# Thermal Cycling for Development of Hybrid Fuel for a Notional Mars Ascent Vehicle

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**A Mars Ascent Vehicle (MAV) would be a critical part of a potential Mars sample return campaign. As currently envisioned, the MAV would launch samples from Mars into Mars orbit. Challenging requirements would be placed on a MAV as it would need to be able to survive in the harsh Martian environment which can get as cold as -120°C in the winter. At these cold temperatures, survival heating could be necessary to keep the MAV within the allowable flight temperature range. Estimates for survival heating power show that a fuel capable of operating at low temperature would significantly reduce the total required energy of the MAV. This has led to consideration of a hybrid propulsion system due to its anticipated low temperature capability. A new wax-based fuel, *SP7*, has been developed for a notional MAV mission. Thermal modeling of the fuel in the Mars environment was completed in order to estimate the temperature response of the fuel during Mars diurnal temperature cycling. Preliminary thermal testing was conducted to determine the max temperature range, radial gradient, and ramp rate the fuel could tolerate without cracking. The modeling and preliminary testing was used to develop a comprehensive, 100-day thermal cycling campaign. A total of 200 cycles are planned that are representative of 200 Martian diurnal cycles, roughly one-third of a Martian year. After 150 cycles, the fuel samples show no signs of cracking that would jeopardize the rocket's performance. Though not yet complete, this testing is showing that *SP7* has the potential to successfully be used on a MAV mission.**

## Nomenclature

| | | |
|---|---|---|
| *AFT* | = | Allowable Flight Temperature |
| $c_p$ | = | Specific heat capacity |
| *CTE* | = | Coefficient of Thermal Expansion |
| $\varepsilon$ | = | Emissivity |
| *EDL* | = | Entry, Descent, and Landing |
| *HRS* | = | Heat Rejection System |
| *k* | = | Thermal conductivity |

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| | | |
|---|---|---|
| *MAV* | = | Mars Ascent Vehicle |
| *MDSC* | = | Modulated Differential Scanning Calorimetry |
| *MPFL* | = | Mechanically Pumped Fluid Loop |
| *MSL* | = | Mars Science Laboratory |
| *MSR* | = | Mars Sample Return |
| SPG | = | Space Propulsion Group, Inc |
| *WCC* | = | Worst Case Cold |
| *WCH* | = | Worst Case Hot |

## I. Introduction

A Mars Ascent Vehicle (MAV) would be a critical part of a potential Mars Sample Return (MSR) campaign. Although NASA has no official plans at this time for a mission to return samples from Mars, the Mars Technology Program sponsors ongoing mission concept studies, systems analyses, and technology investments which explore different strategies for the potential return of samples from Mars, consistent with the charter of the program and stated priorities of the science community. Additionally, MSR has been named the highest priority science objective for this decade (2013-2022) by the planetary science community[1]. As it is currently envisioned, MSR would consist of three elements: collecting samples, launching the samples into Mars orbit, and returning the samples to Earth. A MAV would complete the second element: launching the samples from the surface of Mars into Mars orbit. Returning samples from Mars would have many benefits including enabling complex, multistep procedures to be performed on the returned samples, as well as demonstrating two-way travel to and from Mars as a precursor to human exploration of the red planet.

The MAV faces challenging requirements, which have directed the evaluation of potential propulsion systems. Strict mass and geometry constraints will be placed on the. The MAV will have to survive in the harsh Martian atmosphere for one year or more, depending on the time phasing of the rest of the campaign. These requirements have led to the desire for a propulsion system that can survive in the Martian atmosphere with minimal thermal insulation and ideally, with no active thermal control. This has led to the consideration of a hybrid propulsion system for a potential MAV due to its anticipated low temperature capability.

Hybrid rockets utilize solid fuel and a liquid (or gaseous) oxidizer. The oxidizer is passed through a main valve, through an injector and enters the combustion chamber, where the fuel is stored. An igniter is used to vaporize a small amount of fuel to initiate combustion, which is self-sustaining until the oxidizer valve is closed. The solid fuel is predicted to have excellent low temperature behavior which makes it a good candidate for use in a MAV mission as well as for use in outer planet exploration. Low temperature oxidizers, such as mixed oxides of Nitrogen (MON) with high NO concentrations, have been known for some time. Additionally, hybrid rockets enjoy many safety advantages over liquid and solid rockets because fuel and oxidizer are physically separate and in different states, making an accidental mixture and ignition difficult to achieve.

**Figure 1. SP7 fuel grain slices. The sample on the right has 20% aluminum by mass added to the SP7. Each slice has approximately 10 inches outer diameter, 5 inches inner diameter, and 2.5 inches height.**

A new hybrid fuel was developed for consideration in a MAV application. Space Propulsion Group, Inc. (SPG) of San Mateo, CA, has formulated and provided a wax-based fuel, called SP7. It was developed specifically to survive extreme temperatures from at least -100°C to 50°C at relatively slow ramp rates. SP7 is also high performance and capable of handling structural loading imposed by the combustion process. SPG has conducted more than 20 labscale tests of SP7 with nitrous oxide as the oxidizer to confirm these requirements. Fig. 1 shows two SP7 fuel slices of different composition. The sample on the left is just SP7 and the sample on the right has 20% aluminum loading by mass. Both have composite liners to restrain the outside of the fuel grain, similar to what would be expected in a flight-like configuration. In addition to the wax-based SP7, a paraffin-based wax fuel has also been considered for a MAV in the past[2]. The weak glass transition temperature of paraffin wax is fairly low, estimated around -80C, making it a good candidate for survival in the Martian environment. However, compared to paraffin, SP7 has a wider temperature range for both storage and operation.

Several thermal cycling experiments were conducted in order to further the technology readiness of SP7 and gain understanding of its survivability for use in a MAV mission. The thermal cycling tests were designed to assess if the fuel can survive the temperature condition that the fuel would experience inside a thin layer of passive insulation on Mars. The criteria for successful testing was for the fuel to not crack. Cracking in the radial and axial directions is of particular concern as this could result in fragmenting of the fuel. A small amount of circumferential cracking or debonding at the fuel outer diameter was expected for these tests as the fuel is wrapped with a composite liner, which has a coefficient of thermal expansion (CTE) mismatch with the fuel. Circumferential cracking and debonding at this interface is a known issue and is being studied in parallel to the thermal cycling efforts.

## II. MAV Thermal Design Concept

One possible mission concept for a MAV to return Mars samples is shown in Fig. 2. In the mobile MAV concept, the MAV would be carried on a rover, which could also be used to fetch samples and transfer them to the MAV. This conceptual mobile MAV is similar in size and weight to the Mars Science Laboratory (MSL) Curiosity Rover, as well as the Mars 2020 rover currently under development at JPL. It would likely use a similar mobility, telecom, and avionics as the previous Mars rovers. In this concept, the MAV would be contained in a launch tube, nestled within the rover chassis. The MAV would remain on the rover during sample retrieval and collection on the Martian surface, and would be erected prior to the MAV's launch. While a mobile MAV might be desirable, no decision has been made to this end. The MAV could be mobile, as shown in Fig. 2 or could be on a pallet lander. The thermal requirements would be similar for both options.

