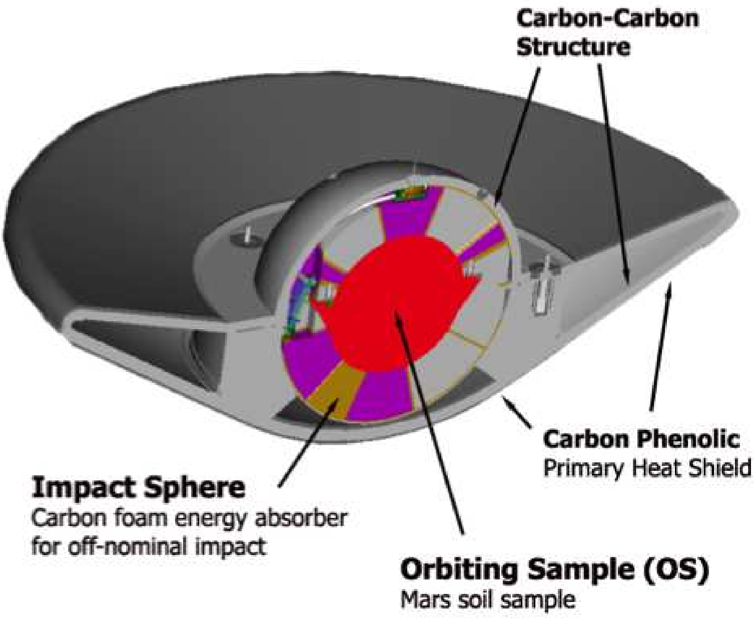

An Integrated Tool for System Analysis of Sample Return Vehicles

By

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***Abstract*— The next important step in space exploration is the return of sample materials from extraterrestrial locations to Earth for analysis. Most mission concepts that return sample material to Earth share one common element: an Earth entry vehicle. The analysis and design of entry vehicles is multidisciplinary in nature, requiring the application of mass sizing, flight mechanics, aerodynamics, aerothermodynamics, thermal analysis, structural analysis, and impact analysis tools.**

Integration of a multidisciplinary problem is a challenging task; the execution process and data transfer among disciplines should be automated and consistent. This paper describes an integrated analysis tool for the design and sizing of an Earth entry vehicle. The current tool includes the following disciplines: mass sizing, flight mechanics, aerodynamics, aerothermodynamics, and impact analysis tools. Python and Java languages are used for integration. Results are presented and compared with the results from previous studies.

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1. INTRODUCTION

Space exploration missions that perform in situ analysis have provided a wealth of information about extraterrestrial bodies. For example, the Mars Phoenix lander was a highly capable spacecraft with many sophisticated instruments that were used to analyze the Martian surface. However, there are certain analyses that can only be performed in laboratories on Earth. The Sample Return mission will address these situations.

Sample return missions abound throughout the history of spaceflight. The Soviets had several successful robotic lunar sample-return missions in the 1970s. The NASA Genesis project was a sample return mission that was launched in August of 2001 to collect a sample of solar wind and return it to Earth. In September of 2004, the Genesis Earth entry vehicle crashed in the Utah desert when the parachutes failed to deploy, and the planned mid-air retrieval could not be performed. Stardust was a NASA sample return mission launched in 1999 to collect cosmic dust. The Stardust entry vehicle successfully landed at the Utah Test and Training Range in 2006. Hayabusa was a Japanese mission that collected dust from an asteroid, and it landed in June of 2010 in the South Australian Outback. There is a plan for a follow-up mission for Hayabusa 2 scheduled for either 2014 or 2015. Phobos-Grunt was a Russian sample return mission to Phobos. The mission was launched in November of 2011, but a failure left the spacecraft stranded in low Earth orbit. China has a mission plan to return a lunar sample in 2017. There is also the Mars Sample Return plan, which is the most challenging of all existing sample return plans. Mattingly and May [1] provide the most up-to-date overview of this mission plan.

