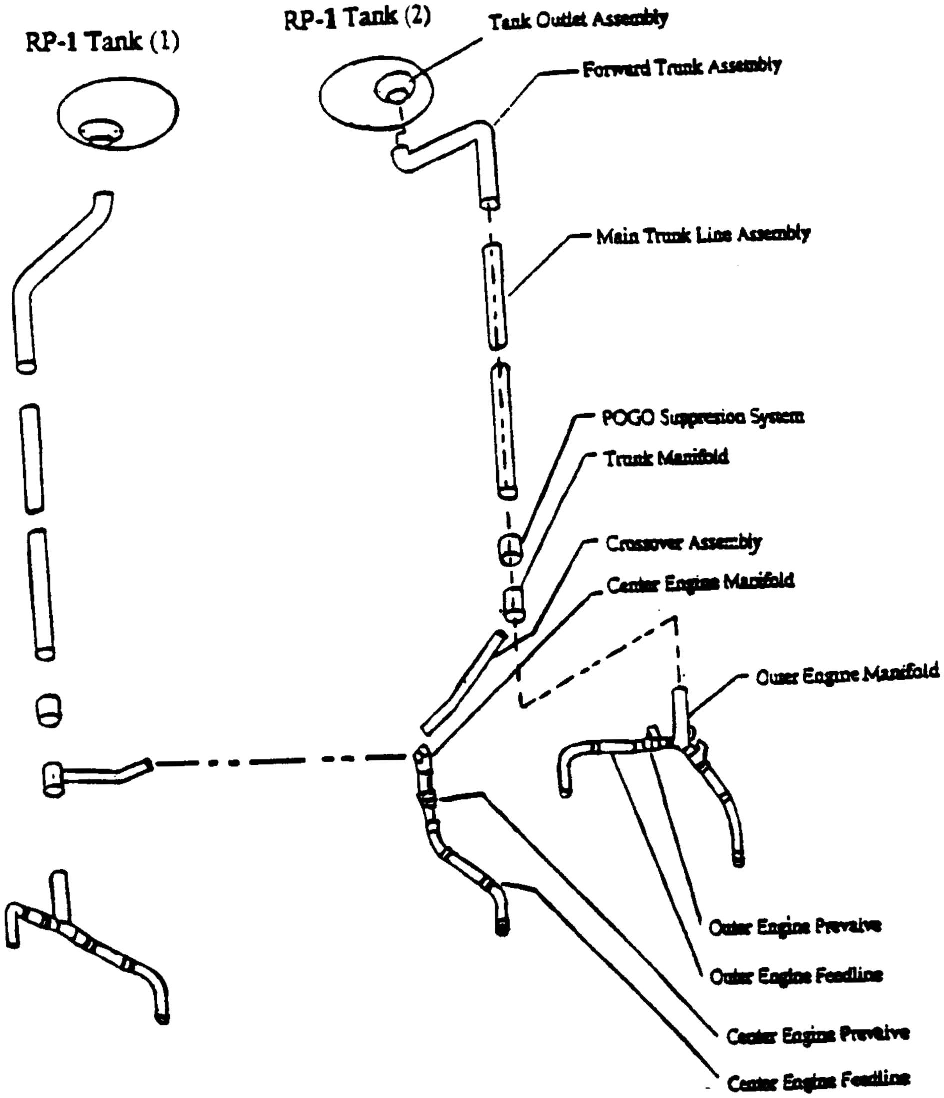

Figure 7.2--RP-1 Feed System Configuration

The main trunk line assembly is composed of four flanged sections flanged together. The entire section is insulated and made of stainless steel.

Qty: 2 Flow Coefficient: 0.68 Diameter: 20"

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The RP-1 POGO Suppression System- These sections of the feed system maintain the controlled flow of the fuel. These sections contain baffles to restrict the fuel from swirling in the pipes before it reaches the engines. These baffles also help maintain the constant flow rate of the fuel. These sections are made of stainless steel and are fully insulated.

Qty: 2 Flow Coefficient: 0.0 Diameter: 20"

The RP-1 Trunk Manifold- These sections of the feed system direct the fuel into two separate paths, one leading to the center engine and the other path leading to the outer engines. The entire manifold is insulated and is made of stainless steel.

Qty: 2 Flow Coefficient: 0.27- Through Diameter: 17"- Through
0.77- Branch 8.5"- Branch

The RP-1 Crossover Assembly- This section directs fuel to the center engine. The section is made of stainless steel and contains three BSTRA flexible mechanisms which account for thermal movement and misalignment. All but the gimbals are insulated.

