MULTI-MISSION EARTH ENTRY VEHICLE DEVELOPMENT BY NASA'S IN-SPACE PROPULSION TECHNOLOGIES (ISPT) PROJECT

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ABSTRACT

The Planetary Science Decadal Survey, published in March 2011, includes several missions to return samples to Earth from around the Solar System. NASA's In-Space Propulsion Technologies (ISPT) Project, funded by the Science Mission Directorate, is continuing to conduct activities that will mature a class of vehicles in support of Earth entry, descent and landing mission phases. This paper will provide an explanation of the Multi-Mission Earth Entry Vehicle (MMEEV) class, concept, context and benefits, and details of Fiscal Year 2011-12 activities, including development of an analysis tool, thermal soak modeling, impact foam testing, space environmental effects arc-jet testing, dynamic subsonic stability testing and design tool development. Plans for follow-on hypersonic testing and analysis are also provided.

The ISPT Project's funding level does not currently support a dedicated flight test prior to MMEEV use. The current strategy is to mature the vehicle critical characteristics for a range of MMEEVs to TRL5-6 before the next Discovery or New Frontiers Announcement of Opportunity.

1. INTRODUCTION

Multi-Mission Earth Entry Vehicles (MMEEVs) are designed to transport payloads from outside of the atmosphere to the surface of the Earth. They serve as the last leg of missions to gather samples from around the solar system for detailed analysis on Earth. Multi-Mission Earth Entry Vehicles can have various sizes, shapes, designs, and concept of operations that reflect unique mission requirements. In general, however, many of the prior and planned future MMEEVs can be viewed as a class of vehicle with many similar characteristics. Usually, MMEEVs have high speeds resulting from direct atmospheric entries. In addition, many MMEEVs adopt what is known as a single-stage entry concept which does not include parachutes or retro-rockets, for example, in order to minimize complexity and weight while maximizing reliability. Energy remaining at impact is absorbed by built-in attenuation systems. Figure 1 illustrates a NASA-LaRC concept for an EEV for Mars Sample Return (MSR).

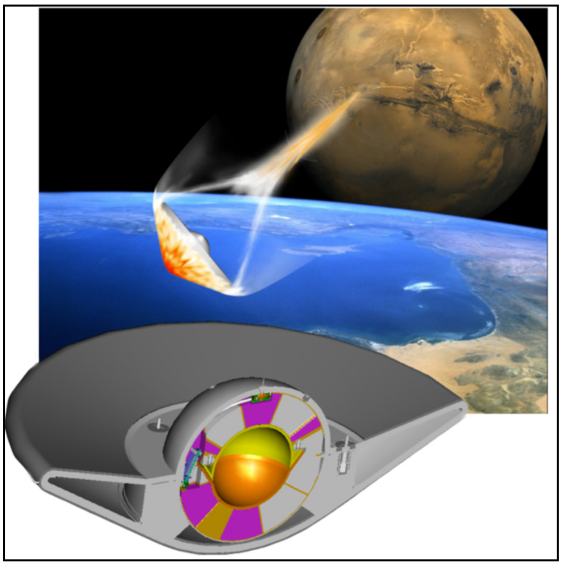

Figure 1 - NASA LaRC MMEEV MSR concept.

To assess vehicle designs for multiple missions, the Multi-Mission Systems Analysis for Planetary Entry (M-SAPE) tool is being developed and improved at NASA-Langley. Parametric assessments of vehicles up to 2 meters in diameter, with a range of small payload masses (up to about 30 kg) can be conducted in a matter of hours, and the tool includes options for varying payload density and probe materials. In 2012, ground testing to validate and expand design trade space coverage for M-SAPE models was performed. Ongoing activities include impact testing and thermal characterization of Rohacell foams, which inform both the structural response models and the thermal soak models in M-SAPE. The goal of thermal soak modeling is to show how the MMEEVs will behave thermally after impact on Earth, and assess whether recovery timeline constraints or active thermal control are needed to meet mission requirements. Vertical spin tunnel testing will be performed to define usable center of gravity (C.G.) ranges and aerodynamic databases for a family of MMEEVs. Planning for test and analysis efforts to build upon prior work on MMEEV's hypersonic stability and capability to withstand off-nominal entry conditions is ongoing. Testing and analysis results will be used to identify other risk reduction activities and drive towards a nominal MMEEV design that can meet a variety of mission requirements. The integration of testing and analysis with the M-SAPE tool provides access to and visualization of the MMEEV trade space to support mission designs.