Multi-Mission Earth Entry Vehicle (MMEEV)

NASA's In-Space Propulsion Technology (ISPT) Program has funded a system analysis project for the development of Multi-Mission Earth Entry Vehicle (MMEEV). Maddock [2-5] has documented the overall MMEEV project and its progress. The goal is to develop a flexible Earth Entry Vehicle (EEV) design that can be utilized by multiple sample return missions [2]. The MMEEV concept is based on the Mars Sample Return (MSR) EEV design [6] that is driven to minimize risks associated with sample containment. The vehicle, by necessity, is designed to be the most reliable space vehicle ever developed. By preserving key common elements, the MMEEV concept will provide a platform by which technologies, design elements, and processes can be developed and flight tested prior to implementation on MSR. This approach could not only significantly reduce the risk and associated cost in development of the MSR EEV, but all sample missions will benefit by leveraging common design elements.

Maddock [3] provides the details of the MMEEV system components and the vehicle trade space. Galahad is one sample mission that MMEEV has used for the analysis and design. Galahad is an asteroid sample return mission proposal in response to the NASA New Frontiers solicitation. The Galahad design using the MMEEV concept is described in Ref. [4]. The second version of MMEEV is described in Ref. [5], where the MMEEV system level integration approach is introduced.

The primary focus of this paper is on MMEEV system analysis tool integration. It also provides a brief description of existing MMEEV components and the details of the new impact module.

This paper is organized into five sections. Section 2 describes the nominal Earth Entry Vehicle (EEV) used in this paper. Section 3 describes the multidisciplinary integration approach used in this study. Section 3 also includes a discussion on the impact sphere and foam characterization used in this study. The results and summary are in sections 4 and 5, respectively.

2. EARTH ENTRY VEHICLES

The potential for terrestrial contamination from returned sample material is a major driver for Earth entry vehicle design. A planetary Entry, Descent, and Landing (EDL) system typically consists of a heatshield for entry, a parachute for descent, and either retro rockets or airbags for landing.

Mitcheltree et al. [6] provide a discussion on two possible options for a reliable EEV design: either the design includes sufficient redundancy for each subsystem or eliminates the need for the subsystem. They propose a simple passive entry system solution that replaces the parachute and landing system with a hardened container surrounded by sufficient energy absorbing material to assure containment during ground impact. Dillman et al. [7] continued refining Mitcheltree's model, which is the basis for the current EEV analysis.

Mission requirements have strong influence on the overall EEV design concept. For example, an EEV returning a solar wind sample will have a different design concept, compared to an EEV returning samples that could expose Earth's biosphere to potentially catastrophic terrestrial contamination. Figure 1 shows an EEV design concept that was used for the MSR mission [7]. The design consists of a sphere cone body, an orbiting sample (OS) canister, an impact sphere to absorb the kinetic energy, a carrier structure, and a thermal protection system (TPS).

The EEV outer mold line (OML) is a 60° sphere-cone with the spherical nose designed to control the maximum stagnation heat rate. The OML is designed to provide hypersonic re-orientation capability, even when spin-stabilized 180º backwards or tumbling, in the event of entry attitude failures due to spacecraft separation or meteoroid impact.

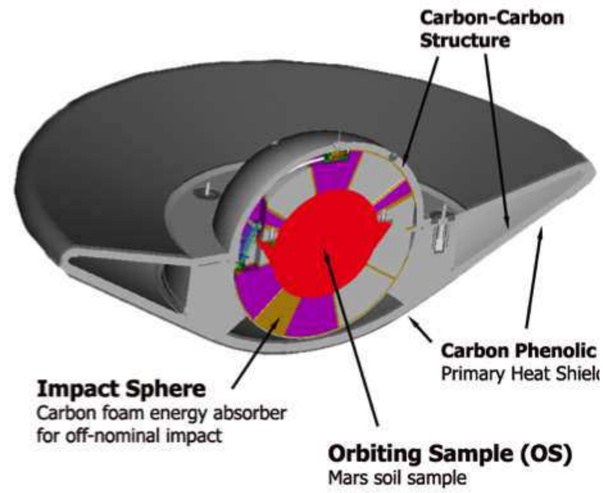

Figure 1 – MSR Earth Entry Vehicle [7]

The backshell is concave, and it is connected to the heatshield at the shoulder with the appropriate shoulder radius to control the maximum heat rate. The baseline for the forward TPS is a fully dense carbon phenolic (PICA may be used for less severe thermal environments). Acusil and Silicone Impregnated Reusable Ceramic Ablator (SIRCA) are the TPS options for the backshell.

