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F. Chandler and M. Scheiern
The Boeing Company
Huntington Beach, CA
R. Champion and P. Mazurkivich
NASA Marshall Space Flight Center
Huntsville, AL

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LAUNCH VEHICLE SIZING BENEFITS UTILIZING MAIN PROPULSION SYSTEM CROSSFEED AND PROJECT STATUS

F. Chandler[*], Ph. D. and M. Scheiern[†]
The Boeing Company
Huntington Beach, California

R. Champion[‡] and P. Mazurkivich[§]
2nd Generation Propulsion Project Office
NASA Marshall Space Flight Center MSFC, Alabama

Abstract

To meet the goals for a next generation Reusable Launch Vehicle (RLV), a unique propulsion feed system concept was identified using crossfeed between the booster and orbiter stages that could reduce the Two-Stage-to-Orbit (TSTO) vehicle weight and Design, Development, Test and Evaluation (DDT&E) costs by approximately 25%, while increasing safety and reliability. The Main Propulsion System (MPS) crossfeed water demonstration test program addresses all activities required to reduce the risks for the MPS crossfeed system from a Technology Readiness Level (TRL) of 2 to 4 by the completion of testing and analysis by June 2003. During the initial period, that ended in March 2002, a subscale water flow test article was defined. Procurement of a subscale crossfeed check valve was initiated and the specifications for the various components were developed. The fluid transient and pressurization analytical models were developed separately and successfully integrated. The test matrix for the water flow test was developed to correlate the integrated model. A computational fluid dynamics (CFD) model of the crossfeed check valve was developed to assess flow disturbances and internal flow dynamics. Based on the results, the passive crossfeed system concept was very feasible and offered a safe system to be used in an RLV architecture. A water flow test article was designed to accommodate a wide range of flows simulating a number of different types of propellant systems. During the follow-on period, the crossfeed system model will be further refined, the test article will be completed, the water flow test will be performed, and finally the crossfeed system model will be correlated with the test data. This validated computer model will be used to predict the full-scale vehicle crossfeed system performance.

Introduction

This paper covers the benefits expected from MPS crossfeed and the design activities, analyses, trade studies, and component analyses performed in the Basic period of performance for the TA-8 Propulsion Risk Reduction MPS Crossfeed project.

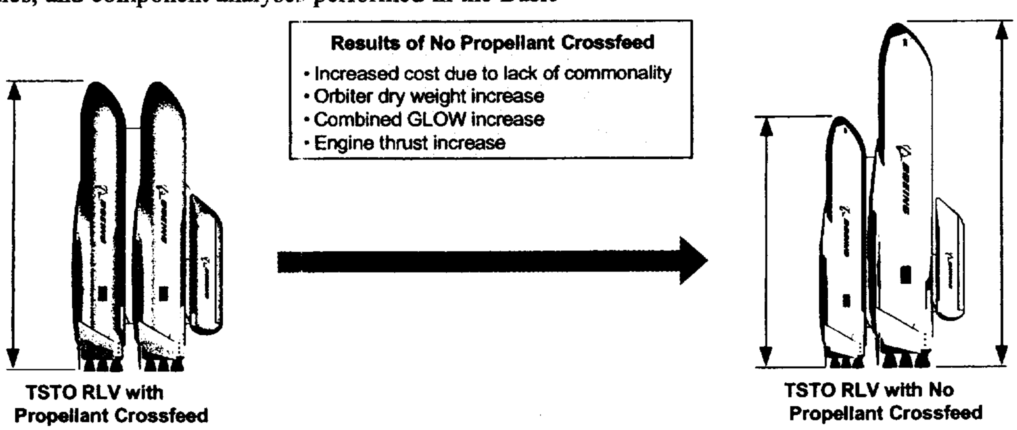

Figure 1: Crossfeed system enables common, smaller and lighter vehicles

The crossfeed system uses similar booster and orbiter stages to reduce the TSTO vehicle size and weight (Figure 1). This system allows the booster and orbiter engines to draw propellant only from the booster tanks during the first part of the ascent. After the propellant flow is transitioned to the orbiter tanks, the booster engines are throttled and the booster is staged. The orbiter, with full tanks at staging, proceeds to orbit.

* Principle Investigator, Boeing MPS Crossfeed Demonstration, Associate Fellow
†Test Article Design Lead, Boeing MPS Crossfeed Demonstration
‡NASA-MSFC, Contracting Officer Technical Representative
§NASA-MSFC, TA-8 Subsystems Manager

Our study shows that, by using crossfeed and staging the depleted booster, we can reduce the overall vehicle dry weight by approximately 25% (Figure 2).
Besides reducing the vehicle size and weight, the crossfeed system emphasizes hardware commonality and uses state-of-the-art design to reduce DDT&E cost by 25% (Figure 3).

