TESTING AND ANALYTICAL MODELING FOR PURGING PROCESS OF A CRYOGENIC LINE

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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 operation for cryogenic main propulsion systems of upper stage is 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 LH_2/GH_2 filled line to support analytical purge model development applicable to any future launch vehicle that uses LH_2 (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 GH_2 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 LH_2 pass through and chill the passage. The LH_2 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.

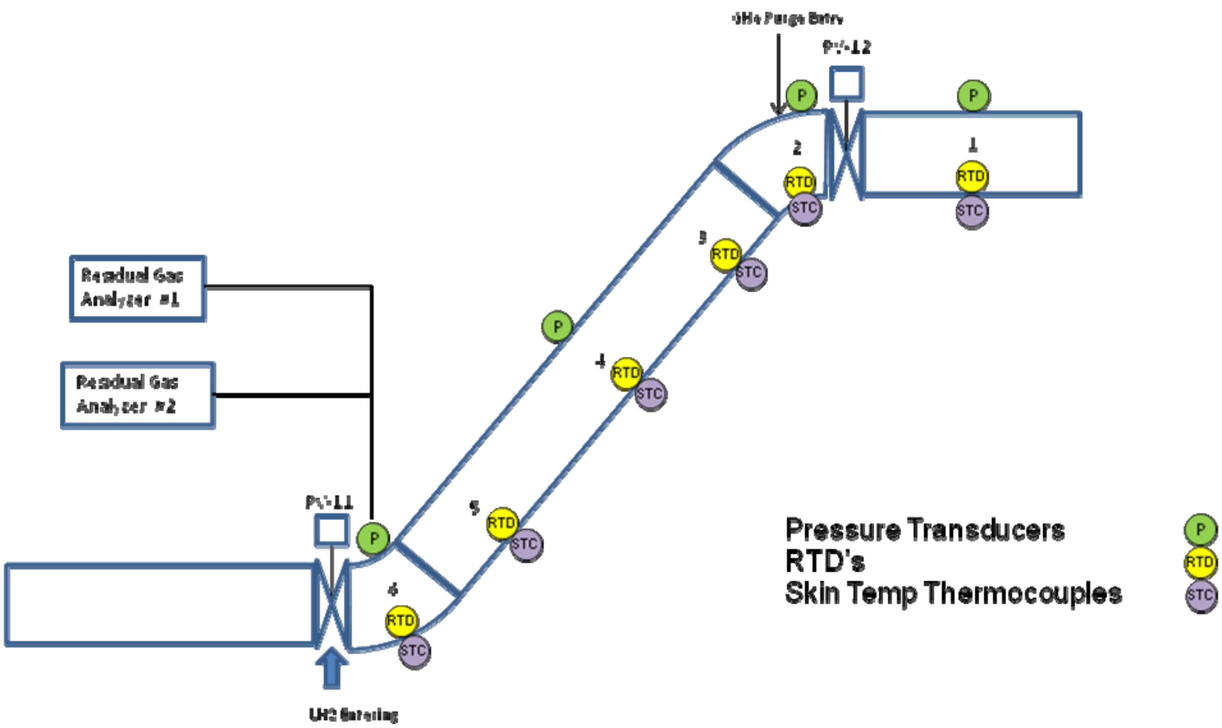

Figure 1. Test Article Schematic.

TEST PROCEDURES

Two test series were conducted at the Hydrogen Cold Flow Facility of West Test Area of Marshall Space Flight Center (MSFC). Test article was filled with LH_2 for the first series, while it was filled with GH_2 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	291.5	5.9
9	GH_2	330	5.9
10	GH_2	330	5.9

Table 1. Description of Each Test.

LH_2 Test

The steps for this test series are as follow:

1. Chilling the test article up with LH_2 by entering via PV-11 and leaving through exit and PV-12. As the test article reached steady state condition, the LH_2 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, 291.5 K, or heated to 330 K.
3. Observed the temperature of station 6, as temperature of this station jumped up, indicating the total displacement of LH_2 and replacing it with warm gas, commanded RGAs to be active and measured the concentration of both GH_2 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 LH_2 to remove entire GHe. When RGA measured the concentration of GH_2 to be 100% or GHe to be 0%, indicating complete removal of GHe, the test article was ready for the next test.

GH_2 Test

The procedure for this series is similar procedures described for LH_2 Test with a few differences. The procedure was as the following:

1. Chilling the test article up with LH_2 by entering via PV-11 and leaving through exit and PV-12. As the test article reached steady state condition, the LH_2 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 GH_2 at the Purge Entry. Then, as the temperature at the station 6 jumped up indicating the removal and replacement of LH_2 with GH_2
3. After verifying that the test article at the end of step 2 was filled with the GH_2 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 GH_2 reached zero or concentration of GHe approached 100%.
5. Purged the test article with LH_2 to remove entire GHe. When RGA measured the concentration of GH_2 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.

