70th International Astronautical Congress (IAC), Washington D.C., United States, 21-25 October 2019.

IAC-19-A3.3A.3

The Multi-Mission Earth Entry Vehicle for Sample Return Missions – Past, Present, and Future

Corliss, J.M.*, Kellas, S.R.*, Maddock, R.W.*

** National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia 23681*
James.M.Corliss@nasa.gov, Sotiris.Kellas@nasa.gov, Robert.W.Maddock@nasa.gov

Abstract

The Multi-Mission Earth Entry Vehicle (MMEEV) is an enabling technology developed at NASA's Langley Research Center (LaRC) over the last two decades for returning samples to Earth across a wide array of space science missions. Currently, the MMEEV is being considered for NASA's Mars Sample Return (MSR) mission. The original vehicle concept, the Earth Entry Vehicle (EEV), was innovated at LaRC in 1998 as a robust solution to return Mars soil samples to Earth under stringent backward contamination requirements. These backward contamination requirements drove the EEV to have higher reliability than any capsule previously designed for a return-to-Earth sample return mission. The EEV achieved this high reliability by employing a passive (no active systems) vehicle architecture optimized for fault tolerance in a compact, low-mass configuration that is extensible to virtually any sample return mission.

The original EEV concept utilized a carbon-carbon primary structure with high-density carbon phenolic thermal protection system. The capsule had a 60-degree sphere-cone forebody and a backshell geometry uniquely tailored to produce aerodynamics that would passively re-orient the vehicle if it entered the atmosphere with an off-nominal attitude. Contrary to every other sample return capsule conceived at the time, the EEV was designed to land without a parachute. The vehicle incorporated an integral energy-absorbing crushable structure that protected the Mars sample for landings on surfaces ranging from soft soil to solid concrete.

This paper describes 20 years of technological advancements LaRC has incorporated into the EEV architecture to evolve it from the original, MSR-enabling vehicle, to a true multi-mission capability relevant to any sample return mission. The vehicle's unique Integrated Composite Stiffener Structure (ICoSS) has been optimized for specific strength - supporting high-G atmospheric entries with steep entry angles that produce precise landing footprints on the ground. The vehicle geometry has been refined through wind tunnel testing and computational fluid dynamics simulations to improve the vehicle's aerodynamic stability and robustness to off-nominal conditions from hypersonic to subsonic flight. The resulting configuration of the current MMEEV architecture is described, with details provided on its sample carrying capacity and atmospheric entry trajectory capabilities. The upgraded vehicle performance is mapped into current space science objectives, showing how the MMEEV supports future sample return missions and continues to be an enabling technology for NASA's vision to return samples from Mars.

Acronyms/Abbreviations

Ames Research Center (ARC)
Comet Rendezvous, Sample Acquisition, Investigation, and Return (CORSAIR)
Containment not Assured (CNA)
Earth Entry Vehicle (EEV)
Earth Return Vehicle (ERV)
Integrated Composite Stiffener Structure (ICoSS)
Jet Propulsion Laboratory (JPL)
Langley Research Center (LaRC)
Mars Sample Return (MSR)
Micrometeoroid and Orbital Debris (MMOD)
Multi-Mission EEV (MMEEV)
National Aeronautics and Space Administration (NASA)
Phenolic-Impregnated Carbon Ablator (PICA)
Probabilistic Risk Assessment (PRA)
Thermal Protection System (TPS)
Utah Test and Training Range (UTTR)

1. Introduction

This paper provides a literature survey and historical perspective describing the technological development of the MMEEV at NASA's Langley Research Center (LaRC). The original EEV concept, formulated at LaRC in 1998, was developed specifically to address the stringent backward planetary protection requirements associated with returning Mars samples back to Earth for the planned 2003/2005 MSR mission. The 2003/2005 MSR mission was eventually cancelled, but the benefits of a fully passive and highly reliable re-entry vehicle were recognized for returning samples from other solar system destinations, including the Moon, asteroids, and comets. The EEV concept proved to be extensible to these other sample return missions, and LaRC initiated the MMEEV development program to expand the vehicle capabilities and establish tools that would enable mission designers to rapidly formulate MMEEV concepts for a multitude of missions.

Development of the MMEEV has continued to the present day. The concept has been utilized for a wide range of mission design studies and planetary science mission proposals, but has not yet been implemented in a flight mission. The vehicle is currently being considered for NASA's planned 2026/2031 MSR mission. Design studies being conducted by NASA's LaRC, Ames Research Center (ARC), and the Jet Propulsion Laboratory (JPL) continue to show that the MMEEV is a viable and enabling technology for MSR.

The objective of this paper is to summarize the MMEEV technological advancements that have been accomplished from 1998-2017, leading up to the current 2026/2031 MSR mission. A literature search was conducted to compile the references describing the MMEEV development history to serve as a resource for future mission designers. The paper is organized into the following five chronological sections.

- Earth Entry Vehicle Conception (1998-2001)
- EEV Technology Advancements (2001-2004)
- Conception of the MMEEV (2004-2010)
- MMEEV Application (2010-2017)
- MMEEV Future (2017 and beyond)

The majority of work described in this paper was conducted or managed by LaRC. However, the paper by no means captures all of the work that has been conducted to develop the MMEEV concept across LaRC, other NASA Centers, and industry. Over the same 20-year time period, ARC has advanced the state-of-the-art in modeling entry environments and developing relevant thermal protection systems (TPS) to support the various MMEEV mission concepts. In the more recent years, JPL has conducted mission design studies and explored alternative MMEEV design concepts specifically for the 2026/2031 MSR mission. It is the authors' hope that compendiums similar to this are assembled to summarize other aspects of MMEEV development history.

2. Earth Entry Vehicle Conception (1998-2001)

LaRC developed the original EEV design concept in 1998 [1] in response to the stringent backward planetary protection requirements imposed on the 2003/2005 MSR mission. NASA's planetary protection requirement for the mission was that the probability of releasing a 0.2 micron or larger particle of Mars material into the Earth's biosphere needed to be less than 1:1,000,000. The most critical mission phase associated with achieving this containment assurance requirement is when the samples are transported from the Earth return spacecraft, through the Earth's atmosphere to the ground, and then to a sample curation facility. Conventional atmospheric entry vehicles that utilized numerous active systems (e.g. guidance control systems, parachutes) would not be capable of achieving these unprecedented levels of reliability. A new entry vehicle concept that was simpler, with fewer potential sources of failures, was needed to meet this reliability requirement and enable the MSR mission.