The crossfeed system consists of the lines and components needed to implement the flow of both propellants from the booster vehicle MPS across the interface to the orbiter vehicle MPS. In this particular design concept, a passively activated check valve is used to terminate the flow between stages. As the orbiter tank isolation valve is opened to initiate flow from the orbiter tankage to supply the orbiter engines, the check valve closes due to higher pressure in the MPS line caused by hydrostatic head and pressure scheduling of the orbiter tankage. After flow termination through the crossfeed line, the disconnects close isolating and sealing the crossfeed sections from the exterior. Then the vehicles perform the separation maneuver and the orbiter continues on to orbit. The most critical part of this system that has not been used before in the performance of crossfeed termination is the crossfeed valve.

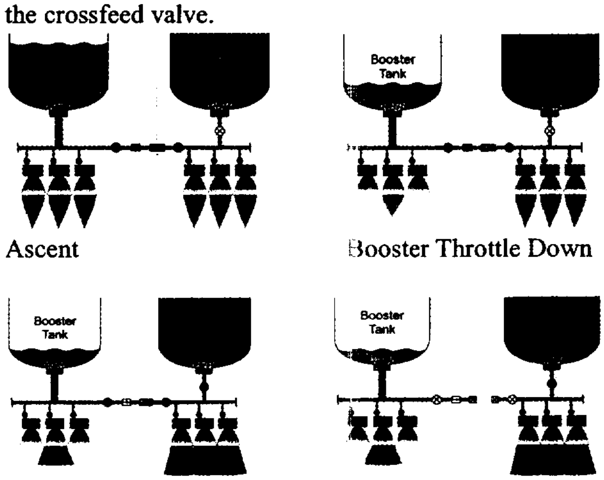

Figure 2: Crossfeed system reduces the dry weight by 25% by staging the depleted booster tanks at a lower altitude.

The MPS Crossfeed Water Demonstration Test addresses all activities required to raise the TRL for the MPS crossfeed system from TRL 2 to TRL 4 by the completion of the follow-on effort by June 2003. The feasibility of using a crossfeed system will be demonstrated for the main propulsion system of a TSTO vehicle.

MPS Crossfeed Technology Demonstration Project Scope

A flow transient model will be developed of the crossfeed system and pressurization models of the booster and orbiter tanks. A subscale crossfeed test article will be designed and fabricated. A subscale crossfeed check valve will be designed, fabricated, and acceptance tested and then installed on the subscale crossfeed test article. The subscale water flow tests will be performed using the available hardware. At the completion of the tests, validation of the subscale transient models will be performed with the test results. Those results will be applied to the full-scale model, and a three-degrees-of-freedom (DOF) ascent simulation will be performed.

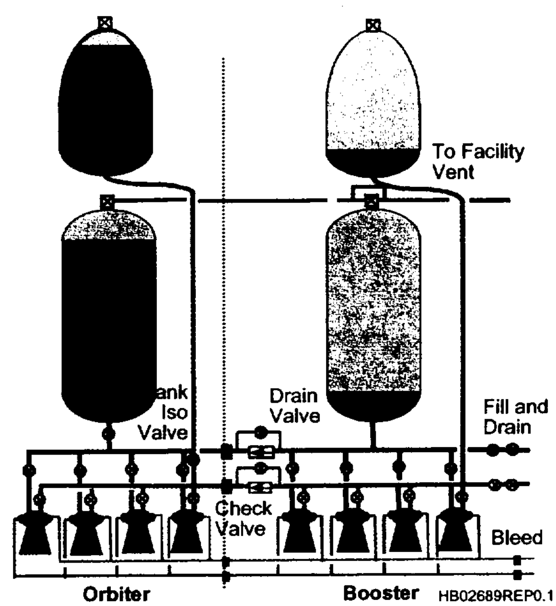

Figure 3. Hardware commonality of crossfeed system reduced the number of required disconnects and umbilicals, therby decreasing costs and increasing reliability and safety

Crossfeed Test Article Design

To fabricate the crossfeed test article, we are using the existing integrated operations technology demonstrator LH_2 and LO_2 tanks to simulate the orbiter and booster tanks (Figure 4). The 19,000-gallon Integrated Propulsion Technology Demonstrator (IPTD) (NASA-MSFC 1996) LH_2 tank is used as the Orbiter tank, and the 12,000-gallon IPTD LO_2 tank as the booster tank. Both tanks are 120 inches in diameter, with a length of 453 inches for the 19,000-gallon tank and 286 inches for the 12,000-gallon tank.

