Robotic Mars Sample Return and Earth Entry Vehicle Concept Development

By Marcus LOBBIA,[1)] Scott PERINO,[1)] Jeremy VANDER KAM,[2)] and James CORLISS[3)]

[1)]*NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA*
[2)]*NASA Ames Research Center, Mountain View, CA, USA*
[3)]*NASA Langley Research Center, Hampton, VA, USA*

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NASA has studied potential Mars Sample Return over many decades, and the most recent Planetary Science Decadal Survey recommended making significant progress on this topic one of its highest priority goals. Recent inter-agency discussions and scientific support are lending credence to current Mars Sample Return planning activities, which notionally target launch of Sample Retrieval Lander and Earth Return Orbiter flight elements in 2026, and return of Martian samples to Earth in 2031. As part of the Mars Sample Return architecture under consideration, an Earth Entry Vehicle would perform the final phase by protecting the samples through severe entry environments using a 60-deg. sphere-cone flying on a passive/ballistic trajectory. The Earth Entry Vehicle design activities in particular are considering a variety of potential challenges, including: minimizing vehicle mass due to the need to travel to Mars and back to Earth, vehicle robustness to Micrometeoroid and Orbital Debris impacts, capability to withstand severe entry environments while minimizing landing ellipse size, and providing impact load attenuation during a high-speed landing to meet Martian sample tube load limits and ensure sample containment in off-nominal scenarios. The present work provides a snapshot of current study work in progress, and highlights paths being taken to address these various design challenges for the conceptual Earth Entry Vehicle.

Key Words: Mars Sample Return, Entry Vehicle

1. Introduction

The most recent Planetary Science Decadal Survey indicated that the Mars Astrobiology Explorer-Cacher element of a potential robotic Mars Sample Return (MSR) architecture should be considered as the highest-priority large mission [1]. The European Space Agency (ESA) also signed a letter of intent with NASA in 2018 to jointly study MSR [2], and funded contractors in 2018 to start studies on the design of mission elements it might contribute to the mission. Finally, the most recent U.S. President's Budget Request for NASA [3] also includes a line item specifically to start funding MSR. Based on these recent developments, there is growing evidence to suggest that MSR may become the next large NASA Mars Program endeavor after the Mars 2020 rover.

While MSR is still in the pre-formulation phase, NASA's upcoming Mars 2020 rover is being designed with a sample-caching system that could fulfil Explorer-Cacher role in MSR. Other elements of the notional architecture include Earth Return Orbiter (ERO) and Sample Retrieval Lander (SRL) concepts. The last step of the overall MSR architecture would be to bring the Mars samples back to Earth's surface via a conceptual Earth Entry Vehicle (EEV), where they would then be transferred to the Sample Receiving and Curation Facility.

NASA is currently executing several concept studies to further develop the MSR architecture and vehicle elements. The present work provides an overview of these activities, along with additional details on the EEV designs being matured.

2. Notional Mars Sample Return Campaign Overview

Due to the complexity of bringing samples from Mars back to Earth, the notional MSR architecture under development splits it into three launches (see Fig. 1). First, the Mars 2020 rover scheduled for launch in 2020 would provide the sample acquisition and caching capability. As Mars 2020 roves the Martian surface, it would collect soil and rock samples into sample tubes, seal them, and leave them on the Mars surface for potential future retrieval by the other MSR mission elements. The Mars 2020 rover belly contains the sampling equipment, including a rotating drill carousel, and 42 sample tubes (at least 20 samples are planned to be collected; the system also contains 5 witness tubes to provide a means to ensure non-contamination of the Martian samples) [4].

In order to retrieve the samples from the Martian surface, the SRL mission element would potentially launch in 2026, and land a Mars Ascent Vehicle (MAV) and fetch rover (currently being studied as a potential contribution from ESA) on Mars. The SRL design would leverage entry vehicle design heritage from Mars Science Laboratory (MSL) and Mars 2020, and current design studies are investigating both a MSL-derived Skycrane descent system, as well as a powered propulsive lander that would land on the Martian surface using deployable legs. After landing, a fetch rover would drive to the sample drop locations, retrieve the sample tubes, and return to SRL to load them into the Orbiting Sample (OS) container in the MAV. The MAV would then launch the OS into Mars orbit for retrieval by the next phase of the mission.

