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Modeling and Test Data Analysis of a Tank Rapid Chill and Fill System for the Advanced Shuttle Upper Stage (ASUS) Concept

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The Advanced Shuttle Upper Stage (ASUS) concept addresses safety concerns associated with cryogenic stages by launching empty, and filling on ascent. The ASUS employs a rapid chill and fill concept. A spray bar is used to completely chill the tank before fill, allowing the vent valve to be closed during the fill process. The first tests of this concept, using a flight size (not flight weight) tank, were conducted at Marshall Space Flight Center (MSFC) during the summer of 2000. The objectives of the testing were to: 1) demonstrate that a flight size tank could be filled in roughly 5 minutes to accommodate the shuttle ascent window, and 2) demonstrate a no-vent fill of the tank. A total of 12 tests were conducted. Models of the test facility fill and vent systems, as well as the tank, were constructed. The objective of achieving tank fill in 5 minutes was met during the test series. However, liquid began to accumulate in the tank before it was chilled. Since the tank was not chilled until the end of each test, vent valve closure during fill was not possible. Even though the chill and fill process did not occur as expected, reasonable model correlation with the test data was achieved.

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Extended Abstract

Data Analysis and Modeling of a Tank Rapid Chill and Fill System for the Advanced Shuttle Upper Stage (ASUS) Concept

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Due to the high energy density of cryogenic propellants, the cryogenic upper stage is a significant asset to the payload community. At the present time, however, the use of these high-energy cryogenic upper stages is limited. The launch of cryogenic upper stages in the Shuttle Transportation System (STS) has been prohibited due to safety considerations. There is the risk of abort with a full load of cryogenic propellants in the cargo bay, which could over-pressurize after landing. The Advanced Shuttle Upper Stage (ASUS) concept addresses this concern. The ASUS would launch empty and begin filling once the shuttle passes most of the abort windows. Due to the short duration of the shuttle ascent, approximately 8.5 minutes, the fill must be accomplished in roughly 5 minutes. The ASUS would collect its propellants from the External Tank (ET) via a tap into the Main Propulsion System (MPS). Thus, the ASUS would make use of propellants normally thrown away as residuals in the ET.

The ASUS employs a rapid chill and fill concept, which is quite simple. The propellant enters the tank through a spray bar, which is installed in, and runs the entire length of the propellant tank. The spray bar is a long tube with numerous holes drilled into it. This configuration allows the propellant to spray radially inside the tank. During a fill operation, the propellant exits the spray bar and impinges on the tank walls, rapidly chilling them. The vaporized propellant would exit the tank through the vent. Once the tank walls are chilled, the tank vent is closed and filling begins. This chill and no-vent fill process is also applicable to in-space propellant transfer, where a no-vent fill is crucial since the location of the propellants in micro-gravity is not always known, and loss of propellants through the tank vent is unacceptable.

The first tests of the rapid chill and fill concept, using a flight scale tank, were conducted at NASA's Marshall Space Flight Center (MSFC) during the summer of 2000. The spray bar was mounted in the Multipurpose Hydrogen Test Bed (MHTB) tank, and the test was conducted in the Structural Test Facility (STF) in MSFC's West Test Area. The test setup is illustrated in Figure 1. The objectives of the testing were to demonstrate that the MHTB could be filled in roughly 5 minutes, and to demonstrate a no-vent fill of the tank. A total of 12 fill tests were conducted at various fill mass flow rates.

Models of the test facility fill and vent systems were constructed using the Generalized Fluid System Simulated Program (GFSSP). The results from these models were used as inputs to a FORTRAN model used to simulate the thermodynamic and heat transfer phenomena inside the tank. The tank model was purposely kept simple with the objective of providing quick analysis of the more complex phenomena occurring inside the tank.

