

TESTING AND ANALYTICAL MODELING FOR PURGING PROCESS OF A CRYOGENIC LINE

A. Hedayat¹, P. V. Mazurkivich¹, M. A. Nelson¹, and A. K. Majumdar²

¹ Propulsion Systems Dep./ER22, Marshall Space Flight Center
Huntsville, AL 35812 U.S.A.

² Propulsion Systems Dep./ER43, Marshall Space Flight Center
Huntsville, AL 35812 U.S.A.

ABSTRACT

To gain confidence in developing analytical models of the purging process for the cryogenic main propulsion systems of upper stage, two test series were conducted. The test article, a 3.35 m long with the diameter of 20 cm incline line, was filled with liquid or gaseous hydrogen and then purged with gaseous helium (GHe). Total of 10 tests were conducted. The influences of GHe flow rates and initial temperatures were evaluated. The Generalized Fluid System Simulation Program (GFSSP), an in-house general-purpose fluid system analyzer computer program, was utilized to model and simulate selective tests. The test procedures, modeling descriptions, and the results are presented in the following sections.

KEYWORDS: Cryogenics, Purging Process, Main Propulsion System.

INTRODUCTION

The purging operations for cryogenic main propulsion systems of upper stage are usually carried out for the following scenarios: 1) Purging of the Fill/Drain line after completion of propellant loading. This operation allows the removal of residual propellant mass; and 2) Purging of the Feed/Drain line if the mission is scrubbed. The lines would be purged by connections to a ground high-pressure gas storage source. The flow rate of the purging gas should be regulated such that the pressure in the line would not exceed the required maximum allowable value. Exceeding the maximum allowable pressure may lead to structural damage in the line.

The objective of the testing was to measure how the purging GHe behaved when it was injected into the cryogenically chilled LH₂/GH₂ filled line to support analytical purge model development applicable to

any future launch vehicle that uses LH₂ (or any cryogenic liquid) as a propellant and purges the Fill/Drain/Feed lines with GHe.

TEST SETUP

The test article schematic is shown in Figure 1. The test article was a 3.35 m long with the diameter of 20 cm stainless steel incline line. The test article was insulated such that the heat leak would be a negligible amount. The sensors were installed in six different stations, namely stations 1- 6. At each station, fluid pressure and temperature and wall temperature were measured by pressure transducer (P), resistance temperature device (RTD), and skin temperature thermocouple (STC), respectively. At the station 6, two residual gas analyzers (RGA) were installed to measure the concentration of both GH₂ and GHe. At the ends of the test article two valves, namely PV-11 and PV-12 were placed. The test article was filled via PV-11. During the test article filling process both PV-11 and PV-12 were opened to allow the LH₂ pass through and chill the passage. The LH₂ entered and exited the test article via PV-11 and PV-12, respectively. Both valves were closed when the test article reached steady state conditions. The test article purging was accommodated via Purge Entry, located between Stations 1 and 2.

