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Methane Lunar Surface Thermal Control Test

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Abstract

NASA is considering propulsion system concepts for future missions including human return to the lunar surface. Studies have identified cryogenic methane (LCH_4) and oxygen (LO_2) as a desirable propellant combination for the lunar surface ascent propulsion system, and they point to a surface stay requirement of 180 days. To meet this requirement, a test article was prepared with state-of-the-art insulation and tested in simulated lunar mission environments at NASA GRC. The primary goals were to validate design and models of the key thermal control technologies to store unvented methane for long durations, with a low-density high-performing Multi-layer Insulation (MLI) system to protect the propellant tanks from the environmental heat of low Earth orbit (LEO), Earth to Moon transit, lunar surface, and with the LCH_4 initially densified. The data and accompanying analysis shows this storage design would have fallen well short of the unvented 180 day storage requirement, due to the MLI density being much higher than intended, its substructure collapse, and blanket separation during depressurization. Despite the performance issue, insight into analytical models and MLI construction was gained. Such modeling is important for the effective design of flight vehicle concepts, such as in-space cryogenic depots or in-space cryogenic propulsion stages.

Introduction

For a lunar outpost exploration mission at the lunar South Pole, NASA has planned a surface stay of up to 180 days for the crew module and Altair ascent stage. NASA internal and contracted trade studies (Refs. 1 and 2) have predicted that LCH_4 ascent stage propellant tank venting can be eliminated on the lunar surface for such a stay by using a high performance passive thermal control design including a Multi-layer Insulation (MLI) system consisting of at least 60 layers to protect the propellant tanks from the lunar surface and solar environmental heating, and tanking with densified LCH_4 at 93 K to approximately 85 percent full at the launch pad, to allow for substantial liquid head absorption and thermal expansion.

In order to verify the trade study results, a NASA inter-center team consisting of Ames Research Center (ARC), Glenn Research Center (GRC), Kennedy Space Center (KSC), and Marshall Space Flight Center (MSFC) conducted a series of baseline passive thermal control technology tests of a spherical LCH_4 propellant tank in simulated lunar mission thermal environments of hard vacuum and 305, 250, 140, and 350 K ambient temperatures at the GRC Creek Road Cryogenic Complex, SMiRF facility; accompanying calorimeter tests of coupons of this same MLI were performed at KSC's Cryogenic Test Bed (Ref. 3).

Objectives

Associated with LCH_4/LO_2 propellants in the propulsion system for Altair Ascent Stage are the thermal control technology challenges to enable mass efficient, long duration cryogenic storage required on the lunar surface. NASA's thermal control analysis (unpublished) predicts that thick MLI systems with the methane initially densified can meet the mission timeline requirement of 180 days of unvented storage. One of the most important details for such a long storage time is the tank applied thermal insulation system performance, which historically has a significant variation due to degradation caused by the penetrations through the MLI, gaps due to fit issues (particularly for spherical tanks or dished ends), and local compression of the insulation and the resultant effect on the overall heating rate. A focus of this test is to address both the unvented storage timeline and the MLI thermal performance. Another objective is to compare the industry standard equations to an updated NASA approach developed after the Multi-purpose Hydrogen Test Bed (Ref. 4) test, which included derivation of an empirical revision (Ref. 5) to existing equations used to predict MLI heating rates at low environment temperatures; this present effort sought to confirm this with additional data using a smaller tank. Further data was collected for MLI performance uncertainty with thick MLI designs, which are recommended for this application, as the tank applied MLI ground test database shows substantial data variation and inconsistencies for 60 or more layers.

