NO VENT TANK FILL AND TRANSFER LINE CHILLDOWN ANALYSIS BY GENERALIZED FLUID SYSTEM SIMULATION PROGRAM (GFSSP)

Alok Majumdar
NASA/Marshall Space Flight Center, Huntsville, Alabama

ABSTRACT

The purpose of the paper is to present the analytical capability developed to model no vent chill and fill of cryogenic tank to support CPST (Cryogenic Propellant Storage and Transfer) program. Generalized Fluid System Simulation Program (GFSSP) was adapted to simulate charge-hold-vent method of Tank Chilldown. GFSSP models were developed to simulate chilldown of LH2 tank in K-site Test Facility and numerical predictions were compared with test data. The report also describes the modeling technique of simulating the chilldown of a cryogenic transfer line and GFSSP models were developed to simulate the chilldown of a long transfer line and compared with test data.

INTRODUCTION

The current interest in pressurized transfer of cryogenic fluids stems in part from NASA's plans for an ambitious human Space Exploration Initiative including manned voyages to the Moon and Mars. These activities will require enormous amounts of propellant stored as cryogenic liquids. The ability to efficiently transfer these cryogens between earth-to-orbit tanker vehicles, orbiting depots, and space transportation vehicles is required for mission success.

One of the objectives of CPST Analytical Tool Development Task is to provide the designers and analysts the capability to model the system operation with reasonable accuracy. It is also desirable that computation time for modeling events are not excessively large. The analytical capability to model no-vent chill and fill and transfer line chilldown was very limited primarily due to complexities of modeling unsteady two phase flows with phase change. In recent years there have been some progress in modeling tank [1] and transfer line chilldown [2] using NASA developed GFSSP [3]. This paper describes the progress of modeling no-vent chill and fill of cryogenic tanks and provides the status of modeling transfer line chilldown using GFSSP.

<u>No-vent Chill & Fill</u>

The practice of tank chilldown in micro-gravity environment is quite different than tank chilldown in ground. In ground, under normal gravity, a vent valve on top of the tank can be kept open to vent the vapor generated during chilling process. The tank pressure can be kept close to atmospheric pressure while tank is chilling down. In micro-gravity environment, due to absence of stratification, such practice may result in dumping large amount of precious propellant overboard. The intent of no-vent chill and fill method is to minimize the loss of propellant during chilldown of propellant tank in micro-gravity environment. No-vent chill and fill method consists of repeated cyclic process of charge, hold and vent.

During the charge cycle, a small quantity of liquid cryogen is injected into the evacuated tank. Some type of spray nozzle is usually used to break the incoming liquid into droplets. Initially, the liquid flashes due to the low tank pressure, and then the remaining liquid droplets evaporate as they contact warm hydrogen vapor or the tank wall. During the hold period, the circulating flow pattern induced from the spray nozzles provides convective heat transfer from cold vapor to the tank wall. The primary mode of heat transfer during the hold is convection. At the completion of the hold period, the pressure has risen considerably and the tank is ready to be vented. Since venting occurs as an isentropic blowdown, some additional cooling may be recovered by stage-wise venting. The key parameters of this method are (1) charge magnitude, (2) spray system selection, (3) mass flow rate, (4) hold duration, (5) acceleration environment, (6) desired tank wall temperature, and (7) maximum operating pressure. A reliable and inexpensive mathematical model will help designers to perform large amount of calculations to optimize the key parameters.

<u>Transfer Line Chilldown</u>

The chilldown of fluid transfer lines is an important part of using cryogenic systems, such as those found in both ground- and space-based applications. The chilldown process is a complex combination of both thermal and fluid transient phenomena. A cryogenic liquid flows through a transfer line that is initially at a much higher temperature than the cryogen. Transient heat transfer processes between the liquid and transfer line cause vaporization of the liquid, and this phase change can cause transient pressure and flow surges in the liquid. As the transfer line is cooled, these effects diminish until the liquid reaches a steady flow condition in the chilled transfer line. If these transient phenomena are not properly accounted for in the design process of a cryogenic system, it can lead to damage or failure of system components during operation. For such cases, analytical modeling is desirable for ensuring that a cryogenic system transfer line design is adequate for handling the effects of a chilldown process.

ANALYTICAL MODELING APPROACH USING 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 mass and energy conservation equations at nodes and momentum conservation equations at branches connecting the nodes. Thermodynamic properties are calculated for propellants using the computer program GASP which is integrated with GFSSP. 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 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 users to incorporate any new physical model, resistance option, fluid etc. in the model.

TEST DESCRIPTION

K-site Test Facility [4]

The test set-up as, shown in Figure 1, consists of a test tank, spray system, test tank valving, instrumentation, and the vacuum chamber.

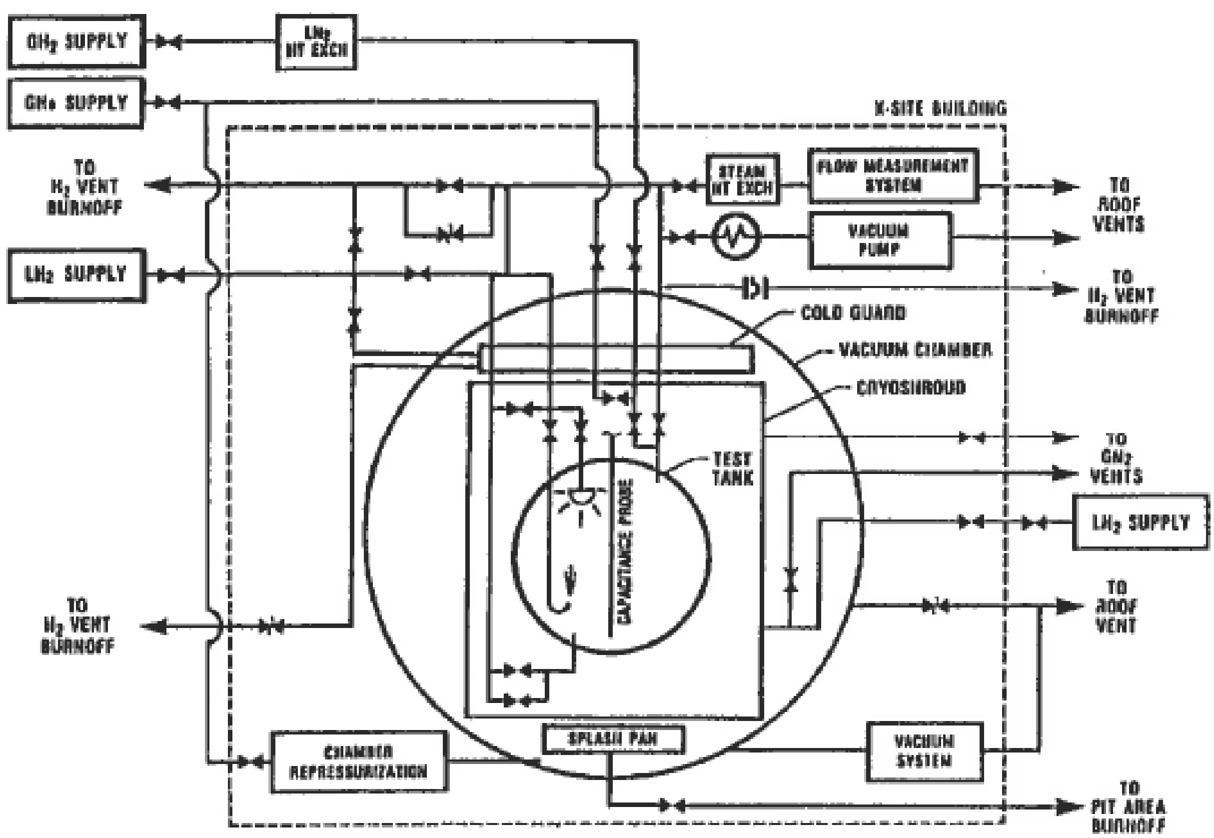

Figure 1. K-Site Test Set-Up for No-Vent Fill Experiment.