The internal structures are made of carbon-carbon, designed to withstand only the launch and entry loads. The OS has a spherical shape and is designed to withstand entry and ground impact loads. An impact sphere with a cellular structure surrounds the OS.

3. MULTIDISCIPLINARY INTEGRATION

The purpose of systems analysis of an EEV is to gain a better understanding of various entry system concepts and their limitations. Systems analysis teams typically include one or more systems engineers and discipline-specific experts in flight mechanics, aerodynamics, aerothermodynamics, structural analysis, impact analysis, thermal soak, and thermal protection systems. The systems analysis process may take from several weeks to several years.

Integrated multidisciplinary analysis tools improve the performance of the systems analysis team by automating and streamlining the process, and this improvement can reduce the errors resulting from manual data transfer among discipline experts. The process improves and speeds up the design activities such as trade studies, sensitivity analyses, Monte Carlo analyses, and vehicle optimization. The role of discipline experts in the systems analysis process is indispensable and cannot be replaced by any tool.

The implementation of the multidisciplinary analysis approach presented here is a modified version of the System

Analysis for Planetary EDL (SAPE) [8] code. This implementation is targeted for Multi-Mission Earth Entry Vehicles using SAPE (M-SAPE). The purpose of M-SAPE is to provide a variable-fidelity capability for conceptual and preliminary analysis within the same framework. M-SAPE uses a combination of Python and Java languages (platform-independent open-source software) for integration and for the user interface. The development has relied heavily on the object-oriented programming capabilities available in Python and Java. Modules will be provided to interface with commercial and government off-the-shelf software components (e.g., finite-element analysis). An important goal for M-SAPE is to provide an integrated environment such that a low fidelity system analysis and trade can be performed in hours (not days or weeks) with sufficient hooks to perform high-fidelity analysis in days. Another goal of M-SAPE is to use existing software components, especially open-source software to avoid unnecessary software development and licensing issues.

A multidisciplinary problem can be decomposed into a set of key disciplines. These discipline tools, in this paper referred to as components, can be represented in matrix form using the Design Structure Matrix (DSM) approach. The matrix is a graphical approach for representing the interdependencies among the various components. The DSM is a square matrix with the analysis modules positioned along the main diagonal. Figure 2 shows a DSM representation for the EEV integrated analysis tool that includes seven analysis components: geometry, mass sizing, impact analysis, structural analysis, flight mechanics, TPS sizing, and thermal soak. For each analysis component shown along the DSM diagonal, relevant outputs are listed in the corresponding row; the inputs are listed in the corresponding column. For example, the required inputs for impact analysis are the OML, mass, terminal velocity, and temperature field. Impact analysis outputs include an estimate for the mass of impact sphere as well as the required impact stroke. The data exchanges among components listed below the DSM diagonal indicate a feedback loop. The DSM can be reordered to reduce the number of feedback loops or to exchange strong feedback loops with weaker ones.

There are two approaches to implement a multidisciplinary analysis system: tightly-coupled or loosely-coupled. In a tightly-coupled implementation, the components are integrated at the module levels. This type of implementation results in a system with faster execution time, but it is difficult to implement and maintain. In a loosely-coupled approach, the components are integrated at the application levels. This type of coupling is relatively easy to implement, modify, and maintain. However, there is an additional computational overhead, albeit a very small one for this implementation.

The current M-SAPE implementation combined geometry, mass sizing, impact analysis, and structural sizing into a single integrated tool referred to as the parametric vehicle model. The aerodynamics and aerothermodynamics models are combined with the flight mechanics tool. The thermal soak model is currently under development, and it will be integrated at a later date. The remainder of this section provides a brief description of each discipline used in the current M-SAPE system.