Accompanying the MLI investigation are tests involving liquid methane densification and tank pressurization. In order to meet the lunar mission requirements, our design assumes the liquid methane is tanked densified (at 93 K) and pressurized with helium and then undergoes a very long loiter causing the tank to pressurize. In this test, data was collected at environmental conditions representing each phase of the mission concept. The ground hold and ascent mission phases were simulated to establish the integrated heating timeline and to better understand the fluid conditions upon reaching orbit. These results are presented elsewhere (Ref. 6). Boil-off and pressurization testing was performed under vacuum and thermal environments of 140 and 350 K, which are representative of lunar transit and lunar surface equator environments respectively, and at 250 K, a representative effective temperature for lunar pole and low lunar and earth orbit environments.

Hardware

SMiRF Test Facility

The Methane Lunar Surface Thermal Control (MLSTC) experiment was conducted at the NASA GRC Creek Road Complex—Small Multi-Purpose Research Facility (SMiRF) (Ref. 7). SMiRF provides the ability to simulate launch ascent, high altitudes and space pressure environments, while simulating the corresponding thermal environment. The test facility contains a 7.38 m^3 cylindrical space simulation vacuum chamber in which the MLSTC test tank was suspended. The facility vacuum system can maintain a vacuum pressure of 10^{-6} torr in the chamber. The vacuum system also allows the chamber to be evacuated at a rate simulating a launch vehicle ascent pressure profile (from atmospheric pressure to 0.01 torr in 2 min). Contained within the vacuum chamber is a programmable thermal cryo-shroud that