2. MULTI-MISSION SYSTEMS ANALYSIS FOR PLANETARY ENTRY (M-SAPE)

2.1. Overview/General Philosophy

M-SAPE is a system analysis tool for design and sizing of Earth entry vehicles. The system is an integrated multidisciplinary analysis tool that is used to gain a better understanding of various entry system concepts and their limitations. The integrated system improves the performance of the systems analysis team by automating and streamlining the process. The tool improves and speeds up the design activities such as trade studies, sensitivity analyses, Monte Carlo analyses, and vehicle optimization. Reference 1 provides additional details on M-SAPE.

2.2. Current status

The initial M-SAPE integration is complete. The current system includes the following disciplines: mass sizing, flight mechanics, aerodynamics, aerothermodynamics, and impact analysis. Results from the initial M-SAPE integration were compared to earlier MMEEV point designs, and the differences in these results are within one percent. Additional modules for thermal soak and finite element analysis are under development and will be integrated with M-SAPE.

As part of model development, a total of 3,000 trajectories have been generated. These trajectories were used to guide the development of aerothermal, thermal soak, and thermal protection system (TPS) models. The aerothermal model is based on the Sutton-Graves model calibrated with high-fidelity CFD analyses.

The TPS Mass Estimating Relationships (MERs) are simple algebraic approximations that were constructed based on high-fidelity TPS analyses. TPS MERs have been developed for MMEEV heatshield using Carbon Phonelic and Phenolic Impregnated Carbon Ablator (PICA). Backshell MERs were developed using Silicon Impregnated Reusable Ceramic Ablator (SIRCA) and Acusil TPS materials.

The Parametric Vehicle Model (PVM) code is used to estimate the MMEEV overall mass. A series of improvements have been made to the PVM code resulting in 50% reduction in runtime with zero failures for 3,000 runs. Two finite element models have been developed for impact and launch-entry load analyses.

2.3. Impact modelling

The current impact dynamic analysis assumes a 1-D cylinder and perfectly vertical impact. The analysis approach uses a simplified energy balance to understand the impact of the MMEEV with a perfectly rigid surface. Because the worst case zero ground penetration is assumed, the payload must decelerate over a finite distance, or stroke, while transferring the kinetic energy by crushing a material designed for this purpose.

Since it is assumed that the payload is the only critical element of the MMEEV that needs to survive, the mass and size of the payload are used in conjunction with the assumed compression properties of impact foam, to determine the resulting payload stroke distance for calculating the design impact load limit.

2.4. Thermal soak modelling

One of the primary goals for MMEEV thermal soak analysis is to identify key factors that affect the peak payload and foam temperatures and to develop simple correlation coefficients based on these factors that support a parametric thermal soak model for M-SAPE. In order to achieve this objective, finite element (FE) thermal modeling is performed for selected representative trajectories from the MMEEV trade space. The FE analysis was performed using Marc.Mentat software from MSC Corporation. The FE model is based on simplified MSR geometry and assumed to be 2-D axi-symmetric. It is meshed in such a way that each of the main sub-components is represented as a separate element set as shown in Figure 2. These sets include forward and aft TPS, substructures, impact and body foam, wing and lid insulation, impact shell, and payload. The inclusion of various element sets will allow for flexibility in implementing different sets of materials properties when needed. The spatially and time varying aerothermal environments on both forebody and aft body are applied to the present model as boundary conditions resulting in an accurate representation of thermal energy input.