The thermal design concept for a MAV would be very similar to that used on the MSL and Mars 2020 rovers[4,5]. Since the landing site for such a mission is not yet known, a bounding approach using Worst Case Cold (WCC) and Worst Case Hot (WCH) environments is needed. The latitude is assumed to be constrained to the +/- 30° range. The thermal design concept for a MAV would use multiple techniques to withstand the extreme diurnal and seasonal temperature variations on Mars. White paint would likely be used on the external structure to protect against overheating in the summer, when ground and atmospheric temperatures can reach 38°C and 13°C, respectively. The external structure and all external components would also need to be designed in such a way so that they would be able to survive the cold Martian winter, when the ground and atmospheric temperatures can drop to -120°C and -124°C, respectively. However, not all components can be designed to survive such cold temperatures. For example, the MSL and Mars 2020 avionics were designed to a cold allowable flight temperature (AFT) of -40°C and were qualified to the cold temperature of -55°C. It is likely that the MAV avionics would have the same cold side temperature requirements. Another key component that cannot be designed to survive such cold temperatures is the MAV itself. The propulsion system baselined for use (bi-prop, solid, or hybrid) determines the allowable cold temperature, ranging from 0°C to -100°C, with the hybrid option being the coldest allowable.

In order to keep components such as the avionics and MAV warm, survival heat would need to be supplied using either survival heaters or a

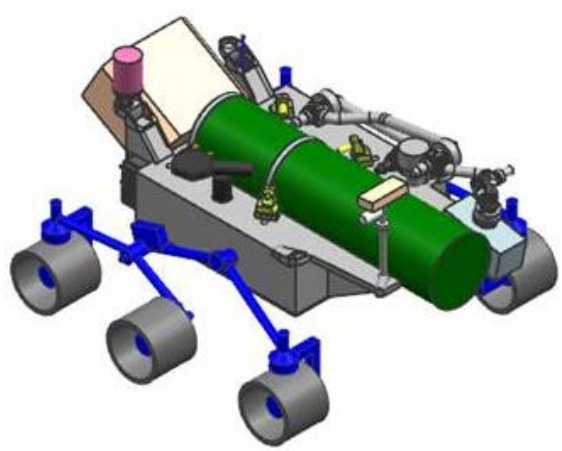


**Figure 2. Mission Concept for a Mobile MAV rover of a similar size and weight as MSL and Mars 2020.**

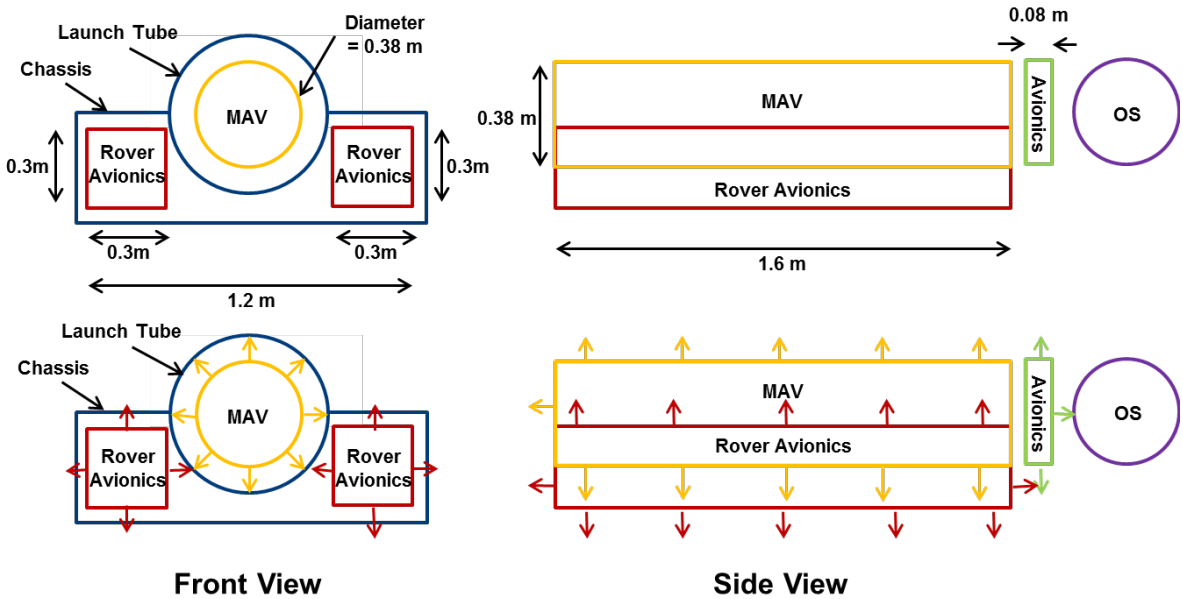



**Figure 3. Notional dimensions, configuration, and heat loss diagram for a MAV thermal design concept.**

Mechanically Pumped Fluid Loop (MPFL) Heat Rejection System (HRS) as is used on MSL and Mars 2020. Insulation would also be necessary to reduce the amount of supplied heat that would be needed for survival; additionally, power savings can be achieved by isolating components which require different thermal conditions. The MAV would likely use a $CO_2$ gas gap for insulation. $CO_2$ gas is used on MSL and Mars 2020 as it presents numerous advantages over other insulation options due to its low density, cost, ease of installation, and good performance[6-10]. Aerogel can offer improved performance over $CO_2$ gas gap insulation when volume is severely constrained, but is disadvantageous from a cost, complexity, and mass standpoint. Finally, the avionics and MAV components would need to have thermally isolating structures and cabling to prevent excessive heat losses through these conductive paths.

Because of the importance of survival heating on the rover's thermal design, a sensitivity study was undertaken to estimate the survival heating needed for the MAV design concept shown in Fig. 2. This study was a first order attempt to capture the survival heating needed at a range of landing latitudes and seasons. A total of 18 assumed environments were considered which represented 6 latitudes (30S, 27S, 15S, 0, 15N, 24N) and 3 seasons at each latitude (Summer, Spring, and Winter). These latitudes and seasons were chosen because they encompass a wide range of environmental variation. For each environment, the launch tube and rover chassis cold structure were assumed to be at the atmospheric minimum temperature for a half sol (Martian day) and the atmospheric maximum temperature for the other half sol.

The notional dimensions, configuration, and heat loss diagram for a MAV design concept is shown in Fig. 3. Using MSL and Mars 2020 as a template, the rover avionics and MAV would both be approximately 1.6 m in length, the rover would be about 1.2 m in width, and the MAV would have a diameter of approximately 0.38 m. The rover avionics volume would have a cross section of roughly 0.3 m x 0.3 m on each side of the MAV, and the MAV avionics would occupy a cylindrical volume with a height of about 0.08 m. The rover avionics, MAV, and MAV Avionics would all lose heat to the rover chassis and launch tube cold structures. The MAV thermal design concept and insulation would not need to change substantially for a platform lander.

In these studies, the MAV and MAV avionics were assumed to be insulated with a total of four inches of $CO_2$ gas gap circumferentially with an aluminized Mylar sheet used to suppress convection within the gap. The MAV and MAV avionics were assumed to have only two inches of $CO_2$ gas gap axially, and the rover avionics were assumed to be insulated with only two inches of $CO_2$ gas gap on all sides due to volume constraints. All internal rover and MAV surfaces were assumed to be low emissivity ($\varepsilon$ = 0.1). Structural heat losses of 0.1 W/C, 0.05 W/C, and 0.02 W/C were assumed for the MAV, MAV avionics, and rover avionics, respectively. These are very rough estimates based on structural heat losses for components of similar size on previous missions. Cabling heat losses were ignored for the purposes of this study, although they should be considered in more detail for future studies.