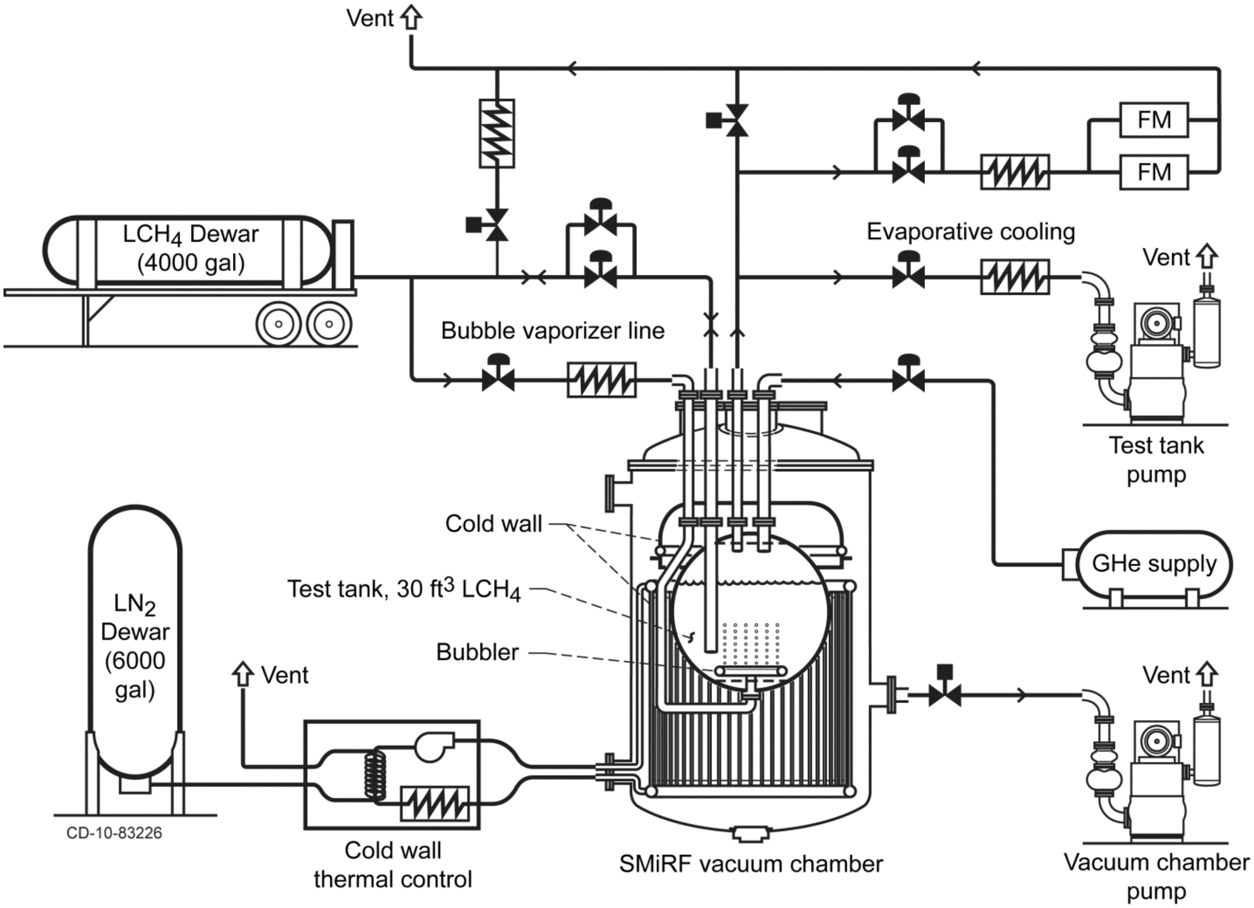

Figure 1.—MLSTC test simplified facility schematic diagram.

provided an isothermal environment for the MLSTC test tank. The cryo-shroud provides a constant environment temperature with steady state temperature control of ±3 K. The shroud average measured emissivity is 0.85. Inside the shroud is the MLSTC tank, a 1.22 m (4 ft) diameter spherical tank that has 0.95 cm (0.375 in.) thick walls. To best encompass the proposed propulsion system engine requirements, a test matrix was developed which defined the initial tank fill level that the liquid methane was initially transferred to the test tank at normal boiling point (112 K), and could be either warmed to 150 K (1550 kPa saturated condition), or cooled to 93 K (21 kPa saturated condition). The liquid was warmed by bubbling warm gaseous methane into the test tank, or was cooled evaporatively using a vacuum system to reduce tank pressure and temperature. A schematic of SMiRF is shown in Figure 1.

Measurements taken at SMiRF were vacuum and test tank pressure, temperatures, flow rate, vent flow gas composition, and pump power output. Research instrumentation was provided to measure the following parameters:

- Bulk LCH_4 and vapor ullage temperature (42 sensors)
- Cryoshroud temperature (19 sensors)
- MLI insulation temperature (64 sensors)
- Test tank structural supports and piping penetration temperature (36 sensors)
- Test tank pressure
- MLI interstitial pressure (2 gauges)
- SMiRF vacuum chamber pressure (4 gauges)
- Recirculation pump power
- Vent flow rate (4 flow meters)

Figure 2.—MLSTC tank insulated with 61 layers of MLI.

Multi-Layer Insulation

The tank MLI system consisted of an underlying reflective Kapton substrate covered with 60 layers of Double Aluminized Mylar (DAM), each separated by double Dacron netting. Its pre-test measured layer density varied from 5 to 16 layers/cm, with an average of 7.1 layers/cm around the equator. The NASA calorimeter tests of the MLI blankets indicated a sub-blanket density of 15 layers/cm and an overall system density of 10 layers/cm. A picture of the installed MLI is shown in Figure 2.

The larger tank fill and vent penetrations were individually wrapped with temperature matched insulation socks while the structural penetration insulation was isolated from the tank insulation.

Analysis

Thermal Desktop (C&R Technologies) was used to build a thermal model of the test configuration to quantify all sources of heat load into the tank, study the tank multi-layer insulation (MLI) system performance and ultimately evaluate the capability for long-term Methane storage for lunar surface operations. The tank wall was modeled as a fixed boundary temperature, and the cryoshroud surfaces were modeled as boundary conditions with temperatures populated by laboratory measurements.

