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Cyclic Cryogenic Thermal-Mechanical Testing of an X-33/RLV Liquid Oxygen Tank Concept

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September 1999

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ABSTRACT

An important step in developing a cost-effective, reusable, launch vehicle is the development of durable, lightweight, insulated, cryogenic propellant tanks. Current cryogenic tanks are expendable so most of the existing technology is not directly applicable to future launch vehicles. As part of the X-33/Reusable Launch Vehicle (RLV) Program, an experimental apparatus developed at the NASA Langley Research Center for evaluating the effects of combined, cyclic, thermal and mechanical loading on cryogenic tank concepts was used to evaluate cryogenic propellant tank concepts for Lockheed-Martin Michoud Space Systems. An aluminum-lithium (Al 2195) liquid oxygen tank concept, insulated with SS-1171 and PDL-1034 cryogenic insulation, is tested under simulated mission conditions, and the results of those tests are reported. The tests consists of twenty-five simulated Launch/Abort missions and twenty-five simulated flight missions with temperatures ranging from -320°F to 350°F and a maximum mechanical load of 71,300 lb. in tension.

INTRODUCTION

Future launch vehicles must be fully reusable to reduce the cost of space access. The Reusable Launch Vehicle (RLV) Program, a partnership between the National Aeronautics and Space Administration (NASA) and Industry, has been created to develop a vehicle that is fully reusable with greatly reduced operational cost and is discussed in Reference 1. The proposed Lockheed-Martin VentureStar™ RLV, shown in Figure 1, is a lifting body, single-stage-to-orbit (SSTO) vehicle that will launch vertically and land horizontally. Current development efforts are directed toward the X-33 vehicle, a half-scale prototype of the VentureStar™ that will be constructed in 1999. There are many systems that require development to enable a reusable launch vehicle. The thermal protection system (TPS), the insulated cryogenic propellant tanks, crew/payload compartments, engines, and control systems require careful consideration for the vehicle to be viable. However, one of the most crucial issues being considered is the development of durable, lightweight, cryogenic propellant tanks.

The cryogenic propellant tank must be leak free, capable of sustaining flight loads, and insulated. Cryogenic insulation must be present to minimize boil-off of cryogenic fuels, prevent the liquefaction of air or oxygen on the surface of the vehicle, prevent cryo-pumping, prevent frost or ice build-up, and prevent phase changes of adhesives in adhesively bonded TPS. Typical cryogenic insulations are closed cell foams that are sprayed on or bonded to the external surface of the tank. Cryogenic foams are generally brittle and prone to cracking under repeated exposure to thermal stresses induced by temperature gradients and transients, and to membrane stresses and bending stresses due to pressurization loads.

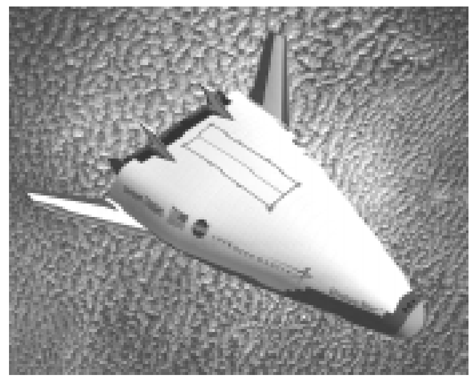


Figure 1. VentureStar™ RLV Concept.

The Lockheed-Martin X-33 liquid oxygen (LOX) tank is a dual-lobed, aluminum alloy (2219) structure with integral external stiffeners and is externally insulated with SS-1171 spray-on-foam-insulation (SOFI). The photograph in Figure 2 shows the X-33 LOX tank during fabrication at Lockheed-Martin Michoud Space Systems. A possible evolution of this tank concept for a RLV LOX tank would utilize weight efficient Graphite Epoxy (Gr-Ep IM7/977) material for the tank structure, see Reference 1. Combined, cyclic, thermal and mechanical tests of an aluminum-lithium alloy (AL 2195) test specimen, insulated with SS-1171 and PDL-1034 cryogenic insulations, are performed at cryogenic and elevated temperatures. A discussion of the test apparatus, test procedures and test results are presented in this paper.

EXPERIMENT

A method of testing cryogenic foams and attachment methods through simulated missions was first developed by A. H. Taylor, et. al., for the Advanced Launch Vehicle (ALS) Program (Reference 2). A series of tests and test facilities were developed at Langley Research Center (LaRC)

Figure 2. X-33 LOX Tank During Fabrication at Lockheed-Martin Michoud Space Systems.

for the X-33/RLV program during Phase I, Thermal Structures Technology Development for RLV Cryogenic Propellant Tanks, see Reference 3. These tests were developed to verify the integrity of the cryogenic tank concept and insulation method at vehicle mission conditions. These tests and the test apparatus were discussed in detail in Reference 4. Either LOX tank concepts or LH_2 tank concepts can be tested to validate their durability and reusability. This test method was used to test a Lockheed-Martin Michoud Space Systems (LMMSS) X-33/RLV LOX tank concept. This test consist of two experiments that simulate both Launch/Abort mission cycles and flight mission cycles. Twenty-five cycles were performed during each of these two experiments.

The first half of the experiment simulates Launch/Abort cycles. This cycle occurs when the cryogenic tanks are filled with fuel, pressurized in preparation for launch, and then drained because the mission is aborted. This experiment also simulates when the vehicle is launched and the mission is aborted in the launch phase of the flight, precluding any heating that would occur upon reentry from orbit.

The second half of the experiment simulates flight mission cycles and includes both thermal and mechanical loading. The panel's internal and external temperatures are varied, simulating cryogenic cooling and reentry heating experienced during flight. In addition to the thermal loading, the mechanical loading due to pressurization of the cryogenic propellant tank is varied.

Both experiments are performed cyclically to determine the effects of cyclic exposure to thermal gradients, thermal transients and mechanical loading at cryogenic and elevated temperature. Several lessons can be learned from these tests: the durability of the proposed cryogenic insulation systems, the reliability of adhesive systems used to bond the cryogenic insulation to the tank structure, the effect of cyclic combined thermal and mechanical loading on the tank concepts, the capability of each concept to withstand thermal gradients and transients, and the failure mechanisms for each concept.

Descriptions of the LOX tank concept test article, its dimensions, fabrication processes, design loads and temperature boundaries are provided in subsequent sections. The test apparatus is described in detail. The test procedure for each experiment is also discussed.

TEST ARTICLE

The LOX tank test article, provided by LMMSS and tested at NASA LARC, is referred to as Panel 2, a designation determined by LMMSS in Reference 5. A photograph of Panel 2 is shown in Figure 3. The test article is 12 inches wide and 24 inches long with a nominal thickness of 0.100 inches. The test article is an aluminum-lithium (AL 2195) panel externally insulated with 1-in.-thick SOFI insulation.

