Computational Model of the Chilldown and Propellant Loading of the Space Shuttle External Tank

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This paper describes a computational model of the chilldown and propellant loading of the Space Shuttle External Tank liquid oxygen and hydrogen tanks at Launch Complex 39B at Kennedy Space Center. The purpose of the computational model is to predict the time required to chilldown the entire assembly consisting of the ground system transfer line and propellant tanks in order to compare with observed loading times, to evaluate the feasibility of similar models developed for the Ares I Upper Stage. The model also predicts the history of inflow and outflow from the tank, pressure and temperature inside the tank, and heat leak through the walls. The Generalized Fluid System Simulation Program (GFSSP), a general purpose network flow analysis code, has been used to develop this computational model. The paper describes the simulation of the loading process for both tanks and compares the resulting predictions to measurements.

Nomenclature

F&G = Flush and Gush
GFSSP = Generalized Fluid System Simulation Program
LH2 = Liquid hydrogen
LO2 = Liquid oxygen
MLP = Mobile Launch Platform
MPS = Main Propulsion System
VTASC = Visual Thermofluid Analyzer of Systems and Components

I. Introduction

One of the very first and longest ground operations before a rocket launch is the loading of cryogenic propellants from the ground storage tanks into the launch vehicle tanks. This process takes several hours because the cryogenic transfer lines and propellant tanks must be chilled down from ambient temperature to liquid propellant temperatures, approximately -423 °F for liquid hydrogen (LH2) and -298 °F for liquid oxygen (LO2). The primary source of this cooling is the latent heat of vaporization: when cryogenic propellants are introduced into the transfer lines and vehicle tanks, they extract energy from the pipe and tank walls and evaporate. The vaporized propellants are vented from the vehicle tank, either to a flare stack, in the case of hydrogen, or to the atmosphere, in the case of oxygen.

This paper describes a computational model of the chilldown and propellant loading of the Space Shuttle External Tank and ground transfer lines at the Kennedy Space Center. The purpose of this effort is to validate a similar model used to predict propellant loading of the upper stage of the proposed Ares-I launch vehicle. This model was created using the Generalized Fluid System Simulation Program (GFSSP), developed at NASA's Marshall Space Flight Center. GFSSP is a general purpose network flow analysis code capable of simulating fluid flow with phase change and conjugate heat transfer to solids[1].

Figure 1 shows an aerial view of Launch Complex 39B at Kennedy Space Center. The LO2 and LH2 storage tanks are located more than a quarter mile away from the Mobile Launch Platform (MLP). The cross-country transfer lines are made of Invar and vacuum-jacketed to provide thermal insulation. The transfer lines in the MLP are made of vacuum-jacketed stainless steel.

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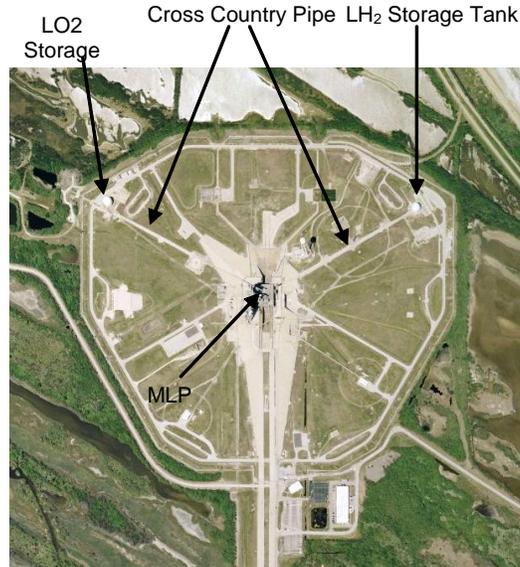
Figure 1. Aerial view of KSC Launch Complex 39B

During pre-launch operations, the LO2 and LH2 tanks are loaded approximately simultaneously. The loading process of each tank is divided into several phases, which include:

Chill-down: During this phase, the ground transfer lines are chilled down to cryogenic temperature by a modest flow from the storage tanks. The orbiter main propulsion system (MPS) is also chilled. The end of the LO2 system chill-down is marked by subphases: orbiter pressure check, flush-and-gush to prevent feedline geysering, and tail service mast refill.

Slow-fill: In this phase, liquid propellant flows through the chilled transfer lines and into the external tank at a slow flowrate. The propellant is driven cross-country by pressurization of the LH2 storage tank ullage or one of a pair of LO2 pumps, through the replenish fill control valve. Slow-fill continues until the LH2 tank is 5% full, or the LO2 tank is 2% full.

