Ground-based cryogenic leak test of fittings for cryogenic fluid management

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Abstract. Mechanically connected fluid joints are virtually unavoidable in complex cryogenic system designs. In the case of spacecraft, the performance of these joints is critical to mission success. This is especially true for long-duration space missions where even very low leak rates can eventually lead to significant propellant losses or failure of vital cryogenic cooling systems. NASA has recently undertaken an effort to quantify the leak rate of Vacuum Coupling Radiation (VCR) fittings over the temperature range from ambient to 20 K, both before and after exposure to a launch vibration profile. A test apparatus employing a cryocooler and a calibrated helium mass spectrometer was developed, validated, and used to obtain quantifiable leak rates at a fitting test pressure of 31 bar (450 psig). Three different fitting sizes were tested, 25.4 mm (1/4 inch), 12.7 mm (1/2 inch), and 6.35 mm (1 inch) and two gasket materials, stainless steel, and silver-plated nickel. Each fitting configuration (size/seal material) was subjected to two consecutive cryogenic thermal cycles/measurement tests, followed by a launch vibration test profile at ambient temperature, and then two additional cryogenic thermal cycles/measurement tests. The design and development of the test apparatus, and test data are presented and discussed in detail.

1.0 Background[4]

The Swagelok Vacuum Coupling Radiation (VCR) fitting is widely used and trusted for ground testing in thermal vacuum environments which are highly sensitive to even minute leakage. A recent survey of NASA cryogenic users found that they are commonly used by every center that performs cryogenic thermal vacuum work. Based on the results of this survey, the VCR fittings, were selected as good candidates for use on future flight vehicles.

This study was undertaken to evaluate the performance of the Swagelok VCR fittings under space flight conditions. This fitting is an alternative for flight systems employing other fluid fittings styles such as 37° flared fittings with copper crush washers, flared tubing, Dynatube, KC fittings, etc. which all have deficiencies some of which could be solved by the VCR fitting.

The data presented here is a follow on to the initial 2020 testing with more extensive testing of additional Swagelok VCR fitting samples. The purpose of this additional testing is to provide a statistically significant larger sample size and be able to evaluate the potential to qualify the VCR fitting for flight use. The Artemis Program will likely need flight qualified cryogenic fittings, and this testing will allow for development of qualification test set-ups and procedures. Additionally, this testing is designed to further demonstrate that VCR fittings, specifically, are good candidates for flight qualification. This testing followed American Society for Testing and Materials (ASTM) F1387-19 Standard Specification for Performance of Piping and Tubing Mechanically Attached Fittings, but it was only a partial subset of the specification. This testing was focused on the space flight relevant portion of the ASTM Spec. Full qualification could be undertaken in the future based on the positive results obtained from this round of testing.

2.0 Objectives

The overall objective of the VCR fittings test was to evaluate if the fittings can operate leak free under space flight conditions. The testing program included the following objectives:

a. Testing of three (3) different VCR fitting sizes: 1/4, 1/2, and 1 inch. (Five (5) samples of each size)
b. Two (2) different seal material types: Stainless Steel and Silver-Plated Ni. These materials were selected because they are the most compatible with the cryogenic space flight fluids.
c. Four (4) complete ambient (300K) to cryogenic (20-30K) thermal cycles in TVAC for each fitting size and seal material combination. Two (2) thermal cycles were performed before and two (2) cycles after vibration testing.
d. Vibration testing to relevant launch dynamic profile
e. Leak checking of fittings throughout the Thermal Vacuum (TVAC) test sequence by pressurizing to 400-420 psi (27.5-29 bar) with gaseous helium (GHe) and monitoring the chamber background with a GHe mass spectrometer leak detector. The leak rate threshold was set to 10^{-6} sccs GHe based on references to Kennedy Space Center (KSC) specifications for installed fittings and fitting assemblies.

3.0 Hardware Enhancements

Based on the lessons learned from the initial proof of concept testing in 2020, hardware enhancements were implemented to enable the efficient execution of numerous tests. These focused on two areas: automation to enable a higher test rate and completion of several thermal cycles per day and enhancing the test hardware to minimize interruptions between tests.