The tests are to be performed at the Boeing Huntington Beach B38 water test laboratory. The tanks will be positioned vertically side-by-side in the configuration expected for the orbiter/booster assembly. The check valve and isolation valve will be installed on the propellant feed lines and the lines routed from the tanks to the orbiter/booster system control valves and engine flow simulators. The engine simulators consist of

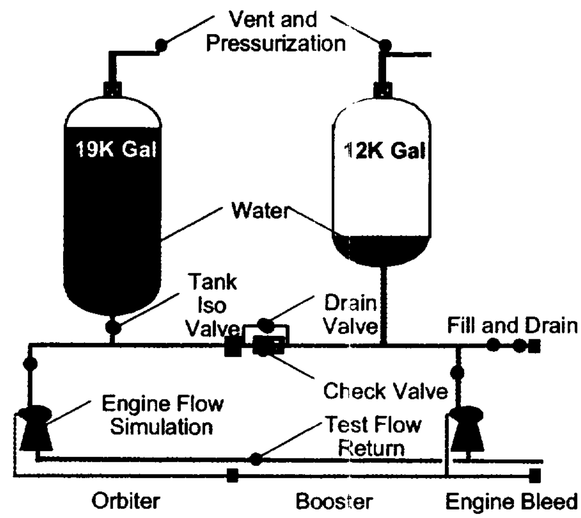

Figure 4: The crossfeed test article uses the IPTD tanks to simulate the orbiter and booster tanks.

laboratory control valves modulated to maintain the required propellant flows. The vent and pressurization systems will be designed, fabricated, and installed for the tanks, which are pressurized with GN_2 during the propellant drain operations.

Crossfeed System Design Analysis

The goal of the crossfeed design analysis task is to develop an integrated crossfeed system transient model to perform full-scale vehicle crossfeed simulation. The model will be correlated and validated with the subscale water flow tests.

The following analysis and modeling activities were completed during the Basic period:

- Dynamic scaling analysis: Identify dynamic scaling parameters and define the crossfeed experiment design requirements that could be scaled to a full-scale crossfeed system,
- Flow Transient Model (FTM) development: Develop a flow transient model of the crossfeed system to predict the pressure and flow transients in the booster, orbiter and crossfeed lines,
- Pressurization model (PM) development: Develop a pressurization model of the booster and orbiter tank to simulate pressurization of the two tanks,
- Integration of FTM/PM: Integrate the independently developed FTM and PM tools to predict liquid flow rate and pressure histories with realistic tank outlet pressures, and
- Crossfeed valve CFD analysis: Develop a computational fluid dynamic model for the subscale crossfeed check valve to characterize the flow through the valve.

The following tasks are to be completed in the Option 1 period:

- Update the integrated FTM/PM tool with the latest layout and component information,
- Update the water flow test predictions using the revised FTM/PM,
- Correlate the integrated FTM/PM to the results of the water flow tests. Compare the predictions with the test data, and
- Update the full-scale model and simulate a full-scale vehicle system.

Dynamic Scaling Analysis

A dynamic scaling analysis was performed to ensure that the subscale crossfeed water experiment can adequately simulate crossfeed operations on a 2nd generation RLV. This entailed identification of significant dynamic parameters for which similitude was needed. The parameters were then used to determine crossfeed experiment design requirements for dynamic similarity. The selected variables can then be used to estimate crossfeed conditions in the RLV from crossfeed experiment test results.

Figure 5 displays a list of non-dimensional scaling parameters important in the crossfeed flow. Since the requirements from the full-scale system are incomplete, it is impractical to match all the parameters particularly for the last three (t^*, P_{CV}^*, and EU_{CV}^*) dimensionless groups. In fact the data generated from the subscale water flow test can be fed back to the full-scale system to assist the design.

Cavitation Number: $$Ca = \frac{P_{TOT,BST} - P_{VAP}}{\frac{1}{2}\rho V^2} = \frac{\text{suction pressure}}{\text{dynamic pressure}}$$

Reynolds Number: $$Re = \frac{\rho V_{LINE} D_{LINE}}{\mu} = \frac{\text{inertia forces}}{\text{viscous forces}}$$

Total Pressure Ratio: $$P_T^* = \frac{P_{TOT,ORB}}{P_{TOT,BST}} = \frac{\text{orbiter feed system total pressure}}{\text{booster feed system total pressure}}$$

Flow Pressure Ratio: $$P_F^* = \frac{P_{TOT,BST}}{\frac{1}{2}\rho V^2} = \frac{\text{total pressure}}{\text{dynamic pressure}}$$

Iso Valve Time Ratio: $$t^* = \frac{t_{VALVE} c_{EFF}}{L} = \frac{\text{flow disturbance time}}{\text{wave propagation time}}$$

Check Valve Pressure Ratio: $$P_{CV}^* = \frac{P_{SEAL}}{\frac{1}{2}\rho V^2} = \frac{\text{valve sealing pressure}}{\text{dynamic pressure}}$$

Check Valve Euler Number: $$Eu_{CV} = \frac{\Delta P_{CV}}{\frac{1}{2}\rho V^2} = \frac{\text{check valve pressure drop}}{\text{dynamic pressure}}$$

Figure 5: Dimensionless Parameters were Considered for Scaling Analysis.

Since low vapor-pressure liquids are used for propellants (densified cryogens), the Cavitation number, Ca, and the flow pressure ratio, P_F*, are similar to that of water. Therefore, the Cavitation number was used instead of the flow pressure ratio. The remaining non-dimensional groups were the Cavitation number (Ca), Reynolds number (Re), and Total Pressure Ratio (P_T*).