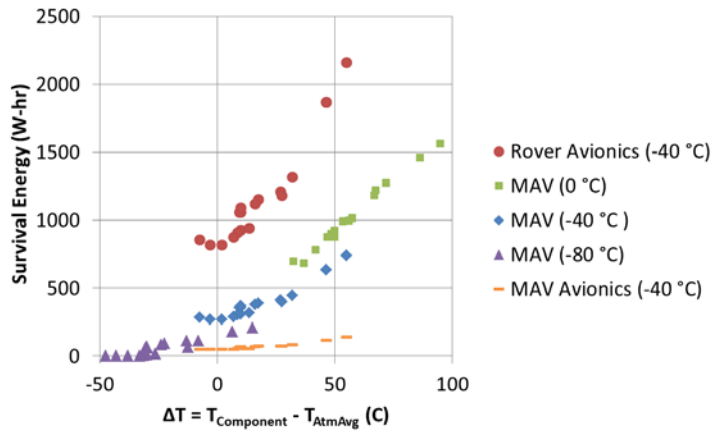



**Figure 4. Estimated survival energy for the rover avionics, MAV, and MAV avionics shown as a function of the difference between the component and average atmospheric temperature for a particular environment.**

The survival energy for the rover avionics, MAV, and MAV avionics were estimated for each of the 18 environments, and are plotted in Fig. 4. For a given series, each value represents the survival energy for a particular latitude and season. In this figure, the survival energy for a component is plotted against the difference between that component temperature ($T_{Component}$), and the average atmospheric temperature over the sol ($T_{AtmAvg}$). Fig. 4 offers several insights. First, a significant amount of survival energy could be saved if the MAV were capable of surviving cold temperatures. A MAV capable of surviving colder temperatures might also only need two inches of gas gap insulation which would be a significant volume savings compared to the four inches of insulation assumed for this survival energy study. The reduction in survival energy and/or insulating volume is the primary motivation behind the effort to study MAV architectures which might be capable of surviving cold temperatures. Second, survival heating may be necessary even when the average atmospheric temperature is warmer than the AFT of a component, however the amount needed would be very small. This is because nights on Mars are very cold, and although the thermal mass of a component would help keep it warm, thermal mass alone might not be sufficient to keep the MAV above its AFT. Third, the survival energy for the rover avionics is larger than that for the MAV or MAV avionics. This means that even if the MAV is qualified cold, a significant amount of survival heat could still be needed. However, the rover avionics, unlike the MAV, would dissipate heat every sol as the rover operates to accomplish its mission. Some of this dissipated heat would help keep the rover avionics warm and would reduce the amount of pure survival heating necessary.

## III. MAV Thermal Analysis

Samples of both the aluminized and non-aluminized compositions of SP7 fuel were analyzed by the Analytical Chemistry Laboratory at JPL to measure their specific heat capacity ($c_p$) and thermal conductivity ($k$). The temperature dependent specific heat capacity of the fuel was measured using Modulated Differential Scanning Calorimetry (MDSC). The temperature dependent thermal conductivity was measured using a Transient Hot Bridge instrument. The measurements for specific heat capacity are shown in Fig. 5, and the measurements for thermal conductivity are shown in Fig. 6. The measured values for the aluminized wax were 1.259 J/g·°C (average specific heat capacity from -80°C to 40°C), and 0.518W/m·°C (average thermal conductivity from -90°C to 35°C). The measured values for the non-aluminized wax were 1.248 J/g·°C (average specific heat capacity from -80°C to 40°C), and 0.348 W/m·°C (average thermal conductivity from -90°C to 35°C). The coefficient of thermal expansion for non-aluminized SP7 is shown in Fig. 7. Finally, the average density of the aluminized samples was calculated as 1194 kg/m$^3$; the average density of the non-aluminized samples was calculated as 1056 kg/m$^3$. The density calculation was completed using a measured mass and measured dimensions to get the volume of each sample. An error of +/- 5% would be appropriate for these calculations.

A simple MAV 1-D thermal model was made using Thermal Desktop® using the SP7 slice geometry and the measured thermophysical properties. The goal of this model was to estimate what the MAV fuel would experience on the Martian surface. A two inch layer of $CO_2$ gas gap with low emissivity surfaces was used as a conservative insulation estimate for the MAV thermal design. Insulation around the fuel guards against the possibility of needing survival heating at the coldest Martian locations and also reduces the diurnal temperature swing and gradients