A higher test rate allowed more comparative testing of fitting sizes and seal types. In addition, the faster test rate enhanced the ability to resolve hardware or sample issues and quickly retest fittings. A LabVIEW program was written and used to automate the test execution and monitoring. This program automated leak testing, solenoid valve operation, and error handling as well as data collection and reporting. The program effectively enabled a succession of fitting tests at a much higher rate than previously possible.

Hardware enhancements included: the addition of cup heaters to speed up the warm-up time, the fabrication of two separate fitting holding fixtures to aid in the rapid swap out of test samples, and the addition of Teflon ferules to the vacuum ports which sped up the sample installation process.

A diagram of the original proof-of-concept hardware is shown on the left side of figure 1. Hardware enhancements recommended in the December 2020 Final Report included the addition of solenoid-operated valves and an electronic pressure regulator to automatically control fitting pressurization, venting and vacuum system isolation. These enhancements were added to the system and are indicated by the circles shown on the right side of figure 1.

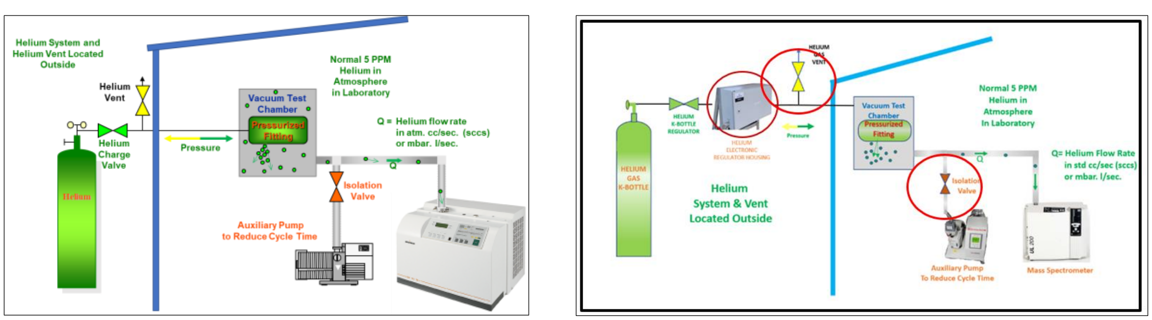

Figure 1. Test Hardware Setup – Initial (L) and with Automation Enhancements (R)

4.0 Test Articles

Each test article consisted of a single Swagelok VCR fitting joint with standard COTS parts and assembled per the manufacturer's instructions. The joint is shown in figure 2 and is composed of a female nut, a "Blind" gland, a seal ring, a "Long Tube Butt Weld" gland and a male nut. The butt weld gland is welded to a reducer(s) which is then welded to a 10-foot length of 1/8" diameter tube to provide a very long thermal conduction path. The tube is coiled within the vacuum chamber and then exits the chamber passing through a 1/8-inch Swagelok compression fitting. The end of the 1/8-inch tube is then mated to the GHe pressurization supply line using a threaded fluid fitting (Swagelok compression fitting).

