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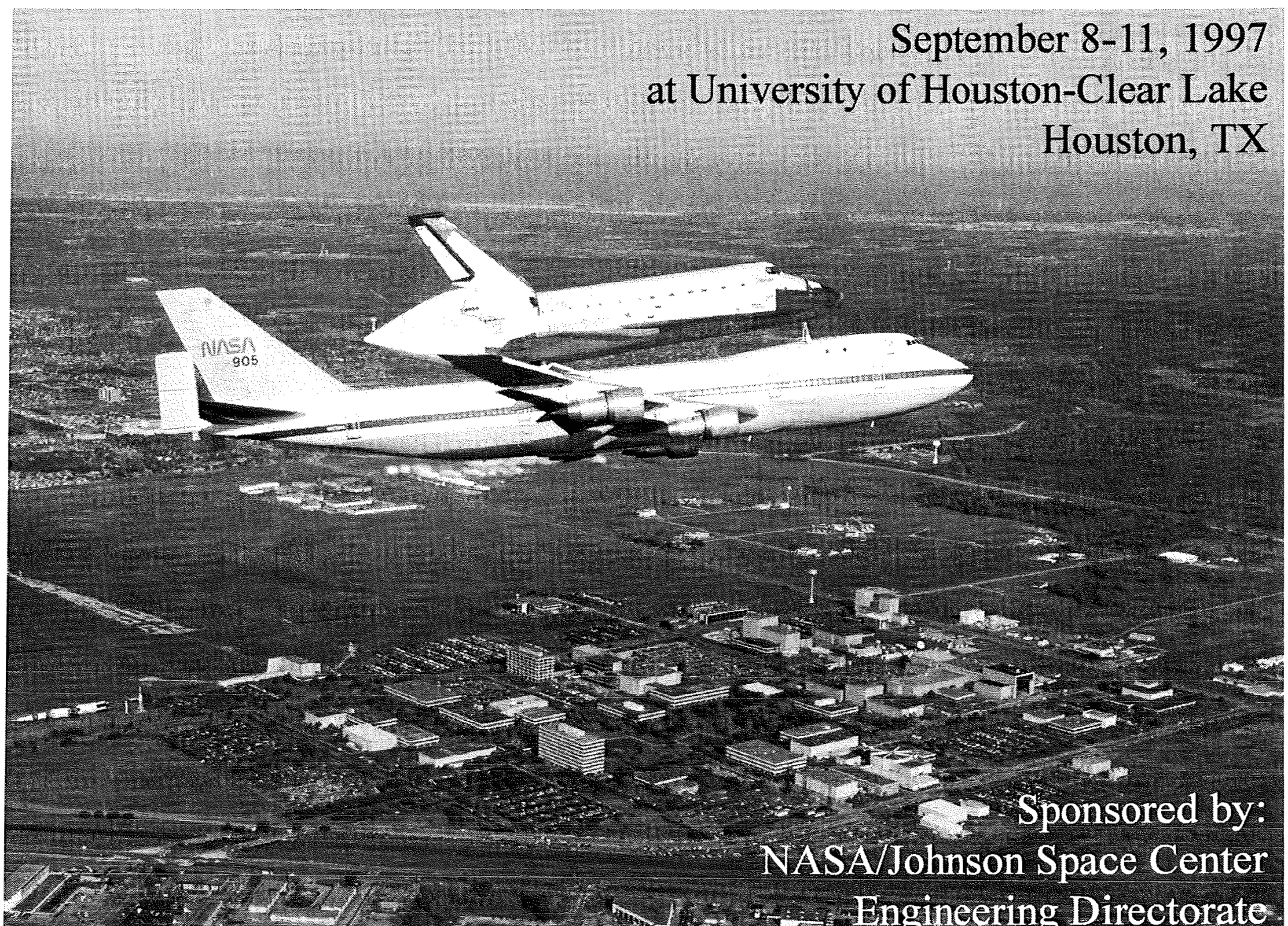
## Spacecraft Analysis and Design



# X-34 HIGH PRESSURE NITROGEN REACTION CONTROL SYSTEM DESIGN AND ANALYSIS

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## Abstract

The X-34 program is developing a reusable launch vehicle that will be capable of reaching Mach 8 and 250,000 feet. The X-34 vehicle will carry a 5,000 psia cold gas nitrogen reaction control system that will be used for augmentation of vehicle control at high altitudes and velocities. The nitrogen is regulated to 1,100 psia and directed to 10 thrusters oriented to provide control capability about all three axes. Orbital Sciences Corporation of Dulles, Virginia has the responsibility for design and performance verification of the system as prime contractor for the X-34 program. *Applied Flow Technology's Arrow* compressible network analysis software was evaluated, selected, and purchased for analyzing the reaction control system performance. The software package uses a graphical interface for network model development and includes unique features such as sonic flow calculations with real gas properties that were crucial for performing X-34 system verification. The results of the analysis confirmed the system is properly configured to meet mission objectives. These results will be verified through component and subsystem level testing of the reaction control system.

## Introduction

The X-34 program is a joint industry/government project to design, develop, test, and operate a small, fully-reusable vehicle that demonstrates technologies and operating concepts applicable to future Reusable Launch Vehicle (RLV) systems. The X-34 is an air-launched, fully-reusable, liquid-fueled system that draws heavily on hardware and procedures developed for other demonstrated launch systems including space shuttle, DC-X/XA, Pegasus, and Taurus.