A schematic of the test panel is shown in Figure 4. The test region, a 12-in. by 12-in. area in the center of the panel, was externally insulated with segments of SS-1171 spray-on cryogenic foam and PDL-1034 poured-in-place (PIP) closeout foam insulation. Portions of the SS-1171 foam were machined to a height of 1 inch while other sections were left as sprayed. The SS-1171 foam segments were bonded to the PDL-1034 with Conathane™ adhesive.

Figure 3. Lockheed-Martin LOX tank Concept (Panel 2).

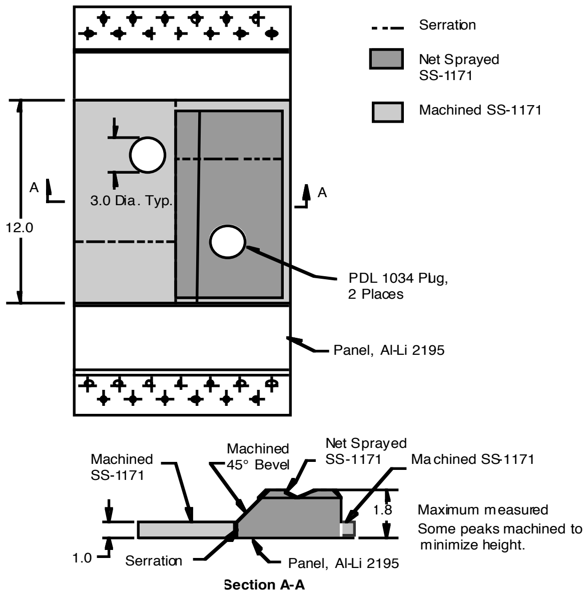


Figure 4. Cryogenic Insulation Layout.

The test article is instrumented with both conventional and NDE/VHM instrumentation. The conventional instrumentation consists of strain gauges and thermocouples while the NDE/VHM (see Reference 6) instrumentation consist of fiber-optic temperature sensors.

The conventional instrumentation layouts for the panel substrate and for the external surface of the foam are shown in Figure 5 and Figure 6, respectively. The panel is instrumented with back-to-back strain gages and with co-located back-to-back thermocouples. There are a total of twenty-two WK-type strain gages and twenty-three Type-E

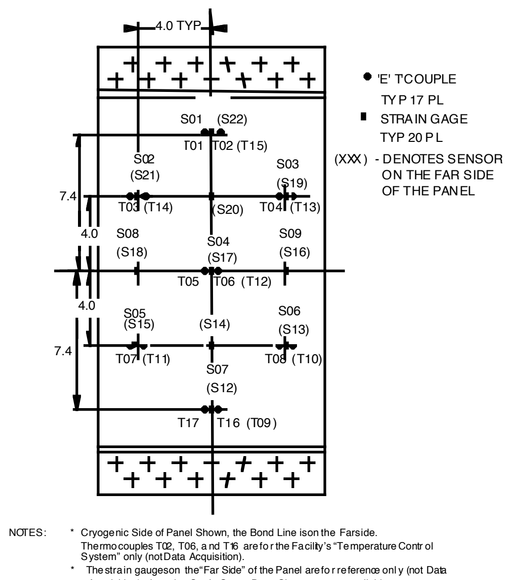


Figure 5. Instrumentation Layout for the Panel Substrate.

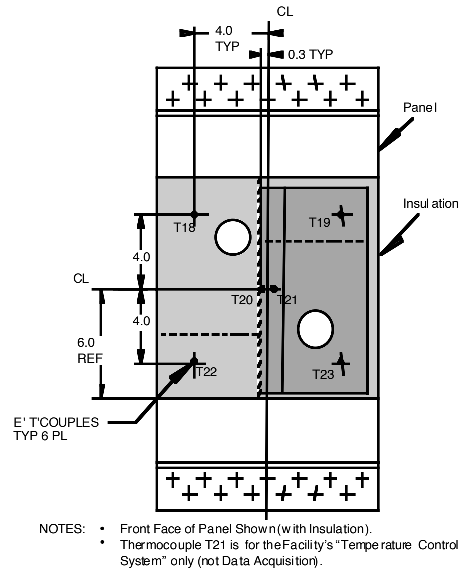


Figure 6. Panel 2 Instrumentation Layout for the Insulation External Surface.

thermocouples mounted to the test specimen. Reference data and the reference thermocouples for each strain gauge are given in Appendix I.

The panel is also instrumented with NDE/VHM (see Reference 6) instrumentation. A Distributed Temperature Sensor (DTS) is located on the external surface of the foam (as shown in Figure 7). The DTS is a fiber-optic sensor that measures temperature along its length. The equipment shown in Figure 8 is used to control the NDE/VHM equipment and collect data from the DTS sensor.

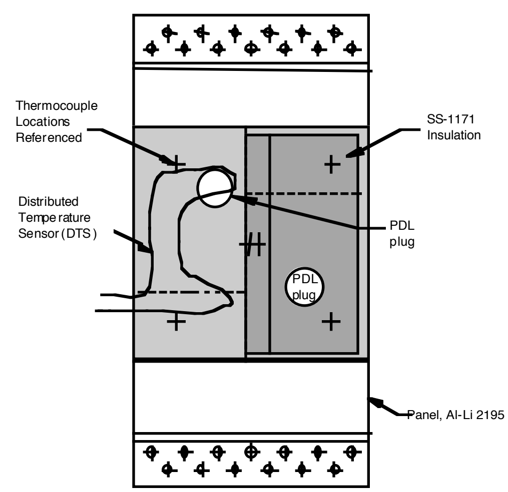


Figure 7. Distributed Temperature Sensor Located on External Surface of Foam.

Figure 8. NDE/IVHM Data Acquisition and Control System.

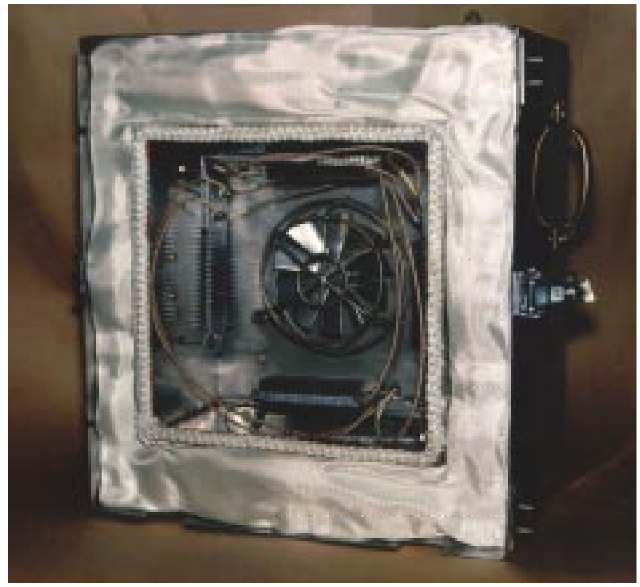


Figure 10. Convection Heater used to Heat External Surface of Insulation.