Aerodynamics

The MMEEV aerodynamic module is a database constructed from several sources, including Direct Simulation Monte Carlo (DSMC), computational fluid dynamics (CFD), wind tunnels, and ballistics range data. The database covers free-molecular, hypersonic, supersonic, and subsonic regimes. The database has been integrated into the flight mechanics code, Program to Optimize Simulated

	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**	Temperature or q at Bondline
Thermal Soak			Temperature Field	Temperature Field			**Thermal Soak**

Columns are inputs, and Rows are outputs

Figure 2 – Design Structure Matrix (DSM)

Trajectories II [9] (POST2).

Aerothermodynamics

The convective heating for the MMEEV vehicle is calculated using the Sutton-Graves equations [10], while the Tauber-Sutton equation [11] is used for the radiative heating calculation. The Sutton-Graves equation is anchored [12] with CFD solutions to quickly characterize quantities pertinent to TPS design such as heat flux, heat load, and surface pressure. These quantities are then used as inputs for material response modeling to size the TPS [13] component. This aerothermodynamic model has been integrated into POST2.

Flight Mechanics

The Program to Optimize Simulated Trajectories II [9] (POST2) software was used for flight mechanics. The POST2 software is a generalized point mass, discrete parameter targeting and optimization program.

Impact Dynamics

The current impact dynamic analysis assumes a 1-D cylinder and perfectly vertical impact. There are three approaches to model the impact dynamics. The first approach is based on the MSR EEV model development, where penetrometers were used to perform ground characterization tests [14] at the Utah Test and Training Range (UTTR). These test data were then used to develop a simple empirical relationship which could determine the total impact, or peak deceleration of the EEV when penetrating the soft clay surface of UTTR. The penetrometer results show that impact g's are a function of EEV diameter, terminal velocity, and payload mass.

The second approach uses a simplified energy balance to understand the impact of the MMEEV with a perfectly rigid surface. In this case, since penetration is not possible, the vehicle and/or payload must be allowed to decelerate over some 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.

The third approach is based on an impact sphere described in Ref. 15. The impact sphere shown in Figs. 1 and 3 is the primary mechanism to protect the payload at landing. Kellas and Mitcheltree [15] describe a model of an energy-absorbing sphere that consists of three main components: a rigid inner shell to protect the OS canister, a crushable foam-filled cellular structure, and an outer shell. The cellular structure is made of fiber reinforcement and a matrix material with some variation in the stacking sequence. The concept is capable of withstanding an omnidirectional impact-load as well as offering penetration resistance (Fig. 3). The cellular concept is an efficient design that may be customized for any specific impact crush load. In addition to impact energy absorption, the foam will act as heat insulation to keep the payload within appropriate temperature limits. Kellas and Mitcheltree provide an analytical approach to predict the theoretical crush load based on the energy dissipated due to the folding of cell walls and the crushing of the impact foam cells. They obtained a good correlation between theoretical results and experimental tests.

The theoretical approach of Kellas and Mitcheltree [15] has been implemented for this study. Figure 4 shows sample results from this implementation. The x-axis is the cellular web thickness, and the y-axis is the foam strength. The

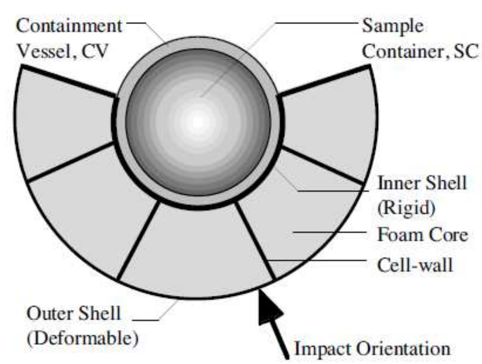

Figure 3 – Impact sphere [15]