Qty: 2 Flow Coefficient: 0.419 Diameter: 8.5"

The RP-1 Center Engine Manifold- This section joins the two crossover lines which bring fuel to supply the center engine. The section is made of stainless steel and is insulated all around.

Qty: 1 Flow Coefficient: 0.56 Diameter: 8.5"- Inlet
12"- Outlet

The RP-1 Center Engine Prevalve- The prevalve allows the flow to the center engine to be cut off in case a leak is detected. The section is made of stainless steel.

Qty: 1 Flow Coefficient: 0.1 Diameter: 12"

The RP-1 Center Engine Feedline- This section delivers fuel directly to the center engine. The feedline has three BSTRA gimbals to accommodate thermal movement and misalignment. This section is made of stainless steel and all but the gimbals are insulated. A screen is present at the end of the feedline to filter out impurities in the fuel.

Qty: 1 Flow Coefficient: 1.08 Diameter: 12"

The RP-1 Outer Engine Manifold- This section of pipe directs the fuel into two branches, each feeding one of the outer engines. This section is made of stainless steel and is fully insulated.

Qty: 2 Flow Coefficient: 0.56 Diameter: 17"- Inlet
12"- Outlet

The RP-1 Outer Engine Prevalve- These prevalves allow flow to be cut off to the outer engines in case a leak in the feedlines is detected. This section is made of stainless steel.

Qty: 4 Flow Coefficient: 0.1 Diameter: 12"

The RP-1 Outer Engine Feedline- These sections of pipe deliver fuel directly to the outer engines. They are made of stainless steel and contain three BSTRA gimbals to allow for thermal movement and misalignment. A screen is located at the end of the feedline to filter out impurities which may exist in the fuel.

Qty: 2	Flow Coefficient: 1.08	Diameter: N/A

7.4.1.1.6 LH2 Feed System Diagram

A diagram showing each part of the LH2 Feed system is shown in Figure 7.3. The LH2 feed system is approximately 100 inches in length. This feed system has three outlets located at the bottom of the LH2 tank. Two of these outlets are identical in diameter while the third one, located in the center, is smaller. Each of these outlets feeds its own trunk line assembly, with the two outer trunk lines providing fuel to the four out board engines. The center feedline is the sole supplier of LH2 to the center engine.

This feed system does not allow for circulation since there is no circular path associated with these feedlines. All of the pipes in the LH2 feed system are insulated except for the flexible gimbals.

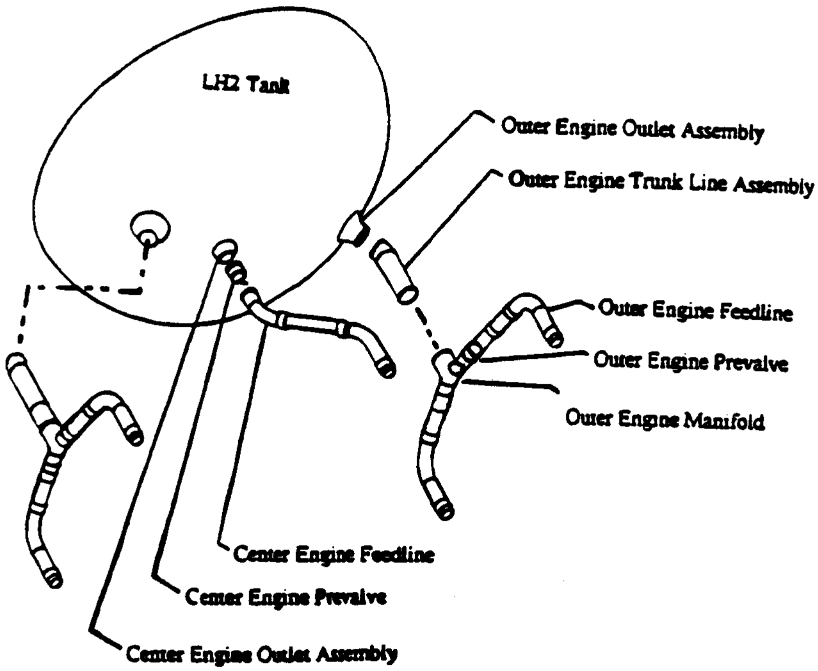

Figure 7.3--LH2 Feed System Configuration

7.4.1.1.7 LH2 Piping Descriptions

The LH2 Outer Engine Outlet Assembly- These two section allow fuel to the leave the LH2 tank and enter the fuel lines. These two sections deliver fuel to the feed lines servicing the outer engines. Located within each of these outlet assemblies is a screen to filter out impurities which exist in the fuel. These sections are made of stainless steel and have been computer analyzed to minimize flow restrictions.

