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Composite Crew Module (CCM) Permeability Characterization

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May 2013

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March 14, 2013

Report Approval and Revision History

NOTE: This document was approved at the March 14, 2013, NRB. This document was submitted to the NESC Director on March 20, 2013, for configuration control.

Approved:	*Original Signature on File*	3/21/13
	NESC Director	Date

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Mr. Michael Kirsch, NESC Principal Engineer, Langley Research Center	3/14/13

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Technical Assessment Report

1.0 Notification and Authorization

Mr. Michael Kirsch, NASA Engineering and Safety Center (NESC) Principal Engineer at the NASA Langley Research Center (LaRC), was selected to lead this assessment, which was the result of the Composite Crew Module (CCM) Primary Structure assessment (NESC-RP-06-019). The assessment plan was approved by the NESC Review Board (NRB) on December 14, 2010.

The key stakeholders for this assessment are the Exploration Systems Mission Directorate and the NASA Office of Chief Engineer.

2.0 Signature Page

Submitted by:

Team Signature Page on File – 4/9/13

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Significant Contributors:

Dr. Daniel L. Polis Date

Mr. William M. McMahon Date

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Mr. Wade C. Jackson Date

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Signatories declare the findings, observations, and NESC recommendations compiled in the report are factually based from data extracted from program/project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analyses, and inspections.

3.0 Team List

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Core Team		
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4.0 Executive Summary

In January 2007, the NASA Administrator chartered the NASA Engineering and Safety Center (NESC) to form an Agency team to design and build a composite crew module in 18 months in order to gain hands-on experience in anticipation that future exploration systems may be made of composite materials. One of the conclusions from this Composite Crew Module (CCM) Primary Structure assessment [ref. 1] was that there was a lack of understanding regarding the ability for composite pressure shells to contain consumable gases, which posed a technical risk relative to the use of a metallic design. After the completion of the CCM test program, the test article was used in a new program to assess the overall leakage/permeability and identify specific features associated with high leak rates. The "International Space Station (ISS) to Commercial Orbital Transportation Services Interface Requirements Document" specifies that the maximum leakage rate cannot exceed 0.01 kilograms (kg) per day of air at 14.7 pounds per square inch differential (psid) (760 millimeters of mercury (mmHg)) while the crew module is mated to the ISS [ref. 2].

The CCM was built as two halves spliced together around the circumference using a double lap shear joint cured under vacuum bag pressure with a heater. The majority of the construction was honeycomb sandwich with unvented aluminum honeycomb. The unvented core was selected to provide double redundancy in pressure containment with the two skins of the sandwich. Six large openings were included for windows and hatches. The minimum gage sandwich skin and the minimum gage laminate consisted of 4 plies and 10 plies of fabric, respectively. Metallic fittings bolted through the pressure shells were used for attachment points for the Service Module/Alternate Launch Abort System (SM/ALAS) and parachutes. An external bracket was attached to the sandwich structure using 20 two-piece inserts that penetrated both face sheets. In addition to these penetrations, two repairs were made using through bolts in the lobed bottom of the lower pressure shell.

An extensive mechanical test program that included 11 test conditions was conducted on the CCM [ref. 3]. The test program consisted of pressurizing the internal volume and applying mechanical loads to the metallic fittings. Each test condition consisted of a number of loading/unloading sequences leading up to either limit or ultimate load. Mechanical loads were applied to four types of metallic fittings (SM/ALAS, parachute, drogue chute, and external bracket) using straps attached to a hydraulic actuator, while the internal pressure was controlled. A damage tolerance program was included in the test program, which involved impacting the vehicle at 18 unique locations at 6 foot-pounds (ft-lb) followed by life cycling (four lifetimes). In addition, five design details were taken to critical impact threat levels (reliable detection or a threshold energy level of 26 ft-lb) and subsequently tested to an additional four lifetimes. At the end of the test program, the CCM was hydraulically pressurized to failure, which occurred at 54 psid (3.5 times the pressure limit).

The CCM did incur significant damage from the test program [ref. 4]. At failure, three of the six bays contained large regions of skin-to-honeycomb debonding in the "shoulder" region (ceiling to conic transition), as well as core splice failures. The potting compound that was used between the upper and lower pressures shells was cracked extensively. Water also was observed escaping from the bolts used on the repair to the lower pressure shell after failure. As a result of the damage tolerance program, localized impact damage was scattered inside and outside the CCM. The impact testing near the docking ring caused a large debond in the doubler and damage to the pressure shell. It was unknown whether extensive microcracking developed in the fabric plies throughout the CCM due to the high loads during the test program.

All leak measurements were performed using helium, instead of the operational fluid (air), in conjunction with a mass spectrometer. This is a very common technique used in many industries to detect small leaks. Because of its extremely small atomic size, helium easily passes through small cracks. However, conversion from a helium flow rate to an air flow rate can be complex due to the different characteristics of the two gases. For example, the permeability of several types of polymeric membranes differed by over 2 orders of magnitude for helium relative to nitrogen [ref. 5]. The use of helium will result in conservative results for leak measurements (air leakage will not be greater than the measured helium leak rate). In this assessment, the helium leak rates were compared directly with the maximum leak rate for air.

The pristine permeability of carbon-fiber-reinforced toughened epoxy laminates, measured at the coupon level, is sufficient to meet vehicle-level requirements of 0.01 kg/day or 1e-1 standard cubic centimeters per second (sccs) of air [refs. 2 and 6]. The CCM Program and subsequent investigations demonstrated that composite permeability is sufficiently low under design limit strains [refs. 6 and 7]. In addition to the damage caused by the test program, several outstanding leakage risks remain that relate to the design and manufacture. These items include but are not limited to bolted fittings, out-of-autoclave joints, potted inserts, bolted repairs, and impact damage repair. The CCM was not designed and manufactured for leakage/permeation testing. Consequently, the aluminum frames, seals, and covers were not "flight like" and may be subject to leakage (e.g., single O-ring seal). Some of the covers also have through-thickness penetrations that could leak.

With these leakage risks in mind, one goal of the CCM permeability characterization investigation was to quantify the leakage of some of these structural features that were readily available on the full-scale structure. The CCM enabled the quantification of the variability associated with these features to better understand the process control aspects of their design.

The investigation quantified the permeability/leakage from coupons with and without impacts and then demonstrated that a sheet appliqué liner solution could mitigate the impact leakage. Following that demonstration, the liner solution was partially installed on the CCM to examine the feasibility of full-scale implementation. The appliqué film was manually installed on the interior of the CCM, covering approximately 25 percent of the upper shell, the splice, and all of the potted inserts. Despite some difficulty in installation, the film was effective at reducing the leak rate associated with the inserts. The film also appeared to reduce the leak rate associated with the splice, although insufficient data were collected to establish the statistical significance of this change. This mitigation scheme could allow for numerous low velocity impacts (i.e., approximately 900, assuming one-inch-diameter damage areas) without compromising the system leak performance.

The leak rate associated with critical features such as bolted penetrations was quantified. The measurements revealed that the sealing process for the bolted fittings was not robust (i.e., similar fittings showed large variability in performance). However, some fittings demonstrated that low leak rates are achievable. This suggests that, with improved process control and/or design improvements, acceptable leak rates through penetrations are possible.

The leak rate associated with the composite shell, absent of penetrations, was estimated using two methods: 1) scaling coupon data and 2) subtracting the critical feature leak rates from the global leak rate. The estimates are 2.3e-3 and 8.4e-2 sccs for methods 1 and 2, respectively. Method 2 required scaling the feature leak rates to the reference operating pressure of 1 atmosphere (atm). The discrepancy in the two methods suggests that there were significant features or defects that were not quantified during the feature test. The coupon estimate should have been an upper bound since the leak rates were measured on a single, minimum gage skin. The CCM shell is either two skins that are at least as thick as the minimum gage skin or a solid laminate that is more than twice as thick. Potential leak sources that were not specifically quantified in this study include the impact sites, three large core debonded zones from the test-to-failure, and areas of undetected damage related to the previous test program. In addition, the coupon tests were performed on pristine laminates, while the test article had an extensive load history.

In summary, the CCM permeability characterization concluded that a pressurized composite vehicle could meet the maximum leakage rate requirements without a liner using improved process controls during manufacturing. However, a liner greatly limits the amount of leakage caused by an impact. A brushable or sprayable coating should be pursued as an alternative to a manually applied appliqué film in applications that involve complex curvatures or other geometric complexities. In addition, process control techniques and improved designs for leakage should be considered for bolted penetrations to reduce variability.

5.0 Assessment Plan

This assessment was the result of the findings and NESC recommendations contained in the NESC Technical Assessment Report for the Composite Crew Module: Primary Structure [ref. 1]. The CCM program was designed to provide NASA engineers with design, build, and test experience, with the expectation that future manned vehicles would utilize composites as pressure-containing primary structures. One of the conclusions from reference 1 was that there was a lack of understanding regarding the ability for composite pressure shells to contain consumable gases, which posed a technical risk relative to the use of a metallic design. At a coupon level, the pristine permeability of carbon-fiber-reinforced toughened epoxy laminates is sufficient in meeting vehicle-level requirements of 0.01 kg/day at 14.7 psid (760 mmHg) [refs. 2 and 6]. In addition, CCM and subsequent investigations demonstrated that composite permeability is sufficiently low under design limit strains [refs. 6 and 7]. However, several outstanding risks remain regarding the permeability/leakage of full-scale composite pressurized structures, particularly after impact damage. This assessment attempted to quantify the CCM permeability/leakage in its current as-manufactured and tested state.

6.0 Problem Description and Scope

The goal of the CCM leak characterization assessment was to quantify leakage/permeability of the entire vehicle and of specific features such as bolted fittings, out-of-autoclave joints, and potted inserts. This assessment was performed after the CCM program completed an extensive test program that included ultimate loads applied to fittings, extensive impact damage, life cycling, and, finally, pressurization to failure (3.5 times the pressure limit). The CCM enabled the quantification of the variability associated with design features to better understand the process control aspects. In addition to examining bolted penetrations, the investigation quantified permeability from coupons with and without impacts and then demonstrated that a sheet appliqué liner solution could mitigate the leakage caused by impact. Following that demonstration, the liner solution was partially installed on the CCM to examine the feasibility of a full-scale implementation.