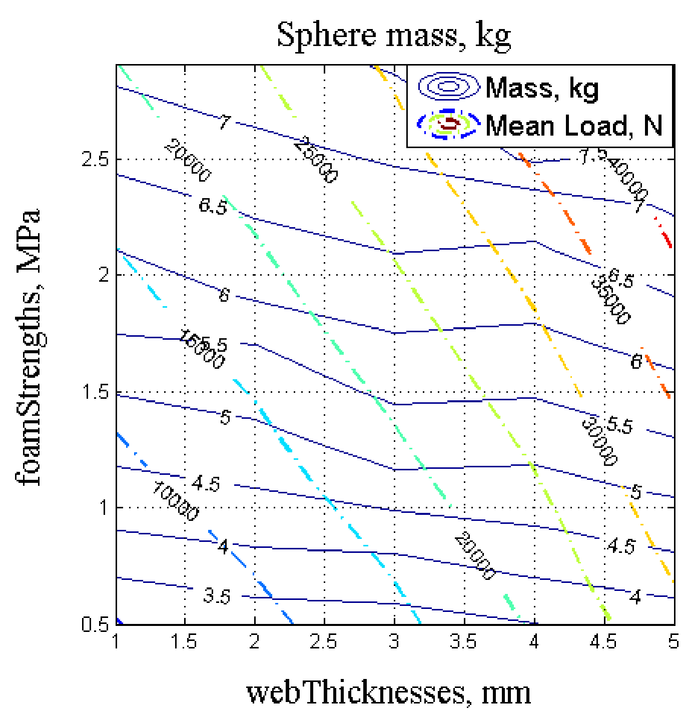

Figure 4 – Impact sphere results

broken contour lines are the mean crush loads, and the solid lines are contours of impact sphere mass. This is a standalone module that has not been yet integrated into M-SAPE.

All impact spheres rely on foam to absorb the entire impact energy or a portion of it. Carbon and polymer foams are credible candidates for EEV applications. Rohacell™ is a polymer foam that comes in various densities and strengths.

A series of static tests were conducted to characterize the mechanical properties of four high performance Rohacell foams: 200 WF-HT, 71 WF-HT, 110 WF-HT, and 110 XT-HT. Figure 5 shows the test setup and sample crushed foams. The tests followed ASTM D1621 (Standard Test Method for Compressive Properties of Rigid Cellular Plastics) to allow for comparison with manufacturer-provided data. The results from this test have been incorporated into the integrated system used in this study.

Figure 5 – Foam test setup and foams

Parametric Vehicle Model

The geometry, mass sizing, impact analysis, and structural sizing disciplines are combined into a parametric vehicle model (PVM), which was introduced in Ref. [3]. The model is a MATLAB script that is based on the MSR EEV design. The script creates the vehicle geometry in 2-D, and then rotates the geometry 360° to generate a 3-D vehicle model from which mass properties are estimated. The model is constructed from a series of curves based on geometric variables and relations defined within the trade space. The approach allows for automatic vehicle rescaling as input parameters are redefined. The script calculates mass, cg location and inertia components of the structure; aft TPS, and forward TPS. The mass and inertia properties are provided to the POST2 component for use in the simulation. The critical input parameters include: mission environment parameters (e.g., maximum entry load and terminal velocity), payload (mass and volume), vehicle shape (e.g., diameter and nose radius), TPS material selection, and carrier structure properties.

Thermal Protection System (TPS)

A mass-estimating relationship (MER [13]) was developed to calculate the thickness of the Carbon Phenolic (CP) and Phenolic Impregnated Carbon Ablator (PICA) TPS required for the MMEEV over the mission trade space. The MERs are based on the Fully Implicit Ablation and Thermal Analysis [16] (FIAT) program. The resulting MERs are fairly simple numerical fits based on 840 different simulations.

4. RESULTS

The results for four sample test cases are presented in this section. Previous EEV baseline models and results [3] were used to verify the integrated analysis tool. Table 1 shows the list of input parameters for the baseline model. The payload mass includes mass of sample return material, as well as the orbiting canister mass.