TEST APPARATUS

The 1-ft. by 2-ft. thermal-mechanical test apparatus is used to perform these tests. A schematic of the test apparatus is shown in Figure 9. The test article is mounted in a Shore Western, Inc. (SW) load machine with a load capacity of 220 kips. A Dimension™ controller controls the temperatures on the external surfaces of the insulation and the panel substrate. A MTS 458 controller operating in load control mode controls the load. The data acquisition system consists of a Neff-470 system to acquire the data and a microcomputer to store and display the data. A dewar of liquid nitrogen supplies the test article with cryogenic fluid during the tests. A more detailed description of this test apparatus is given in Reference 3.

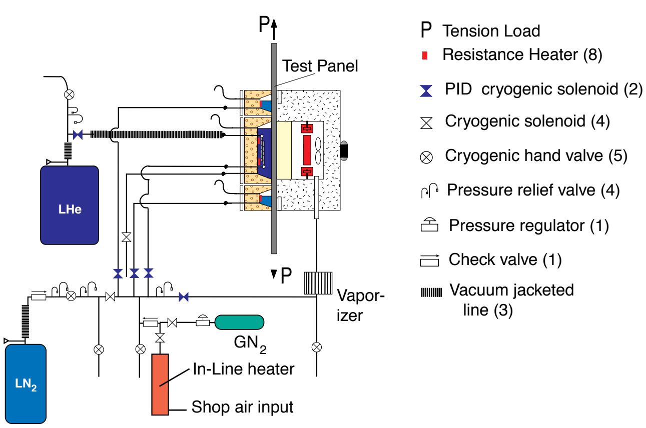


Figure 9. 1-foot by 2-foot Thermo-mechanical Test Apparatus.

The test apparatus can be configured to heat the external surface of the insulation by convection while cooling the aluminum face of the panel with cryogenic fluids. A cryogenic cooling apparatus and a heating apparatus are sandwiched around the concept.

The cooling apparatus located on the aluminum face of the panel consist of three insulated cryogenic chambers sealed to the test panel with a 0.5-in.-wide GORETEX™ gasket material. This gasket material is expanded polytetrafloraletheline (EPTFE) and remains flexible at cryogenic temperatures. The top and bottom chambers are filled with liquid nitrogen and used to prevent the flow of heat into the center region of the test panel from the load introduction structure. The center chamber is filled with liquid nitrogen during testing. The cryogenic plumbing shown in Figure 10 is used to control the flow of cryogenic fluids to the chambers. The same plumbing is also used to deliver warm nitrogen gas to the aluminum face of the panel to simulate soak-through heating.

The external surface of the foam is heated by convection using an insulated convection chamber, shown in Figure 10. The convection chamber is sealed to the surface of the foam with 0.5-in.-wide glass-fiber rope. Four 6-in.-long fin-strip heaters mounted to the sides of the heater chamber supply heat. The heaters are each rated at 150 watts and are operated at 220 volts. A 100-cubic-feet-per-minute (CFM) fan circulates air in the chamber to transfer heat from the fin strip heaters to the surface of the panel. Cool nitrogen gas is also supplied to the chamber to prevent overheating of the specimen.

TEST PROCEDURES

Procedures for the two experiments performed are given in the following section. The first test is a Launch/Abort simulation. The second test is a flight mission simulation. Each test is repeated for twenty-five cycles to assess the concept's response to cyclic loading.

LAUNCH/ABORT SIMULATION

The panel is first mounted in the MTS test machine and then the loading conditions for a typical Launch/Abort simulation are given as follows:

1 Verify the integrity of the DTS.

2. Verify the conventional instrumentation is functional.

3. Record the conventional instrumentation at two scans per minute. Record the DTS sensors at two scans per second.

4. Steadily ramp the tensile load to 6400 lbs.

5. Chill the test panel's aluminum face to -320°F in ten minutes while maintaining a foam face temperature of 90°F. Maintain temperatures until a steady state condition is achieved and hold for 5 minutes.

6. Increase the recording rate of the conventional instrumentation to one scan per second

7. Apply the thermal/mechanical load profile shown in Figure 11.

8. After completing the profile, maintain a 13000 lb. tensile load and the 90°F external insulation surface temperature, and begin steadily warming the panel's aluminum face until it reaches 30°F min. using nitrogen as a purge gas.

9. Reduce the tensile load to 500 lb. maximum and stop any heating or cooling of the panel.

10. Reduce scan rate to one scan every 30 secs.

11. Stop data recording on conventional instrumentation. Stop recording the DTS.

12. Visually inspect the test panel.

13. Review the test data and verify that a peak strain of 4700 ± 10% microstrain was achieved.

14. Perform additional Launch/Abort cycles on this test panel by repeating step (1) through (13) until a total of twenty-five cycles have been performed.

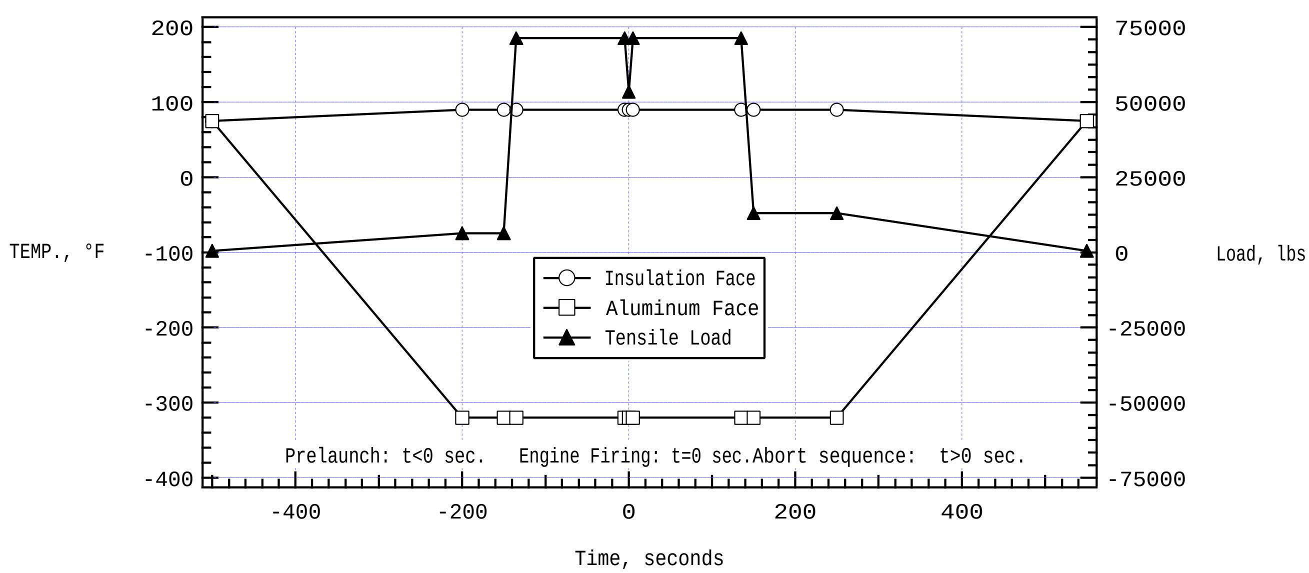


Figure 11. Launch/Abort Simulation Temperature and Load Profiles.