Qty: 2 Flow Coefficient: 1.08 Diameter: N/A

The LH2 Outer Engine Trunk Line Assembly- These sections contain one elbow and direct the fuel from the center of the structure in an outward direction to serve the out-board engines. The entire section is insulated and made of stainless steel.

Qty: 2 Flow Coefficient: 0.4[10] Diameter: 17"

The LH2 Outer Engine Manifold- This section of piping in the feed system channels the fuel off into two branches each delivering fuel to one of the outer engines. This section is made of stainless steel and is fully insulated.

Qty: 2 Flow Coefficient: 0.56 Diameter: 17"- Inlet
12"- Outlet

The LH2 Outer Engine Pre Valve- These sections allow the fuel going to the engines to be cut off in case a leak is detected in the feed system. The section is made of stainless steel and is fully insulated.

Qty: 4 Flow Coefficient: 0.1 Diameter: 12"

The LH2 Outer Engine Feedline- This section of piping delivers fuel directly to the out board engines. It contains three BSTRA flexible gimbals to allow for thermal movement and misalignment. Located at the end of the feedline is screen which is used to eliminate impurities in the fuel. This section contains one elbow, is insulated, and is made of stainless steel.

Qty: 4 Flow Coefficient: 1.1[11] Diameter: 12"

The LH2 Center Engine Outlet Assembly- This section allows fuel to leave the LH2 tank and be delivered to the center engine. This section is made of stainless steel and has been computer analyzed to reduce the flow restrictions. Located within this assembly is a screen used to eliminate impurities in the fuel.

Qty: 1 Flow Coefficient: 1.08[12] Diameter: 12"

The LH2 Center Engine Prevalve- This section allows the fuel to be cut off to the center engine when a leak is detected in the feed system. The prevalve is fully insulated and is made of stainless steel.

Qty: 1 Flow Coefficient: 0.1 Diameter: 12"

The LH2 Center Engine Feed Line- This section delivers fuel directly to the center engine. The section contains two elbows and three BSTRA flexible gimbals. The gimbals allow for thermal movement and misalignment. The section is made of stainless steel and all but the gimbals are insulated.

Qty: 1 Flow Coefficient: 1.26 [13] Diameter: 12"

7.4.1.1.8 Feed System Assumptions

The LOX and LH2 feed systems configurations described in the above sections of this report were based on the National Launch System (NLS) configurations. The piping configurations, diameters, and flow coefficients were all taken from the NLS data. The RP-1 configuration was modeled after the LOX configuration since many of the design parameters were the same.

Because the NLS configuration was designed for a six engine set up in which the booster engines disconnected, certain assumptions had to made which would allow for the SSTO five engine set up. The assumptions and the feed systems to which those assumptions pertain are described below.

The LOX Feed System Configuration- The center engine plumbing was changed to accommodate a single center engine. The center engine manifold and center engine feedline were changed to convert the twin center engine NLS configuration into the single center engine SSTO configuration. The diameter of the crossover pipes were also reduced to compensate for the reduced fuel flow to the center engine. The disconnect valves used in the NLS system were scrapped since the SSTO vehicle is designed to stay with its engines. All of the other pipe characteristics, including diameters and flow rates, were kept the same.

The RP-1 Feed System Configuration- The RP-1 configuration was modeled directly after the modified LOX system described above. A few minor changes were made to the system since the RP-1 feed system uses two separate tanks located closer to the outer shell of the vehicle. This altered configuration led to the shortening of the forward and main trunk lines. Other than the changes to these two piping sections the rest of the characteristics of the configuration were kept the same

The LH2 Feed System Configuration- To accommodate for a single center engine one of the center outlets and feedlines was dropped from the LH2 configuration. All of the pipe dimensions and flow coefficients were kept the same as those described in the NLS configuration.

7.4.1.1.9 Error Analysis

The feed systems described in this section of the report provide preliminary plans for fuel feed systems which could be used in the SSTO vehicle. Since the system described here is based on the NLS configuration there are some errors which are present. These errors include:

- possible variations in pipe diameters
- possible variations in flow coefficients
- possible variations in pipe routing
- possible variations in pipe materials

The largest error will probably be seen in the flow coefficients since they depend upon the pipe dimensions, routing and construction. Although the flow coefficients may change along with the other variables the changes should be small enough such that the validity of the calculations made in reference to the three feed systems is maintained.