The test tank selected was an ellipsoidal with an 87 inch major diameter and a 1.2 to 1 major to minor axis ratio. The two ends are joined by a short 1.5 inch cylindrical section. The tank is made of 2219 aluminum chemically milled to a nominal thickness of 0.087 inches. Thicker sections exist where they were required for manufacturing (mainly weld lands). The tank has a 28.35 inch access flange on the top. The tank weighs 329.25 pounds, and the tank's volume is 175 ft^3. The tank was originally designed for a maximum operating pressure of 80 psia. Prior to the start of testing the tank was requalified by pneumatic test for a maximum operating pressure of 50 psia. The tank is covered with a blanket of 34 layers of multi-layer insulation (MLI) made with doubled aluminized mylar and silk net spacers, and is supported by 12 fiberglass epoxy struts. Tank ambient temperature was uniform and maintained at 530R ± 1R by an electrically heated shroud located outside the tank and inside the vacuum chamber.

The hydrogen flow rate and hydrogen temperature profile during the test are shown in Figure 2.

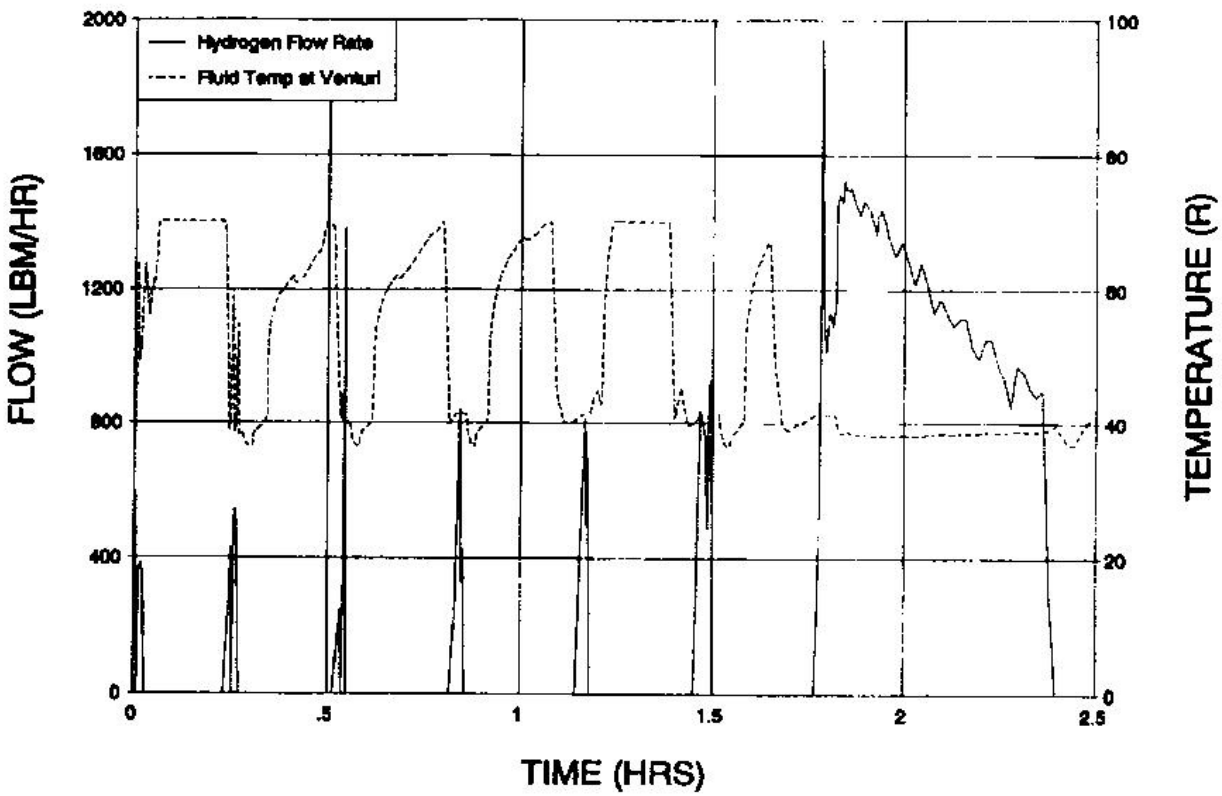

Figure 2. Hydrogen Test Flowrate and Temperature.

<u>NBS Test Facility [5]</u>

Figure 3 shows a schematic of the NBS (National Bureau of Standard) experimental setup, which consists of a 200-ft-long, 0.625-in-inside diameter copper tube supplied by a 300-L tank through a valve and exits to the atmosphere (≈12.05 psia). The tank was filled either with LH_2 or LN_2. At time zero, the valve at the left end of the pipe was opened, allowing liquid from the tank to flow into the ambient pipeline driven by tank pressure. Pressure and temperature were recorded at four downstream stations along the line. These stations are located at 20, 80, 141, and 198 ft, respectively.

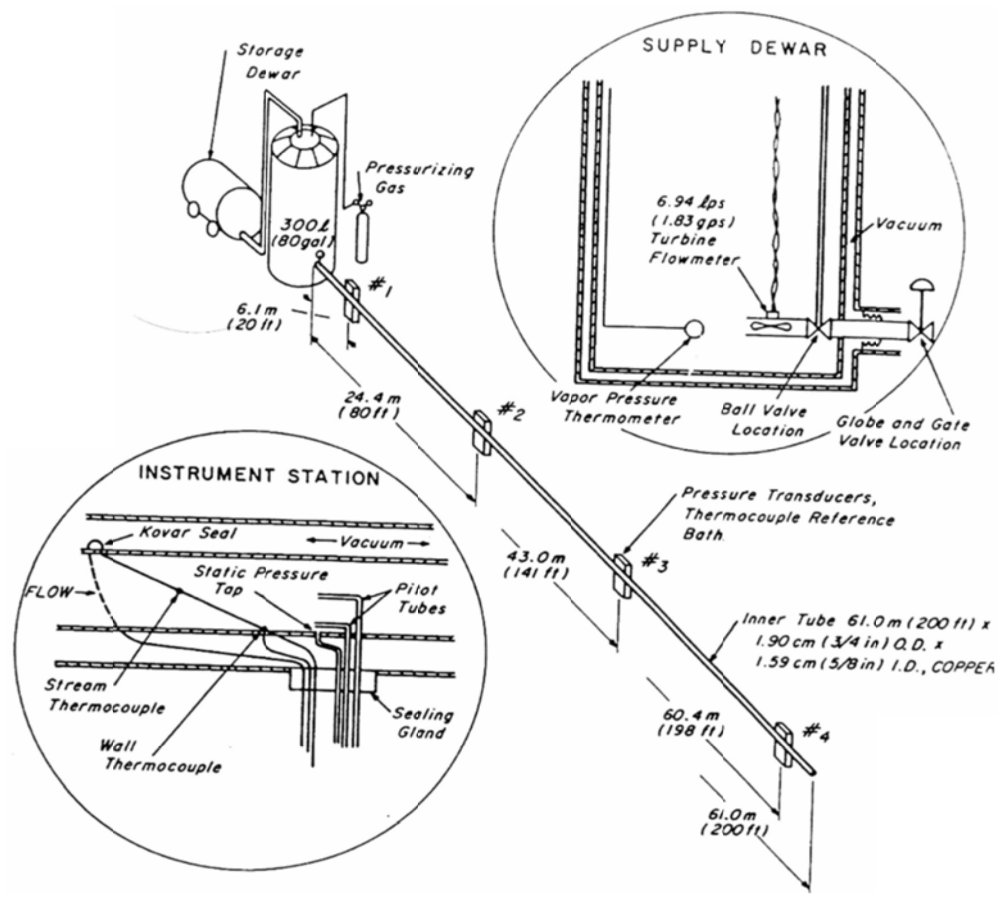

Figure 3. NBS Test Setup for Chilldown of Cryogenic Transfer Line.