In the MLSTC boil-off tests, the heat load into the tank was derived by measuring the vapor vent rate in a steady-state condition. Conductive heat loads through the tank penetrations such as the vent line, fill/drain line, pressurization line, tank supports and wire bundles were calculated from penetration temperature measurements and the physical characteristics of the lines. The tank MLI system heat load was calculated from the difference between the total heat load and the sum of the conductive heat loads. The theoretical MLI system performance was calculated with a customized subroutine utilizing MLI performance Lockheed Equations (4-15) and (4-56) (Ref. 8) and the Modified Lockheed Equation (see Ref. 5), which are shown in Table 1. These equations are for flat plate calorimeters and represent the ideal heat flux through an MLI blanket. As such, they serve as a reference against which to compare our tank applied MLI heat, which will always be greater than that found through calorimeter testing. Our resulting heat loads were then correlated to these equations by using a degradation factor, a multiplier applied to the reference value. The primary difference between the Lockheed Equations (4-15) and (4-56) and the Modified Lockheed Equation is that the latter equations incorporate a conduction model for Dacron netting spacer material, which was used in the MLSTC MLI system in place of silk netting, used by Lockheed for their testing. Because at low temperature the Dacron's conductivity is higher than that of silk, the Modified Lockheed Equation predicts higher heat rates at low boundary temperatures.

TABLE 1.—EQUATION USED FOR MLI MODELING

	Equation
Equation 4-15	$q=\left[\frac{C_s(\overline{N})^{3.56}(T_h^2-T_c^2)}{2(N_s+1)}+\frac{C_r\varepsilon(T_h^{4.67}-T_c^{4.67})}{N_s}+\frac{C_gP(T_h^{0.52}-T_c^{0.52})}{N_s}\right]$ *Cs = 2.11E-9, Cr = 5.39E-10, Cg = 14600.*
Equation 4-56	$q=\left[\frac{C_s(\overline{N})^{2.56}(T_h^2-T_c^2)}{2(N_s+1)}+\frac{C_r\varepsilon(T_h^{4.67}-T_c^{4.67})}{N_s}+\frac{C_gP(T_h^{0.52}-T_c^{0.52})}{N_s}\right]$ *Cs = 8.95E-8, Cr = 5.39E-10, Cg = 14600.*
NewQ Equation	$q=\left[\frac{C_s(0.017+7.0E-6*(800.0-T_{avg})+2.28E-2*\ln(T_{avg}))(\overline{N})^{2.63}(T_h-T_c)}{N_s+1}+\frac{C_r\varepsilon(T_h^{4.67}-T_c^{4.67})}{N_s}+\frac{C_gP(T_h^{0.52}-T_c^{0.52})}{N_s}\right]$ *Cs= 2.4E-4, Cr = 5.39E-10, Cg = 14600.*
Modified Lockheed Equation	$q=\left[\frac{C_s(0.017+7.0E-6*(800.0-T_{avg})+2.28E-2*\ln(T_{avg}))(\overline{N})^{2.63}(T_h-T_c)}{N_s}+\frac{C_r\varepsilon(T_h^{4.67}-T_c^{4.67})}{N_s}+\frac{C_gP(T_h^{0.52}-T_c^{0.52})}{N_s}\right]$ *Cs= 2.4E-4, Cr = 4.944E-10, Cg = 14600.*
Variables and units:	q heat flux through MLI, W/m^2, Th hot boundary temperature, K, Tc cold boundary temperature, K, Tavg average of hot and cold boundary temperatures, K, N* MLI layer density, layers/cm, Ns number of MLI layers, ε MLI layer emissivity, $\varepsilon = 0.031$, P interstitial gas pressure, torr

Pre Test Predictions

The pre-test MLI performance prediction at an environment of 250 K (Thot) by the MLI vendor was 0.49 W. Our corresponding NASA predictions were between 0.4 and 0.74 W, using the various models specified and a layer density of 7.1 layers/cm.