Fast-fill: During this loading phase, the LO2 pump speed is increased, and the main fill control valve is opened. A fast flowrate is maintained until the LO2 tank is 98% full. The LH2 flowrate is also increased, tapering off as the tank nears 98% full.

Topping: During topping, the tanks are filled to 100% at a slower flowrate. This is followed by several hours of replenishment flow to compensate for boil-off.

The objective of this numerical model is to predict a) the chilldown time of the entire assembly, including the ground system transfer lines and vehicle propellant tank, in order to develop a timeline for the launch, b) the vent flowrate history during the loading process, and c) propellant consumption. Chilldown of the cryogenic transfer line and propellant tank is a complex thermo-fluid dynamic process that involves change of phase (boiling and condensation), two-phase flow with gravity, and conjugate heat transfer between solid and fluid. A simplified analysis scheme such as that of Drake et al[2] is not adequate to answer all these questions. Therefore, GFSSP has been used to develop a loading model integrating the ground system and propellant tanks of the Shuttle ET as validation for similar models of Ares I propellant loading. Prior to this effort, GFSSP has been used to predict the chilldown of short as well as long cryogenic transfer lines[3,4].

II. Model Description

This section describes the Generalized Fluid System Simulation Program used in this analysis. Then it details the elements of the propellant loading and chilldown models, including the major components of the ground transfer lines and the External Tank, as well as boundary conditions and assumptions.
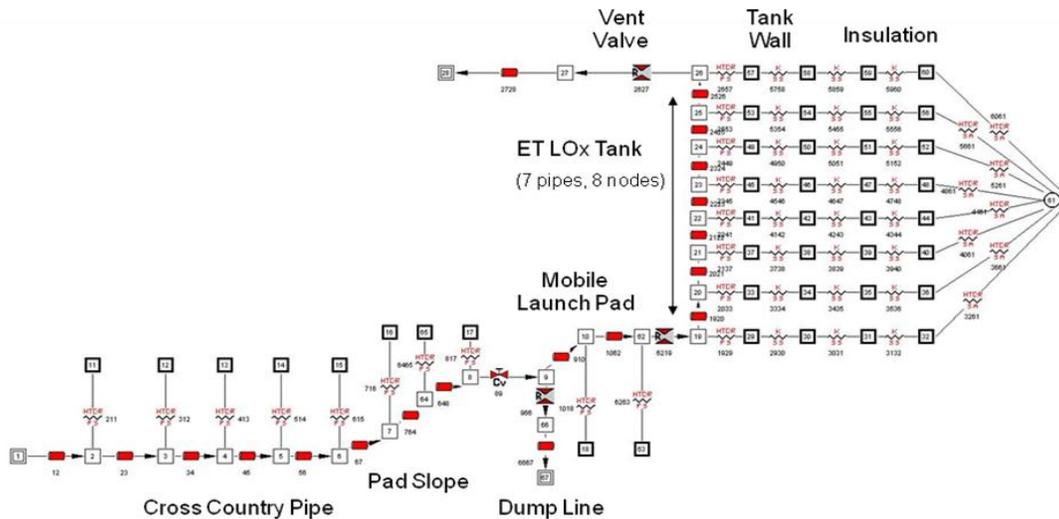
A. Description of GFSSP

GFSSP is a general-purpose computer program for analyzing fluid flow and heat transfer in a complex network of fluid and solid systems. It employs a pressure based finite volume algorithm that solves the mass and energy conservation equations in fluid nodes and the momentum conservation equations in the branches connecting those

nodes. It also solves the energy equation for temperature in a network of solid nodes connected by conductors. Thermodynamic properties are calculated for propellants using the computer program GASP[5], which is integrated with GFSSP. The fluid resistance library includes pipes, orifices, common fittings, and valves. GFSSP has three major parts. The first part is the graphical user interface, the Visual Thermofluid Analyzer of Systems and Components (VTASC). VTASC allows users to create a flow circuit by a 'point and click' paradigm. It creates the GFSSP input file after the completion of the model building process. It can also create a customized GFSSP executable by compiling and linking User Subroutines with the solver module of the code. The user can run GFSSP from VTASC and post-process the results in the same environment. The second major part of the program is the Solver and Property Module. This is the heart of the program, which reads the input data file and generates the required conservation equations for the fluid and solid nodes and branches with the help of thermodynamic property programs. It also interfaces with User Subroutines to receive any specific inputs from users. Finally, it creates output files for VTASC to read and display results. The User Subroutine is the third major part of the program. This consists of several blank subroutines that are called by the Solver Module. These subroutines allow the user to incorporate any new physical model, resistance option, fluid, etc. into the model.