The temperature contours resulting from thermal soak are shown in Figure 3 for one of the high heat-load MSR candidate trajectories. It takes several hours for the payload container to heat up and indicate significant temperature rise. The peak temperature in the body foam and impact foam for the same trajectory were also obtained. The results indicate that for a high heat-load trajectory the temperature in the foams could

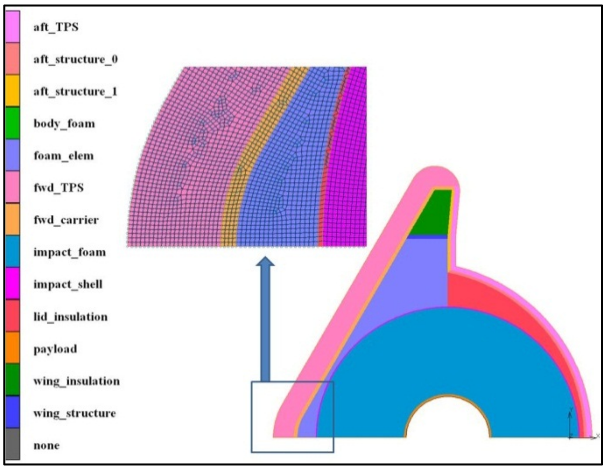

Figure 2 - Finite element mesh with component sets.

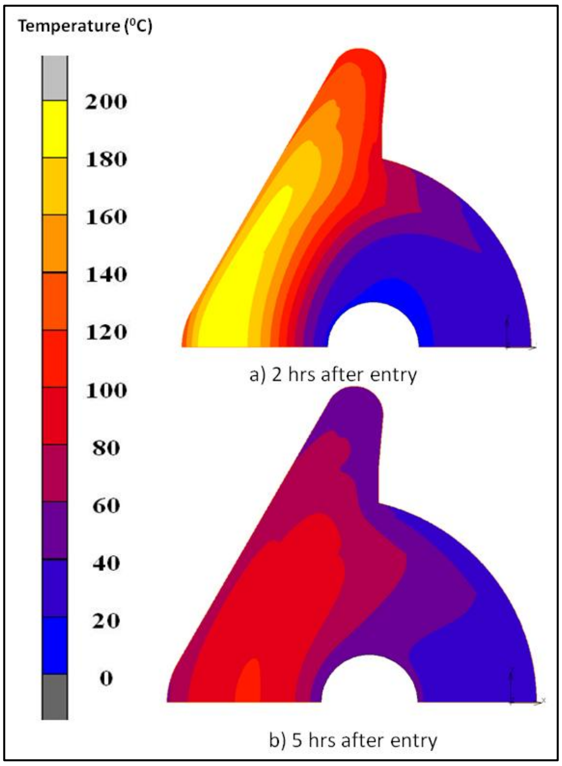

Figure 3 - Temperature contours in the MMEEV.

exceed 200^0C. Therefore it is important to understand material performance at higher temperatures. Several simulations were performed to develop parametric thermal soak models. The first few sets of parametric simulations suggest that a linear relationship can be established between peak payload temperature, heatflux magnitude and vehicle diameter. This is the first step towards developing a simplified thermal soak model that can be integrated into M-SAPE. Agrawal [2] provides details for thermal analysis work recently performed in support of MMEEV design and trade space development.

3. TRADE SPACE DEVELOPMENT TESTING

3.1. Motivation

The analysis performed with the M-SAPE tool can be limited by the extent and fidelity of the fundamental system models. Testing is performed to: 1) Provide modelling coverage to areas where we have less certainty; or 2) Improve current models to enable higher-fidelity design analysis. Areas to receive testing support are determined based on the uncertainties and risks to the various MMEEV designs combined with funding, resource, and facility priorities. In fiscal year 2012 (FY-12), three tests series were planned in direct support of M-SAPE models. One test will significantly enhance impact and thermal soak analysis while a second test will define usable C.G. limits and aerodynamic data for simulations of an array of MMEEV designs. The third test is an arc-jet test, conducted to determine the effects of micrometeoroid/orbital debris (MMOD) and other space environmental effects (SEE) on TPS materials. Planning for a subsequent test and analysis effort to examine the hypersonic stability of MMEEVs has been initiated and will conclude in fiscal year 2013.