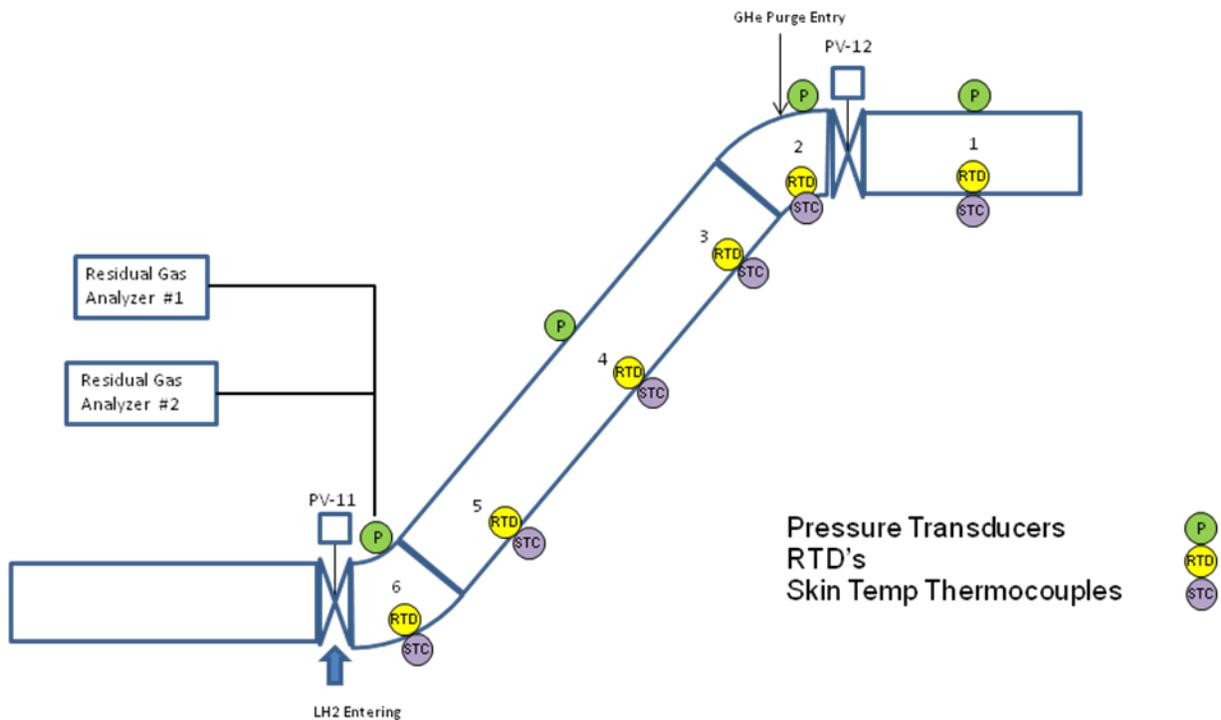


Figure 1. Test Article Schematic.

TEST PROCEDURES

Two test series were conducted. Test article was filled with LH₂ for the first series, while it was filled with GH₂ for the second test series. Table 1 shows the description of each test. The detailed procedure for performing each test series is described in the following subsection.

Test #	Fluid	GHe Initial Temperature (K)	Purge Flow rate g/s
1	LH ₂	291.5	3.18
2	LH ₂	291.5	3.18
3	LH ₂	291.5	5.9
4	LH ₂	291.5	5.9
5	LH ₂	330	5.9
6	LH ₂	330	5.9
7	GH ₂	291.5	5.9
8	GH ₂	19.5	5.9
9	GH ₂	330	5.9
10	GH ₂	330	5.9

Table 1. Description of Each Test.

LH₂ Test

The steps for this test series are as follow:

1. Chilling the test article up with LH₂ by entering via PV-11 and leaving through exit and PV-12. As the test article reached steady state condition, the LH₂ flow was stopped and both PV-11 and PV-12 were closed.
2. After verification of steady state condition, PV-11 was commanded to be opened followed by injection of helium at the Purge Entry. The initial purge gas, GHe, either was at surrounding temperature or heated to 130-140 K.
3. Observed the temperature of station 6, as temperature of this station jumped up, indicating the total displacement of LH₂ and replacing it with warm gas, commanded RGAs to be active and measured the concentration of both GH₂ and GHe.
4. The testing was completed and was stopped as concentration of GH₂ reached zero or concentration of GHe approached 100%.
5. Purge the test article with LH₂ to remove entire GHe. When RGA measured the concentration of GH₂ to be 100% or GHe to be 0%, indicating complete removal of GHe, the test article was ready for the next test.

