MSFC-300

ANALYZING THE USE OF GASEOUS HELIUM AS A PRESSURANT WITH CRYOGENIC PROPELLANTS WITH THERMODYNAMIC VENTING SYSTEM MODELLING AND TEST DATA

A. Hedayat, S.L. Nelson
NASA-Marshall Space Flight Center, MSFC, AL

L. J. Hastings
Alpha Technology Inc., Huntsville, AL

R.H. Flachbart, D. J. Vermilion, S.P. Tucker
NASA-Marshall Space Flight Center, MSFC, AL

ABSTRACT

Cryogens are viable candidate propellants for NASA's Lunar and Mars exploration programs. To provide adequate mass flow to the system's engines and/or to prevent feed system cavitation, gaseous helium (GHe) is frequently considered as a pressurant. During low gravity operations, a Thermodynamic Venting System (TVS) is designed to maintain tank pressure during low gravity operations without propellant resettling. Therefore, a series of tests were conducted in the Multi-purpose Hydrogen Test Bed (MHTB) of Marshall Space Flight Center (MSFC) in order to evaluate the effects of GHe pressurant on pressure control performance of a TVS with liquid hydrogen (LH_2) and nitrogen (LN_2) as the test liquids. The TVS used in these test series consists of a recirculation pump, Joule-Thomson (J-T) expansion valve, and a parallel flow concentric tube heat exchanger combined with a longitudinal spray bar. Using a small amount of liquid extracted from the tank recirculation line, passing it through the J-T valve, and then through the heat exchanger, thermal energy is extracted from the bulk liquid and ullage thereby enabling pressure control. The LH_2/GHe tests were performed at fill levels of 90%, 50%, and 25% and LN_2/GHe tests were conducted at fill levels of 50% and 25%. Moreover, each test was conducted with a specified tank ullage pressure control band. A one-dimensional TVS performance program was used to analyze and correlate the test data. Predictions and comparisons with test data of ullage pressure and temperature and bulk liquid saturation pressure and temperature with test data are presented.

KEYWORDS: cryogenic, pressurant, liquid nitrogen, liquid hydrogen, heat transfer, data analysis

INTRODUCTION

By maintaining the ullage pressure within a specified control band, the pressurization system provides the required propellant flowrate and thermodynamic state to the engine in order to prevent cavitation. In addition, the development of efficient advanced cryogenic upper stages and manned vehicles requires the maintaining of tank pressure control while minimizing propellant boil-off which poses significant challenges associated with the storage of cryogens in the near zero gravity environment of space. Traditionally auxiliary thrusters are used to settle the propellants in order to accomplish tank pressure control through venting. However, such systems incur weight penalties (associated with the propellant and hardware required) that increase with the number of settling sequences required during the mission. In addition, tank venting/resettling may become necessary at inopportune times in a mission timeline and thereby increase mission complexity. The TVS concept enables tank pressure control through venting without resettling.

The feasibility of the spray-bar TVS concept application was investigated and validated at NASA-MSFC by conducting a series of successful tests [1-3]. In the earlier test series, the ullage was only comprised of the propellant vapor. To evaluate the effect of a non-condensable pressureant gas such as GHe on the TVS performance, tests with GHe in the ullage were conducted with LN_2 and LH_2 [4, 5]. An overview of the spray-bar TVS concept is presented in the following section.

Thermodynamic Venting System (TVS) Concept

Originally, the spray-bar TVS concept was introduced for LH_2 applications [1, 5]. The TVS, as shown in Figure 1, consist of a recirculation pump, a Joule-Thomson (J-T) expansion/shutoff valve, and a parallel flow concentric tube heat exchanger/spray-bar apparatus. The pump extracts liquid propellant from the tank and flows it through the heat exchanger/spray bar apparatus. The fluid re-enters the tank through orifices in the spray bar that expel the fluid radially into the tank. This results in propellant destratification and ullage condensation through mixing. When pressure control within the tank cannot be maintained through mixing alone (bulk liquid is saturated at the ullage pressure), a small amount of fluid extracted from the recirculation flow is passed through the J-T valve where it is expanded to a lower pressure and temperature. The subcooled two-phase fluid mixture is then passed through the heat exchanger, which extracts heat from the recirculation flow, and subsequently is vented to the environment. Details of spray-bar TVS hardware development effort are provided by Lak and Wood [6].

To adapt the system for LN_2 testing, several modifications were made to the original TVS components and configuration. The recirculation pump and J-T valve were replaced to accommodate the much higher mass flow rate required for LN_2 test series. The original composite MHTB legs were replaced with stainless steel legs which could support a full tank of LN_2. Due to much larger mass of stored LN_2, compared to LH_2, stored in the MHTB, two graphite heaters were installed in the bottom of the tank, thereby delivering a specified quantity of energy into the bulk liquid and accelerating the thermodynamic state changes.

TVS TEST SETUP AND PROCEDURES

All Tests were conducted at the MSFC East Test Area thermal vacuum facility, Test Stand 300. The facility systems, in combination with the MHTB's shroud, enabled simulation of on orbit thermal and vacuum conditions. For LN_2 tests, to accelerate the testing, the heaters were turned on. For each test series, a boiloff test was performed in order to determine the ambient heat leak and heater input into the MHTB. For LN_2 testing, an additional boil-off test with the graphite heaters turned on was conducted in order to measure the total heat leak from ambient sources and the heaters. For each tank fill level, after the boil-off testing was completed, the tank was locked up and allowed to self-pressurize until the ullage pressure attained the maximum tank pressure set point. Upon reaching this pressure, depending on the propellant tested and fill level, the pump or the pump/JT combination were used to reduce the pressure to the minimum tank pressure set point. At this point the pump and/or pump and the J-T valve was/were turned off, the tank was allowed to self-pressurize. The automated operation of the TVS continued with a specified control band according control algorithms established for the two test series described in the references [4, 5]. For TVS operation with GHe pressurant, GHe was injected into the ullage until the total ullage pressure reached the minimum tank pressure set point for GHe operation. Again, the automated operation of the TVS maintained the ullage pressure within the specified control band according the control algorithm.

MODEL OVERVIEW

The TVS code is based on a transient one-dimensional analytical model and was formulated to characterize the TVS performance. The TVS performance formulation is comprised of four combined thermal-fluid models including the heat exchanger, the spray manifold and injector tubes, the recirculation pump, and the tank. The heat exchanger model calculates the quality and two-phase pressure loss at the vent exit. The spray manifold and injection tube model determines the pressure drops within the manifold and tubes along with the spray flow rates and velocities leaving the injection orifices. The recirculation pump model calculates the pump head increase from the pump speed and the head coefficient curve provided by the pump manufacturer. The tank model is a lumped node model consisting of four control volumes: the ullage, the tank wall, the tank wall liquid, and the bulk liquid. The ullage is comprised of two species, the propellant vapor and a non-condensable gas, GHe. A detailed description of the TVS analytical model is given by Nguyen [7].

The TVS performance program originally was developed to analyze LH_2 MHTB spray-bar TVS configuration. To utilize the TVS program for the LN_2 application, the original code was modified by incorporating LN_2/GN_2 properties and LN_2 pump and J-T valve characteristics. Also, the tank model was modified by adding an additional heat source term, representing heater input and heat transfer through the new stainless steel legs, to the bulk liquid control volume. Therefore, the total heat source represented the energy received by the bulk liquid via environmental heat leaks, heaters, and heat transfer through the MHTB's legs. The details of TVS analytical model are not provided here, since the major thrust of the paper is to address correlation of this analytical model/code with the MHTB test data.

RESULTS AND DISCUSSIONS

The LN_2/GHe and LH_2/GHe test series were conducted in 2004 and 2005, respectively. For LN_2/GHe testing heaters were installed in the lower section of the tank. For each test series, first the boil-off testing was conducted, then one or more TVS tests (depending on the propellant tested) were conducted with single specie ullage, then GHe was injected and TVS tests resumed with two species ullage. In this paper, only the analysis and test data correlation of test series were reviewed. Details of each test series are given by Flachbart et al. [4, 5]. The TVS model predicted ullage pressure and temperature and bulk liquid saturation pressure and temperature were compared with the test data. The modeling and data correlation for each test series were reviewed in the following sections.

LN_2/GHe Test Series

The LN_2/GHe tests were conducted at 50% and 25% fill levels. As determined by boil-off testing, the total heat input was measured from boiloff tests. For each test, the total heat input into the system (environmental heat leaks + heat via legs + heat added by heaters) was measured to be 450 W. After the tank was locked up and completion of the GHe injection process, the ullage pressure increased steadily until reaching a specified maximum set point; then, both the pump and J-T were turned on. The pump and J-T valve were operated at nearly constant mass flow rates of about 1.5 kg/s and 0.025 kg/s, respectively. As the ullage pressure was reduced to the specified minimum set point, the pump and the J-T were turned off. In the following sections, detailed model predictions and comparisons for each test were discussed.