GFSSP MODELS

No Vent Fill Model of K-site Test Facility

Two GFSSP models, a single node tank and a nine node tank, were built to simulate the test as described above. The single node tank model, as shown in Figure 4, represents the first GFSSP model that has a single propellant node and a single mass flowrate path. Node 1 is a boundary node that represents the Supply Tank which is supplying hydrogen at -420F and with a pressure curve as given in Figure 5 for Inlet Pressure. Branch 12 represents the set flowrate pattern as given in Figure 2. The overall flowrate that was used in the single node model has been simply divided by nine and is flowing through the nine branches. Node 2 represents the test tank with initial pressure set to 1.97 psia, initial temperature set to -19.57F, and internal volume equal to 302,400 in^3. Branch 23, modeled as a restriction, simulates the vent valve open and close. Node 3 is a boundary node which represents the vent to ambient at Pressure equal to 14.7 psia and Temperature equal to 60F. Branch 42 represents the heat transfer from the hydrogen fluid to the aluminum 2219 tank wall. The heat transfer area is the surface area of the tank which is 21,601.6 in^2. Node 4 represents the tank material and mass which is Aluminum 2219 and 329 lb respectively. The initial temperature was set to -19.57F.

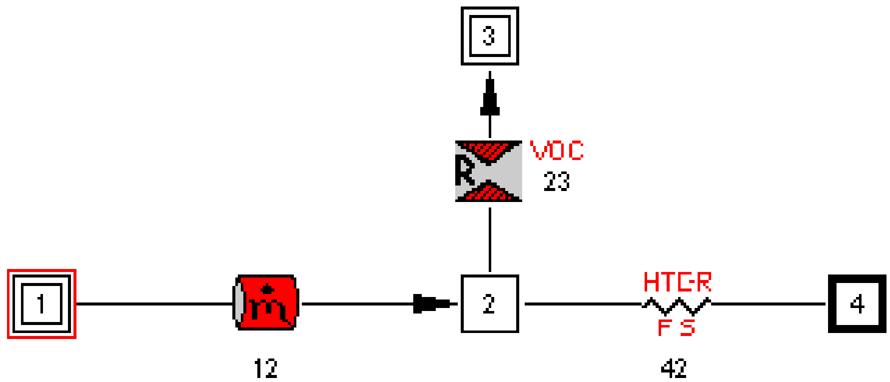

Figure 4. GFSSP Single Node Tank Model.

This model evolved into the nine node tank model as shown in Figure 6 which accounts for stratification inside the tank. Node 13 is a boundary node that represents the Supply Tank which is supplying hydrogen at -420F and with a pressure curve as given in Figure 5 for inlet pressure. The total flowrate, as given in Figure 2, was evenly distributed through Branches 131, 132, 133, 134, 135, 136, 137, 138, and 139. Figure 7 shows the transformation of the actual tank configuration to model configuration where the tank geometry was assumed to consist of nine volumes or “tank slices”. The total volume and surface area of heat transfer between solid and fluid are identical between actual and model configurations. Nodes 1 through 9 represent the inside tank volume where propellants reside, transfer from one control volume to another, exchange heat with neighboring solid nodes and change phases from liquid to vapor and vice versa. The mass and energy conservation equations are solved in branches connecting these nodes. Node 12 is another boundary node that represents the tank outlet. Nodes 10 and 11, branches 910, 1011, and 1112 represent the vent line. Nodes 1 through 9 are connected with metal solid nodes 14 through 22 through fluid to solid conductors that allow convective heat transfer between solid and fluid nodes. The model neglects axial conduction of heat.

Nodes 1 through 9 represent the test tank with initial pressure set to 1.97 psia and initial temperature set to -19.57 ^{o}F. The lengths and diameters of each branch that represent the tank are given in Table 1. Summing the individual tank slice volumes yields a total tank volume of 301,836.93 in^3. Branch 1112, modeled as a restriction, simulates the vent valve open and close. Node 12 is a boundary node which represents the vent to ambient at Pressure equal to 14.7 psia and Temperature equal to 60F. Conductors 149, 158, 167, 176, 185, 194, 203, 212, and 221 represent the heat transfer from the hydrogen fluid to the aluminum 2219 tank wall. The heat transfer area is the surface area of each tank slice as given in Table 2. Summing the individual heat transfer areas yields a total model tank heat transfer area of 21,599.43 in^2. The heat transfer coefficients were calculated from free convection correlation [6]. Nodes 14 through 22 represents the tank material and mass which is Aluminum 2219 and masses given in

Table 3. Summing the individual tank slice masses yields a total model tank mass of 329.247 lb respectively. The initial temperature was set to -19.57F.

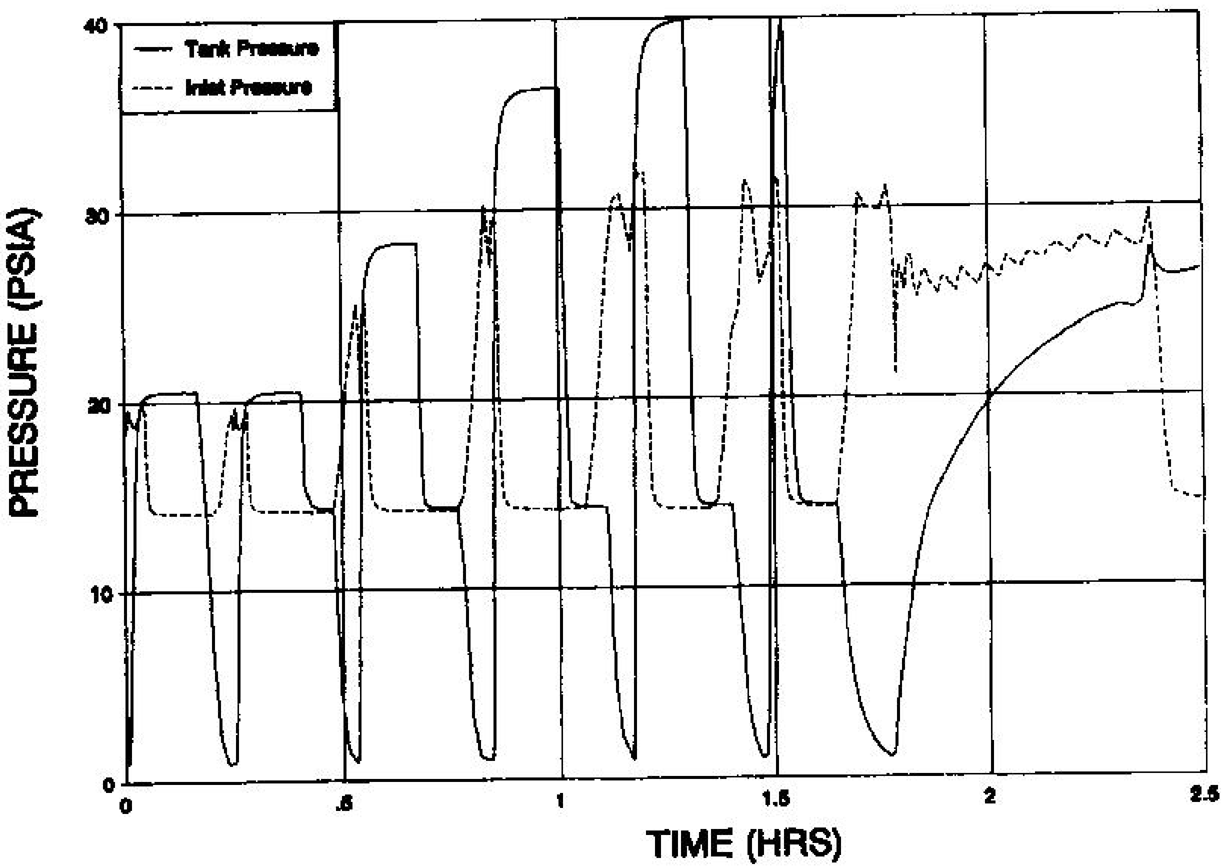

Figure 5. K-Site Test Tank Inlet Pressure Curve.