GH₂ Test

The procedure for this series is similar procedures described for LH₂ Test with a few differences. The procedure was as the following:

1. Chilling the test article up with LH₂ by entering via PV-11 and leaving through exit and PV-12. As the test article reached steady state condition, the LH₂ flow was stopped and both PV-11 and PV-12 were closed.
2. After verification of steady state condition, PV-11 was commanded to be opened and injected saturated GH₂ at the Purge Entry. Then, as the temperature at the station 6 jumped up indicating the removal and replacement of LH₂ with GH₂
3. After verifying that the test article at the end of step 2 was filled with the GH₂ and was at the steady state, started injecting helium and commanded the RGA's to measure the concentration of gaseous species.
4. The testing was completed and was stopped as concentration of GH₂ reached zero or concentration of GHe approached 100%.
5. Purged the test article with LH₂ to remove entire GHe. When RGA measured the concentration of GH₂ to be 100% or GHe to be 0%, indicating complete removal of GHe, the test article was ready for the next test.

ANALYTICAL MODELING

Using GFSSP [1], an MSFC in-house software, the purge operation for each case was modeled and simulated. The GFSSP is a general-purpose computer program for analyzing steady state and time-dependant flow rates, pressures, temperatures, and concentrations in a complex flow network. GFSSP employs a finite volume formulation of mass, momentum, and energy conservation equations in conjunction with the thermodynamic equations of state for real fluids. The system of equations describing the fluid network is solved by a hybrid numerical method that is a combination of the Newton-Raphson and successive substitution methods.

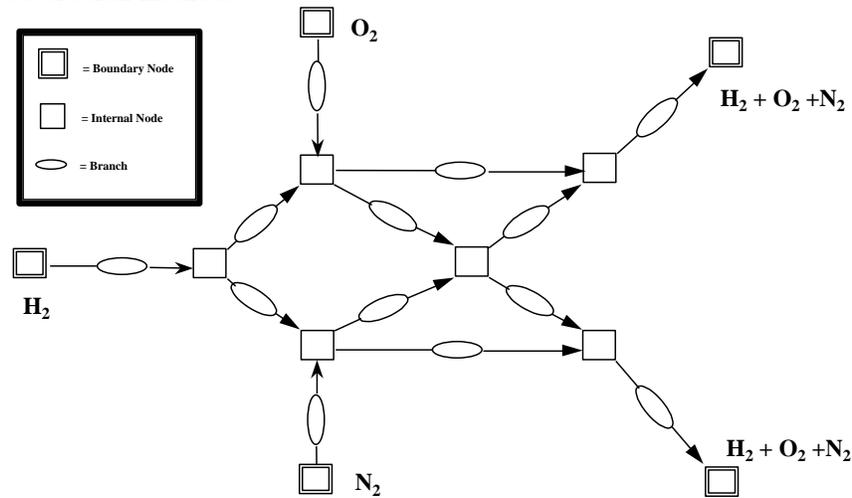


Figure 2. Schematic of GFSSP's Flow Network

Figure 2 shows a GFSSP network consisting of nodes and branches where mass, energy and species conservations are solved at the nodes and flowrates are solved at the branches. A pressure based finite volume scheme is employed. Table 2 shows the mathematical closure of the system equations solved to calculate the primary variables. GASP [2] provides the thermodynamic and thermo-physical properties of Helium and Hydrogen. Figure 3 shows a schematic representation of GFSSP's numerical scheme to solve the system of equations shown in Table 2. The details of the mathematical formulation and solution method are explained in User's Manual [1].

Principal Variables:

Unknown Variables

1. Pressure
2. Flowrate
3. Fluid Temperature
4. Solid Temperature
5. Specie Concentrations
6. Mass

Available Equations to Solve

1. Mass Conservation Equation
2. Momentum Conservation Equation
3. Energy Conservation Equation of Fluid
4. Energy Conservation Equation of Solid
5. Conservation Equations for Mass Fraction of Species
6. Thermodynamic Equation of State