LN_2/GHe, 50% Fill Level Test

The maximum and minimum pressure set points during this test were 165.3 kPa and 158.8 kPa, respectively. The ullage pressure comparison was depicted in FIGURE 2. The average predicted and measured ullage pressure rise rates were 0.6 Pa/s and 0.58 Pa/s, respectively. The average predicted and measured pressure drop rates were 2.7 Pa/s and 3.3 Pa/s, respectively. The average predicted and measured cycle durations were 4.02 hrs and 3.56 hrs, respectively. Since the ullage region was modeled as a single node by the TVS code, the predicted ullage temperature was compared to two ullage temperature measurements. These temperatures were measured by the closest sensor to the liquid-ullage interface—location 1, and the highest sensor in the ullage region—location 2. The ullage temperature comparison, as shown in FIGURE 3, indicated a close agreement between the calculated and measured values. The average predicted and measured ullage temperatures were about 81.7 K and 80 K, respectively. The predicted bulk liquid saturation pressure was compared with the test data, as shown in FIGURE 4. The bulk liquid saturation pressure was overpredicted. The average predicted and measured bulk liquid saturation pressures were about 162 kPa and 109 kPa, respectively. As depicted in FIGURE 5, the predicted bulk liquid saturation temperatures were close to the values of test data. The average predicted and measured bulk liquid saturation temperatures were about 81.5 K and 78 K, respectively. Considering the bulk liquid saturation pressure to be a function of saturation temperature, during the testing the saturation pressure was determined by measuring the bulk liquid temperature at specified location of liquid region within tank. Therefore, overprediction of the bulk liquid saturation pressure could be due measurement inaccuracy of the sensor representing the saturation temperature.

LN_2/GHe, 25% Fill Level Test

The maximum and minimum pressure set points during this test were 165.3 kPa and 158.8 kPa, respectively. The ullage pressure comparison was depicted in FIGURE 6. Average predicted and measured ullage pressure rise rates were 1.25 Pa/s and 0.98 Pa/s, respectively. Average predicted and measured pressure drop rates were 5.7 Pa/s and 6.8 Pa/s, respectively. Average predicted and measured cycle durations were 1.83 hrs and 2.17 hrs, respectively. The ullage temperature comparison, as shown in FIGURE 7, indicated a close agreement between the calculated and measured values. The average predicted and measured ullage temperatures were about 82.5 K and 81.6 K, respectively. The predicted bulk liquid saturation pressure was compared with the test data, as shown in FIGURE 8. The bulk liquid saturation pressure was overpredicted. The average predicted and measured bulk liquid saturation pressures were about 162 kPa and 124 kPa, respectively. As depicted in FIGURE 9, the predicted bulk liquid saturation temperatures were close to the values of test data. The average predicted and measured bulk liquid saturation temperatures were about 81.5 K and 79 K, respectively.

LH_2/GHe Test Series

LH_2/GHe tests were conducted at the 90%, 50%, and 25% fill levels. During boil-off testing, the total heat input was measured to be about 70 W (in this test series the heaters were not used). After tank lock up and completion of GHe injection process, the testing continued with TVS operation within a prescribed pressure control band of specified maximum and minimum set points. The data correlations for this test series were carried out for 50% and 25% fill levels, similar to the fill levels of LN_2/GHe test series. The data correlations for each fill level test were discussed in the following sections.

LH_2/GHe, 50% Fill Level Test

The maximum and minimum pressure set points during this test were 172.2 kPa and 165.3 kPa, respectively. The ullage pressure comparison was depicted in FIGURE 10. Average predicted and measured ullage pressure rise rates were 1.45 Pa/s and 1.3 Pa/s, respectively. Average predicted and measured pressure drop rates were 19 Pa/s and 14 Pa/s, respectively. Average predicted and measured cycle durations were 1.45 hrs and

1.51 hrs, respectively. The ullage temperature comparison, as shown in FIGURE 11, indicated a close agreement between the calculated and measured values. The average predicted and measured ullage temperatures were about 22.5 K and 24 K, respectively. The predicted bulk liquid saturation pressure was compared with the test data, as shown in FIGURE 12. The bulk liquid saturation pressure was overpredicted. The average predicted and measured bulk liquid saturation pressures were about 166 kPa and 164.2 kPa, respectively. As depicted in FIGURE 13, the predicted and measured bulk liquid saturation temperatures were matched very well.

LH_2/GHe, 25% Fill Level Test

The maximum and minimum set points during this test were 172.4 kPa and 165.3 kPa, respectively. The ullage pressure comparison was depicted in FIGURE 14. Average predicted and measured ullage pressure rise and pressure drop rates were in agreement, 1.3 Pa/s and 2.4 Pa/s for ullage pressure rise and pressure drop rates, respectively. Average predicted and measured cycle durations also in agreement, at about 1.5 hrs. The ullage temperature comparison, as shown in FIGURE 15, indicated a close agreement between the calculated and measured values. The average predicted and measured ullage temperatures were about 22.5 K and 24 K, respectively. The predicted bulk liquid saturation pressure was compared with the test data, as shown in FIGURE 16. The predicted and measured bulk liquid saturation pressures were in a close agreement. The average predicted and measured bulk liquid saturation pressures were about 168 kPa and 163 kPa, respectively. As depicted in FIGURE 17, the predicted and measured bulk liquid saturation temperatures were in good agreements.

SUMMARY

A one-dimensional TVS performance program was used to analyze and correlate two test series conducted. Correlation and data analysis were performed for 50% and 25% fill level for both LH_2/GHe and LN_2/GHe tests. Predicted and measured values of ullage pressure and temperature and bulk liquid saturation pressure and temperature were compared with those of test data. For LN_2/GHe test series, predicted ullage pressures, temperatures, and cycle times were in agreement with the data. However, the model overpredicted the bulk saturation pressure for both 50% and 25% LN_2/GHe tests. The predicted bulk liquid saturation temperature matched reasonably well with the data. For selected LH_2/GHe test cases, the predicted ullage pressures and temperatures and bulk liquid saturation pressures and temperatures were in good agreement with those of the measured values.

In general, the deviations of predicted values from the test data could be due to the oversimplification of the TVS model. It is believed that the analytical modeling, which assumed that the liquid and ullage were each represented by a single node, did not accurately simulate the complex energy exchange occurring at the liquid vapor interface, and also did not address stratification within ullage and liquid regions.

REFERENCES

1. L.J. Hastings, L.J., R.H. Flachbart, J.J Martin, A. Hedayat, M. Fazah, L.Lak, H Nguyen, "Spray Bar Zero Gravity Vent System for On-Orbit Liquid Hydrogen Storage," NASA/TM-2003-212926, , J.W. Bailey, October 2003.

2. Flachbart, R. H., Hastings, L. J., and Martin, J. J., "Testing of a Spray Bar Zero Gravity Cryogenic Vent System for Upper Stages," 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, June 20-24, 1999, Paper Number AIAA 99-2175.

3. R. H. Flachbart, L. J. Hastings, A. Hedayat, S. L. Nelson, and S. P. Tucker, "Testing of a Spray-Bar Thermodynamic Vent System in Liquid Nitrogen," Paper C1-G-05, CEC2005.

4. R. H. Flachbart, L. J. Hastings, A. Hedayat, S. L. Nelson, S. P. Tucker, , "Testing of a Spray-Bar Thermodynamic Vent System in Liquid Nitrogen," pp. 240-247, *Advances in Cryogenic Engineering*, Volume 51A, American Institute of Physics, 2006.

5. R. H. Flachbart, L. J. Hastings, A. Hedayat, S. Nelson, S. Tucker, "Testing the Effects of Helium Pressurant on Thermodynamic Vent System Performance with Liquid Hydrogen," Cryogenic Engineering Conference, Chattanooga, TN, July 16-20 2007.

6. Lak, Tibor and Wood, Charles, "Zero-G Thermodynamic Venting System Final Report," Rockwell Aerospace, Downey Operations, Report Number SSD 94M0038, Contract Number NAS8-39202.

7. Nguyen, H, "Zero-G Thermodynamic Venting System (TVS) Performance Prediction Program," Rockwell Aerospace, Contract NAS8-39202, May 24, 1994.

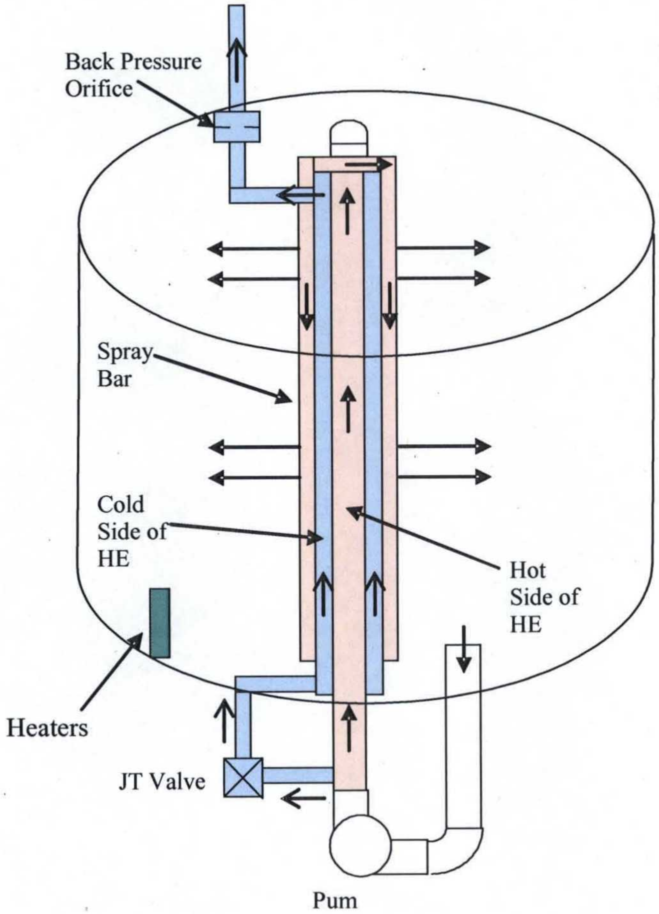

Figure 1. TVS Configuration.