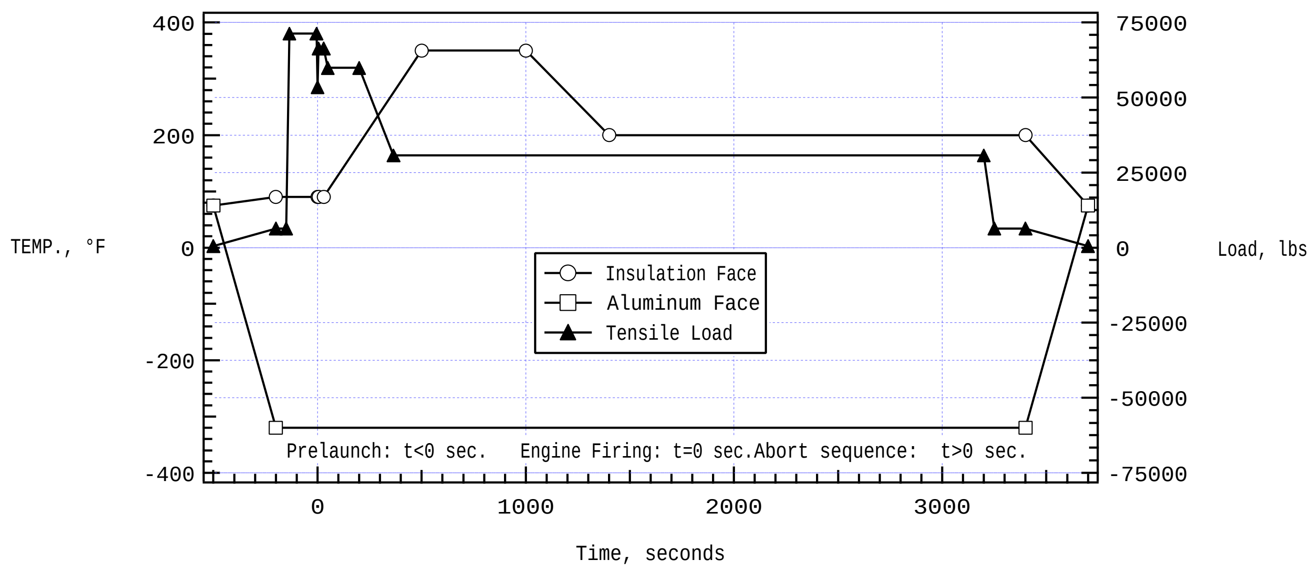


Figure 12. Flight Simulation Thermal and Mechanical Profiles.

FLIGHT SIMULATION

After completion of twenty-five Launch/Abort cycles, the following procedure for performing Flight Missions is followed:

1. Verify the conventional instrumentation is functional. Verify the DTS are functional.
2. Start recording of all conventional instrumentation at two scans per minute. Start recording the DTS at two scans per second.
3. Steadily ramp the tensile load to 6400 lbs. to apply a pre-load to the panel.
4. Chill the test panel's aluminum face to -320°F in 10 minutes while maintaining an external insulation face temperature of 90°F. Maintain these temperatures until a steady state condition is achieved. Hold the steady state condition for 5 minutes.
5. Increase the recording rate of the conventional instrumentation to one scan per second.
6. Apply the thermal/mechanical load profile shown in Figure 12.
7. After completing the profile, maintain the 6400 lb. tensile load and begin steadily cooling the foam face and steadily warming the panel's aluminum face until its temperature reaches 30°F min. and the foam face temperature reaches 130°F max. using nitrogen as a purge gas.
8. Reduce the tensile load to 500 lbs. maximum and stop any heating or cooling of the panel.
9. Decrease scan rate to one scan every 30 secs.
10. Stop data recording on conventional instrumentation. Stop recording the DTS.
11. Visually inspect the test panel.
12. Review the test data and verify that a peak strain of 6000 ± 10% μin./in. was achieved.
13. Perform additional Flight Mission cycles by repeating step (1) through (12) until a total of twenty-five cycles have been performed.

EXPERIMENTAL RESULTS

GENERAL

Experimental results of both Launch/Abort cycles and Flight Mission simulations are given. The concept is tested through fifty cycles lasting from 20 to 90 minutes per cycle. With the addition of set-up and tear down time, these tests span a period of almost two months. The experimental data reported include histories of temperature, strain corrected for thermal output (Reference 7), load and displacement for only one typical mission simulation. The data for all other cycles are similar and are not reported. Photographs of the test panel taken as testing progressed are also shown.

Launch/Abort Simulation Testing

Temperature, load and displacement data, and temperature-corrected strain from Launch/Abort cycle 12 are shown in the plot in Figure 13a, b and c, respectively and are typical of other Launch/Abort simulations. Also plotted with the experimental data are 95% confidence intervals (Reference 8) for the data. These intervals quantify the precision in the measurement of the data but exclude any bias errors.

The temperature of the aluminum face of the test specimen was exposed to liquid nitrogen and its temperature decreased to –300±25°F within 5 minutes. The aluminum face temperatures and the foam bond line temperatures were then maintained at –300±25°F while the external surface of the foam was maintained at 90±5° F for 17 minutes. The cryogenic cooling was then stopped and the cryogenic chambers were purged with nitrogen gas, warming the panel to room temperature. The entire cycle lasted 30 minutes.

During the first 10 minutes of the Launch/Abort simulation the load level was held constant at 6400 lb. At this point, the load was increased to a peak value of 71,200 lb. Thirteen minutes into the simulation, load was reduced to 55,200 lb. It was then increased to 71,200 lb. again. This load level was held for 3 minutes. The load was then reduced to 13,000 lb. and held until the thermal profile ended (30 minutes into the cycle). The load was then reduced to 500 lbs.

During the first phase of the test, the displacement reduced to -0.062 in. due to thermally induced contractions in the test specimen. The displacement reached a peak value of 0.1 in. when peak tensile load was applied. The indicated displacement was measured at the base of the hydraulic piston and included deformation in the entire load train.

Strain responses, corrected for thermal output and gage factor variance with temperature, are surface strains measured on the bond line and external surface of the aluminum panel. During the cryogenic chill the panel was allowed to contract while a 6400 lb. preload was maintained. Ten minutes into the cycle, when tensile load was applied, the strains increased to peak values of 5000±50 μin./in. for both the aluminum face and the foam bond line face of the panel. All strain measurements indicated the same overall trend and magnitudes.