As shown in Figure 6, with a 4"-diameter test apparatus, Cavitation number and Total Pressure Ratio similarities were obtained with a water flow rate of 32.5 lbm/s, a booster tank total pressure of 53.5 psia and an orbiter tank total pressure of 57.5 psia. The Reynolds number, however, was about 2% of the full-scale LO_2 system value. Although Reynolds numbers were not equivalent, the flows were far into the turbulent flow regime and thus qualitatively the results would be similar.

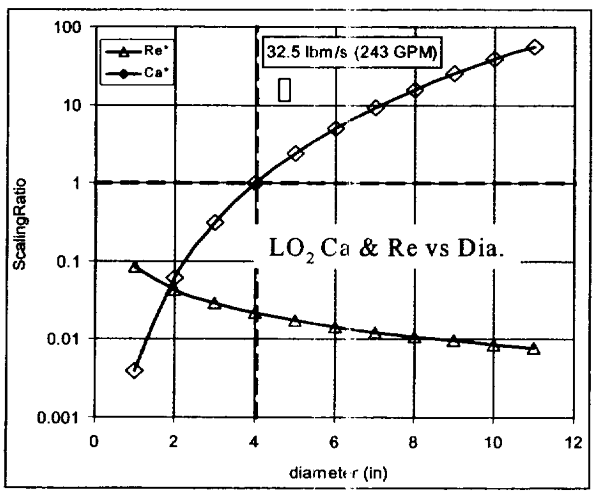

Figure 6: Scaling Ratio for LO_2 Case

Similarly, the full-scale LH_2 system similarity for Cavitation number and Total Pressure Ratio were achieved with a water flow rate of 43.5 lbm/s, a booster tank total pressure of 53.5 psia and an orbiter tank total pressure of 56.5 psia. As with the LO_2 simulation, Reynolds number similarity was not achieved for the LH_2 system where the Reynolds number was about 1% the LH_2 system.

Flow Transient Model (FTM)

The Flow Transient Model was developed in the EASY5[1] environment and utilizes components from the EASY5 thermal-hydraulic library[2] to simulate the transient fluid dynamics. The EASY5 software is a graphical-user-interface-based software used to model, analyze, and design dynamic systems characterized by differential, difference, and algebraic equations. Models are assembled from functional blocks such as summers, dividers, lead-lag filters, integrators, and application-specific components from hydraulic, mechanical, multi-phase fluid, pneumatic, and thermal libraries.

Analysis tools include non-linear simulation, steady-state analysis, linear analysis, control system design, data analysis, and plotting. Source code is automatically generated to support real-time requirements. An open architecture provides easy access to a broad set of software and hardware tools used in computer-aided control systems engineering. EASY5 runs on Unix and Windows 95/NT operating systems. EASY5 has been quantitatively validated with test data for simple water hammer problems induced by valve actuation.

The model is displayed graphically in Figure 7. The water flow test schematic is shown in Figure 15. The subscale test apparatus is described in detail in the test section of this report so it is described briefly here. The apparatus is composed of two simulated propellant tanks for Booster and Orbiter, pressurization system and crossfeed test section and Booster and Orbiter engine simulators. Initially, water in the simulated Booster tank passes through the Booster engine simulator and the crossfeed test section to the Orbiter engine simulator. During the transition period, the iso-valve of the simulated Orbiter tank is opened to simulate the Booster to Orbiter feed transition.

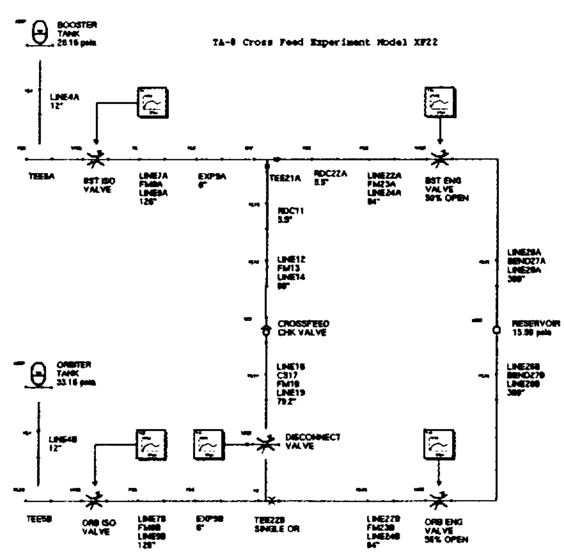

Figure 7: EASY5 Model of Flow Transfer Model

The resulting pressure history of the crossfeed check valve is shown in Figure 8. The model is run for eight seconds of simulation time. At t = 0 sec the booster tank isolation valve begins to open and start the flow of water through the engine simulators. The booster tank isolation valve is fully open at t = 1 sec. At t = 4 secs the orbiter tank isolation valve begins to open and is fully open at t = 5 sec. Sometime during the orbiter valve opening, the crossfeed valve (CFV) will close ceasing the flow. The CFV closes due to higher pressure on the orbiter side versus the booster side of the crossfeed line. This is due either to hydrostatic head or tank pressure scheduling. In flight, following closure of the CFV, the disconnects close isolating the crossfeed circuit and prepare the vehicles for separation.