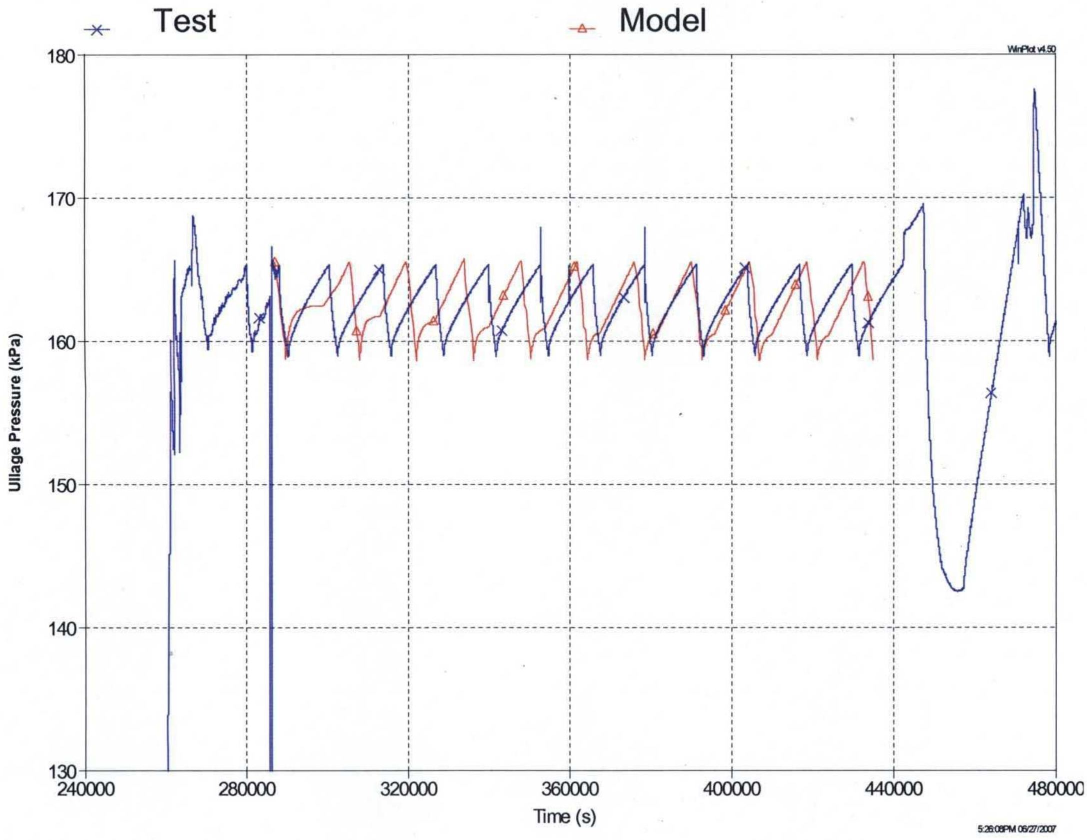

Figure 2. Ullage pressure history, LN_2/GHe test, 50% fill level.

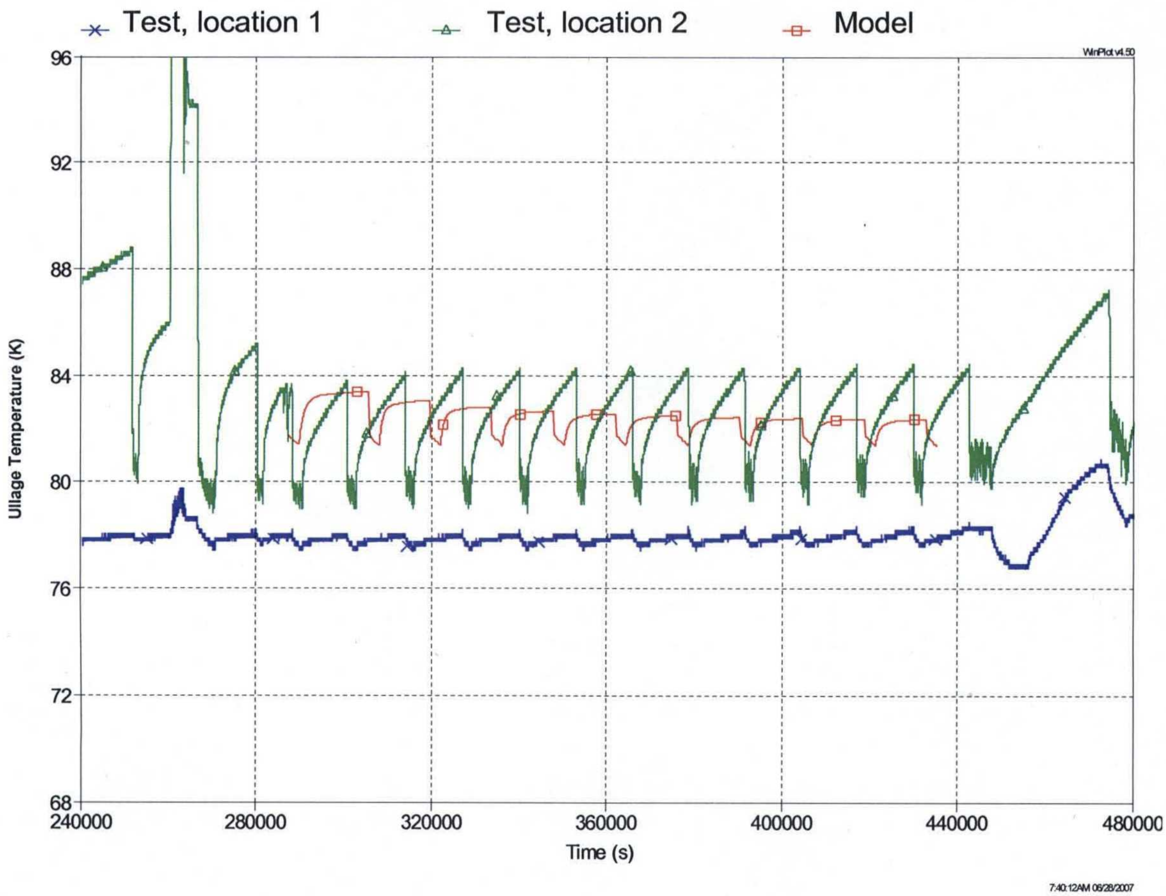

Figure 3. Ullage temperature history, LN_2/GHe test, 50% fill level.