RLV technologies embedded in the vehicle include an all-composite primary airframe structure, composite fuel tank, an advanced leading edge thermal protection system (TPS), and autonomous flight control with safe abort capabilities. The X-34 vehicle is carried uprange by Orbital's L-1011 carrier aircraft, can perform missions that reach Mach 8 and 250,000 feet, land horizontally on a conventional runway, and can quickly be prepared for subsequent flights using aircraft-style turnaround operations. A high operational rate of up to 25 flights per year, with rapid integration and low operating cost per flight is achieved through a simple, maintainable design.

Orbital Sciences Corporation (Orbital) is the prime contractor responsible for the design, development, fabrication, integration, and flight testing of the X-34 test bed demonstration vehicle. This baseline flight test program (BFTP) includes two flights to verify the integration with the carrier aircraft, performance of the vehicle, operation of ground support equipment, and ground crew operations. The vehicle will not reach maximum altitude or velocity performance capability during this phase of the program. The option flight test program (OFTP) will gradually expand these limits on the vehicle until the target design parameters are reached. In addition to expanding the performance envelope of the vehicle, the OFTP will demonstrate the RLV operability of the X-34 through 25 flights in one year and completion of two flights within a 24 hour period. A crucial part of this performance expansion is the ability to maintain control of the vehicle in the near-vacuum of the extreme flight envelope.

Prior to the first flight of X-34, the vehicle and all its subsystems will be rigorously tested to ensure the designs are capable of withstanding the expected flight environments. Tests reaching the component level will verify static/dynamic structural margins, functional performance, electrical/avionic system compatibility, maintainability, and safety. Subsystems will be integrated together for a variety of ground-based testing including vibration, propulsion static fire and cold flow, and captive carry integration.

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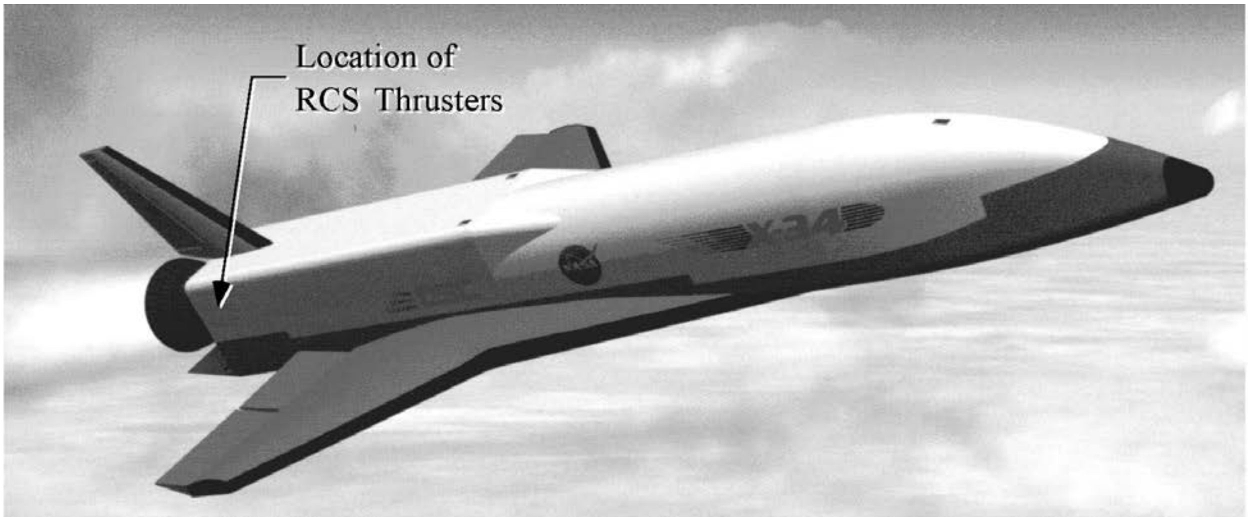


**Figure 1 - X-34 Vehicle In Flight**

First flight of the vehicle is planned for the fourth quarter of 1998. The X-34 vehicle, shown above in Figure 1, is approximately 58 feet long with a wing span of nearly 28 feet.

**Propulsion System Requirements**

Propulsion system functions required to support the X-34 program objectives include:

- generating thrust to meet mission velocity and altitude targets,
- controlling vehicle direction/orientation when control surfaces are incapable of providing sufficient response,
- dumping excess propellants to reduce vehicle weight and safe the systems in nominal and abort flights, and
- protecting ground and flight crews through redundancy and operational safeguards.

The X-34 propulsion system is separated into two major subsystems to meet these complex requirements: the main propulsion system (MPS) and reaction control system (RCS).

Main Propulsion System

The purpose of the X-34 MPS is to generate the thrust necessary for the X-34 vehicle to meet mission trajectory requirements. The X-34 MPS features conventional rocket technology, off-the-shelf components, and a low-cost reusable engine based on NASA-MSFC Fastrac technology to provide Mach 8 performance with low development, maintenance, and operations cost. All of the basic propulsion subsystems are simple in design, construction, and require minimal maintenance to meet operability requirements. The propellants used, kerosene (RP-1) as fuel and liquid oxygen (LO2) as oxidizer, are non-toxic to avoid specialized handling procedures. Subsystems are segregated to avoid complexity, maximize safety, and avoid potential interferences. Other published papers discuss the design and development of the MPS in more detail. [1]

Reaction Control System

The RCS is used to provide vehicle directional control during periods of flight during which control surface effectiveness is insufficient to meet commanded maneuvers or respond to atmospheric disturbances. This reduced effectiveness is caused by lower atmospheric density at the high X-34 flight altitudes and "shadowing" of the vehicle vertical tail by the fuselage at high angles of attack during reentry. The RCS installations provide directional control through torque generated by thrusters, fired alone or in various combinations, whose lines of force do not pass through the vehicle center of gravity (CG).