2.1 Early MSR EEV Concepts

The first MSR EEV concepts focused on addressing the challenge of removing all active systems from the entry vehicle. Eliminating an active guidance control system meant that the vehicle would need to conduct a completely ballistic entry through the Earth's atmosphere, and that the Earth entry targeting would need to be accurate enough to ensure that the vehicle landed within a prescribed footprint on the surface to ensure landing survival and a rapid and safe recovery. Eliminating the parachute system introduced two unique requirements. First, the vehicle would need to be aerodynamically stable throughout all flight regimes, from atmospheric entry to subsonic terminal descent and landing. Secondly, without the aid of a parachute to slow the vehicle's descent, there would need to be a means of limiting the loads during ground impact to protect the science integrity of the samples, and also to prevent the sample container from breaching and risking the release of Mars particles into the Earth environment.

These were conflicting requirements because blunter entry vehicles with higher aerodynamic drag, which are beneficial for reducing the ground impact velocity and loads, are typically less stable than vehicles with more streamlined shapes and less aerodynamic drag. In order to balance the conflicting design goals of aerodynamic drag and aerodynamic stability, a series of subsonic tests in LaRC's Vertical Spin Tunnel were conducted [2] to evaluate the entry vehicle geometries shown in Figure 1, which included a 60-deg sphere-cone (6025), sharp and blunt 45-deg sphere-cones (4525 and 4550), and a hemispherical forebody (3050).

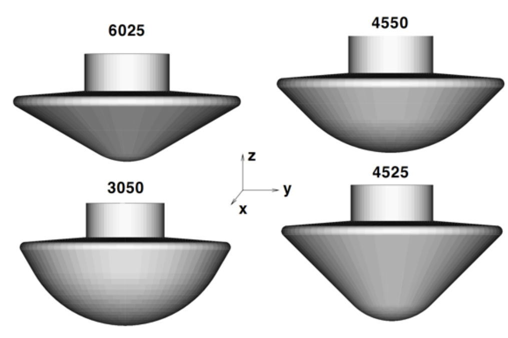

Fig. 1. Early MSR EEV Geometries Tested for Aerodynamic Drag and Stability [2]

As the aerodynamics of different EEV geometries were being evaluated, the implementation of these shapes into an integrated vehicle design were also being explored [3]. Conceptual designs of the Mars sample container were developed by JPL, and these different container concepts were integrated into the wide range of vehicle design solutions illustrated in Figure 2. As design studies progressed, the MSR EEV configuration converged to focus on designs with a single spherical sample container combined with a 60-deg sphere-cone capsule shape, similar to the four concepts shown to the right in Figure 2. This basic configuration exhibited sufficient aerodynamic stability and enough aerodynamic drag to limit ground impact velocities and impact loads to the levels needed to protect the Mars samples and assure sample containment when landing on soft soil.

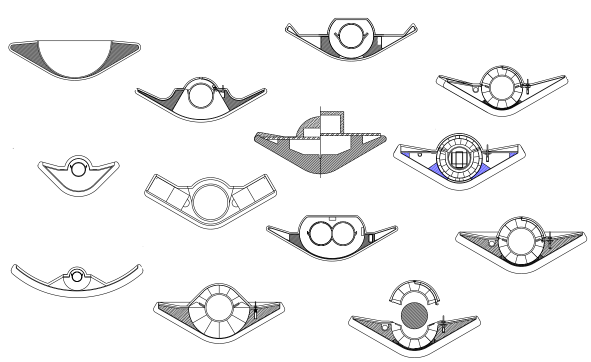

Fig. 2. Early MSR EEV Design Evolution

2.2 Landing Site and Ground Impact Evaluations

Without a parachute system, the EEV terminal velocity was anticipated to be 40-45 m/s. The MSR science team established a maximum allowable impact acceleration of 2,500 G to preserve the science integrity of the Mars samples. A second limit of 3,500 G was set as the maximum allowable impact acceleration to assure sample containment for planetary protection. The Utah Test and Training Range (UTTR), outlined in green in Figure 3, was selected as the EEV landing site because it provided a controlled airspace with a safe landing area large enough to accommodate the EEV's predicted landing footprint, shown in yellow in Figure 3.

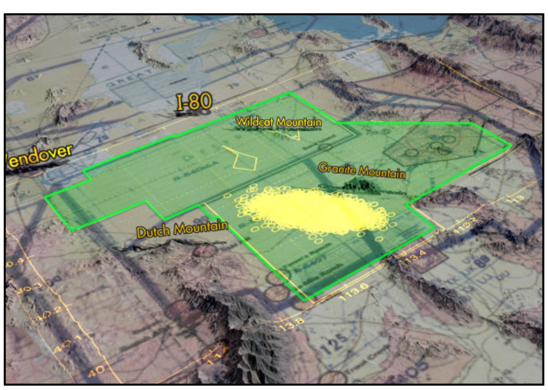

Fig. 3. Utah Test and Training Range (in green) with MSR EEV Landing Footprint (in yellow) (c. 2001)

The second unique feature of UTTR is that the majority of the ground surface is part of the Great Salt Lake Desert. This large lakebed playa is an exceptionally level surface comprised of clay and silt soil remarkably consistent in composition, and provides a relatively soft surface which absorbs and attenuates the majority of the impact energy when the EEV lands at its terminal velocity. LaRC characterized the energy absorbing capability of the UTTR soil through a series of drop tests with hemispherical penetrometers (Figure 4) at velocities up to approximately 45 m/s. These test data were used to develop analytical modelling techniques and empirical relationships to predict the impact accelerations for MSR EEV landings [4].

Fig. 4. Hemispherical Penetrometer and Impact Crater at UTTR from Drop Test in 2000

The energy absorbing capabilities of the UTTR soil were further verified with a full-scale EEV drop test conducted by the LaRC team in 2000 (Figures 5 and 6). The EEV drop-tested at UTTR had a mass of 42 kg and impacted the UTTR surface at 39.5 m/s. The resulting peak impact acceleration measured at the mock sample container was approximately 1,500 G [5, 6], well below the 2,500 G science limit established for the 2003/2005 MSR mission.