Table 2. GFSSP's Mathematical Closure

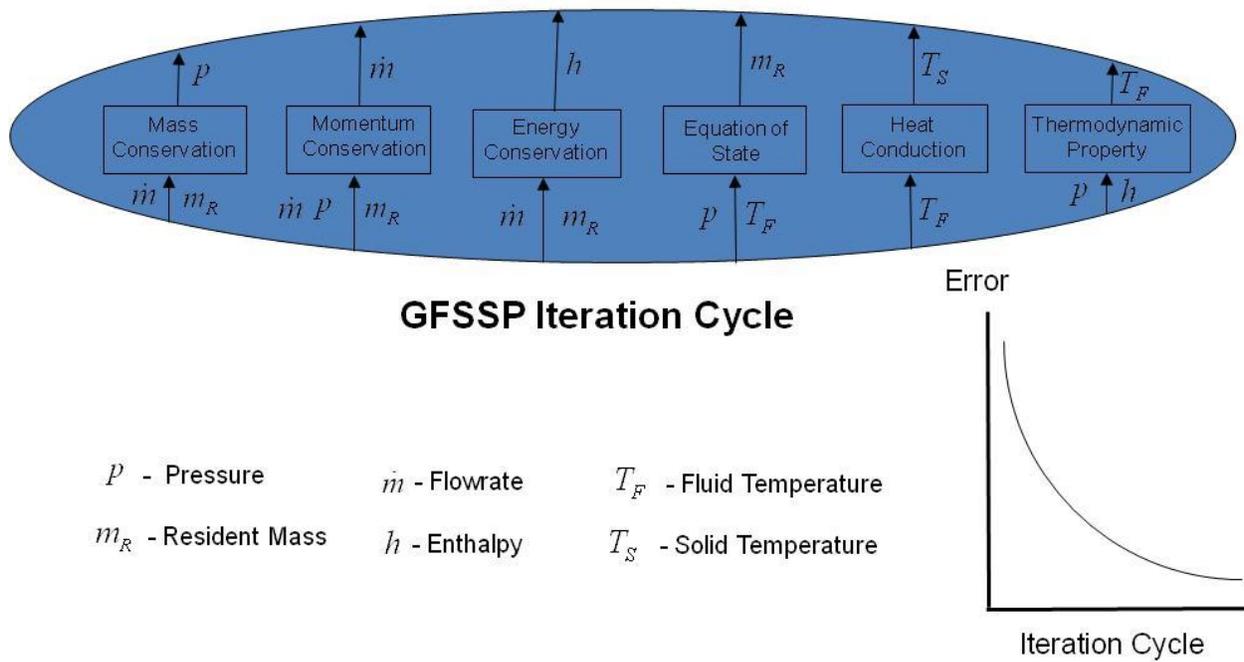


Figure 3. GFSSP’s Finite Volume Solver

RESULTS AND DISCUSSIONS

As shown in Table 1, two test series were performed at the Hydrogen Cold Flow Facility of West Test Area of Marshall Space Flight Center (MSFC). In the first test series, three pairs of tests were conducted where each pair comprised of two similar LH2 tests. Similarly, four tests were performed with the test article filled with the GH2. The tests were designed to evaluate the influence of GHe flowrate and injecting temperature on the purging process. Then, analytical models were compared with the test data. The parameters influencing purge process and comparison of analytical models with the data are presented in the following subsections.

LH2/GH2 Testing

Figures 4 - 8 depict GH2 and GHe concentration histories at the exit of test article (station 6) for the tests 1, 3, 5, 7, and 9. At the beginning of each test, the test article was filled with only hydrogen, so hydrogen concentration was 100%. As GHe was injected into the test article, it displaced and mixed with the hydrogen so the concentration GHe increased while hydrogen concentration decreased until hydrogen concentration reached zero indicating complete removal of hydrogen and the end of the purge process.