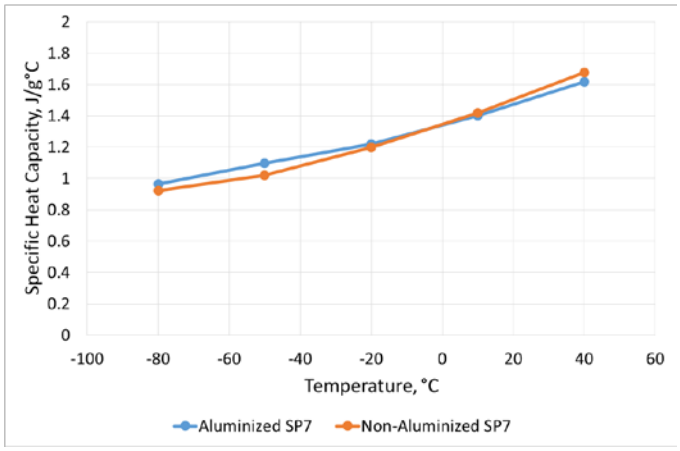



**Figure 5. Specific heat capacity measurements for aluminized and non-aluminized SP7 fuel.**

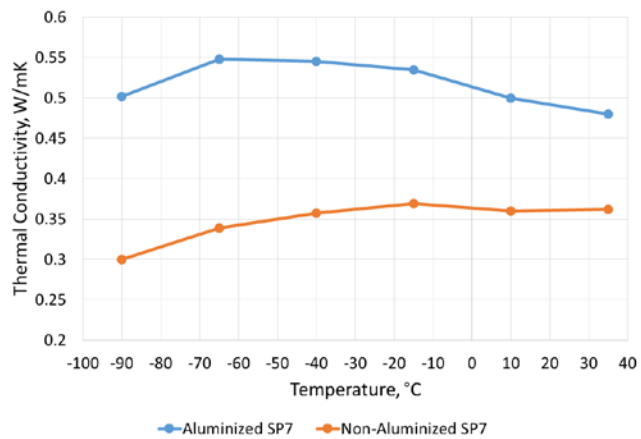



**Figure 6. Thermal conductivity measurements for aluminized and non-aluminized SP7 fuel.**

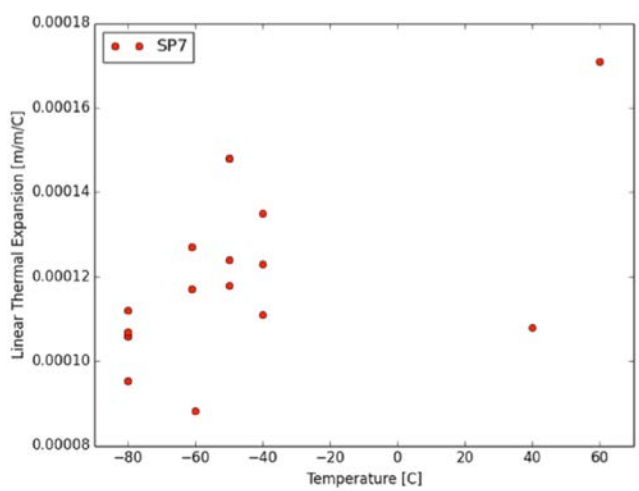
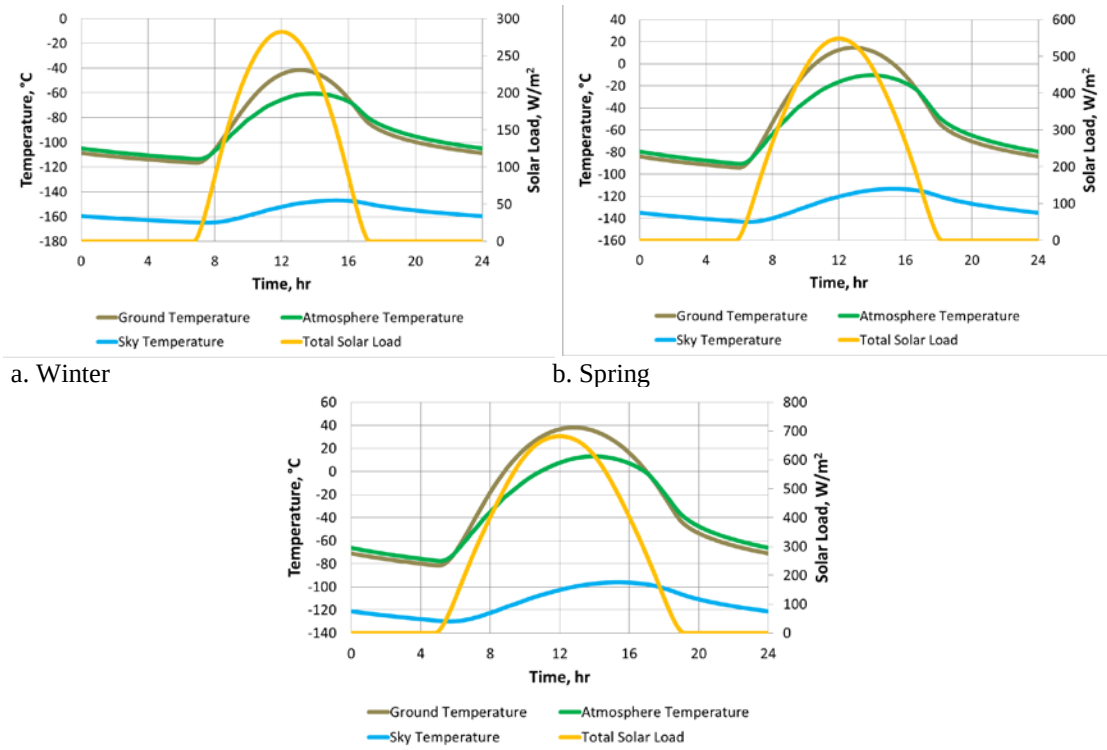



**Figure 7. Temperature dependent coefficient of thermal expansion for SP7 fuel**

experienced by the fuel. No insulation would produce extreme temperature swings and gradients in the fuel that might be difficult to survive, whereas a four inch gas gap imposes a large design volume. A two inch gas gap was used as a compromise between no insulation and four inches of gas gap. Future missions considering the use of hybrid fuel will need to assess the desires of reducing thermal loads against the need to reserve volume.




a. Winter b. Spring

c. Summer

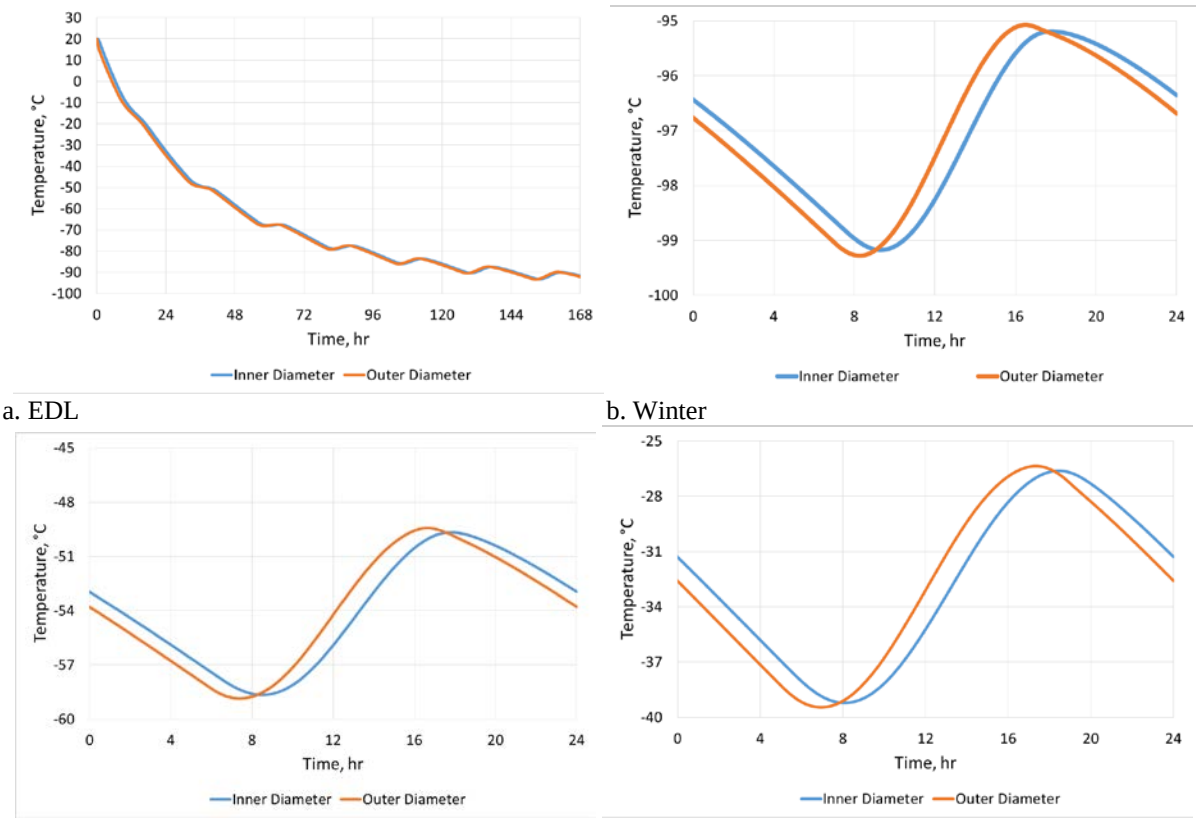
**Figure 8. Mars environments used for MAV thermal analysis**

Four environments were used to estimate the diurnal temperature cycling that SP7 could experience on the surface throughout the Martian year. The four environments are: worst case cold (WCC) winter, average spring, worst case hot (WCH) summer, and entry-descent-landing (EDL) during winter. The winter, spring, and summer environments enabled estimates for the diurnal temperature response of the MAV fuel throughout the mission lifetime. The spring environment also serves as a good approximation for fall. The ground temperature, atmosphere temperature, sky temperature, and solar load for these three environments are shown in Fig. 8. In the EDL scenario the MAV is at an initial temperature of 20°C and is assumed to land on the surface during the WCC environment. This EDL scenario results in the largest temperature swing, from 20°C to approximately -100°C, that the MAV could experience within a short amount of time. The predicted fuel temperatures in the four environment cases are shown in Fig. 9.