Flight Simulation Testing

Temperature, load and displacement data, and temperature-corrected strain from Flight Cycle 12 are shown in the plot in Figure 14a, b and c, respectively and are typical of other Launch/Abort simulations. Also plotted with the experimental data are 95% confidence intervals for the data.

The temperature of the internal surface of the test specimen decreased to –300±25°F within 5 minutes. The internal surface temperatures and the bond-line temperatures were maintained at –300±50°F for 65 minutes. At 15 minutes into the mission, the external surface of the foam was heated to 350±10°F in 10 minutes. The external foam surface was held at this temperature for 8 minutes. Thirty-three minutes into the simulation, the external surface temperature was reduced to 200±5°F in 8 minutes and held at that temperature for 32 minutes. Heating was halted and the cryogenic chambers were purged with nitrogen gas, warming the substrate to room temperature and cooling the external foam surface to room temperature within 20 minutes. The entire mission lasted 90 minutes.

The load level was held constant at 500 lb. for 5 minutes and then at 6400 lb. for 5 minutes. The load was then increased to a peak value of 42,500 lb.

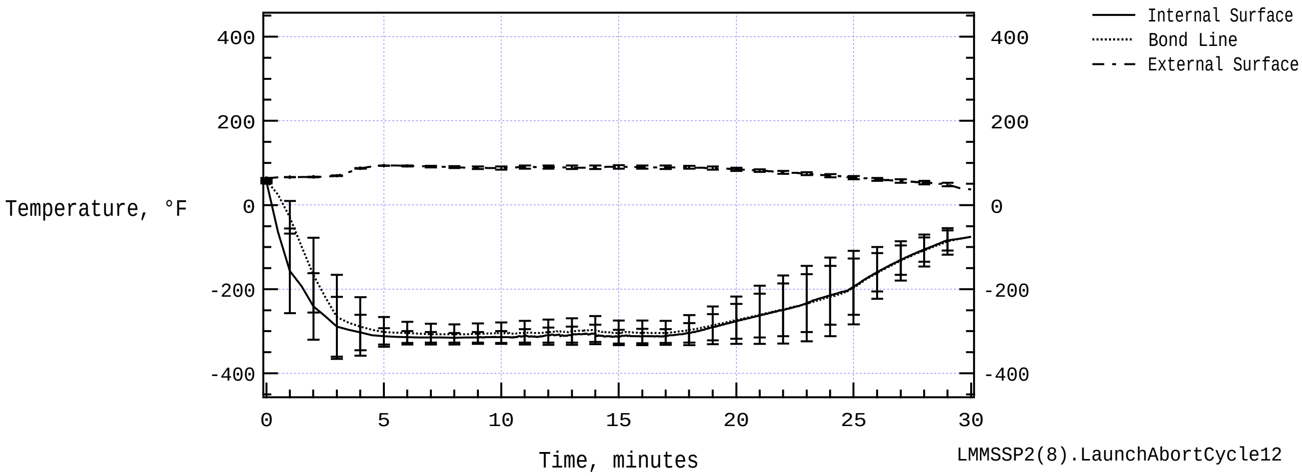
During the first phase of the test, the peak displacement is -0.05 in. and then increases to a peak value of 0.20 in. during the next phase of the simulation (when the peak tensile load is applied).

During the cryogenic chill the panel undergoes a thermally induced contraction. Eight minutes into the cycle, when peak tensile load is applied, the internal surface strains increase to peak values of 4250±25 microstrain, and the bond line strains increased to peak values of 4000±1000 μin./in. As the panel was unloaded and as its temperature returned to room temperature, the strains tended toward their initial unstrained magnitudes.

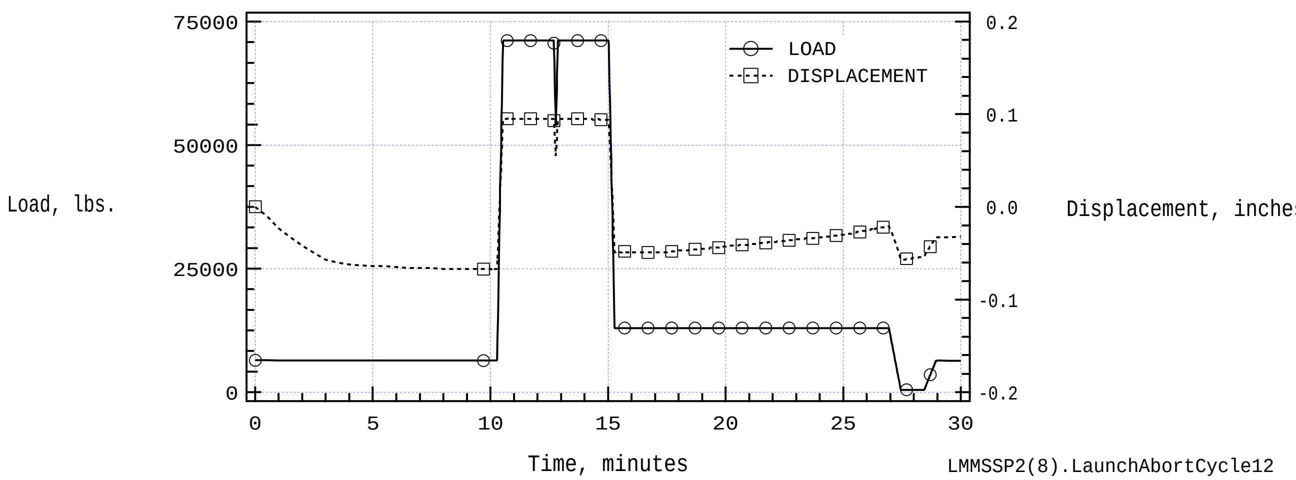
PHOTOGRAPHS, ETC.

Photographs of the external surface of the insulation are taken at the conclusion of the twenty-fifth mission cycle during Launch/Abort Simulation Testing and between mission cycles during Flight Simulation Testing. A photograph of Panel 2, taken after the twenty-fifth Launch/Abort cycle, is shown in Figure 15a. As can be seen in the photograph, the external surface of the foam is not degraded. Photographs of Panel 2 taken after the first, thirteenth, and twenty-fifth Flight cycles are shown in Figure 15b, c and d. The surface of the SS-1171 foam began to char early in the test and continued to darken as testing progressed.