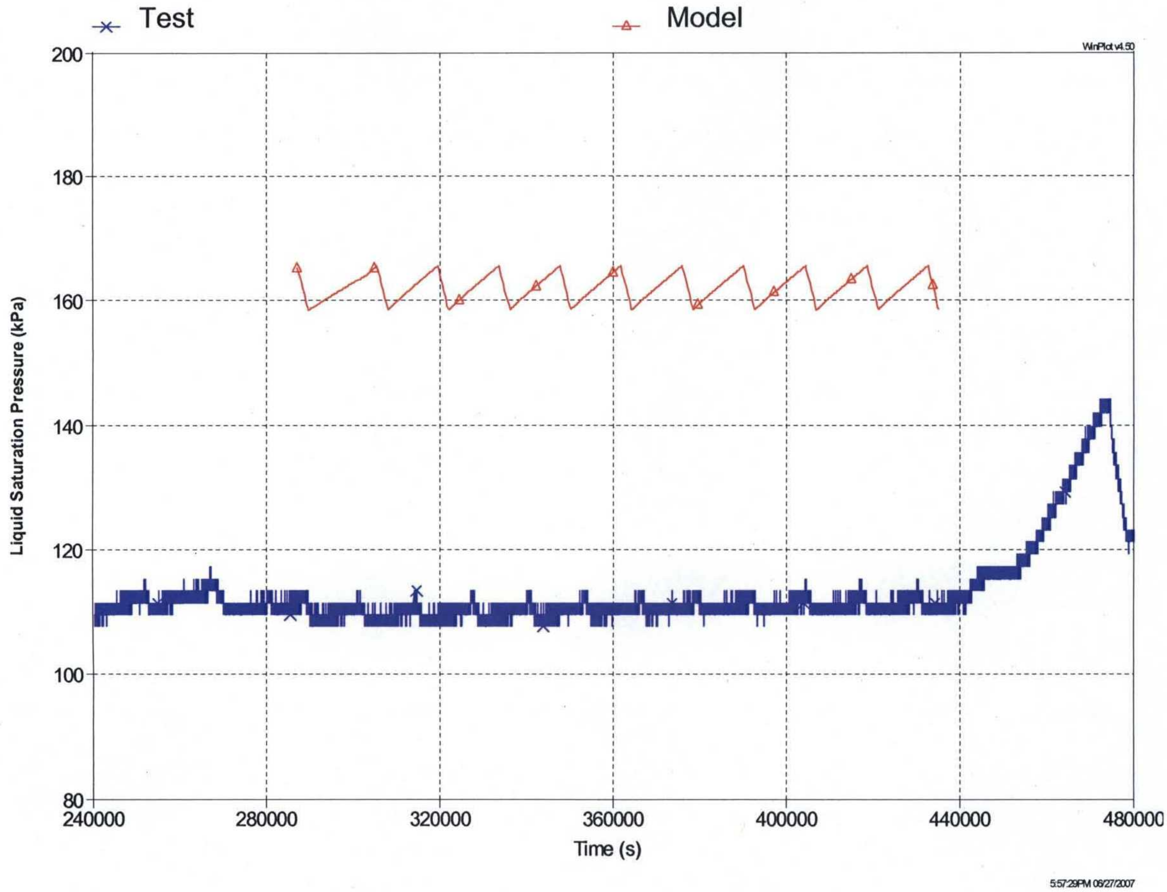

Figure 4. Liquid saturation pressure history, LN_2/GHe test, 50% fill level.

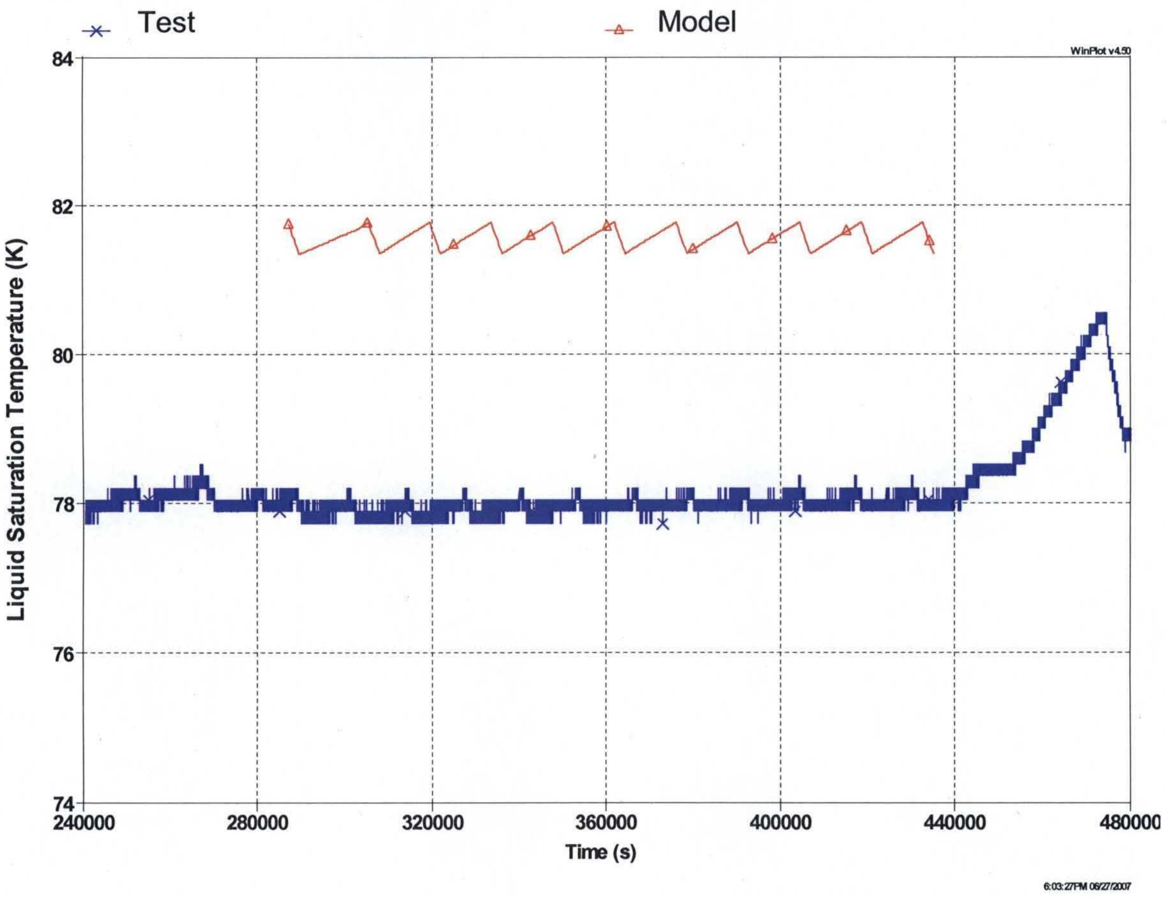

Figure 5. Liquid saturation temperature history, LN_2/GHe test, 50% fill level.

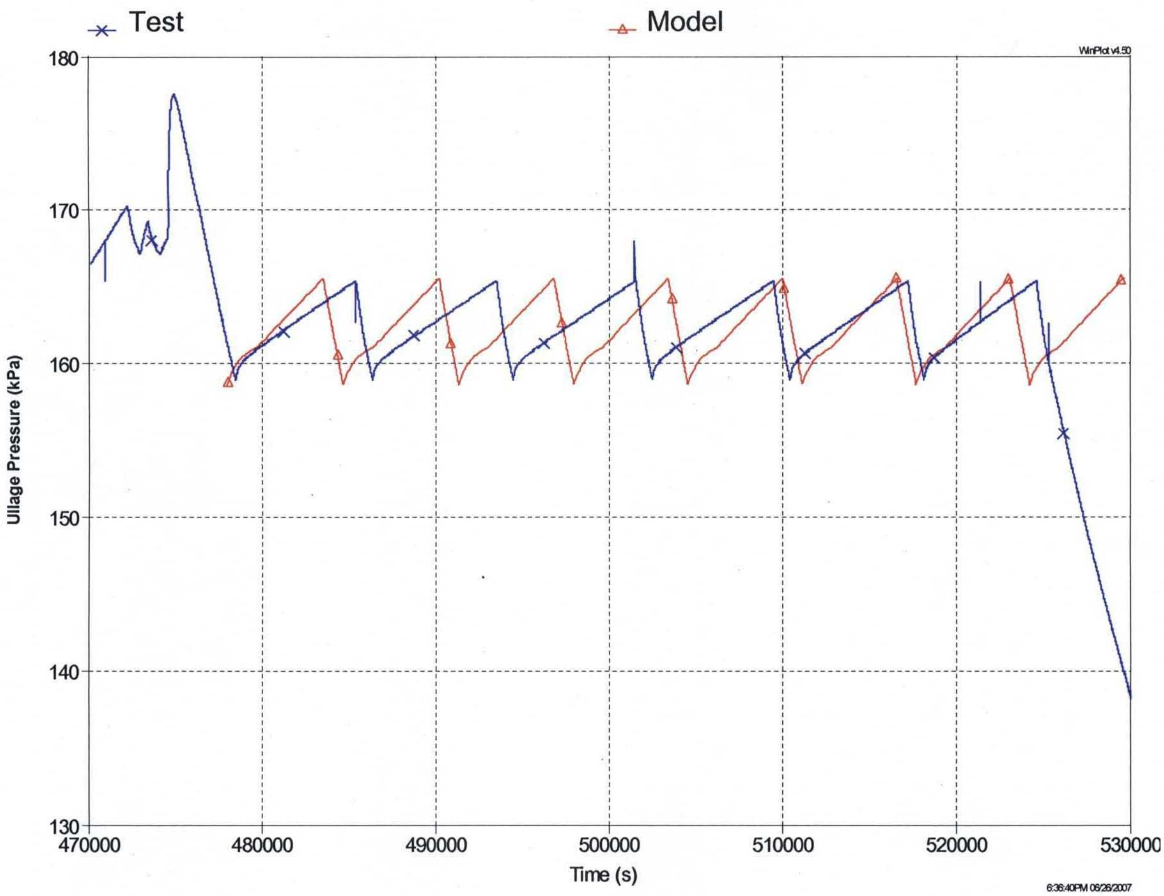

Figure 6. Ullage pressure history, LN_2/GHe test, 25% fill level.

