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A Methodology of MSL Breakup Analysis for Earth Accidental Reentry and its Application to Breakup Analysis for Mars Off-Nominal Entry

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Vehicle breakup analysis has been performed for missions that may carry nuclear fuel for heating or power purposes to assess nuclear safety in case of launch failure leading to atmospheric reentry. Also, failure scenarios exist which could lead to breakup during Entry / Descent / Landing (EDL) at Mars due to off-nominal entries, with implications for planetary protection requirements. Since the Mars Science Laboratory (MSL) spacecraft may include a Multi-Misssion Radioisotope Thermoelectric Generator (MMRTG), an analysis of breakup in case of launch failure is required. Also, breakup during Mars EDL due to off-nominal entries could release the RTG heat source that has implications for planetary protection requirements. This paper presents a methodology of MSL breakup analysis for launch failure with application to Mars off-nominal entry.

INTRODUCTION

Mars Science Laboratory (MSL) is a NASA / Jet Propulsion Laboratory mission to develop and launch a roving long-range, long-duration science laboratory that would take a major leap in surface measurements and pave the way for a future sample return mission. The proposed rover has one Radioisotope Power Supply (RPS) that would contain eight General Purpose Heat Sources (GPHS). Each GPHS module contains four fuel pellets with a nuclear substance. The mission architecture consists of four phases: launch, cruise/approach, Entry/Descent/Landing (EDL), and the surface mission. Two of these phases (launch and EDL) would be impacted by the presence of the GPHS modules. It is customary in missions involving atmospheric entry/reentry (for the purpose of launch approval, aerospace nuclear safety, planetary protection, and safe sample return) to perform breakup and debris analyses to assess consequences of potential failures. The analyses are required in the launch phase to assess accidental Earth reentry for launch approval and in the EDL phase in case of Mars off-nominal entry for planetary protection purposes. This paper presents a methodology of MSL breakup analysis for launch failure with application to Mars off-nominal entry.

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MSL Breakup Analysis in Inadvertent Earth Reentry

For decades, vehicle breakup analysis has been performed for space missions using nuclear heater or power units to assess aerospace nuclear safety in the event of a launch failure leading to inadvertent atmospheric reentry. Such pre-launch risk analysis is imperative to assess environmental impact, obtain launch approval, and for launch contingency planning.

In the launch phase, failure leading to the loss of the launch vehicle and spacecraft can occur at any time prior to Earth escape, leading to suborbital or orbital reentry. The vehicle is subjected to aerodynamic loads during the accidental reentry and component failure may occur due to thermal load, g-load, or combined thermal/structural loads. Vehicle breakup analysis provides an estimate of both the vehicle breakup characteristics and the impact footprint based on trajectory simulations coupled with thermal/structural analyses. Since MSL may have GPHS modules, vehicle breakup analysis is required to predict (1) vehicle breakup and release of the modules, (2) nominal impact point and impact conditions of the modules or the vehicle component containing them, and (3) uncertainty in impact point position (impact ellipse).

This paper presents a methodology and approach for MSL breakup analysis due to thermal and structural loads in the event of launch failure to assess the risk for the MSL spacecraft M option design. It addresses both failures during ascent (suborbital) and from parking orbit (orbital).

MSL Breakup Analysis in Mars Off-nominal Entry

As the spacecraft begins the Mars EDL phase, several failure scenarios could lead to breakup as well. Since the baseline design of the MSL M option contains GPHS modules, a breakup during EDL due to off-nominal entry could release the modules. This heat source could melt water ice if it exists near the surface and produce liquid water that has implication for planetary protection requirements.

The methodology and approach for breakup analysis in accidental Earth reentry can be modified to provide a first-order understanding of the implications of failures during Mars approach and EDL that lead to various breakup scenarios for planetary protection. In these failure scenarios, the presence of a heating source on the spacecraft coupled with an off-nominal landing in an area where water ice may be near the surface requires a careful and thorough breakup analysis. Since microorganisms carried from Earth are the main concern from a planetary protection perspective, the objective of this paper is to quantify breakup scenarios assuming various credible failure modes during approach and EDL and answer the following questions:

1. What failures lead to the breakup of the RTG and release of the GPHS modules?

2. What failures lead to the RTG surviving and crashing intact on Mars?

3. What are the conditions at impact?

The Mars entry breakup analysis presented in this paper was an element of a larger effort conducted by the MSL project to develop a planetary protection strategy and propose a categorization that meets NASA requirements.