Fig. 5. Full-Scale EEV and its Impact Crater Following UTTR Drop Test in 2000 [5, 6]

Fig. 6. LaRC Team Displaying Undamaged EEV Prototype Following UTTR Drop Test in 2000

2.3 EEV Energy Absorber Development

As demonstrated by the full-scale EEV drop tests, the soft soil of the UTTR playa provides sufficient impact attenuation to protect the science integrity and assure containment of the Mars samples at landing. However, while the surface of the UTTR South Range is comprised predominantly of soft playa, there are also roughly 40 km of compacted gravel roads (including exposed rocks), buildings, storage equipment, and numerous other landing hazards (e.g. expended aircraft fuel tanks, target structures) that have accumulated on the range over years of flight operations. The EEV team determined early in conceptual design that the vehicle required an internal energy absorber to protect the samples if the EEV landed on one of these hazardous surfaces or objects.

A spherical energy absorber that utilized a foam-filled composite cellular structure was developed and tested at LaRC (Figure 7) to protect the Mars samples for these off-nominal landings [7]. Test data from the cellular energy absorber tests were used to develop and validate non-linear models (Figure 8) for these stressing design cases [8, 9, 10] with hard surface landings.

Fig. 7. LaRC Test Engineer Inspecting EEV Cellular Energy Absorber after Successful Impact Test

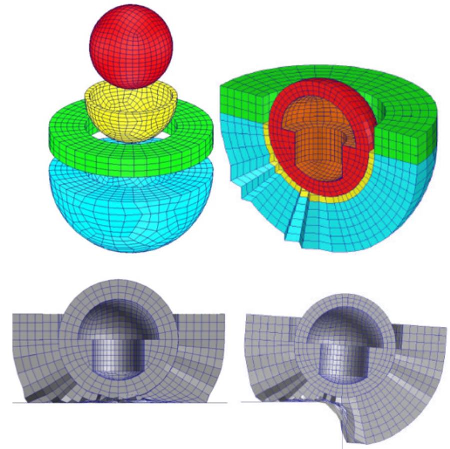

Fig. 8. Non-Linear Finite Element Modelling of the MSR-EEV Cellular Structure Energy Absorber [9, 10]

2.4 Close-Out of the 2003/2005 MSR EEV Design

The EEV design, analysis, and testing to support the 2003/2005 MSR mission concluded in 2001. Design iterations included concepts utilizing 3D and 2D carbon-carbon structures and different forebody TPS options such as Phenolic-Impregnated Carbon Ablator (PICA). The final design, illustrated in Figure 9, consisted of a carbon-carbon primary aeroshell structure, a fully-dense carbon-phenolic primary heatshield TPS, and a spherical composite/foam cellular energy absorber.

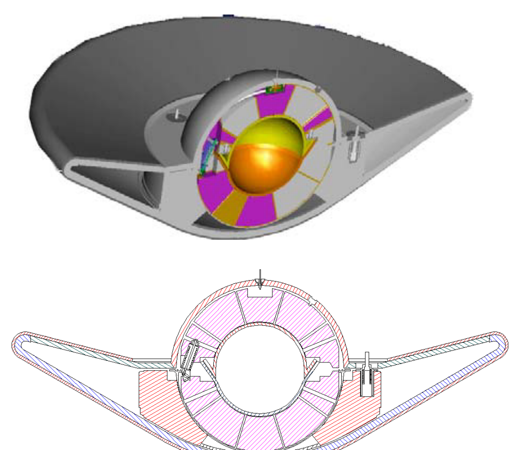

Fig. 9. Views of the EEV Design Developed for the 2003/2005 MSR Mission

Several detailed performance analyses were conducted as part of the design close-out to verify that the design concept would achieve the mission requirements. Thermal analyses [11, 12] for the mission cruise, EEV entry, and post-landing soak-back conditions showed that, while the TPS bond-line temperature would reach its peak after landing, the temperature of the Mars samples would not exceed the prescribed science threshold requirements. Two probabilistic risk assessments (PRAs) were also conducted in this time frame. The first scoping PRA [13] indicated that the probability of Containment not Assured (CNA) for the Mars samples was 3.07E-6, which was close enough to the planetary protection requirement of CNA<1.0E-6 that the EEV concept was considered a viable solution for returning the Mars samples to Earth. The top five contributors to CNA risk that were identified by the scoping PRA are summarized in Table 1.

Table 1. Top Five Contributors to CNA Risk Identified by Scoping PRA [13]

Contributor Description	Probability	Percent
Orbiting sample canister (OS) contaminated or undetected OS seal failure	1.20E-6	39%
EEV structural failure during entry phase	6.92E-7	22%
TPS failure results in exposure of EEV structure to re-entry environment	4.94E-7	16%
Recontact follows spin-eject and aerodynamics fails to reorient EEV	3.95E-7	12%
OS and containment vessel (CV) fail to maintain containment under impact loads	1.47E-7	4.7%

A second PRA [14] was completed in 2001 to refine the results of the first scoping PRA based on EEV design updates, and also to evaluate the feasibility of using the Space Shuttle to return the Mars samples to Earth instead of the EEV. This PRA concluded that the mean CNA risks for an EEV return and a Space Shuttle return were 1.3E-6 and 3.9E-6 respectively. Since both return strategies were within the ballpark of the 1.0E-6 planetary protection requirement, both concepts continued to be examined further during the technology advancement period from 2001-2004 (see Section 3).

The 2001 EEV design work concluded with a System Validation Flight Test study [15]. The purpose of the study was to scope out the feasibility and implementation options to conduct a flight test of an EEV with relevant geometry, mass, and entry conditions. The study examined launch and re-entry options (vehicles and sites), instrumentation suites and data acquisition, vehicle integration, and cost and schedule.

3. EEV Technology Advancements (2001 - 2004)

Development of critical MSR technologies continued from 2001 to 2004 as part of NASA's Mars Technology Program. For the EEV specifically, the key technologies addressed during this period were the following.

- Alternative Landing Scenarios PRA
- Thermal Protection System Demonstrations
- Vehicle Sterilization Methods
- Micro-meteoroid and Orbital Debris Protection

The technology advancements accomplished during this phase of EEV development history are summarized in several reports [17, 18], with a brief synopsis being provided here.

3.1 Alternative Landing Scenarios PRA

The MSR PRA work was further expanded during the technology advancement period to examine a variety of Earth return scenarios [16]. These scenarios included a more-detailed evaluation of the Space Shuttle return concept, including a conceptual design of a vault that would be used to secure the Mars samples inside the Space Shuttle cargo bay (Figure 10). The vault was designed to have the capability to maintain sample containment for ground and water impacts up to 120 m/s.