B. LO2 Propellant Loading Model

Figure 2 shows the GFSSP model of the KSC ground system and Shuttle ET liquid oxygen tank. LO2 is pumped from the boundary node, Node 1 at the lower left, with the pressure and temperature set by measurements taken near the exit of the LO2 pump. The fluid travels cross-country through approximately ¼ mile of 6 in. pipe, and then climbs the pad slope to the Mobile Launch Pad (MLP). The fluid nodes in the pipeline are connected by solid-to-fluid conductors to solid nodes which represent the mass of the metal in the transfer lines; because the lines are vacuum-jacketed, convection to the ambient is ignored. Flowrate is controlled by a single valve used to simulate the effective resistance of the dual-valve set-up on the MLP. Just after this control valve, LO2 can be routed to the vehicle or down the dump line, which can be closed off as needed. Because the primary consideration is to model chilldown, not determine pressure drop, the ground facility has been greatly simplified by ignoring the effects of numerous bends. Thus to match the observed flowrates, the effective Cv of the fill control valve must be set slightly lower than that of the real valve assembly.

Figure 2. GFSSP Model of the KSC Ground System and Shuttle LOx Tank

The ET LO2 tank is represented by eight nodes connected by seven pipes. The overall length of the pipes is the same as that of the LO2 tank, and their diameter is set to match the overall volume. The tank fluid nodes are connected to a network of solid nodes representing the mass of the tank wall and foam insulation. Heat conduction is modeled in the radial direction, but has been found to be negligible in the axial direction. The outer surface of the tank features natural convection to an 85 °F ambient node. Oxygen vapor exits the tank through the vent to the atmosphere at 14.7 psia. The vent is modeled as a restriction with a pressure-dependent effective area.

More than 27,000 lb of facility lines and tank must be chilled down. The tank holds approximately 1.4 million pounds of LO2, and the filling process takes several hours and involves various stages, the first of which, pump pre-

chill, is not modeled. Also not modeled is a return loop from the pump exit back to the storage tank, which allows the pump to keep operating when the MLP flow control valve is closed.

The simulation begins with the chilldown of the quarter-mile transfer line. The LO2 is vaporized and flows both out the dump line and through the vehicle tank. As the pipe reaches LO2 saturation temperature and liquid begins to approach the orbiter, the dump line flow is restricted, to allow liquid to chill down the orbiter MPS. Before liquid enters the vehicle tank, a pressure check is performed. During this period, the fill control valves are closed, so that LO2 drains out the dump line; meanwhile, the pumps continue to operate, circulating LO2 in the return loop back to the storage tank. Because this return loop is not modeled in GFSSP, predicted pressure and flowrate will not agree with observations during this period. After pressure checks, the fill control valves are re-opened, the tail service mast is refilled, and the vehicle tank begins its slow fill through the replenishment valve. When the tank is 2% full, the pump speed is increased and main flow valve opened, starting fast fill, ending when the tank is 98% full and the topping and replenishment phase commences. The simulation ends at the conclusion of fast fill.

Upon entering the tank at near-ambient temperature, the liquid propellant immediately turns into vapor. The heat of vaporization is received from the metal which is cooled by rejecting heat to the propellant. After the solid is cooled to the saturation temperature of liquid, the vapor starts condensing. The condensation is determined from the thermodynamic state. The liquid-vapor mixture is assumed homogeneous. The amount of liquid and vapor in a control volume is determined from the vapor fraction, or quality, of the mixture.

Because GFSSP assumes a homogeneous mixture of two-phase flow, at the end of the loading process, there is a possibility of reaching a saturation condition at the top-most node representing the ullage space. In such a circumstance, there is a likelihood of liquid leaving the vent valve. As a result, the predicted flowrate through the vent valve could be larger than in reality. To address this issue, a phase separation model is developed. This model allows a modification to the formulation of the energy conservation equation. When one of the nodes representing a volume of the tank is under saturated conditions, only vapor is allowed to leave the control volume. The liquid remains in the control volume as long as the quality remains between 0 and 1, thus allowing the homogeneous model to approximate a steadily rising liquid level in the tank.