In these simulations, the min and max temperature, radial gradient, and temperature ramp rate were predicted and are shown in Table 1. The predicted temperature range is desired so that the SP7 samples can be tested to those temperatures. If the fuel experiences cracking within these temperature ranges then survival heating or additional insulation could be necessary in the MAV thermal design. The radial gradient and temperature ramp rate are of interest as they may have a role in fuel cracking mechanism. The temperature conditions provided by this thermal analysis are estimated values for what the MAV fuel could see experience during its mission; therefore, these values should be achieved at minimum during the thermal cycling tests. Conducting thermal cycling tests with a wider temperature range and larger gradients and ramp rates will give confidence that SP7 fuel could survive a MAV mission.

| | EDL | Winter | Spring | Summer |
|---|---|---|---|---|
| **Max Temperature, °C** | N/A | -95 | -49 | -27 |
| **Min Temperature, °C** | N/A | -100 | -59 | -40 |
| **Max Radial Gradient, °C** | 7.0 | 0.9 | 1.8 | 2.3 |
| **Max Ramp Rate, °C/hr** | 7.3 | 0.8 | 1.6 | 2.0 |

**Table 1. Fuel temperature predictions throughout the Martian year assuming a 2-inch $CO_2$ gas gap around the fuel diameter for passive insulation.**




a. EDL b. Winter

c. Spring d. Summer

**Figure 9. Fuel temperature predictions throughout the Martian year assuming a 2-inch $CO_2$ gas gap around the fuel for passive insulation.**

## IV. Preliminary Thermal Testing

A preliminary testing program for the SP7 fuel was performed at JPL in ambient, 1 atm, pressure conditions to complete a rapid test of the fuel's temperature capabilities[11]. The goal of this testing was to determine the conditions that the fuel could experience without cracking. The set up for the preliminary testing is shown in Fig. 10. Two SP7 slices, one aluminized and one non-aluminized, were sandwiched between Styrofoam insulation. The insulation ensured that the primary thermal gradient was in the radial direction as well as allowing for a simple way to determine that the entire sample reached the desired cold temperatures since the inner diameter lags in temperature more than any other part of the sample. Thermocouples were instrumented at the inner and outer sample diameters.

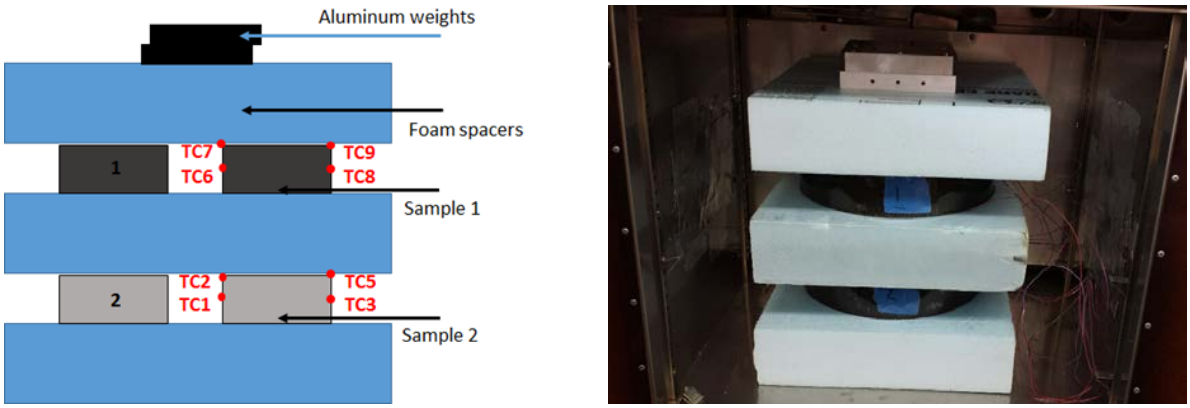



**Figure 10: Experimental set up for preliminary thermal testing of SP7 fuel samples[11]**

| | Preliminary Test Results |
|---|---|
| **Max Temperature, °C** | 53 |
| **Min Temperature, °C** | -115 |
| **Max Radial Gradient, °C** | 17.5 |
| **Max Ramp Rate, °C/hr** | 10.8 |

**Table 2. Most severe temperatures experienced by the SP7 fuel samples during preliminary testing. These results serve as do-not-exceed values for further testing.**

Temperature cycling of the samples was performed over an increasing range in order to determine the capabilities of the samples. First, three cycles were performed from 50°C to -70°C, followed by an inspection, three more cycles from 50°C to -90°C, followed by an inspection, and finally three more cycles from 50°C to -110°C. Chamber ramp rates were set as slow as reasonably possible (6°C/hr) in order to make the temperature the only variable of interest by reducing gradient or ramp rate effects. A 12 hour soak was used at the temperature extremes of each cycle to ensure all of fuel reached the desired temperature extremes. Both samples survived the three rounds of increased temperature range testing (no significant cracking was observed). Further testing was conducted with increased temperature ramp rates. Neither sample cracked at a ramp rate of 10°C/hr, and one of the two samples had significant cracking at a ramp rate of 15°C/hr. A varying radial gradient was observed in testing at increased temperature ranges and increased ramp rate. Table 2 shows the maximum conditions experienced by the fuel for which no cracking was observed in either sample. These values therefore served as upper limits for further tests as cracking may occur beyond these values.

## V. Long Term Thermal Cycling

The preliminary testing cycled the samples for a maximum of three cycles. This is not representative of what would be experienced on Mars where temperature cycling would occur on a daily basis. The goal for the long term testing is to perform as many cycles as possible that are representative of what a MAV could experience on Mars. Performing many 24.6 hour temperature cycles that tracks the temperature of Mars would be cost and time prohibitive. Ideally the cycles should be short as possible while remaining within the temperature bounds set by the thermal analysis and preliminary thermal testing. The thermal analysis and simulation using the four environments gives temperature results that could be expected during a MAV mission. The thermal cycles for the long term testing should at minimum induce these temperature responses in the samples. The preliminary testing at JPL serves as the upper limit temperature values that should not be exceeded as samples may experience cracking beyond those values.

The long term cycling testing was performed at NASA's thermal/vacuum facility at MSFC. This specific setup utilized a vacuum chamber and an internal shroud controlled by a cooling cart which utilizes liquid Nitrogen and heater control arrangement to control to a desired temperature and rate. The configuration for the long term thermal cycling test is shown in Fig. 11. Eight SP7 fuel samples (four with aluminum and four without) are vertically stacked inside a temperature controlled shroud within a vacuum chamber with 6 torr $GN_2$. A thermal model of this test configuration was made in Thermal Desktop® in order to develop shroud temperature profiles that would result in fuel temperatures within the bounds of the thermal analysis and the preliminary testing. The thermal model was correlated to a checkout test that was performed for validating the testing equipment. Shroud temperature cycles were designed and iterated using this correlated model. The predicted min/max temperature, max gradient, and max ramp rate were checked for each of the eight fuel samples at each iteration. The goal of the iteration process was to minimize the cycle time so that more cycles could be achieved with the allotted test timeframe and budget while ensuring the temperature response is within our desired bounds. The final cycle durations are: EDL cycle 36 hours, winter cycle 15 hours, spring cycle 10 hours, and summer cycle 12 hours. Appendix E details these cycles. With these cycles we expect to conduct 1 EDL cycle, 50 winter cycles, 100 spring/fall cycles, and 50 summer cycles. This is representative of roughly 200 Martian diurnal cycles (roughly 1/3 of a Martian year). The predicted temperature response of the samples based on the designed cycles is shown in Fig. 12. The testing of the fuel samples with the designed shroud temperature profiles commenced in February 2015. A snapshot of the test data from the first 5 days of testing is shown in Fig. 13. The temperature data from only one sample is shown for clarity.