The ERO element (currently being studied as a potential ESA contribution) would also potentially launch in 2026 with the NASA-provided EEV used to bring the samples back to Earth's surface. The use of solar electric propulsion is being investigated to minimize interplanetary flight times and open up departure/arrival windows. Once in Mars orbit, the ERO

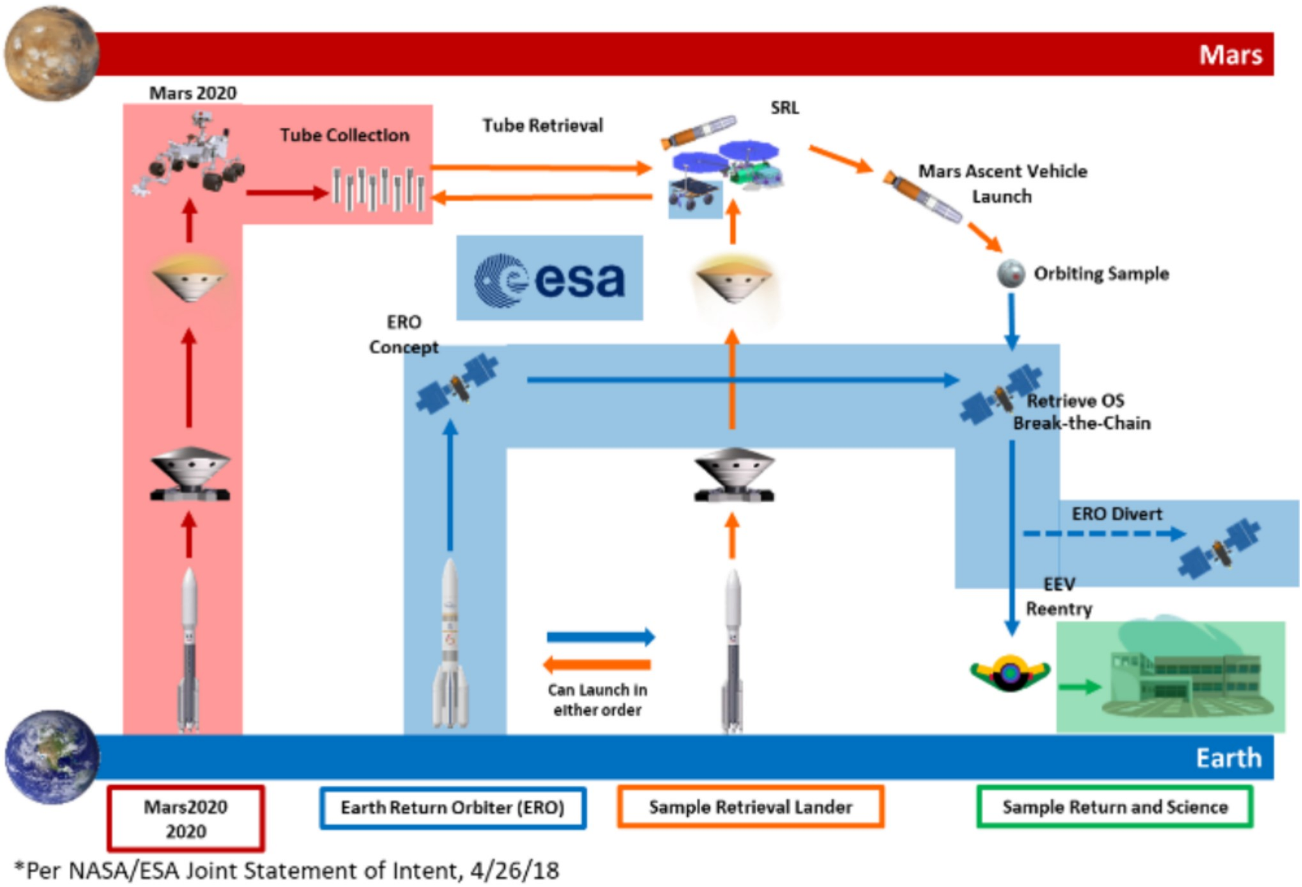

Fig. 1. Notional MSR Architecture, including three flight elements (Mars 2020, ERO, and SRL) and one ground element (Sample Receiving and Curation Facility.

would find and track the OS, rendezvous, and capture it into the NASA-provided Capture/Containment and Return System (CCRS). The OS would be robotically loaded into the EEV, and the ERO would travel back to Earth to deliver the EEV to its Earth entry interface in 2031.

3. Planning for the Return of Mars Samples to Earth

3.1. Key Design Constraints

As the last step in bringing the Martian samples back to Earth, the EEV design faces a number of challenging constraints. First, the vehicle mass should be minimized due to the need to bring the EEV to Mars orbit and back to Earth. On the other hand, due to potential planetary protection concerns associated with bringing fully contained but unsterilized Mars material to Earth, the robustness and reliability of the EEV is of paramount concern. Finally, based on the ERO Earth-return trajectory design trades and the need to minimize the landing ellipse size, the EEV would have be designed to potentially see a higher entry velocity and steeper flight path angle (and corresponding entry aerothermal environments) than previous sample return missions.