C. LH2 Propellant Loading Model

The GFSSP model of the Shuttle LH2 propellant loading and chilldown is similar in configuration to the LO2 model shown in Figure 2. However, there is no dump line between the fill control valve and the vehicle tank, and the vehicle vents to a flare stack instead of to the ambient. Boundary condition pressures are set by measurements taken at the exit of the ground storage tank and in the flare stack line.

More than 56,000 lb of LH2 facility lines and tank are to be chilled down. The tank holds more than 220,000 lb of LH2 fuel. The simulation begins with the chilldown of the transfer line. This chilldown starts out slowly with a gravity-fed trickle; after a few minutes the storage tank ullage is pressurized to increase the flowrate. The vehicle tank is also pre-pressurized, and the remainder of the loading process will take place under pressure maintained by operation of the vent valve. When the tank is 5% full, slow fill ceases, and opening of the main valve at the storage tank increases the flowrate to the fast fill rate. At 72% full, the pressure of the storage tank is reduced, and the flowrate tapers off, until at 85% full the flow is redirected through the replenish valve. This reduced fast fill continues until the tank is 98% full, at which point the simulation ends.

III.   Results

In this section measurements from the propellant loading of STS-116, the last Shuttle launch from Pad 39B, are compared to predictions from the GFSSP models. The inlet boundary conditions are also taken from STS-116 observations. GFSSP predictions are shown in green; measurements, in orange.

A. LO2 Propellant Loading Model

Figure 3 shows the measured and predicted LO2 flowrates as observed at the LO2 pump. During transfer line chilldown the GFSSP prediction shows fluctuations attributed to numerical instabilities associated with two-phase flow. Agreement with measurements is generally good during other loading phases, except when flow is primarily through the recirculation line that has not been modeled.
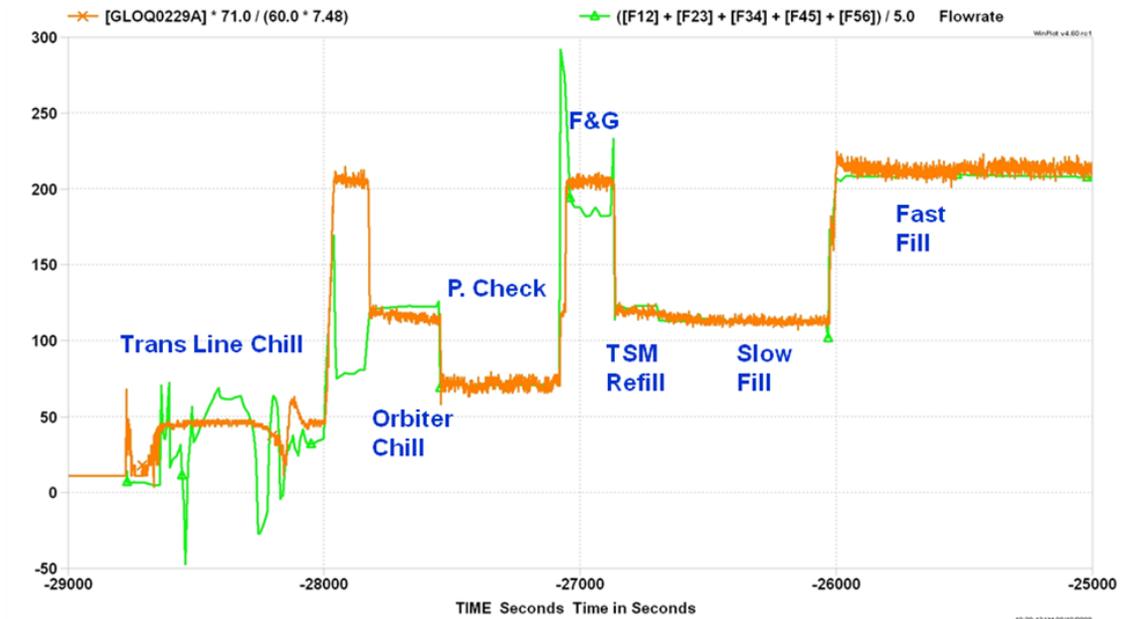
Figure 3. Measured (Orange) and Predicted (Green) LO2 Mass Flowrates (lb/s)