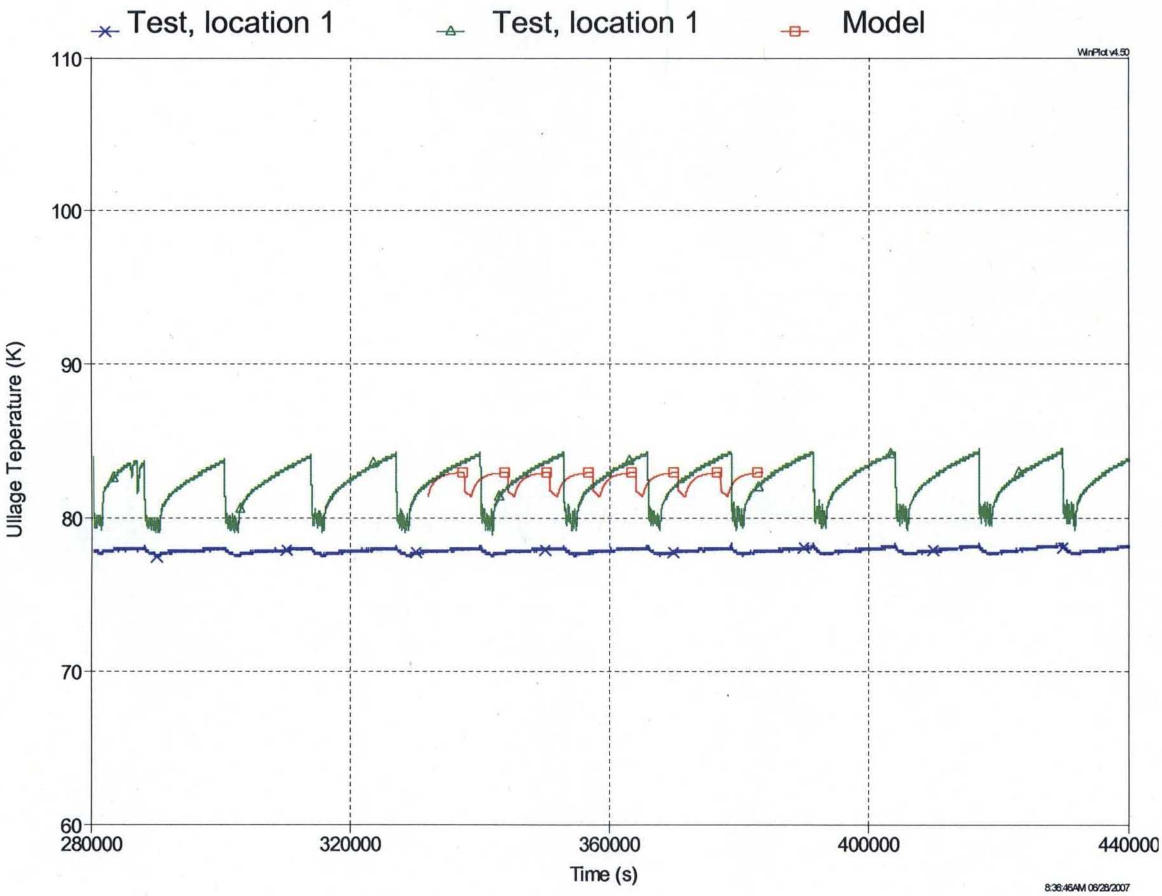

Figure 7. Ullage temperature history, LN_2/GHe test, 25% fill level.

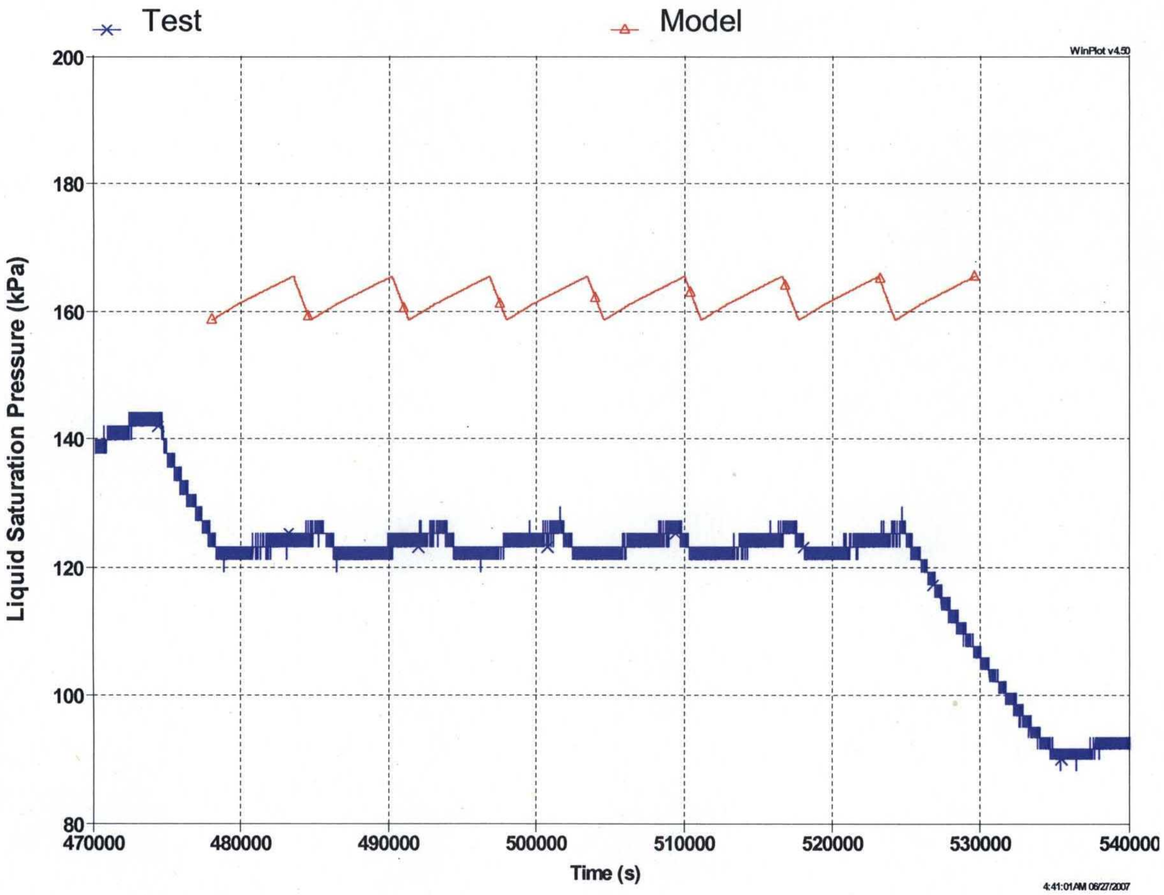

Figure 8. Liquid saturation pressure history, LN_2/GHe test, 25% fill level.

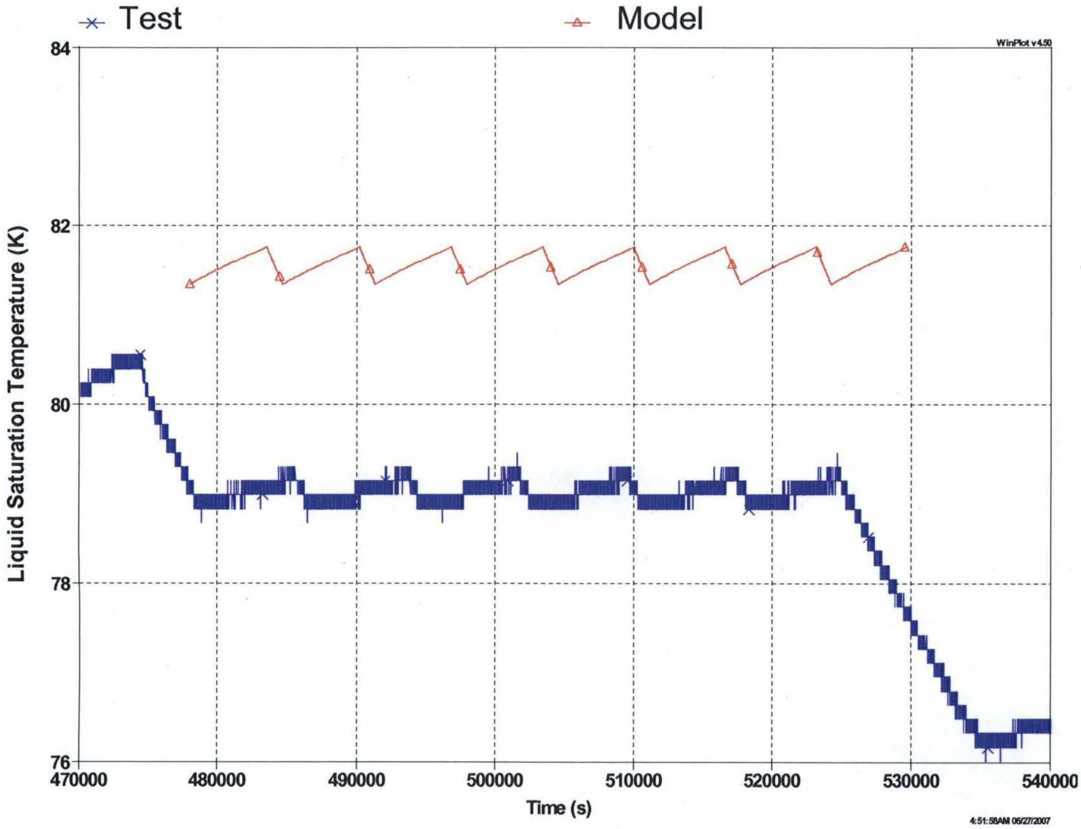

Figure 9. Liquid saturation temperature history, LN_2/GHe test, 25% fill level.

