SOFI/Substrate integrity testing for cryogenic propellant tanks at extreme thermal gradient conditions.

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Abstract. Liquid propellant tank insulation for space flight requires low weight as well as high insulation factors. Use of Spray-On Foam Insulation (SOFI) is an accepted, cost effective technique for insulating a single wall cryogenic propellant tank and has been used extensively throughout the aerospace industry. Determining the bond integrity of the SOFI to the metallic substrate as well as its ability to withstand the in-service strains, both mechanical and thermal, is critical to the longevity of the insulation. This determination has previously been performed using highly volatile, explosive cryogens, which increases the test costs enormously, as well as greatly increasing the risk to both equipment and personnel.

CTD has developed a new test system, based on a previous NASA test that simulates the mechanical and thermal strains associated with filling a large fuel tank with a cryogen. The test enables a relatively small SOFI/substrate sample to be monitored for any deformations, delaminations, or disjunctures during the cooling and mechanical straining process of the substrate, and enables the concurrent application of thermal and physical strains to two specimens at the same time. The thermal strains are applied by cooling the substrate to the desired cryogen temperature (from 4 K to 250 K) while maintaining the outside surface of the SOFI foam at ambient conditions.

Multiple temperature monitoring points are exercised to ensure even cooling across the substrate, while at the same time, surface temperatures of the SOFI can be monitored to determine the heat flow. The system also allows for direct measurement of the strains in the substrate during the test.

The test system as well as test data from testing at 20 K, for liquid Hydrogen simulation, will be discussed.

1. Introduction
Maintaining the Thermal Protection System (TPS), which includes the SOFI, integrity through the thermal, acceleration and frictional variations of launch and pre-launch is challenging. The loss of TPS foam during the shuttle launches, shown in Figure 1, eventually resulted in tragedy, making stress testing of the bond integrity between the tank substrate and the TPS, and between the multiple layers of TPS themselves of greater importance.
Figure 1 Loss of TPS foam from external tank caused damage to the Space Shuttle during launch. 

The test method described here, called the Cryoflex Test, relies on both mechanical strain loading of the tank wall substrate as well as concurrent thermal strain loading of the substrate and the SOFI interface. NASA historically has performed thermo-mechanical testing on these types of systems using liquid Hydrogen. However, the use of liquid Hydrogen is extremely hazardous, which results in a more complex and expensive test that must be conducted and monitored remotely. The lack of direct access to the test specimen during the test is a detriment to evaluating material performance during the test since real time observation of the SOFI is more difficult if done through remote video feeds.

Due to increased interest by various commercial space companies in evaluating the cryogenic performance of SOFI for cryogenic fuel tanks, CTD developed a Cryoflex test fixture to address this commercial testing need. Use of flammable or explosive cryogens was not an option for both economic and safety reasons.

2. Test Description

The Cryoflex itself is designed to apply thermal stresses to the substrate, the interface between the insulation and the substrate and to the insulation to simulate the filling of the cryogenic tank with the cryogen. Once the thermal stresses have been applied, additional mechanical stresses are applied that simulate the pressurization of the tank. The initial design called for testing a single part at one time, cooling the substrate material to 20 K, while keeping the TPS foam material exposed to ambient atmospheric conditions.

Based on past NASA Cryoflex history and commercial customer input, specimen dimensions for the substrate insulation and the test fixturing was designed. The specimens were comprised of two proprietary insulating SOFI layers knit together with a proprietary ablative SOFI layer. The substrate was a nominal 46 cm x 5 cm x 3.5 cm thick 2024 aluminum alloy. The substrates had a 36 cm gage section with a reduced width of 3.8 cm with 5 bolt holes on each end to enable gripping for mechanical loading. The SOFI foam layers were nominally 25 mm total thickness with a 12 mm ablative layer on top and a tapered end profile leaving a 30 cm long full thickness foam layer. Figure 2 shows representative Cryoflex test specimens.
3. Cryoflex Test Fixture Design

The primary challenges that needed to be overcome to perform these tests included:
- How to cool the substrate of the specimen below 20 K while keeping the outer surface of the SOFI insulation at ambient conditions;
- How to cool a flat plate substrate to sub-liquid nitrogen (LN$_2$) temperatures without use of a vacuum jacketed chamber as a thermal break;
- How to monitor the applied strain on the flat substrate while actively cooling the substrate;
- How to ensure even cooling of the substrate while monitoring the temperature.

Potential cooling systems that were investigated included cryocoolers, direct LHe contact and use of a flow-through cooling block. Following a review of options, the test parameters were modified to accommodate the testing of two specimens at one time, as shown in Figure 3. Redesign of the concept to this configuration made the definition of the cooling block and grip system more amenable to even cooling and reduced the need for additional insulation and block retention techniques. It also made for a more efficient test since two specimens could be tested at the same time.
cooling block, acting as a cold shroud for the cooling portion of the block. These exhaust channels were subsequently insulated using commercially available foam cut to fit tightly at room temperature.

The cooling block was minimally relieved to allow strain gages to be mounted at the center of the gage section to monitor the applied strain within the substrate. Pocket relief for two silicon diodes were also created in order to acquire thermal verification of each of the substrate temperatures throughout the testing.

Test specimens were length matched in pairs to achieve more uniform loading within the fixture. Each specimen was gripped independently, ensuring that similar strains could be applied to each specimen. The cooling block was clamped into place by the substrates, cooling the gage sections and utilizing an insulated contact patch to the grip portions of the test fixture, to decrease parasitic losses.