**RCS Installation/Design Description**

The X-34 mission requirements (operability and maintainability) and available vehicle resources (mass, power, and volume) required a RCS that was simple in design. Details on the system architecture will be described at a high level in this paper; other papers are available that discuss this subject in more depth.[1]

The X-34 RCS is a cold gas propulsion system that uses nitrogen stored at high pressure (5,000 psia). These systems are not the most efficient in delivering impulse to perform maneuvers. However, they use available ("off-the-shelf") hardware, are easy to maintain, and perform reliably. These aspects, as well as meeting mission performance requirements, best supported the X-34 program objectives leading to the selection of the cold gas nitrogen system.

The RCS is activated prior to release of the X-34 from the L-1011 carrier aircraft. The system performs a variety of self-checks to verify component health and system integrity. The system is placed in a standby mode while the vehicle is released from the L-1011 and propelled, by the MPS, to the required shutdown altitude and velocity. The X-34 continues to climb in the ever-thinning atmosphere until it peaks at maximum altitude. Once the atmospheric density is lower than a pre-determined threshold level, the vehicle controls switch the RCS to an active mode. The RCS thrusters are then used to orient the vehicle until aerodynamic surface effectiveness on the vehicle returns to desirable levels. Once the thrusters are no longer needed, the RCS is transitioned to a purge mode. In this mode, opposing thrusters are opened to reduce system pressure without generating a resulting torque on the vehicle. This process allows for the safe approach by the ground crew once the vehicle has landed and come to rest. The thrusters are closed and the system is placed in a shutdown mode once the remaining propellant has been removed from the system.

A simplified schematic of the system is shown in

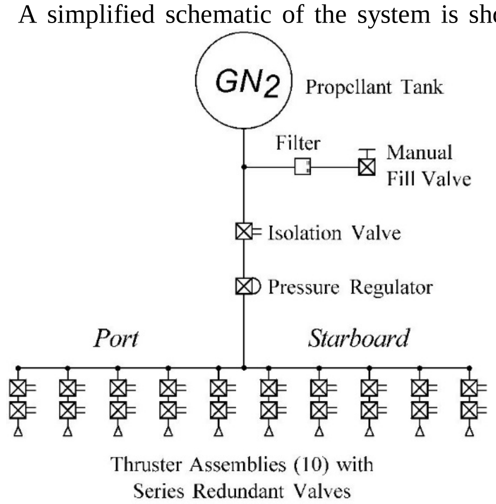


**Figure 2 - Simplified RCS Schematic**

Figure 2. The layout of the system follows the classic arrangement for a cold gas propulsion system. The major components of the system shown include the propellant (high pressure, gaseous nitrogen), pressure regulator, control valves, and thruster nozzles. The isolation valve is used to retain the propellant in the tanks prior to the standby mode. This valve is opened to allow the propellant to flow to the rest of the system.

The primary RCS design challenge was the packaging of the components in the vehicle. Space was severely limited and occupied primarily by the MPS installation. The thrusters are mounted as separate assemblies, one on the port side and one on the starboard side, on the vehicle side panels. This integral assembly allows the panels and thrusters to be removed in one operation to permit access to internal vehicle components quickly and easily. The RCS thruster panel assembly can also be tested as a separate dedicated unit as required.

A drawing of this installation concept is shown in Figure 3. This isometric view shows both RCS panels in the installed configuration without vehicle structure or TPS included. Nitrogen propellant arrives at the panels through tubing from the propellant tanks located in the front of the vehicle.

## RCS Analysis

An analysis is required to verify the RCS will deliver the expected force from each thruster during operation. The vehicle control system will be programmed to expect constant thrust from the RCS, within some tolerance. Variations in thrust can be accommodated but must be known a priori. Since there is no combustion involved, the analysis can be performed as the study of a compressible flow network. A variety of aspects makes this analytical effort particularly challenging.

### Analytical Challenges

Four aspects of this study make this analysis unique; compressible flow with multiple choked orifices, real gas effects, heat transfer, and multiple firing combinations. Undoubtedly, the flow will choke at the throats of the nozzles with the high system pressure directed to the low (near-vacuum) environment. Assumptions of ideal gas will no longer hold true at the high system pressures (up to 5,000 psia) and low temperatures (below 0°F). Rapid changes in pressure through the regulator and long runs of tubing allow significant heat transfer which also must be considered.