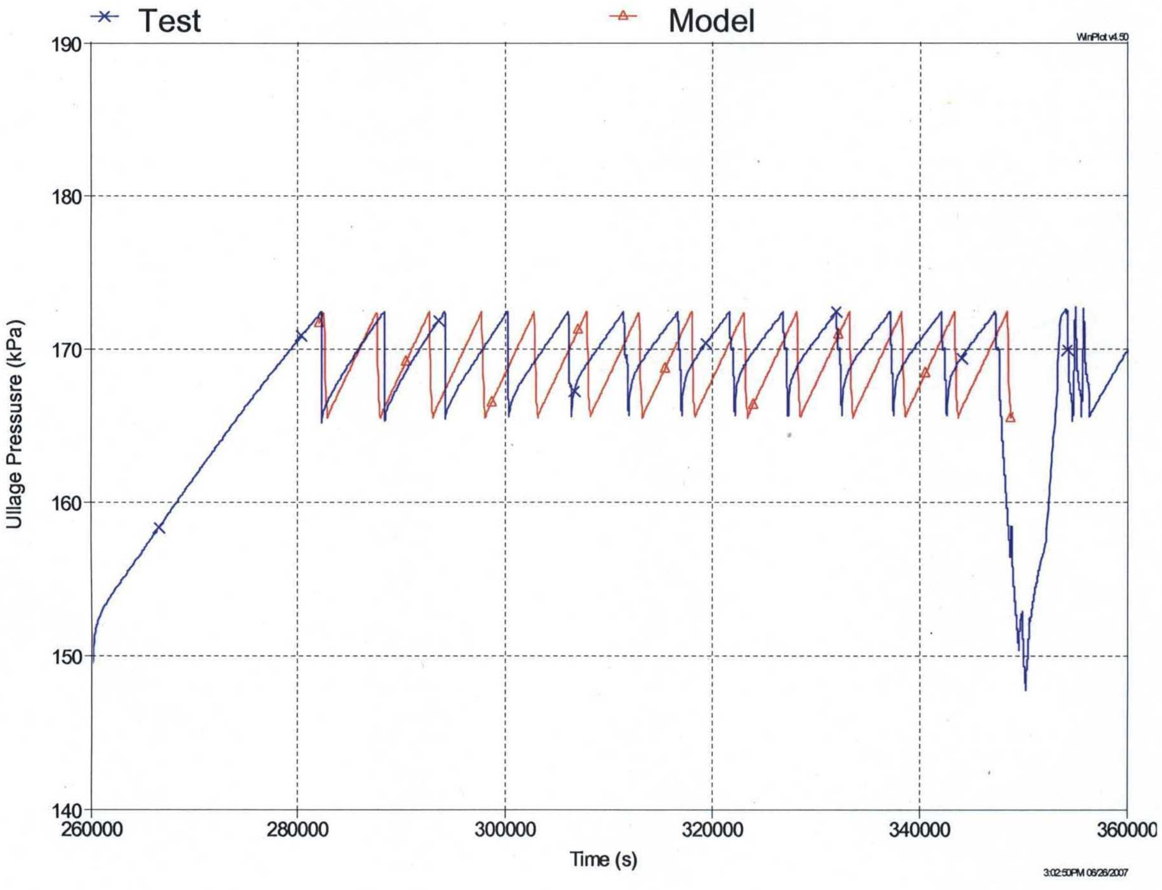

Figure 10. Ullage pressure history, LH_2/GHe test, 50% fill level.

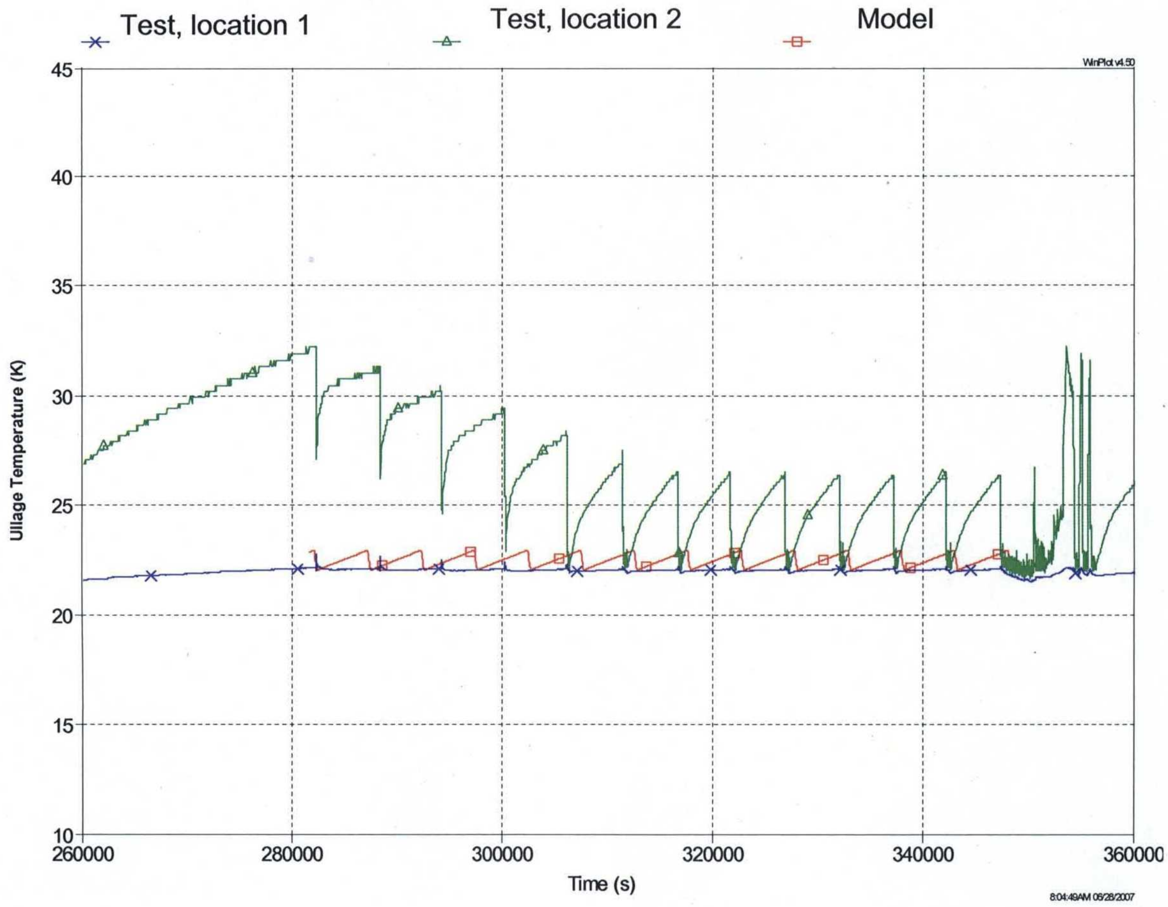

Figure 11. Ullage temperature history, LH_2/GHe test, 50% fill level.

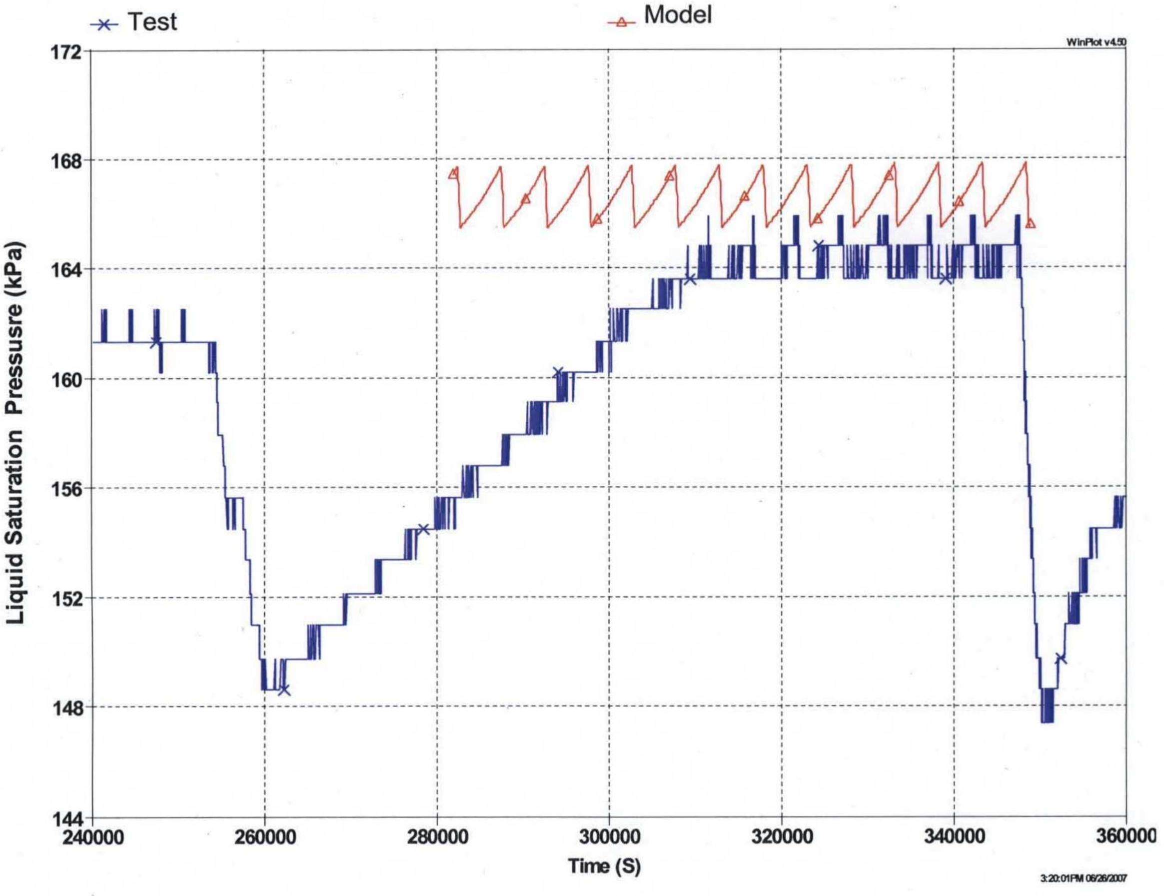

Figure 12. Liquid saturation pressure history, LH_2/GHe test, 50% fill level.