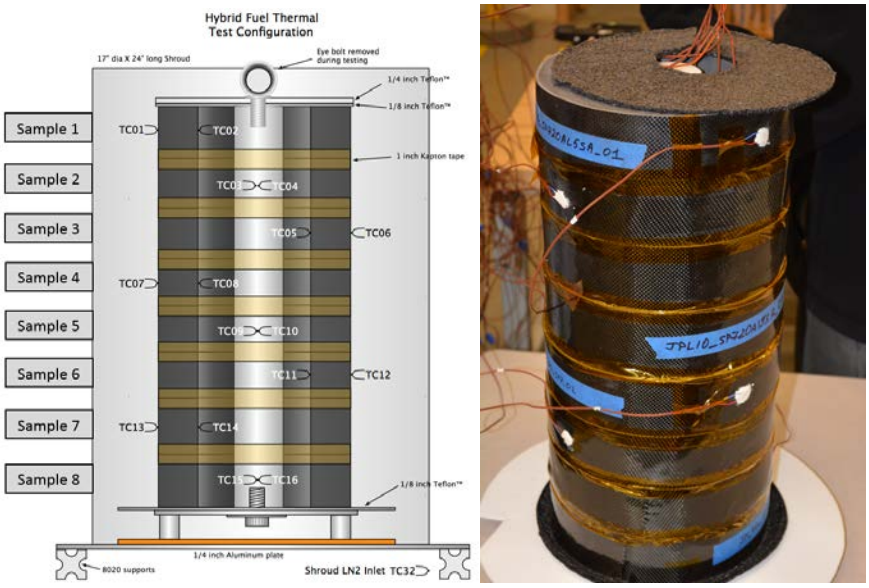



**Figure 11. Test configuration for long term temperature cycling of eight SP7 fuel samples. Each fuel sample is instrumented with a thermocouple at the inner and outer diameters.**

The EDL cycle and the 50 winter cycles have been completed. The samples were removed from the test chamber for inspection following the completion of the 50 winter cycles. Small cracks were observed on a couple of samples; no large radial cracks were observed. Some small cracks were visible in the circumferential direction as expected. Further testing will determine if these cracks are an issue if they propagate into larger cracks or if they can be prevented. All eight samples successfully survived the EDL and winter cycles and will continue testing with the 100 spring/fall cycles.

The EDL cycle results are shown in Table 3. All samples had temperature ranges exceeding 38°C to -96°C. The maximum predicted gradient for EDL on Mars is 7.0°C and all the samples exceeded 10°C gradient in the EDL test cycle. The max expected ramp rate for EDL on Mars is 7.3°C/hr. Three of the samples did not achieve this max ramp rate, with the lowest sample being 6.9°C/hr. However, these samples did exceed 7.3°C/hr during the winter cycling. The goal of meeting the estimated temperature response for the EDL environment was therefore achieved.

The 50 winter cycle results are shown in Fig. 14. The samples all survived 50 cycles and each sample experienced a different temperature range. The coldest sample reached -112°C, and all the samples reached temperatures colder than -100°C. This gives confidence that the fuel could be qualified to this temperature. Furthermore, the samples' success at -100°C dramatically reduces the needed survival heating and can be seen on the low end of Fig. 4. Both the ramp rate and gradient exceeded what would be expected on Mars based on the analysis while staying within the limits imposed by the preliminary testing. Survival at these large values of gradient and ramp rate gives further confidence for the fuel's performance on a MAV mission. Appendix D shows before and after photos of the eight samples from the winter cycling.

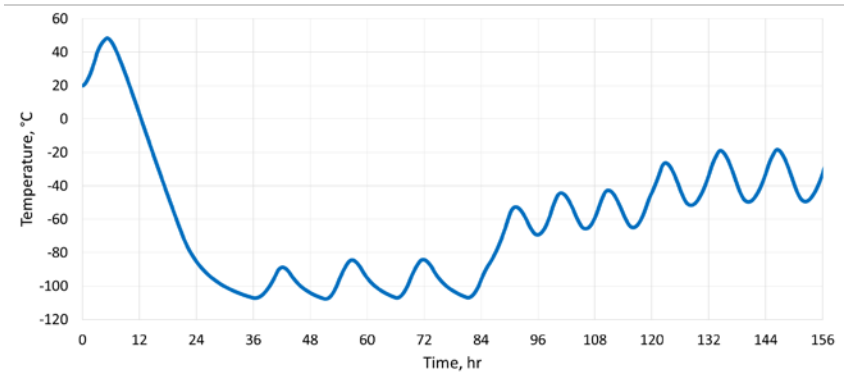
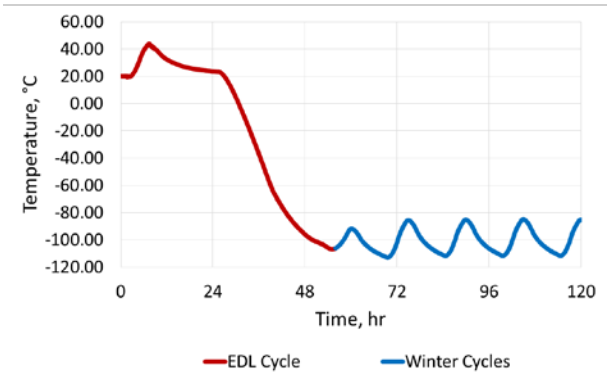
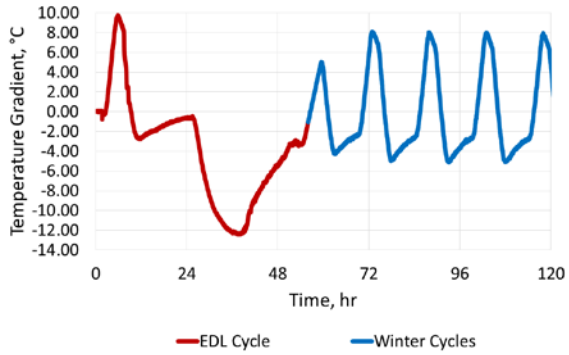