Influence of purge gas (GHe) flowrate in purging process is illustrated in Figure 9 by comparing GH2 concentration histories for tests 1 and 3. The purge flowrate for the Test 3 is almost twice than that of Test 1 and consequently the purging time of test 3 is much shorter than that of Test 1. Figures 10 and 11 illustrate the influence of initial purge gas (GHe) temperature. Figure 10 compares Test 1 to Test 3 while Figure 11 compares purging process for tests 3 and 5. Both Figures 10 and 11 indicate that the purging process is not influenced significantly by initial GHe temperature.

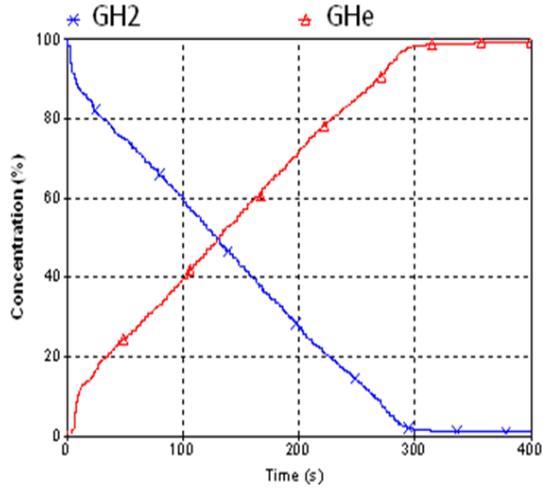


Figure 4. Concentration Histories, Test 1.

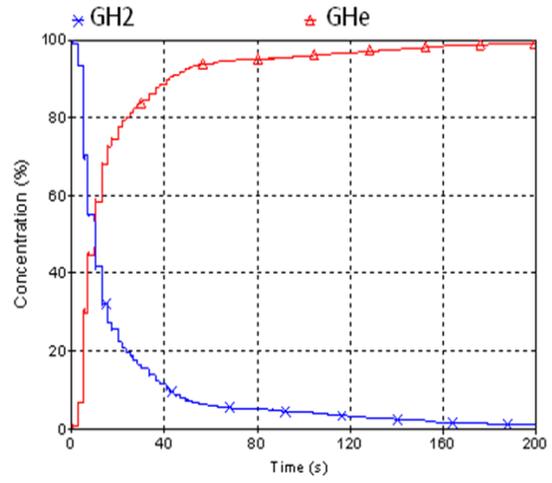


Figure 5. Concentration Histories, Test 3.

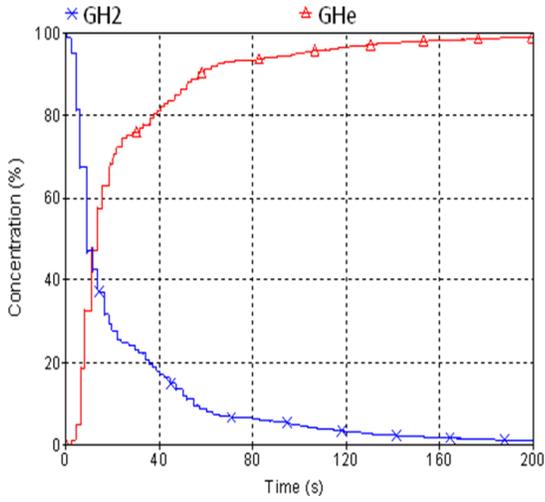


Figure 6. Concentration Histories, Test 5.

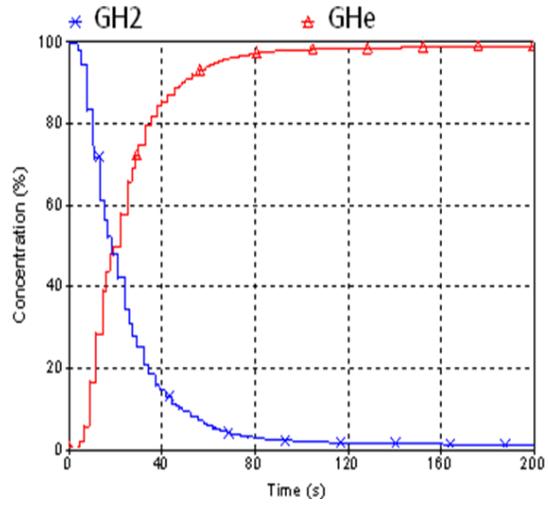


Figure 7. Concentration Histories, Test 7.