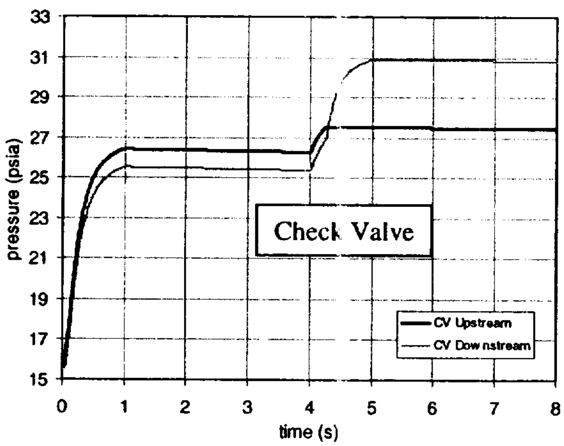

Figure 8: Check Valve Pressure History

Pressurization Model (PM)

The pressurization models of the Booster and Orbiter tanks were developed using Fortran language. The Fortran model is based on the flight verified Space Shuttle model and was used for flight and static fire test predictions for Delta IV.

Integration of Flow Transient and Pressurization Models

The process of the model integration was to develop a Fortran equivalent pressurization model using the EASY5, compare the results with the Space Shuttle flight verified Fortran model and validate the EASY5 pressurization model, and combine the model with the flow transient model in the EASY5.

The EASY5 pressurization model is assembled from functional blocks using the same governing equations as the Fortran model. The model is connected to the Fortran components to calculate the internal heat transfer rates between the ullage, liquid, and wall (qUL, qUW, qWL), and the time rate of change of the ullage temperature. It uses a function generator to define the liquid flow rates of the Booster and Orbiter tanks as a function of time, and a deadband controller to control the tank pressure within a pressure band. The same data for the tanks and thermophysical properties of air, pressurant, and water are externally provided to the model in tabular functions.

The EASY5 model was verified with the Fortran pressurization model for two subscale water flow test cases; low water flow case (700 gpm) and high water flow case (1400 gpm). The results are compared in Figures 9 for the low water flow cases. The number of pressurization cycles for the flow duration is 8 for the Booster tank and 11 for the Orbiter tank. Results of the both Fortran and EASY5 models were identical. Similar conclusions were made for the high water flow case also.

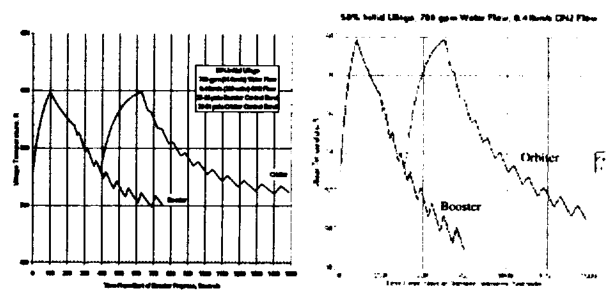

Figure 9: Ullage pressure for low water flow

The pressurization model was then integrated with the flow transient model. The integrated model is shown in Figure 10. A sample test case was run to verify functionality of the integrated model and shown in Figure 11. The detailed water flow test cases will be run in Option 1 period.