Figure 4 shows the measured and predicted pressure at the inlet to the fill control valve skid. There is qualitative agreement, although GFSSP consistently shows greater pressure drop between the pump and the valve skid.
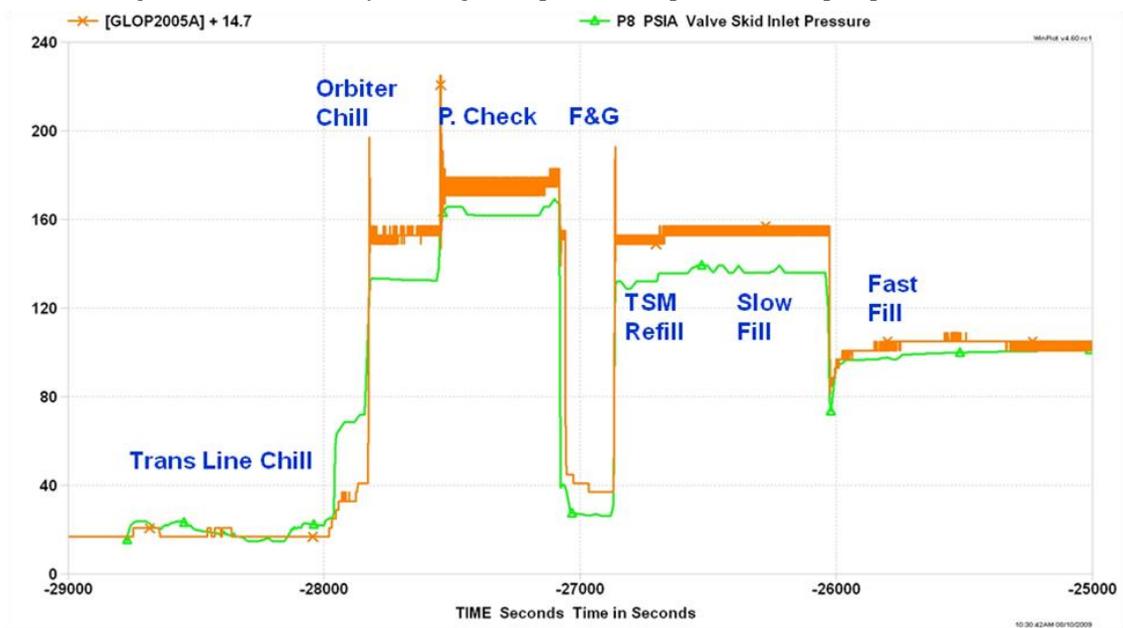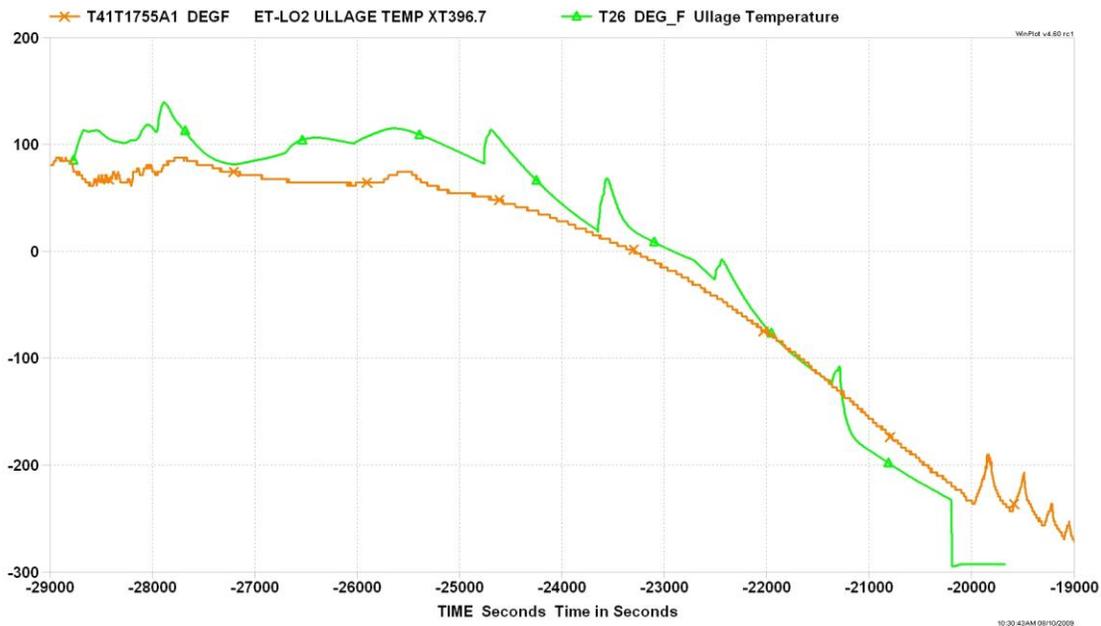