A METHODOLOGY & APPROACH FOR MSL BREAKUP ANALYSIS IN INADVERTENT EARTH REENTRY

This section outlines a methodology and approach for MSL breakup analysis in case of accidental Earth reentries and includes those which may arise both in the departure from parking orbit (orbital failures) and in the ascent to parking orbit (suborbital failures). Depending on the condition of the off-nominal entry, the spacecraft follows a particular ballistic trajectory and may be relatively unprotected against aerodynamic heating and g-loads. Therefore, the MSL vehicle breakup analysis is basically a trajectory propagation, coupled with a thermal and structural analysis to determine if (and where along the trajectory) various components peel off in a progressive destruction approach to expose the RTG, and then if and where the RTG itself fails and exposes GPHS modules. If the modules are released, the analysis follows them to the ground to predict the impact footprints.

The process of performing vehicle breakup analysis includes these steps:

1. Determine the probable failure scenarios prior to Earth escape from mission timeline and launch trajectory for suborbital and orbital reentries.

The V-gamma map (Reference 1) consisting of the envelope of possible entry speed (V) and entry flight path angle (gamma) pairs that can result from burning the onboard propellant in a steady but incorrect direction, referred to as a steady misaligned burn (SMB), provides the initial conditions of reentries which may occur during the departure from parking orbit. Similarly, failures during ascent lead to fallback trajectories. Thus different types of reentry categories may be identified and examined such as PWE (powered entry), ELP (prompt elliptic), ELD (elliptic delayed), and COD (circular orbit decay). The vehicle in a PWE enters the atmosphere with the engine/motor still burning. In an ELP, it proceeds with a downward velocity and enters the atmosphere prior to the apogee. In the ELD, the vehicle passes the apogee before entering the atmosphere near the perigee. In addition, there is a category representing a failure to burn, resulting in decay of the parking orbit, ending in COD.

2. Set assumptions to bound the failure scenarios.

As in any vehicle breakup analysis, simplifying assumptions have to be considered to bound failure scenarios.

3. Determine probable spacecraft configurations and select the thermal/force nodes by identifying the weak points in the spacecraft.

The MSL spacecraft design considered in this analysis is the M option as illustrated in Figure (1). Examining Figure (1) indicates that the following nodes need to be considered to examine the failure of the RTG. Data on spacecraft components (material properties and node dimensions) are then acquired:

- Cruise Stage (solar array, propellant tanks, propellant tank support, ribs, launch vehicle adapter)
- Aeroshell
- RTG adapter
- Rover panel where RTG is attached
- Descent Stage (DS) tanks
- Descent Stage connecting tubes
- RTG housing (fins, cylinder, end cap), GPHS modules released when failed
- Structural interface (i.e. sep nuts)

4. Form the expected sequence of failure.

5. Determine the ballistic coefficients of various vehicle configurations.

6. Perform vehicle breakup analysis for several example reentry conditions, and spacecraft entry configurations and attitudes.

7. Perform sensitivity analysis to address uncertainties in the reentry condition and reentry vehicle configuration, and to calculate the impact footprint.

