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Entry, Descent and Landing Systems Analysis Study: Phase 2 Report on Mars Science Laboratory Improvement

Mark C. Ivanov - Study Lead, Eric M. Blood, Brant T. Cook, Louis R. Giersch, Myron R. Grover, Julie K. Jakobowski, Tommaso P. Rivellini and Robbie P. Su
NASA Jet Propulsion Laboratory, Pasadena, California

Jamshid A. Samareh, and Thomas A. Zang
NASA Langley Research Center, Hampton, Virginia

Richard G. Winski
Binera, Inc., Yorktown, Virginia

Aaron D. Olds
Analytical Mechanics Associates, Inc., Hampton, Virginia

David J. Kinney
NASA Ames Research Center, Moffett Field, California

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Binera, Inc., Yorktown, Virginia

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Analytical Mechanics Associates, Inc., Hampton, Virginia

David J. Kinney
NASA Ames Research Center, Moffett Field, California

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
Pasadena, CA 91109-8099

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NASA Center for AeroSpace Information
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443-757-5802

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MSL-I Team

The following people comprise the MSL-I team and made significant contributions to the content of this report:

Flight Performance	
Rick Winski	LaRC
Aaron Olds	LaRC
Jeremy Shidner	LaRC
Alicia Dwyer Cianciolo	LaRC
Dick Powell	LaRC
Juan Cruz	LaRC
Mass Modeling	
Jamshid Samareh	LaRC
Sasan Armand	LaRC
Aerothermal/Aerodynamics	
Dave Kinney	Ames
Dinesh Prabhu	Ames
Kathy McGuire	Ames
Joseph Garcia	Ames
Matt McMullen	Ames
Paul Stremel	Ames
Eric Lau	Ames
Technology Evaluation	
Rob Grover	JPL
Eric Blood	JPL
Mechanical Integration	
Tom Rivellini	JPL
Robbie Su	JPL
Brant Cook	JPL
Louis Giersch	JPL
Julie Jakoboski	JPL
Tom Moreno	JPL
Bill Allen	JPL
Management	
George Chen	JPL
David Hash	Ames
Aga Goodsell	Ames
Tom Zang	LaRC
Walt Engelund	LaRC
Ron Sostaric	JSC
Mark Ivanov	JPL

1 Executive Summary

The Mars Science Laboratory Improvement (MSL-I) study is an effort to identify and assess promising, next-step technologies that provide incremental performance improvement to the Mars Science Laboratory (MSL) entry, descent and landing (EDL) architecture. Initiated with an exhaustive effort to identify all EDL technologies with potential to enable more capable robotic Mars missions, selection criteria that included being flight ready by 2024 at a development cost of less than $200M are applied establishing seven technologies for further focus of the study. The seven technologies are subsonic ringsail parachute, supersonic ringsail parachute, an iso-tensoid supersonic inflatable aerodynamic decelerator (SIAD), a tension cone SIAD, an aeroshell trim tab, a rigid deployable aeroshell drag augmentation technology called Supersonic Air Brake (SABr), and SABr combined with trim tab. These seven technologies are assessed on the basis of performance, mechanical implementation, cost, risk and cross cutting applicability, with the goal of providing an investment recommendation on next-step Mars EDL technologies.

In assessing performance, the seven EDL technologies are paired into eight technology sets. Each technology set contains a parachute, either subsonic or supersonic, and one of the four other technologies. Performance was assessed using a dynamic simulation, each technology set sized and optimized to maximize landing site elevation and/or landed mass. The results show that technologies that augment the drag of the aeroshell during the supersonic flight phase, such as the SIAD technologies or the SABr, are able to achieve the best landing site elevation performance. Because of its structural mass efficiency, the trim tab technology provided the greatest landed mass performance. The addition of a supersonic ringsail parachute alone provides the second best landed mass performance. Two of the technology sets contain the subsonic ringsail parachute paired with one each of the SIAD technologies, and resulted in the least benefit to performance.

A mechanical implementation concept is developed for each of the seven technologies included in the assessment. The implementation concepts serve as proof of implementation feasibility, inform mass estimates used in the performance simulations, and help establish a basis for cost and risk assessments.

Using past and current analog technology development efforts, a very preliminary development cost estimate is provided for each technology, and each technology set. A major distinguisher of development cost is the need or no need for a supersonic high altitude flight test program. Technologies requiring a supersonic flight test program, which include the supersonic ringsail parachute and SIAD technologies, fall into a ~$150M development classification. The SABr technology falls into the $100M classification, and the subsonic ringsail and trim tab are the lowest costed technologies falling in the $50M classification. Considered as a technology set, because all technology sets contain either a supersonic ringsail parachute or a SIAD and thus require a supersonic high altitude flight test, all technology sets fall into development cost estimation range of $100M to $250M. The cost estimates are an initial assessment and further refinement is needed. The assessment of development risk leads to the general conclusion that flexible technologies, particularly the SIAD technologies, have higher development risk than rigid technologies. Performance risk and overall risk also divide in a similar way into higher risk and lower risk based on flexible versus rigid technologies.

The work of the MSL-I study results in the following technology conclusions and recommendations for missions on or before 2024:

Conclusions

1. The best altitude performers provide higher drag earlier in the supersonic phase
   - Iso-Tensoid with Supersonic Parachute (TS-1) 6.0 km
   - Tension Cone with Supersonic Parachute (TS-3) 6.0 km
   - SABr with Supersonic Parachute (TS-7) 4.9 km
2. The best landed payload performers provide higher lift (Trim Tab) or higher drag (Supersonic Parachute)
   - Trim Tab with Supersonic Parachute (TS-5) 1462 kg
   - Supersonic Parachute alone (TS-6) 1309 kg
   - Trim Tab + SABr with Supersonic Parachute (TS-8) 1256 kg
3. A subsonic parachute with an IAD in lieu of a supersonic parachute provides the least performance improvement
   - Iso-Tensoid with Subsonic Parachute (TS-2) 2.5 km / 1086 kg
   - Tension Cone with Subsonic Parachute (TS-4) -1.28 km / 1123 kg
4. The maximum payload that can be landed in 2024 using an Atlas V with an improved MSL architecture is
   - 0 km MOLA: ~1450 kg
   - +3 km MOLA: ~1250 kg
5. Based on the technologies assessed, a larger supersonic parachute combined with one other technology is necessary to make any significant increase in landed payload mass and/or altitude
6. The following technologies have some feed-forward potential
   - Trim Tab (aero control surfaces in general)
   - SIADs (as a step towards HIADs)
   - Bi-propellant engines (not included directly in the technology sets but was reviewed as a potential enhancer)

Recommendations

1. Although all the technologies require more study, it can be concluded from the results to date that the following key enabling technologies strongly warrant investment:
   - Supersonic ringsail parachute (critical for all technologies identified)
   - Bi-prop engines (critical for all the heavier payload options)
2. Conduct Pre-Phase A studies for all the MSL-I technologies to fill in the remaining performance, design, risk, and cost gaps to better inform investment decisions
   - Add bi-prop engines to the technologies
     - TS-9: capsule + parachute + bi-prop engines
     - TS-10: trim tab + parachute + bi-prop engines
   - Evaluate landed accuracy for all Technology Sets
   - Conduct thorough Development Risk assessment of all technologies
   - Mature all technologies to Pre-Phase A level

Further information on the MSL-I work is available in the report NASA/TM-2011-216989[1].