3.2. Impact Foam Testing

One common aspect to MMEEV designs is the use of built-in impact attenuators to absorb the payload energy remaining at impact. Single-stage entry, descent and landing (EDL) concepts have been adopted as the baseline MMEEV design due to the simplicity and inherent reliability of these types of systems. However, one negative aspect of single-stage EDL concepts is that a significant amount of energy remains at the moment of impact with the vehicle traveling at speed on the order of 40 m/s. Various types of materials are viable impact attenuators for MMEEV applications. Structural impact foams, such as Rohacell, are considered reasonable design options. Rohacell, as well as other foams, can be acquired in various densities with associated crush strengths and thermal conductivities.

Three different densities of Rohacell foam were selected for the test series. An additional, 110-kg/m^3 foam capable of higher temperatures was also selected (110-xtht, gray in the table below). Table 1 provides the foam types selected, their advertised density, compressive strength, and heat distortion temperature.

Table 1 Rohacell foams tested.

#	Name	Density (kg/m^3)	Compressive strength (MPa)	Heat distortion temp (C)
1	71-wfht	75	1.7	200
2	110-wfht	110	3.6	200
3	110-xtht	110	3.6	240
4	200-wfht	205	9	190

During the initial portion of the impact, strain rates can be on the order of 10,000%/sec. This rate of strain decreases as the payload decelerates into the impact attenuator, eventually reaching zero. Given the widely varying strain rates the impact attenuators endure, stress-strain models for a range of strain rates are required.

Testing was conducted in FY-12 to complement prior quasi-static (0.1%/sec) testing to develop an impact foam model capable of supporting design analysis for the entire impact sequence of strain rates. Overall, three strain rates were investigated: 0.1%/sec, 100%/sec, and 10,000%/sec. Impact foam testing was conducted using a hydraulic test machine to provide 0.1%/sec and 100%/sec data. Higher strain rates (e.g.; 10,000%/sec) required the use of the drop tower test technique, as described by Kellas [3]. Approximately 10 samples of each foam were tested for each strain rate. Results were smoothed and averaged to generate the final result.

Figure 4 shows the stress-strain relationship for the 71-wfht foam for the 0.1%/sec, 100%/sec, and 10,000%/sec tests. The effect of strain rate is apparent, resulting in an approximately 20% increase in max stress for the 100%/sec data compared to the 0.1%/sec data. The 10,000%/sec data indicate decaying sinusoidal behavior based on strain and are an average of all samples tested. The maximum crush stresses for the 71-wfht foam are approximately 1.6, 2.0, and 2.5 MPa for the 0.1, 100, and 10,00%/sec strain rates, respectively. This illustrates the need to perform testing at different strain rates to develop accurate models of these foam types. Plans call for further analysis of the impact foam data to be documented in a NASA Technical Memorandum.

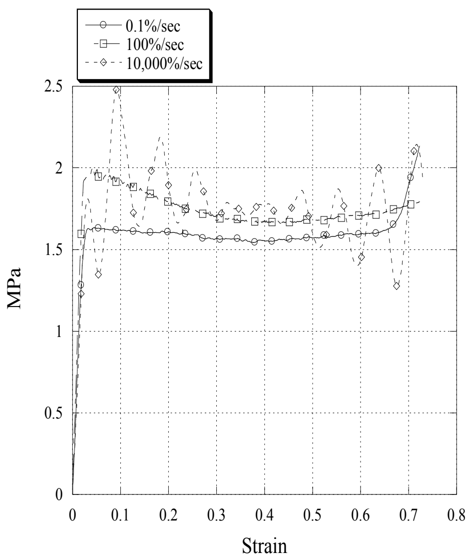

Figure 4 - Stress/strain curve for 71-wfht foam.

During impact the geometric properties of the impact attenuator foam are permanently changed. Thermal conductivity testing including both virgin and impacted foam samples is underway. The objectives of the thermal conductivity testing are to establish the baseline values for these types of foams as well as to determine if the foam experiences any changes in thermal conductivity as a result of impact. Results from this testing will significantly improve thermal soak analyses that rely heavily on the thermal characteristics of the foam after impact.