Figure 6 shows the results for various entry velocities and flight-path angles. The six plots in Fig. 6 share the same x-axis (velocity) and y-axis (flight path angle). The EEV escapes back to space for velocities greater than 12 km/s and flight path angles greater than -5° degrees. The EEV mass ranges from 40-48 kg. The entry load is a strong function of flight path angles and can vary from 20 to 220 Earth g's. The terminal velocity and foam thickness tend to follow the EEV entry mass. The heat load is higher for cases with shallow flight path angles and high entry velocities. Maximum heat rate is primarily a function of the entry velocity.

The next three test cases demonstrate M-SAPE capability. The results are compared with the previous MMEEV version 2 results, and it is expected that the results will be slightly different, because the analysis modules have been updated.

The second test case is a Mars Sample Return application [2]. The results from Ref. [2] and M-SAPE results are shown in Table 2. The peak heating and peak deceleration values are higher, and the terminal velocity is slightly lower. These differences are primarily due to the updates made to the aerodynamic model.

The third case is the Galahad model [4], which is an asteroid sample return mission proposal response to the NASA New

Frontiers solicitation. The mission goal is to return a sample from the binary C-asteroid 1996 FG3 and to make extensive orbital measurements. The plan is to return 60 g of samples to Earth. Figure 7 shows the Galahad EEV concept. Table 3 shows sample results for the Galahad EEV. The results are very similar: the total mass is within 4% of Ref. [4].

The last demonstration case is based on a Stardust-like mission that is based on the EEV concept presented in section 2. The MMEEV payload mass was adjusted, such that overall vehicle masses matched the Stardust entry mass. Table 4 shows a comparison between M-SAPE results and results from Ref. [17].

Table 1. Input Parameters for Case 1

Diameter, m	1.3
Payload mass, kg	12.5
Payload density, kg/m3	4000
Nose radius/base radius	.25
Shoulder radius/base radius	.07
Mass margin, %	30

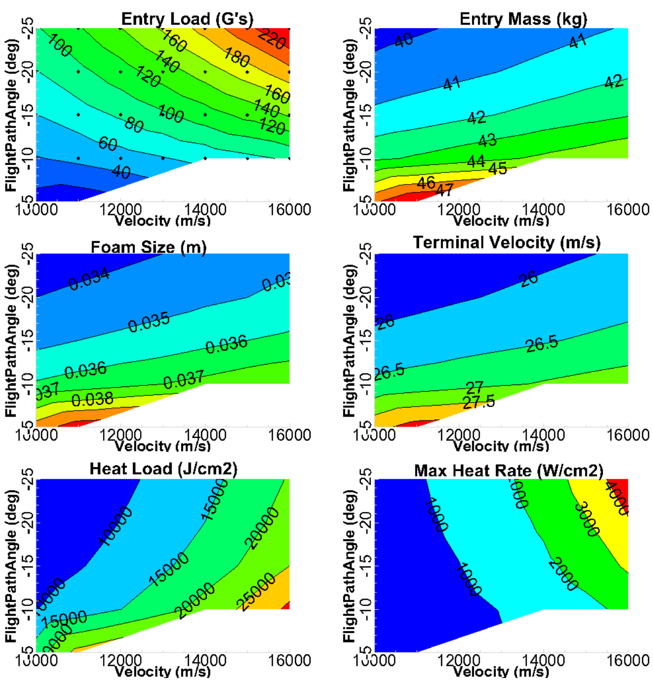

Figure 6 – Sample results for case 1

The M-SAPE TPS thickness result is significantly lower than the Stardust value, but this is not unexpected for two reasons. First, the model stackup in the FIAT ablative thermal analysis code differed. For Stardust, the stackup included PICA, HT-424 adhesive, and the aluminum 2024 honeycomb; whereas the MMEEV FIAT analysis used only PICA. Second, the Stardust TPS thickness was margined

Table 2. MSR Model Comparison

Parameters	Ref. [2]	M-SAPE
Diameter, m	0.9	0.9
Mass, kg	44	44
Entry velocity, km/s	12	12
Peak heating, w/cm2	1500	1611
Peak deceleration g's	130	146
Terminal velocity, m/s	41	39