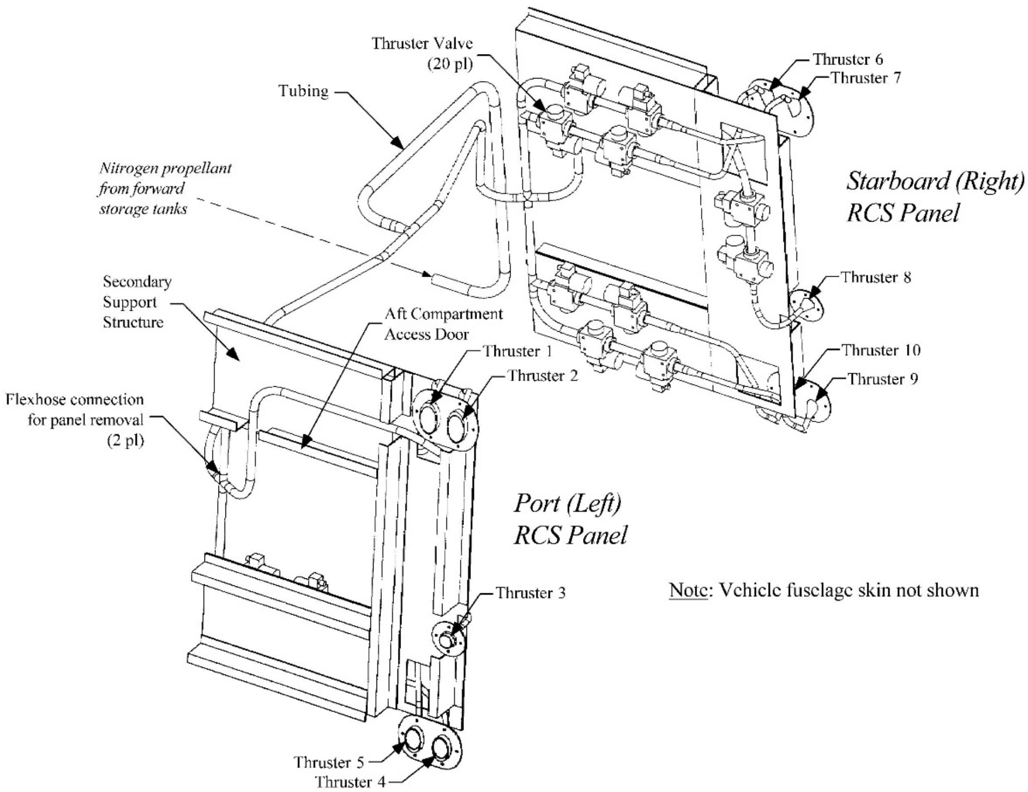


**Figure 3 - Aft RCS Installation**

Finally, the installation of ten thrusters can be fired in many different combinations, complicating the configurations of networks that must be analyzed. Each of these aspects will be discussed in detail.

Compressible Flow

The flow of gases in piping systems involves complexities not shared by flowing liquids. The changing density along a constant diameter pipe results in a changing velocity because of mass balance requirements. Further, the density is directly coupled to the gas temperature through an equation of state. The gas temperature thus changes along the pipe, even for a perfectly insulated pipe.

Another distinct phenomenon in compressible flow is that of sonic velocity. The sonic velocity is the maximum macroscopic "communication time" between gas molecules. The gas velocity cannot exceed the sonic velocity, thus flow discontinuities (i.e., shock waves) can occur in the piping system when pressure and/or flow requirements cannot be supplied at subsonic velocities. This results in "sonic" choking, which means alterations in boundary conditions downstream of a shock wave cannot change the flow rate in the pipe. The X-34 nitrogen RCS will experience such conditions, and a proper analysis must take into consideration these issues.

Heat Transfer

The thermal environment of a gas piping system is of importance because the gas temperature is linked to density and pressure by an equation of state. In addition, when gas delivery temperatures are important, as they are at the X-34 RCS thrusters, the thermal environment must be properly modeled or inaccurate thruster predictions will be obtained. To provide the needed accuracy, a complete energy balance must be performed for each pipe computing section, as well as all diverging or converging branch sections.

Real Gas Properties

The most basic relationship between gas pressure, density and temperature is through the ideal gas equation. A number of analytical simplifications result when a gas can be considered ideal. Further, the gas enthalpy is an important parameter, and the relationship of enthalpy to temperature can take on several forms. Again, the most basic is that the enthalpy change is directly proportional to temperature change (the proportionality constant being the specific heat at constant pressure). When combined with the ideal gas assumption, this is sometimes referred to as a perfect gas. In reality, the enthalpy is dependent on both temperature and pressure.

The X-34 nitrogen propellant will be stored at pressures up to 5,000 psia. The ideal gas model breaks down at such high pressure conditions. For example, at 70° F, nitrogen departs from the ideal gas law by 16%. In addition, with pressure dropping from 5,000 psia to vacuum conditions through the thrusters, the perfect gas law for enthalpy also does not apply. A real gas model must be used for the nitrogen to properly predict the fluid dynamics and thermodynamics of the X-34 RCS system.

Thruster Firing Combinations

The ten thrusters installed in the vehicle could conceivably be fired in 100 ($10^2$) different combinations. Obviously, some of these combinations do not make sense from the standpoint of orienting the vehicle. Firing opposing yaw thrusters is effective in reducing propellant load. It does not, however, provide a net torque on the vehicle and is not an effective means to control the vehicle. Each of the 100 firing combinations was examined to identify the primary thrusting modes. These modes are the combination of thrusters that are fired to achieve a specified response from the vehicle. These responses include pure roll, pitch, and yaw maneuvers. The specific cases chosen for study will be described shortly.

## Equation Derivation

The first three unique aspects of this analysis are handled by representing them through governing physical mathematical expressions. Unknowns in these expressions are solved for the various firing combinations (the last unique aspect) through different computational techniques. First, the governing equations will be derived.

Compressible Flow

There are five governing equations that apply to a gas flowing in a constant area pipe:

Mass:

$$\frac{d\rho}{\rho} + \frac{dV}{V} = 0 \qquad (1)$$

Momentum:

$$dP + \frac{1}{2}\rho V^2 \frac{f}{D} dx + \rho V dV = 0 \qquad (2)$$

Energy:

$$\dot{m}\, d\left( h + \frac{1}{2}V^2 \right) = q \qquad (3)$$

Equation of State:

$$P = Z\rho RT \qquad (4)$$

and Mach Number:

$$M = \frac{V}{\sqrt{\gamma ZRT}} \qquad (5)$$

Among the five equations there are five unknowns: *P, T, ρ, V*, and *M*. Other parameters such as *Z*, $\dot{m}$, *f, Z, h* and $\gamma$ are functions of the five unknowns. The heat rate, *q*, is a boundary condition supplied from other calculations.