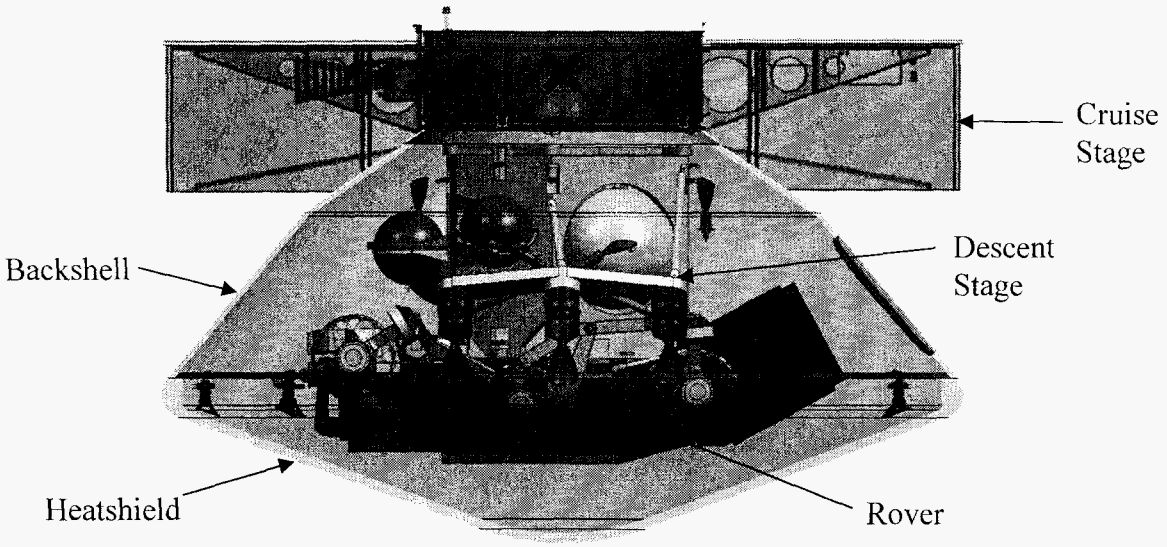

Figure (1). Design Concept -- MSL Spacecraft Components (M Option)

MSL OFF-NOMINAL LANDING WITH A PERENNIAL HEAT SOURCE

This section modifies the launch failures methodology presented above to be applicable to breakup scenarios associated with MSL Mars off-nominal entry and landing with a perennial heat source. The software tool used in the analysis of accidental Earth reentries was modified to take into account the nature of Mars off-nominal entry scenarios as well as the Martian conditions. Earth accidental reentry analyses use a software tool (Vehicle Breakup Analysis, VBA) designed and built specifically for launch approval[2]. The tool used in this analysis is a modified version of VBA that takes into account the nature of Mars off-nominal entry scenarios as well as the Martian conditions.

Planetary Protection Requirements and Objectives

The inclusion in the spacecraft design of a "perennial heat source," the RPS, coupled with the possibility of an off-nominal landing in an area where water ice may be relatively near the surface requires a careful and thorough assessment of MSL's options for meeting planetary protection requirements and objectives (with contamination by microorganisms from Earth the main concern). One element of this assessment is entry failures and breakup analysis. Its objective is to quantify breakup scenarios assuming

various credible failure modes during approach and EDL. The analysis is focused on answering the following questions:

1. Which failures would lead to breakup of the current baseline RPS, RTG and release of the GPHS modules?

2. Which failures would lead to the RTG and GPHS surviving and crashing intact on Mars?

3. What are the conditions at impact?

Thus, the analysis presented here provides a first-order understanding of the implications of catastrophic failures during approach and EDL that lead to various breakup scenarios.

MSL EDL Nominal Timeline

Figure (2) shows the nominal EDL timeline. The analysis must consider failures at any point during this timeline. Thus, the failures analyzed in this paper are during approach (pre-entry failure), at entry interface (EI), during parachute descent, and descent stage powered descent.