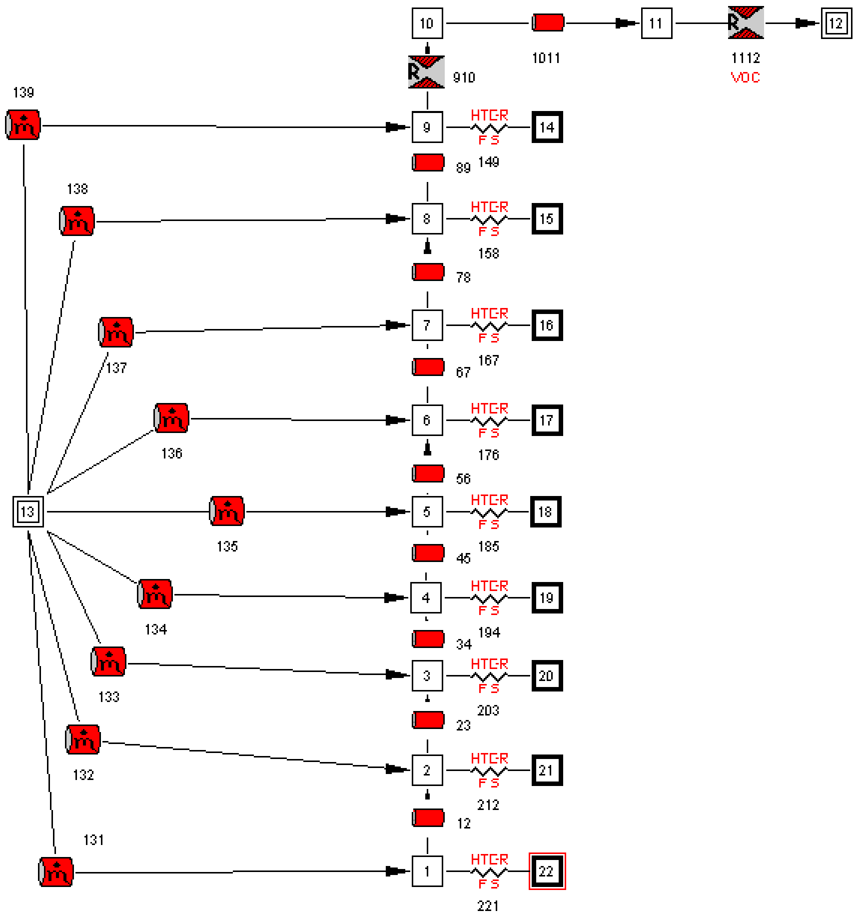

Figure 6. GFSSP Nine Node Tank Model.

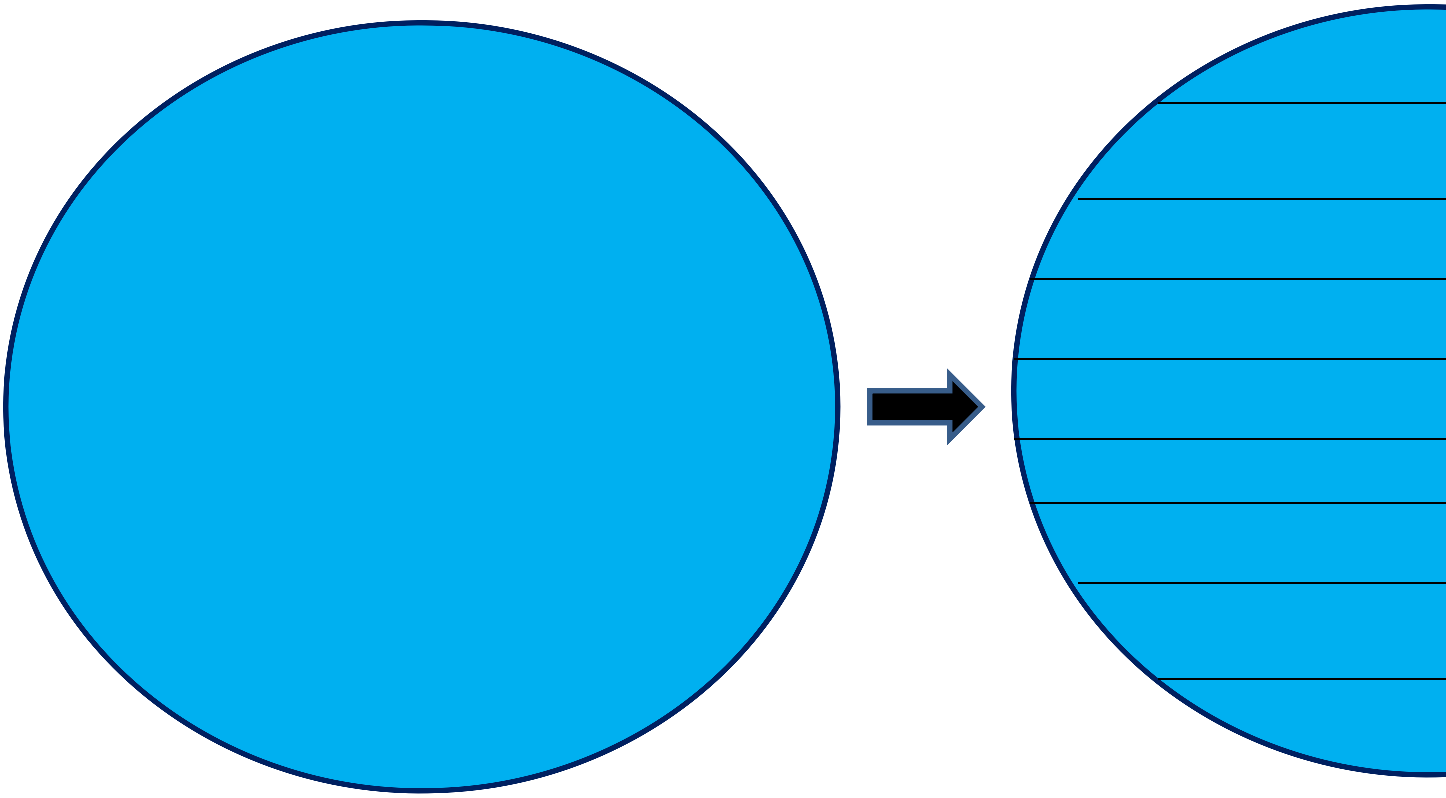

Figure 7. Conversion of LH2 Tank Geometry.

Table 1. Internal Model Tank Parameters

Branch Number	Branch Length (in)	Branch Diameter (in)	Branch Volume (in^3)
12	11.063	38.59	4,118.72π
23	11.063	62.71	10,876.43π
34	11.063	74.61	15,395.96π
45	11.063	79.88	17,647.73π
56	11.063	79.88	17,647.73π
67	11.063	74.61	15,395.96π
78	11.063	62.71	10,876.43π
89	11.063	38.59	4,118.72π

Table 2. Tank Slice Heat Transfer Area

Branch	Area (in^2)
221	462.27
212	1684.92
203	2952.94
194	3715.48
185	3968.21
176	3715.48
167	2952.94
158	1684.92
149	462.27

Table 3. Tank Slice Mass Distribution

Node	Mass (lb)
14	7.046
15	25.683
16	45.013
17	56.636
18	60.491
19	56.636
20	45.013
21	25.683

22	7.046

Transfer Line Chilldown Model of NBS Facility

Figure 8 shows a schematic of the network flow model that was constructed to simulate the transfer line. The tube was discretized into 33 fluid nodes (two boundary nodes and 31 internal nodes), 31 solid nodes, and 32 branches. The upstream boundary node represents the cryogenic tank, while the downstream boundary node represents the ambient where the fluid is discharged. The first branch represents the valve; the next 30 branches represent the transfer line. Each internal node was connected to a solid node (nodes 34 through 64) by a solid to fluid conductor. At the internal fluid nodes and branches, mass, momentum, and energy equations are solved in conjunction with the thermodynamic equation of state to compute the pressures, flow rates, temperatures, densities, and other thermodynamic and thermophysical properties. The heat transfer in the wall is modeled using the lumped parameter method, assuming the wall radial temperature gradient is small. At the internal solid nodes, the energy equation is solved in conjunction with all other conservation equations. The heat transfer coefficient of the energy equation for the solid node was computed from the Miropolski correlation [7]. The experimental work did not provide details concerning the flow characteristics for the valve used, nor did they give a history of the valve opening times that they used. An arbitrary 0.05-s transient opening of the valve was used while assuming a linear change in flow area.