Results

Measured Heating Rates

The measured heating rates are documented in Table 2. For the 250 K hot side, note that the heat through the MLI at 250 K is 1.6 W, much higher than the predicted half watt. This MLI heating rate and the others at their respective hot side temperatures are correlated to the equations in Table 1 by finding the degradation factors, which are shown in Figure 3. Here you can see they vary substantially with temperature, particularly for Equations (4-15) and (4-56). Note that the empirically derived Lockheed equations were designed to be good predictors of MLI performance for hot side temperatures between 39 and 389 K. The heat load for the diodes at 140 K hot side T is higher than that at other hot side T's, due to the temperature sensors being in liquid sensing mode, which adds more heat to the tank. Note that the resultant MLI heating at 140 K is small compared to Q total and, as such, it is more sensitive to the instrument error associated with the penetration measurements. It is less accurate than the other MLI results.

TABLE 2.—THE MEASURED HEATING RATES AT THE SPECIFIED HOT SIDE TEMPERATURE

Hot side T	Q Total (W)	Q MLI (W)	Q Pen. (W)	Q Support (W)	Q Wires (W)	Q Diodes (W)
350 K	9.1	4.8	2.6	0.59	1.1	0.00019
250 K	4.1	1.6	1.3	0.4	0.88	0.00019
140 K	2.2	0.16	0.79	0.35	0.74	0.19

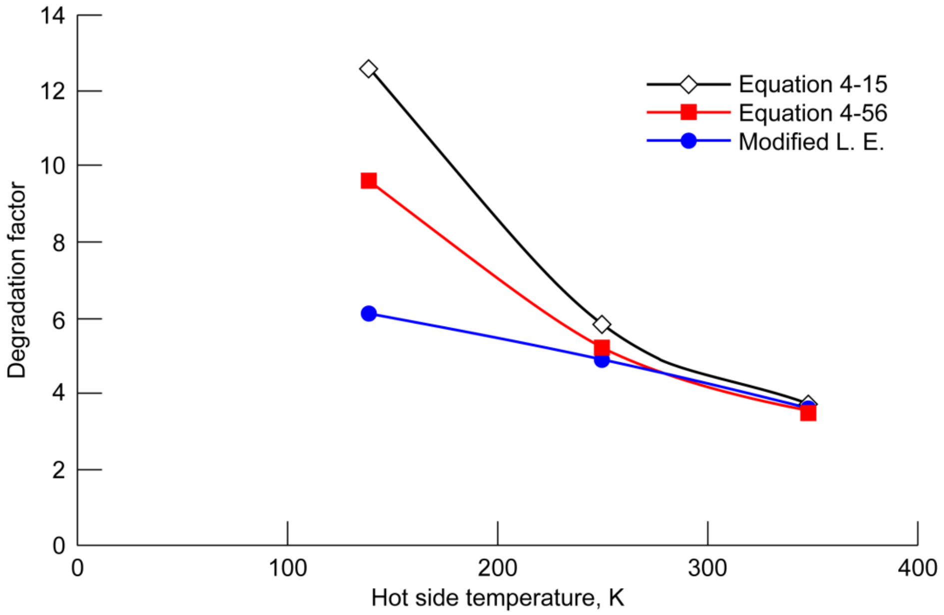

Figure 3.—A comparison of the resultant degradation factors found at each hot side temperature. The MLI layer density used was the as built 7.1 layers/cm.

MLI Disassembly

Given the lower than expected performance, we inspected and disassembled the MLI after the test to investigate the possible problems. We noted that there was a 1.5 cm wide by 45 cm long opening in one of the outer seams, something we had noted in previous test chamber depressurizations during checkout and pre-test operations. While this was a concern regarding the MLI's structural ability to handle depressurization cycles, we did not feel this opened area in a few mylar layers would result in a noticeable increase in radiation heat transfer. In addition to the opening, we noticed many irregularities in the MLI surface and decided map the MLI exterior using a Faro (Faro Technologies, Inc.) Arm 3-D mapping tool (Figs. 4 and 5). It found large inconsistencies in the MLI thickness, which varied from 200 to 54 mm. Note that at right equatorial side of Figure 4, the thickness of the outer 36 mylar layers is 23.8 mm (or 2.38 cm), which is a layer density of 15.1 layers/cm, substantially higher than the as built layer density of 7.1 layers/cm measured at the equator during installation. These variations in the outer MLI shape clearly caused many localized compressions. Also, after removing all of the MLI we found that the substrate, which was originally a cylindrical middle and semi-rigid conical shape on the tank ends, had collapsed to mostly take on the shape of the spherical tank; it supported the MLI only on a few ridges. This issue can even be seen in the outer MLI image shown in Figure 5.