2 Overview of the MSL-I Study

The MSL-I study is a continuation of the analysis performed for the Entry, Descent and Landing Systems Analysis study year one effort[2]. The purpose of the MSL-I study is to examine enabling technologies that incrementally improve performance of the MSL EDL system while minimizing change to the MSL EDL architecture, as a way of shedding light on a path forward to landing heavier payloads and/or payloads at higher landing site elevations. Technologies considered are required to be feasibly mission-ready on or before 2024. Constraining the technologies considered is a cumulative development cost limit of $200M to develop new technologies in a given architecture option. As well, launch mass/volume is constrained to the capability of an Atlas V-551 launch vehicle.

2.1 Design Reference Mission

As a point of departure, a modified MSL EDL architecture serves as the design reference mission (DRM) for the study, and includes the following high level features:

- A rigid, blunt-body hypersonic entry vehicle
- Guided, lifting entry
- The use of a parachute to achieve terminal descent initiation conditions
- A sky crane architecture for providing terminal descent and landing of the payload

Shown in Figure 1 is the MSL EDL sequence of events illustrating the salient features of the MSL-I DRM. MSL-I DRM variations from MSL include a slightly larger diameter 4.7 m entry aeroshell, a 5.75 km/s entry velocity, and a 0 km with respect to MOLA reference landing site elevation. The performance of the DRM architecture serves as a reference starting point for assessments of enhancing technologies.

2.2 Study Process

A study process with multiple stages is used in the MSL-I study to first exhaustively identify possible enabling technologies, then down select to the most promising technologies based on

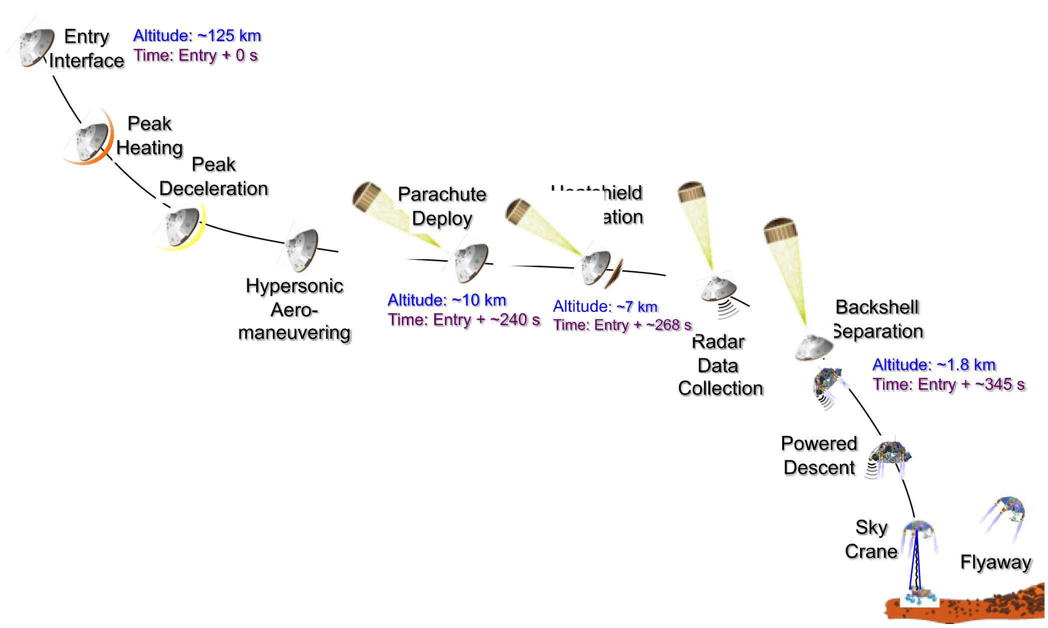


Figure 1. MSL EDL Sequence of Events

predicted cost, performance potential, development scope and technical feasibility. This pool of down-selected technologies become a set of seven technologies assessed in more detail during a second phase of the MSL-I study. The criteria used to assess the seven technologies are performance, mechanical implementation feasibility, and cost/risk estimation. In order to provide a selection of technology sets for possible Mars applications, eight technology set pairings (discussed further in Section 3) of the seven selected technologies are generated forming eight variations on the MSL-I DRM, called Technology Sets 1-8. Landed payload mass performance as well as mechanical implementation feasibility are assessed for each set. Figure 2 illustrates by flight regime the variations in technologies contained in the eight technology sets.

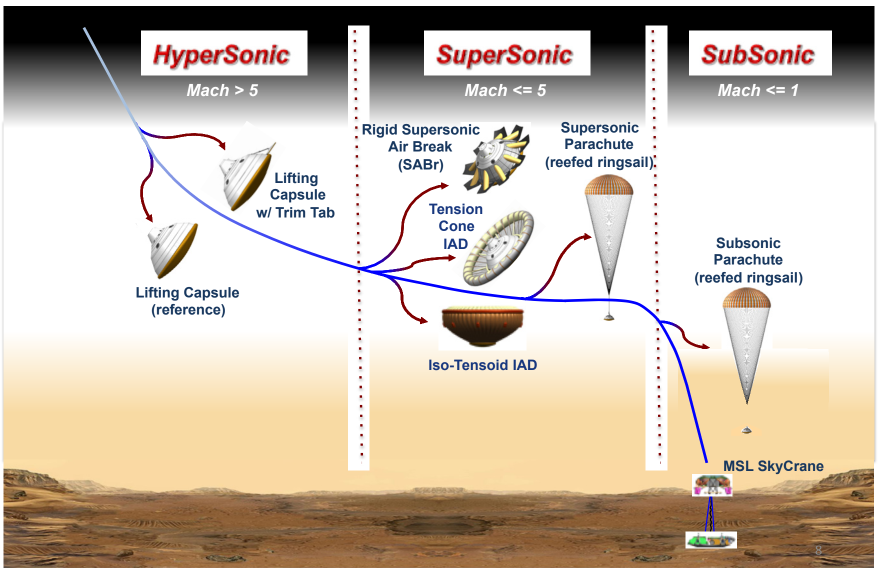


Figure 2. MSL-I Primary Technologies Studied

3 EDL Enabling Technologies

In February of 2010, the MSL-I team identified EDL technologies that enable an increase of landed payload mass capability, increase of landing elevation capability, increase of landing accuracy capability, reduction of risk or a combination of the aforementioned to the existing MSL architecture. This identification served as the EDL-SA Team Initial Evaluation of the MSL-I technologies, a crucial step in the MSL-I study plan. Section 3.1 identifies the criteria of selection that all technologies that passed the first down-select met. Section 3.2 lists all of the initial technology families that were brainstormed (the full list is in Appendix B: Initial Technology List). Section 3.3 presents the reduced technology list and the final technologies that were chosen for the MSL-I FY10 Study.