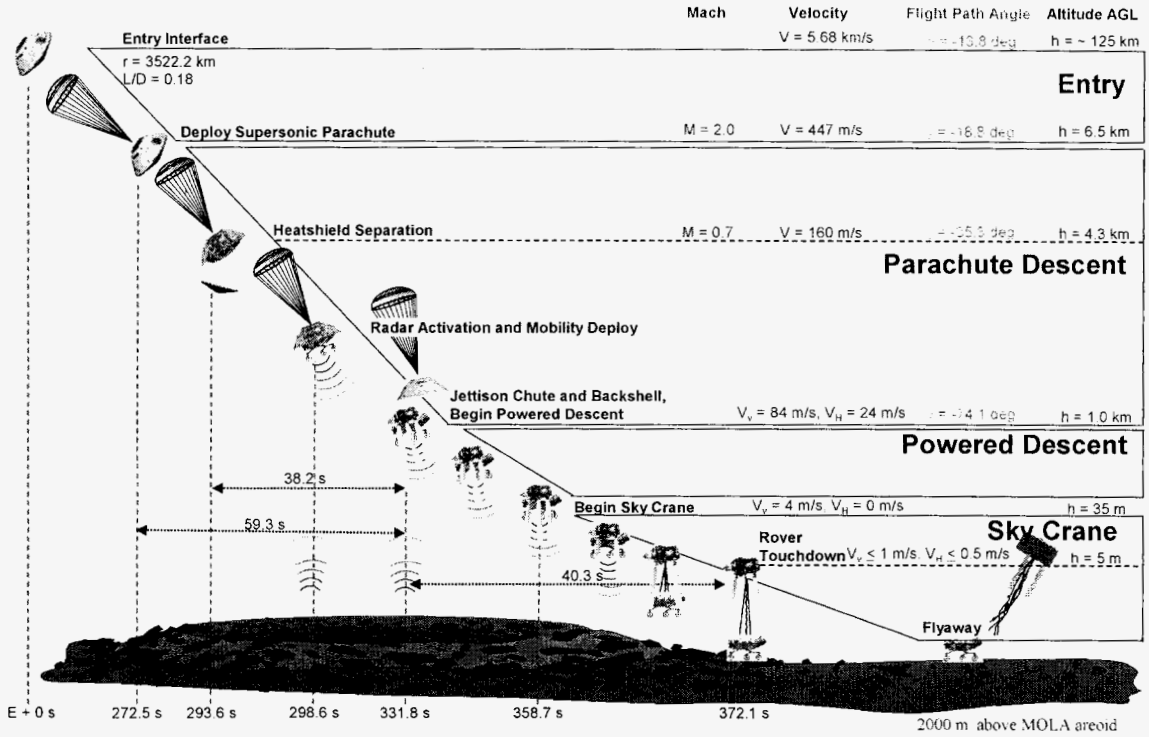

Figure (2) Nominal EDL Timeline

Failure Scenarios and Breakup Sequence During EDL

Figure (2) schematically illustrates the range of failure scenarios that could occur in approach and during EDL. The failure scenarios and breakup sequence analyzed in this paper are shown in Figure (3).

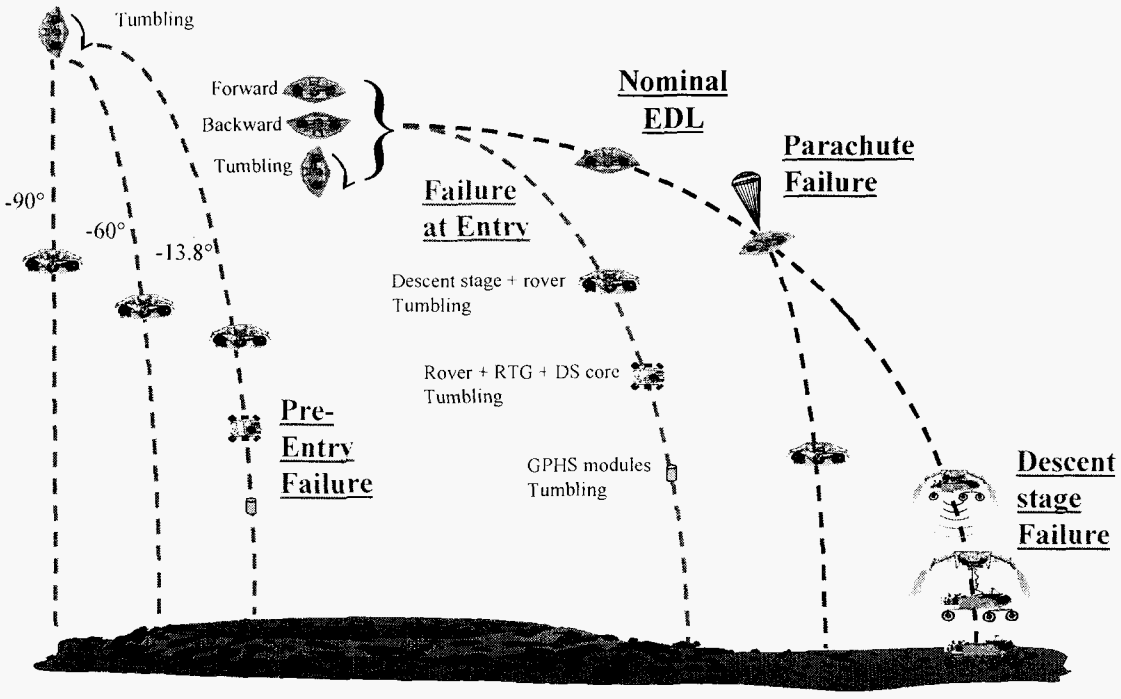

Figure (3) Failure Scenarios and Breakup Sequence During EDL

Specifically, the following cases were studied in this analysis:

- Pre-entry failures
  - PE.1: Failure before targeting Mars
  - PE.2: Failure after targeting Mars with Flight Path Angle (FPA) of 90 degrees
  - PE.3: Failure after targeting Mars with FPA of 60 degrees
  - PE.4: Failure after targeting Mars with FPA of 9 – 19 degrees

- Failures during entry
  - E.1: Loss of control during entry resulting in a normal attitude entry
  - E.2: Loss of control prior to entry resulting in a backward entry
  - E.3: Loss of control prior to entry resulting in a tumbling entry

- Parachute failures
  - P.1: Failure of supersonic chute

- Descent stage failures
  - D.1: Loss of control at high altitude resulting in an impact at arbitrary attitude
  - D.2: Hard landing in nominal orientation
  - D.3: Loss of control anywhere between release and normal landing

NAVIGATION, AERODYNAMIC, AND SPACECRAFT DATA (OPTION M DESIGN)

As in any vehicle breakup analysis, an extensive amount of information is required to perform the analysis. The following is the navigation, aerodynamic, and spacecraft design data.

Entry Conditions

Two cases with different entry velocity and landing site to illustrate impact on breakup are considered.

- Entry Case V_high (higher entry velocity)
  - 27 October 2010 arrival (southern spring), Landing at 41.45 deg S
  - Inertial velocity at entry = 5.8604 km/s
  - Inertial flight path angle = -14.5399 deg, Azimuth = 94.8966 deg
  - Longitude = 270.89 deg, Latitude = -41.5583 deg
  - Surface pressure 3.997 mbar
  - Average density 9.801E-3 kg/m3

- Entry Case V_low (lower entry velocity)
  - 17 Sept. 2010 arrival (northern spring/southern fall), Landing at 0.33 deg N
  - Inertial velocity at entry = 5.5452 km/s
  - Inertial flight path angle = -14.5 deg, Azimuth = 95.6625 deg
  - Longitude = 35.7799 deg, Latitude = 1.9576 deg
  - Surface pressure 3.773 mbar
  - Average density 8.548E-3 kg/m3

Aerodynamic Properties

The aerodynamic properties of various configurations are given in Table (1).

Table (1)
Nominal Vehicle Configuration Data

Configuration		Mass (kg)	C_D	Area (m^2)	Ballistic Coefficient
Entry Vehicle	**Forward (supersonic)**	1883	1.55	11	110
	Forward (subsonic)	1853 (less supersonic parachute system)	0.78	11	216
	Backward	1883	1.4	11	122
	Tumbling	1883	1.0	11	171
Descent Stage + Rover	**Tumbling (hypersonic)**	1328	1.32	3.8	265
	Forward (subsonic)	1328	1.0	3.8	349
Rover +RTG +DS Core (tumbling)		1089	1.56	2.0	349
GPHS Module (tumbling)		1.6	1.9	0.008	105

In the sensitivity analysis conducted in this paper, the following aerodynamic properties uncertainties are used (Table 2)

Table (2)
Uncertainties in Aerodynamic Data

Configuration		Range of Failure Integrated Heating (J/cm^2)	Range of C_D	Range of Ballistic Coefficient (kg/m^2)
Entry Vehicle	**Forward (supersonic)**	4828 ± 5%	1.55 ± 5%	105 - 116
	Forward (subsonic)	N/A	0.78 ± 5%	206 – 227
	Backward	1062 ± 5%	1.4 ± 10%	111 - 136
	Tumbling	2897 ± 15%	0.8 – 1.2	143 - 214
Descent Stage + Rover	**Tumbling (hypersonic)**	244 ± 10%	1.32 ± 10%	241 - 294
	Forward (subsonic)	N/A	1.0 ± 10%	318 - 388
Rover + RTG + DS Core (tumbling)		204 ± 10%	1.56 ± 10%	317 - 388
GPHS Module (tumbling)		N/A	1.8 – 2.0	100 – 111