The objective of achieving tank fill in 5 minutes was met during the test series. However, the chill portion of the test did not occur as expected. Instead of completely chilling

before accumulating liquid, the tank actually chilled as it was filled. Thus the total chill time was longer than originally expected. The following are potential reasons for this phenomenon:

1. The tank wall thickness (0.5 inches) is much greater than a flight weight tank, and thus the thermal mass to cool is much greater.
2. Hydrogen film boiling at the warm tank walls reduced the heat transfer between the walls and the bulk propellant.
3. The ambient heat leak, especially through the manhole at the top of the tank, is much greater than expected, and is having a significant impact on the ability to chill the tank.
4. The jets exiting the spray bar are not directly impinging on the tank wall, thus accounting for the slower tank wall chill.

Since the tank was not completely chilled until near the end of each test, the closure of the vent valve during fill was not possible. During each attempt to close the vent valve, the ullage pressure rose rapidly, activating the redline cut off for the test. This redline was well below the tank maximum operating pressure.

The GFSSP models were successful in predicting the fill and vent system flow rates given the system components, supply pressures, and MHTB pressures. A representative plot of the fill system flow rate, versus MHTB pressure, is included in Figure 2. These results were used as inputs to a model of the tank itself.

The FORTRAN model of the tank consisted of one node each for the tank wall, ullage, and propellant. Plots of actual test data versus the model predictions are included in Figures 4 and 5. The prediction for tank wall temperature matches the test data fairly well for a one-node model. However, the ullage pressure plot does not match the data well. The significant difference between the actual data and the prediction is due to the fact that the actual system behaved differently than originally thought. The model was set up for a chill, then fill, scenario, when the actual tank began to fill almost immediately. The model would need to be completely changed in order to simulate the chill during fill scenario, since that would require multiple nodes for the tank wall and contents.