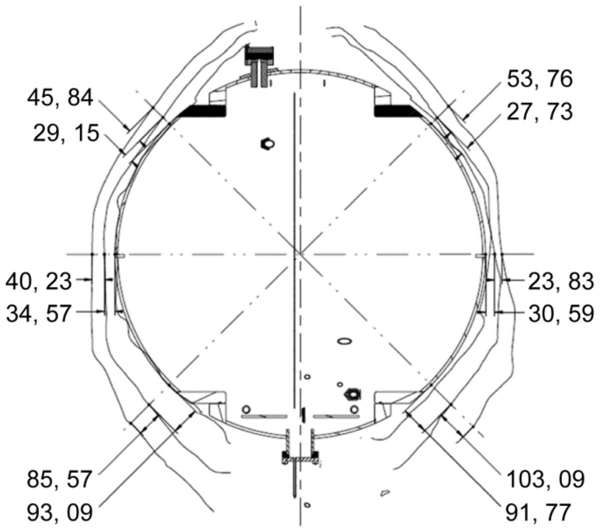

Figure 4.—The 3-D mapping tool images were over layed on the tank drawings to reveal the MLI perimeter. The first diametric line is the tank wall, the second is the MLI substrate, the third is the MLI profile of the 24 mylar shields closest to the tank, with the dimension being the difference (MM) between that surface and the substrate, and the fourth the outer MLI profile and the accompanying dimension of the difference between it and the 24th layer.

Figure 5.—Post test tank image with MLI outer shape sprayed with talcum power, which the 3-D mapping tool needed to map the MLI. Notice the MLI ridges near the top, which reveal that the MLI substructure failed.

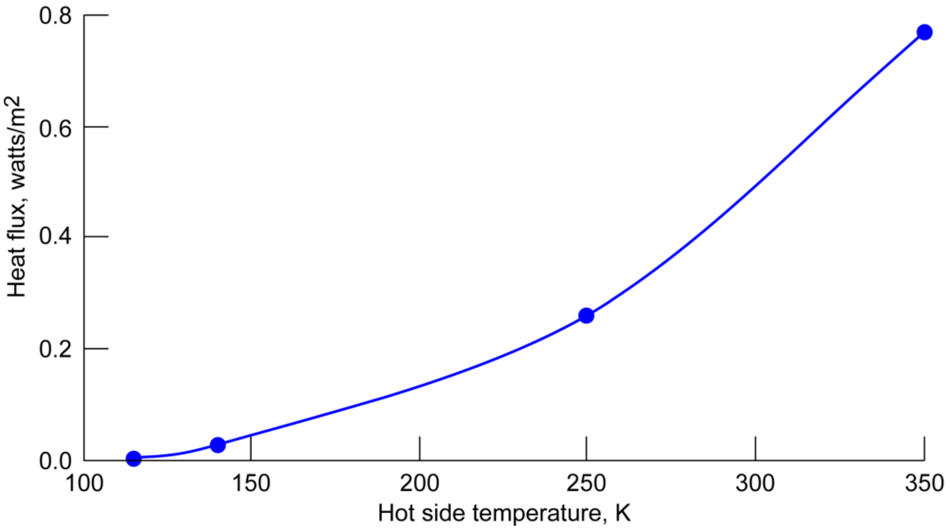

Figure 6.—By using the Modified Lockheed equation and solving for a density of 14.1 layers/cm and a degradation factor of 2.0, the test data points fall on the curve, confirming the temperature dependency of the predictive equation.