3.1 Criteria of Selection

The MSL-I team chose specific criteria in which to evaluate every technology against. These include development time, DRM/GR&A, flight system technology, EDL-SA scope, technology relevance, and FY10 scope. For definition of each criterion, please see Table 6 in Appendix B. As well, technologies were also eliminated from further evaluation based on whether the technology did or did not fall within the technical expertise domain of the MSL-I team.

3.2 Initial Technology List

The initial technology list was split up into the following technology families: Angle of Attack (AoA) and Drag Control, Alternate Entry Geometries, Improved Inertial and Atmospheric Relative Knowledge (onboard vs. external), Improved Terrain Relative Knowledge, TPS Improvements, Inflatable Aerodynamic Decelerators (IADs), Improved Parachutes, Propulsive Augmentation, Improved Staging (Mechanisms and Triggers), General Systems Improvements, Policy Changes, Improved Guidance Algorithms, Entry from Orbit, Skip Entry, and Propulsive Targeting. The entire list of technologies considered is in Appendix B: Initial Technology List. The technologies listed in red were not selected for this study in the first reduction phase due the inability to meet one or more of the aforementioned criteria. The technologies listed in orange meet all of the criteria, but were not selected for this study in the second reduction phase due to a perceived lower priority.

3.3 Reduced Technology List

After the initial down-select in which technologies that did not meet all of the criteria were eliminated, eleven technologies were chosen for their perceived higher potential for improving the MSL architecture. They are: Trim Tab, Lifting SIAD, Drag SIAD (AoA and Drag Control); Apollo, Alternate TBD (Alternate Entry Geometries); Terrain Relative Navigation, Hazard Detection (ALHAT Type Sensors); Larger and/or faster parachute (improved parachute); Simple Supersonic Retro-propulsion (Propulsive Augmentation); Upgrade Apollo, NPC (Improved guidance algorithms, entry and prop).

A rigid deployable aerodynamic decelerator was added after the initial technology list was created. This technology effectively falls under the "SIAD or L/D Augmentation" family. This technology was named the Supersonic Aerodynamic Brake (SABr). Two variants of SABr were considered: webbed and non-webbed. Because of the added complexity of the webbed version, only the performance of the non-webbed version of SABr was evaluated in this study. The MSL-I study evaluated the following reduced set of seven technologies: trim tab, SABr, SABr combined with trim tab, drag only iso-tensoid, lifting tension cone, supersonic ringsail parachute and subsonic ringsail parachute.

3.4 Technology Sets

Performance of the technologies is evaluated by combining each technology with either the supersonic ringsail parachute or the subsonic ringsail parachute, yielding the eight technology sets (TS) shown in Figure 3, all technology sets a variation on the reference DRM. Technology set two (TS-2) and TS-4 utilize the subsonic ringsail parachute while all other technology sets utilize the supersonic ringsail parachute. TS-6, contains only the supersonic ringsail parachute without pairing with an additional technology. In evaluating TS performance, each technology set is optimized to exploit its performance strengths.

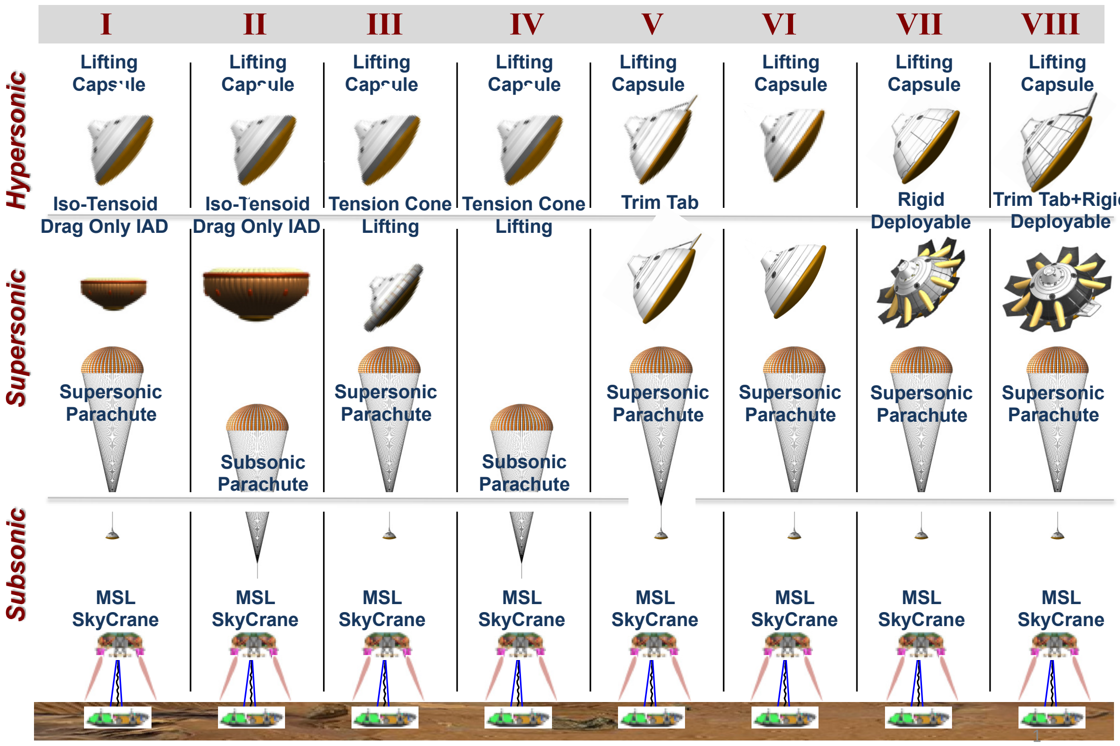


Figure 3. Eight MSL-I Study Technology Sets

4 Simulation Models & Integration

4.1 Mass Model

Mass models used for the MSL-I project are parametric models represented by mathematical equations that relate mass components to vehicle dimensions and mission key environmental parameters such as maximum dynamic pressure and total heat load. The major mass components shared across the MSL-I architecture sets are: backshell (structure and TPS), balance masses (cruise and entry), descent stage, heatshield (structure and TPS), parachutes (ring sail & DGB), payload, propellant, SABr drag device, SIADs (iso-tensoid and tension cone), and trim tab. There were additional miscellaneous mass components allocated for avionics, cabling, cover panels, parachute can, and scar masses (e.g., scar masses for trim tab and SIAD). A 30% margin, a factor of 1.43, was applied to all mass components except SABr and DGB parachute. A 25% mass margin was applied to SABr.

The backshell and the heatshield TPS masses were based on total heat load and their projected areas. The trim tab mass was based on the Shuttle body flap with correction for higher aspect ratio. A subsequent finite-element analysis showed that the trim tab mass estimate was very conservative. The SIAD mass models are based on models proposed and tested in the 1960's and on some recent model updates. The iso-tensoid parametric mass model accounted for the radial cords, canopy fabric, 50% inflation gas based on airbag gas generators, burble fence, inlet assembly, reinforced webbing, and joints. The tension cone parametric mass model consisted of radial straps, gores, gas barrier, and gas generators. The SIAD mass models are based on using a load factor of safety of 4, per NASA requirement[3]. There were no knock-down factors on the material strength due to possible elevated temperatures, and the SIAD models did not include a TPS component. The SIAD aerothermal and TPS requirements need to be further investigated.