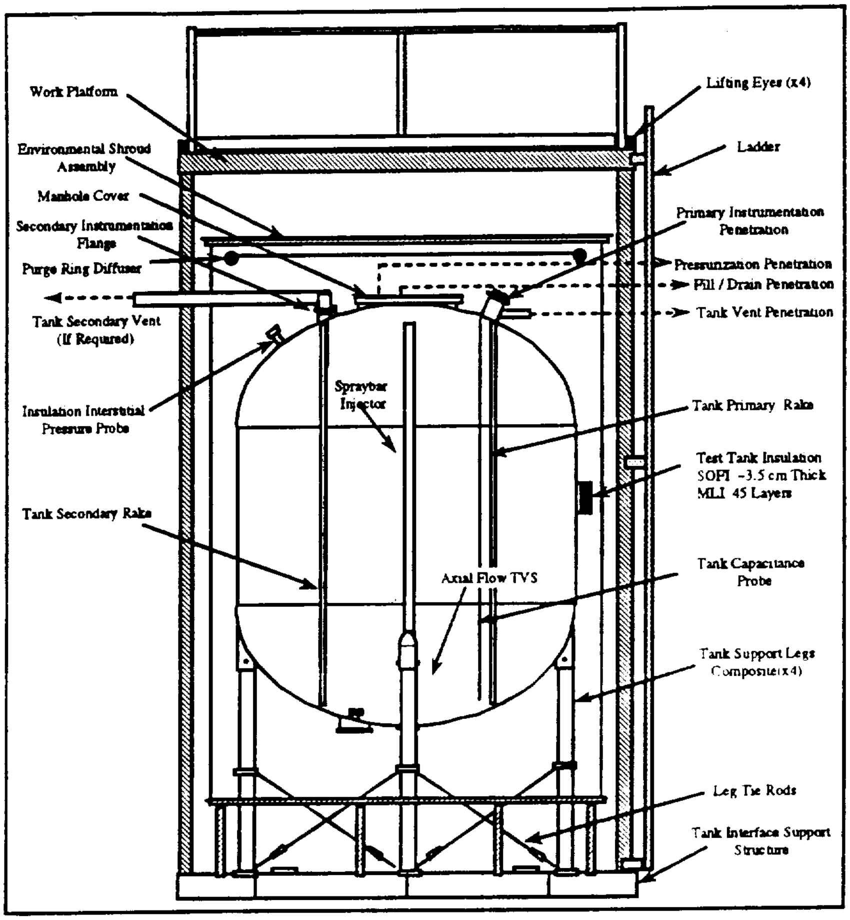

Figure 1: ASUS Setup in the MHTB

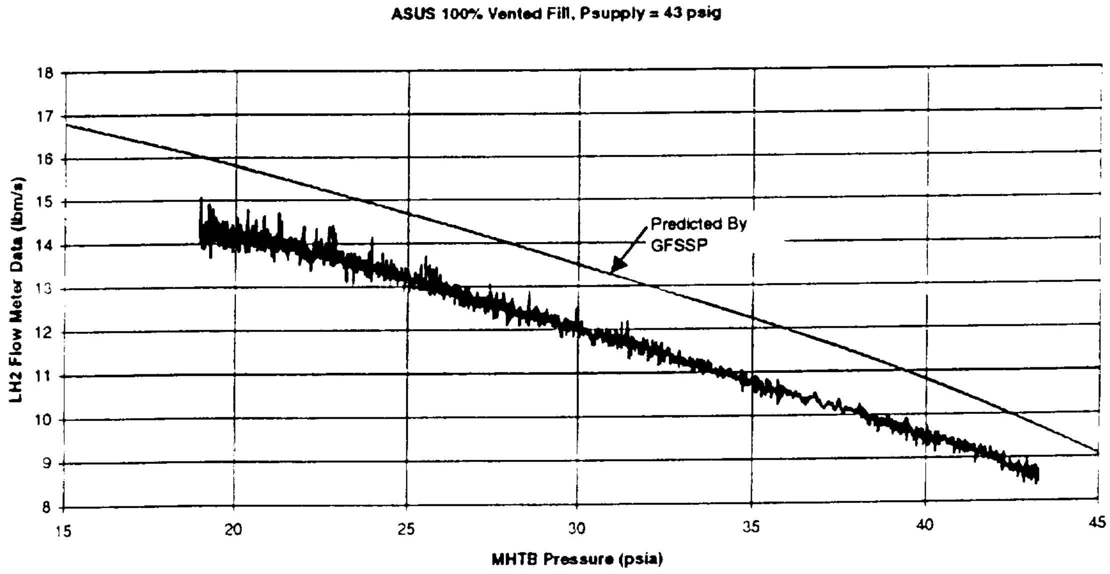

Figure 2: Supply Flow Versus MHTB Pressure, Actual and Predicted