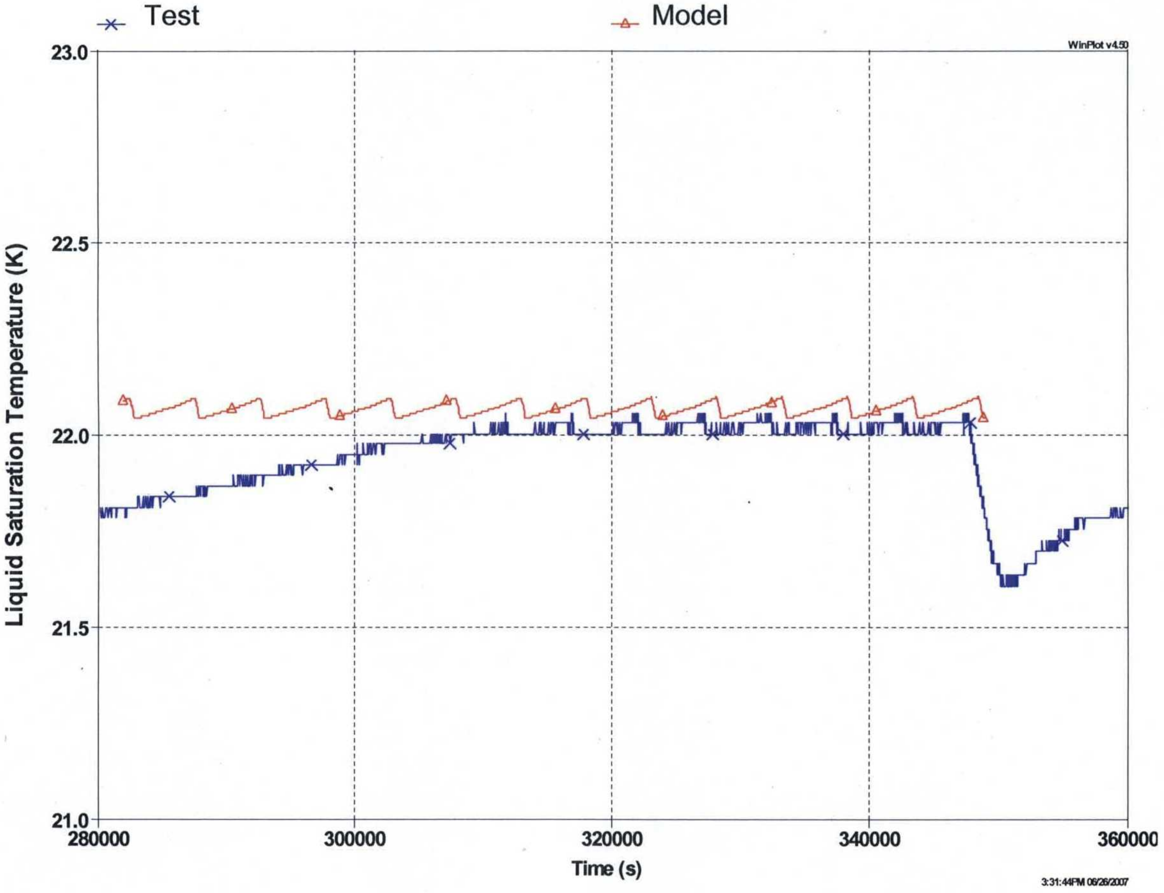

Figure 13. Liquid saturation temperature history, LH_2/GHe test, 50% fill level.

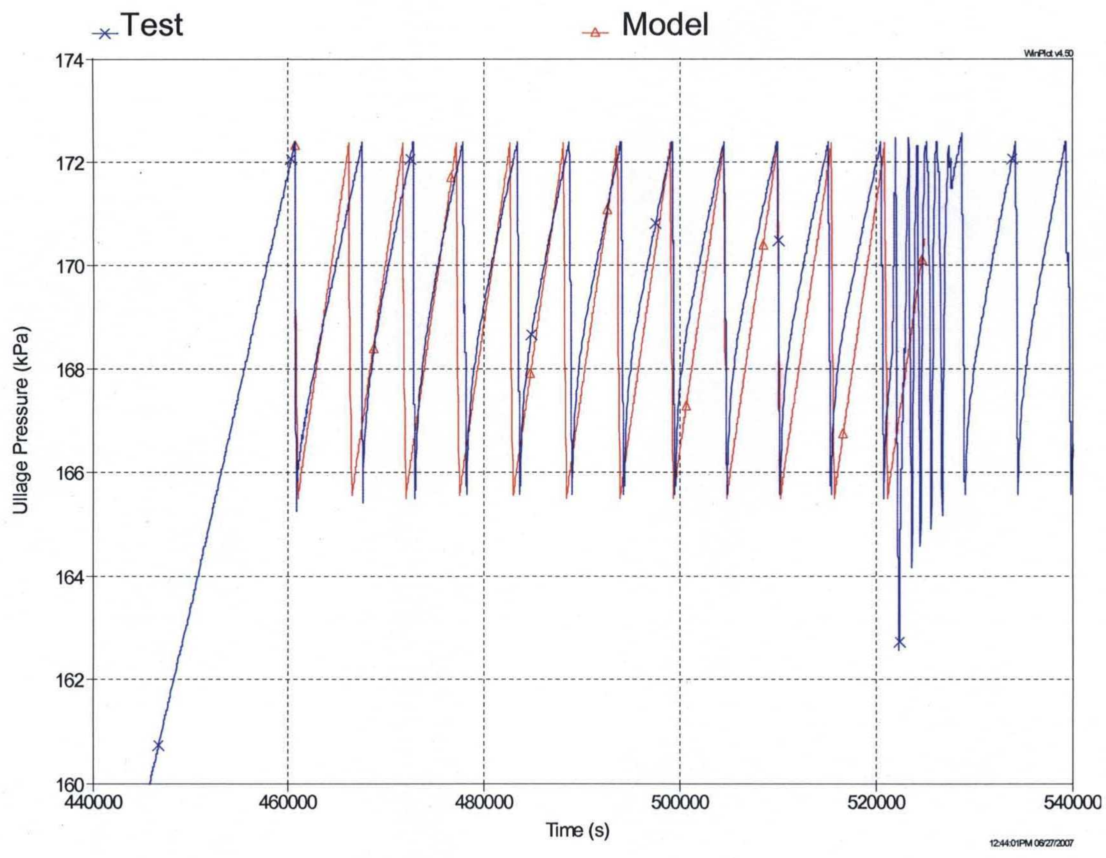

Figure 14. Ullage pressure history, LH_2/GHe test, 25% fill level.