4.2 Aerothermal Modeling

Seven different vehicle configurations were analyzed for the MSL-I effort. These configurations included:

1. Baseline capsule configuration, based on a circular heat shield and an MSL backshell
2. Three parametric variations of a tension cone Inflatable Aerodynamic Decelerator (IAD)
3. Three parametric variations of an iso-tensoid IAD
4. Two variations of the SABr concept, one with, and one without webbing
5. A baseline entry trim tab configurations
6. A Tab concept which uses a single SABr panel on entry

The aerodynamic models for all the configurations were a combination of engineering, Euler, and Navier Stokes solutions. The engineering level analysis was performed with the CBAERO software tool set. CART3D was used to provide Euler level analysis, and both DPLR and LAURA were used to provide high-fidelity aerodynamic and aerothermal analysis. The baseline capsule aerodynamics and aerothermal models were generated by leveraging the CEV aerodynamic and aerothermal databases, allowing CBAERO to correct for both vehicle size and atmosphere. The aerodynamics for the IAD and SABr concepts in the subsonic to supersonic range were developed using CART3D, with viscous corrections provided by CBAERO. The aerodynamics for the trim tab, and SABr + trim tab configurations were generated using CART3D, using a priori calculated post shock ratio of specific heats appropriate for the flight Mach numbers evaluated.

The final aerodynamic databases were provided as FORTRAN front ends to an underlying C++ software tool that performed simple table look up for axial, normal force, and pitching moments. Aerothermal indicators were provided for the heatshield of the baseline capsule configuration.

4.3 Parachute Model

The ringsail parachute model consists of two parts: the inflation model and the aerodynamics model. The ringsail parachute inflation model was adapted from a Launch Abort System (Orion) POST2 simulation. The actual inflation times were assumed to be instantaneous for conservatism on parachute loads. The over-inflation factor was scaled from the Knacke data using the same margin as was used for the MSL DGB design. The ringsail aerodynamics was based on Knacke data and assumed a drag coefficient of 0.75 as the nominal used for performance analysis. Due to the lack of supersonically deployed ringsail test data a Mach efficiency curve, from the MSL DGB parachute model, was used to scale the drag coefficient across the Mach range. A high drag curve was also generated for use in the parachute loads calculation, which was constrained to an upper limit of 65,000 lbs. This model does not model mortar fire or time to line stretch. In the optimizations the disreef time and reefing ratio were varied. Note that this study made assumptions about the ringsail aerodynamics since there exists little test data at the current time. Results in this study and future system level studies depend on having believable and realistic models.

4.4 POST2 Simulation Integration

The simulation used to evaluate the MSL-I technology sets is the Program to Optimize Simulated Trajectories (POSTII), which has extensive heritage for simulating ascent, descent, and orbiting trajectories. The code employs standard atmosphere (MarsGRAM), planet and gravity models as well as MSL-I specific models including aerodynamics, mass properties, guidance and terminal descent. MSL-I specific models were delivered and integrated into the POST2 source code as needed.

The hypersonic guidance scheme used was designed to mimic the Apollo guidance, which has a range control phase and a heading alignment phase and is called the theoretical guidance. During the range control phase the bank angle magnitude is used to control range to the target and bank angle direction is used to control cross range. After, during the heading alignment phase, the bank angle is used to remove residual cross range error. For this study landing accuracy is not assessed.

Powered descent in the MSL-I simulation is modeled in a simplified fashion with correction factors applied to the results to mimic MSL performance in terms of propellant and altitude required. The MSL powered descent profile includes a number of phases that account for uncertainties and sensor limitations that would be difficult or impractical to reproduce effectively for the range of architectures in the MSL-I study. Similar to MSL, powered descent in the MSL-I simulation is a constant thrust gravity turn performed by 8 descent engines at 80% throttle. The total propellant mass result is designed to represent the minimum propellant required to complete powered descent with an MSL-like strategy with 3σ dispersions.

5 Performance Results

The system performance results presented here are the end product of optimization of trajectories that have included some margined criteria based on MSL experience. No Monte Carlo analysis was performed for this study. Generally, the technology sets were optimized for multiple reasons. One case was designed to deliver the maximum amount of payload to 0 km MOLA. Another case was designed to deliver to the maximum altitude. Where the maximum altitude was felt to be high considering near term mission requirements, a 6 km MOLA landed altitude case was run. This level of landed altitude would allow the vehicle to land at nearly any point on the surface of Mars. For other technology sets, if the vehicle could not deliver the payload to 0 km MOLA then the altitude was maximized without lowering the maximum entry mass. For comparison, the MSL Eberswalde landing site under consideration is approximately -1.4 km MOLA and the MSL rover payload is approximately 919 kg.

Some sensitivity cases were also generated by changing the parachute size, using the MSL DGB parachute, or varying the parachute deployment velocity. Note that the MSL DGB has a different drag performance than the ringsail parachute as well as a smaller diameter, 21.5 m. The first round of analysis was performed using a 35 m maximum diameter ringsail parachute. After

Table 1. Technology Set Final Design Points

Objective/Constraint	TS-1 Max Payload 6 km MOLA	TS-2 Max Altitude Max Entry Mass	TS-3 Max Payload 6 km MOLA	TS-4 Max Altitude Max Entry Mass	TS-5 Max Altitude Max Entry Mass	TS-6 Max Altitude Max Entry Mass	TS-7 Max Altitude Max Entry Mass	TS-8 Max Altitude Max Entry Mass
Touchdown Altitude (km)	6	2.53	6	-1.28	1.83	2.86	4.89	4.77
Payload (kg)	1134.9	1086	1156.7	1123.16	1462.36	1309.3	1131.72	1255.84
Entry Mass (kg)	4295	4295	4295	4295	4490	4295	4295	4490
IAD								
IAD Diameter (m)	7.95	15.44	5.76	9.19	----	----	6.9 (rigid)	6.9 (rigid)
Max IAD dyn pressure (kPa)	1.51	2.64	1.31	4.09	----	----	1.44	1.58
IAD mass (kg)	54.52	200.0 (limit)	14.5	200.0 (limit)	----	----	256.2	342.99
Parachute								
Parachute Diam. (m)	30	30	30	30	30	30	30	30
Mach at Deployment	2.3	0.8	2.3	0.8	2.3	2.3	2.3	2.3

iteration with mechanical design, the maximum diameter was lowered to 30 m due to packaging concerns of the parachute within a mortar. Another important point that applies to all the technology sets is the launch mass limitation. The study assumed launch on an Atlas V 551 which limits the launch mass to 5130 kg. This constraint becomes active for multiple technology sets, which limits the achievable payload mass. No cases were run to analyze what payload could have been achieved without this constraint. Table 1 details the performance and design parameters of the final design points for the technology sets.

5.1 TS-1 - Iso-tensoid

Design Point	TS-1
Payload (kg)	1134.9
Landed Altitude (km MOLA)	6.0

Technology set one (TS-1) is a hypersonically guided entry with a supersonically deployed iso-tensoid, modeled as a drag only IAD, coupled with a supersonically deployed ringsail parachute.