Basing the equations on a constant area pipe helps to simplify the equations. However, area changes are possible from pipe to pipe, and also at branching sections. It is therefore helpful to work with stagnation conditions, which combine the thermodynamic and fluid dynamic effects into single entities.

Perhaps the best starting point for discussing stagnation properties is enthalpy. If the energy state changes due to elevation changes are small (as they usually are for gas systems), a statement of the First Law of thermodynamics is

$$h_1 + \frac{V_1^2}{2} + \frac{q}{\dot{m}} = h_2 + \frac{V_2^2}{2}$$

The stagnation enthalpy is thus defined as,

$$h_o = h + \frac{V^2}{2}$$

It can then be said that in the absence of heat transfer (i.e., $q = 0$), the stagnation enthalpy in a pipe is constant.

Following from this definition is that of the classic definition of stagnation temperature,

$$T_o = T\left(1+\frac{\gamma-1}{2}M^2\right)$$

which can be shown to be valid for real gases as well. Definitions of stagnation pressure and density follow similarly.

By combining these definitions with the governing equations (Eqns. 1-5), the following equation can be obtained:

$$\frac{dP_o}{P_o} = -\frac{\gamma M^2}{2}\left(\frac{fdx}{D}+\frac{dT_o}{T_o}+\frac{dZ}{Z}+\frac{d\gamma}{\gamma}\right) \quad (6)$$

which, after integration, becomes

$$P_{o,2} = P_{o,1}\exp\left[-\frac{\overline{\gamma M^2}}{2}\left(\frac{f}{D}(x_2-x_1)+\ln\frac{T_{o,2}}{T_{o,1}}+\ln\frac{Z_2}{Z_1}+\ln\frac{\gamma_2}{\gamma_1}\right)\right] \quad (7)$$

where the bar over the parameters represents the average over the computing section. This method takes a fixed length step $x_2$ - $x_1$, and marches down each pipe. The nature of the change in stagnation temperature is related to heat transfer, to be discussed in the next section.

Another form of the preceding equation (Eqn. 6) is as follows,

$$\frac{dM^2}{M^2} = F_{To}\frac{dT_o}{T_o}+F_f\frac{fdx}{D}+F_{To}\frac{dZ}{Z}+F_{To}\frac{d\gamma}{\gamma} \quad (8)$$

where

$$F_{To} = \frac{\left(1+\gamma M^2\right)\left(1+\frac{\gamma-1}{2}M^2\right)}{1-M^2}$$

$$F_f = \frac{\gamma M^2\left(1+\frac{\gamma-1}{2}M^2\right)}{1-M^2}$$

Integrating the Eqn. 8 yields

$$x_2 = x_1 + \frac{\ln\frac{M_2^2}{M_1^2}-\overline{F}_{To}\ln\frac{T_{o,2}}{T_{o,1}}-\overline{F}_{To}\ln\frac{Z_2}{Z_1}-\overline{F}_{To}\ln\frac{\gamma_2}{\gamma_1}}{\overline{F}_f\frac{f}{D}} \quad (9)$$

In this method the length step is variable, depending on the velocity.

When a branching section is encountered, the mass and energy must balance. The following equations must therefore be satisfied at all branching sections:

*Balance Mass at Branches*

$$\sum_{j=1}^{n}\dot{m}_{ij} = 0 \quad (10)$$

*Balance Energy at Branches*

$$\sum_{j=1}^{n}\dot{m}_{ij}\left(h_{ij}+\frac{1}{2}V_{ij}^2\right) = 0 \quad (11)$$

Heat Transfer

The stagnation enthalpy changes because of heat transfer. However, convective heat transfer is dependent on the gas stagnation *temperature*, not enthalpy. The amount of stagnation temperature change is calculated as follows:

$$\frac{T_\infty - T_{o,2}}{T_\infty - T_{o,1}} = e^{-\left(\frac{P_h L}{\dot{m}c_p}U\right)}$$

where states 1 and 2 are the inlet and exit of the computing section, respectively. During iteration towards a converged solution, the mass flow rate is that which exists at the current solution state. Once the solution is converged, the correct mass flow rate will have been used.

Real Gas Properties

The real gas effects come into play in a couple ways. First, Eqns. 6 and 8 have terms which describe the change in compressibility factor, $Z$, over the computing section. There are also terms for change in $\gamma$, the specific heat ratio. The compressibility factor is calculated from one of two equation of state models. These models employ the gas critical pressure and critical temperature to obtain density. Similar methods are used to obtain enthalpy from temperature and pressure data.

**Computational Methods**

To solve each pipe, the governing equations are iteratively solved over each computing section. The conditions at location 1 are all known. One parameter must be known at location 2, the target location. With the fixed length step method, Eqn. 7, the distance is known. This allows solution of the energy equation to obtain the stagnation enthalpy, which becomes the known parameter. At this point, the static enthalpy is calculated based on a velocity guess, and density can be obtained from the continuity equation. With density and enthalpy determined, static pressure and temperature are obtained from equation of state. These parameters are iterated upon until they converge over the computing section, then the converged parameters are used as the input to the next computing section.