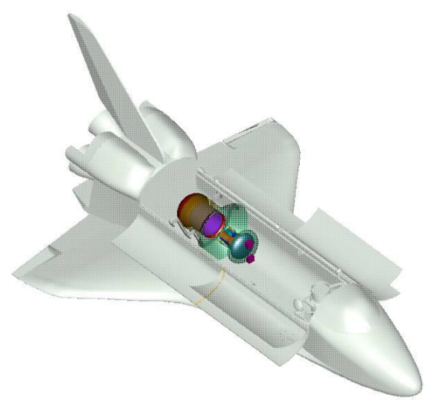

Fig. 10. Conceptual Design of a Vault that Secures the Mars Samples in the Space Shuttle Cargo Bay [16]

One of the complexities of the Space Shuttle sample return approach is conducting the rendezvous and sample transfer between the Earth Return Vehicle (ERV) and the Space Shuttle. The preliminary mission concept initially placed the ERV in a "safe Earth orbit" with a very long decay time. The ERV would gradually descend into a lower orbit that could be reached by the Space Shuttle. The shuttle would rendezvous with the ERV, and then utilize its robotic arm to grapple the ERV and stow it inside the vault illustrated in Figure 10. The CNA risk estimated by the PRA for this architecture remained similar to that predicted by the earlier 2001 PRA, which was 3.9E-6.

The updated PRA also considered Earth return scenarios utilizing EEV water landings at Kwajalein

Lagoon in the Pacific Ocean, and also parachuted landings and parachuted mid-air recoveries at both UTTR and Kwajalein Lagoon. Flight mechanics Monte Carlo analyses concluded that the EEV landing footprints could roughly be accommodated within the Kwajalein atoll (Figure 11). However, there was found to be some probability, albeit low, that the EEV could land outside the atoll islands, which would increase the risk of the vehicle and the Mars samples being lost at sea.

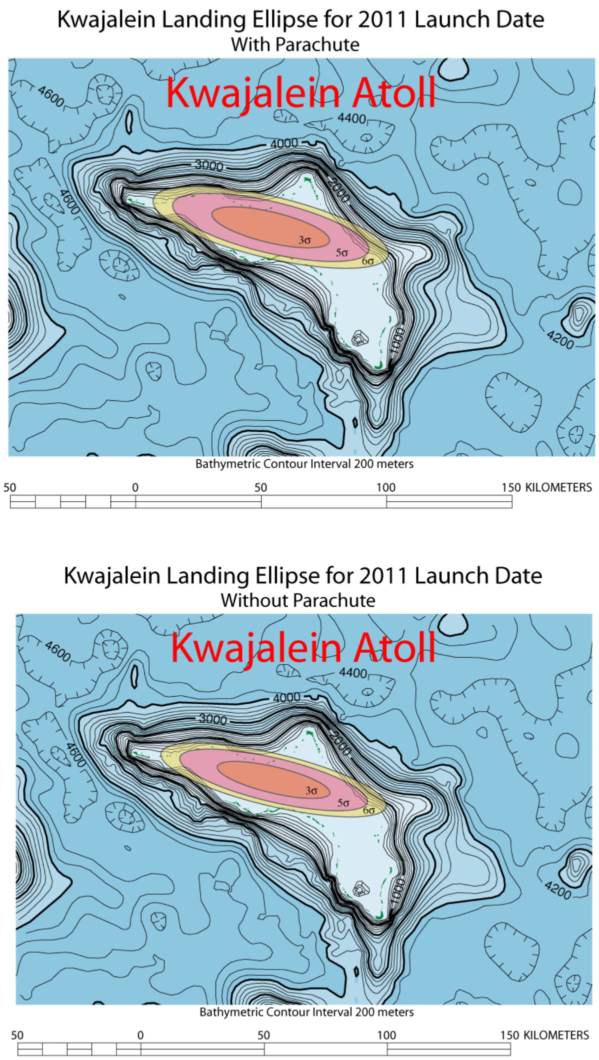

Fig. 11. Projected EEV Landing Footprints with and without a Parachute at the Kwajalein Lagoon

The CNA risks estimated for the six different EEV landing scenarios, summarized in Table 2, were found to be very similar between the UTTR options and the Kwajalein options. For both landing sites the mid-air recoveries yielded the highest mean CNA risk of 2.1E-6. The addition of a parachute system produced a small improvement in CNA risk for UTTR and Kwajalein landings, but the improvement was not considered significant enough to warrant adding the mass and complexity of a parachute system to the vehicle.

Table 2. CNA Probabilities for Alternative EEV Landing Scenarios [16]

EEV Landing Scenario	5%	Mean	95%
UTTR No Parachute	4.3E-7	1.3E-6	3.1E-6
UTTR With Parachute	3.8E-7	1.2E-6	2.9E-6
UTTR Air Capture	4.3E-7	2.1E-6	4.7E-6
Kwajalein No Parachute	4.8E-7	1.4E-6	3.2E-6
Kwajalein with Parachute	4.0E-7	1.3E-6	3.0E-6
Kwajalein Air Capture	3.7E-7	2.1E-6	4.6E-6

3.2 Thermal Protection System Demonstrations

The MSR EEV forebody TPS was selected to be fully-dense carbon-phenolic because of the extensive flight heritage this material has accumulated through its use on missile nose cones, solid rocket nozzles, and the Galileo and Pioneer Venus entry capsules. This high degree of flight heritage was considered to be necessary in order to achieve the EEV's stringent reliability requirements.

Two types of carbon-phenolic specimens were tested in the ARC 60 MW Interaction Heating Facility. The first set of specimens were fabricated using the "Chopped-Molded" technique, necessary to form the material around the spherical nose of the EEV where the stagnation point is located and peak heating occurs during entry. The second set of specimens was fabricated using the "Tape-Wrapped" method to represent the material that would be utilized along the flanks of the EEV conical section. Different sets of arc-jet tests were conducted to produce the peak heat flux environment expected during entry, and also the total integrated heat load that typically drives the thickness sizing of the material. All tests were successful and demonstrated that carbon-phenolic was a suitable TPS material for the MSR EEV (Figure 12).