The design point achieves a payload mass slightly more than the MSL rover mass. To take advantage of the iso-tensoid and achieve this altitude, the trajectory does loft some amount. This could possibly cause some guidance challenges although no analysis was done in this study to determine the impact.

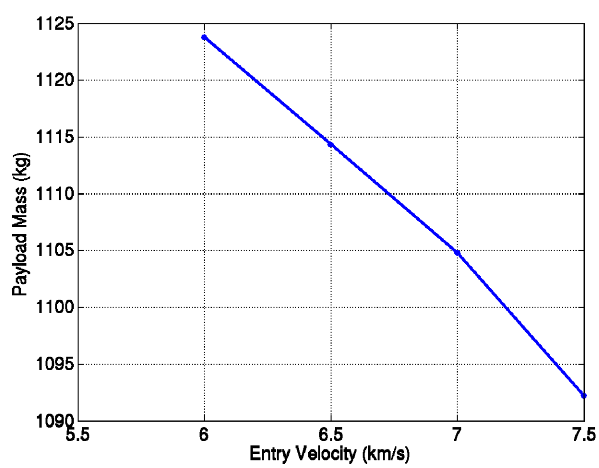


Figure 4. Sensitivity to Entry Velocity

An additional sensitivity was examined for higher entry velocities. A set of simulation runs were performed to parametrically vary the entry velocity for TS-1 (iso-tensoid) from 6-7.5 km/s. The cases generated are 6 km MOLA landed altitude cases. Figure 4 shows a low sensitivity to higher entry velocities. For this study the assumption of a variable entry point was made to account for downrange differences corresponding to variable entry velocities.

5.2 TS-2 - Iso-tensoid

Design Point	TS-2
Payload (kg)	1086.0
Landed Altitude (km MOLA)	2.53

Technology set two (TS-2) is identical to TS-1 with the exception that the ringsail parachute is deployed subsonically, at Mach 0.8. The design point achieves a payload mass slightly more than the MSL rover mass. As expected, using the IAD to decelerate the vehicle to subsonic velocities necessitates a larger IAD. Two main drivers appeared in the TS-2 results. One was the IAD performance through the transonic and subsonic regimes. The aerodynamic model used for the IADs in this study shows a spike in the drag coefficient in the transonic regime followed by a precipitous decrease in the subsonic regime. Therefore, for a subsonic parachute deployment, the IAD design diameter must grow to increase the drag area to compensate for the low subsonic drag.

The second driver, the terminal velocity margin, became a problem for the parachute deploy event. Like the vehicle approaching terminal velocity on the parachute, the vehicle can also approach it on the IAD, which occurred in TS-2. The effect was to drive a steeper entry flight path angle which increased the maximum dynamic pressure on the IAD resulting in an increased IAD mass.

5.3 TS-3 - Tension Cone

Design Point	TS-3
Payload (kg)	1156.7
Landed Altitude (km MOLA)	6.0

Technology set three (TS-3) is a hypersonically guided entry with a supersonically deployed tension cone, modeled as a lifting IAD, coupled with a supersonically deployed ringsail parachute. The design point achieves a payload mass higher than the MSL rover mass. To achieve this altitude and take advantage of the tension cone, like the iso-tensoid, the trajectory does loft some amount. Again, this could possibly cause some guidance challenges although no analysis was done in this study to determine the impact.

5.4 TS-4 - Tension Cone

Design Point	TS-4
Payload (kg)	1123.2
Landed Altitude (km MOLA)	-1.28

Technology set four (TS-4) is a hypersonically guided entry with a supersonically deployed tension cone, modeled as a lifting IAD, coupled with a subsonically deployed ringsail parachute, nominally at Mach 0.8. This design point is the maximum altitude case which has the maximum allowed entry mass. This altitude is below the desired altitude of 0 km MOLA and bumps against the 200 kg limit of IAD fabric mass. The same reasons that TS-2 has poor altitude performance and high IAD masses, the terminal velocity margin at parachute deploy, apply to TS-4. Two methods for achieving a 0 km MOLA altitude were investigated; one was to decrease the entry mass and the other was to relieve the IAD mass constraint. Both solutions worked but allowing a larger IAD mass enabled a larger payload mass. Note that using the latter solution might impose more pressure on packaging the IAD. Figure 5 illustrates the sensitivity in altering the parachute deployment from supersonic to subsonic; this very sensitive result illustrates the dependency of the results on the IAD aerodynamic model. This result applies to TS-2 also and highlights the dependence of the systems analysis results on the fidelity of the models.

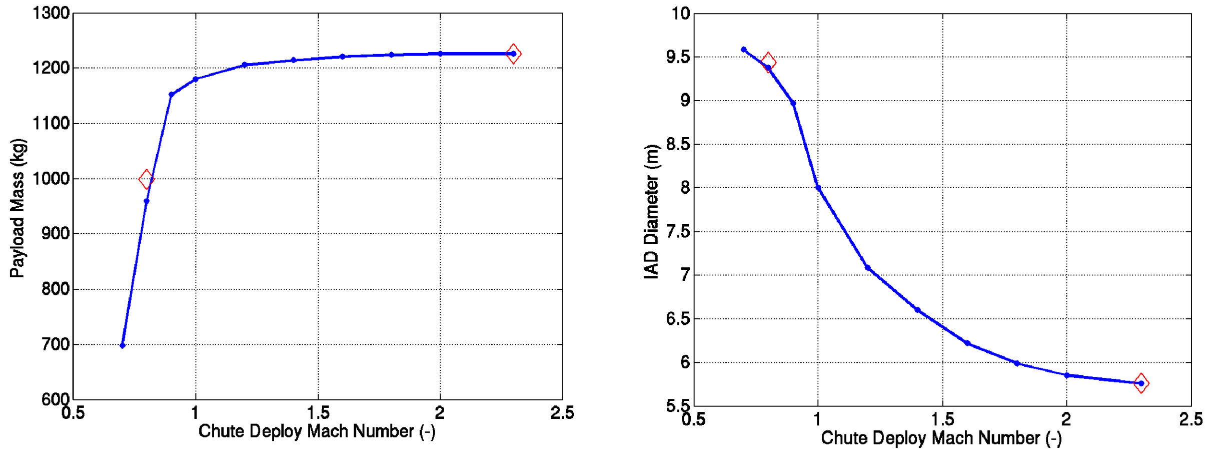


Figure 5. Performance as Chute Deploy Mach Number Varies

5.5 TS-5 - Trim Tab

Design Point	TS-5
Payload (kg)	1462.4
Landed Altitude (km MOLA)	1.83

Technology set five (TS-5) is a hypersonically guided entry using a trim tab to generate lift instead of entry balance masses (EBM) coupled with a supersonically deployed ringsail parachute. One advantage is the mass savings as the EBM consist of hundreds of kilograms and the trim tab is on the order of tens of kilograms. This mass savings can be directly transformed into payload mass. The TS-5 design point is the maximum altitude mission which achieves a large payload mass beyond the MSL rover mass.