7.0 Testing

7.1 Leak Measurements

All leak measurements were performed using a helium mass spectrometer. Using this technique, one surface is in a helium environment, while a vacuum attached to the mass spectrometer is located on the opposite surface. The vacuum system carries the helium into the analyzer cell to determine the helium concentration. This technique is commonly used in many industries, including the aerospace industry, to locate and measure small leaks. For the Constellation Program (CxP), the molecular size of the leak test fluid is required be equal to or less than the molecular size of the operational fluid [ref. 8]. However, molecules of nitrogen and oxygen are 2 to 3 orders of magnitude larger than helium atoms. Consequently, the conversion from a helium flow rate to an air flow rate can be complex and depends on many factors associated with the medium, gas, and test conditions. For simple viscous flow, the flow rates between helium and air should be similar. However, for flows through dense polymeric membranes, the permeabilities to helium and air/nitrogen have been reported to differ by a factor up to 600 [ref. 5]. The use of helium results in conservative conclusions (leakage rate of air will be less than for helium) for leakage/permeability measurements. For the CCM assessment, the differences in leakage rates between helium and air were not investigated and may vary depending on the transport mechanisms and materials involved at specific locations. All measured leak rates are reported in sccm of helium. In some cases (e.g., permeability measurements), the total leak rate was divided by the test area to obtain a leak rate per unit area. The flow rates in sccm were not converted to English units such as standard cubic feet per minute (scfm) since the measurements were made in sccm and are commonly reported for leak rates.

7.2 Coupon Testing

To examine leakage after impact, coupon testing was focused on the CCM minimum gage sandwich skin, which is composed of four plies of CCM-SPEC-001, Type II material [ref. 9]. While the minimum gage solid laminate was eight plies of Type II material, the four-ply laminate for sandwich skin served as a bounding case for the CCM shell where a penetration or splice was not present. The NESC team was able to estimate an expected leak rate for the CCM acreage (no penetration or damage) for full-scale testing based on the coupon tests.

A four-ply laminate billet (approximately 30 inches × 30 inches), was manufactured according to the Type I process specified in reference 10. The layup is given in Table 7.2-1 and mimics the full-body plies in the pre-cured CCM inner mold line (IML) skin.

Table 7.2-1. Coupon Billet Layup

Ply Number	Orientation	Warp Direction	**Material** [ref. 9]
1	45	Up	CCM-SPEC-001, Type II
2	0	Up	CCM-SPEC-001, Type II
3	0	Down	CCM-SPEC-001, Type II
4	45	Down	CCM-SPEC-001, Type II

From this laminate billet, 15 (7 inch × 7 inch) coupons were extracted for impact testing. Note that a 1-inch border around the billet was removed before extracting the coupons to eliminate edge bleed artifacts. Nine of the 15 coupons had appliqué film (i.e., 3M™ Paint Replacement Tape 5004) installed on the laminate tool side prior to testing. Table 7.2-2 summarizes the coupon matrix, where the letter denotes either composite only (C) or composite with film (F), and the number represents the impact energy (ft-lb).

Table 7.2-2. Coupon Test Matrix

Impact energy (ft-lb)	0	0.5	1.0	2.0	3.0	4.0	6.0	9.0	12.0
Four-ply laminate (C)	C0	C0.5	C1	C2	C3	C4			
Four-ply laminate w/ appliqué (F)	F0	F0.5	F1	F2	F3	F4	F6	F9	F12

Impacts were performed with a 1-inch-diameter hemispherical tip impacter on the four-ply laminates resting on an aluminum honeycomb core. The laminate bag side was in contact with the core; therefore, the impacts occurred on the tool side, consistent with an IML impact.

Each coupon was tested using the hood method, which consisted of a bell jar centered over the marked center/impact film area and connected to a helium mass spectrometer, as shown in Figures 7.2-1 and 7.2-2. Prior to each test series, the mass spectrometer system was calibrated to a known leak rate so that leak sensitivity could be established. The helium containment bag was centered on the opposite side (Figure 7.2-1) and a constant helium flow was injected into the bag. The mass spectrometer measured the helium flow rate through the sample. This rate was monitored until the mass spectrometer output stabilized.

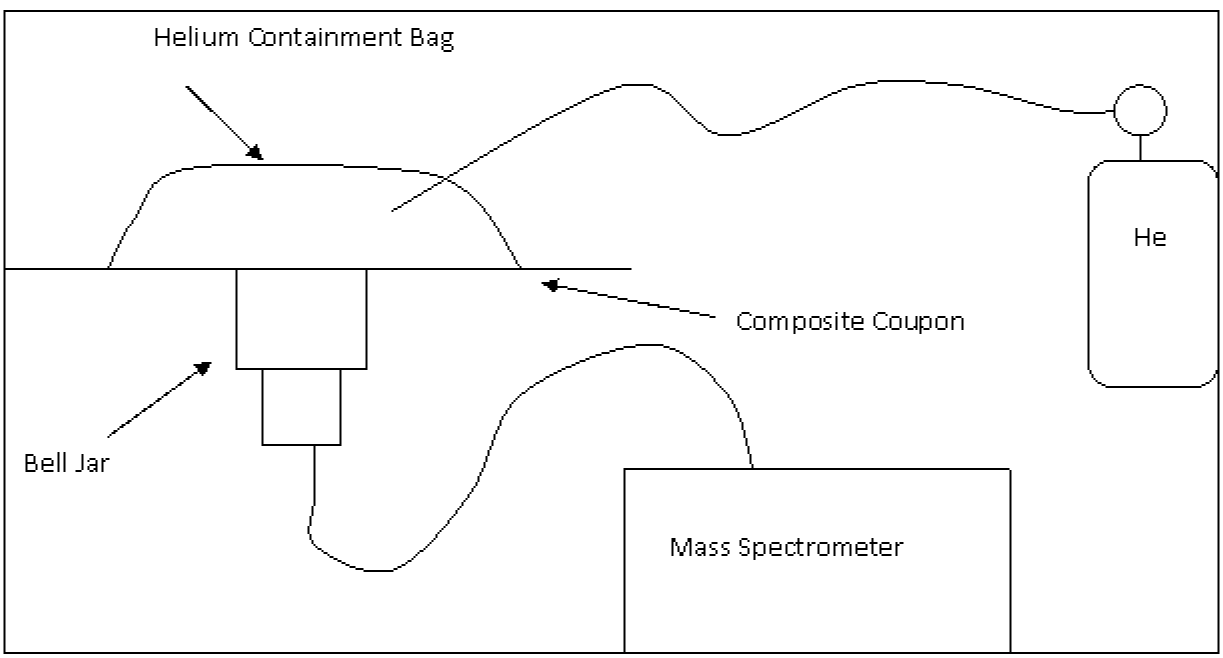

Figure 7.2-1. Coupon Leak Test Configuration Setup

Figure 7.2-2. 7-inch × 7-inch Coupon Leak Test (helium containment bag not shown)

The appliqué film, the laminate, and the laminate with appliqué film were leak tested. A summary of these results is given in Figure 7.2-3. The measurement area for these coupons was 4.9 square inches (in^2), and the measured leak rate was in sccs per unit area. The pressure differential was 1 atm. It should be noted that the deformation on these coupons from the pressure differential was not specifically constrained. The deformations may affect the leakage rates relative to an unstressed specimen.

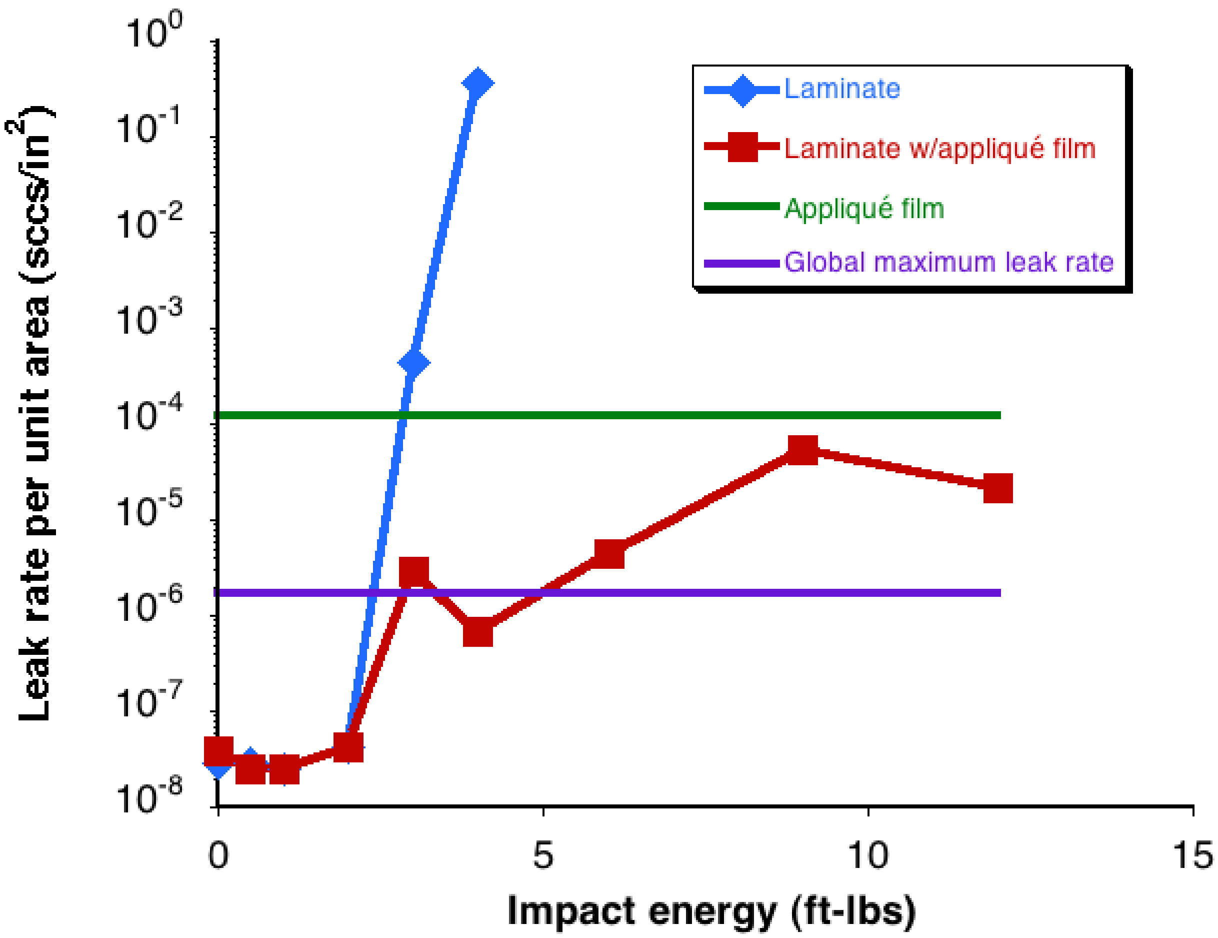

Figure 7.2-3. Effect of Appliqué Film and Impact Energy on the Leak Rate per Unit Area

Figure 7.2-3 contains two reference lines: a global maximum and appliqué film leak rates. The global leak rate is based on the CxP leak requirement (1e-1 sccs) divided by the CCM internal shell surface area (400 ft^2 = 57600 in^2). The figure shows the appliqué film is not sufficient to act as the sole permeability barrier on the entire 400 ft^2. However, as discussed earlier, the permeability of the film to air may be significantly improved relative to the helium used in the leak measurement.