GFSSP has been developed at NASA- MSFC as a general fluid flow system solver capable of handling phase changes, compressibility, mixture thermodynamics, and transient operations. It also includes the capability to model external body forces such as gravity and centrifugal effects in a complex flow network. GFSSP constructs a fluid network using fluid and solid nodes.

The fluid circuit is constructed with boundary nodes, internal nodes, and branches, as shown in Figure 4, while the solid circuit is constructed with solid nodes, ambient nodes, and conductors. The solid and fluid nodes are connected with solid-fluid conductors. Users must specify conditions such as pressure, temperature, and concentration of species at the boundary nodes. These variables are calculated at the internal nodes by solving conservation equations of mass, energy, and species in conjunction with the thermodynamic equation of state. Each internal node is a control volume where there is inflow and outflow of mass, energy, and species at the boundaries of the control volume. The internal node also has resident mass, energy, and concentration. The momentum conservation equation is expressed in flow rates and is solved in branches. At the solid node, the energy conservation equation for solid is solved to compute temperature of the solid node.

GFSSP employs a unique numerical scheme known as simultaneous adjustment with successive substitution, which is a combination of Newton-Raphson and successive substitution methods. The mass and momentum conservation equations and the equation of state are solved by the Newton-Raphson method while the conservation of energy and species are solved by the successive substitution method. The details of the mathematical formulation and solution method are described in User’s Manual [1].

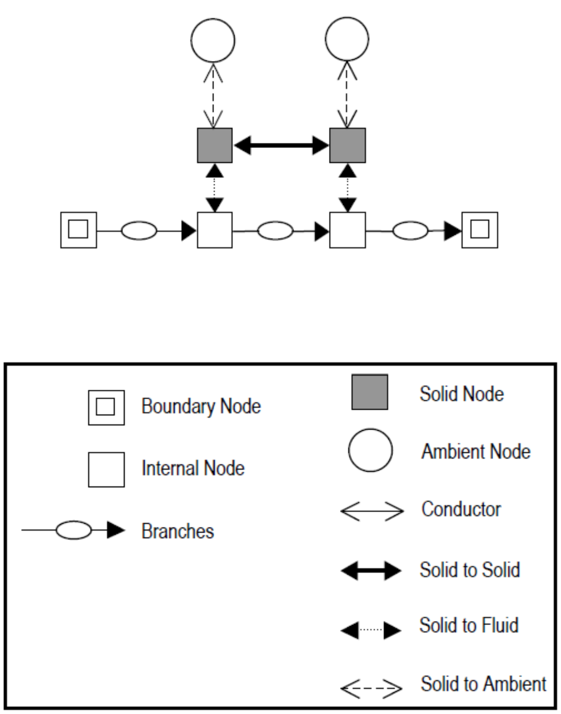

Figure 4. Schematic of GFSSP's Flow Network

RESULTS AND DISCUSSIONS

Two test series were performed, as is shown in Table 1, at the Hydrogen Cold Flow Facility of West Test Area of MSFC. In the first test series, three pairs of tests were conducted where each pair comprised of two similar LH_2 tests. Similarly, four tests were performed with the test article filled with the GH_2. 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.

LH_2/GH_2 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 Test1 and consequently the purging time of test 3 is much shorter than that of Test1. 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.

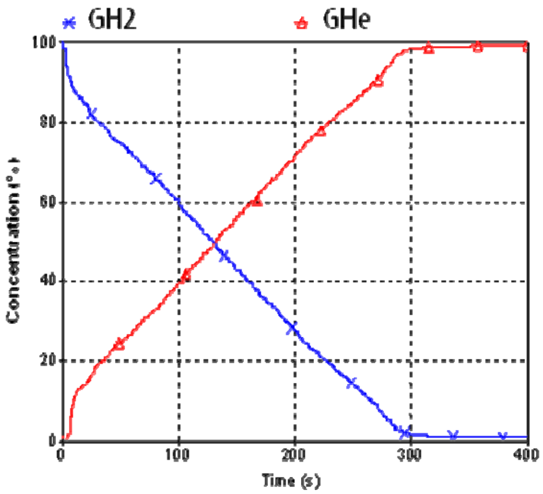

Figure 4. Concentration Histories, Test 1.