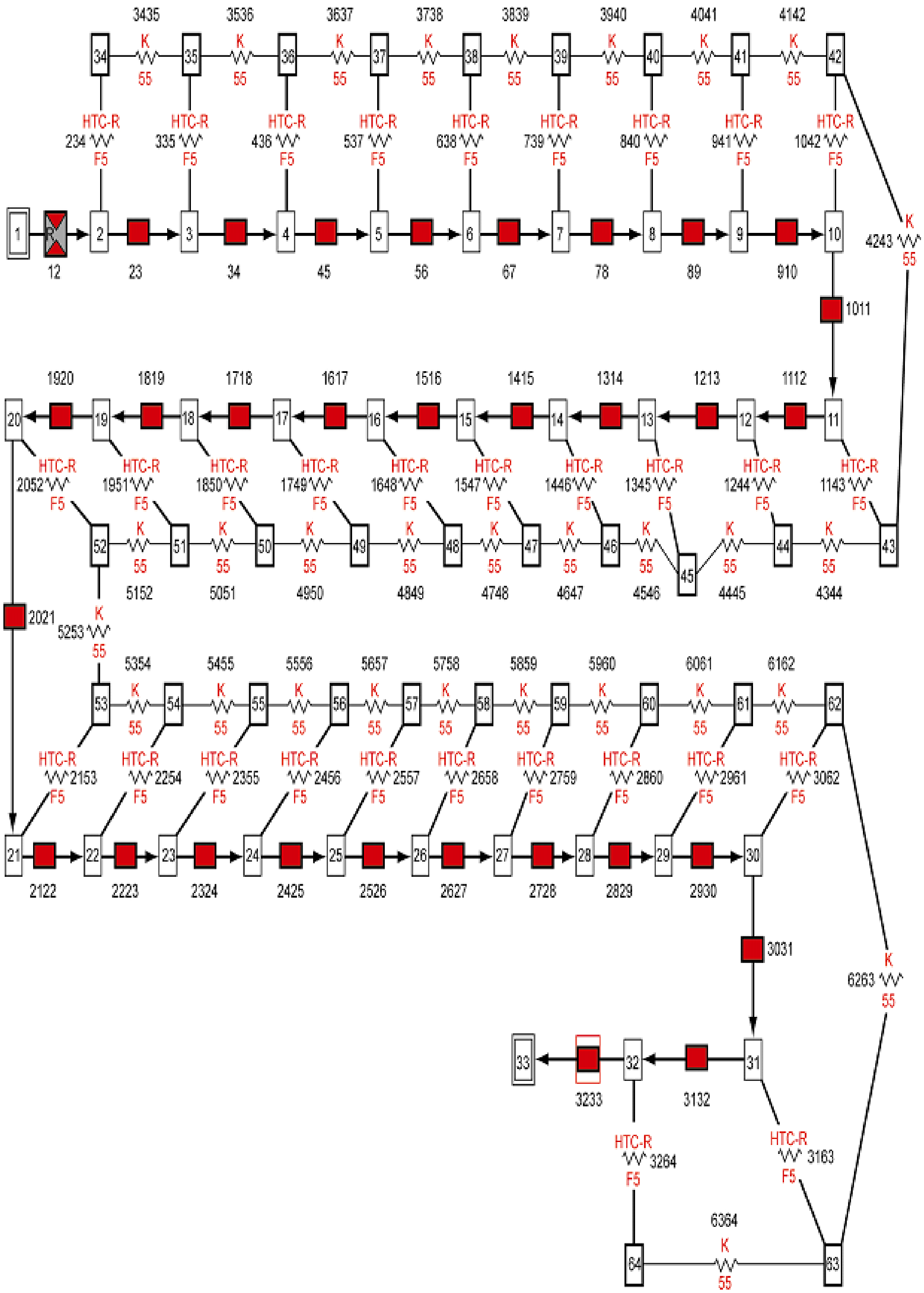

Figure 8. GFSSP model of the NBS Experimental setup.

RESULTS & DISCUSSION

No Vent Fill Model Results

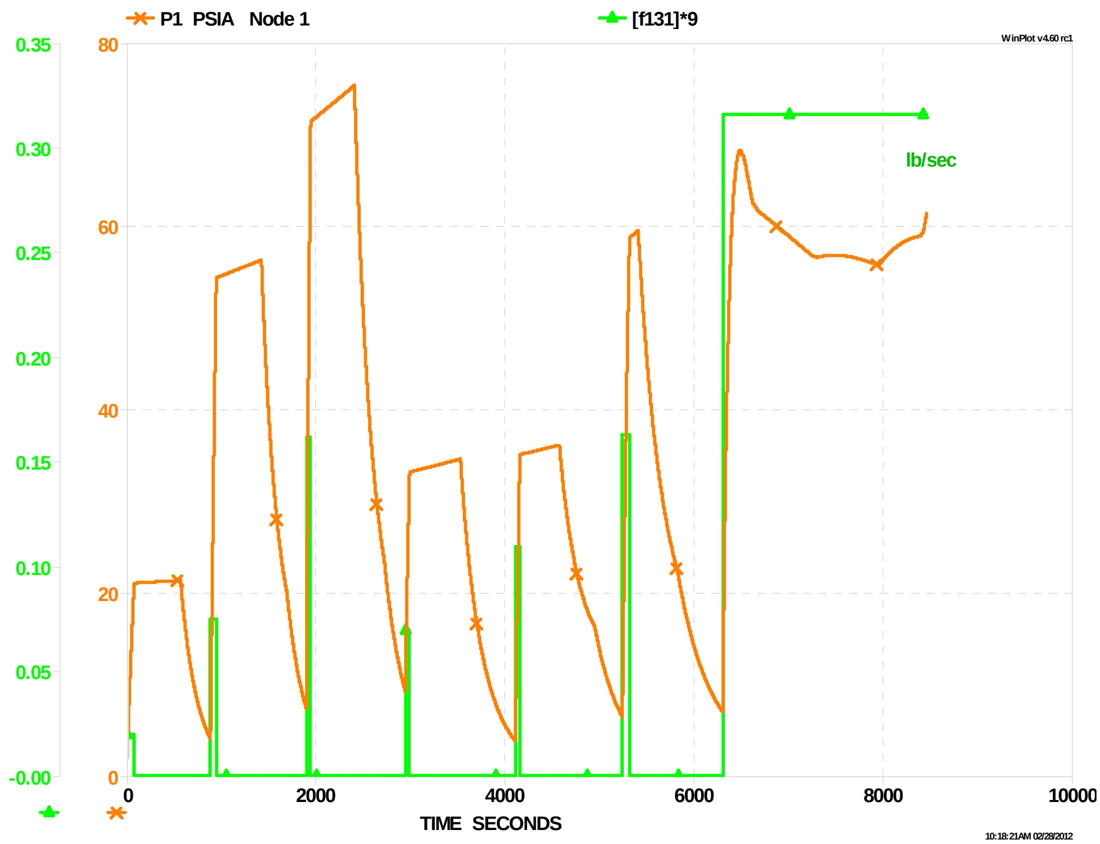

Figure 9. Specified Inlet Flowrate (green) and Predicted Pressure (red) History.