7.4.1.2 Computer Feed System Model

7.4.1.2.1 Computer Program Introduction

A computer model was written to determine the time necessary to accelerate the fuel to the necessary velocity within the required time period. The model is based on the conservation of momentum principle and calculates the velocity of the fuel based on the inlet and outlet pressures, the geometric properties of the feed system, and the fuel properties. The simplifying assumptions limit the accuracy and applicability of the model, but when the correct parameters are input into the program, a realistic simulation is achievable.

7.4.1.2.2 Model Development

The computer model is based on the conservation of momentum equation

$$\oiint_s -p\hat{n}ds = \frac{\partial}{\partial t}\iiint_v \rho\vec{u}dv + \oiint_s \rho\vec{u}(\vec{u}\cdot\hat{n})ds \qquad (7.1)$$

which can be written in time discreet form as

$$P_iA_i - P_oA_o = \frac{\rho V[u(t+\Delta t) - u(t)]}{\Delta t} - \rho u_i(t)^2 A_i + \rho u_o(t)^2 A_o \qquad (7.2)$$

where p_i and p_o represent the inlet and outlet pressures, A_i and A_o represent the inlet and outlet areas, u_i and u_o represent the inlet and outlet velocities, u(t) represents the velocity of the fuel at time t, u(t+Δt) represents the velocity of the fuel at time t+Δt, and n represents the normal vector.[14]

Several assumptions are necessary to simplify the equation into a form which can be used to model the fuel flow. It was assumed that the flow through the pipes was one-dimensional. This means that the fuel velocity is identical at all points within a cross-section. Since the fuel is in liquid form, it was assumed that the fuel is incompressible. Therefore, the fuel velocity is identical at all points within a constant diameter pipe. It is also assumed that the fuel properties are constant throughout the system.

Assuming that the velocities at all points within similar diameter pipes are equal allows the last two terms of the equation to cancel if we assume similar diameter pipes. The pressure terms in the equation need to be modified to account for the pressure losses through the system and for the affect of gravity. The pressure losses are determined from

$$\Delta P = \frac{1}{2}\rho u(t)^2 \Sigma K \qquad (7.3)$$

where K is the loss coefficient[15]. The final equation is

$$P_iA - P_oA - \frac{1}{2}\rho u(t+\Delta t)^2 \Sigma KA + \rho ghA = \frac{\rho Ah[(u(t+\Delta t) - u(t)]}{\Delta t} \qquad (7.4)$$

The computer program solves this equation numerically for each time step. The final equation was solved for u(t+Δt).

$$u(t+\Delta t) = [\frac{2hg - Ku(t+\Delta t)}{2h} + \frac{P_i - P_o}{h\rho}]\Delta t + u(t) \qquad (7.5)$$

The equation was solved numerically by guessing the value for u(t+Δt) and substituting that into the right-hand side of the equation. The value for u(t+Δt) obtained from the equation was used to obtain a new guess for u(t+Δt). The iteration continued until the value for u(t+Δt) was constant. This process was repeated for each time step. The control volume used for the calculations includes all fuel inside the feed system from the tank's outlet to the engine's inlet. The computer code was written using Turbo Pascal 6.0 and is shown in Appendix I.

7.4.1.2.3 Computational Results

Using the values for the geometric properties of the feed system and the fluid properties of the fuel, the computer code calculates the velocity history for the transient period of the fuel flow. Using the feed system described in Section 7.4.1.1, velocity histories for each of the fuels (LOX, LH2, RP-1) were calculated. The properties are shown in Table 7.1. The velocity curves are shown in Figure 7.4. The curves show the fuel velocity increasing up to the steady-state solution. The steady-state solution is the same as the solution calculated using Bernoulli's equation. From the curves, the time required to reach the steady-state velocity can be determined and, from that, the duration of the transient period.