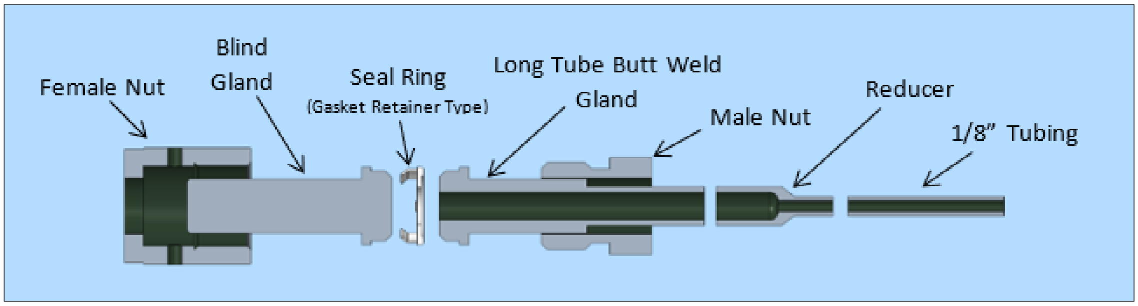

Figure 2. VCR Fitting Test – Typical Test Article Assembly

Several steps were involved in preparing a test article for testing. First, the welded gland, reducer(s) and 1/8-inch tube were joined using a Swagelok Automatic Orbital Welding machine to produce precise, consistent, quality welds that are leak-free. The next step was to bend the 10-foot length of tubing into the coiled shape. Because the test article includes fabricated tubing it required a hydrostatic pressure test. With the assembly filled with water, both halves of the fitting were assembled per the Swagelok VCR assembly procedure using a copper seal ring, and then pressure tested to 750 psig (which is 150% of leak test system design pressure). The fitting assembly was then disassembled and dried using a nitrogen purge and the copper seal ring is discarded. Finally, the fitting joint is assembled with the test-specific seal ring. A gross leak check is performed on the bench with helium at 400-500 psig as a final quality verification prior to installation into the vacuum chamber.

5.0 Cold Leak Measurement Test Apparatus

Testing of the fittings took place inside a purpose built TVAC chamber. A cut-away of the vacuum test chamber is shown in figure 3. The chamber was designed to be quickly opened and samples removed/installed in an efficient manner. The sample fittings were mounted on top of the cryocooler cold tip inside an aluminum cup with copper fastenings to achieve good thermal contact. Heat leakage was minimized by the aluminum cup and coiled tube. Flexible Kapton heaters were added to the cold head to speed up the warmup time, which was one of the lessons learned from the initial test runs in 2020. Several ports on the chamber were used for connecting the vacuum pump, the leak detector and pressure gages.

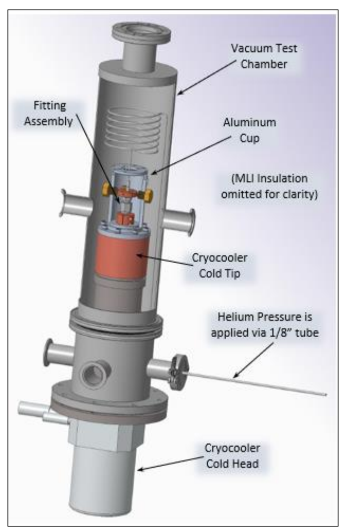

Figure 3. VCR Fitting TVAC Chamber Cutaway

The Test Setup inside the CTL high bay is shown in the left side of figure 4. The Cryomech AL325 cryocooler is used to attain the 20-30K cold test temperature required. The INFICON UL 200 Mass Spectrometer Helium Leak Detector measures the GHe background inside the vacuum chamber during the TVAC cycles. An Edwards TIC Vacuum Pumping station is used to evacuate the vacuum chamber surrounding the fitting. The DAQ System monitors fitting pressure, vacuum chamber pressure, and temperature transducer values during each test. A LabVIEW software program controls valves and can automatically terminate any test if the measured leak rate of any fitting is above a predetermined ceiling value.

Figure 4. VCR Test Setup – Internal (L); VCR Test Setup – External (R)

The external components of the test setup are shown in the right side of figure 4. including the chiller for the cryocooler, the GHe K-Bottle, and Tescom auto regulator. They are located outside on the North side of the CTL building to minimize helium accumulation around the leak-check hardware and to avoid excessive noise in the lab. The TESCOM model ER5000 electropneumatic motor actuated regulator connected to the GHe K-bottle is controlled by the LabVIEW program. When in the OPEN configuration the test fitting is pressurized with GHe.

5.1 Test Method

The "inside-out" method of leak measurement method was used for all testing. The fittings were placed inside of an evacuated chamber and pressurized with GHe. Any leakage of the GHe from the test article into the evacuated chamber was measured by the leak detector. This method of leak measurement is ideal for this application because the fitting is pressurized internally and exposed to the same stresses that it would be in its intended application. It is a reliable, quantitative method that is highly sensitive and capable of measuring a wide range of leak rates. In these tests, the leak measurement technique is augmented with the fittings being thermal cycled from ambient to cryogenic temperature under vacuum conditions while pressurized.