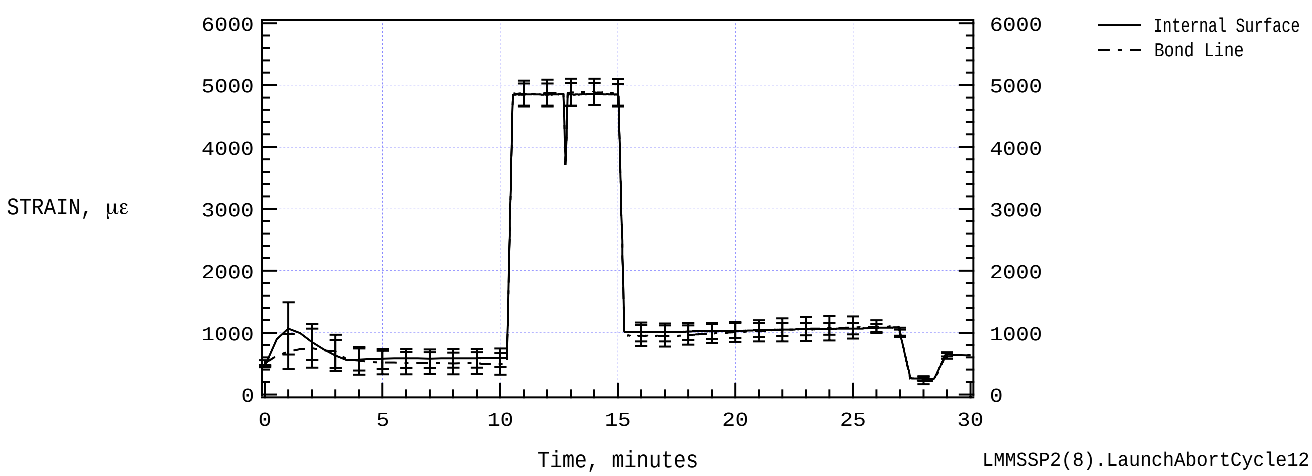
Panel 2 was tested through twenty-five Launch/Abort cycles and through twenty-five cycles. The concept appeared to be an effective insulator at cryogenic temperature.



a) Temperature

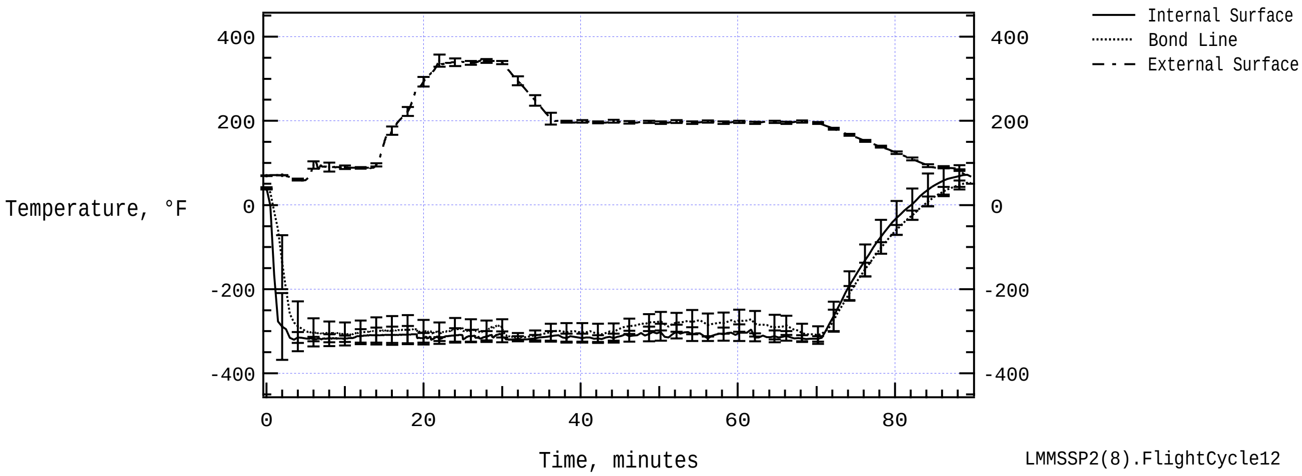


b) Load and Displacements

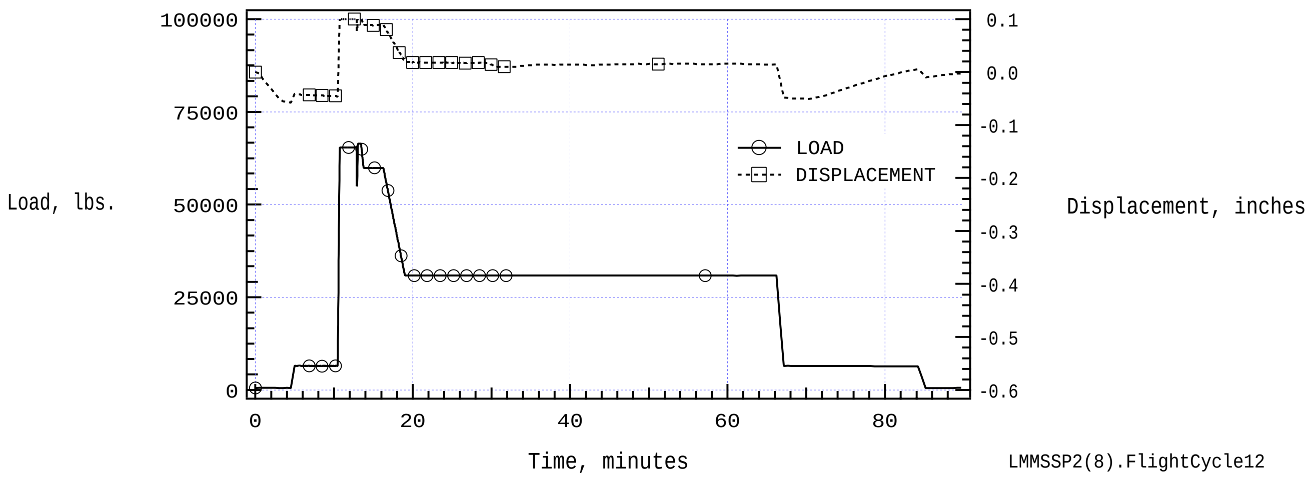


c) Temperature Corrected Strain Data

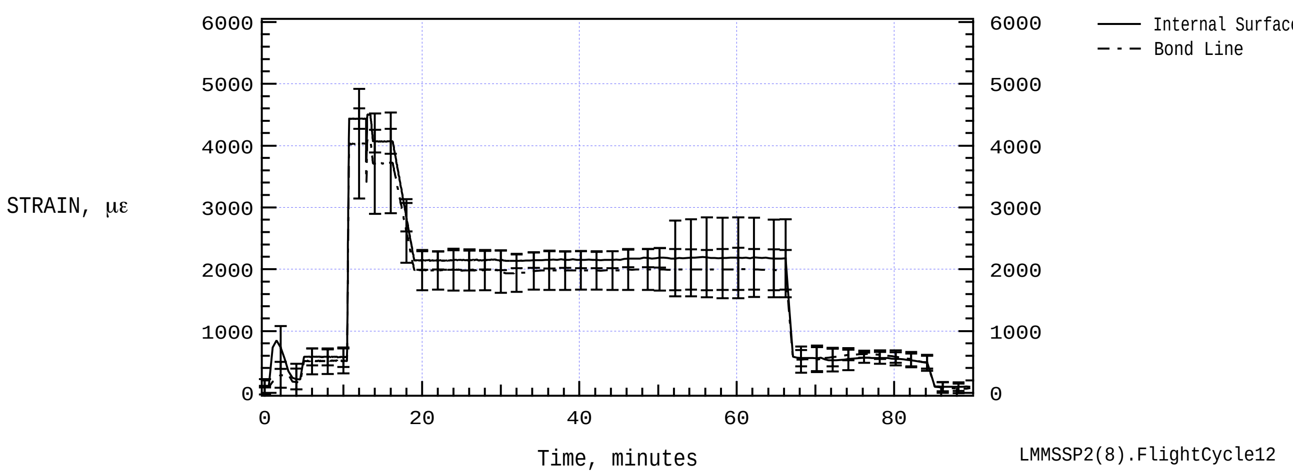
Figure 13. Test Data from Launch/Abort Simulation Cycle 12.