3.2. Notional Mission Architecture

As shown in Fig. 2, the final sequence in the notional Mars Sample Return architecture would have the ERO approach Earth on a hyperbolic trajectory. As the ERO would initially be targeted to not enter Earth's atmosphere (to provide protection against off-nominal situations), an Earth Targeting Maneuver (ETM) would be initiated several days prior to the desired entry date to put the ERO and EEV on an Earth-impact trajectory. Radiometric tracking and (if needed) a Trajectory Correction Maneuver (TCM) would be conducted, and the EEV would be released from the ERO one or more days prior to entry. Shortly afterwards, the ERO would conduct an Earth Avoidance Maneuver (EAM) to avoid entering the atmosphere, and flyby Earth at a safe miss distance.

After release from ERO, the EEV would enter Earth's atmosphere with an entry velocity as high as 13 km/s. After a short flight through the atmosphere, the vehicle would notionally land at the Utah Test and Training Range (UTTR). As the EEV entry is ballistic and does not use a parachute or any active electronics for reliability reasons, the EEV would passively impact the ground at approximately 35-45 m/s. Therefore, the EEV design should limit loads on the Martian sample tubes to less than 1300 g's in nominal soft-soil landing scenarios, and it should also maintain sample containment in off-nominal impacts (e.g., hard surfaces or sharp object impacts).