Figure 4. Measured and Predicted Pressure at the Inlet to the Fill Control Valve (psia)

Figure 5 is a plot comparing the measured and predicted ullage pressure in the LO2 tank. The pressure rise at the end of the transfer line chill is duplicated, but a second pressure rise between slow and fast fill is not. This may be due to the two-phase mixture in the tank at the latter time. Other fast fill pressure spikes seen in the GFSSP prediction are attributed to numerical instabilities that occur when a tank node changes from a vapor to a two-phase mixture, causing a sudden change in density.
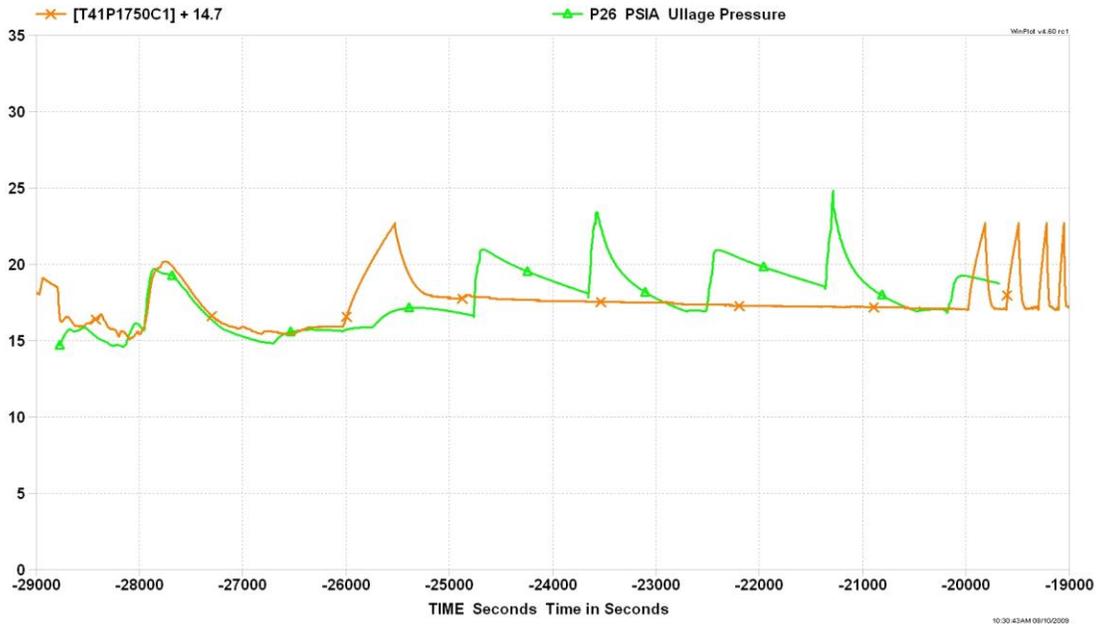
Figure 5. Measured and Predicted Ullage Pressure (psia)

Figure 6 shows the measured and predicted ullage temperature in the LO2 tank. Early in the filling process, the predicted ullage temperature is steady but higher than measured. As the tank fills with liquid, the ullage temperature decreases, with the prediction showing a sudden drop when the top tank node reaches saturation. The temperature spikes during fast fill are consistent with the instability-induced pressure spikes seen in Figure 5.