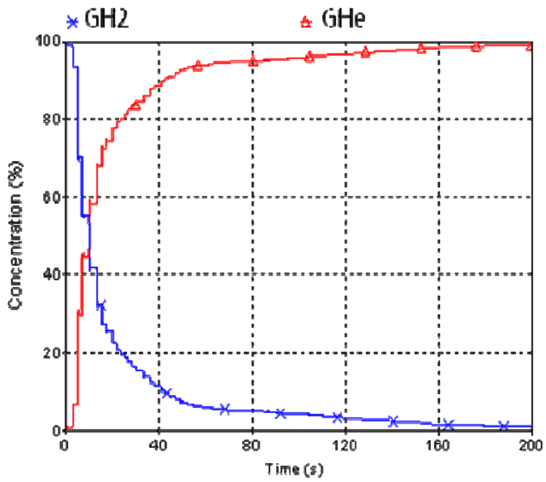

Figure 5. Concentration Histories, Test 3.

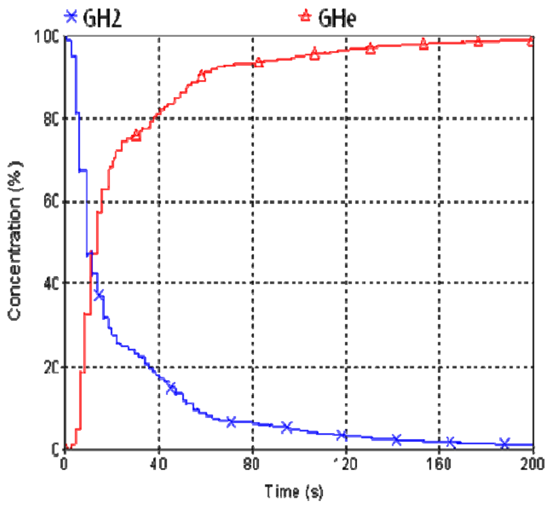

Figure 6. Concentration Histories, Test 5.

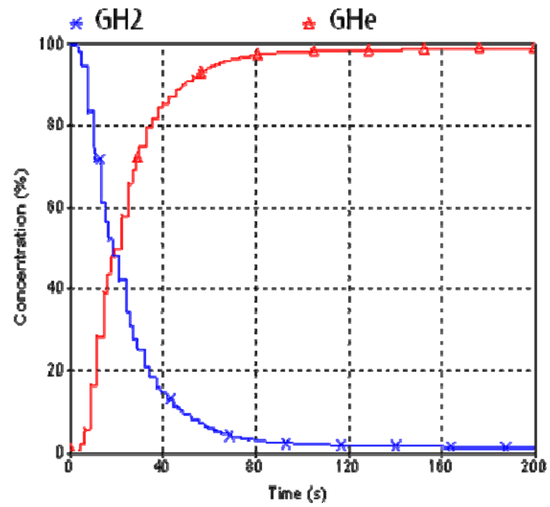

Figure 7. Concentration Histories, Test 7.

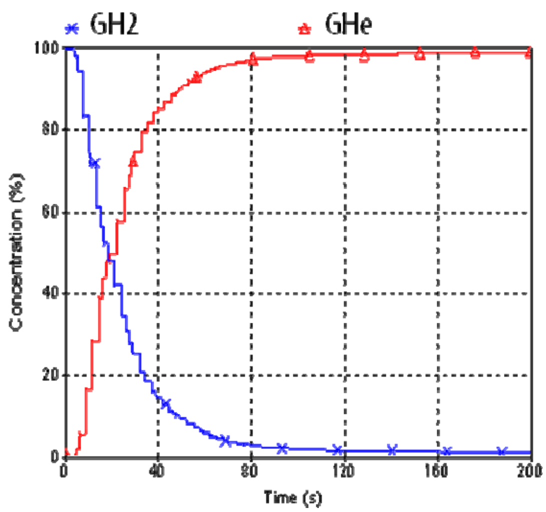

Figure 8. Concentration Histories, Test 9.

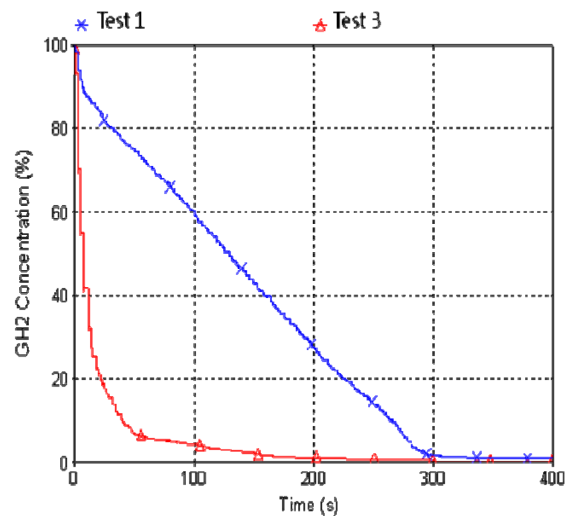

Figure 9. Purge Durations for Test 1and Test 3.