3.2. Previous Design Iterations

MSR has been studied to various levels of detail over several

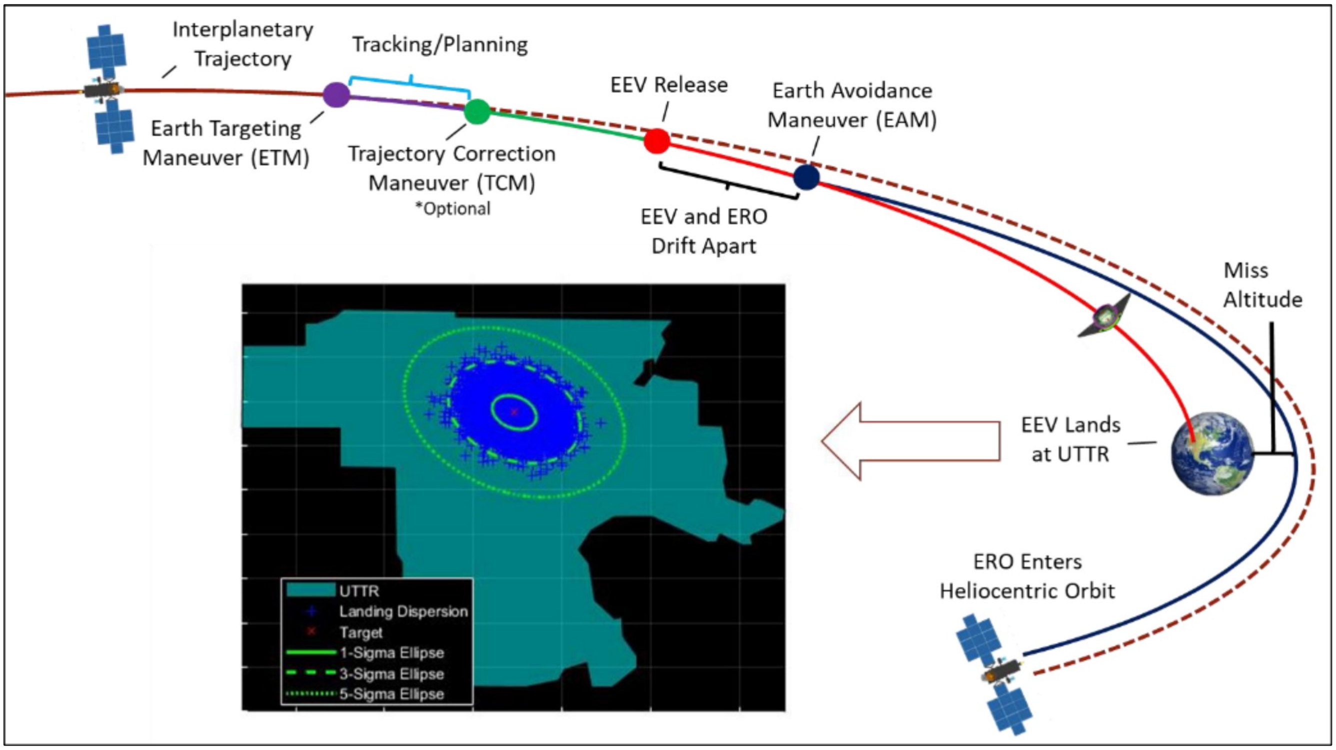

Fig. 2. Concept for ERO and EEV final approach and entry to Earth.

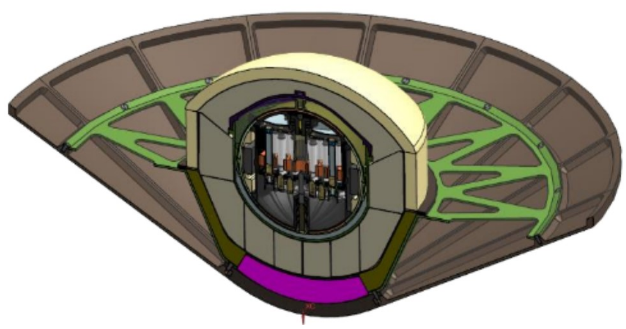

Fig. 3. Conceptual hot-structure EEV design using Carbon-Carbon

decades [5]. In general, most studies of the EEV have looked at ballistic/passive entry vehicles similar to the current architecture, as the concerns related to preventing contamination from returning samples in the event of a failure was expected to be a strong design driver.

In the past, NASA conducted extensive development work for a 2003-2005 notional mission timeline. This conceptual architecture looked at the use of a 60-deg sphere-cone shape and Carbon-Phenolic thermal protection system (TPS) on the EEV. A small 5 kg OS container with the Martian samples was used in the design. Substantial analysis and testing was conducted at the time to mature the EEV, although ultimately the 2003-2005 mission development activity was cancelled.

