Abstract. To gain confidence in developing analytical models of the purging process for the cryogenic main propulsion systems of the upper stage, two test series were conducted. The test article, 3.35 m long with a 20-cm-diameter incline line, was filled with liquid or gaseous hydrogen and then purged with gaseous helium (GHe). A 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, modelling descriptions, and the results are presented in the accompanying text.

1. Introduction

The purging operation for the cryogenic main propulsion systems of the upper stage is usually carried out in the following scenarios: 1) Purging of the fill/drain line after completion of propellant loading, allowing 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 this testing was to investigate how the purging gaseous helium (GHe) behaved when injected into the cryogenically chilled liquid hydrogen (LH₂)/gaseous hydrogen (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.

The influence of the initial temperature and flow rate of the stored purging gas on the purge operation was investigated. Since the purging operation for cryogenic main propulsion systems is performed prior to the launch, which could be any day of the year, the minimum and maximum average temperatures of the launch pad environment are considered to be about 290 K and 330 K, respectively. Therefore, the tests were conducted at initial GHe temperatures of 291.5 and 330 K. Also, to evaluate the influence of the GHe mass flow rate on the purging process, tests were performed at two different flow rates: 3.18 and 5.9 g/s.

2. Test setup

The test article schematic is shown in figure 1. The test article was a 3.35-m-long, 20-cm-diameter stainless steel incline line (inclination angle ≈41°). 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, fluid temperature, and wall temperature were measured by pressure transducers (P), resistance temperature devices (RTDs), and skin temperature thermocouple (STCs), respectively. At station 6, two residual gas analyzers (RGAs) were installed to measure the concentration of both GH\textsubscript{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\textsubscript{2} pass through and chill the passage. The LH\textsubscript{2} entered and exited the test article via PV-11 and PV-12, respectively. Both valves were closed when the test article reached a steady-state condition. The test article purging was accommodated via the purge entry, located between stations 1 and 2.

![Figure 1. Test article schematic.](image)

### 3. Test procedures

Two test series were conducted at the Hydrogen Cold Flow Facility of the West Test Area of Marshall Space Flight Center (MSFC). The test article was filled with LH\textsubscript{2} for the first test series (i.e., tests 1–6), and it was filled with GH\textsubscript{2} for the second test series (i.e., tests 7–10). Table 1 shows the description of each test. Tests 2, 4, 6, 8, and 10 were performed for redundancy, so they were a repetition of tests 1, 3, 5, 7, and 9, respectively. For all tests, initial hydrogen and helium pressures were about 101.28 kPa and 103.42 kPa, respectively. The detailed procedure for performing each test series is described in the following subsection.

| Test No. | Fluid | GHe Initial Temperature (K) | Purge Flow Rate (g/s) |
|----------|-------|-----------------------------|-----------------------|
| 1        | LH\textsubscript{2} | 291.5                       | 3.18                  |
| 2        | LH\textsubscript{2} | 291.5                       | 3.18                  |
| 3        | LH\textsubscript{2} | 291.5                       | 5.9                   |
| 4        | LH\textsubscript{2} | 291.5                       | 5.9                   |
| 5        | LH\textsubscript{2} | 330                         | 5.9                   |
| 6        | LH\textsubscript{2} | 330                         | 5.9                   |
| 7        | GH\textsubscript{2} | 291.5                       | 5.9                   |
| 8        | GH\textsubscript{2} | 291.5                       | 5.9                   |
| 9        | GH\textsubscript{2} | 330                         | 5.9                   |
| 10       | GH\textsubscript{2} | 330                         | 5.9                   |
3.1. LH₂ test series

The steps for this test series were as follows:

1. The test article was chilled with LH₂ by entering via PV-11 and leaving through the exit via PV-12. As the test article reached a steady-state condition, the LH₂ flow was stopped and both PV-11 and PV-12 were closed.

2. After verification of a steady-state condition, PV-11 was commanded to be opened, followed by the injection of helium at the purge entry. The initial purge gas, GHe, either was at the surrounding temperature, 291.5 K, or heated to 330 K.

3. As the temperature at station 6 jumped up, indicating the total displacement of LH₂ and replacing it with warm gas, the RGAs were commanded to be active, which then the concentration of both GH₂ and GHe was measured.

4. The testing was completed and was stopped as the concentration of GH₂ reached 0% or the concentration of GHe approached 100%.

5. The test article was purged with LH₂ to remove all GHe. When the 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.

3.2. GH₂ test series

The procedures for this series were similar to the procedures described for the LH₂ test with a few differences. The procedures were as follows:

1. The test article was chilled with LH₂ by entering via PV-11 and leaving through the exit via PV-12. As the test article reached a steady-state condition, the LH₂ flow was stopped and both PV-11 and PV-12 were closed.

2. After verification of a steady-state condition, PV-11 was commanded to be opened, and near saturated GH₂ was injected at the purge entry. After the temperature at station 6 jumped up (indicating the removal and replacement of LH₂ with GH₂), the GH₂ injection was continued until the line filled with GH₂ reached steady-state condition. Then, the flow of GH₂ was stopped and PV-11 was commanded to be closed.

3. After verification of a steady-state condition, PV-11 was commanded to be opened, followed by the injection of helium at the purge entry. The initial purge gas, GHe, either was at the surrounding temperature, 291.5 K, or heated to 330 K.

4. The testing was completed and was stopped as the concentration of GH₂ reached 0% or the concentration of GHe approached 100%.