5.6 TS-6 - Supersonic Ringsail Parachute

Design Point	TS-6
Payload (kg)	1309.3
Landed Altitude (km MOLA)	2.86

Technology set six (TS-6) is a hypersonically guided entry coupled with a supersonically deployed ringsail parachute, which allows quantification of the independent effect of the ringsail. The TS-6 design point is the maximum altitude mission which achieves lands payload mass larger than the MSL rover mass. Figure 6 shows some sensitivity to

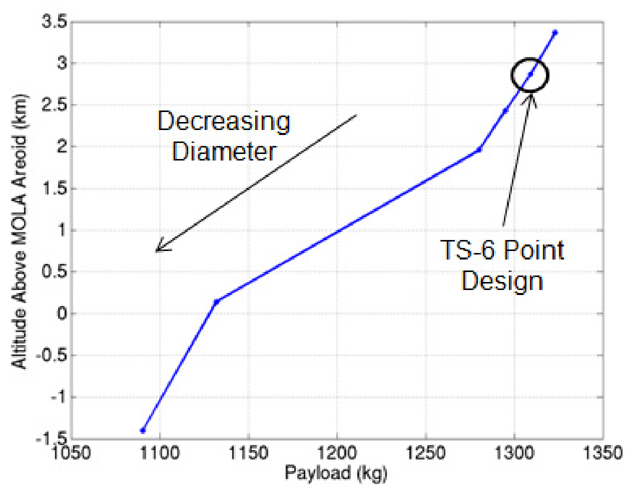


Figure 6. TS-6 Parachute Size Sensitivity

ringsail maximum diameter.

A benefit of the ringsail parachute is the ability to deliver large payloads to significant altitudes; generally the MSL (21.5 m) DGB performance falls off quickly at these payload masses. To determine the dependency on the maximum diameter of the ringsail, the diameter was parametrically varied, from 21.5 m to 35 m, for a set of optimized cases. The cliff on the curve occurs with maximum diameters lower than 25 m.

5.7 TS-7 – "SABr " Supersonic Air Brake

Design Point	TS-7
Payload (kg)	1131.7
Landed Altitude (km MOLA)	4.89

Technology set seven (TS-7) is a hypersonically guided entry utilizing a supersonically deployed rigid decelerator (SABr) coupled with a supersonically deployed ringsail parachute. This design point is the maximum altitude mission which achieves a payload mass larger than the MSL rover mass. Note that the rigid deployable used a different mass margin policy than the inflatable decelerators. Also, the rigid deployable design was fixed, not allowing any growth in the diameter, unlike the inflatable decelerators. An additional option is to have a webbing between the deployable panels or not which alters the aerodynamic performance.

5.8 TS-8 – "SABr with Trim Tab"

Design Point	TS-8
Payload (kg)	1255.8
Landed Altitude (km MOLA)	4.77

Technology set eight (TS-8) is a hypersonically guided entry utilizing a deployable panel as a trim tab, a supersonically deployed rigid decelerator coupled with a supersonically deployed ringsail parachute. Like TS-5, TS-8 uses a deployable trim device instead of EBM thereby saving mass; the difference here is that the trim device is one of the SABr panels, not a specifically designed trim tab. The TS-8 design point is the maximum altitude mission, non-webbed supersonic rigid deployable, which achieves a payload mass of greater than the MSL rover mass. Note that the rigid deployable used a different mass margin policy than the inflatable decelerators. Also, the rigid deployable design was fixed, not allowing any growth in the diameter, unlike the inflatable decelerators.

5.9 Unconstrained IAD mass for TS-2 and TS-4

Both TS-2 (iso-tensoid) and TS-4 (tension cone) ran up against the IAD fabric mass limit of 200 kg, which was instituted due to packaging concerns. In an effort to quantify possible benefit from additional IAD mass, parametric results were generated. Figure 7 shows the potential altitude gain with increased IAD mass for TS-2 and Figure 8 shows the TS-4 results. As expected, the payload mass is traded with the IAD mass to generate the altitude gain.

5.10 MSL-I Performance Summary

Figures 9 and 10 indicate that there is not one technology set that will achieve all foreseen competing mission goals, in terms of altitude and payload performance. Some of the decelerator technologies investigated perform well in a region of high landed altitude where others can

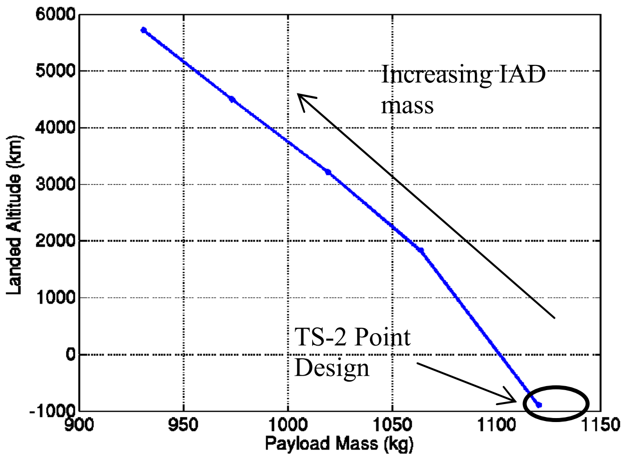


Figure 7. TS-2 Altitude Gain

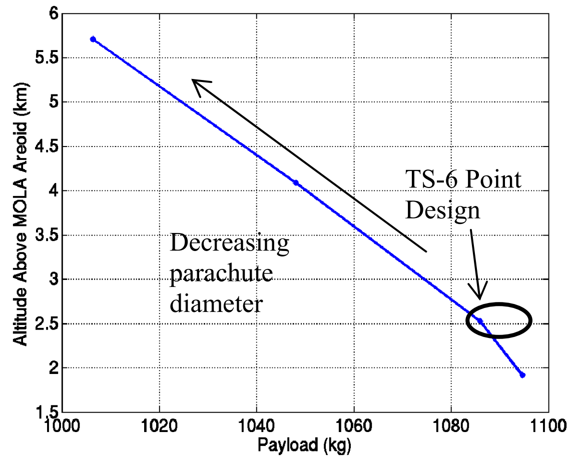


Figure 8. TS-4 Altitude Gain

deliver more payload to lower altitudes. And other solutions may be preferable when a vehicle component reaches its current technological limit, e.g. parachute deployment Mach.

Figure 9 depicts payload as a function of altitude for the eight technology sets that use a reefed ringsail parachute with a maximum diameter of 35 meters. Figure 10 shows results for a selection of these architectures with a 21.5 m DGB parachute. All of the technologies investigated achieve a higher altitude payload delivery by the larger parachute. The technology sets most affected by the addition of a larger supersonic parachute are those with deployable drag devices: TS-1, 3, 7, and 8, i.e., the SIAD and SABr architectures. The lower ballistic coefficient of these technology sets allow the parachute deployment condition (Mach 2.3) to be met at higher altitude, where the vehicle can only be decelerated effectively by the larger parachute.