	Pi (psi)	Po (psi)	Density (lb/ft^3)[16]	L (in.)	K
LOX	43	38	71.03	1100	4.8
LH2	6	5	4.42	100	3.08
RP-1	25	18	50.28	850	4.8

Table 7.1--Properties Used in Computer Code

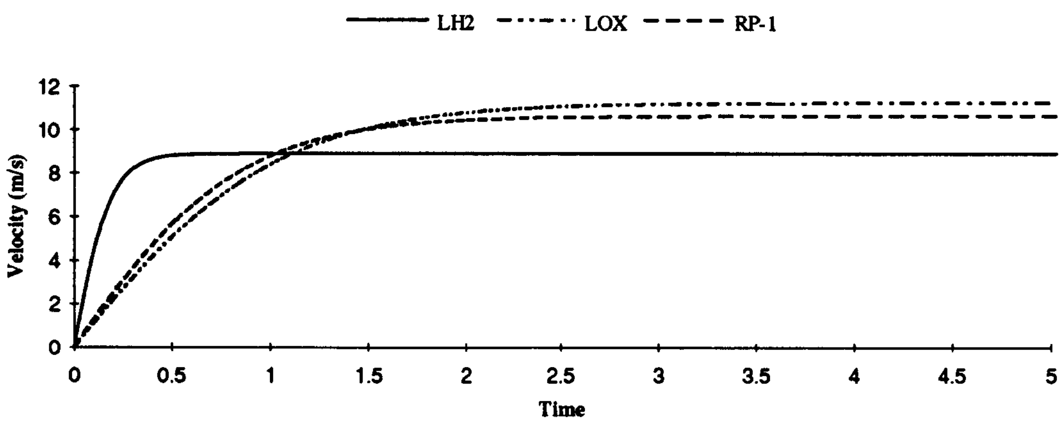

Figure 7.4--Fuel Velocity vs. Time

The duration of the transient period, defined as the time required for the velocity to reach 99% of the steady-state velocity, is 0.51 seconds, 2.73 seconds, and 2.26 seconds for LH2, LOX, and RP-1 respectively.

7.4.1.2.4 Errors

Errors in the calculations are introduced through the assumptions used to simplify the model. The actual feed system does not use pipes of identical diameter. The model assumes that constant diameter pipes are used. This assumption allowed for one of the terms in the conservation of momentum equation to be eliminated. The eliminated terms do affect the calculation and their absence introduces an error. An additional error is introduced by the change in diameter because the exit velocity is affected.

The model does not account for the multiple pipes which are present as the main pipe is split into a pipe for each engine. The flow through the individual pipes will vary depending on the configuration and the pressure losses associated with each section. The model assumes that the flow remains in one pipe, therefore the model does not accurately reflect the affects of multiple pipes.

Although there are errors present in the computer program, the program provides a preliminary estimate of the fuel flow characteristics. The program can be corrected to account for these errors producing more exact results.

7.4.1.2.5 Future Efforts

The next improvements in the computer model should be to model the presence of multiple pipes at the exit of the system. This can be accomplished by determining the pressure at the location of the split and calculating the flows through all of the pipes based on the intermediate pressure. The intermediate pressure should be adjusted iteratively until the continuity equation is satisfied between the main pipe and the smaller secondary pipes. If this adjustment is made correctly, it will be possible to analyze the effects of staggering the starting of the engines on the overall performance of the feed system. A more realistic simulation of a simultaneous start can also be achieved by properly handling multiple pipes.

The code can be used to analyze the other feed systems considered, the LBPFS and the recirculation system, by altering the code to account for the hardware configuration used in each system. The code's calculations could be used to determine the requirements of each system. Accurate comparisons between the systems could then be made on specific performance issues. The analysis presented here is an example of the capabilities of this code; further modifications are necessary for the code to be applicable to the feed system designs considered.

7.4.2 Fluid Recirculation Feed System

Another concept for eliminating the need for back pressure in the tanks involves the circulation of the fluids before ignition. The main purpose of this would be removing the need for the fluids to reach the engine as quickly as possible. The fluids could be recirculated before ignition until the appropriate flow rates are achieved, then the engines could be ignited. Eliminating the need for rapid startup could allow lighter pumps in the feed system and remove the need for back pressure in the storage tanks, resulting in thinner and lighter tanks.

7.4.2.1 Description

In each of the current space shuttle main engines, there are two pumps in the feed line for each fluid leading into the combustion nozzle. A low pressure pump is located near the entrance of the engine, and a high pressure pump is located near the nozzle. The purpose of these two pumps, along with the back pressures in the storage tanks, is to push the fluids rapidly from the tanks to the combustion chambers so that thrust can be attained as quickly as possible. As expected, the pressure differences across these pumps are enormous due to the inertial effects of the fluids.

The theory of the recirculation system is to place a valve downstream of the pumps and circulate the fluids back up to the storage tanks before ignition. The pumps would be given as much time as required to achieve the appropriate flow rates, so transient times would not be as critical. Also, with the need for rapid startup removed, the engine would require only one pump for each fluid which could handle the same flow rates but achieve less pressure gains and a slower response time.