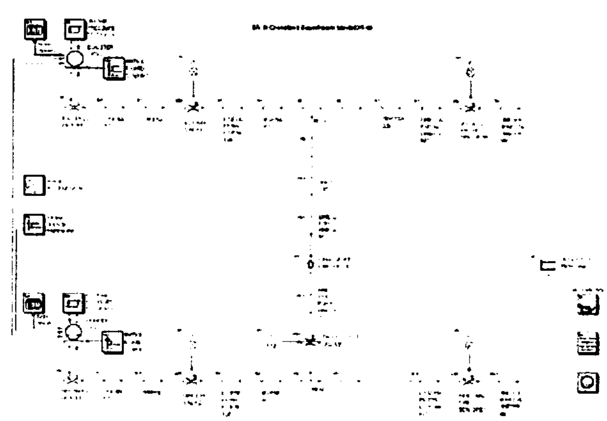

Figure 10: Integrated FTM/PM

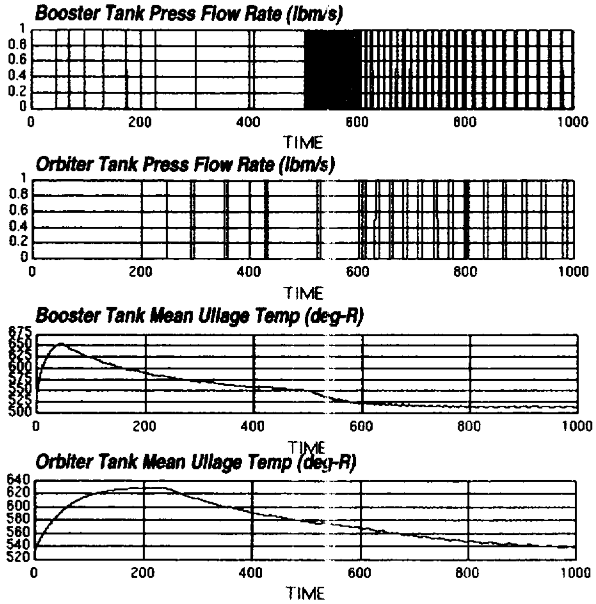

Figure 11: Preliminary Results of Integrated Model

CFD Model of Crossfeed Check Valve

A CFD model was created of an early configuration representative crossfeed check valve, shown in Figure 12. The results were used to characterize the valve's flow field and assess downstream flow instabilities induced by the valve. The FLOW-3D[3] general Navier-Stokes solver was used. FLOW-3D is routinely used to the model propellant behavior inside propellant tanks and has been verified with experimental data. The code has an extensive aerospace history in propellant modeling and quantitative validation for internal flows[4,5,6].

The early configuration crossfeed check valve (CFV) consisted of two-flappers that fold back over a wedge-shaped stop when open as shown in Figure 12. Torsion springs are used to keep the flappers closed. Four feet of pipe are simulated both upstream and downstream of the valve to ensure that the boundary conditions do not affect the flow field near the check valve in a non-physical manner.

A grid sensitivity study was performed to determine the necessary mesh and concluded that at least 1.2 million cells were required. Figures 13 and 14 display the velocity and pressure fields near the crossfeed check valve as the flow starts up and reaches steady state. At 0.2 seconds most of the steady-state flow structure has formed, however, the flow rate and total pressure drop are still increasing in the model. The predicted pressure loss at 0.2 sec is about 5 psi and the average pipe

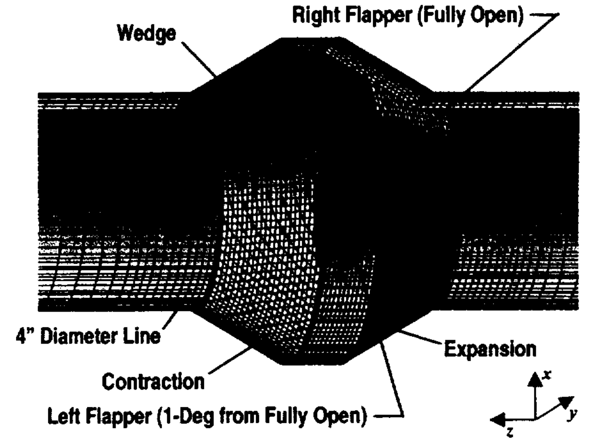

Figure 12. Early configuration of crossfeed check valve

velocity is 28.1 ft/s. At 1.0 second the flow was essentially at steady-state conditions. The pressure drop and flow velocity are 13 psi and 38.6 ft/s, respectively.

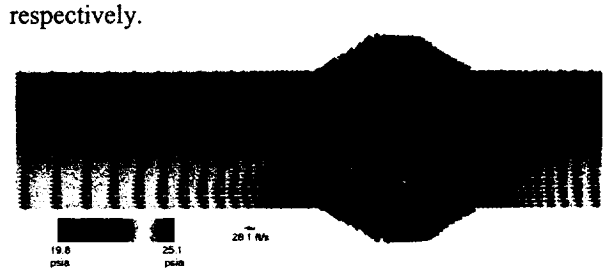
Figure 13: Flow Field at 0.20 sec

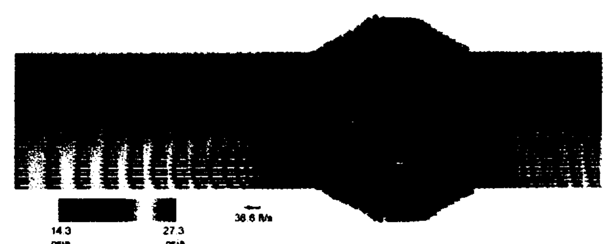
Figure 14: Flow Field at 1.00 sec

Test Objectives and Rationale

The top-level objectives of the water flow test are:

1) To validate the passive crossfeed system through test and to verify the crossfeed system's ability to transition propellant flow from a Booster tank to an Orbiter tank,
2) To provide test data for CFD and Flow Transient Model validation. These models can then be used for full-scale system design and analysis,
3) To obtain test data using a 4-inch subscale crossfeed valve that can be used for the development of a full-scale or near full-scale crossfeed valve,
4) To increase the Crossfeed technology readiness level to 4, and

5) To gain operational experience with a test article that can later be used in a cryogenic liquid experiment with liquid nitrogen and liquid oxygen.

The water flow test configuration is based on a 2nd Generation RLV main propulsion system architecture that uses a Crossfeed valve to passively transition flow from a Booster tank to an Orbiter tank. During the vehicle Boost phase, the Crossfeed system allows propellant to flow from the Booster tank to both the Booster and Orbiter main engines. The propellant in the Orbiter tank is held in reserve until the end of the Boost phase, at which time the Orbiter tank isolation valve is opened slowly to initiate flow into the MPS feed lines. The Orbiter tank ullage pressure is set at a sufficient level and the isolation valve opening is timed to passively decelerate and stop flow within the Crossfeed line and to close the Crossfeed valve. The objective here is to perform the flow transition without creating a transient pressure surge to a level that may be unacceptable to the engines. Once the flow in the Crossfeed line is stopped, the Booster/Orbiter disconnect valve is commanded shut to seal the feedlines for disconnect separation.