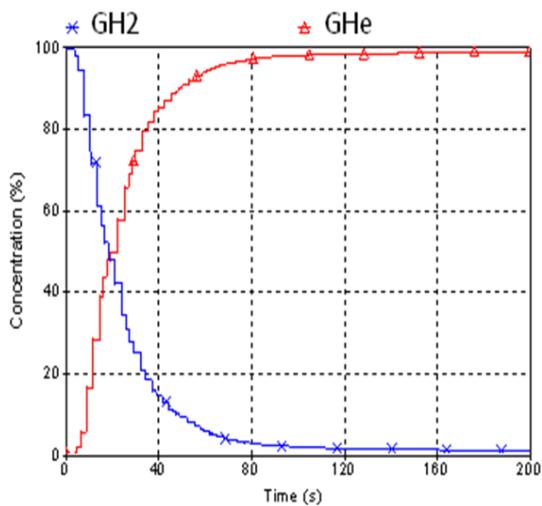


Figure 8. Concentration Histories, Test 9.

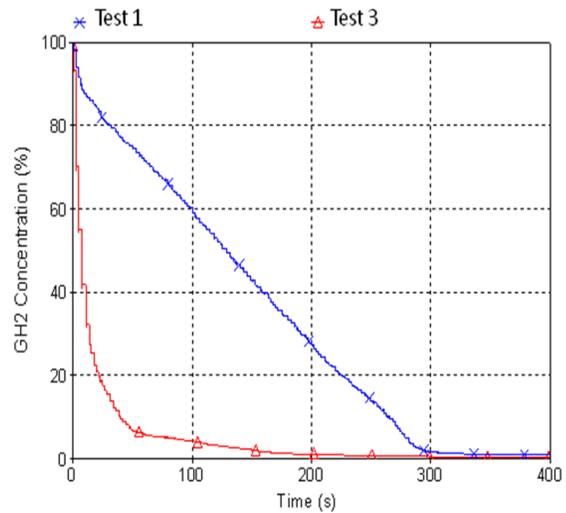


Figure 9. Purge Durations for Test 1 and Test 2.

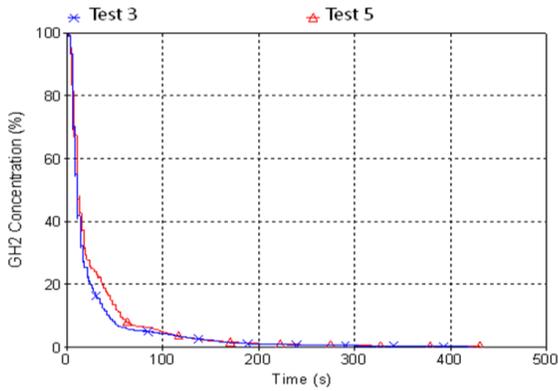


Figure 10. Purge Durations for Test 3 and Test 5.

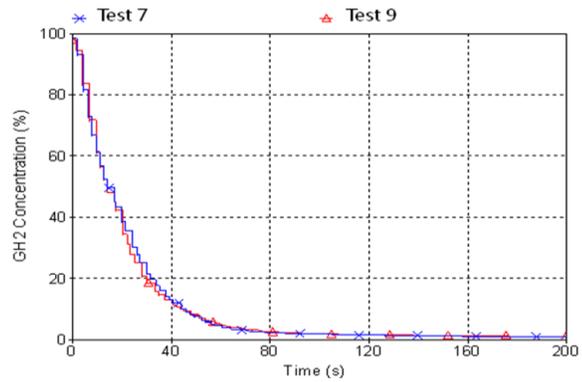


Figure 11. Purge Durations for Test 7 and Test 9.