Figure 7.2-3 shows a permeability that is largely unaffected by impacts less than 2 ft-lb. This result is consistent with what was reported using the nitrogen flow technique [ref. 2] (i.e., there appears to be an impact threshold at ~2 ft-lb). However, this technique provides quantification below the impact threshold. The leakage rises rapidly with impact energy so that even one impact of the laminate at low energy (<6 ft-lb) would produce a leak that is in excess of the global maximum leak rate. In contrast, the laminate with the appliqué film shows the same impact threshold, but rather than showing a continued rise versus impact energy, displays a shallow rise and appears to approach an asymptote below the leakage rate of the pure appliqué film.

If it is assumed that the CCM is composed of mostly pristine laminate and sandwich (i.e., impacts <2 ft-lb), with several higher energy impacts (i.e., below the barely detectable threshold, ~6 ft-lb) the question then would be: how many impacts could be tolerated before the global maximum leak rate is exceeded? One method to estimate the allowable impact area is equation 7.1-1:

$$R = (T - x)*(P) + x*(A) \qquad \text{(Eq. 7.1-1)}$$

Where:

R = CxP vehicle requirement = 1e-1 sccs
T = total shell area = 57,600 in^2
P = pristine minimum gage leak rate = 4e-8 sccs/in^2
A = appliqué leak rate = 1.4e-4 sccs/in^2
x = allowable impact area

The value for P was 4e-8 sccs/in^2, which was obtained for F0 (see Table 7.2-2). This conservative value was chosen because the measurement for C0 was ~25 percent lower than that for F0. These results illustrate the variability in the measurements.

Solving for x yields 700 in^2 (4.86 ft^2) of allowable impact area. This can be thought of in terms of the number of tool drops or hardware bumps that could go undetected. If it is assumed that each impact results in a damage zone equivalent to a 1-inch-diameter open hole in the laminate, then the allowable impact area can be translated into almost 900 impacts. However, this number would be adjusted based on the estimated leak rate of other technical features such as joints and penetrations.

A final result from the coupon test is a leak rate estimate for the composite shell, given as T*P, which assumes a shell absent of any penetrations. This approach yields 2.3e-3 sccs and serves as an order-of-magnitude estimate for the full-scale testing.

7.3 Full-scale Leak Testing

The goals of the full-scale testing were to determine the overall vehicle leak rate and to quantify the significant contributing features to the overall leak rate.

7.3.1 Test Article Condition and Preparation

The CCM was built as two halves, an upper and lower pressure shell, and is shown in Figure 7.3-1. It was manufactured in an autoclave on two different male tools: one for the upper and one for the lower. The two shells were joined using a double lap shear joint, with 12 different internal and external doublers: 1 for each longeron and 1 for the acreage between longerons. The splice cures were done under vacuum bag pressure with a purpose-built Kapton® heater. The major openings in the CCM included two side windows, two docking windows, a docking tunnel cover, and a main hatch. The cutouts were machined into the side of the pressure shell and fit with matching aluminum frames after cure.

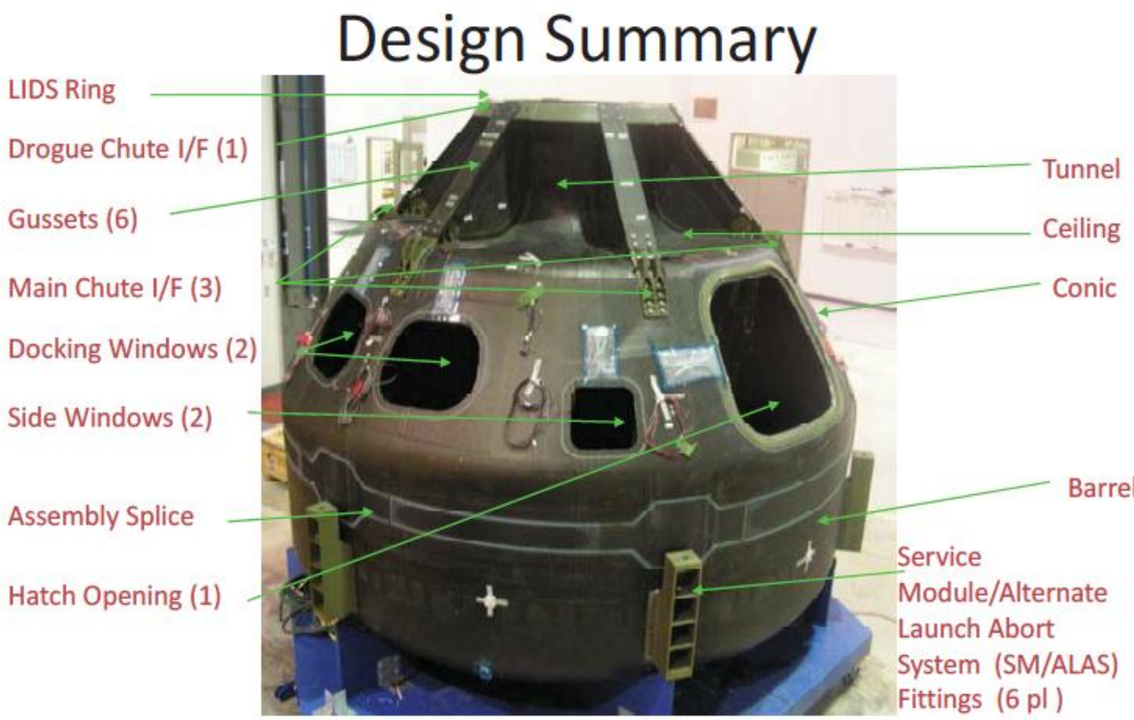

Figure 7.3-1. CCM Design Features

The CCM leak integrity approach was to use predominantly sandwich systems with unvented cores. The approach provided two barriers against through-thickness permeability: the IML skin and the outer mold line (OML) skin. The skins in the acreage areas consisted of four plies of fabric. It was shown that exceedingly low impact damage (less than 2 ft-lb) could cause leakage and would not be detectable visibly or with NDE techniques. Given the extensive subsystem integration both on the inside and the outside of the CCM, there was a possibility of undetected damage coincident on the inside and outside that could provide an undetected leak path. Some areas of solid laminates were also used in the design, specifically the tunnel, the backbone cap, and the pan down regions where metallic fittings such as parachute fittings and SM/ALAS interface fittings were bolted through the shell. Although higher impact energies are required to damage these regions, there is no redundancy to prevent leakage.

The full-scale CCM mechanical test program [ref. 3] consisted of 11 test conditions (Table 7.3-1). Each test condition consisted of a number of loading/unloading sequences leading up to the maximum intended load. Mechanical loads were applied to three types of metallic fittings

(SM/ALAS, parachute, and drogue chute) using straps attached to a hydraulic actuator while the CCM was pressurized. Mechanical loads were also applied to an external bracket attached to the sandwich structure using 20 two-piece aluminum inserts that were potted into the core and penetrated both skins.

Table 7.3-1. List of Individual Full-scale Tests

Test	Test Description	Number of Runs
1	Internal pressure to limit load	5
2	SM/ALAS fitting pull to limit load	4
3	Main parachute fitting to limit load	4
4	Internal pressure to ultimate load	6
5	External bracket/insert pull to ultimate load	2
6	Drogue chute to limit (no pressure)	1
7	Internal pressure to ultimate load after 6-ft-lb impacts	2
8	Main parachute fitting to ultimate after 6-ft-lb impacts	5
9	Four-lifetime cyclic test to 110%* limit load after 6 ft-lb	5**
10	Four-lifetime cyclic test to 110%* limit load after 26 ft-lb	4**
11	Internal pressure to failure using water	2

* The 110 percent corresponds to a life enhancement factor of 1.1 times the limit load. This is explained in more detail in the sections describing the cyclic tests.
** Here, one run corresponds to one lifetime, which is equal to 22 load/unload pressure cycles plus 9 load/unload main-parachute pull cycles.

A full-scale damage tolerance program was included in the test program to demonstrate that the CCM could meet the intent of current NASA requirements with minimal design changes. This included impacting the vehicle at 18 unique locations at 6 ft-lb, defined as the allowable threat level. Following these impacts, the test article was taken through two critical design ultimate load cases followed by life cycling (four lifetimes). Subsequently, five design details were impacted at critical threat levels (reliable detection or threshold energy of 26 ft-lb) and then tested to an additional four life times. In all cases, no detrimental growth of damage was shown.

Following the damage tolerance testing, the CCM was pressurized to failure using water. Water was used instead of air to limit the amount of damage that occurred at failure. A structural failure was detected at 54 psi, which was 3.5 times the pressure limit, and resulted in a small drop in pressure. After the CCM was drained, three large regions were discovered where the core debonded from the face sheets [ref. 4]. All three debonded regions were located on the upper pressure shell in the shoulder region between the conic and the ceiling. Of the six bays, the debonded regions were located in every other bay and covered most of the bay width.
Prior to leak testing, potential sources were identified that may have high leak rates (Table 7.3-2). The CCM frames, covers/hatches, and associated penetrations were not flight-like designs and, therefore, did not possess the necessary characteristics to minimize leakage. The NESC team had a concern that the single O-ring hatch seals would be insufficient to meet the

leak requirements for the testing. The splice was cured out of the autoclave using a prepreg that was formulated for an autoclave. The splice showed a 3- to 4-percent void content that made it a concern for leakage [ref. 6]. In addition, the potting between the two pressure shells was cracked extensively [ref. 4]. Given these two conditions, a leak path could be present between the IML and OML. Two bolted repairs were made to the lobed bottom of the lower pressure shell to attach the backbone after the pi joint failed to position correctly during a secondary bonding procedure. These repairs used 55 bolts to secure the backbone to the lobed bottom. After the CCM test-to-failure, water was observed on the OML in one of the repair areas.

Table 7.3-2. High-Potential Leak Sources

1	Cutout frames and seals
2	Covers for cutouts
3	Splice
4	Bolted repairs to lower pressure shell
5	Bolts for fittings (SM/ALAS, parachute)
6	Potted inserts (20)
7	Impact sites
8	Debonded bays

Each parachute and SM/ALAS fitting was installed using 14 0.25-inch bolts and 32 0.25-inch bolts, respectively. For fastener penetrations through the pressure shell, the design baselined the use of polysulfide sealant, wet installed with the fasteners, as the method for managing leak integrity around the penetrations. The polysulfide passed the NASA Test Standard 6001 for compatibility but presented an odor problem. It is believed that an alternative that preserves the advantages of polysulfide, without the obnoxious odor, could be identified and demonstrated if a composite pressure shell was adopted for a human spaceflight program.

Twenty potted inserts were installed into the pressure shell midway through the full-scale test program. Previously in the CCM test program, the leakage around these inserts was investigated at the coupon level using a bottled nitrogen test method [refs. 3 and 6]. No leakage was found on any of the 18 inserts in the test specimens prior to testing. After testing, one insert that had been tested to failure was found to leak through the hole used for the potting installation.