After analysis of the three fluids and their feed systems, it was determined that only the LOX feed system would be altered. The liquid hydrogen is such a light substance that the inertial effects of its flow into the engines are not substantial. Also, because of the cylindrical shape of the LH2 storage tank, its design is limited by buckling instead of stress failure. As a result, some back pressure is required in the tank to prevent failure, so the design of the tank would remain the same. The RP tank's relative size would not produce a significant weight loss.

7.4.2.2 Preliminary Assumptions

The pump used in the recirculation system would need to satisfy initial requirements. The mass and volume flow rates must remain constant at all stages of the feed system. The pump must also supply the liquid oxygen with enough pressure to overcome the pressure head and flow back up to the storage tank.

General calculations were made to determine the specifications of the pump necessary to operate the conceptual feed system. The diameter of the recirculating feed line was assumed to be the same size as the line entering the pump. The recirculating line was also assumed to be straight with no bends or elbows. The velocity of the fluid was set at zero where reentering the storage tank. The fluid was also considered to have the same density at all areas of the feed system, so that both the volumetric and mass flow rates are constant throughout the lines.

7.4.2.3 Feed Line Specifications

In the preliminary design of the single stage shuttle, NASA made some information on shuttle operation available. A diagram with the shape and dimensions of the shuttle was supplied, and is shown in Figure 7.5. This information included estimates of distances between tanks and from tanks to engines.

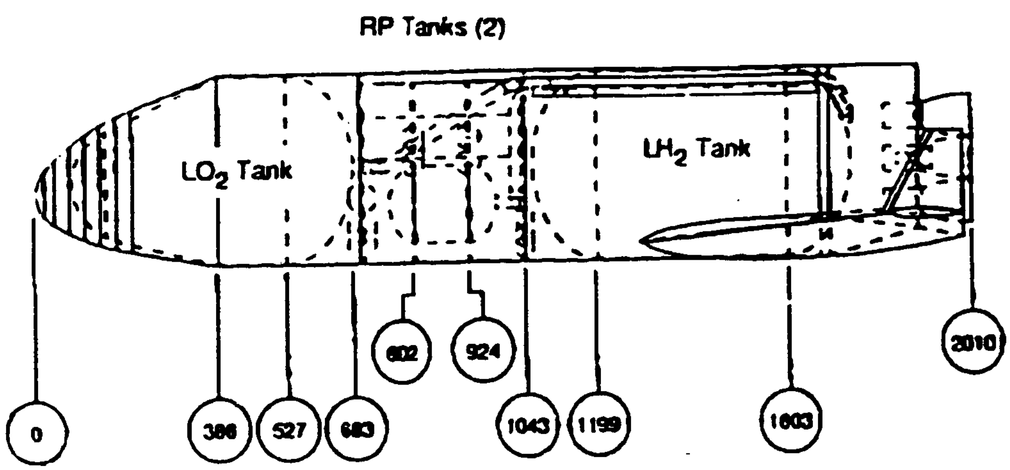

Figure 7.5--SSTO Configuration

For this project NASA also supplied feed system characteristics. The feedline velocity was set at about 20 feet per second, and the feedline diameter was set at 26 inches. From these numbers and knowing the density of liquid oxygen (at -297° F), the volumetric and mass flow rates for the feed system were determined.

density of LOX =	2.208 slug/ft^3
volume flow rate =	73.74 ft^3/s
mass flow rate =	162.8 slug/s

7.4.2.4 Calculation of Pump Requirements

The general pump specifications were determined using basic principles of fluid mechanics. Position 1 was placed just upstream of the desired pump, and position 2 was at the recirculation line's entrance back into the tank. Bernoulli's equation was used to roughly estimate the pressure head the pump would need to supply to push the fluid back up to the tank.

$$\frac{p_1}{\gamma} + z_1 + \frac{V_1^2}{2g} = \frac{p_2}{\gamma} + z_2 + \frac{V_2^2}{2g} + h_L \qquad (7.6)$$

V_1 was set as the feedline velocity of 20 ft/s, while V_2 was set at zero. The height of the line, $z_2 - z_1$, was estimated from the shuttle dimensions as 100 ft. The head loss in the feed line was determined through the calculation of the Reynolds number and friction factor of the pipe.

$$\mathbf{R} = \frac{DV}{\upsilon} \qquad (7.7)$$

$$f = \frac{h_L}{(L/D)V^2/2g} \qquad (7.8)$$

The pipe was assumed to be rather smooth, so the friction factor f was found from a Moody diagram to be only 0.008. The head loss h_L was then found to be 2.29 feet. Therefore, the pressure supplied by the pump ($p_1 - p_2$) was calculated to be about 48 psi.