During testing, temperature is monitored at three primary locations within the test chamber using silicon diodes: the cryocooler cold tip temperature (T1), the aluminum cup temperature (T2), and the fitting assembly temperature (T3). The fitting assembly temperature diode is attached to the wrench flats of the male or female nut. The reducer temperature (T4) is monitored as a secondary fitting temperature. In comparison, the fitting pressure (P1) is monitored as a primary measurement for the leak test. The leak detector indicates the GHe leak rate and inlet pressure (vacuum). The pressure in the vacuum test chamber (P2 and P3) is monitored as a guide for performing various stages of the test.

6.0 Vibration Testing

Vibration testing of the VCR fittings was utilized to expose each fitting to launch-like conditions and ascertain whether the sealing capability of any fitting was compromised due to vibration loads. All vibration testing was performed on an Unholtz Dickey vibration shaker table at the KSC Vibration Test Laboratory.

The vibration test profile used for the testing is per flight standard vibration profile (Reference General Environmental Verification Standard (GEVS) Table 2.4-3, *GSFC-STD-7000B Goddard Space Flight Center Approved: 04-28-2021 Greenbelt, MD 20771 Revalidation Date: 04-28-2026 Superseding GSFC-STD-7000A* for GSFC Flight Programs and Projects). The vibration testing was performed at ambient temperature and with the fitting unpressurized. For reference, figure 5 shows the addition of the attached accelerometer used for the collection of vibration responses.

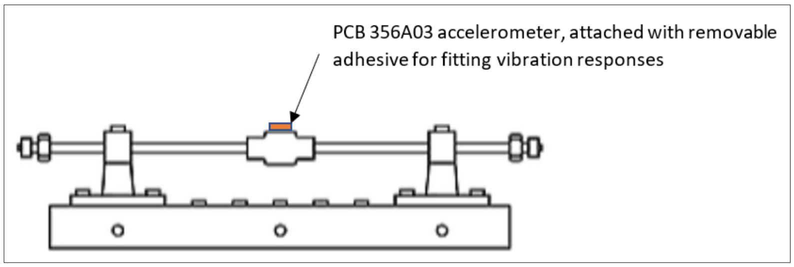

Figure 5. Schematic of the vibration fixture and attachment of the fitting hardware (from the ASTM F1387-19 S8 specifications)

The overall shaker table/adapter/VCR fitting assembly shown in figure 6 was used during all vibration tests with test fixtures/specimens extending over the edge of the test cube.

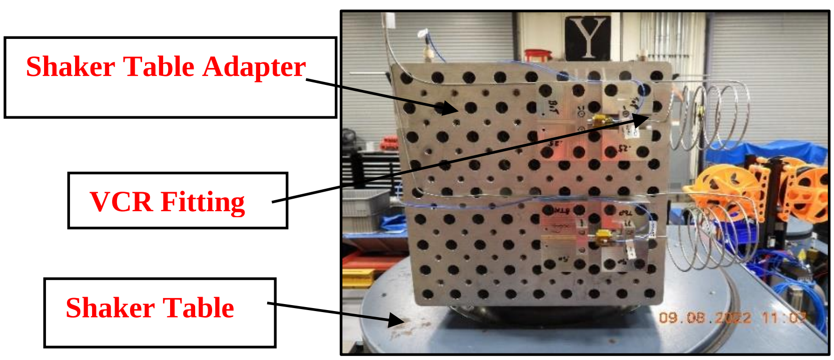

Figure 6. Vibration Test and Shaker Table Fitting Assembly

Because the shaker table produces a linear acceleration in a single direction, each fitting assembly was subjected to two separate tests to evaluate both axial and radial vibration loads, with the fitting rotated 90 degrees on the table between tests.

7.0 Test Results

A typical single data run is shown in figure 7. The graph for each data run shows the fitting pressure (P1-red), fitting temperature (T3 - purple) and leak rate (green).