Resultant MLI Density

Because of the MLI density uncertainty and the fact that the MLI heat flux test data did not correlate well to the Lockheed equations presented, we turned the Lockheed equation around and solved for layer density, inputting the test temperatures and MLI heat. We used the Modified Lockheed Equation, which correlated best with the test data. This curve fit is shown in Figure 6. Here the data points fall on the curve at the warm boundary temperatures used in our test. Using this approach, the resultant MLI density was 14 layers/cm with a temperature independent degradation factor of 2.0. Interestingly enough, this layer density is consistent with the blanket layer density for the KSC calorimeter tests and the post test density discovered on part of the tank by the mapping tool. The degradation factor is also consistent with that of the MLI on the Space Shuttle PRSA Dewars and with the overall discussion presented by Lockheed Martin (Ref. 9).

A further issue with the modeling of the MLI is the application of the Lockheed Equations at low MLI densities. These equations were empirically developed from flat plate calorimeter data with layer densities of between 28 and 91 layers/cm, at least double the layer density in this test. This is seen as affecting the thermal contact between spacers and reflectors (and the associated contact resistances), and the gas conduction paths. As such, it is uncertain how applicable these industry standard equations are to low layer density MLI systems.

Pressurization

Integrating the tank heating from the established simulated launch ascent heating profile, which is documented in a separate paper (Ref. 3), plus the measured lunar transit, orbit, and lunar surface heating for their respective durations of the estimated mission timeline, one can estimate the state of the liquid for an unvented lunar lander concept. Given our initial densified state of 93 K, we project this insulation applied to this lander concept to allow the cryogen last unvented for 64 days, much less than the planned 180 days. This duration corresponds to the time it takes methane to reach 113 K, an upper bound set by the propulsion engineer to meet the engine start box requirement for lunar launch ascent. Our original model with an MLI degradation factor of 2 predicts 201 days of storage; the same MLI protected by a lunar and sun shade was projected for 243 days of unvented storage.

Summary

After 77 days of testing, which included a simulated ground hold, a simulated launch ascent atmospheric pressure profile, four different background temperatures at vacuum, and densified propellants generation, our test series generated much MLI, launch ascent heating, and tank pressurization data. While the data was disappointing as the MLI insulation heating rate significantly exceeded model predictions, several discoveries are of interest. MLI density must be maintained to ensure this important performance parameter is consistent and to prevent local blanket compressions. Any substrate used must be reinforced to handle the depressurization cycles. Also, the industry standard Lockheed equations do not predict MLI performance well at cold boundary temperatures for systems using Dacron netting as spacer material. In its place, the Modified Lockheed Equation is recommended with a degradation factor of at least two.

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14. ABSTRACT

NASA is considering propulsion system concepts for future missions including human return to the lunar surface. Studies have identified cryogenic methane (LCH_4) and oxygen (LO_2) as a desirable propellant combination for the lunar surface ascent propulsion system, and they point to a surface stay requirement of 180 days. To meet this requirement, a test article was prepared with state-of-the-art insulation and tested in simulated lunar mission environments at NASA GRC. The primary goals were to validate design and models of the key thermal control technologies to store unvented methane for long durations, with a low-density high-performing Multi-layer Insulation (MLI) system to protect the propellant tanks from the environmental heat of low Earth orbit (LEO), Earth to Moon transit, lunar surface, and with the LCH_4 initially densified. The data and accompanying analysis shows this storage design would have fallen well short of the unvented 180 day storage requirement, due to the MLI density being much higher than intended, its substructure collapse, and blanket separation during depressurization. Despite the performance issue, insight into analytical models and MLI construction was gained. Such modeling is important for the effective design of flight vehicle concepts, such as in-space cryogenic depots or in-space cryogenic propulsion stages.

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