Fig. 12. Fully-Dense Carbon-Phenolic Arc-Jet Test and Post-Test Coupons [18]

3.3 Vehicle Sterilization Methods

One of the planetary protection risks identified during the technology advancements period was the possibility of unsterilized Mars dust being deposited onto the EEV during earlier mission phases, and then that dust remaining on the EEV and being carried to the Earth's surface. A potential mitigation to this risk is to ensure that all exterior vehicle surfaces where dust could reside are sufficiently heated during Earth atmospheric entry to sterilize the Mars particles. For example, heating the dust particles to 500C for at least 0.5 seconds was considered an accepted technique to sterilize the particles and achieve the planetary protection requirements.

Figure 13 shows the results of a thermal analysis predicting the peak temperatures across the EEV exterior surfaces during atmospheric entry. Surfaces shown as red exceed 500C, while all other surfaces are less than 500C. The forebody surfaces of the EEV, where the primary aerothermal environments are applied, easily experience temperatures beyond 500C.

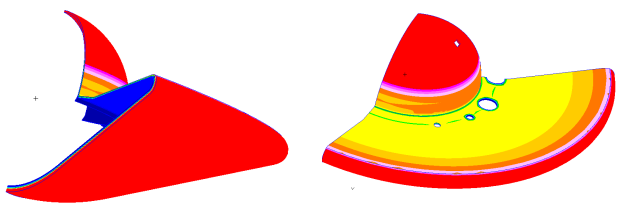

Fig. 13. Example EEV Forebody and Aft-Body Exterior Temperature Distributions During Entry

The majority of the vehicle aft-body surfaces, however, remain below 500C as illustrated by the yellow/orange regions in Figure 13. If these regions were required to exceed 500C during entry, then the aft-body geometry would need to be revised to expose these surfaces to higher aerothermal environments. The geometry changes shown in Figure 14 were considered as potential options to produce the aft-body aeroheating needed to sterilize dust particles [18]. Each option posed varying degrees of implementation complexity related to mass, volume, and payload access. The MSR technology development work concluded, however, before these configurations could be examined in more detail.

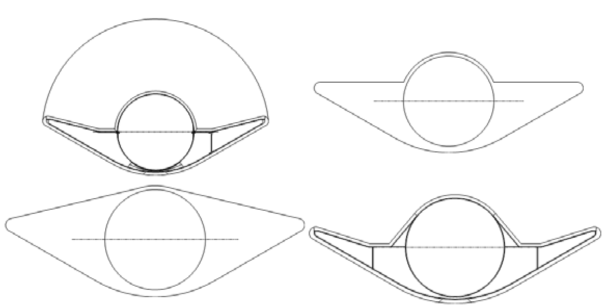

Fig. 14. Potential EEV Geometry Changes to Increase Aft-Body Heating and Sterilize Dust Particles [18]

3.4 Micrometeoroid and Orbital Debris Protection

A particularly challenging CNA risk to address in the EEV design is the potential of micrometeoroid and orbital debris (MMOD) strikes causing a downstream failure during EEV atmospheric entry and descent. For example, MMOD damage to the forebody heatshield could potentially lead to TPS failure and eventual break-up of the EEV during entry.

Initial studies of the MMOD environment during the mission cruise phases (Earth-to-Mars, Mars-to-Earth), and also during the 4-day EEV free-flight period prior to Earth entry, indicate that the probability of a damaging MMOD strike is high enough that mitigation steps are needed. One approach for mitigating this risk is to encapsulate the EEV within an MMOD shield that protects the vehicle throughout the mission, but passively separates during Earth entry prior to the aerothermal heat pulse. The shield concept illustrated in Figure 15 was comprised of individual segments secured together with low-melting point webbing [18]. During the initial phases of entry when the dynamic pressure and aeroheating are beginning to build up, the webbing would experience enough heating to loosen the segments such that the dynamic pressure would cleanly separate them from the EEV. This concept posed many challenges that would be difficult to verify through analysis and testing, such as ensuring that the segments would separate cleanly without perturbing the vehicle's attitude or flight path.

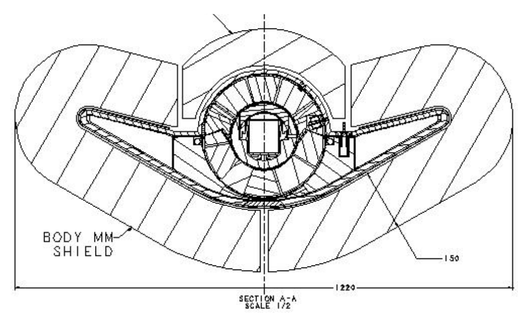

Fig. 15. Concept for an MMOD Shield that Separates from the EEV During Earth Entry [18]

4. Conception of the Multi-Mission EEV (2004-2010)

When the MSR EEV technology advancements period ended, LaRC began to outline an approach to develop a flexible EEV design which could continue to be utilized by MSR, but which would also be applicable to a multitude of other potential missions returning samples from various destinations [19].

The Multi-Mission EEV concept is based on the MSR EEV design, which was driven by minimizing risk associated with sample containment. Therefore, the MSR EEV, by necessity, was designed to be the most reliable space vehicle ever developed. Such a high reliability concept provides a logical foundation by which individual missions can build upon in optimizing an EEV design which meets their specific needs.

By preserving key EEV elements, such as a chute-less design and a well-understood aerodynamic shape, the MMEEV concept provides a platform by which technologies, design elements, and processes could be developed and flight tested prior to implementation on MSR. This approach could not only significantly reduce the risk and associated cost to develop the MSR EEV, but also by leveraging common design elements, all sample return missions utilizing the MMEEV concept would benefit.

4.1 Key MMEEV Design Considerations

Developing any entry vehicle requires consideration of several mission and design elements, e.g.: the payload mass will drive the vehicle entry mass; entry flight path angle and entry velocity affect the heating environment; entry flight path angle will also drive the landing footprint; vehicle geometry will affect aerodynamics across all flight regimes, including the terminal descent velocity which will also drive the landing system design (e.g. parachute or crushable?). This multidisciplinary problem can be decomposed into a set of key disciplines where a Design Structure Matrix, illustrated in Figure 16, can be developed to understand the interaction between the various disciplines [20].