During the damage tolerance program, the CCM received nearly 30 impacts. While impact damage located on one side of a sandwich structure should not result in a through-shell leak, others locations may be susceptible to leakage from the damage. The CCM pressurization-to-failure test caused three large debonded regions to form in the shoulder-to-ceiling region. With the core no longer bonded to the face sheets, a leakage path could be created between any of the IML and OML skins in that region. Previously, a leak path could only be created by having damage on each end of a honeycomb cell. In addition, the strains that may have occurred in the skins during the test as a result of the failure are unknown.

Prior to leak testing, six distinct openings had to be sealed: one docking tunnel cover, one main entry hatch, two docking windows, and two side windows. The single O-ring hatch seals were not expected to be sufficient to meet the leak requirements; additional sealing was provided with vacuum putty. The putty was placed around the inside of the hatch seals just outside the O-rings. Additional putty was placed in gaps around the hatch IML once installed. Figures 7.3-2 through 7.3-5 show the various stages of the hatch installation.

Figure 7.3-2. Vacuum Sealant Tape (i.e., vacuum putty) Installed on a CCM Hatch Cover on the Outside Flange Next to the O-ring

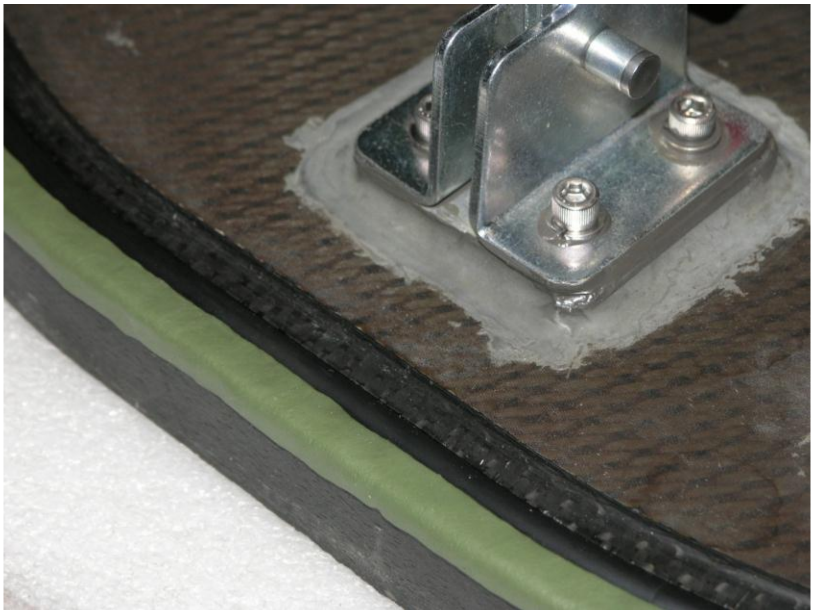

Figure 7.3-3. Close-up of the Vacuum Putty Placed Outside the Hatch Cover O-ring

Figure 7.3-4. Positioning the Main Hatch Cover

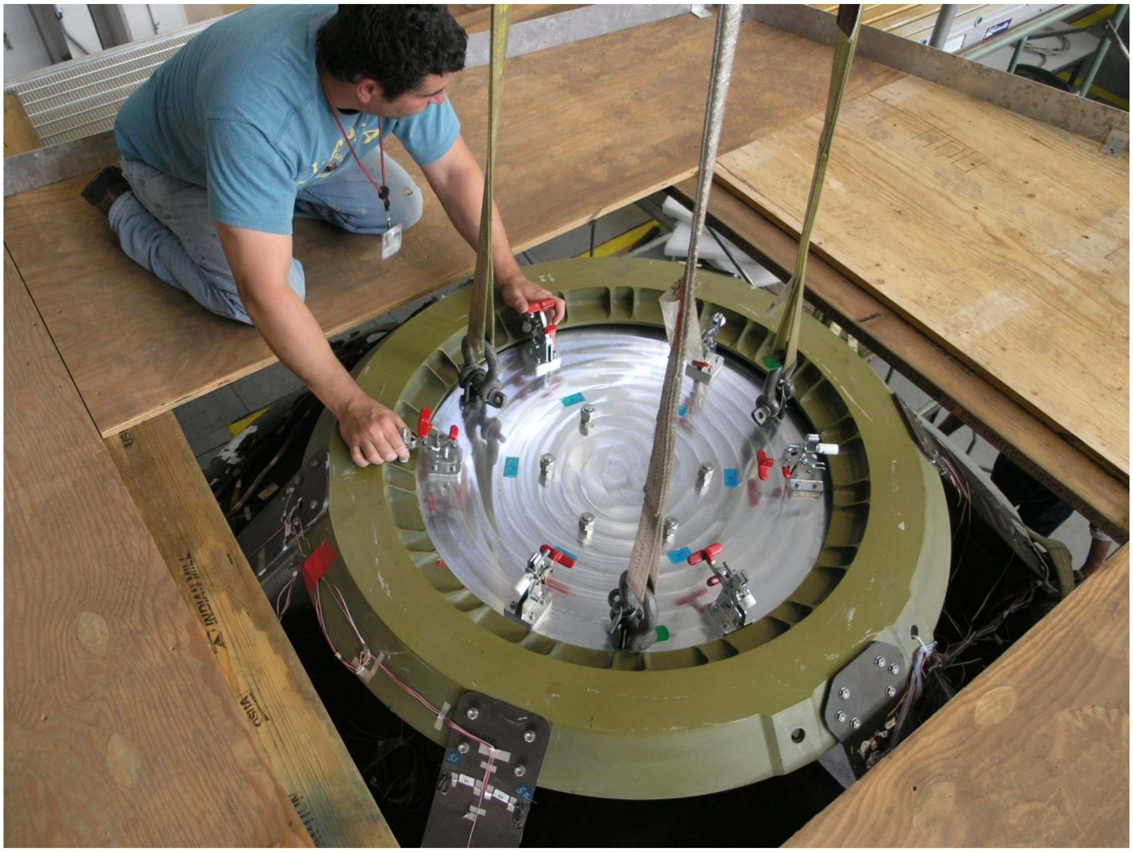

Figure 7.3.5. Docking Tunnel Hatch Cover Installation

7.3.2 Vacuum Bag Usage

To measure leak rates across a specific CCM feature, a hybrid leak test method was devised that involved placing an active vacuum bag on the feature's external surface and then measuring the helium migration while the CCM was pressurized. This technique was used to measure leak rates on the closed hatch covers and the permanently attached fittings (e.g., six parachute attach points and six SM/ALAS fittings). A schematic of the CCM in shown in Figure 7.3-6; each detail that was measured with an external vacuum bag is labeled in the figure.

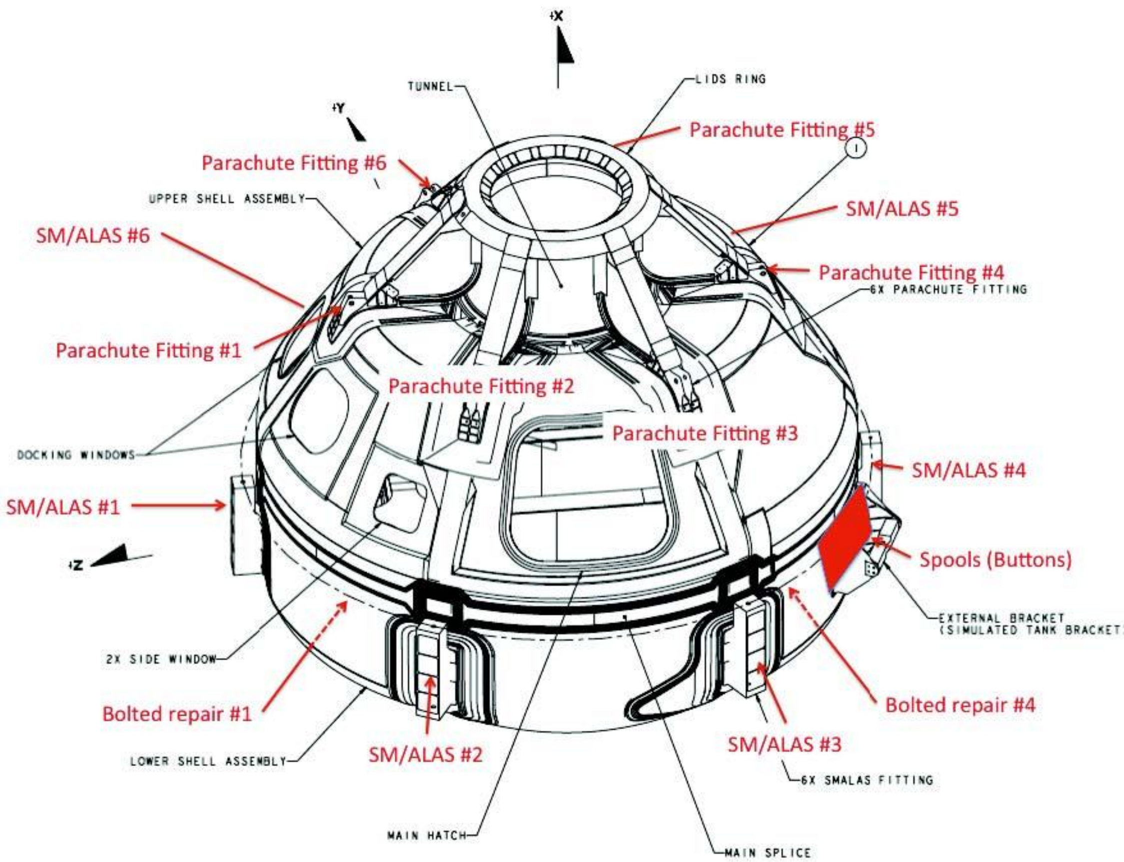

Figure 7.3-6. Schematic Illustrating the Features that were Measured Using the Vacuum Bag Technique (indicated in red)

Sealing the vacuum bags to the CCM exterior around the complex fittings was more labor intensive than initially envisioned. There were strain gages and wires that had to be removed or relocated. In addition, the outside surface was scrubbed/lightly abraded with Scotch-Brite™ pads and abrasive paper to remove paint and resin ridges. Figures 7.3-7 through 7.3-9 show the CCM vacuum bag installation.