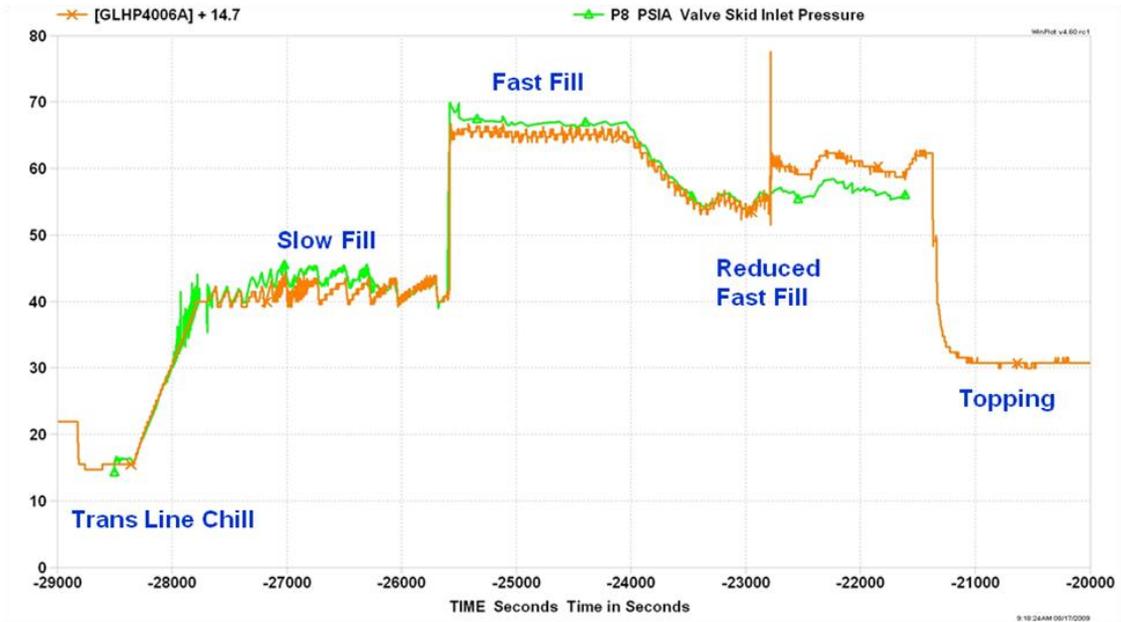**Figure 6. Measured and Predicted Ullage Temperature (°F)**

As shown in Table 1, GFSSP predicts that the LO2 tank will reach the 5% full level four minutes earlier than actually observed. The 98% full level is predicted to occur 11 minutes earlier. It is estimated that 8100 lb of oxygen will be vented off between transfer line chill and 98% full. At the end of of fast fill, the predicted heat leak through the tank walls is 54 BTU/s, somewhat lower than the estimated range of 61-100 BTU/s[6]. The discrepancy is attributed to the coarse solid temperature grid.

Table 1: Comparison of GFSSP Predictions with STS-116 LO2 Loading

	STS-116	GFSSP
5% Full	49 min	45 min
98% Full	164 min	153 min
O_2 Vented During Loading	N/A	8075 lb_m
Heat Leak (through tank walls)	61-100 BTU/s (est. range)	54 BTU/s

## B. LH2 Propellant Loading Model

Figure 7 shows the measured and predicted pressure at the inlet of the LH2 fill control valve skid. The GFSSP prediction is slightly higher during slow fill and fast fill, slightly lower during reduced fast fill.
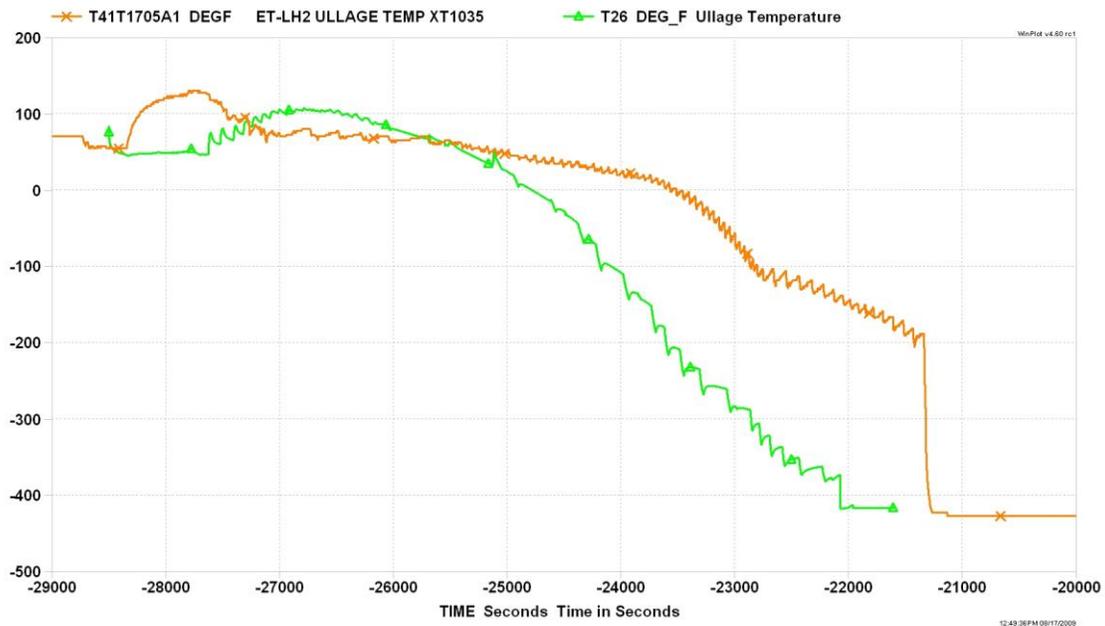

Figure 7. Measured and Predicted Pressure at the Inlet to the Fill Control Valve (psia)

Figure 8 is a plot of the measured and predicted ullage pressure in the LH2 tank. Agreement is excellent until slow fill begins, at which point the model is no longer able to match the pressure cycling that occurs during loading. This may be caused by the two phase mixture present in the tank once slow fill begins.