5. The test article was purged with LH₂ to remove all GHe. When the 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.

4. Analytical modelling

Using the Generalized Fluid System Simulation Program (GFSSP) [1], an MSFC in-house software, the purge operation for three different tests was modelled and simulated. GFSSP was developed at NASA MSFC as a one-dimensional 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 2, 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.
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 a solid is solved to compute the temperature of the solid node.

![Figure 2. Schematic of GFSSP’s flow network.](image)

GFSSP employs a unique numerical scheme known as simultaneous adjustment with successive substitution, which is a combination of the Newton-Raphson method 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 the user’s manual [1].

5. Results and discussions
Two test series were performed, as described in section 3. In the first test series, three pairs of tests, tests 1–6, were conducted where each pair was comprised of two similar LH2 tests. Similarly, in the second test series, two pairs of tests, tests 7–10, were performed where each pair represented two similar GH2 tests. The tests were designed to evaluate the influence of GHe flow rate and initial injecting temperature (for the prescribed launch pad environment temperature range) on the purging process. The parameters influencing the purging process and a comparison of the results of the analytical models with the test data are presented.

Figures 3–7 depict GH2 and GHe concentration histories at the exit of the test article (station 6) for tests 1, 3, 5, 7, and 9. Since tests 2, 4, 6, 8, and 10 were similar to tests 1, 3, 5, 7, and 9, respectively, the results for these tests are not presented. 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 or mixed with the hydrogen, leading to an increase of GHe concentration and a decrease in hydrogen concentration until hydrogen concentration reached 0%, indicating complete removal of hydrogen and the end of the purge process.
Figure 3. Concentration histories, test 1.

Figure 4. Concentration histories, test 3.

Figure 5. Concentration histories, test 5.

Figure 6. Concentration histories, test 7.

Figure 7. Concentration histories, test 9.
The influence of the purge gas (GHe) flow rate in the purging process is illustrated in figure 8 by comparing the \( \text{GH}_2 \) concentration histories for tests 1 and 3. The purge flow rate for 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.

![Figure 8. Purge durations for tests 1 and 3.](image)

Figures 9 and 10 illustrate the influence of initial purge gas (GHe) temperatures. Figure 9 compares test 3 to test 5, while figure 10 compares the purging process for tests 7 and 9. Both figures 9 and 10 indicate that the purging process is not influenced significantly by initial GHe temperatures of 291.5 K and 333 K.

![Figure 9. Purge durations for tests 3 and 5.](image)  ![Figure 10. Purge durations for tests 7 and 9.](image)

5.1. Analytical modelling
Tests 1, 3, and 7 were modelled and simulated utilizing GFSSP. Tests 5 and 9 were not simulated because, as discussed previously, the purging process is influenced significantly by the purge gas flow rate not by its initial temperature. Moreover, the flow rates of the purge gas for tests 5 and 9 were the same as of those in tests 3 and 7, respectively. Figures 11–13 depict a comparison of the predicted and measured \( \text{GH}_2 \) concentration histories at the exit of the test article for these tests.
Figure 11 shows the GH$_2$ concentration history results for test 1, representing a slower purging process. Initially, the difference between the predicted values of GH$_2$ concentration with those of the test 1 data are small; however, at approximately 100 seconds, this gap is widened and the model predicts a much faster purging process. Figures 12 and 13 depict the predicted GH$_2$ concentration histories and those data for tests 3 and 7, respectively, representing a faster purging process. Initially, for test 3, depicted in figure 12, the model predictions and the measured values of hydrogen concentrations are in agreement, but after approximately 10 seconds, the predicted values deviate from the test data and the model predicts a faster purging process. For test 7, shown in figure 13, the GH$_2$ concentration decreases slower than those of the test data until around 80 seconds; however, after this point the model prediction leads to a shorter completion of the purging process. The discrepancy between the model predictions and the test data may be due to the fact that hydrogen displacement or mixing with helium during the purging process is a more complex so one-dimensional model, using the GFSSP, would not represent an accurate interaction of hydrogen with helium during the purging process.

**Figure 11.** GH$_2$ concentration histories, test 1.

**Figure 12.** GH$_2$ concentration histories, test 3.

**Figure 13.** GH$_2$ concentration histories, test 7.
6. Summary
To gain confidence in developing analytical models of the purging process for the cryogenic main propulsion systems of the upper stage, two test series were conducted. The test article, 3.35-m-long with a 20-cm-diameter incline line, was filled with LH$_2$ or GH$_2$ and then purged with GHe. A total of 10 tests were conducted. It was concluded that the higher purge flow rate would lead to a shorter purge duration. Moreover, the test results indicated that the purge process would not be influenced within the prescribed initial temperature range of GHe. Three tests were modelled and simulated. Overall, the model predicted a faster purging process. The discrepancy between the model predictions and the test data may be due to the fact that hydrogen displacement or mixing with helium during the purging process is a more complex and one-dimensional model, using the GFSSP, would not contain an accurate interaction of hydrogen with helium during the purging process.

7. References
[1] Majumdar A K, LeClair A C, and Schallhorn P A October 2013 Generalized Fluid System Simulation Program, Version 6.0 (NASA/TM—2013–217492)

Acknowledgements
The authors would like to extend their appreciation to Kent Chojnacki from MSFC XP30 and Carl Ise from MSFC XP03 for their support. The authors would also like to thank Mike Nichols and the test team at the Hydrogen Cold Flow Facility of the MSFC West Test Area. Special thanks also go to Ken Knable and Mathew Miles.