More recently, the current MSR study team took a fresh look at the EEV design starting in 2017. The EEV payload had grown substantially from the earlier studies (i.e., approximately 2-3 times the size and mass), and ERO trajectory studies were indicating that an entry velocity of 13 km/s or more might be required to realize an accelerated mission timeline (launch in 2026, with samples returned to Earth in 2029). In addition to looking at Carbon-Phenolic and Phenolic-Impregnated Carbon Ablator (PICA) TPS designs, this drove investigation into alternative TPS materials that could meet these stressing environments. In particular, a "hot-structure" EEV concept that utilized Carbon-Carbon as the TPS and aeroshell structure [6] was developed, with later revisions to this looking at the use of 3D Carbon-Carbon materials (see Fig. 3). It was thought that this would provide a mass-benefit vs. Carbon-Phenolic, as well as increase robustness to potential Micrometeoroid impacts due to the Carbon-Carbon structure being functional at very high temperatures. However, recent iterations on ERO trajectories (with Earth return in 2031) indicated that lower entry velocities (<13 km/s) were likely attainable, and the focus shifted back to more heritage-style "cold-structure" EEV designs using PICA and the Heatshield for Extreme Entry Environment Technology (HEEET) TPS materials.

4. Current Earth Entry Vehicle Concept Development

Current EEV design studies are focused on maturing two specific concepts, with the primary difference being the choice of TPS material (PICA vs. HEEET), along with small differences in the designs as needed to accommodate the use of the different TPS options.

4.1. Design Overview

For both EEV concepts currently being studied, the overall shape and size of the EEV is the same – a 60-deg sphere-cone forebody shape, with a 30 cm nose radius and 1.3 m max aero-shell diameter. An example of the current HEEET design is shown in Fig. 4. The PICA design looks very similar, with the primary difference being the different forebody TPS material.

The EEV is divided into several elements, including: Aero-Thermal Structure (ATS), TPS, and EEV Payload Module

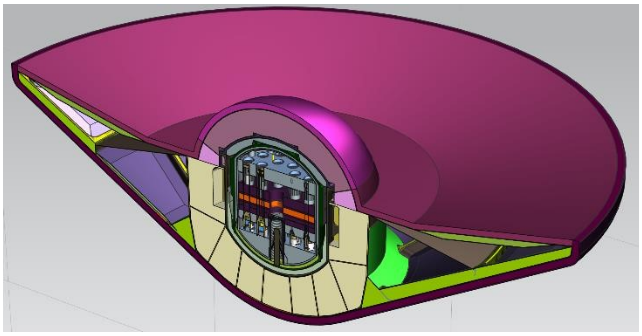

Fig. 4. Notional HEEET EEV concept.

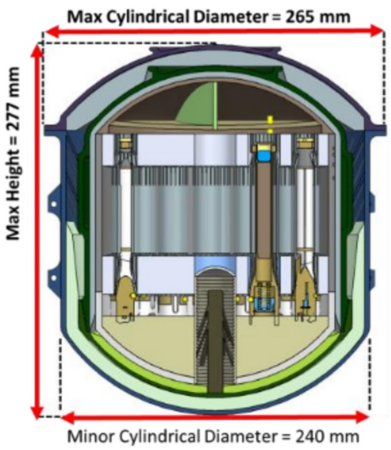

Fig. 5. Contained-OS design used in most-recent EEV studies.

(EPM). The ATS primarily consists of the composite load-bearing structure used to support the TPS, as well as carbon foam used in the fabrication of the composite ribs present in the design. The ATS also includes a composite-web/foam structure surrounding the EPM, which provides thermal insulation and impact load attenuation during nominal and off-nominal landing scenarios.

The EPM consists of the Orbiting Sample (OS), as well as the Primary and Secondary Containment Vessels (PCV and SCV, respectively) used to provide robust containment of the Martian samples and meet potential planetary protection guidelines. Earlier design iterations assumed a 33 kg Contained-OS (33 cm diameter with a spherical OS) – for example, the hot-structure design shown in Fig. 3 used this. The current design cycle, however, is investigating the potential benefits of using a smaller 23 kg Contained-OS (non-spherical OS with 20 sample tubes) shown in Fig. 5.