The water flow test is designed to simulate the vehicle operations described in the preceding paragraph. The opening time of the Orbiter tank isolation valve is one key parameter that will be varied from test to test in order to determine the optimum time to minimize pressure surges to the simulated engines valves. Water is the fluid of choice at this time due to increased safety and to reduce cost. Water also has a vapor pressure (0.4 psia at 530 R) close to that of densified LO_2 (0.48 psia at 120 R), which provides similarity for cavitation performance.

The test article is to be constructed primarily of material that is compatible with cryogenic fluids such that most of the test equipment could be used in follow-on cryogenic tests. The Cross Feed Valve is a nominal 4-inch dual check valve assembly using two (2) spring-loaded parallel flappers in order to prevent reverse flow. This overall valve configuration, during the course of the test program, will be subject to performance evaluation to determine its suitability for a much larger diameter valve.

Test Article Architecture

The crossfeed water flow test article consists of a simulated Booster tank, an Orbiter tank, a tank structural support grid, feedlines, a crossfeed valve, tank isolation valves, simulated engine valves, a tank pressurization system, vent systems, a pneumatic panel and distribution system, pressurant gas supply trailers, a fill and drain system, and a water supply and recycle tank. The test system covers an area roughly 30 ft wide x 48 ft long and is located east of building 38 on the Boeing Huntington Beach facility.

To determine the required tank operating pressures for the water flow tests, a Nodal Diagram (Figure 15) was created to perform steady-state fluid dynamic analyses. The Nodal Diagram includes the lengths of piping required for each line segment, pipe diameters, associated tees and bends, and elevation change at each station. The overall simulated engine feed line lengths are approximately 48 feet from the center of the two tanks and the Crossfeed line is 16 feet long to the center of each feedline. The two engine feedlines will pass through the open roll-away door of building 38 and drop 5 feet into the 1,000,000 gallon underground water pool.

The test setup will be built to reflect the nodal diagram and schematic that has been developed during the preliminary design stages to analyze the system for performance and compliance to the EASY5 analytical model. The piping system will be metallic and will be insulated for cryogenic testing during a later follow-on phase of the test program. The initial tests will be performed using water as a test fluid

Test Description

The critical test parameters, which will be varied during the water flow tests, are:

- Orbiter Isolation Valve timing,
- Booster Engine Flow Rate,
- Orbiter Engine Flow Rate,
- Booster Tank Ullage Pressure, and
- Orbiter Tank Ullage Pressure

The Orbiter Isolation valve timing is critical to the successful Crossfeed flow transition operation. This parameter will be varied incrementally from 5 seconds to 0.5 sec in order to study the pressure surge sensitivity resulting from the Orbiter feedline pressure rise and consequent Crossfeed valve closure. The Booster and Orbiter Engine flow rates to be tested are based on dynamically scaled values that have traceability to the nominal vehicle level flow requirements. The current scaled water flowrates range from 240 gpm to 640 gpm.

The water flow test architecture is based on a pressure fed flow system. Consequently, the Orbiter and Booster tank ullage pressures must be varied to achieve the required flow rate of water. The tank pressures are currently based on steady-state flow analyses, which were performed using a nodal layout of the test setup.