a) Temperatures

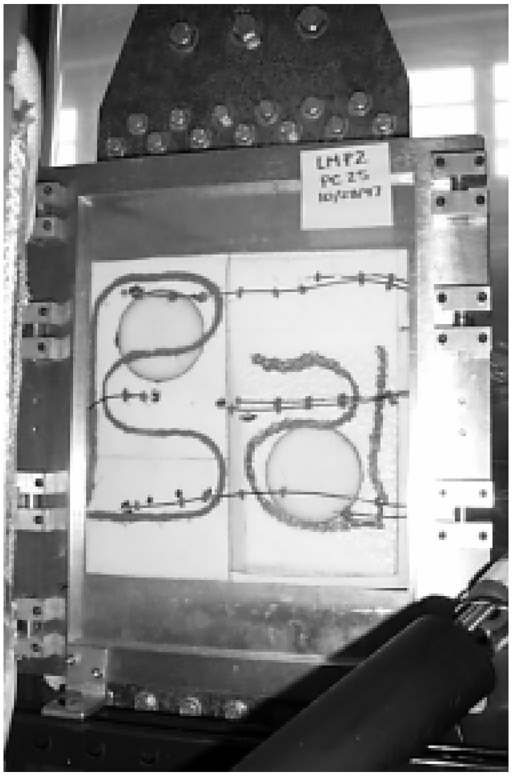


b) Load and Displacement

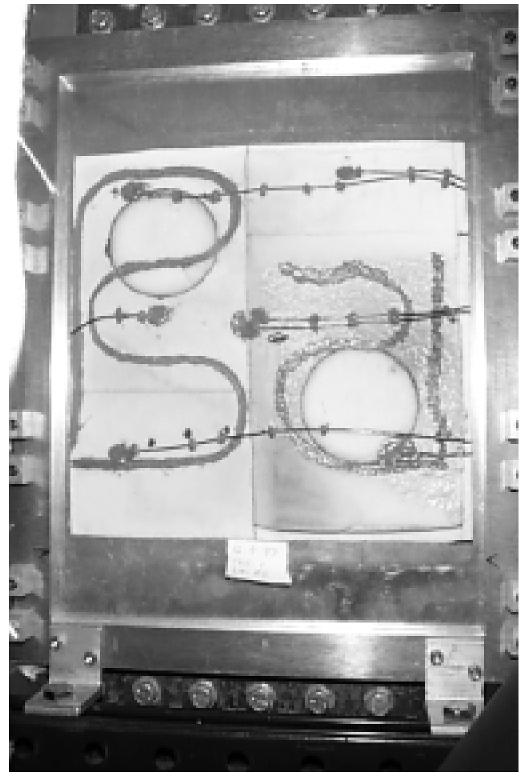


c) Temperature Corrected Strain

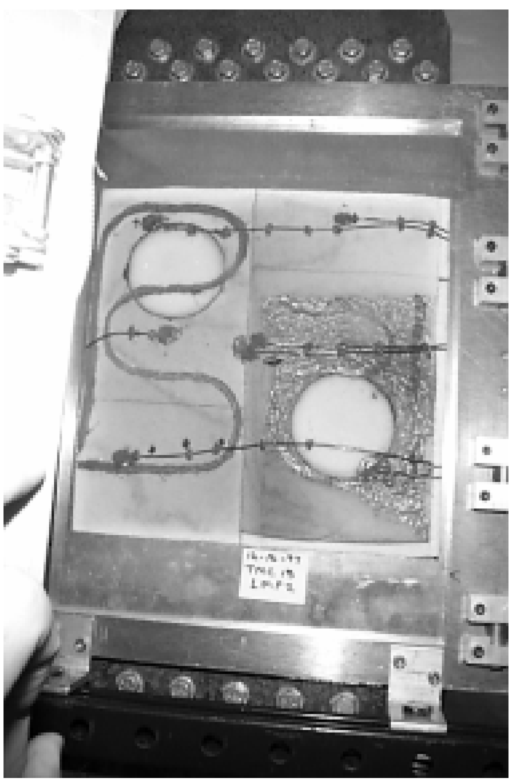
Figure 14. Test Data from Flight Mission Simulation Cycle 12.



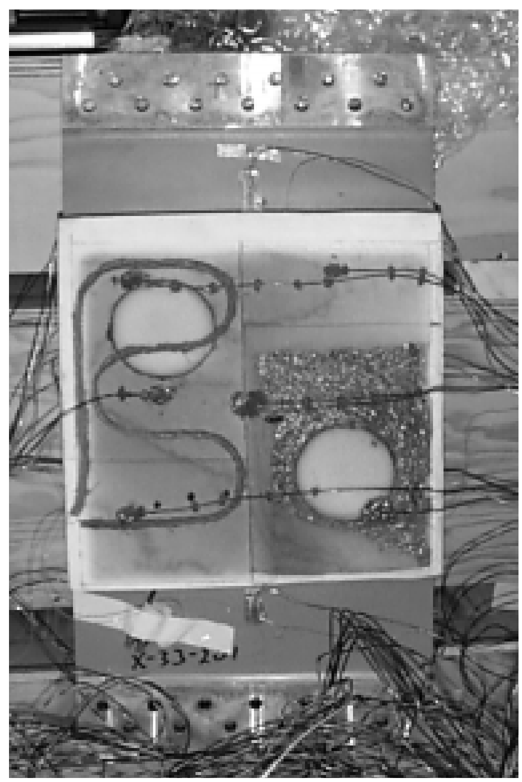
a) Launch/Abort Cycle 25



b) Flight Cycle 1



c) Flight Cycle 13



d) Flight Cycle 25

Figure 15. Photographs taken during Flight Mission Simulations.

Measurements from the DTS instrumentation were not taken during the either the Launch/Abort simulations or the flight simulations because the fiber-optic sensor failed during installation of the panel into the test machine.