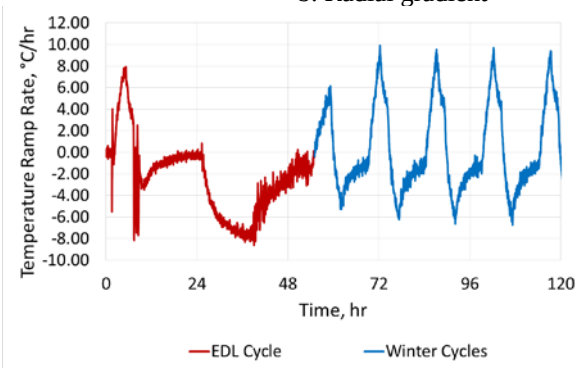

**Figure 12: Predicted temperature response for an EDL cycle, 3 winter cycles, 3 spring cycles, and 3 summer cycles.**




a. Temperature profile

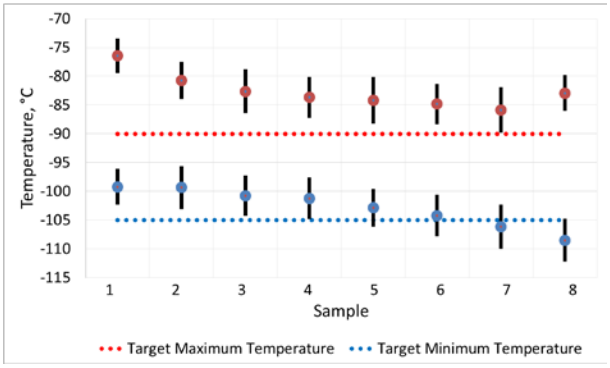



b. Radial gradient

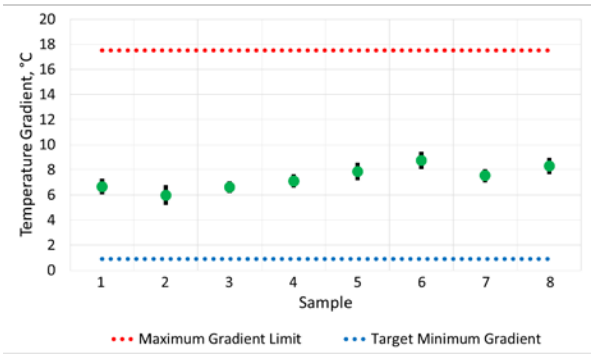



c. Temperature ramp rate

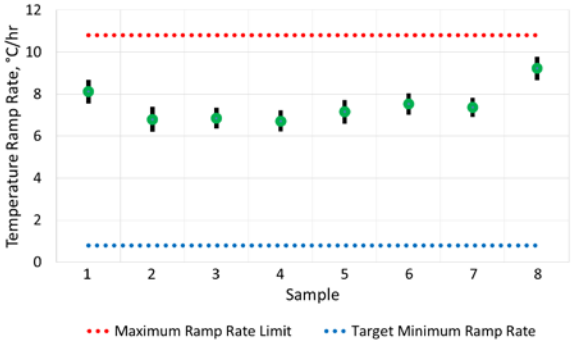
**Figure 13. Raw data from first 5 days of thermal testing**




a. Temperature range




b. Radial gradient




c. Temperature ramp rate

**Figure 14. The average temperature results from the 50 winter cycles for the 8 fuel samples.**

| | Sample | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| **Max Temperature, °C** | 39.2 | 38.3 | 38.1 | 38.4 | 40.5 | 41.6 | 42.1 | 44.1 |
| **Min Temperature, °C** | -96.3 | -96.3 | -96.7 | -97.4 | -98.9 | -101.3 | -104.2 | -107.1 |
| **Max Radial Gradient, °C** | 10.2 | 10.6 | 11.4 | 11.7 | 13.7 | 15.7 | 14.1 | 12.4 |
| **Max Ramp Rate, °C/hr** | 7.5 | 7.5 | 6.9 | 7.1 | 7.2 | 7.9 | 8.1 | 8.6 |

**Table 3. EDL cycle temperature results for the eight samples.**

## VI. Ramp Rate and Radial Gradient Effect on Fuel Cracking

Not all of the testing resulted in crack-free fuel samples, and some of the testing resulted in severe cracks. The criteria for success was no visual cracking of the fuel in the radial or axial directions (small amounts of cracking in the circumferential direction was expected due to the CTE mismatch between the fuel and the outer liner). Some of these conditions were planned, while others were unplanned, caused by test equipment malfunctions and unexpected events. Regardless, all of these tests provide useful information which provides insight into the causes of cracking in the fuel samples. Four cases that resulted in cracking are detailed below and summarized in Table 4.

1. During the third cycle of the 50°C to -110°C test a power outage occurred that stopped the flow of $LN_2$ into the chamber. This resulted in a quick temperature rise and the samples experienced gradients and ramp rates above the limits from Table 2. No cracking was observed in either sample. Before and after photos of the two samples from this case are shown in Appendix A. (Preliminary testing)
2. During the planned temperature cycling at a ramp rate of 15 °C/hr, both samples experienced gradients and ramp rates above the limits from Table 2. However, only one of the samples cracked. The sample that cracked experienced the larger gradient. Before and after photos for the cracked sample is shown in Fig. 15. Before and after pictures of the both samples from this case are shown in Appendix B. (Preliminary testing)
3. During testing with eight samples, a solenoid valve failed open and flooded the chamber shroud with $LN_2$. Nitrogen flow was cut off to prevent the chamber and samples from becoming too cold. The shutoff resulted in a quick temperature rise of the samples and the samples experienced gradients and ramp rates above the limits from Table 2. Six of the eight samples cracked, though there was no clear relationship between either between gradient or ramp rate and cracking. A representative photo of a cracked sample in this test case is shown in Fig. 16. Before and after pictures of the eight samples from this case are shown in Appendix C. (Long term testing)
4. Midway through the planned winter cycling a contact relay failed, resulting in a valve to remain closed and preventing flow of $LN_2$ into the chamber. This resulted in a quick temperature rise and the samples experienced ramp rates (but not gradients) above the limits from Table 2. None of the eight samples cracked. Before and after pictures of the eight samples from the winter cycling are shown in Appendix D. (Long term testing)

A key observation that is made from these four cases is that the thermal gradient may be responsible for the fuel cracking. In general, samples that experienced high gradients, as in the 15°C/hr case and solenoid failure case, were more likely to crack. The ramp rate, on the other hand, appears to not be responsible for cracking. High ramp rates were experienced during the power outage, solenoid failure, and contact relay failure, yet samples only broke in the solenoid failure case where radial gradients were high. The data suggests that radial gradients less than or equal to about 20°C do not cause cracking, gradients of about 20 to 25°C may cause cracking, and gradients of greater than about 25°C are likely to cause cracking. These observations should be kept in mind for future work, although more rigorous testing will be required to validate these claims.

| | **Preliminary Test Results** |
|---|---|
| **Max Temperature, °C** | 53 |
| **Min Temperature, °C** | -115 |
| **Max Radial Gradient, °C** | 17.5 |
| **Max Ramp Rate, °C/hr** | 10.8 |

**Table 2. Most severe temperature results for the SP7 fuel samples during preliminary testing. These results serve as "do not exceed" values for the next set of thermal testing.**

**Figure 15: Before and after pictures of SP7 fuel that cracked during the 15°C/hr test.**

**Figure 16: Before and after picture of SP7 fuel that cracked during the solenoid failure.**

## VII. Future Work

The 100 spring/fall cycles have recently been completed. Data from this second part of the test campaign has not yet been analyzed, but a visual inspection did not reveal any cracking in the samples. The 50 summer cycles recently began and a final visual inspection will conclude the testing. Once the temperature cycling is completed, the circumferential fuel cracking will be studied in more detail. It is likely that circumferential cracking is caused by the CTE mismatch between the fuel and the outer liner. Future work on determining the cause of radial and axial cracking in the failed samples also should be completed.

Finally, the implications of cracked samples will need to be studied in more detail to determine if they can be tolerated. Preliminary testing at JPL has shown that paraffin-based fuels burn slightly faster in regions with radial cracks due to the slightly increased available surface area[12]. This could lead to a burn through or the requirement for more insulation to protect the fuel grain. However, wax-based hybrids have also been thought to be self healing. Melted wax may fill the crack and heal it during combustion. Either way, a crack in a hybrid fuel grain is not as catastrophic as it would be in a solid fuel grain, where the flame will propogate into a propellant crack, increase the total surface area and increase the pressure which could lead to case over pressure or burn thru. Combustion cannot be sustained down the length of the crack, since there is no oxidizer available in that area. The final effect of cracks on the MAV design still must be evaluated.

## VIII. Conclusion

Challenging thermal requirements would be placed on a MAV mission as it would need to be able to survive in the Martian environment. In the winter ambient temperature can reach as cold as -120°C. At these cold temperatures, survival heating could be necessary to keep the MAV fuel within the allowable flight temperature range. Estimates for survival heating show that a fuel capable of operating at low temperature would significantly reduce the required survival heating energy. Use of a low temperature capability fuel would significantly reduce the necessary survival heating. A new wax-based fuel, *SP7*, has been developed for testing for a MAV application.