Spacecraft Properties (M Option Design)

As a first-order analysis, the spacecraft is assumed to only have 3 major thermal and structural configurations (Figure 1 excluding the cruise stage):

- Aeroshell
- Descent stage + rover with fully exposed RTG
- Rover with fully exposed RTG + descent stage core

It is assumed that the GPHS modules are released if the RTG fails. The following specific nodes are analyzed in this study:

- Aeroshell
- RTG adapter
- Rover panel where the RTG is attached
- Descent stage tanks
- Descent stage connecting tubes
- RTG housing (fins, cylinder, end caps)
- Structural interface (i.e., separation nuts)

Extensive amount of data (material and physical) of these nodes are obtained from the MSL project and Reference (3) to determine their failure criteria and conduct breakup analysis.

MARS OFF-NOMINAL ENTRY BREAKUP ANALYSIS

Vehicle breakup analysis conducted on the above failure scenarios of off-nominal entry is basically a trajectory propagation coupled with thermal and structural analysis to determine which failures lead to breakup of the RTG and release of the GPHS modules and the conditions at impact. The following modeling assumptions are considered:

- Entry conditions shown presented above for high and low entry velocity.
- 3 Degrees Of Freedom (DOF) propagation
- Gravity model: J3 effects
- Density model: MarsGram 2001
- Thermal/structural failure criteria: combined integrated reference heating and common g-load as linear function
- No bio-burden temperature requirements considered

The software tool is a modified version of the VBA[2]. VBA is designed and built for launch approval purposes, and the code used in this paper is a modified version to implement the nature of Mars off-nominal entries and the Martian conditions.

Approach

The approach used is:

- Investigate for each failure scenario the sequential breakup of the 3 major nodes.
  - After each generated trajectory, sequentially compute integrated heating and common g-load
  - Use combined constant g-load failure criterion and failure integrated heating to examine breakup (failure integrated heating depends on attitude and which spacecraft component in flight).
  - When a component fails, update vehicle configuration data defined by C_D, mass and area, and restart propagation.
- Determine if and when the RTG fails and the GPHS modules are released.
- Identify the scenarios in which the RTG impacts the surface intact.
- Determine conditions at impact

BREAKUP ANALYSIS RESULTS

Tables (3) through (8) show the major results obtained in the analysis presented in this paper. Table (3) shows the pre-entry failure results for PE2, PE3, and PE4 where the GPHS modules are only released and impact the ground in PE4. Among the E1, E2, and E3 failure scenarios of failure at entry shown in Table (4), the GPHS modules are only released and impact the ground in E2 and E3. Table (5) combines the results of parachute and descent stage failures. Table (6) presents the results of the sensitivity analysis. The shredded parachute failure results are shown in Table (7). A final summary is given in Table (8).

Table (3)
Pre-Entry failure Results

	Failure Time (sec)	Failure Altitude (km)	Impact Time (s)	Impact speed (m/s)	Impact FPA (deg)	*Terminal Velocity (m/s)	Max qdot (W/cm2)	Integrated heating (J/cm2)	Max g-load (Earth g's)
FPA = -90 deg (PE2)							148	937	55.5
Entry vehicle			24.6	4018	-89.85	333.9			
FPA = -60 deg (PE3)							133	981	50.2
Entry vehicle			28.7	3774	-59.04	333.9			
FPA = -13.8 deg (PE4)							61.7	3403	13.2
Entry vehicle	129	13.8							
DS + Rover	140	10							
Rover + RTG + DS Core	153	6.1							
GPHS Module			187.9	554	-14.6	283			

Table (4)
Failure at Entry Results

	Failure Time (sec)	Failure Altitude (km)	Impact Time (s)	Impact speed (m/s)	Impact FPA (deg)	*Terminal Velocity (m/s)	Max qdot (W/cm2)	Integrated heating (J/cm2)	max g-load (Earth g's)
Forward (E1)							50.9	2600	10
Entry vehicle			202.7	444.8	-22.3	289.5			
Backward (E2)							61.9	2581	11.3
Entry vehicle	94	33.5							
Descent stage + Rover (tumbling)	99	29.9							
Rover + RTG + DS Core (tumbling)	102	27.9							
GPHS Module (tumbling)			203.4	422.8	-23.3	283.2			
Tumbling, (E3)							54.9	2192	15
Entry vehicle	92	21.6							
Descent stage + Rover	94	20.2							
Rover with semi-embedded RTG	97	18.3							
GPHS Module			162.7	469.6	-22.6	314.8			