Figure 11 shows the design points selected for each of the eight technology sets. The design points were chosen to represent the highest touchdown elevation attainable utilizing the full launch mass. This figure presents a set of non-dominated solutions, in terms of payload as a function of altitude, namely technology sets 1, 3, 5, 6, and 8. Technology sets 1 and 3, the SIADs coupled with supersonically deployed parachutes provide more altitude capability than any of the other options. Technology set 5, utilizing the hypersonic trim tab, provides the most payload mass at the relatively lower site elevations, due to the mass savings over replacement of the entry balance masses. The architectures that are not the best at delivering payload to a particular altitude, TS 2, 7, and 4, each have strengths not quantified in this study. TS 2, and 4 have large SIADs that allow for subsonic deployment of the large ringsail parachute, which can relieve the parachute environment and would reduce the cost of a parachute development program. Additionally there are a range of solutions for parachute deployments between Mach 0.8 and Mach 2.3 for the SIAD options that allow trades in performance and level of supersonic ringsail technology development. TS-7 is the SABr rigid, deployable drag device, which could provide lower uncertainty in deployment dynamics than an inflatable device.

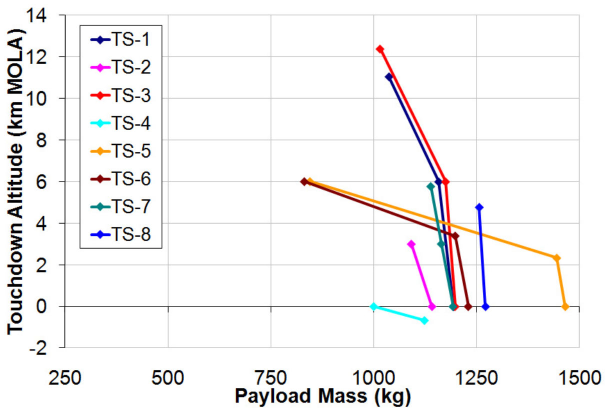


Figure 9. Ringsail Results

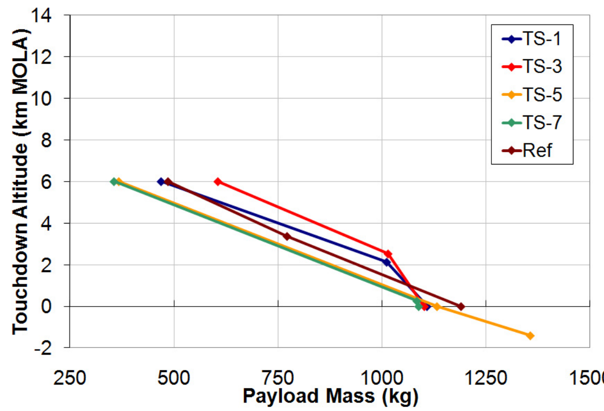


Figure 10. MSL DGB Result

For architectures limited to a 21.5 m DGB parachute, Figure 10 shows that the MSL-like reference case more effectively delivers payload with the exception of SIAD's landing above

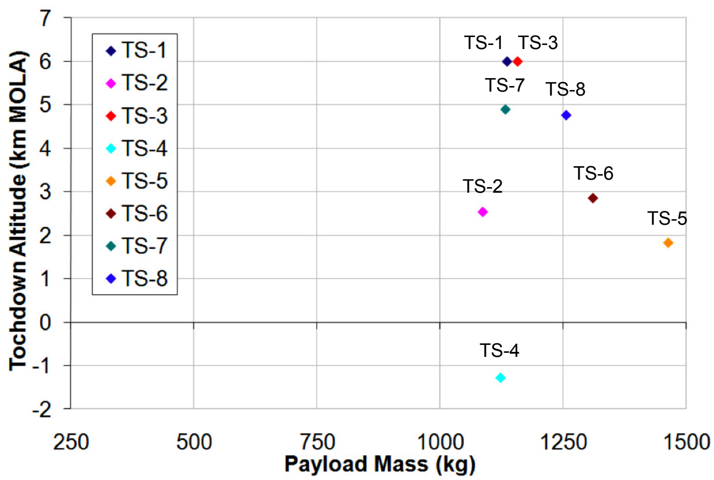


Figure 11. Summary of Technology Set Touchdown Performance

1 km MOLA. Results for TS-8 were not obtained with the 21.5 m DGB parachute. The SIADs are able to land more payload at higher altitudes than the reference design due to their capacity to decelerate the vehicle to parachute deployment conditions at higher altitude. However, the limited drag performance of the 21.5 m parachute doesn't allow the level of improvement seen on TS-1 and 3 with the addition of the larger parachute.

6 Mechanical Integration Concepts

6.1 Parachute and Parachute Accommodation

Mechanical accommodation of the parachute for each of the technology sets was patterned after the mortar system used on MSL, with modifications made to increase stowage capacity for the larger parachutes with minimal impact to the backshell outer mold line (OML). Figure 12 compares the MSL-I aeroshell with the MSL aeroshell.

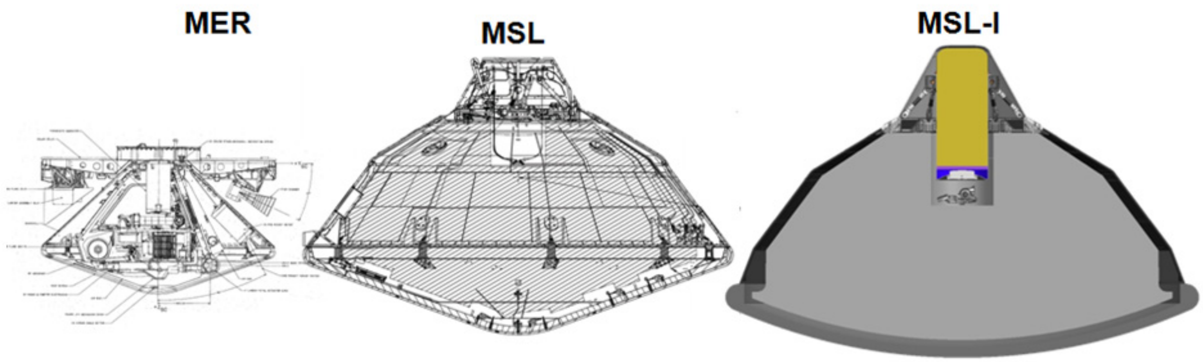


Figure 12. Aeroshell Evolution and Parachute Accommodation

6.1.1 30 meter Ringsail Parachute

A ringsail style parachute was selected for this study due to the previous parachute work done in the Mars Program as late as 2005. The two prime motivators for selecting a ringsail type parachute are that it has excellent subsonic drag performance and is much easier to reef than a disk gap band parachute. Reefing is required to minimize the peak accelerations of the spacecraft at parachute inflation. MSL's 9 G's (achieved with a 21.5 m parachute) was used as a working upper limit.

The Subsonic Parachute Technology Task (SPTT) developed by Mitcheltree, Slimko, Cruz in 2005 was used as the configuration for this effort. The SPTT parachute, shown in Figure 13, was designed for a 20,000 lbf peak inflation load, so the mass of the SPTT parachute was scaled up to account for a maximum flight limit load of 65,000 lbf. The parachute subcontractor, Pioneer Aerospace, confirmed the mass estimate of 130-145 kg.