To support the variety of analyses being conducted during the concept development, a master equipment list was created and component masses estimated for each EEV design. Mass growth allowances (typically 25% or greater) were also applied considering the early-stage design maturity, which resulted in maximum expected entry masses of 63.3 and 85.0 kg for the PICA and HEEET designs, respectively. Subsequent performance analyses (e.g., entry trajectory simulations, landing impact dynamics analyses) are using these mass allocations to assess overall EEV performance against meeting expected design requirements.

4.2. Micrometeoroid and Orbital Debris Risk

For the notional MSR mission, the EEV would be required to spend several years in space, with transit from Earth to Mars (approximately 1 year), spiral down to and loiter in Mars orbit (3 years), and transfer back from Mars to Earth (1 year). While the likelihood is very small, there is still the possibility of Micrometeoroid (MM) and Orbital Debris (OD) impacts to the vehicle TPS during the mission. This could lead to the potential for a TPS failure during entry due to hot gas ingestion or other mechanisms [7], and is one of the reasons NASA investigated the hot-structure EEV concept earlier. Therefore, work is being conducted to ensure that the EEV is protected in line with expected risk tolerance.

To protect the EEV during the majority of the mission when it is attached to the ERO spacecraft, a notional "garage" is being developed that would shield the EEV from stray Martian dust and the space environment. While several different garage concepts are being studied, in the most simple form they include a "bumper" outer layer(s) to break up an MM/OD particle, and a "catch" material spaced some distance away to collect the broken particle fragments [8]. Larger standoff distances between the bumper and catch surfaces generally improves MM/OD protection, with recent EEV garage designs considering approximately 20 cm of spacing.

In the final days prior to entry, the ERO spacecraft would open the garage using a hinge mechanism, and release the EEV onto its final entry trajectory. At this point, the EEV would be in free-flight without supplemental MM/OD protection for up to several days. While the time duration is short relative to the overall mission timeline, in this period the EEV TPS would have to be capable of absorbing MM/OD impacts. To characterize the TPS robustness to MM/OD impacts, hyper-velocity impact testing and hydrocode simulations of TPS materials are being conducted as part of the maturation process to better characterize the PICA and HEEET materials to different impact conditions. These results will be combined with stakeholder inputs to determine if TPS thicknesses need to be increased to provide MM/OD robustness.

4.3. Entry Trajectory Performance

As part of the ERO/EEV final approach analysis, a dispersed set of EEV entry states were created based on ERO spacecraft assumptions (e.g., maneuver and EEV release uncertainties), as well as the desired entry conditions for the EEV. The designs were then simulated from the entry interface altitude of 125 km down to the UTTR landing site using a 6-degree of freedom (DOF) Monte Carlo trajectory simulation (NASA's Program to Optimize Simulated Trajectories II – POST2) code. Additional simulation input dispersions considered included vehicle aerodynamics (based on NASA's aerodynamic database from the 2003-2005 MSR work), atmosphere and wind uncertainties (NASA EarthGRAM model), and mass uncertainties. In addition to the POST2 baseline results, JPL's DSENDS (Dynamics Simulator for Entry, Descent and Surface landing) code [9] was also applied to run 3-DOF trajectory Monte Carlo simulations and provide inputs into ERO/EEV capability vs. requirement trades.

The POST2 Monte Carlo trajectory simulations formed the basis for identifying stressing trajectories to assess the EEV

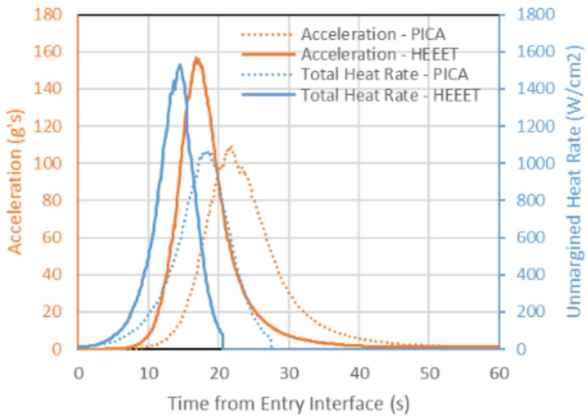

Fig. 6. Example of heating and loads experienced by PICA and HEEET concepts in 99.87% high heat rate trajectories for each.