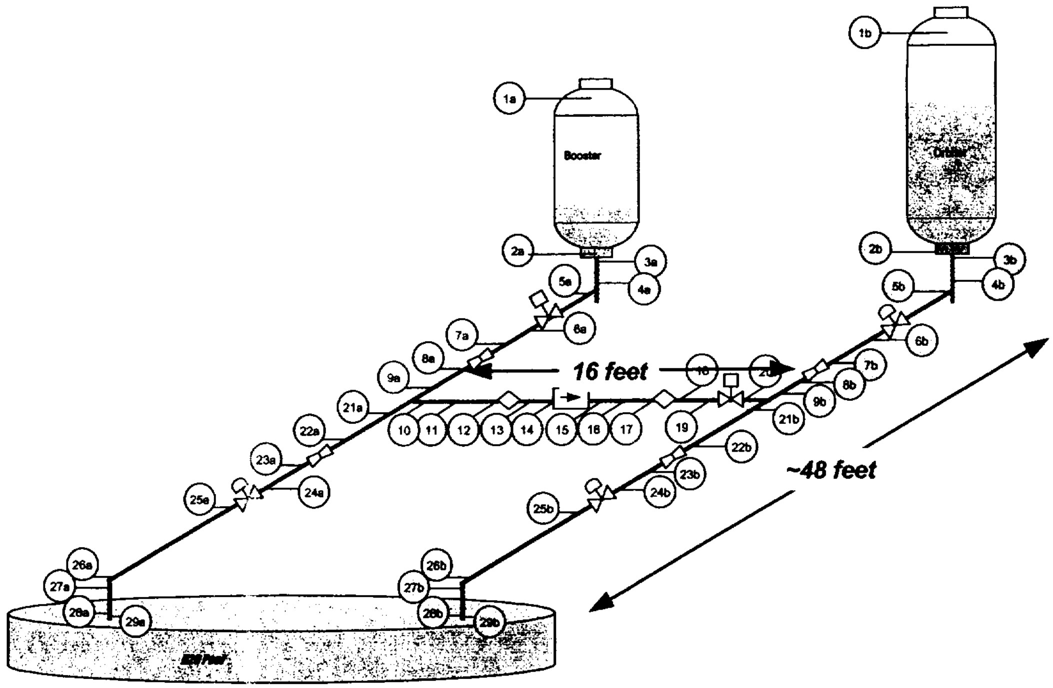

Figure 15: Nodal Diagram of Water Flow Test

Test Matrix

A water flow test matrix was developed to determine the number of tests required to meet the objectives of the TA-8 Crossfeed water flow test. These tests cover the full range of flowrates, including two nominal and two off nominal flow conditions. The Orbiter tank isolation valve timing is varied with each series of tests from 5 seconds, initially, to a minimum opening time of 0.5 second to capture the effects of pressure surge as a result of the Crossfeed valve closure. A few of the tests will simulate flight flow profiles simulating engine throttling and disconnect closure.

Off-nominal testing will be performed to determine conditions with the crossfeed valve chattering and with the crossfeed valve having one of the two flappers failed closed. Transitioning flow with the booster and orbiter tank pressures similar (2 psi) and far apart (25 psi) will be performed. Some of the tests will keep the engine simulator valves fixed to determine if changing the engine simulator valve position affects the test results. Tests are repeated on a regular basis to maintain credibility that the test results are repeatable.

Test Success Criteria

The Success Criteria for the Crossfeed water flow test are:

- That the required number of flow tests is achieved successfully,
- That the Crossfeed water flow tests validate the passive crossfeed system concept through test by successfully transitioning propellant flow from a Booster tank to an Orbiter tank under nominal and off nominal flow conditions,
- That test data is obtained successfully for use in Model Validation and for use in scaling to a full-scale or near full-scale crossfeed system, and
- The Crossfeed technology readiness level of 4 is achieved.

Test data will be used to validate the Crossfeed Valve transient flow models. The pertinent data used for model validation are:

- Pressure at the engine simulation valves,
- Orbiter tank isolation valve timing,
- Pressures upstream and downstream of the Crossfeed valve,
- Delta pressure across the Crossfeed valve,
- Tank Pressures, and
- Water flowrates.

Pressure data at the engine simulator valves will provide the surge pressure level as a function of the Orbiter tank isolation valve timing. Pressures upstream and down stream of the crossfeed line, and the pressure drop across the valve are to be used to validate the check valve model used in the flow transient model as well as to provide insight into the design of the full-scale crossfeed valve. Tank pressure level and water flow rates are used in the flow transient model, including the tank pressurization portion of the model.

Summary and Conclusions

The benefits of utilizing propellant crossfeed have been discussed. The proof that the passive crossfeed concept will work will be the result of subscale testing. Definition of the test article for the subscale testing has included the sizing analyses, which provide the specifications for the various components to be used in the buildup of the test article. The test article procurement has been initiated with the CFV and the L&T production material procurements.

We have successfully developed the separate analytical models (fluid transient model and the pressurization model) and have integrated them and initially correlated them to existing codes. The test matrix for the water flow test has been developed and coordinated which will be used to correlate these models. We have successfully developed a CFD model of the CFV using a generalized Navier-Stokes Solver (FLOW3D) and have developed assessments of flow disturbances and internal flow dynamics.

The PDR for the test article was successfully completed. The PDR and CDR for the CFV were successfully completed as well.

Based on our results, the passive crossfeed system concept using a check valve is very feasible and offers a safe system to be used in a RLV architecture. The CFD modeling of the CFV has shown no flowfield disturbances due to the check valve, which could potentially, cause difficulty in engine inlets. The analysis of the test article has shown that the water system can be designed to accommodate a wide range of flows simulating a number of different types of propellant systems.

We are moving into the Option 1 activities. These include further development and refinement of the crossfeed system modeling, further development and assessments using the CFD modeling for the CFV model, test article buildup and checkout and testing, and finally the crossfeed system model correlation with the test data.

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The Boeing TA-8 technical core team provided most of the analysis and studies included in this paper under leadership of Dr. Frank Chandler, Principal Investigator. The team includes: Mr. Mike Scheiern, Deputy Principle Investigator; Mr. Alex Yi, Systems Engineer; Mr. Martin Lozano, Lead Test Article Engineer; Dr. Han Nguyen, Lead Analyst; Mr. Gary Grayson, Analyst; Mr. Andy Messina, Test Engineer and Mr. Paul LaBelle, Designer.

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