Figure 9 shows the specified inlet flowrate and predicted pressure history. During the charging period, pressure increases rapidly due to evaporation. During hold period, pressure increases slightly due to heat transfer from the wall. During venting, pressure in the tank reduces rapidly. The predicted pressure is higher than observed during the test. The reason for this discrepancy is the use of fixed flow boundary condition. With fixed flow boundary condition, GFSSP is not aware of supply pressure and therefore the calculated pressure has no reference. The alternative to fixed flow boundary condition is to extend the calculation domain to storage tank and include the modeling of transfer line and predict the flowrate into the tank. However, the K-site test is not a good candidate for such an extension as there is no information available of the transfer line in the report. During charging period, the flowrate was assumed constant and was obtained from the reported test data.

Figure 10 shows the predicted mass history of hydrogen during the operation. There is very little hydrogen during chilling process because of venting.

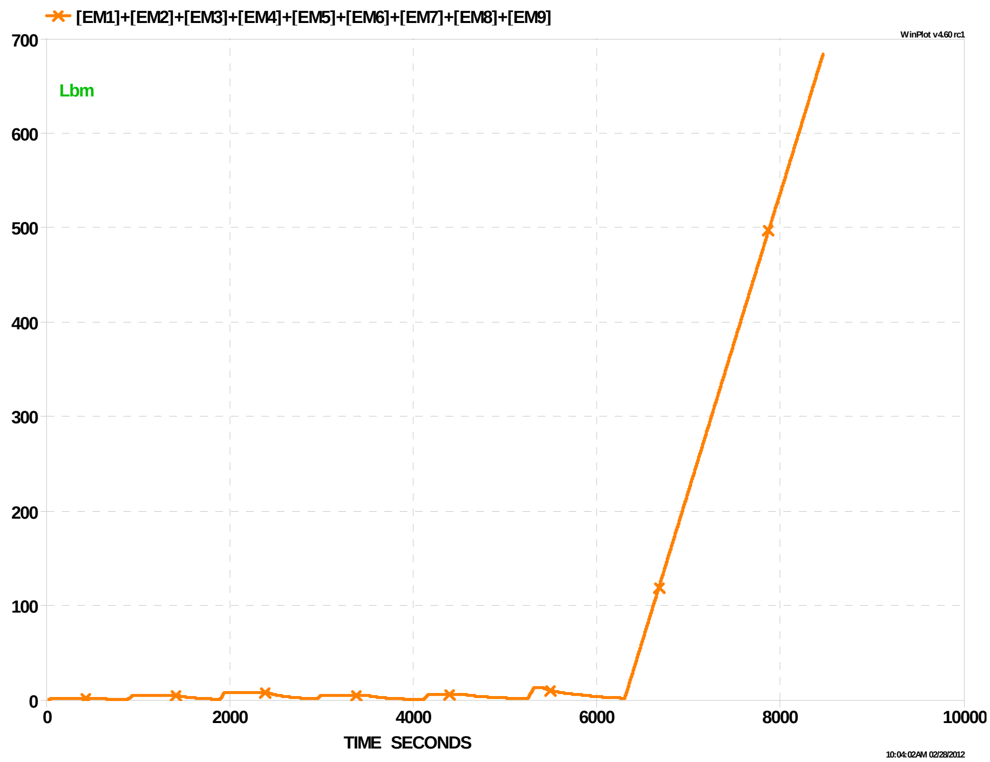

Figure 10. Predicted Hydrogen Mass History in the Tank.

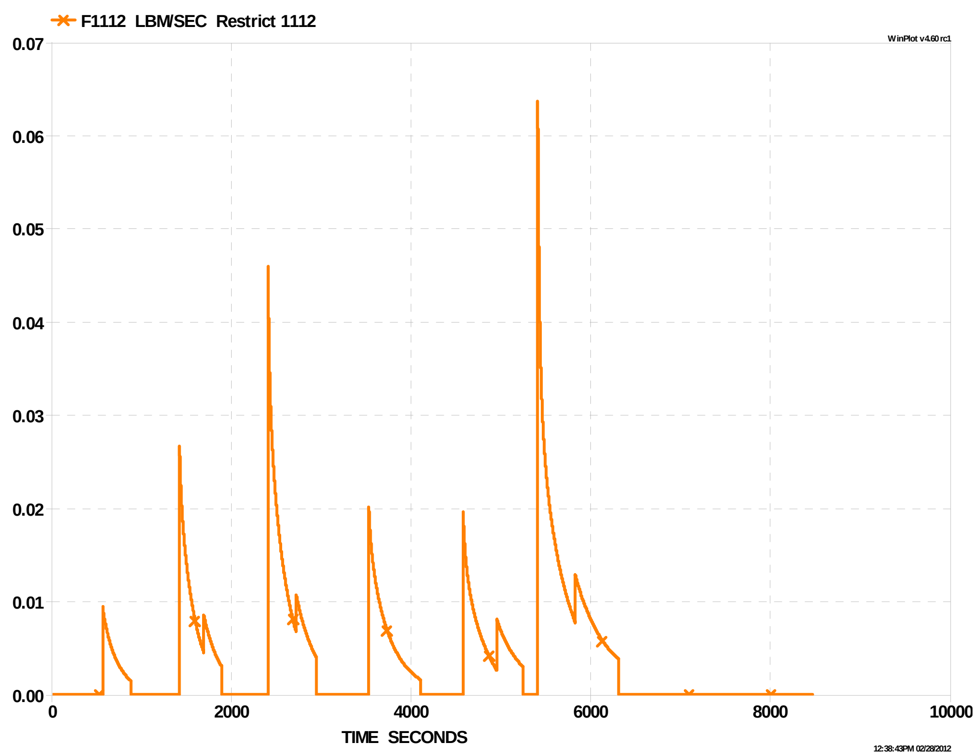

Figure 11. Predicted Vent Flowrate History during Tank Chilldown.

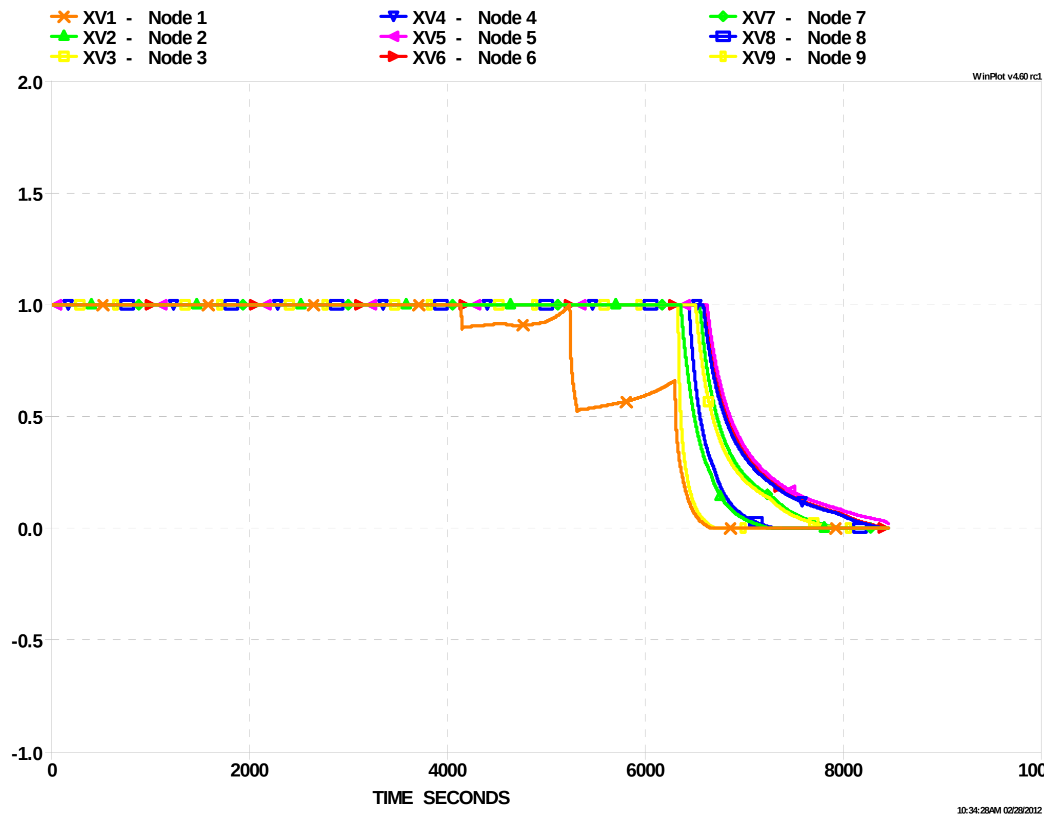

Figure 12. Predicted Vapor Quality during Tank Chilldown.