TPS and ATS. This included looking at 99.87% high heat flux, heat load, and peak acceleration trajectories. As the HEEET TPS is a higher density material capable of withstanding more severe entry conditions than PICA, the HEEET design was developed using a steeper -25 deg. entry flight path angle (vs. the -18 deg. used in the PICA design trajectories). An example of the stagnation heating and acceleration experienced on these 99.87% high heat flux trajectories are shown in Fig. 6; it is readily apparent that the steeper trajectory of the HEEET design results in higher heating and acceleration environments. Figure 7 shows examples of landing ellipses estimated for both HEEET and PICA EEV designs using the POST2 simulations. While the steeper flight path angle for the HEEET design results in higher heating and loads, it does provide the benefit of reducing the ellipse size as compared with the PICA design, which could help ensure landing in nominal soft-soil locations such as UTTR.

Using the 99.87% high heating trajectories above, a high-fidelity TPS sizing analysis was conducted with the DPLR (Data-Parallel Line Relaxation) [10] and NEQAIR (Nonequilibrium Radiative Transport and Spectra) codes to develop detailed convective and radiative heat flux distributions over the EEV. These results were used to anchor a CBAERO (Configuration-Based Aerodyanmics) aerothermal model, which was then applied with inputs from each trajectory into a stochastic TPS sizing process using the 1D thermal-ablation code FIAT. This resulted in the identification of fully-margined TPS thicknesses for each concept that meet expected aerothermal environments.

4.3. Landing and Impact Assessments

The EEV entry trajectories would terminate with the EEV notionally impacting the UTTR soil at 35-45 m/s. This results in landing dynamics analyses that must consider the high-strain rate behavior of materials (vs. typical quasi-static structural tests). NASA is performing testing on PICA, HEEET, and relevant ATS structural materials (e.g., Carbon foam, graphite epoxy composite) to characterize these material responses in this regime. Simulations of both nominal and off-nominal landing scenarios are also being performed using the LS-DYNA finite element code; an example of LS-DYNA analysis on an earlier EEV design concept is shown in Fig. 8, along with

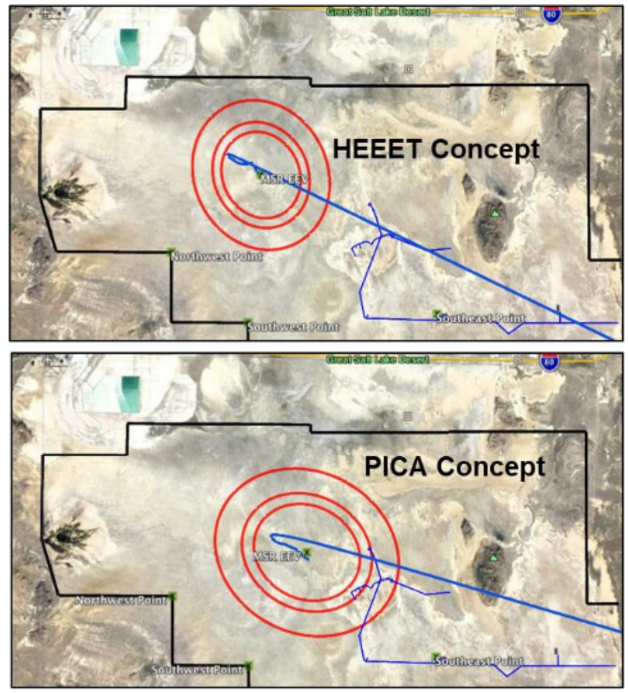

Fig. 7. Example of landing ellipses (99.0, 99.9, and 99.9999 percentiles) for the HEEET and PICA concepts.