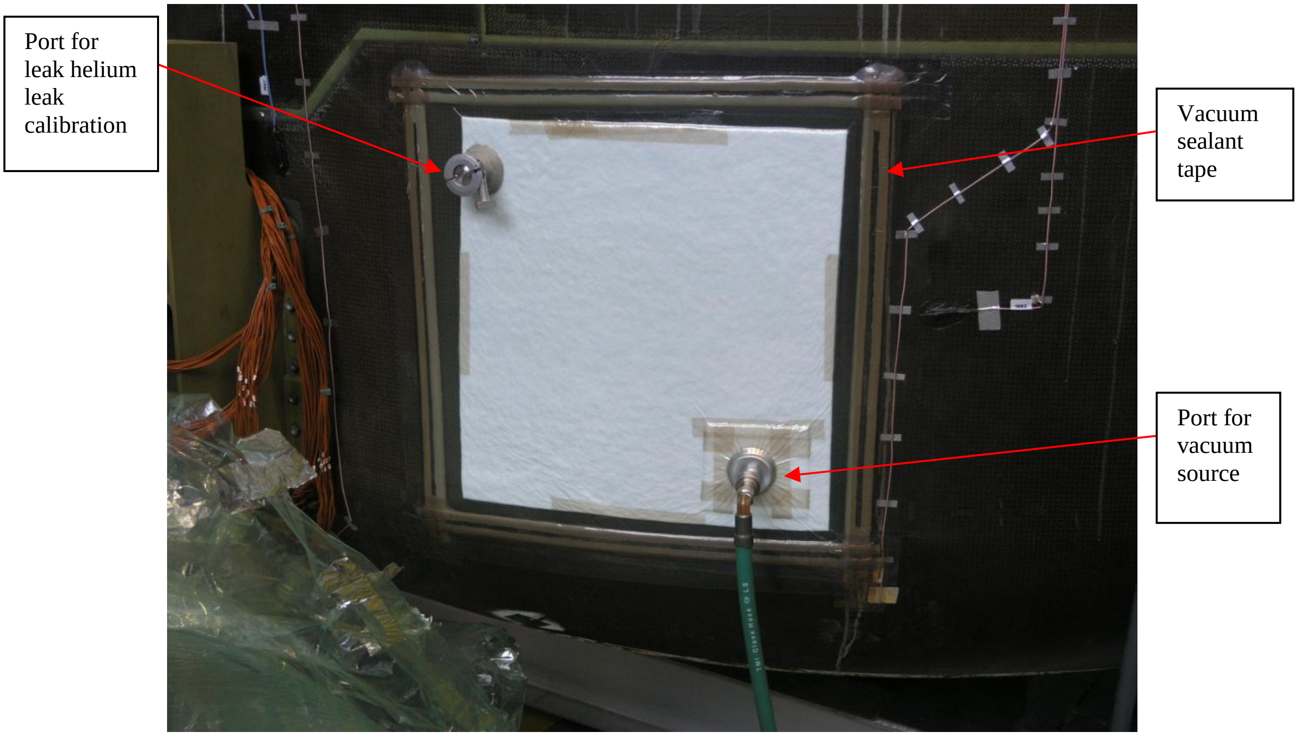

Figure 7.3-7. Example Vacuum Bag Installation

Figure 7.3-8. Vacuum Bag Installation around an SM/ALAS Fitting

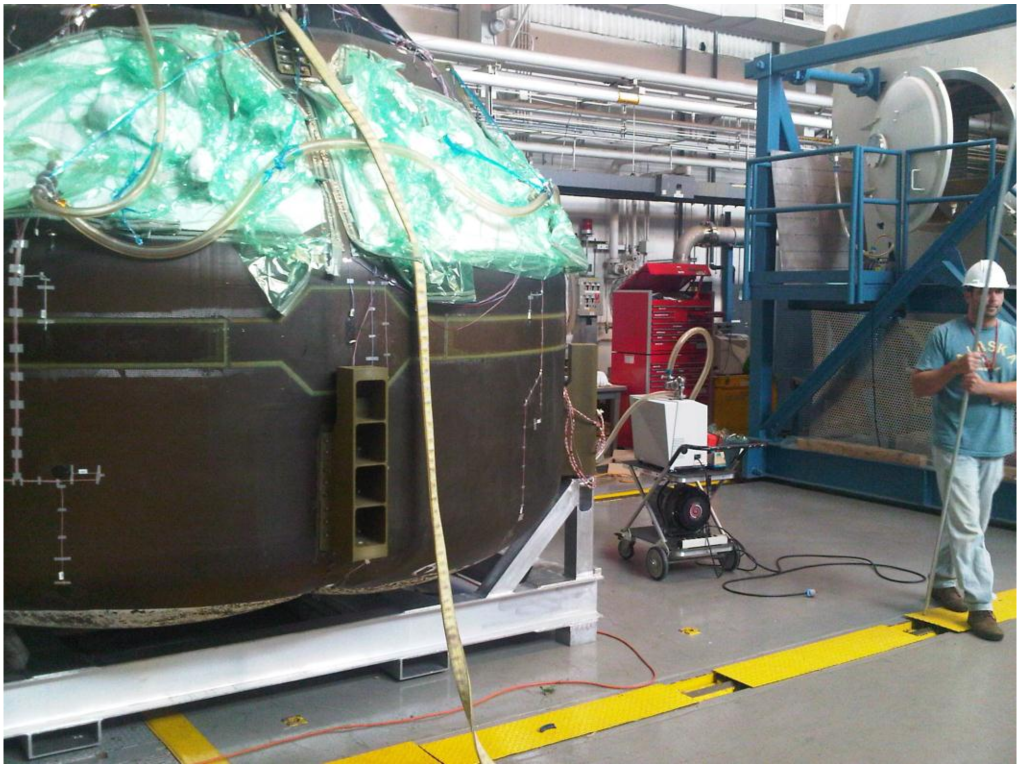

Figure 7.3-9. Installed Hatch Vacuum Bags Attached to a Mass Spectrometer

The details of the full-scale leak testing can be found in reference 11, with excerpts contained herein. All the leak rate tests were conducted in the Marshall Space Flight Center (MSFC) V-20 vacuum chamber located in Building 4619. The setup is shown in Figure 7.3-10.

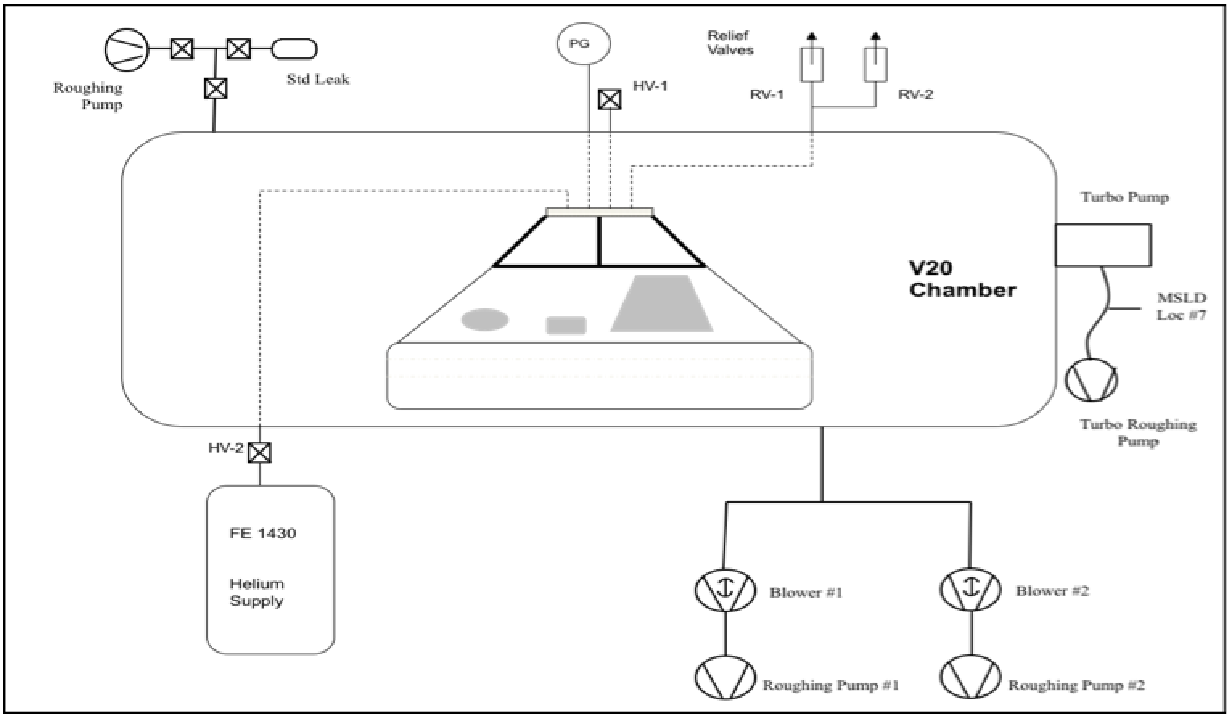

Figure 7.3-10. Schematic for Measuring the Total Leak Rate of the CCM

In all cases, helium leak rate measurements were conducted using a mass spectrometer. The tests were conducted in one of two scenarios: 1) the CCM was at 1 atm while the vacuum chamber was evacuated or 2) the CCM was at 2 atm while the chamber was at 1 atm. Figure 7.3-11 shows the CCM sitting outside the vacuum chamber.