	Geometry Module	Mass Sizing	Impact Analysis	Structural Analysis	Flight Mechanics	TPS Sizing	Thermal Soak
Geometry Module	Geometry	OML	OML	OML	OML	OML	OML
Mass Sizing	Overall Size	Mass Sizing	Mass	Mass	Mass		
Impact Analysis	Energy Absorber Stroke	Energy Absorber Mass	Impact Analysis				
Structural Analysis		Structural Mass		Structural Analysis			
Flight Mechanics			Terminal Velocity	Entry Loads	Flight Mechanics	Heat Load	Heat Rate
TPS Sizing		TPS Mass				TPS Sizing	Heat at Bondline
Thermal Soak			Temperature Field	Temperature Field			Thermal Soak

Fig. 16. MMEEV Design Structure Matrix [20]

In order to cover the widest range of mission applications possible, the MMEEV design must take all of these disciplines into account, and must consider their interaction over a wide range of possible design criteria, in order to properly assess the qualitative performance and determine the optimal trade space to focus on for the particular application.

4.2 Multi-Mission Systems Analysis and Models

During early sample return mission concept studies, a "design map" can be developed which looks across the likely range of MMEEV optimization parameters and provides a suite of candidate vehicle classes or configurations to select from based on the unique requirements of each sample return mission [21]. During mission development, this concept can then be modified along the way, as needed.

To achieve this, a tool was developed to generate the "design map" from which early design options can be assessed; the MMEEV–System Analysis for Planetary Exploration (M-SAPE) tool [22]. The M-SAPE tool includes parametric models for vehicle elements (Figure 17) encompassing geometry, mass, impact analysis, structural analysis, flight mechanics and thermal environments (including TPS materials) to generate a quick-look assessment of the desired trade space. An important goal for M-SAPE is to provide an integrated environment such that a low fidelity system analysis and trade can be performed quickly, typically in a matter of hours instead of weeks or months. An example of M-SAPE trade study results is shown in Figure 18.

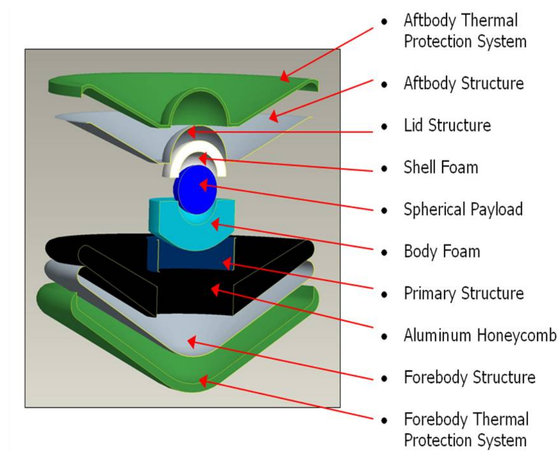

Fig. 17. M-SAPE Parametric Model Elements [22]

5. MMEEV Application (2010 - 2017)

With the development of the M-SAPE tool, opportunities arose where the MMEEV concept could be applied to various sample return mission studies. A key consideration at the beginning of any mission study is whether or not a parachute system is required due to mission or payload constraints.

Galahad, an asteroid sample return mission study, was the first external partnership utilizing the MMEEV concept [23]. Later, Comet Rendezvous, Sample Acquisition, Investigation, and Return (CORSAIR), a comet surface sample return mission study, also applied the MMEEV concept to its sample return vehicle [24, 25]. In both cases, the passive (chute-less) vehicle design was determined to provide the best payload or science capability.

5.1 Passive vs. Parachute

The advantages of a passive (or chute-less) vehicle extends beyond reliability [26, 27]. There are real, tangible benefits to a passive system, e.g. higher payload mass fraction (payload mass / vehicle entry mass). When the landing velocity is restrictively low (i.e. < 20 m/s), the vehicle entry mass is driven by the required parachute system and not the payload. For higher lander velocities, the parachute system mass becomes comparable to that of the impact absorption system, creating a threshold of payload mass fraction as a function of vehicle diameter. If landing loads are allowed to be sufficiently large (i.e. 100's of g's), the passive system clearly provides the most mass efficient approach as shown in Figure 19 for a payload mass of 20 kg.

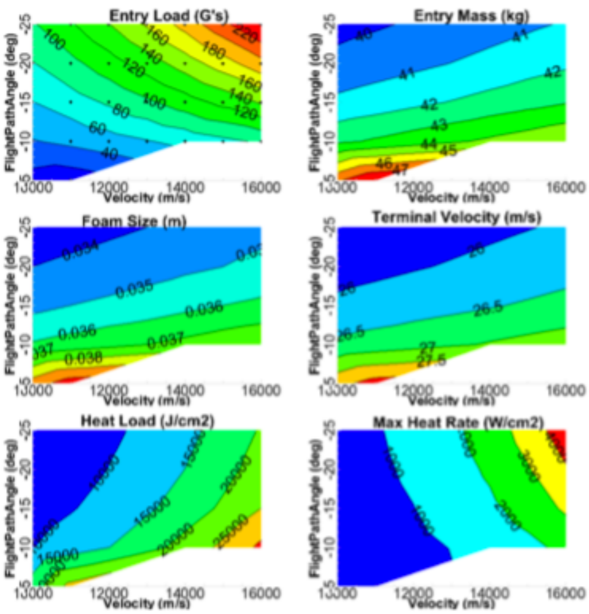

Figure 18: Example of M-SAPE results (using vehicle diameter of 1.3 m, payload mass of 12.5 kg, payload density of 4000 kg / cu. m, nose radius to body radius ratio of 0.25, shoulder radius to body radius ratio of 0.07, and a mass margin of 30%)

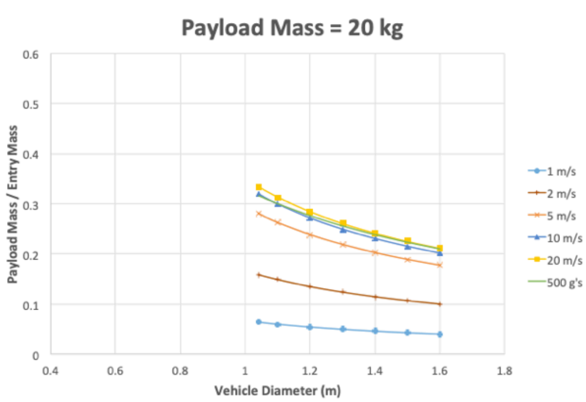

Figure 19: Passive MMEEV @ 500 g's vs. Parachute Payload Mass Fraction Summary

The key to a robust passive vehicle design will lie in optimizing the vehicle structure (or impact absorption system) for the given ground conditions at the desired landing site.