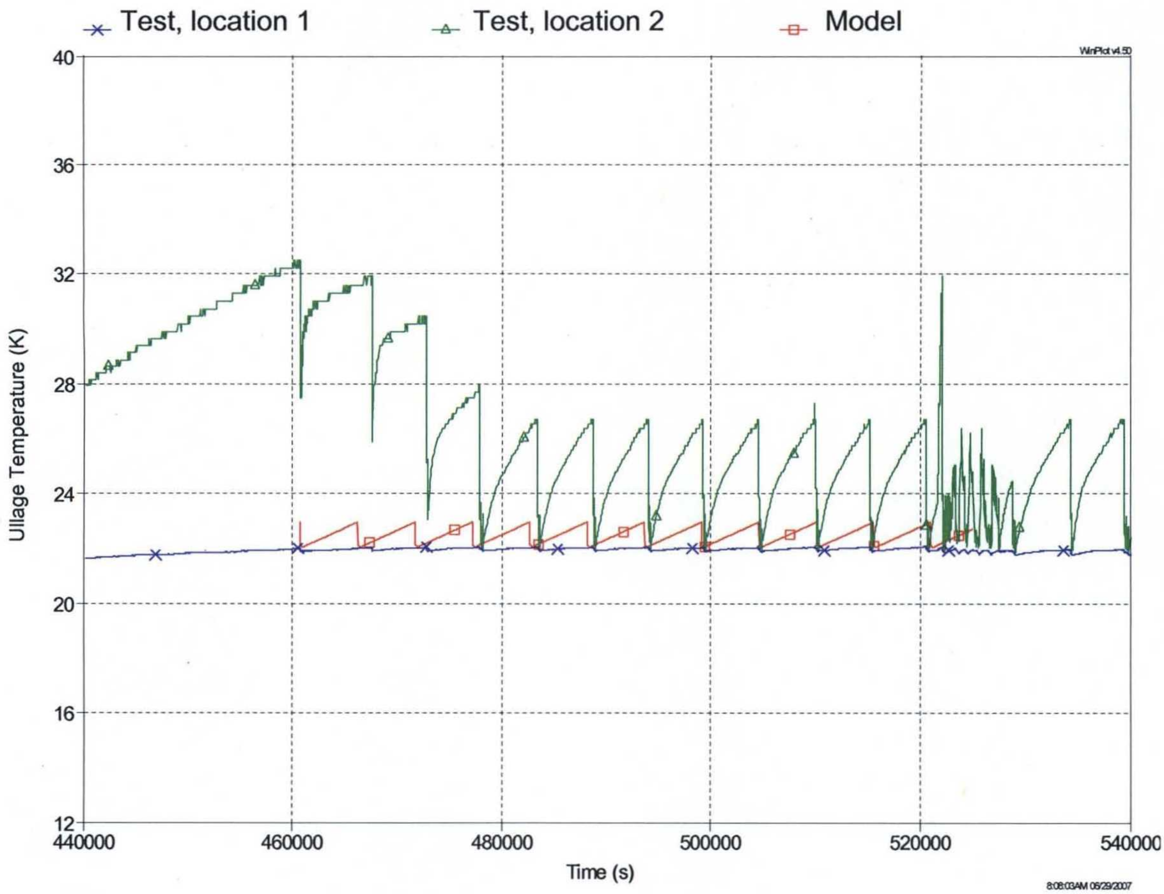

Figure 15. Ullage temperature history, LH2/GHe test, 25% fill level.

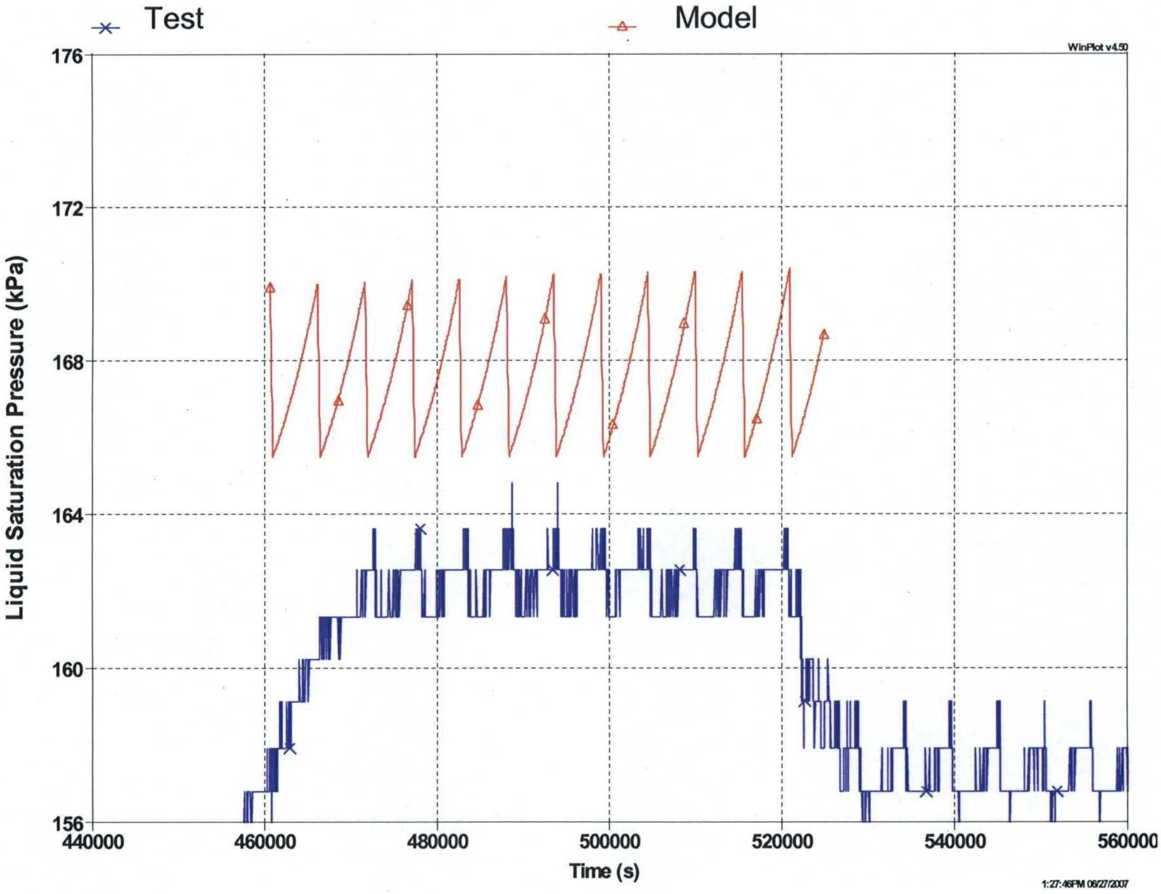

Figure 16. Liquid saturation pressure history, LH_2/GHe test, 25% fill level.

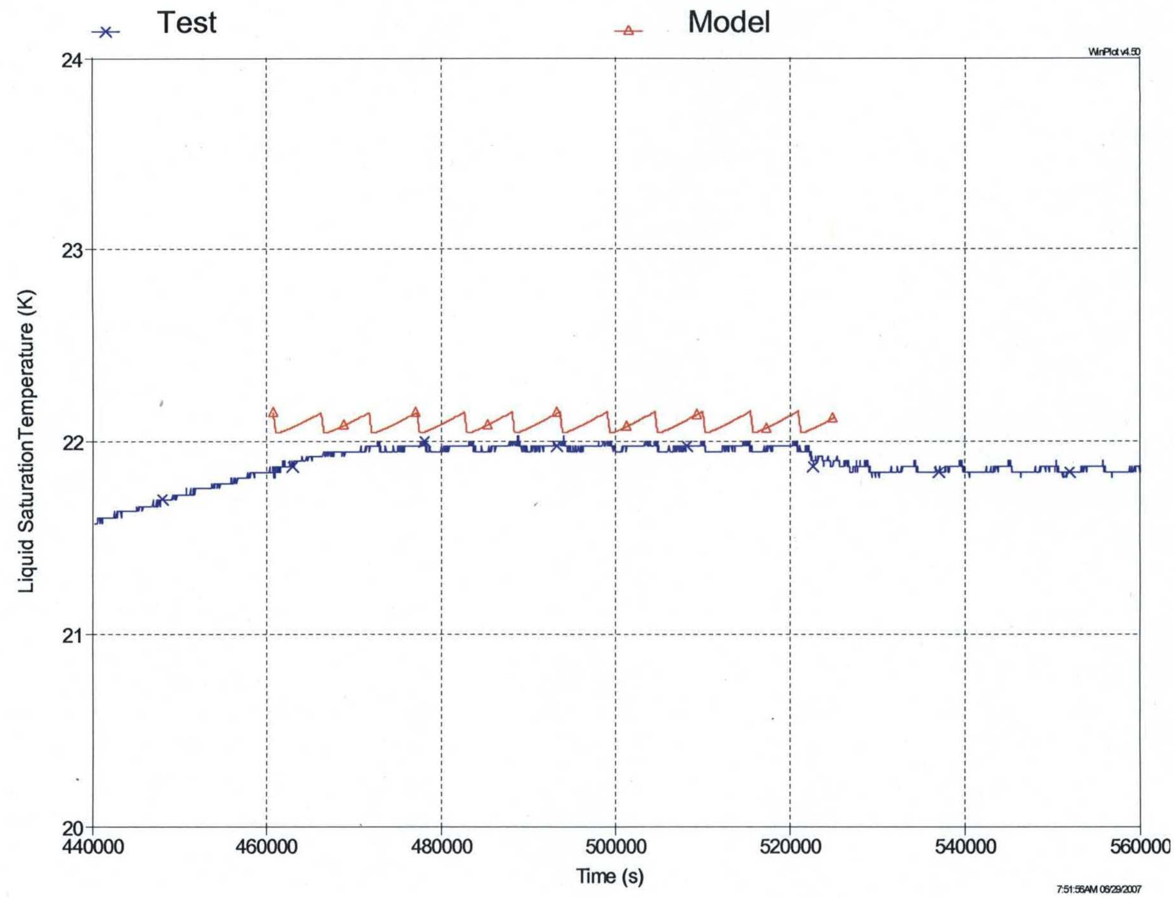

Figure 17. Liquid saturation temperature history, LH_2/GHe test, 25% fill level.