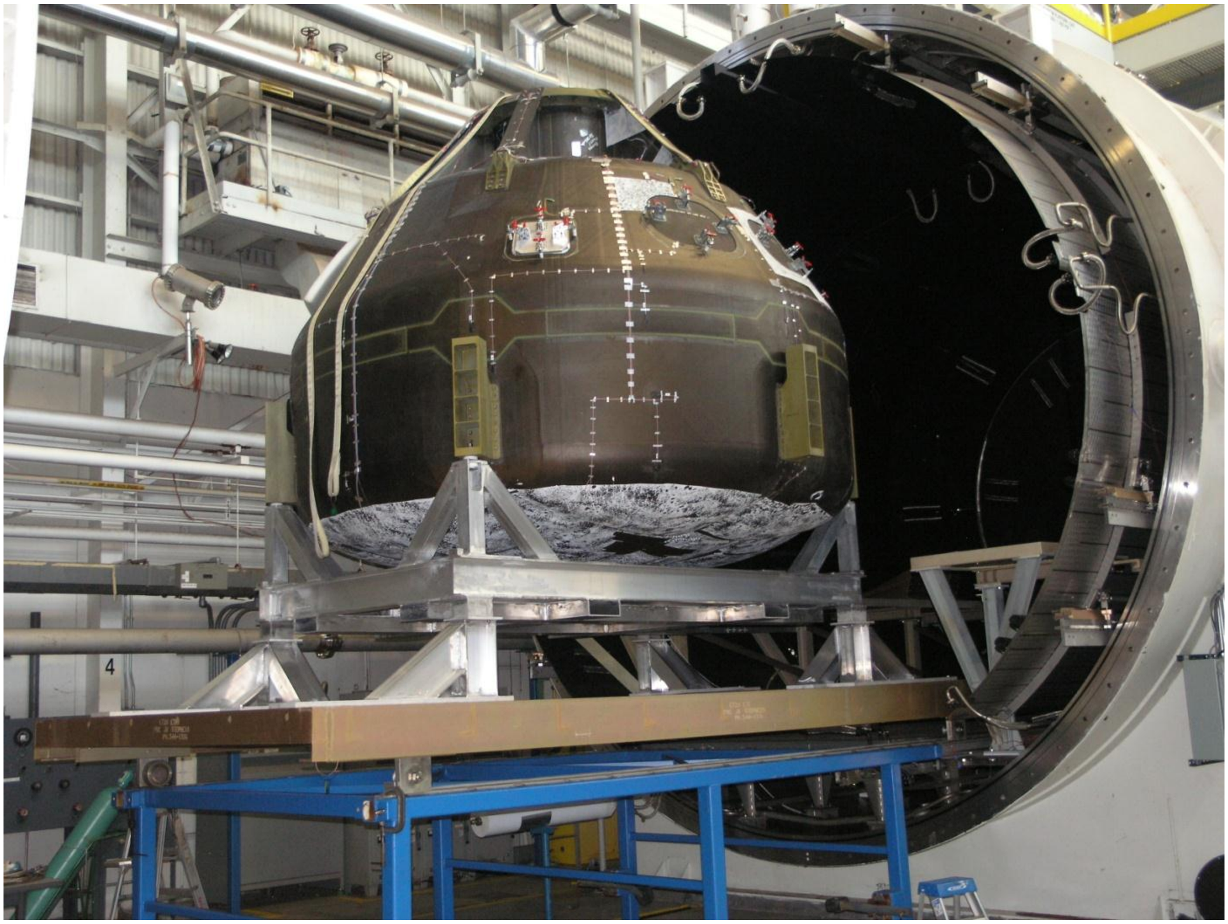

Figure 7.3-11. CCM Outside the V-20 Vacuum Chamber

In the first scenario, the mass spectrometer was connected to the vacuum chamber to measure the CCM total leak rate. In the second scenario, feature vacuum bags were evacuated and the helium leak rates were measured on each bag. The shell strains were maintained within the 1-atm limit pressure (CCM pressure – vacuum chamber pressure).

One of the complicated details of the vacuum bag measurements was that the leak rates were determined under a pressure differential of 2 atm (shell pressure – vacuum bag pressure = 2 atm), rather than the reference pressure differential of 1 atm. Since pressure differential directly impacts permeability/leak rates, the raw measurements needed to be scaled for comparison to the global measurements that were performed at a differential pressure of 1 atm. Many factors affect how the leak rates scale with pressure and include medium characteristics, gas properties, absolute pressure, flow behavior, and flow paths.

Poiseuille's equation for laminar flow of a compressible fluid is often used to scale flow rates during leak measurements [ref. 12]. Using this equation, the measured leak rates are reduced by

25 percent to coincide with the reference pressure condition of 1 atm on the interior and 0 atm on the exterior. In reference 6, leak rates were measured using nitrogen for an insert loaded to failure and were found to vary linearly with pressure. Also in this reference, leakage rates for impacted four-ply laminates (CCM minimum-gage skins) with various coatings were measured with impact damage. The leak rates were reduced by 44 to 60 percent when the pressure difference was reduced from 2 to 1 atm. Since Poiseuille's equation provided the most conservative estimate of flow reduction, the CCM feature measurements were reduced by 25 percent to the reference pressure differential.

In several instances, a high leak rate guided the NESC team to modify or improve a feature to demonstrate understanding of the leakage mechanism and to bring it within compliance at the vehicle level. In these instances, measurements were performed before and after the modifications to evaluate the modification effectiveness. The following modifications were made during testing:

1. Appliqué film installed over the out-of-autoclave splice and the upper eight inserts (full-scale leak test before and after).
2. Appliqué film installed over the lower eight spools (local leak test before and after).
3. Bolts removed from repair #1 and polysulfide added (local leak test before and after).
4. Full-scale leak test after modifications 1, 2, and 3.

7.3.3 3M™ 5004 Film Application

Any through penetrations are at risk of being a leak source during testing and use. The composite structure acreage will have a baseline permeability. The 3M™ 5004 film was suggested as a leak barrier. In practice, the 5004 film was easier to install on the CCM acreage, less so when applying to/over IML joints/fittings. FiberSIM software was used to aid in film placement and sizing. Figure 7.3-12 shows the 3M™ 5004 film (grey color) applied over inserts (spools) embedded in the CCM wall. The upper two rows of inserts were covered with 5004 film while the bottom three rows were not.

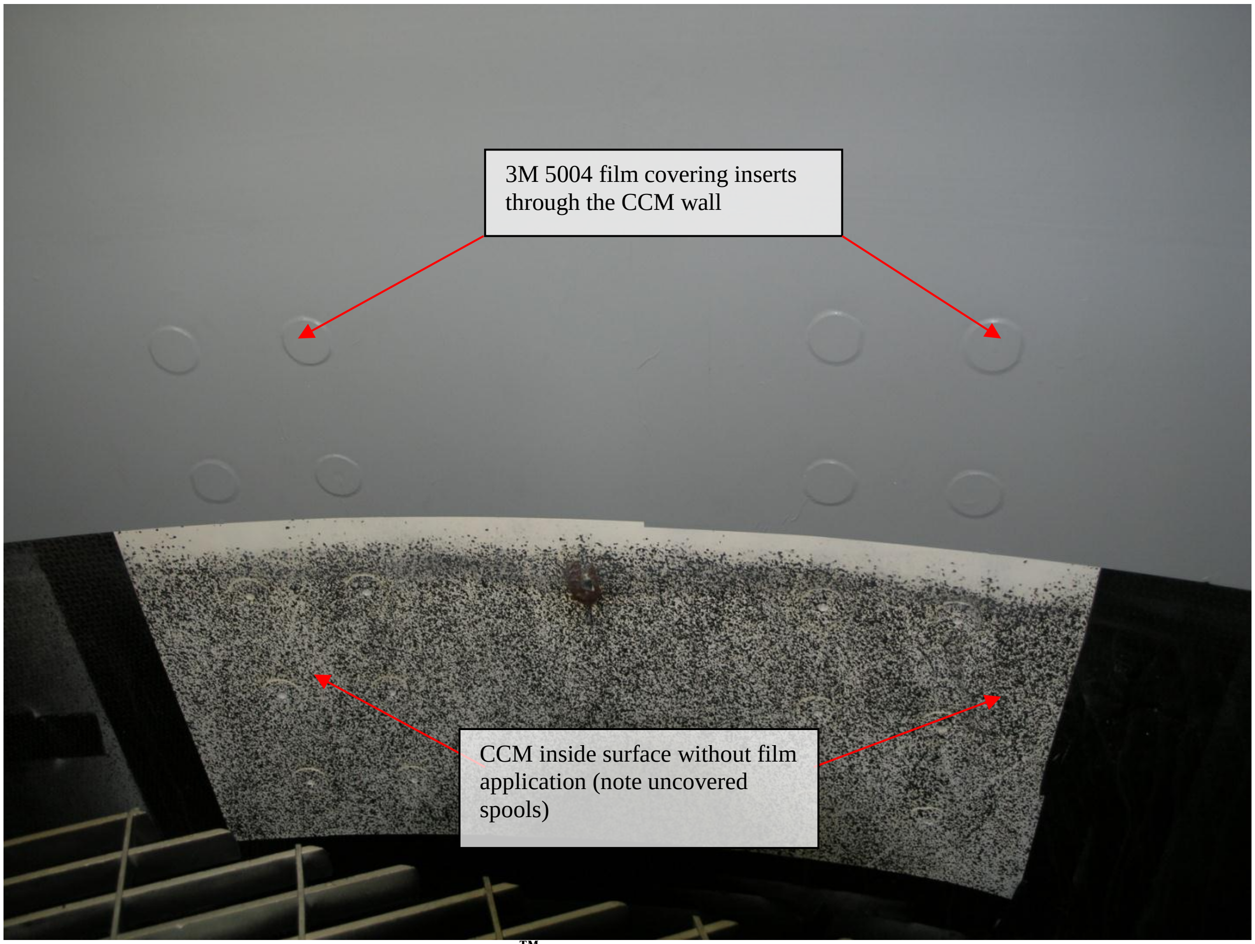

Figure 7.3-12. 3M™ 5004 Film Application over spools

Figures 7.3-13 through 7.3-17 show the various stages of the manual application of the 3M™ 5004 film.

Figure 7.3-13. Technician Starts to Apply the 3M™ 5004 Film around CCM IML Features