Southern Research Institute (SRI) will provide thermal conductivity data for the foam samples listed in Table 1. The foam samples will be composed of the four different Rohacell foams, both in the virgin and impacted conditions. SRI will perform thermal conductivity tests via the comparative rod method.

3.3. Space environmental effects testing

Multi-Mission Earth Entry Vehicles are designed to spend long durations in space and need to function reliably to meet mission objectives. Applications involving MSR also imply very high reliability requirements due to Earth planetary protection requirements. In order to meet these mission objectives and requirements, the TPS needs to function as designed. During prolonged spaceflight, vehicles are subjected to extreme conditions that can lead to degraded TPS performance during atmospheric entry.

Space Environmental Effects testing endeavours to determine the effects of realistic mission environments on the ability of the TPS to function during entry. The effects of three characteristics of the space environment are included within the SEE testing. Those characteristics are: 1) Radiation; 2) Cold temperatures, and most critically, 3) MMOD. A series of TPS samples was exposed to these space characteristics in a controlled manner then subjected to arc-jet testing at NASA-Ames Research Center.

The materials tested include those previously receiving investment from ISPT; the SEE testing will help mature these materials for use in space. The materials were supplied by Applied Research Associates (ARA, Inc.) in Centennial, CO and Lockheed Martin Space Systems in Denver, CO. ARA materials include two types; Silicone, Reinforced Ablative Material (SRAM) and Carbon Phenolic-type (PhenCarb), both honeycomb-packed, at densities ranging from 14 lb/ft^3 to 28 lb/ft^3. The Lockheed Martin materials included Super-Lightweight Ablator (SLA-561V) and a carbon-carbon hot structure system similar to, but more efficient than, the Genesis heatshield construction. This range of materials is applicable to both forebody and backshell use on MMEEVs, as well as other entry vehicles.

All samples were cooled to 77K and impacted with 1-mm glass bead projectiles at 7 km/sec at the White Sands Testing Facility in Las Cruces, New Mexico. One half of the samples were exposed to dosages of ionizing radiation representative of deep space cruise conditions prior to impact tests. Zero and 60 degree impact angles were included in the test matrix. Table 2 provides a definition of the TPS materials tested. All materials and impact angles listed in Table 2 were tested for both irradiated samples receiving cold impact damage and those not irradiated, only receiving cold impact damage.

Table 2- SEE test samples

Test No.	Target Type	Impact Angle (deg)
1	SRAM-14	0
2	SRAM-14	60
3	SRAM-14	0
4	SRAM-14	60
5	SRAM-20	0
6	SRAM-20	60
7	PhenCarb-24	0
8	PhenCarb-24	60
9	PhenCarb-28	0
10	PhenCarb-28	60
11	SLA-561V	0
12	SLA-561V	60
13	SLA-561V	0
14	SLA-561V	60
15	Carbon-Carbon	0
16	Carbon-Carbon	0
17	Carbon-Carbon	60
18	Carbon-Carbon Coated	0
19	Carbon-Carbon Coated	60

Arc-jet testing was performed using the AHF for the backshell samples with a target heating rate of 60 W/cm^2. All samples were able to withstand 100 seconds of exposure. A photograph of a SRAM test sample before arc-jet testing is presented in Figure 5. In this figure the MMOD-damaged area is clearly visible on the surface of the test sample. Figure 6 provides an image of the same SRAM test sample after arc-jet testing in the NASA ARC Aerodynamic Heating Facility (AHF), and the impact area shows no significant shape change at the sample surface. A photograph of a sample undergoing arc-jet testing in the AHF is provided in Figure 7.

Figure 5 - SRAM sample before arc-jet testing.

Figure 6 - SRAM sample after arc-jet testing.

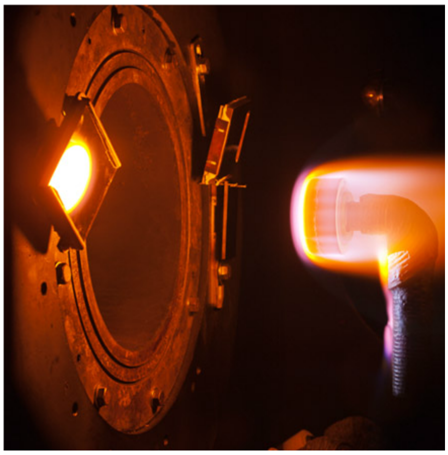

Figure 7 - SEE testing in the NASA ARC AHF facility.