Figure 11 shows the predicted vent flowrate history during tank chilldown. Vent flowrate reaches a peak value at the opening of the vent valve and diminishes as tank pressure reduces. Figure 12 shows vapor quality at all 9 nodes during the process. As expected, liquid first forms at the bottom node while remaining nodes remain superheated. The sudden drop in the quality in the bottom node is due to blow down effect. Predicted propellant loss agrees extremely well with estimated propellant loss during the test:

- Predicted – 32.5 lbs (9-node model) & 33.5 lbs (1-node model)
- Test – 32 lbs

Figure 13 and 14 show the comparison of predicted and measured fluid and wall temperatures respectively. Single node model predicts temperature lower than the measured data. Nine-node model appears to predict temperature closure to the test data. The observed discrepancies are mainly due to uncertainties in heat transfer coefficient and discrepancies in pressure prediction.

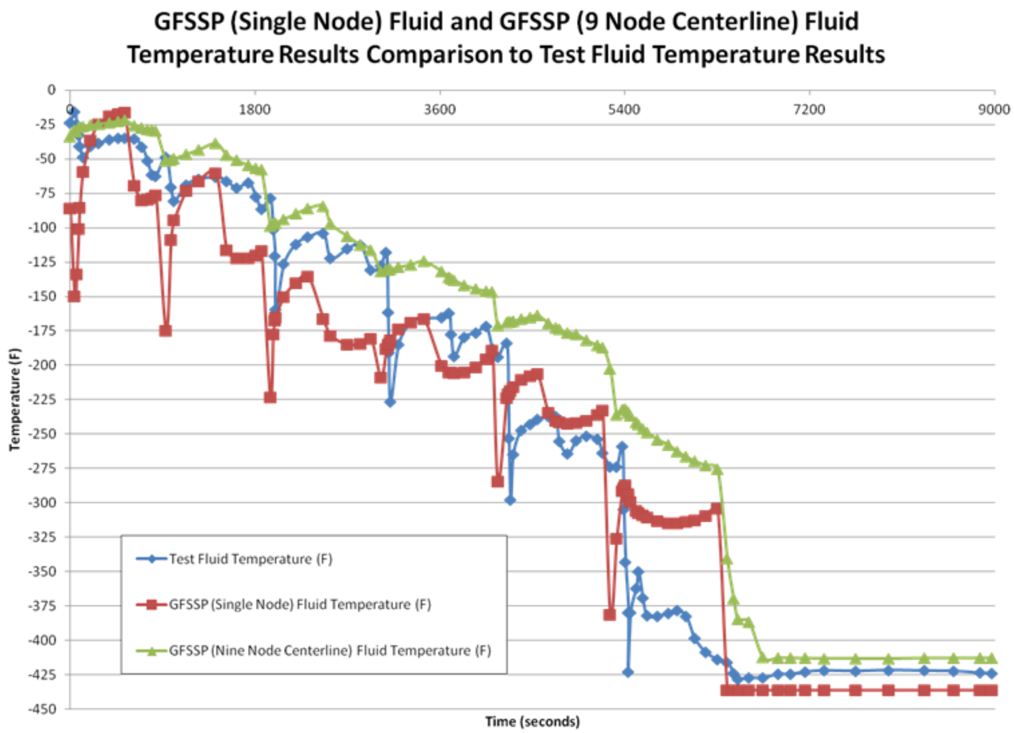

Figure 13. Comparison of Predicted and Measured Fluid Temperature.

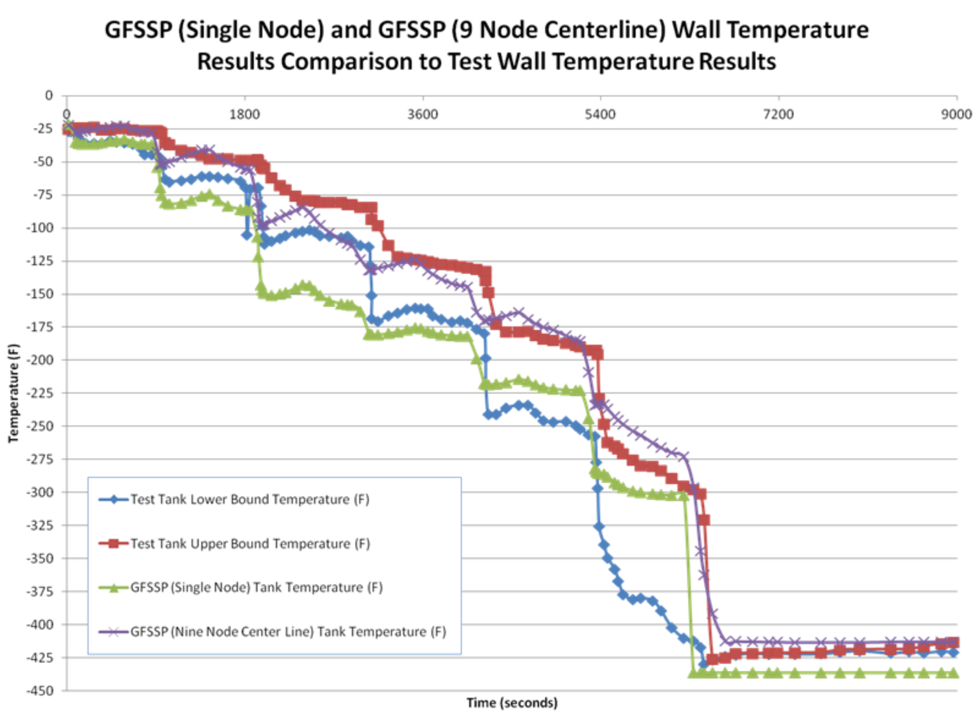

Figure 14. Comparison of Predicted and Measured Wall Temperature.

Transfer Line Chilldown Model Results

For the subcooled LH_2 cases, propellant temperature in the tank was –424.57 ºF and pressure was varied to get different levels of subcooling. Whereas for the saturated cases, the propellant temperature in the tank was the saturation temperature at the indicated driving pressure listed in Table 4. Figure 15 compares the wall temperature of the 33-node transfer line, grid-resolution predictions of the network model with the experimental transfer line wall temperatures reported in [5] for four different inlet driving pressures. Stations 1 through 4 are nodes in the computational model whose locations correspond to four measurement stations in the original experimental setup. It can be seen by comparing the four cases in Fig. 15 that the 33-node network models' predictions agree reasonably well with the experimental results. Some discrepancy exists between prediction and experiments. This is mainly due to the inaccuracy in heat transfer coefficient and partly due to coarseness of the network node—both solid and fluid.