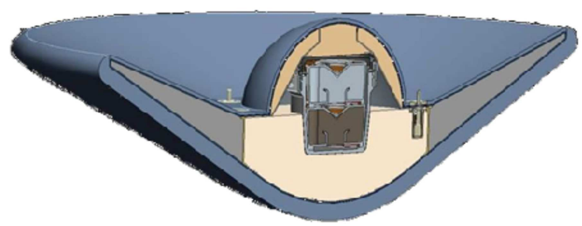

Figure 7 – Galahad EEV concept [4]

Table 3. Galahad Model Comparison

Parameters	Ref. [4]	M-SAPE
Total mass, kg	37.9	36.3
Maximum entry load, g's	34.6	34.1
Total peak heat rate, W/cm2	373*	355*
Total heat load, kJ/cm2	10.3*	9.8*
PICA thickness, cm	3.3†	2.24
Time of flight, sec	629	638
Impact velocity, m/s	28.9	28.5
Impact load, g's	400	456
Impact stroke, cm	3.1	3.9

*unmargined
†conservative thickness estimate [4]

Table 4. Stardust-like Model Comparison

Parameters	Ref. [17]	M-SAPE
Mass, kg	45.8	45.6
Entry Load, g's	Unavailable	37.59
Total heat rate w/cm2	1200	1062
Total heat load kJ/cm2	28	26.79
PICA thickness	4.8	2.58

beyond what the MMEEV vehicle uses, which is just based on the convective heating. Also, subsequent analysis showed that the Stardust bondline temperature prediction was approximately 74°C lower than the design analysis [18].

5. Summary

The paper describes an integrated system for the analysis and design of an Earth entry vehicle for sample return missions. The system includes geometry, mass sizing, impact analysis, structural analysis, flight mechanics, and TPS. The initial system integration has been completed, and four sample test cases were used to verify the integration. The test results compare favorably with the previous sample results.

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BIOGRAPHIES

Jamshid Samareh *is a senior research aerospace engineer in the Vehicle Analysis Branch of NASA Langley Research Center. He received his Ph.D. in Mechanical Engineering and Mechanics from Old Dominion University in 1987. His current research interests are in multidisciplinary analysis and design optimization (MDO), Entry and Descent Landing (EDL), mass modeling, fluid-structure interaction, geometry modeling, and shape optimization. He is the recipient of NASA Public Service Medal in 1995 and two-time winner of NASA Software of the Year Award as a member of TetrUSS team in 1996 and 2004. He was an Associate Editor of the AIAA Journal, a member of the AIAA MDO technical committee (TC) and is an associate fellow of the AIAA.*

Rob Maddock *is a senior engineer in the Atmospheric Flight and Entry Systems Branch at NASA Langley Research Center. He received his Bachelor's degree in Aerospace Engineering from Parks College of St. Louis University in 1992, and then went on to receive a Master's degree in Aerospace Engineering from The University of Tennessee Space Institute in 1995. In 1996 he joined the Jet Propulsion Laboratory where he worked in mission and trajectory design and systems engineering on several flight projects, including Cassini, the Shuttle Radar Topography Mission, and the Mars Science Laboratory. He also spent over 5 years in the Mars Advanced Studies Office supporting Mars Sample Return mission studies and technology development. In 2005, Rob joined NASA Langley to support EDL systems engineering and design for MSL. Since then, he has provided simulation and development support for the ALHAT technology project, lead Earth Entry Vehicle technology and systems analyses for sample return missions, and currently he is supporting the development of the Autonomous Aerobraking Development Software system.*

Richard Winski *is an aerospace engineer in the Atmospheric Flight and Entry Systems Branch at NASA Langley. He received a B.S. in Aerospace Engineering from the Virginia Polytechnic Institute and State University(Virginia Tech) in 2004 and M.S. in 2006 through Virginia Tech and the National Institute of Aerospace (NIA). While completing his M.S. he worked in the Atmospheric Flight and Entry Systems Branch at NASA Langley. His current work is in the area of flight dynamics and simulation for Entry, Descent and Landing (EDL).*