Alternatively, using Eqn. 9 as the solution basis, the distance is not known, but the Mach number is known at location 2. Similar to the previous iterative method, the relevant fluid dynamic and thermodynamic parameters are iterated upon until convergence.

Each of the previous two methods relate the propagation of the solution down each pipe. If a pipe connects to another pipe, then the conditions at the exit of the upstream pipe are propagated to the inlet of the downstream pipe, taking into account any pressure losses (or increases, if a compressor) at the junction that connects the two pipes. Thermal changes may also exist such as a heat exchanger.

If a branch is the connector, then the mixing stagnation enthalpy is obtained for all pipes flowing into the branch based on Eqn. 11. This stagnation enthalpy is used as the inlet stagnation enthalpy for all pipes flowing out of the branch.

The previous methods all function as described until sonic choking occurs. After iteration, the Mach number is known at all computing sections, so that a check for sonic choking can be made. For example, in a particular pipe without flow restrictions, sonic choking can only occur at the pipe endpoint. If during iteration at the current mass flow rate the Mach number reaches sonic inside the pipe, then the solution method enters into a special iteration loop where the flow rate is lowered until sonic choking occurs right at the end point.

If sonic choking occurs because there is a flow restriction at the end of the pipe, then a similar special iteration loop is employed to determine the mass flow rate through the pipe and restriction based on the conditions at the restriction. This flow rate must also be iterated downward until sonic conditions are matched. Such a solution method requires extensive iteration, but also provides accurate and detailed solutions of a compressible flow system.

Software Implementation

Applied Flow Technology (AFT) has incorporated the described solution methodology into a commercial Microsoft Windows software product called *AFT Arrow*. All modeling with *AFT Arrow* is performed with drag-and-drop operations, which offers the side benefits of a short learning curve, rapid model setup, and straightforward verification of pipe and nodal connectivity.

*AFT Arrow* has been commercially available for two years. It has been successfully used on wide variety of gas system analyses including steam, natural gas, air, and high pressure nitrogen, oxygen, hydrogen and helium. Besides aerospace applications, *AFT Arrow* has been used heavily by engineers in power generation, gas transmission, and chemical and petrochemical processing. While the *Arrow* software product has been used to confirm the performance of the X-34 RCS design, *AFT* is not a direct participating member of the X-34 design team.

## Model Description

The model of the X-34 nitrogen RCS was built using *AFT Arrow* is shown in Figure 4. Component data required for the model included information to represent the pressure loss and the geometry. Pressure loss data can be represented in a variety of formats including (but not limited to) K factors, discharge/flow coefficients, polynomial expressions, and lookup in built-in component databases.

The geometry of the component included the minimum flow area. This minimum flow area is required to calculate the sonic choking of the flow through the component. The geometry is represented by an equivalent orifice area with an associated discharge coefficient.

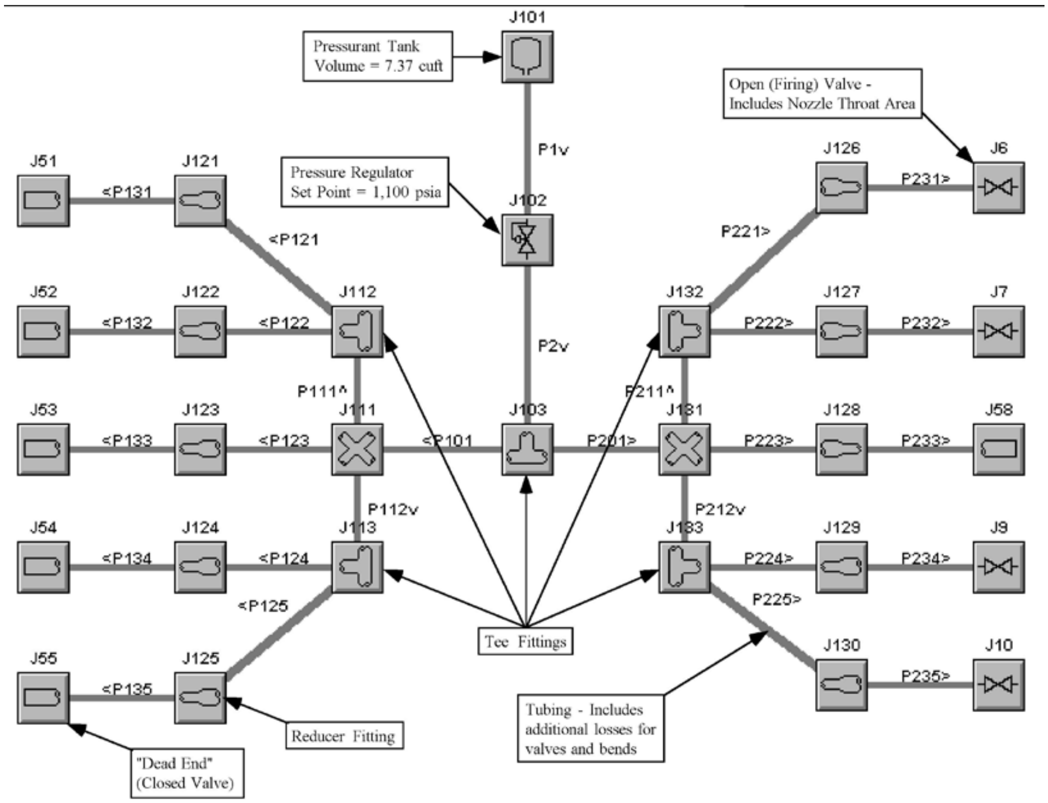


**Figure 4 - X-34 RCS Arrow Model**

The boundary conditions for the model included the definition of the propellant in the storage and the thrusters to be used in a particular case. The propellant storage was represented as a tank component at a specified pressure and temperature. The thrusters were represented by a valve component including the throat geometry of the nozzle.