7.4.2.5 Disadvantages of the Recirculation System

One of the major disadvantages of the recirculation system is the additional plumbing configurations required. For each of the five engines, an additional liquid oxygen line must be attached that leads back to the storage tank. This necessity creates problems in adding more weight to the vehicle, taking up space in the vehicle, and complicating the insulation of the feedlines. The weight savings in the storage tank design from the removal of the back pressure must be compared to the weight gained from the additional plumbing. The additional weight available for payload in the shuttle must be compared to the space lost to the new feedlines. Finally, more insulation must be added to the system to prevent the LOX from vaporizing and causing more problems in the feed system.

7.4.2.6 Conclusions

Several tasks would be ahead in order to determine if the recirculation system would be possible to use. First a proper pump must be chosen which would satisfy all the requirements listed above. A study would be performed on the reactions that would occur inside the tank when the return fuel pipe reenters.

This includes calculating the pressure changes inside and an ideal velocity that the incoming fuel should have. From a structural point of view, research has to be done on how the additional piping would fit into the current system. Another important task would be to find out if the pump used would be suitable for the spacecraft once it leaves the ground and begins ascending.

7.4.3 Land Based Pressurized Fuel System

The LBPFS reduces the required pressure in the fuel tank by providing the engine with the necessary start-up conditions. The LBPFS is not a component of the shuttle itself, but instead a supplement to reduce the high pressures in the fuel tank.

7.4.3.1 Description

Although the actual LBPFS has not been designed, the essential components have been defined. The shuttle will not need excess amounts of the three fuel types for the interval from startup to steady state conditions. Each of these fuels (LOX, LH2, and RP-1) will be contained in a separate pressurized container inside the LBPFS. The LBPFS will also contain necessary turbo pumps in order to transport the fuel to the shuttle fuel lines through a pipe. The LBPFS will be run by a computer which monitors and controls the flow rates of each of the fuels during the initial, transition, and steady state conditions.

7.4.3.2 Safety Concerns

The largest safety concerns are in the area of leakage. Since the LBPFS contains highly flammable fuels, leakage must be prevented to avoid the risks of explosion. The focus area involving leakage concerns is around the joint were the LBPFS connects to the shuttle fuel lines. After examining several connectors, the connector selected was the one currently used to connect the external fuel tank to the space shuttle tank.

Once the gate valve is closed on the LBPFS, the excess fuel in the hoses will be sucked out by vacuum pressure for safety reasons. If the fuel remained in the hoses, the shuttle engines could heat the fuel to the point of ignition. Therefore it is necessary to evacuate the fuel from the hoses to prevent a back flow explosion. Although other safety concerns may arise with a more detailed design, the primary safety concerns with the LBPFS have been addressed.

7.4.3.3 LBPFS Operation

The purpose of the LBPFS is to provide the fuel to the engines from the period of the start-up conditions until steady state is reached, and then the shuttle can provide its own fuel. First the LBPFS pipes should be connected to the shuttle using the joints described in the above section. Once the shuttle is cleared for lift-off, the LBPFS begins its operation. The LBPFS provides the engine with the initial (start-up) engine requirements, and maintains necessary fuel flow rates during the transition to steady state conditions. Once steady state conditions are reached, valves simultaneously close on the LBPFS and open on the shuttle fuel tanks. The pipes on the LBPFS are immediately evacuated for safety reasons, and disconnected from the shuttle. The shuttle system has reached steady state and is providing its own fuels, and lift-off can quickly be achieved.

7.4.3.4 LBPFS Weight Reduction

The reduction in the required flow rate potential and inertial effects represents the basis of the LBPFS weight reduction. The flow rates in the system lines is a function of the fuel properties and the tank pressure. Therefore a direct relationship exists between the flow rates and tank pressure for the shuttle fuel system.

Although the on-board system consists of three different tanks, this study only examines the LOX tank. The LH2 tank was not examined because it is limited by buckling, and a pressure reduction would not prove beneficial. The RP-1 tank was not examined because of its small tank size, and any weight reduction in this area would be negligible. The LOX tank was the selected because it presents the largest inertial problems due to the long distance from the tank to the engine.