Table 4. Saturated LH_2 Chilldown Time For Various Driving Pressures

Driving Pressure (psia)	Saturation Temperature (°F)	Experimental Chilldown Time (s)	Predicted Chilldown Time (s)
74.97	–411.06	68	70
86.73	–409.08	62	69
111.72	–406.4	42	50
161.72	–402.13	30	33

Table 5. Subcooled LH_2 Chilldown Time For Various Driving Pressures; LH_2 Subcooled at –424.57 ºF

Driving Pressure (psia)	Experimental Chilldown Time (s)	Predicted Chilldown Time (s)
36.75	148	150
61.74	75	80
86.73	62	60
111.72	41	45
136.72	32	35
161.7	28	30

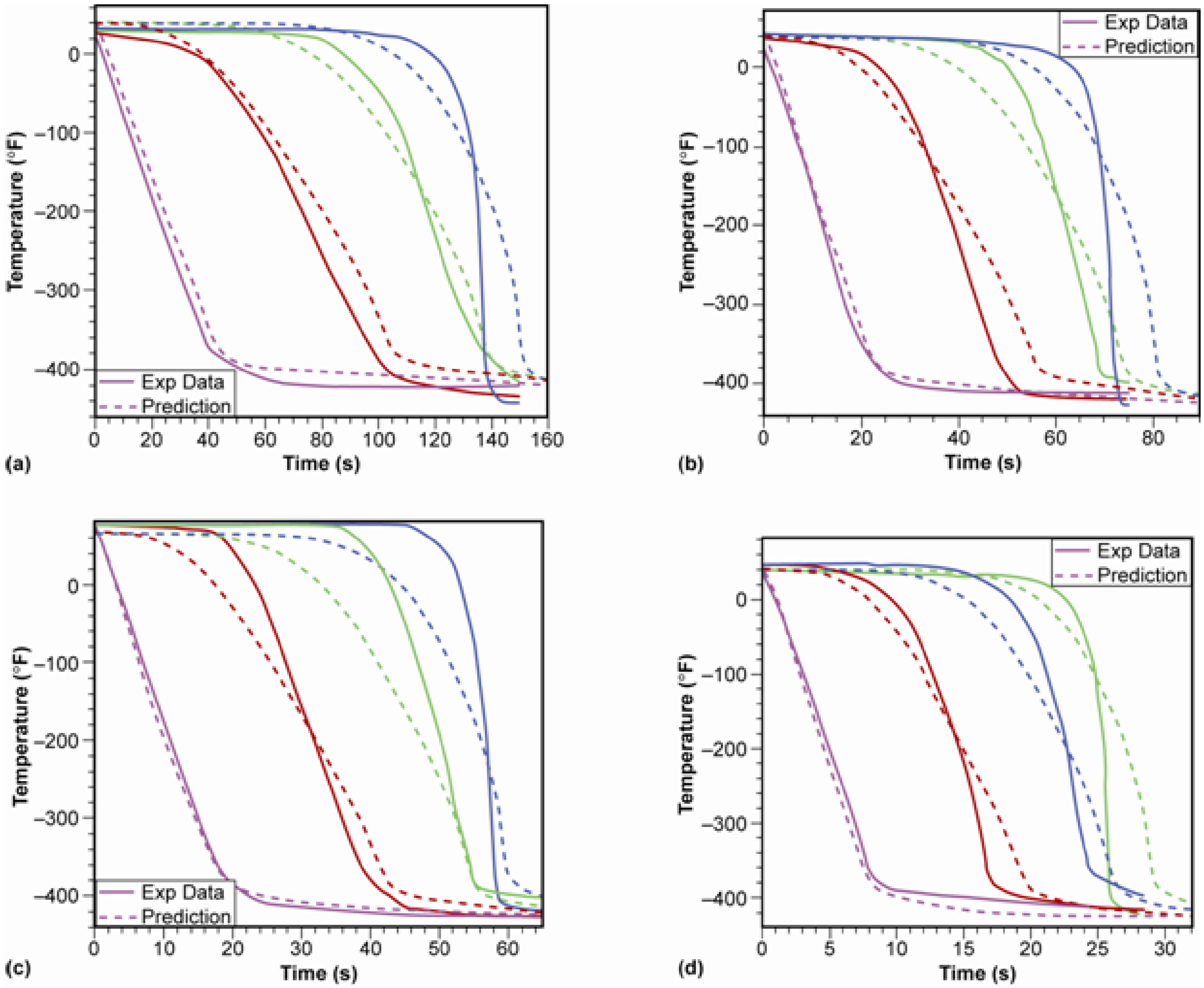

Figure 15. Comparison of temperature histories for subcooled LH_2 for various driving pressures: (a) *p*=36.74 psia, (b) *p*=61.72 psia, (c), *p*=86.7 psia, and (d) *p*=161 psia at four longitudinal stations: Station #1 (violet)—20 ft from tank inlet, station #2 (red)—80 ft from tank inlet, station #3 (green)—141 ft from tank inlet, station #4 (blue)—198 ft from tank inlet.

The predicted LH_2 chilldown time for various inlet driving pressures for saturated and subcooled cases are presented in Tables 4 and 5 respectively. Here, the chilldown time is defined as the time corresponding to the low-temperature knee for a given transfer line wall temperature curve. The network flow model prediction again compares well with experimental results even with a 33-node grid. As can be seen in the Tables, the numerical model tends to slightly overpredict the chilldown time.

This observed discrepancy can mainly be attributed to the heat transfer coefficient. It may be noted that the Miropolski correlation does not account for the enhanced heat transfer coefficient during nucleate boiling regime. Chilldown time decreases with the increase in the driving pressure and thereby reduces the liquid consumption, as can be seen in Tables 4 & 5.

This is to be expected since the higher driving pressure produces higher mass flux that, in turn, yields higher heat transfer coefficients. Subcooling the propellant in the tank reduces the chilldown time in general for all the cases studied.

CONCLUSIONS

GFSSP has been adapted to simulate Charge-Hold-Vent process in No-Vent Chill and Fill method of loading propellant in a Cryogenic Tank. Chilldown Test Data from K-site test has been used for model verification. Agreement between test and predictions are good for propellant consumption. Discrepancies between test and prediction are observed in pressure and temperature history. The model predictions can be improved by including the transfer line in the tank system model.

GFSSP has also been adapted to simulate the chilldown of a long transfer line. Chilldown test data from NBS experiments has been used for model verification. Good agreement between test and prediction has been observed for chilldown time for different test conditions. The model correctly predicts the effects of varying the inlet driving pressure on chilldown time for both subcooled and saturated conditions. There is, however, discrepancy in temperature history between test and predictions. The observed discrepancy may be attributed to the inaccuracy in heat transfer coefficient correlation.

ACKNOWLEDGEMENT

The author wishes to acknowledge Jeff Moder of Glenn Research Center for providing the information about K-site test data, Johnny Maroney of Jacobs/Marshall Space Flight Center for support in no-vent fill modeling analysis, and Andre LeClair of Marshall Space Flight Center for reviewing the paper.

REFERENCES

1. André LeClair & Alok Majumdar, "Computational Model of the Chilldown and Propellant Loading of the Space Shuttle External Tank" 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Nashville, TN, 25-28 Jul. 2010.
2. Alok Majumdar & S.S. Ravindran, "Numerical Modeling of Conjugate Heat Transfer in Fluid Network", AIAA Journal of Propulsion and Power, Volume 27(3), pp.620-630, 2011.
3. "GENERALIZED FLUID SYSTEM SIMULATION PROGRAM (GFSSP) VERSION 5.0" https://gfssp.msfc.nasa.gov/pdf/GFSSPUsersManual_V5.pdf
4. David Chato & Rafael Sanabria, "Review and Test of Chilldown Methods for Space-Based Cryogenic Tanks", NASA Technical Memorandum 104458, AIAA-91-1843.
5. Brennan, J. A., Brentari, E. G., Smith, R. V., and Steward, W. G., "Cooldown of Cryogenic Transfer Lines, An Experimental Report," National Bureau of Standards Report 9264, November 1966.

6. Ring, E., *Rocket Propellant and Pressurization Systems*, Prentice Hall, 1964.

7. Miropolski, Z. L., “Heat Transfer in Film Boiling of a Steam-Water Mixture in Steam Generating Tubes,” *Teploenergetika*, Vol. 10, No. 5, 1963, pp. 49–52; transl. AEC-TR-6252, 1964.