Analytical Modeling

Utilizing GFSSP, three tests, namely Tests 1, 3, and 7, were selected and simulated. Figures 10 – 12 depict comparison of predicted and measured GH2 concentration histories at the exit of test article for these tests. Figure 12 shows the GH2 concentration history results for Test 1. There is a reasonable agreement between predicted values of GH2 concentration with those of data. The prediction deviates at around 100 seconds until the end of purge process. The predicted completion of purge time is in a good agreement with the test data. Figures 13 and 12 indicate a reasonable agreement between the predicted GH2 concentration histories and those of measured values. Again, the model predictions for the completion of the purge times are in good agreements for both Tests 3 and 7.

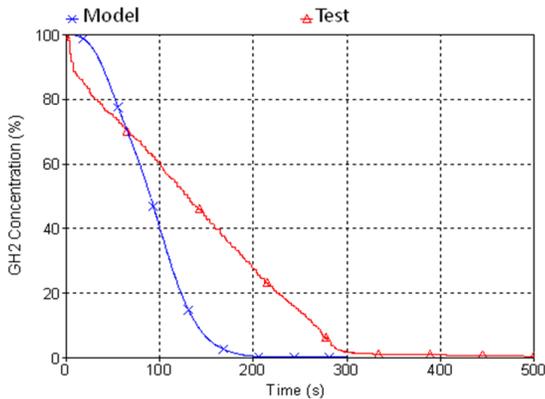


Figure 12. Concentration Histories for Test 1.

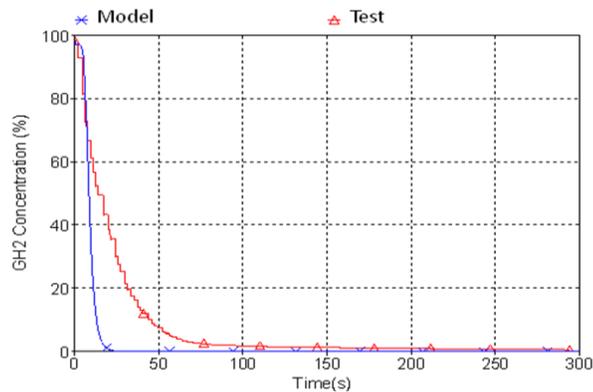


Figure 13. Concentration Histories for Test 3.

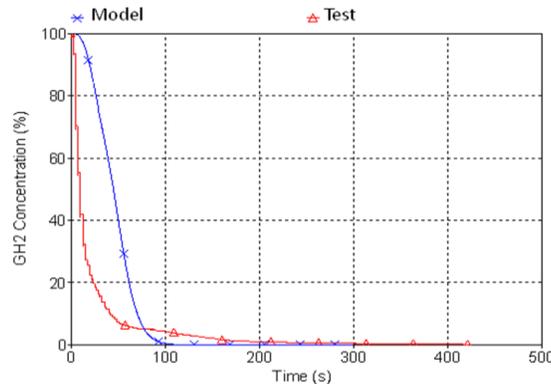


Figure 14. Concentration Histories for Test 7.

SUMMARY

To gain confidence in developing analytical models of the purging process for the cryogenic main propulsion systems of upper stage, two test series were conducted. The test article, a 3.35 m long with the diameter of 20 cm incline line, was filled with liquid or gaseous hydrogen and then purged with gaseous helium (GHe). Total of 10 tests were conducted. It was concluded that the higher purge flowrate would lead shorter purge duration. Moreover, the test results indicated that the purge process would not influence significantly by initial GHe temperature. An in-house general-purpose fluid system analyzer computer program, GFSSP, was utilized to model and simulate 3 tests. There were reasonable agreements between the predicted GH₂ concentration histories and those of obtained from the data.

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