7.4.3.5 LBPFS Weight Reduction

The outside geometry of the LOX tank is fixed therefore any reduction in tank weight will be a function of the tank wall thickness. The LOX outside geometry consists of a short cylindrical shell, two ellipsoid caps, and a conical section. The following equations were found relating the tank pressure to the tank wall thickness:

$$\text{Cylindrical shell: } P = \frac{SEt}{R - .4t} \tag{7.9}$$

$$\text{Ellipsoid: } P = \frac{2SEt}{D - 1.8t} \tag{7.10}$$

$$\text{Cone: } P = \frac{2SEt\cos\alpha}{D - .8t\cos\alpha} \tag{7.11}$$

P = pressure
S = stress = 50ksi
E = joint efficiency = 1
t = wall thickness
R = outer radius = 201"
D = outer diameter = 402" bottom/ 219" top
α = cone angle = 23 degrees

The limiting section for the LOX tank is the conical section. The reason the conical section is the limiting one is that the stress is always greatest in this section. Equation 7.8 was then used to create the following graph relating tank pressure to tank wall thickness.

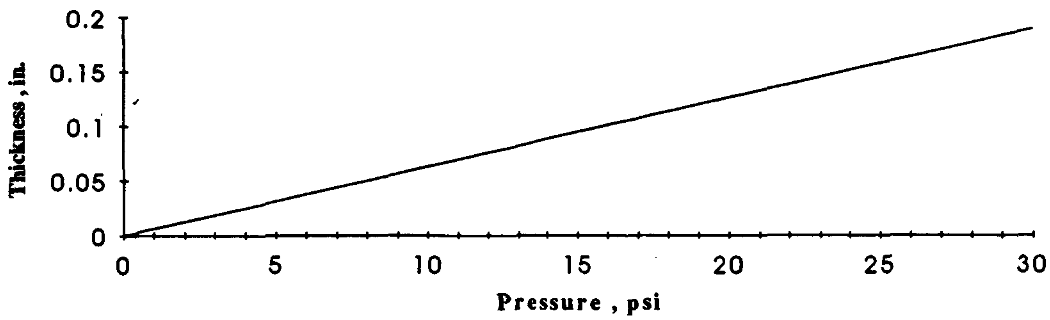

Figure 7.6

Figure 7.6 can be used to show that by reducing the back pressure required in the tanks, the wall thickness of the tank can be reduced. This reduction in tank wall size produces weight savings for the vehicle. The percentage reduction in tank wall thickness will be the same percentage reduction in tank weight. Figure 7.6 gives a means of relating the required tank pressure to the wall thickness. Two pressures can be used to determine the percentage weight reduction for the pressure drop. The equation relating tank pressure to thickness is as follows:

$$P = .0063[\text{lb/in}]\ t\ [\text{in}] \qquad (7.12)$$

Other weight savings exist due to the lower required potential of the feed system. These are in area of the piping system and the saved fuel. Since most of the fuel consumed during early stages of takeoff is provided by the LBPFS, the tanks will not have to carry as much fuel. Also, the pipes will not have to be as thick because they will not have to handle the high flow rates necessary at start-up. These weight reductions although not as sizable as that of the tank, do provide additional means of reducing the weight of the vehicle.

7.4.3.6 Deficiencies and Future Efforts

The deficiencies in this study are primarily due to certain assumptions. The most significant assumption is that the LOX tank is yield limited and not buckling limited. If the tank is not yield limited , then a reduction in tank pressure has a negative affect on the tank. The tank though is thought to be yield limited because it is on the top and does not support the weight of the other tanks and fuel as does the LH2 tank which is buckling limited. Equations exist which can prove if the LOX tank is indeed yield limited. These assumptions are thought to be valid, but should be addressed in any further studies. The pipe system could be analyzed in a similar fashion as the tank. The amount of fuel saved could be determined by integrating the fuel flow curves over the time the LBPFS is active.

7.5 Recommendations

The LBPFS in conjunction with the feed system configuration described in Section 7.4.1.1 is the most promising system considered. The LBPFS is a feasible method for reducing the pressure in the tank and thereby reducing the weight of the tank. The feed system described in Section 7.4.1.1 offers the basis for a feasible piping configuration to be combined with the LBPFS. Further analysis should be directed into adapting the computer model to handle the LBPFS and refining the LBPFS to quantify the improvements which would be achieved.

The recirculation plan was eliminated because of the considerable problems caused by the addition of the recirculation piping. The weight savings obtained from the tank would be negated by the additional weight from the pumps and piping. Additionally, the recirculation piping would be restricted by spatial constraints.

7.6 References

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(6) Ibid, p.3.1.29.
(7) Ibid, p.3.1.35.
(8) Ibid, p.3.1.31.
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