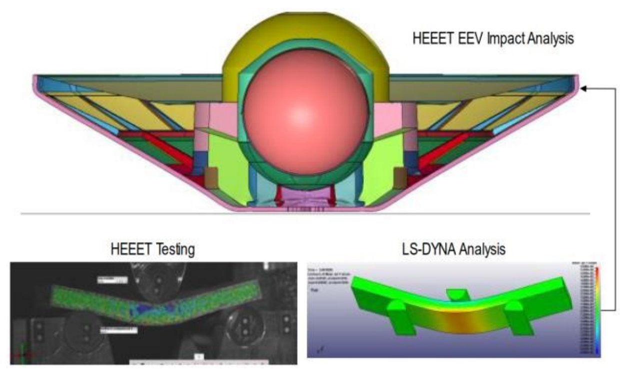

Fig. 8. Example of material testing feeding into landing impact analysis using LS-DYNA.

some material testing and corresponding analysis. These results are being used to iterate various aspects of the structural design and ensure that the Martian sample tube load limit and containment requirements discussed earlier are met.

5. Conclusion

While Mars Sample Return has seen many starts and stops over the decades, recent events (including demonstrated U.S. and European political and science community support) are providing renewed optimism that the mission may finally be executed in the 2020-2030 timeframe. The present work provided a short overview of the current notional MSR architecture under study, as well as a focus on some of the EEV-specific maturation work in progress. The EEV concept design must consider a multitude of potential requirements, including robustness to MM/OD risk, minimizing mass, and capability of meeting Martian sample tube load limits and containment during the high-speed landing, notionally at

UTTR. While EEV concepts designed around both PICA and HEEET TPS materials are concurrently being studied, NASA is planning to downselect to a single TPS design in the near future, assuming funding and political support for MSR continues on the current trajectory towards a potential ERO/EEV launch in the 2026 timeframe.

Acknowledgments

The decision to implement Mars Sample Return will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process. This document is being made available for information purposes only.

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References

1) Squyres, S., et. al., "Visions and Voyages for Planetary Science in the Decade 2013-2022," National Academies Press, 2011.
2) Zurbuchen, T, and Parker, D., "Joint Statement of Intent between the National Aeronautics and Space Administration and the European Space Agency on Mars Sample Return," April 26, 2018.
3) NASA FY 2020 Full Budget Request, https://www.nasa.gov/sites/default/files/atoms/files/fy_2020_congressional_justification.pdf (accessed April 8, 2019).
4) Mars 2020 Mission: Sample Handling Mechanism, https://mars.nasa.gov/mars2020/mission/rover/sample-handling (accessed April 8, 2019).
5) Perino, S., Vander Kam, J., and Corliss, J., "A New Era and a New Tradespace: Evaluating Earth Entry Vehicle Concepts for a Potential 2026 Mars Sample Return," 15th International Planetary Probe Workshop, Boulder, CO, 2018.
6) Lobbia, M., Perino, S., and Parrish, J., "Hot-Structure Earth Entry Vehicle Concept for Robotic Mars Sample Return," 15th International Planetary Probe Workshop, Boulder, CO, 2018.
7) Agrawal, P., Munk, M. M., Glaab, L. A., "Arcjet Testing of Micro-Meteroid Impacted Thermal Protection Materials," AIAA Paper 2013-2903, 2013.
8) Christiansen, E., "Handbook for Designing MMOD Protection," NASA JSC-64399, 2009.
9) Balaram, J., et al, "DSENDS – A High-Fidelity Dynamics and Spacecraft Simulator for Entry, Descent, and Surface Landing," IEEE Paper AC-302, 2001.
10) Wright, M. J., et al, "Data-Parallel Line Relaxation Method for the Navier-Stokes Equations, AIAA Journal, Vol. 36, No. 9, pp. 1603-1609, 1998.