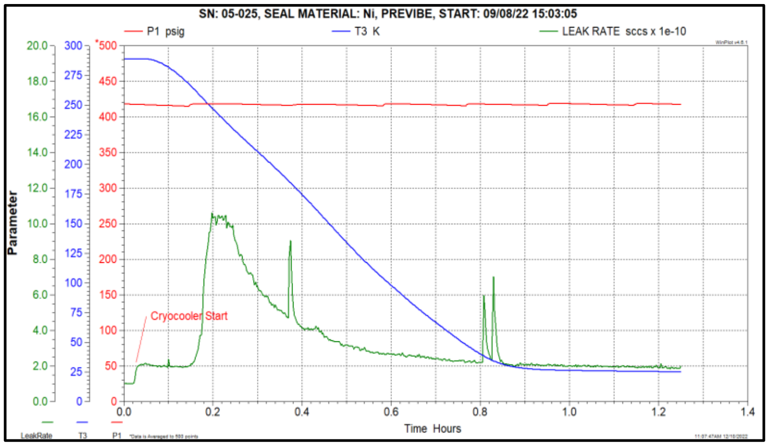

Figure 7. Representative Graph of ¼ inch Swagelok fittings

All fittings passed the leak rate criteria (maximum allowable rate of 10^{-6} sccs). Measured leak rates were, at a minimum, 2-3 orders of magnitude below this value. For reference, the limits of the leak detector measuring range are 1 x 10^{-1} to 5 x 10^{-11} sccs, and for most tests were at the lower end of this range around 10^{-10}. When leaks in the range of 10^{-9}-10^{-10} sccs are noticed they seem to consistently occur between 10 – 30 minutes in the chill-down cycle and over a corresponding temperature range of 250K – 100K. This observed leak rate may be due to the "settling" of fitting/seal pairs during chill-down. The fact that some fitting/seal pairs do not exhibit detectable leaks may be due to smoother sealing surfaces or minor differences in component assembly. The spikes observed during testing may be the result of mechanical vibrations or pressure variations.

7.1 Maximum Helium Leak Rate Comparisons

The graphs in this section (figure 8, figure 9, figure 10) compare the **maximum** measured leak rates of the ¼", ½" and 1" fittings. Each plotted leak rate is the average of the maximum leak rate for four (4) tests: pre-Vibe (2) and post-Vibe (2). The observed leak rates across all tested fitting sizes, seal materials, and fitting serial numbers were 3-4 orders of magnitude BELOW the maximum allowable leak rate of 10^{-6} sccs. On the average, the leak rates for ¼" and ½" SST seals are higher than those for the Ni. In comparison, the Ni seals show a higher average leak rate for the 1-inch fittings. These results are comparable to data previously reported in 2020. Additional testing may be needed to verify the results of larger fittings.

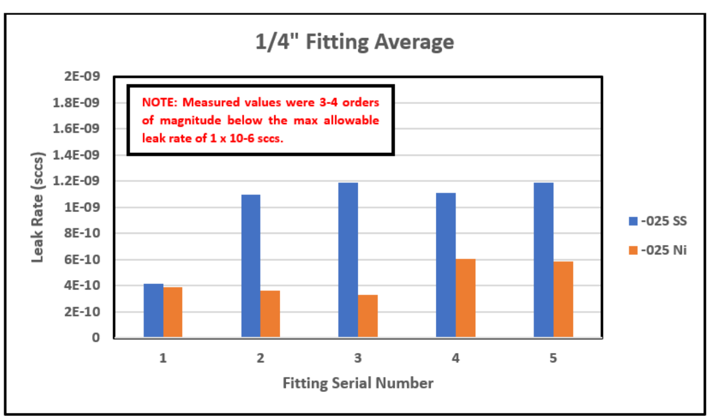

Figure 8. Maximum Helium Leak Rate Comparisons (1/4" fittings)