Table (5)
Supersonic Parachute & Descent Stage Failure Results

	Impact Configuration	Impact Time (sec)	Impact Speed (m/sec)	Impact Flight Path Angle (deg)
Parachute	Entry vehicle	56 from parachute failure	298	-46
Descent Stage	Descent Stage + Rover flying forward	10 from engine failure	85	-89.7

Table (6)
Results of Sensitivity Analysis

Failures		Impact Speed (m/sec)	Impact FPA (deg)	Nominal Impact Speed (m/sec) & FPA (deg)	Comments
Pre-Entry Failure	-90° FPA entry	3714 – 4319	-89.8° – -89.9°	4018, -89.8°	No atmospheric breakup.
	-60° FPA entry	3464 – 4111	-59.03° – -59.05°	3774, -59.0°	No atmospheric breakup.
	-19° FPA entry	841 – 1149	-15.6° – -17.1°	988, -16.2°	GPHS modules released at high alt.
Failure at Entry	Forward	397 – 447	-21.7° – -24.4°	421, -23.0°	No atmospheric breakup
	Backward	451 – 519	-19.0° – -21.5°	483, -20.2°	GPHS modules released at high alt.
	Tumbling	431 – 569	-18.5° – -24.7°	470, -22.6°	GPHS modules released at high alt.
Parachute Failure	Supersonic chute	291 – 304	-45.3° – -46.2°	298, -45.8°	Aeroshell impacts intact.
Descent Stage Failure		84.9 – 85.1	-89.7065° – -89.7067°	85, -89.7066°	Rover and descent stage impact

Table (7)
Shredded Supersonic Parachute Results

	Increase in Drag Coefficient	Impact Configuration	Impact Time (sec)	Impact Speed (m/sec)	Impact Flight Path Angle (deg)
Partially Shredded	50%	Entry vehicle + shredded parachute	60 from Parachute failure	244	-51
Fully Shredded	21%	Entry vehicle + shredded parachute	58	271	-48

Table (8)
Summary of Failure and Impact Conditions

Failures		**Nom. Impact Speed (m/sec), FPA (deg)**	**Comments**
Pre-Entry Failure	-90° FPA (PE2)	4018, -89.8°	No atmospheric breakup.
	-60° FPA (PE3)	3774, -59.0°	No atmospheric breakup.
	-13.8° FPA (PE4)	554, -14.6°	GPHS modules released
Failure at Entry	Forward (E1)	445, -22.3°	No atmospheric breakup
	Backward (E2)	423, -23.3°	GPHS modules released
	Tumbling (E3)	470, -22.6°	GPHS modules released
Parachute Failure	Supersonic chute (P1)	298, -45.8°	Aeroshell impacts intact.
Descent Stage Failure (D1)		85, -89.7066°	Rover and descent stage impact

CONCLUSIONS

A wide range of breakup scenarios was analyzed assuming credible failure modes during Mars approach and EDL of the MSL spacecraft in its baseline design concept. Nominal impact conditions (speed and flight path angle) are given for an intact vehicle or GPHS modules at time of surface impact for all failure scenarios considered. Generally, the study shows that ballistic coefficients have more impact on severity of breakup and impact speeds than entry speeds or atmospheric model variation. From the results presented, it can be seen that a component of the vehicle with higher ballistic coefficient has the following characteristics:

- It maintains horizontal speed longer resulting in a more shallow flight path angle at impact.
- It does not slow down as much and the impact speed is greater.
- It reaches the ground sooner.
- It travels further in range.
- It has higher terminal velocity.

A sensitivity analysis that was conducted to examine sensitivity of models used in this analysis to model parameters shows that uncertainty in vehicle configuration data and failure criteria change impact conditions in only a minor way. Specifically, nominal impact conditions are about half-way between low and high impact cases and the sensitivity analysis did not result in any change in the general nature of the pre-impact initial conditions.

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