5.2 Leveraging the ICoSS Structure for MMEEV

The most obvious difference between a conventional entry vehicle and the passive (chute-less) EEV is the landing velocity, which in the case of the passive vehicle could exceed 30 m/s. High landing velocity requires dynamic load attenuation and hence specialized structures that can be tailored to meet these severe impact conditions. In many cases, maintaining a known vehicle shape after impact is beneficial for many reasons including; (a) prediction of impact loads using empirical equations derived during the early UTTR soil characterization tests [28] and (b) facilitating soak back analysis to predict sample temperature as a function of time elapsed between landing and sample retrieval.

To meet the demanding landing requirements of a passive EEV, the ICoSS structure was introduced [29]. A prototype ICoSS aeroshell is shown in Figure 20.

Figure 20: ICoSS Aeroshell Structure for the MMEEV

In addition to structural tailoring, the integrally stiffened and co-cured structure offers low mass and damage tolerance as demonstrated during drop tests at UTTR in 2016 [28, 30]. Two MMEEV prototypes using the ICoSS construction were tested, one of which is shown in Figure 21. During these tests, one of the vehicles survived a near 600 G landing with only minor and very localized resin fillet failures at the nose of the forward shell. This vehicle was subsequently tested for a second time, and despite experiencing an off-nominal landing, still maintained the volume around the sample container as required.

In addition to demonstrating the integrity of the ICoSS construction for passive EEV application, the 2016 tests also demonstrated that for as long as the shape of the vehicle was maintained during impact, the resulting G-loads could be predicted from the empirical relationship derived from rigid penetrometers [28].

Figure 21: Intact MMEEV Prototype with ICoSS Aeroshell Following UTTR Drop Test [28]

It is worth noting that an energy absorber is only required if the vehicle is either expected to land on a hard surface, or the attenuation provided by soil penetration is not adequate. For example, an MMEEV configuration that does not require an energy absorber is shown in Figure 22. This concept was designed for a sample return mission in which the sample materials were tolerant to impact accelerations above 1,000 G, and the lack of backward planetary protection requirements allowed unlikely off-nominal landings on a hazardous surface to be ignored in the design.

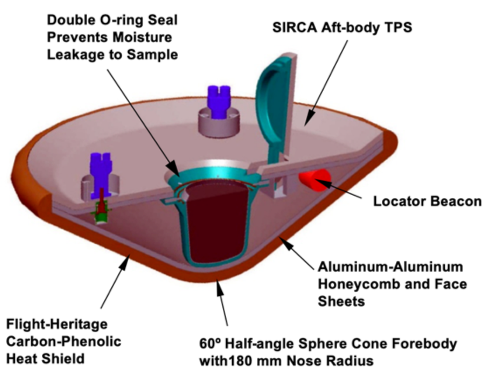

Figure 22: MMEEV Concept without an Integral Energy Absorber

The secondary challenge in designing an MMEEV without an integral energy absorber is protecting the samples from excessive heat during and after landing. The MMEEV energy absorber concepts developed by LaRC are comprised of a composite/foam cellular structure which also serves as an effective thermal insulator between the forward heatshield and the sample container. Without this insulating material in the nose of the vehicle, the thermal energy stored in the heatshield is more likely to soak back and raise the temperature of the samples to unacceptable levels. In these cases, a detailed thermal soak-back analysis, as illustrated in Figure 23, is necessary to demonstrate that the sample temperatures will comfortably satisfy the science requirements.

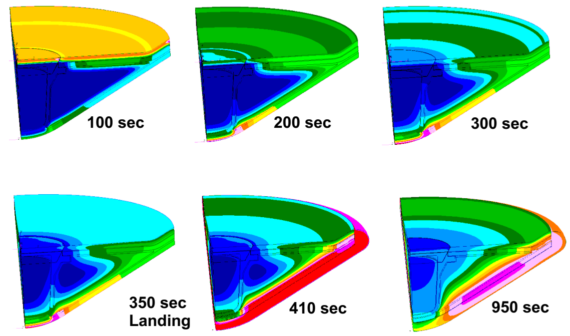

Figure 23: Post-Landing Thermal Soak-Back Analysis of an MMEEV Design without an Integral Energy Absorber

5.3 MMEEV Aerodynamic Refinements

As the application of the MMEEV to various sample return missions was being pursued, activities to better understand and define the vehicle's static and dynamic aerodynamics were continuing. These activities included sting-mounted tests in the LaRC 12-Ft Wind Tunnel to measure static aerodynamics (Figure 24), and free-flight tests in LaRC's Vertical Spin Tunnel [31, 32]. Both sets of tests examined the influence of different backshell configurations and capsule shoulder geometries on the vehicle aerodynamics.

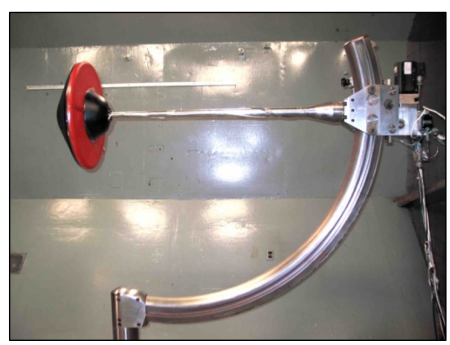

Figure 24: An MMEEV Concept Undergoing Aerodynamic Tests in LaRC's 12-FT Wind Tunnel

6. MMEEV Future (2017 and Beyond)

NASA is currently formulating an MSR mission to return Mars samples to Earth in 2031. The MSR mission formulation is being managed by JPL, and the mission design currently incorporates an MMEEV-type passive vehicle to return the Mars samples to the Earth's surface.

The vehicle development team, comprised of subject matter experts from JPL, LaRC, and ARC, is examining vehicle configurations that utilize different structural concepts and TPS solutions to meet the MSR objectives within the context of maintaining very high reliability for backward planetary protection.

7. Summary

The MMEEV has evolved from an MSR-specific enabling technology in 1998 to a broader present-day capability adaptable to a wide array of sample return missions. The last two decades of focused technology development and design tool validation have positioned the MMEEV passive entry vehicle concept to be rapidly integrated into mission design studies and implemented in flight missions.

References

[1] R. Mitcheltree, S. Kellas, J.T. Dorsey, P.N. Desai, C.J. Martin, A Passive Earth-Entry Capsule for Mars Sample Return, AIAA Paper 98-2851, 7th AIAA/ASME Joint Thermophysics and Heat Transfer Conference, Albuquerque, New Mexico, June 15-18, 1998.