The NASA ARC Interaction Heating Facility (IHF) will be used for the forebody samples and is planned for August 2012. The IHF testing will have a target heating rate of 500 W/cm^2. Prior to and after arc-jet testing, selected samples were scanned using a Computed Tomography (CT) scanning technique at NASA LaRC. Through the use of CT scanning, the size and extent of the subsurface MMOD damage can be characterized. Any changes in size of the MMOD damage can be quantitatively defined. The CT scanning also affords the ability to study density variations in the test samples. Surface laser scanning of the test samples was also performed.

All test samples were instrumented with thermocouples. Virgin control samples were included in the test matrix for the PhenCarb-24 and PhenCarb-28 TPS materials. Results from the SEE testing will enable better decisions regarding MMEEV designs and the risk of MMOD damage in particular. Analysis of data from the AHF testing and preparations for the IHF testing are underway at this time.

3.4. Vertical spin tunnel (VST) testing

During approximately the final 10 minutes of descent MMEEVs can be flying at subsonic Mach conditions. Shapes designed to optimize aerothermal heating, such as large angle blunted cones, can possess limited usable CG ranges due to subsonic static and dynamic aerodynamic stability issues [4]. Depending on the mission, payload mass and density, entry trajectory, and impact and temperature requirements, MMEEVs can have varying overall diameters and backshell sizes. A sample of MMEEV designs are included in Figures 8, 9, and 10 that illustrate the similar, yet diverse outer mold lines (OMLs) to be considered for 1.8, 1.1, and 0.8m MMEEV designs, respectively. Note that all MMEEVS in Figures 8, 9, and 10 are spherically-blunted cone designs with half-cone angles of 60 degrees.

The M-SAPE program requires a comprehensive data base to support its system engineering functions. For low-fidelity analysis, a range of usable C.G.s for a family of MMEEVs designs is desired. Higher-fidelity 6-degree of freedom (6-DOF) simulation analysis requires accurate aerodynamic databases. Vertical Spin Tunnel (VST) testing is planned, with the objectives of defining usable C.G. limits and establishing subsonic aerodynamic databases.

Table 3 - VST test configurations.

#	Configuration	V_{CL}/D
1	1.8m	0.264
2	1.2m	0.361
3	1.2m+back shell extender	0.449

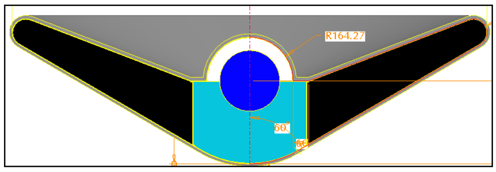

Figure 8 - 1.8m MMEEV.

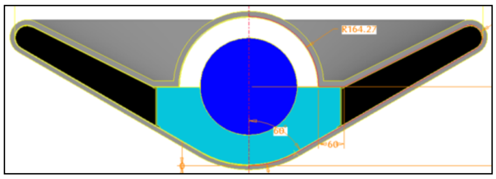

Figure 9 - 1.1m MMEEV.

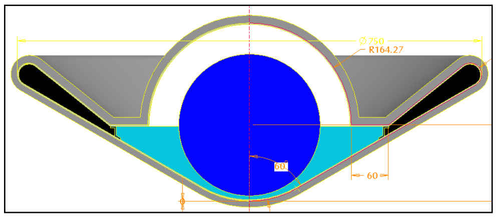

Figure 10 - 0.8m MMEEV.