Figure 7.3-14. Technician Uses a Plastic Tool to Help Avoid Wrinkles and Bubbles

Figure 7.3-15. Technician Finalizes 3M™ 5004 Film Application

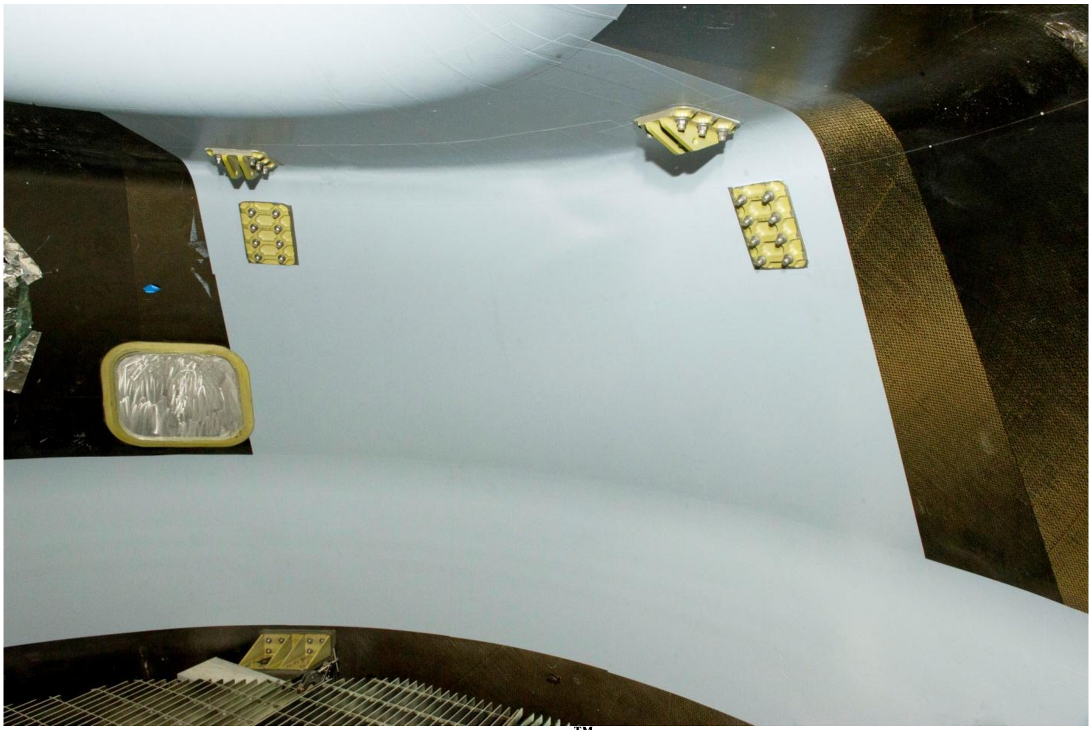

Figure 7.3-16. Completed 3M™ 5004 Film Application

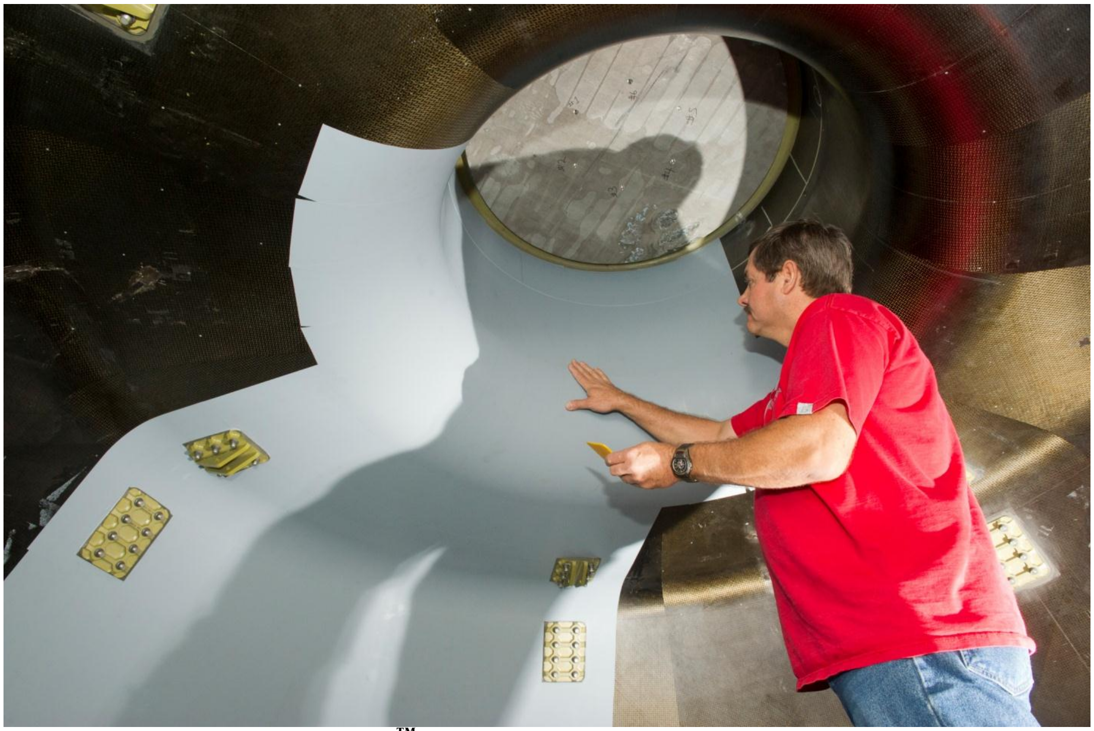

Figure 7.3-17. 3M™ 5004 Film Inspection in Docking Tunnel

7.3.4 Full-Scale System Leak Rate Results

Before addressing feature leak rates, a baseline test was conducted to obtain an overall leak rate before modifications. After 18 hours under vacuum, the stable leak rate was 0.35 sccs helium, which was 3.5 times the maximum allowed rate of 0.1 sccs for air. Additional sealant was applied to four windows and hatches, and the overall leak test was repeated. The leak rate after 65 hours was 0.88 sccs helium, which indicated that the additional sealing tape did not improve the leakage around these openings. An additional attempt was made to seal the openings externally with vacuum bags, but the bags detached turning testing. During this measurement, the leak rate was 0.57 sccs helium.

The techniques for sealing vacuum bags around the openings were further developed. To measure the leakage rate coming from the openings after the improvements, vacuum bags were installed on all the closeouts and connected to a common line. The CCM internal pressure was increased to 14.7 psig helium, but the chamber was not evacuated. The combined leak rate for all of the closeouts was 7e-5 sccs helium. As previously discussed, the local pressure differential around the vacuum bags was 2 atm. Consequently, the flow rates were reduced by 25 percent to correspond to a 1-atm pressure differential.

A similar method was used to determine the leakage rate of other CCM features. Bolted repair

1 (on lobed bottom) and the through-thickness inserts (spools) had leak rates that were of the same magnitude (i.e., 1e-1 sccs) as the overall vehicle requirement. Figure 7.3-18 shows the overall CCM leak rate, the insert leak rate, and the bolted repair leak rate on a time line as modifications were made to reduce the leak rates. Figure 7.3-18 also illustrates the effect of the improvements on the feature and the overall leak rate. Again, the leak rates from the feature tests were adjusted for the 2-atm pressure differential. After modification, these features had a leak rate that was lowered by at least a factor of 10. However, the rate for the bolted repair remained higher than the rates for the other bolted fittings, suggesting that this feature was not appropriately prepared for managing leakage. With the modifications, the overall leak rate was reduced to 1.1e-1 sccs, which is close to the maximum allowable leak rate of 1e-1 sccs.

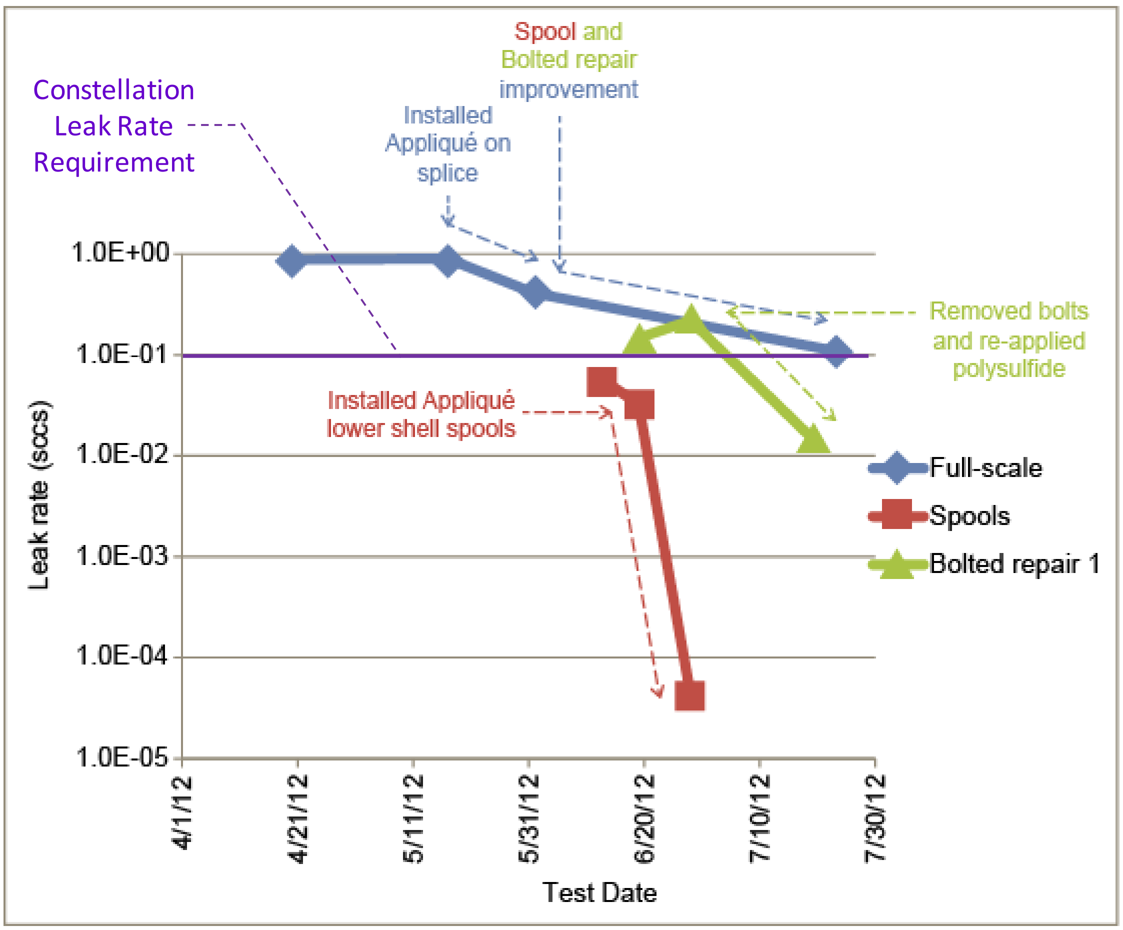

Figure 7.3-18. History of Leak Rate Measurements for Full-scale CCM and for Individual Features (modifications are identified)

As discussed, some local measurements were made multiple times, either to account for modifications or to examine repeatability. However, attention was focused on the last measurement that was made for each feature as this measurement incorporated the best practices for vacuum bagging.

Figure 7.3-19 shows the leak rate for the local features studied with the results adjusted for a 2-atm pressure differential. Four features are noted as being significant contributors: the bolted repairs and SM/ALAS fittings #1 and #2. These features are out-of-family with the other bolted fittings and are significant contributors to the overall vehicle leak rate. It is clear from the remainder of the fittings that significant improvement in the leak rate of a bolted fitting is possible through the adoption of sealing method process improvements.