The fixture grips were designed to hold two specimens back to back with enough room between them for the cooling block to remain in intimate contact with both specimens at 20 K. The Cryoflex mechanical test system was designed to fit CTD’s 450 kN Servo-Hydraulic load frame, which is capable of acquiring up to 10 channels of strain, 10 channels of thermal input, load and displacement at speeds of up to 100 Hz.

4. Cryoflex Test Procedure

The specimen assembly was installed into the cryostat, the exposed cooling block sides were insulated, and the temperature diode and strain gage functions checked. The specimens were then pre-loaded to 225 N and cooled to 50 K using Liquid Helium. The cooldown from 50 K to 20 K (-5 K, +0 K) was performed as quickly as possible, usually within 105 seconds, to simulate the thermal strains encountered with a quick fill scenario for an actual cryogenic fuel tank. When the specimen temperature is within the specified range (20 K, -5, +0 K), the loading portion of the test was started. The specimens saw an average of -0.32% thermal strain during the cool down phase from 295 K to 20 K, which was zeroed out prior to the mechanical stress portion of the test. The test configuration during cool down is shown in Figure 4.
After the initial cool-down, the aluminum substrates of the specimens were kept within the test temperature range (20 K ±0, -5 K) for the duration of the mission cycle. Each “mission cycle” typically consists of mechanically loading the two specimens in tension to an initial load of approximately 29 kN with a force hold for 60 seconds prior to being further loaded up to approximately 58 kN and then unloaded to 5.8 kN to end the load cycle. All loading and unloading was performed at a rate of around 4 kN/s. At the 58 kN load level, each specimen substrate saw an average strain of 0.21% strain at a stress of approximately 213 MPa. A typical load cycle might be performed up to 20 times, making up a single “mission cycle” depending on the expected fill/drain cycles of the tank being studied. The example shown in Figure 5 included twelve separate mission cycles that were performed on the same two specimens.
The failure criteria for the SOFI insulation is set by the customer and based on their application and expected failure modes. Failure criteria typically used includes:

1) A crack in the foam perpendicular to the substrate connected to a delamination at the substrate bond line in excess of 7.6 mm.
2) 2 or more cracks separated by less than 25 mm
3) 2 or more cracks with delaminations, where the sum of the delaminations length is greater than 20% of the distance between the two cracks
4) One single delamination at the bondline in excess of 15mm with no cracks

5. Test Results

SOFI surface temperatures were monitored at specified intervals throughout each set of mission cycles through contact measurements within a 12 mm diameter location mid-height on the ablative surface. In the example shown in Figure 6, the lowest temperature recorded on the ablative layer was 190 K, well above the condensation temperature of Oxygen. The average ablative layer temperature seen was 226 K, though the temperature in close proximity to the cracks tended to be lower due to atmospheric condensation in the localized area.
Usually, each crack formation is accompanied by an acoustic emission, and is able to be immediately located and identified. At the test temperature, the cracks are visible to the naked eye both along the width of the insulation and along the edge of the ablative layer. These same cracks are not visible after active cooling had ended, indicating the necessity of having first hand observance during this type of test. Each of the cracks within the foams was additionally identifiable by the accumulation of frost during the warm up period as shown in Figure 6.

![Figure 6: Crack in Cryoflex specimen insulation at 20 K](image)

In the test example shown in Figure 6, over the course of one set of twelve mission cycles, only three cracks presented themselves, one on each specimen during mission cycle #2, and a third one during mission cycle #11. Most cracks initially formed through the harder, denser ablative material and during the following cycles they propagated through the SOFI to the substrate. Some cracks which appear during the later cycles went through the foam and on to the substrate immediately, but almost all cracks propagated through both layers of foam (ablative and insulation) to the substrate.

Since the cooling of the specimens is produced through cyclic flow of LHe, observation of the SOFI foam during and immediately after the testing is quite easy. Through visual observation, most cracks are visible while cooling of the specimen is actively occurring. However, once active cooling is ceased and the specimen starts to warm up, thus expanding, the cracks close up and are very hard to distinguish. Therefore, during the test, crack locations are marked through the use of ink marks made at crack onset. Additionally, on warmup, the knit line between the two layers of insulation will usually show signs of frost buildup after cracks have propagated through them, a possible indication of higher thermal transmission at that interface than elsewhere in the SOFI.
6. Conclusion

Thermal insulations are a necessary part of any cryogenic tank application, and the ability to withstand multiple fill and drain cycles without cracking within the insulation is even more critical in the manned space flight arena. CTD’s Cryoflex test system has demonstrated the ability to use LHe to achieve an intermediate cryogenic temperature of a metallic substrate and ambient temperature exposure to SOFI foam, while at the same time allowing mechanical loads to be applied to the substrate. This test system can be used to simulate actual conditions in the fill, pressurization, and draining of a cryogenic fuel tank used in aerospace applications.

The ability to directly monitor the condition of the foam and the foam/substrate interface to immediately locate and identify a disjuncture within the foam or the foam to substrate bond enables immediate feedback on the performance of the insulation system to the designers and engineers responsible for the testing and evaluation of these subsystems. In addition, the ability to reduce the safety precautions by using LHe (as opposed to the many precautions necessary with the use of more volatile cryogens) results in additional cost savings to the customer and test program.

7. References

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