The subsonic MMEEV stability trade space is being modelled by the ratio of vehicle length along the centerline divided by vehicle diameter (V_{CL}/D). Testing is being conducted in the NASA LaRC 20 ft VST to address the issue of C.G. limits and 6-DOF simulation requirements for MMEEV designs with various V_{CL}/D values. Test techniques employed involve free-flying models with adjustable C.G. locations and inertias as described by Mitcheltree [4]. For the FY-12 tests, both 1.8m and 1.2m MMEEV designs will be investigated. In order to acquire additional data for designs with larger V_{CL}/D ratios without fabricating another complete model, a backshell extender is being developed that will provide a 50% increase in radius compared to the 1.2m MMEEV design. The backshell extender will provide data for smaller diameter MMEEVs or those with larger payload sizes. Table 3 provides the configurations and range of V_{CL}/D to be investigated during the FY-12 VST tests.

3.5. Hypersonic reorientation testing and analysis

During atmospheric entry, the desired attitude is nose forward with a small angle of attack to ensure that the TPS can function appropriately to protect the vehicle. This attitude is initially provided by the carrier spacecraft at separation and nominally includes spin stabilization. Multi-Mission Earth Entry Vehicles have no attitude control systems and rely on accurate release from the carrier spacecraft and aerodynamic stability to effectively accomplish the EDL trajectory. Given the lack of control systems, there is a risk that an MMEEV could be released from the host spacecraft in such a way to have almost any attitude at atmospheric interface. In addition, previous work in this area performed in the late 1990s [5] indicates that MMEEV designs may have a rearward stability point in the hypersonic regime over a significant angle of attack range.

A prolonged rearward facing entry event would lead to the loss of the vehicle and payload due to excessive heating of the backshell TPS. For the MSR mission, planetary protection concerns require the likelihood of loss of sample containment be one in a million. For other sample return missions, loss of the MMEEV during atmospheric entry would mean loss of the mission. For the non-MSR missions, it is desired that the risk of rearward entry be of the same order of magnitude (or less) than all other loss-of-mission risks.

While Mitcheltree [5] provides a summary of the previous work and some insight into the rearward stability issue, additional work is warranted to fully characterize and mitigate this risk, especially for MSR applications or other costly sample return missions.

Advances in CFD since the late 1990s are expected to add significant insight into the rearward entry risk. A complementary wind-tunnel test would provide an alternate source of data and the ability to validate the CFD results, as well provide substantial trade space coverage. Planned work for FY-12 includes planning and preparations for an integrated CFD/Wind-Tunnel test effort in FY-13 that will build upon and extend the work performed in the late 1990s.

4. SUMMARY

Activities conducted during FY-11 and FY-12 by the In-Space Propulsion Technology program aimed at maturing the MMEEV class have been presented. These activities include development of the Multi-Mission System Analysis for Planetary Entry (M-SAPE) tool, thermal soak analysis and modeling, impact foam testing, Space Environmental Effects testing, and dynamic subsonic stability testing. Plans for follow-on hypersonic analysis and testing to be completed in FY-13 were also provided.

The initial M-SAPE model integration is complete, and additional models are under development. The integrated model has been used to develop the trade space for two sample return applications.

Thermal soak analysis of earth entry vehicles based on MSR geometry is being performed for representative trajectories from the MMEEV trade space. Preliminary work shows that a linear relationship can be established between the peak payload temperature, stagnation heatflux magnitude and vehicle diameter.

Results from impact foam testing indicate a strong dependence of crush stress on strain-rate for the Rohacell foams tested. Planned thermal conductivity testing will greatly improve thermal soak analysis and the ability to predict payload temperatures before and especially after impact.

Arc-jet space environmental effects testing has been completed for candidate backshell TPS samples. Preliminary results are encouraging with all samples performing well for the 100 seconds of test exposure. Preparations are underway for the forebody TPS testing scheduled to be completed in August.

Planned dynamic stability testing of an array of MMEEV designs will enable definition of usable subsonic C.G. limits for these vehicles. Aerodynamic data acquired during the VST testing will also enable high-fidelity 6-DOF trajectory simulations.

Hypersonic CFD analysis and wind-tunnel testing, planned for FY-13, will complement prior work in this area and mitigate the risk associated with rearward entries.

In summary, analysis and testing efforts performed in support of the MMEEV trade space have advanced this class of vehicle. These efforts significantly contribute to the maturation of critical MMEEV characteristics in support of the next Discovery or New Frontiers Announcement of Opportunity.

5. REFERENCES

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