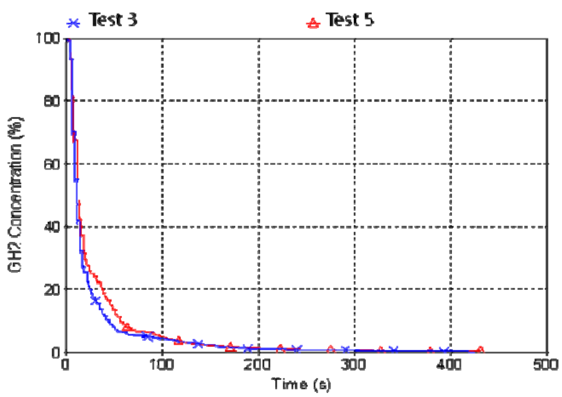

Figure 10. Purge Durations for Test 3 and Test 5.

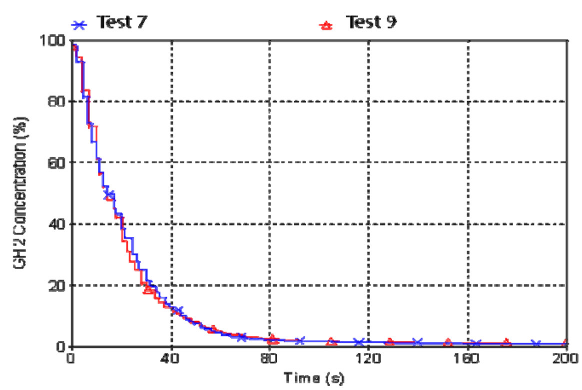

Figure 11. Purge Durations for Test 7 and Test 9.

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 test data up to around 100 seconds, then prediction deviates from 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 reasonable agreements for both Tests 3 and 7.

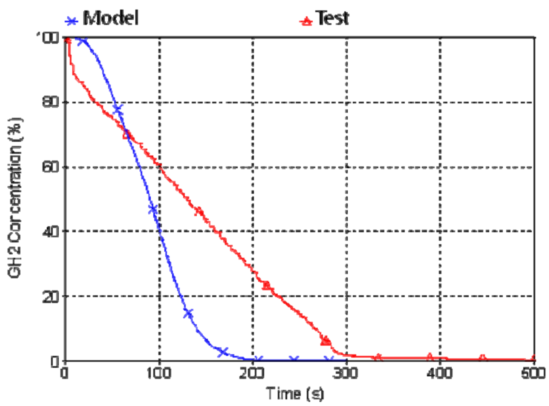

Figure 12. Concentration Histories for Test 1.

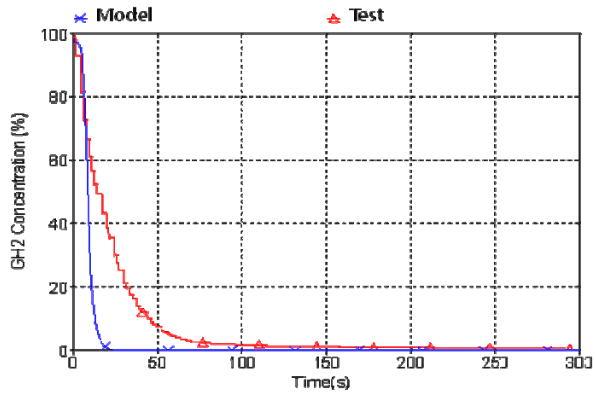

Figure 13. Concentration Histories for Test 3.

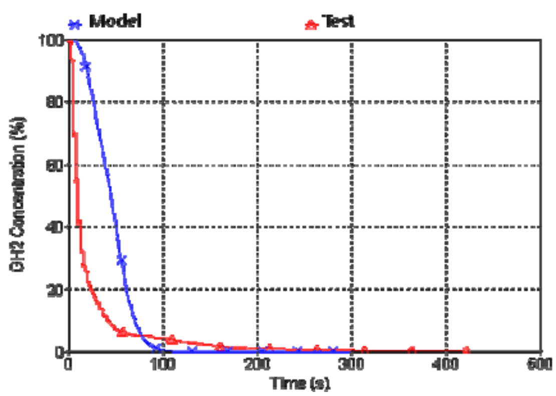

Figure 14. Concentration Histories for Test 7.

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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