## Cases Examined

The cases to be studied were limited to the primary combinations of thrusters that would yield pure roll, pitch, or yaw maneuvers. This reduced the number of combinations from 100 to 34. In practice, the X-34 control system will fire thrusters in various coupled combinations as required. Disturbing moments will not be applied as ideal, single axis events. It is assumed the study of these 34 combinations will provide sufficient insight into the system. With this data, confidence will be gained to qualitatively assess the performance of the system under those conditions. The cases that were studied are shown in Table 1. Thruster numbers referenced in this table are defined in Figure 3.

For each of these firing combinations, two tank pressure/temperature conditions were examined. The first case represents the initial firing condition predicted in the tanks. The propellant is loaded on the ground to 5,000 psia and is chilled while the X-34 is carried to launch altitude. As the temperature in the tank drops, the pressure is reduced isochorically. The amount of pressure/temperature drop experienced in the tanks depends on the length of captive carry, atmospheric temperature conditions (hot or cold day), heat transfer characteristics of the hardware, and mass of propellant loaded. This case is represented by setting the pressure in the tanks to 4,000 psia and 460 R.

The second case depicts the propellant tanks at a reduced load later in flight. Pressure in the tanks is assumed to be 2,000 psia and the temperature has dropped as a result of expansion of the gas. As before, the assumed temperature is affected by the same influences noted in the first case. The temperature is assumed at 420 R.

## Results

The 68 different conditions examined in this analysis provided each thruster different conditions to be simulated. Pressure and mass flow data were compiled for each thruster, pressure/temperature, and firing

**Table 1 - Cases Studied**

| | | Thrusters Fired | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Case | Description | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 | Pos. Roll 1 | X | | | | | | | | | X |
| 2 | Pos. Roll 2 | X | | | | | | | | X | |
| 3 | Pos. Roll 3 | | X | | | | | | | | X |
| 4 | Pos. Roll 4 | | X | | | | | | | X | |
| 5 | Pos. Roll 5 | X | X | | | | | | | X | X |
| 6 | Neg. Roll 1 | | | | | X | X | | | | |
| 7 | Neg. Roll 2 | | | | | X | | X | | | |
| 8 | Neg. Roll 3 | | | | X | | X | | | | |
| 9 | Neg. Roll 4 | | | | X | | | X | | | |
| 10 | Neg. Roll 5 | | | | X | X | X | X | | | |
| 11 | Pos. Pitch 1 | | | | | X | | | | | X |
| 12 | Pos. Pitch 2 | | | | | X | | | | X | |
| 13 | Pos. Pitch 3 | | | | X | | | | | | X |
| 14 | Pos. Pitch 4 | | | | X | | | | | X | |
| 15 | Pos. Pitch 5 | | | | X | X | | | | X | X |
| 16 | Neg. Pitch 1 | X | | | | | X | | | | |
| 17 | Neg. Pitch 2 | X | | | | | | X | | | |
| 18 | Neg. Pitch 3 | | X | | | | X | | | | |
| 19 | Neg. Pitch 4 | | X | | | | | X | | | |
| 20 | Neg. Pitch 5 | X | X | | | | X | X | | | |
| 21 | Pos. Yaw 1 | | | X | | | | | | | |
| 22 | Pos. Yaw 2 | X | | | | X | | | | | |
| 23 | Pos. Yaw 3 | X | | | X | | | | | | |
| 24 | Pos. Yaw 4 | | X | | | X | | | | | |
| 25 | Pos. Yaw 5 | | X | | X | | | | | | |
| 26 | Pos. Yaw 6 | X | X | | X | X | | | | | |
| 27 | Pos. Yaw 7 | X | X | X | X | X | | | | | |
| 28 | Neg. Yaw 1 | | | | | | | | X | | |
| 29 | Neg. Yaw 2 | | | | | | X | | | | X |
| 30 | Neg. Yaw 3 | | | | | | X | | | X | |
| 31 | Neg. Yaw 4 | | | | | | | X | | | X |
| 32 | Neg. Yaw 5 | | | | | | | X | | X | |
| 33 | Neg. Yaw 6 | | | | | | X | X | | X | X |
| 34 | Neg. Yaw 7 | | | | | | X | X | X | X | X |

combination. Mass flow was considered the primary parameter to examine since this is used in measuring the efficiency of the thruster. The efficiency is measured through the specific impulse, or ratio of thrust to mass flow as shown in the equation below. For a given design, this efficiency is relatively constant.

$$I_{sp} = \frac{F}{\dot{m}}$$

This relationship shows the thrust from the RCS is directly proportional to the mass flow into the nozzle.

**Table 2 - Summary of Thruster Performance**

| | Mass Flow (lbm/sec) | | |
|---|---|---|---|
| Thruster | Minimum | Maximum | Average |
| 1 | 0.755 | 0.972 | 0.901 |
| 2 | 0.756 | 0.975 | 0.903 |
| 3 | 0.764 | 1.003 | 0.881 |
| 4 | 0.756 | 0.975 | 0.903 |
| 5 | 0.755 | 0.972 | 0.901 |
| 6 | 0.755 | 0.972 | 0.901 |
| 7 | 0.756 | 0.975 | 0.903 |
| 8 | 0.764 | 1.003 | 0.881 |
| 9 | 0.756 | 0.975 | 0.903 |
| 10 | 0.755 | 0.972 | 0.901 |

This information is readily available from the *Arrow* model. A summary of the thruster mass flow results is shown in Table 2. The data shown includes minimum, maximum, and average mass flow for the various firing combinations and propellant tank conditions.