Thermal modeling of the fuel was performed to estimate the fuel's temperature response during diurnal temperature cycles on Mars. Preliminary thermal testing was then conducted to determine the max temperature range, radial gradient, and ramp rate the fuel could experience before cracking. The modeling and preliminary testing was used to develop a comprehensive 100-day thermal cycling campaign encompassing cycles for EDL, winter environment, spring environment, and summer environment. The fuel samples have finished the EDL, winter, and spring cycling without sustaining cracks. This successful testing shows that this fuel has the potential to be successfully used in a MAV mission. Further testing, however, will be required to raise the Technology Readiness Level of the fuel for consideration on a flight-mission.

## Appendix

### A. Power Outage Photos: Before and After

Aluminized SP7: no cracking was observed

Non-Aluminized SP7: no cracking was observed

### B. 15°C/hr Photos: Before and After

Aluminized SP7: cracking was observed

Non-Aluminized SP7: no cracking was observed

### C. Solenoid Failure Photos: Before and After

Sample 5

Sample 6

Sample 7

Sample 8

Sample 10

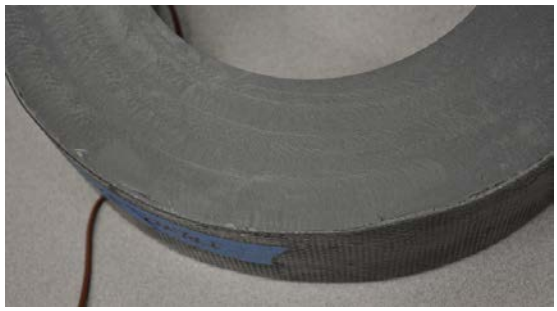
Sample 11

Sample 12

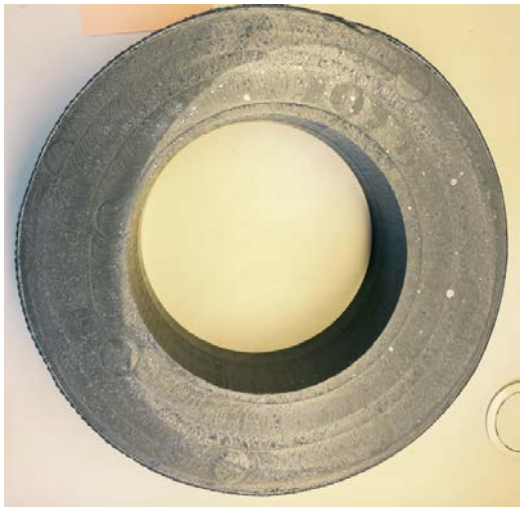
Sample 14

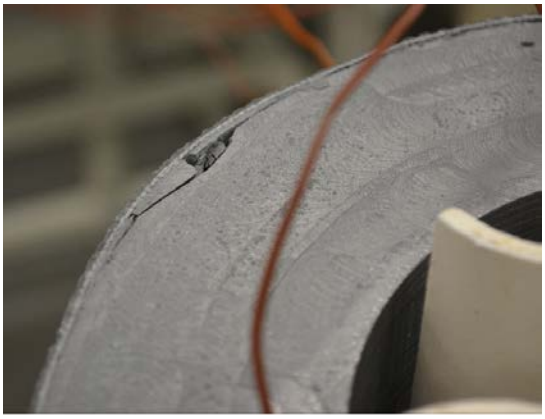
### D. Winter Cycling Photos: Before and After

Sample 1

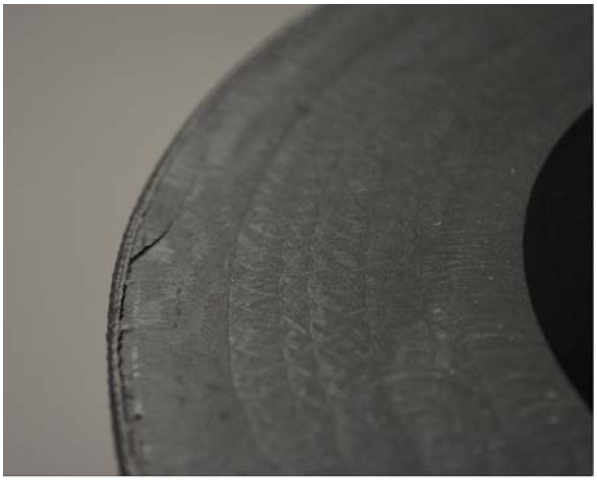


Sample 2

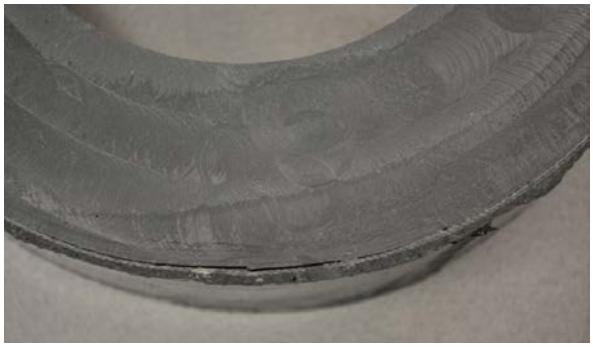




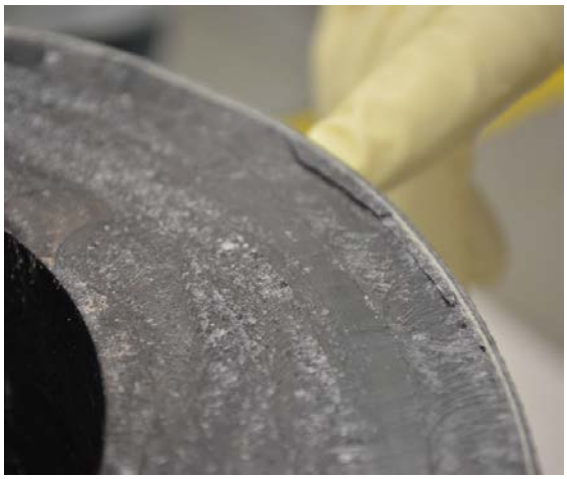
Sample 3



Sample 4



Sample 5



Sample 6

Sample 7

Sample 8

### E. Long term thermal cycling procedure: temperature control for chamber shroud

EDL: 1 Cycle

1. Start at room temp
2. Increase to 55C at rate of 10C/hr [approx. 3 hours]
3. Dwell at 55C for 2 hours
4. Decrease to -115C at rate of 10.6C/hr [approx. 16 hours]
5. Dwell at -115C for 15 hours

Winter Cycle: 50 Continuous Cycles

1. From -65C, decrease to -115C at rate of 16.6C/hr [approx. 3 hours]
2. Dwell at -115C for 7 hours
3. Increase to -65C at rate of 16.6C/hr [approx. 3 hours]
4. Dwell at -65C for 2 hours
5. Perform cycle 50 times continuously

Spring Cycle: 100 Continuous Cycles

1. From -25C, decrease to -85C at rate of 15C/hr [approx. 4 hours]
2. Dwell at -85C for 1 hour
3. Increase to -25C at rate of 15C/hr [approx. 4 hours]
4. Dwell at -25C for 1 hour
5. Perform cycle 100 times continuously

Summer Cycle: 50 Continuous Cycles

1. From -5C, decrease to -70C at rate of 16.3C/hr [approx. 4 hours]
2. Dwell at -70C for 1 hour
3. Increase to -5C at rate of 11.8C/hr [approx. 5.5 hours]
4. Dwell at -5C for 1.5 hours
5. Perform cycle 50 times continuously

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