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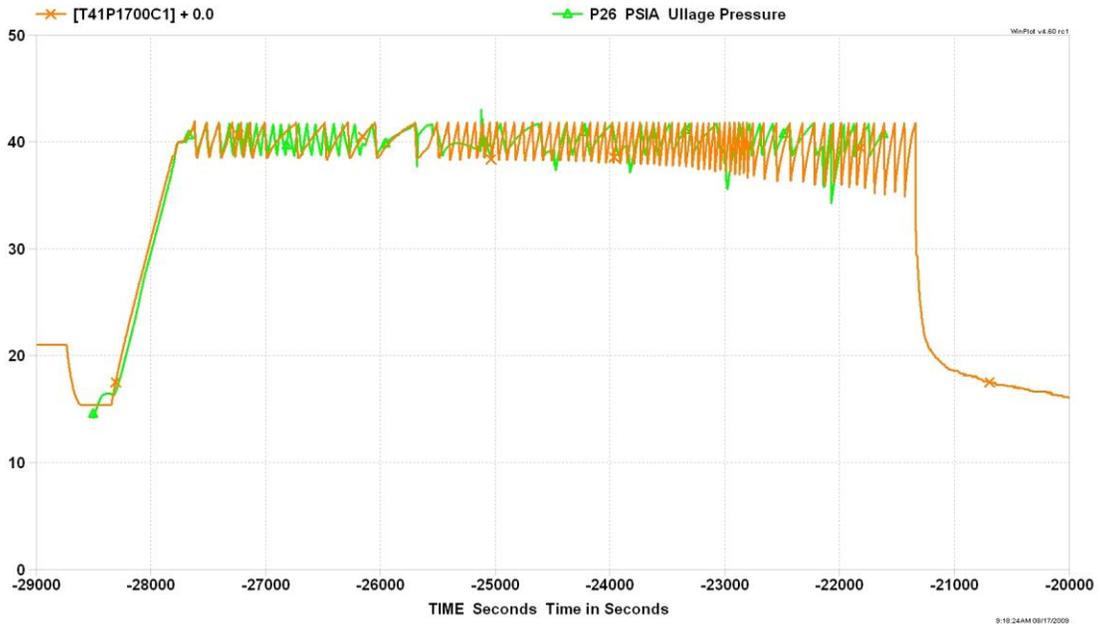
Figure 8. Measured and Predicted Ullage Pressure (psia)

Figure 9 plots the measured and predicted ullage temperature in the LH2 tank. GFSSP is unable to match the temperature increase that occurs during pressurization, although there is a small increase that occurs when the tank first begins to fill. As the liquid level in the tank rises, the predicted rate of temperature decrease is greater than actually observed.

Figure 9. Measured and Predicted Ullage Temperature (°F)

As outlined in Table 2, GFSSP predicts that the LH2 tank will reach the 5% full level two minutes later than observed. The 98% full level is predicted to occur three minutes earlier. It is estimated that 4900 lb of hydrogen will be vented to the flare stack between transfer line chill and 98% full. The predicted tank wall heat leak falls within the expected range.

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Table 2: Comparison of GFSSP Predictions with STS-116 LH2 Loading

	STS-116	GFSSP
5% Full	48 min	50 min
98% Full	119 min	116 min
H$_2$ Vented During Loading	N/A	4931 lb$_m$
Heat Leak (through tank walls)	68-140 BTU/s (est. range)	96 BTU/s

IV. Conclusion

Numerical models to analyze the loading of the LO2 and LH2 tanks of the Space Shuttle External Tank have been developed. The model includes the ground system transfer line, and the propellant tank with insulation and vent/relief valve. The model accounts for unsteady flow, change of phase, and conjugate (solid to fluid) heat transfer. The model predicts the loading time with reasonable accuracy, and also provides estimates of ullage temperature, vent flowrate, and wall heat leaks. It is believed that modifying the model to support two heterogeneous phases would remove the numerical instabilities seen in the ullage pressure prediction.

Acknowledgments

References

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