[2] R. Mitcheltree, C. Fremaux, L. Yates, Subsonic Static and Dynamic Aerodynamics of Blunt Entry Vehicles, AIAA Paper 99-1020, January 1999.

[3] R. Mitcheltree, S. Kellas, A Passive Earth Entry Capsule for Mars Sample Return, International Symposium on Atmospheric Reentry Vehicles and Systems, Archachon, France, 1999, 16-18 March.

[4] E. Fasanella, Y. Jones, N. Knight, Jr., S. Kellas, Low Velocity Earth-Penetration Test and Analysis, AIAA Paper 2001-1388, 42nd Structures, Structural Dynamics, and Materials Conference, Seattle, Washington, April 2001.

[5] R. Mitcheltree, S. Hughes, R. Dillman, J. Teter, An Earth Entry Vehicle for Returning Samples from Mars, AAAF Paper ARVS-102, 2nd International Symposium and Atmospheric Reentry Vehicles and Systems, Archachon, France, 2001, 26-29 March.

[6] R. Mitcheltree, R. Braun, S. Hughes, L. Simonsen, Earth Entry Vehicle for Mars Sample Return, IAF-00-Q.3.04, 51st International Astronautics Federation Congress, Rio de Janeiro, Brazil, 2000, 2-6 October.

[7] Kellas S., Design, Fabrication and Testing of a Crushable Energy Absorber for a Passive Earth Entry Vehicle, NASA CR-2002-211425, January 2002.

[8] S. Kellas, R. Mitcheltree, Energy Absorber Design, Fabrication and Testing for a Passive Earth Entry Vehicle, AIAA-2002-1224, 2002.

[9] M. Billings, E. Fasanella, S. Kellas, Impact Test and Simulation of Energy Absorbing Concepts for Earth Entry Vehicles, AIAA-2001-1602.

[10] E. Fasanella, M. Billings, Dynamic Finite Element Predictions for Mars Sample Return Cellular Impact Test #4, NASA TM-2001-211023, June 2001.

[11] R. Amundsen, J. Dec, R. Mitcheltree, M. Lindell, R. Dillman, Preliminary Thermal Analysis of a Mars Sample Return Earth Entry Vehicle, AIAA Paper 2000-2584, June, 2000.

[12] R. Amundsen, J. Dec, M. Lindell, Thermal Analysis Methods for an Earth Entry Vehicle, 11th Thermal and Fluids Analysis Workshop, Cleveland, Ohio, August 2000.

[13] J. Fragola, J. Minarick, B. Putney, S. Yazdpour, Scoping Risk Assessment: Earth Entry Vehicle for the Mars Sample Return Project, Science Applications International Corporation Report, March, 2000.

[14] J. Fragola, J. Minarick, B. Putney, An Evaluation of Containment Assurance Risk for Earth Entry Vehicle and Space Shuttle Sample Return, Science Applications International Corporation Report, Revision 1, August, 2001.

[15] R. Greene, Mars Sample Return / Earth Entry Vehicle: System Validation Flight Test Scoping Study, Sandia National Laboratory, 2001.

[16] J. Fragola, J. Minarick, B. Putney, An Evaluation of Containment Assurance Risk for Earth Entry Vehicle and Space Shuttle Sample Return, Science Applications International Corporation Report, Revision 2, September, 2002.

[17] R. Gershman, M. Adams, R. Mattingly, N. Rohatgi, J. Corliss, R. Dillman, J. Fragola, J. Minarick, Planetary Protection for Mars Sample Return, COSPAR PTP1-0011-02, 2002.

[18] R. Dillman, J. Corliss, Overview of the Mars Sample Return Earth Entry Vehicle, 6th International Planetary Probe Workshop, Atlanta, Georgia, June 2008.

[19] R. Maddock, Sample Return Challenges; Multi-Mission Earth Entry Vehicle Design Trade Space and Concept Development Strategy, 6th International Planetary Probe Workshop, Atlanta, Georgia, June 2008.

[20] J. Samareh, R. Maddock, R. Winski, An Integrated Tool for System Analysis of Sample Return Vehicles, IEEE Aerospace Conference, Big Sky, Montana, March 2012.

[21] R. Maddock, Multi-Mission Earth Entry Vehicle Design Trade Space and Concept Development Status, 7th International Planetary Probe Workshop, Barcelona, Spain, June 2010.

[22] J. Samareh, L. Glaab, et al, Multi-Mission System Analysis for Planetary Entry (M-SAPE) Version 1. NASA TM-2014-218507, August 2014.

[23] R. Maddock, An Application of the Multi-Mission Earth Entry Vehicle: Galahad – An Asteroid Sample Return Mission, 7th International Planetary Probe

Workshop (Poster Session), Barcelona, Spain, June 2010.
[24] T. White, R. Maddock, et al, Earth Entry Vehicle Design for Comet Surface Sample Return, 13th International Planetary Probe Workshop, June 2016.
[25] T. White, R. Maddock, et al, Detailed Design of Earth Entry Vehicle for Comet Surface Sample Return, 14th International Planetary Probe Workshop, The Hague, Netherlands, June 2017.
[26] A. Henning, R. Maddock, J. Samarah, Passive vs. Parachute System Trade Applied to the Multi-Mission Earth Entry Vehicle Concept, AAS 15-550.
[27] R. Maddock, J. Samarah, M. Munk, A. Henning, Passive vs. Parachute System Trade Applied to the Multi-Mission Earth Entry Vehicle Concept, 12th International Planetary Probe Workshop, Cologne, Germany, June 2015.
[28] S. Kellas, Passive Earth Entry Vehicle Landing Test, IEEE Aerospace Conference, Big Sky, Montana, 2017, 4-11 March.
[29] S. Kellas, Integrated Composite Stiffener Structure (ICoSS) Concept for Planetary Entry Vehicles, AIAA SciTech Forum, San Diego, California, 2016, 4-8 January.
[30] J. Littell, S. Kellas, Full-Scale Passive Earth Entry Vehicle Landing Tests: Methods and Measurements, NASA TM-2018-219802.
[31] C. Fremaux, R. Johnson, Subsonic Dynamic Stability Tests of a Sample Return Entry Vehicle, 4th International Planetary Probe Workshop, Pasadena California, 2006.
[32] L. Glaab, J. Bean, G. Morelli, C. Fremaux, M. Schoenenberger, Vertical Spin Tunnel Testing and Stability Analysis of Multi-Mission Earth Entry Vehicles, NASA TP-2016-219009.