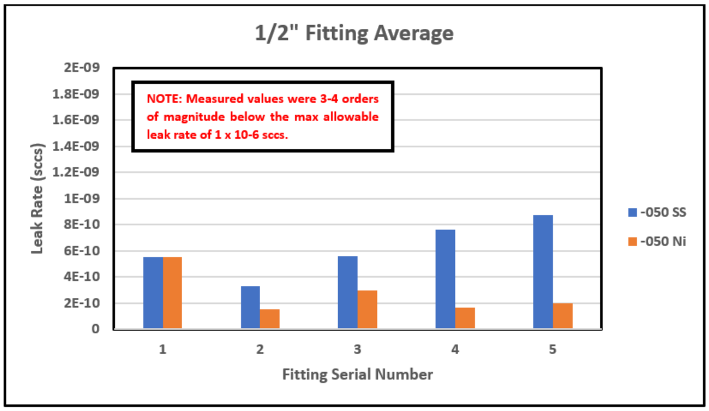

Figure 9. Maximum Helium Leak Rate Comparisons (1/2" fittings)

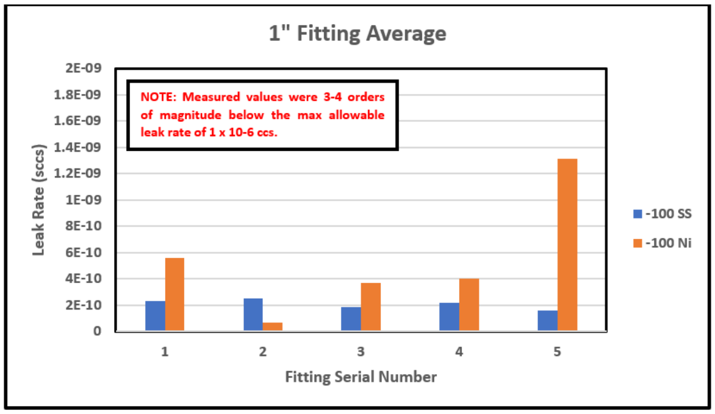

Figure 10. Maximum Helium Leak Rate Comparisons (1-inch fittings)

8.0 Lessons Learned

Seal rings are delicate and must be handled with care during assembly. There were 2-leaky fittings due to damaged/scratched seal rings. The test data for two (2) fitting/seal pairs: ½ inch Ni and 1 inch Ni were inconsistent. Upon further examination it was found that both seals contained scratches and imperfections that may explain the inconsistencies in the test data. Data from these fittings were discarded and not used in the final analysis.

Data file labeling is very important for efficient tracking/sorting of large data sets. Some tests were repeated due to lost data because of incorrect data labeling.

The sequence of operations is important and can affect the quality of measurements. Isolation valves were installed due to vacuum pump cycling that corrupted leak detector data.

9.0 Summary

Mechanically connected joints used in cryogenic fluid lines as part of space flight elements need to survive launch vibrations and remain leak-free to minimize the loss of on-board commodity and hazardous gas accumulation. In 2020, a cryogenic test apparatus was developed which can evaluate the leak performance of pressurized threaded fluid fittings and their ability to survive launch vibrations and remain leak-free under extreme thermal cycling. The test articles for the initial proof of concept testing were ¼ and 1 inch Swagelok VCR fittings with three different types of seal rings Copper, Nickel, and silver-plated Nickel.

As a follow-up, a larger set of fittings was tested under the same conditions as the initial proof of concept evaluation. Data presented in this paper illustrate the results for three Swagelok VCR fitting sizes: ¼, ½ and 1 inch. In all, five (5) samples of each fitting size were tested with Stainless-steel and silver-plated Nickel seal rings (Total of 30 unique test articles). Each test article was subjected to four (4) thermal cycles. Half of these cycles were performed before vibration testing and half were performed after vibration testing. The results of this testing showed that the fittings remain leak tight at cryogenic temperature (20K- 30K). The measured leak rates for the 30 fitting/seal pairs were typically in the range of 10^{-9} -10^{-10} sccs during both Pre-Vibe and Post-Vibe thermal vacuum cycles. These values are well below the maximum allowable leak rate of 10^{-6} sccs.

The results showed that the Ni seals had a lower leak rate, but the SST was more rugged. These fittings show great promise for space flight use. Further testing is recommended to fully qualify the fittings per the ASTM F1387-19 and/or other relevant NASA specifications. With slight modifications to the TVAC fixturing, the automated test apparatus detailed here could also be useful for future projects with similar goals of qualifying cryogenic fluid components for space flight, such as valves, couplings, instrumentation, and other types of fittings.

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