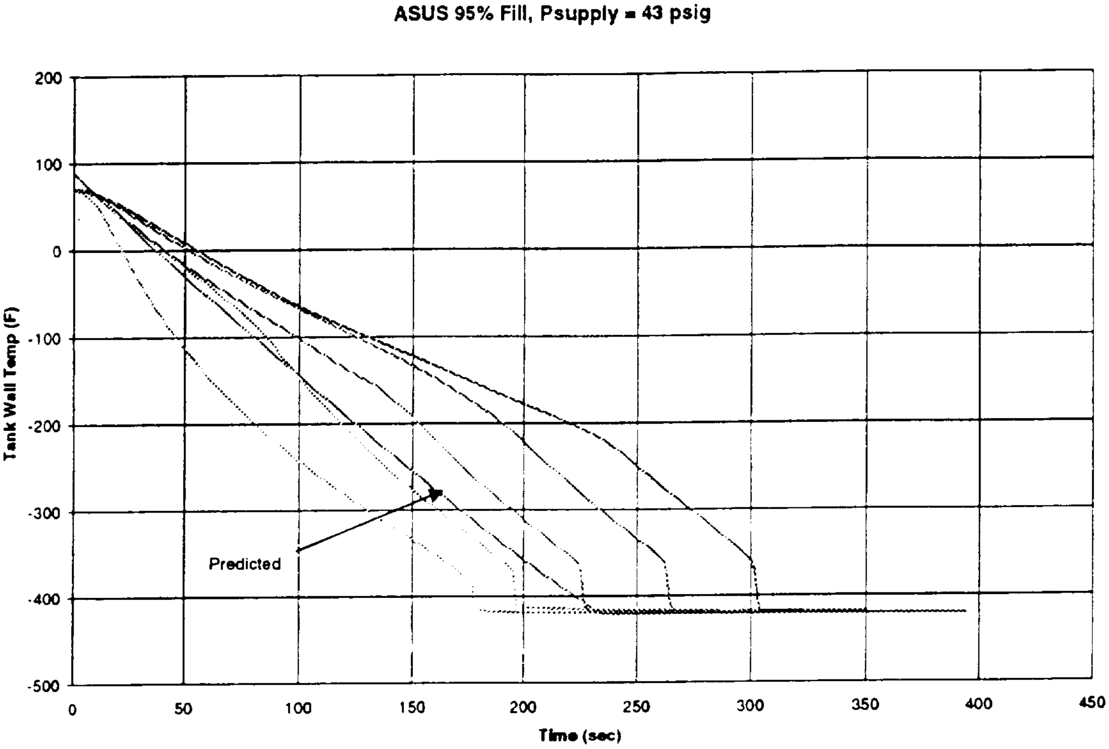

Figure 3: MHTB Tank Wall Temperatures Versus Prediction

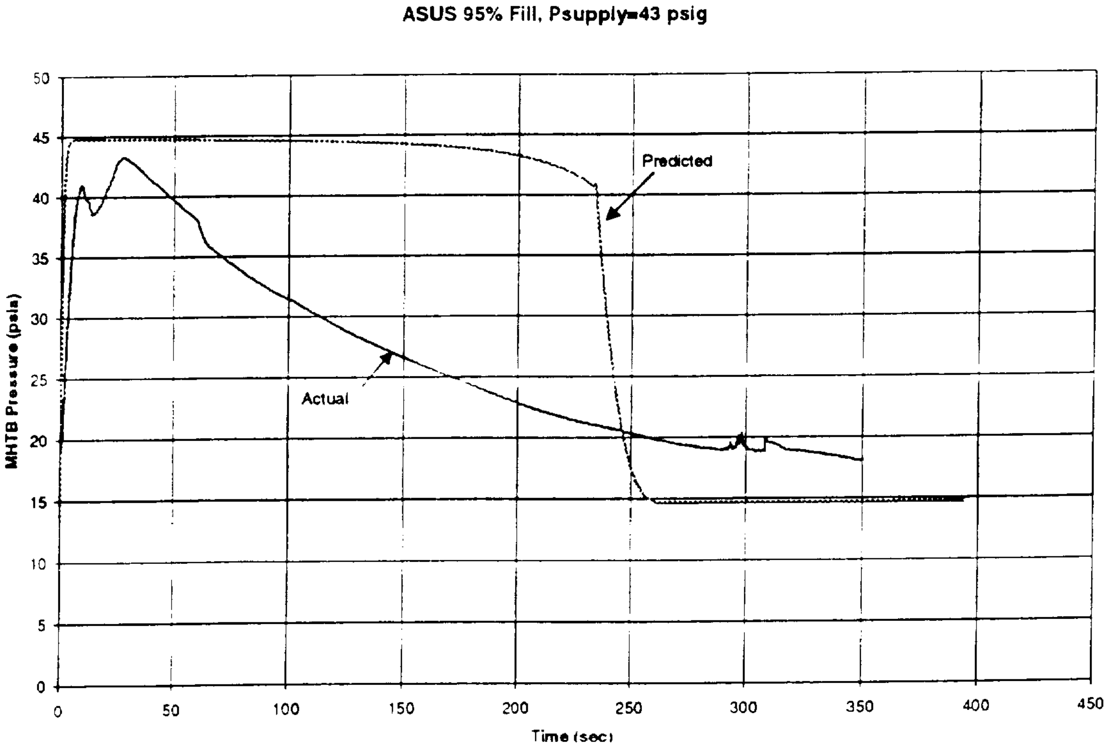

Figure 4: MHTB Ullage Pressure Versus Prediction