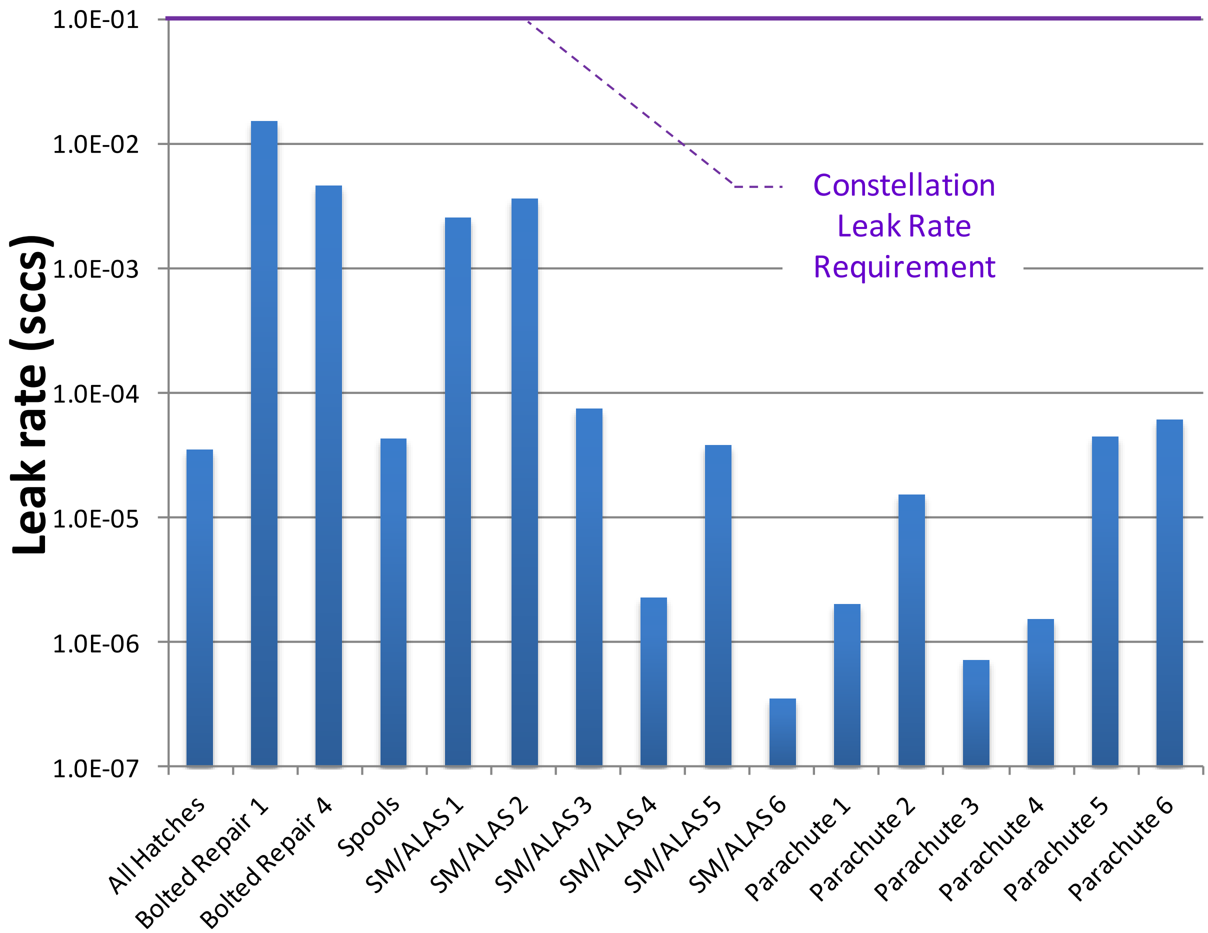

Figure 7.3-19. Local Leak Rate versus Feature

The magnitude of the leakage from the composite shell was estimated by subtracting the local leak rates, summarized in Figure 7.3-19, from the final global leak rate of 1.1e-1 sccs. The shell leak rate is estimated at 8.4e-2 sccs. Figure 7.3-20 shows a pie chart where the global leak rate of 1.1e-1 sccs is divided into the contributing leak factors. While this figure shows that the shell is the largest contributor to the overall leak rate, it suggests there may be a discrete leak source on the shell (i.e., the scaling of the coupon result suggests that this rate should be much lower). Possible sources for discrete leaks are the impact sites from the damage tolerance test investigation [ref. 3] that were not covered with appliqué film, the damage created by the test-to-failure, and other undetected regions of damage.

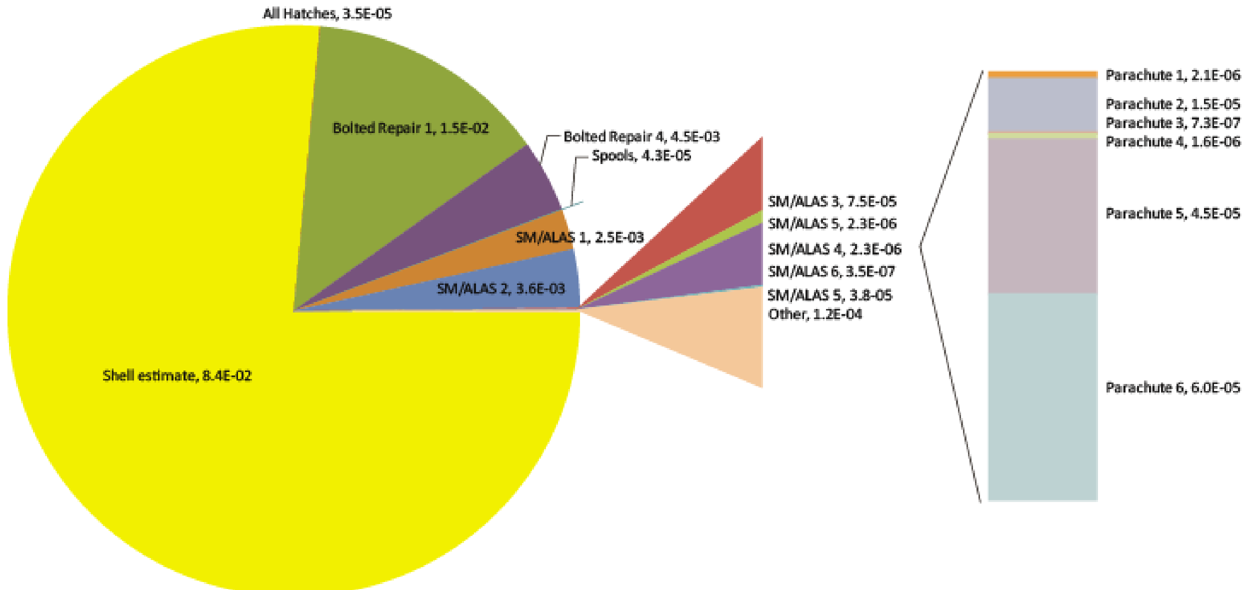

Figure 7.3-20. Global Leak Rate of 1.1e-1 sccs (separated by contribution)

8.0 Findings and NESC Recommendations

8.1 Findings

The following findings were identified:

F-1. The overall volumetric leak rate of the CCM, measured with helium, was 10 percent greater than the CxP system leak rate requirement of 1 kg/day of air. With improved process controls while sealing around penetrations, a non-lined pressurized vehicle made from composite materials could meet program leakage requirements.

F-2. The leak test investigation was able to demonstrate at a coupon level that a polymeric liner (appliqué film) is capable of mitigating leakage after impact damage.

F-3. The appliqué film appeared to reduce the leak rate associated with the splice and other acreage features such as through inserts, although not enough data were collected to establish the statistical significance of this change.

F-4. Manual application of the appliqué film on large complex or concave surfaces posed installation challenges; thus, a brushable or sprayable coating would be preferred from an ease-of-installation perspective.

F-5. The highest leak rates were associated with through-shell fasteners. However, the bolted fitting sealing method utilized was able to get to sufficiently low leak rates utilized per fitting, but it was not robust (i.e., similar fittings showed large variability in performance).

F-6. The observed discrepancy in the leak rate estimates using the coupon data and subtracting the critical feature leak rates from the global leak rate suggests there were significant features or defects that did not get quantified during the feature testing.

8.2 NESC Recommendations

The following NESC recommendations were identified and directed toward the Exploration Mission Directorate:

R-1. A brushable or sprayable coating should be pursued as an alternative to the appliqué film in applications that involve complex curvatures or other geometric complexities. ***(F-4)***

R-2. Process control techniques and improved designs for leakage should be considered for bolted penetrations to reduce variability. ***(F-5)***

9.0 Alternate Viewpoint

There were no alternate viewpoints identified by the NESC team or the NRB quorum during the course of this assessment.

10.0 Other Deliverables

No unique hardware, software, or data packages, outside those contained in this report, were disseminated to other parties outside this assessment.

11.0 Lessons Learned

No applicable lessons learned were identified for entry into the NASA Lessons Learned Information System (LLIS) as a result of this assessment.

12.0 Recommendations for NASA Standards and Specifications

No recommendations for NASA standards and specifications were identified as a result of this assessment.

13.0 Definition of Terms

Corrective Actions	Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.
Finding	A relevant factual conclusion and/or issue that is within the assessment scope and that the team has rigorously based on data from their independent analyses, tests, inspections, and/or reviews of technical documentation.
Lessons Learned	Knowledge, understanding, or conclusive insight gained by experience that may benefit other current or future NASA programs and projects. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure.
Observation	A noteworthy fact, issue, and/or risk, which may not be directly within the assessment scope, but could generate a separate issue or concern if not addressed. Alternatively, an observation can be a positive acknowledgement of a Center/Program/Project/Organization's operational structure, tools, and/or support provided.
Problem	The subject of the independent technical assessment.
Proximate Cause	The event(s) that occurred, including any condition(s) that existed immediately before the undesired outcome, directly resulted in its occurrence and, if eliminated or modified, would have prevented the undesired outcome.
Recommendation	A proposed measurable stakeholder action directly supported by specific Finding(s) and/or Observation(s) that will correct or mitigate an identified issue or risk.
Root Cause	One of multiple factors (events, conditions, or organizational factors) that contributed to or created the proximate cause and subsequent undesired outcome and, if eliminated or modified, would have prevented the undesired outcome. Typically, multiple root causes contribute to an undesired outcome.
Supporting Narrative	A paragraph, or section, in an NESC final report that provides the detailed explanation of a succinctly worded finding or observation. For example, the logical deduction that led to a finding or observation; descriptions of assumptions, exceptions, clarifications, and boundary conditions. Avoid squeezing all of this information into a finding or observation

14.0 Acronyms List

ALAS	Alternate Launch Abort System
atm	atmosphere
C	composite
CCM	Composite Crew Module
COTS	Commercial Orbital Transportation Services
CxP	Constellation Program
F	film
ft-lb	foot-pound
GSFC	Goddard Space Flight Center
IML	Inner Mold Line
ISS	International Space Station
kg	kilogram
LaRC	Langley Research Center
mmHg	millimeters of mercury
MSFC	Marshall Space Flight Center
NESC	NASA Engineering and Safety Center
NRB	NESC Review Board
OML	Outer Mold Line
psid	pounds per square inch differential
sccs	standard cubic centimeters per second
scfm	standard cubic feet per minute
SM	Service Module

15.0 References

1. "Composite Crew Module: Primary Structure," NESC-RP-06-019, also referenced as NASA/TM–2011-217185, November 2011.
2. "The International Space Station (ISS) to Commercial Orbital Transportation Services (COTS) Interface Requirements Document," Rev. C, SSP 50808, November 2011.
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11. Boeing Final Leak Test Report for NESC CCM, NDT12-00020REP.
12. Nondestructive Testing Handbook, Third Edition: Volume 1, Leak Testing, The American Society of Nondestructive Testing, 1997.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
In January 2007, the NASA Administrator chartered the NASA Engineering and Safety Center (NESC) to form an Agency team to design and build a composite crew module in 18 months in order to gain hands-on experience in anticipation that future exploration systems may be made of composite materials. One of the conclusions from this Composite Crew Module Primary Structure assessment was that there was a lack of understanding regarding the ability for composite pressure shells to contain consumable gases, which posed a technical risk relative to the use of a metallic design. After the completion of the Composite Crew Module test program, the test article was used in a new program to assess the overall leakage/permeability and identify specific features associated with high leak rates. This document contains the outcome of the leakage assessment.

15. SUBJECT TERMS
Composite Crew Module; NASA Engineering and Safety Center; Service Module; Alternate Launch Abort System; International Space Station

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