CONCLUSIONS

An important step in developing a cost-effective, reusable, launch vehicle is the development of durable, lightweight, insulated, cryogenic propellant tanks. As part of the X-33/RLV Program, an experimental apparatus for evaluating the effects of combined thermal and mechanical loading on cryogenic-tank concepts was developed at the NASA Langley Research Center. Studies to determine the behavior of an externally insulated LOX tank concept under simulated Launch/Abort and Flight mission conditions were performed.

The concept was an aluminum-lithium alloy (Al 2195) panel, externally insulated with SS-1171, spray-on-foam-insulation and PDL-1034, poured-in-place foam. The concept was tested through twenty-five Launch/Abort simulations and twenty-five flight simulations. The test results were repeatable and indicated that the concept should withstand predicted flight conditions for the life of the vehicle. The surface of the SS-1171 foam charred during the flight mission simulations but did not appear to effect the foam's performance.

REFERENCES

1. Cook, Stephen A.: *The X-33 Advanced Technology Demonstrator*, AIAA-96-1195, 1996.
2. McAuliffe, Patrick S., Davis, Randall C., and Taylor, Allan H., *Development of Reusable, Flight-Weight Cryogenic Foam Insulation Systems*, AIAA Paper No.1189-CP, June 1986.
3. Theodore F. Johnson, Roderick Natividad, H. Kevin Rivers and Russell Smith, *Thermal Structures Technology Development for a Reusable Launch Vehicle Cryogenic Propellant Tanks* , Space Technology and Application International Forum (STAIF), 3rd Conference on Next Generation Launch Systems, Albuquerque, NM, January 25-29, 1998.
4. Rivers, H. Kevin: Thermal and Mechanical Behavior of Cryogenic Tank Concepts. M. S. Thesis, Old Dominion Univ., 1997.
5. Eddlestone, Kenneth N., "Thermo-Mechanical Testing of X-33 Cryogenic Insulation", LMMSS Test Plan, October 1998.
6. Melvin, L., Childers, B., Rogowski, R., Prosser, W., Moore, J., Froggatt, M., Allison S., Wu, M. C., Bly, J.,Aude, C., Bouvier, C., Zisk, E., Enright, E., Cassadaban, Z., Reightler, R., Sirkis, J., Tang, I., Peng, T., Wegreich, R., Garbos, R., Mouyos, W., Aibel, D., Bodan, P. (1997), *Integrated Vehicle Health Monitoring (IVHM) for Aerospace Vehicles*, Presented at the International Workshop on Structural Health Monitoring, Structural Health Monitoring: Current Status and Perspectives, Edited by Fu-Kuo Chang, Stanford, CA, September 1997, pp. 705-714.
7. Kowalkowski, Matthew K., H. K. Rivers, R. W. Smith: *Thermal Output of WK-type Strain Gages on Various Materials at Cryogenic and Elevated Temperatures*, NASA/TM-1998-208739, 1998.
8. Coleman, Hugh W. and W. Glenn Steele, *Experimentation and Uncertainty Analysis For Engineers*, Vol I. First Ed., John Wiley and Sons, Inc. 1989.

APPENDIX 1. Conventional Instrumentation Data.

STRAIN GAGES						
Gage Type	Micro-Measure-ments Part #	Micro-Measurements Lot #	Gage Factor	Transverse Sensitivity	Resistance, Ohms	Temp. Coeff. of Gage Factor
uni-axial	WK-13-250BG -350	DU-K47FF01	2.07 ±1.0%	-4.8 ±0.2%	350 ±0.3%	(-1.3±0.2)%/100C

Micro-Measurements Apparent Strain Curve
Thermal Output (ue) = -65.1 + (1.04)T - (.00338)T^2 + (2.76 X 10^{-5})T^3

Strain Gages		
I. D.	**Location**	**Reference Th'couple**
S01	Cryo side of substrate	T01
S02	Cryo side of substrate	T03
S03	Cryo side of substrate	T04
S04	Cryo side of substrate	T05
S05	Cryo side of substrate	T07
S06	Cryo side of substrate	T08
S07	Cryo side of substrate	T17
S08	Cryo side of substrate	T05
S09	Cryo side of substrate	T05
***S12**	Bond-line side of substrate	N/A
***S13**	Bond-line side of substrate	N/A
***S14**	Bond-line side of substrate	N/A
***S15**	Bond-line side of substrate	N/A
***S16**	Bond-line side of substrate	N/A
***S17**	Bond-line side of substrate	N/A
***S18**	Bond-line side of substrate	N/A
***S19**	Bond-line side of substrate	N/A
***S20**	Bond-line side of substrate	N/A
***S21**	Bond-line side of substrate	N/A
***S22**	Bond-line side of substrate	N/A

* **All the strain gauges on the Cryo side of the substrate are installed on the panel, but are not to be used for data acquisition since their data sheets are not available.**

THERMOCOUPLES		
I. D.	**Type***	**Location**
T01	E	Cryo side of substrate
T02*	E	Cryo side of substrate, Control Thermocouple
T03	E	Cryo side of substrate
T04	E	Cryo side of substrate
T05	E	Cryo side of substrate
T06*	E	Cryo side of substrate, Control Thermocouple
T07	E	Cryo side of substrate
T08	E	Cryo side of substrate
T09	E	Bond-line side of substrate
T10	E	Bond-line side of substrate
T11	E	Bond-line side of substrate
T12	E	Bond-line side of substrate
T13	E	Bond-line side of substrate
T14	E	Bond-line side of substrate
T15	E	Bond-line side of substrate
T16*	E	Cryo side of substrate, Control Thermocouple
T17	E	Cryo side of substrate
T18	E	Exterior RCI surface
T19	E	Exterior RCI surface
T20	E	Exterior RCI surface
T21*	E	Exterior RCI surface, Control Thermocouple
T22	E	Exterior RCI surface
T23	E	Exterior RCI surface

***** - Thermocouples T02, T06, T16 and T21 are used for the “Temperature Control System” and are not recorded for data acquisition.

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An important step in developing a cost-effective, reusable, launch vehicle is the development of durable, lightweight, insulated, cryogenic propellant tanks. Current cryogenic tanks are expendable so most of the existing technology is not directly applicable to future launch vehicles. As part of the X-33/Reusable Launch Vehicle (RLV) Program, an experimental apparatus developed at the NASA Langley Research Center for evaluating the effects of combined, cyclic, thermal and mechanical loading on cryogenic tank concepts was used to evaluate cryogenic propellant tank concepts for Lockheed-Martin Michoud Space Systems. An aluminum-lithium (Al 2195) liquid oxygen tank concept, insulated with SS-1171 and PDL-1034 cryogenic insulation, is tested under simulated mission conditions, and the results of those tests are reported. The tests consists of twenty-five simulated Launch/Abort missions and twenty-five simulated flight missions with temperatures ranging from -320°F to 350°F and a maximum mechanical load of 71,300 lb. in tension.

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