These data show the system is capable of delivering the target mass flow of 0.92 lbm/sec. Examination of the detailed results indicates the primary factor influencing the mass flow for the system is the number of thrusters firing. This result is not surprising - the increased mass flow through the system drives up the pressure drop to the nozzles, reducing propellant density. The system delivers propellant at a mass flow within +9% and -18% of rated flow. The large difference seen for the reduced flow is for cases where 5 thrusters are firing simultaneously in yaw, an unlikely event.

The effect of different initial conditions is driven primarily by the temperature difference. The system is regulated to a set pressure upstream of the thruster nozzles. The density increase, nearly inversely proportional to the change in propellant storage temperature, causes the higher mass flow. If greater fidelity in thrust control is required, heaters can be added at various points in the system to reduce mass flow variations as propellant is depleted.

## Verification

It is important in any computer-based analysis to confirm and verify the results. The first step in the process is simply to perform a reasonableness test on the numbers; do they make sense? If so, simplifications or non-complex cases can be examined and results estimated with hand calculations.

In the case of X-34 RCS, hand calculations were used to initially size most of the system components. Particularly, initial assumptions made in the conditions of the fluid at the thruster nozzle inlets were used to size the throats. This throat geometry was combined with a typical discharge coefficient for a conical nozzle (0.95) to determine the choking characteristics of the component. The mass flow at the nozzles is determined from the inlet conditions and the size of the throat. First estimates at the mass flow based on the desired thrust level (60 lbf.) and known performance of cold gas nitrogen systems (actual 65 lbf-sec/lbm) suggested a target mass flow of approximately 0.92 lbm/sec. The *Arrow* model confirmed the sizing of the throat for this flow rate as shown previously in the results.

The best confirmation of these analysis results is through operation of the system under flight conditions. These flight conditions can be simulated on the ground through component and subsystem (assembly) level testing. Reproducing flight conditions, particularly for a vehicle with high performance capability such as X-34, is difficult.

Component tests are being performed by the component suppliers as part of the qualification programs. Most of the procurements include flow tests that represent extreme flight conditions. The suppliers will test their components under these flight-like conditions and report the results to Orbital. This information will be used to refine the component data included in the *Arrow* model and update the performance analysis.

Subsystem level tests are also being planned to verify the performance of the integrated system. The current plan calls for one thruster panel assembly to be mounted in a vacuum chamber. Facility services would provide the nitrogen at conditions similar to flight operations. The performance of the thrusters will be measured and compared with results from the compressible flow model. The model will be updated to reflect the test data and rerun to generate predictions of upcoming flight trajectories. The model will continue to be used to investigate discrepancies in flight data from predicted performance.

## Conclusions

The X-34 RCS is a vital system in a reusable vehicle that demonstrates high speed and altitude operation. The compressible network flow analysis performed using *AFT Arrow* confirmed system performance predicted through design efforts and hand calculations. The model also provided insight on the effect of various parameters such as tank temperature to make informed decisions on design trades. These results will continue to be verified and improved with continuing component and subsystem testing through model refinement. The ultimate validation of the system performance analysis will happen through the utilization of the X-34 RCS while successfully expanding the vehicle flight envelope.

## Nomenclature

| | |
|---|---|
| $a$ | Sonic speed |
| $A$ | Cross-sectional flow area of a pipe |
| $c_p$ | Specific heat |
| $D$ | Diameter of a pipe |
| $f$ | Friction factor |
| $F$ | Thrust |
| $F_{To}$ | Parameter in Equation 9 |
| $F_f$ | Parameter in Equation 9 |
| $h$ | Enthalpy, static |
| $h_o$ | Enthalpy, stagnation |
| $I_{sp}$ | Specific impulse |
| $L$ | Length of a pipe |
| $\dot{m}$ | Mass flow rate |
| $M$ | Mach Number |
| $P$ | Pressure |
| $P_h$ | Heated perimeter |
| $P_o$ | Pressure, stagnation |
| $R$ | Gas constant |
| $T$ | Temperature, static |
| $T_o$ | Temperature, stagnation |
| $T_\infty$ | Temperature, ambient |
| $U$ | Overall heat transfer coefficient |
| $V$ | Velocity |
| $x$ | Length |
| $Z$ | Compressibility factor |
| $\gamma$ | Specific heat ratio |
| $\rho$ | Density |

Subscripts

| | |
|---|---|
| *1* | Location 1 in pipe |
| *2* | Location 2 in pipe |
| *i* | Junction at which solution is sought |
| *j* | Junctions with pipes connecting to junction i |

## Acronyms

| | |
|---|---|
| AFT | Applied Flow Technology |
| BFTP | Baseline flight test program |
| CG | Center of gravity |
| GN2 | Gaseous nitrogen |
| LO2 | Liquid oxygen |
| MSFC | Marshall Space Flight Center |
| NASA | National Aeronautics and Space Administration |
| OFTP | Optional flight test program |
| OML | Outer mold line |
| RLV | Reusable launch vehicle |
| RP-1 | Rocket propellant (kerosene) |
| TPS | Thermal protection system |

## References

[1] Sgarlata, P., and Winters, B., "X-34 Propulsion System Design," AIAA-97-3304, Seattle, Washington, July 1997