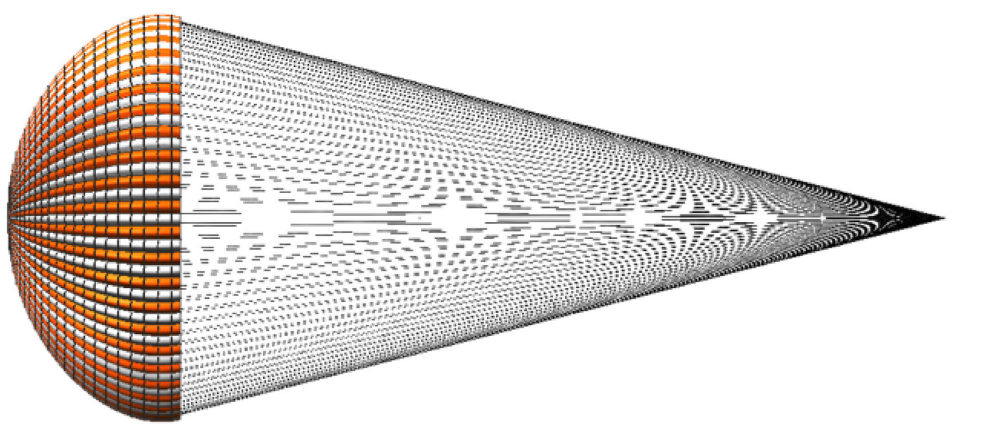


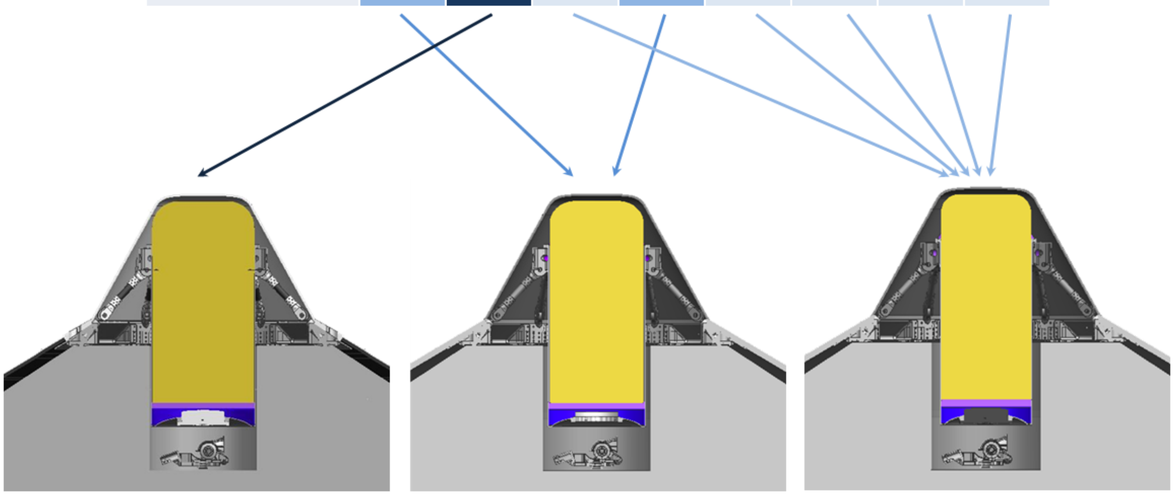
Figure 13. SPTT Parachute Configuration

Using a guideline that trailing distance should be 8 times the forebody diameter for subsonic chutes, and 10 times for supersonic chutes, the differences in forebody diameter for TS-1 through

TS-8 resulted in a large variance of riser length, and therefore total chute mass and stowed volume among the technology sets. The masses were broadly binned into 160, 185, and 230 kg variants, for which mortar can configurations were modeled in CAD. This is summarized in Table 2.

Table 2. Technology Set Parachute Sizing Metrics

	TS-1	TS-2	TS-3	TS-4	TS-5	TS-6	TS-7	TS-8
Trailing Distance X/D	10	8	10	8	10	10	10	10
Trailing Distance (m)	79	123	58	73.6	47	47	47	47
Riser Length (m)	40	84.2	19	34.6	6	6	6	6
Packed Mass (kg)	185	230	165	180	150	150	150	150



The MSL-I design interfaces with the MSL Backshell Interface Plate (BIP), and uses a similar support structure sized for the same peak loads.

Assumed parachute packing density was kept at a very conservative 42 lb/in^3, in line with MSL's design density and below the densities used on Mars Pathfinder, MER, and Apollo. The addition of reefing components (cable cutters and reefing rings) limits the max pack density that can be safely achieved without incurring damage to these components.

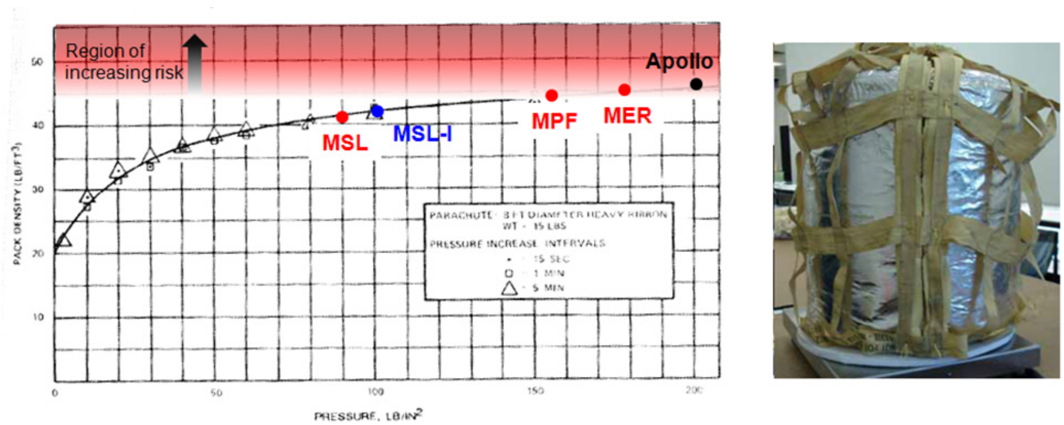


FIGURE 6-67. Pack Density as a Function of Pack Pressure and Packing Application Interval. Knacke, T. W. Parachute Recovery Systems Design Manual. 1st ed.

Figure 14. MSL-I Parachute Packing Density

6.2 Iso-Tensoids and Tension Cones

A Supersonic Inflatable Aerodynamic Decelerator is a deployable softgoods device that increases the drag of a vehicle after SIAD deployment. Because the SIAD is a softgoods device, it can be stowed in a compact volume and deployed to a large size. In order to minimize the changes to an MSL-like vehicle while still allowing the integration of a SIAD, the SIAD configuration was chosen such that the SIAD-vehicle interface was near the heat shield-backshell interface plane at the perimeter of the vehicle; a SIAD could also be configured such that the SIAD trails the vehicle in a way similar to a parachute, however this configuration was not examined here due to the lower drag coefficient of a SIAD in the trailing configuration.

Four types of SIAD were considered here: a 7.95m diameter iso-tensoid, a 15.44m diameter iso-tensoid, a 5.76m attached torus (small diameter tension cone), and a 9.19m diameter tension cone. Shown in Figure 15, these configurations correspond to TS-1, TS-2, TS-3, and TS-4, and the masses for these SIAD softgoods was estimated to be 55 kg, 200 kg, 15 kg, and 200 kg, respectively. The mechanical interfaces to the vehicle were similar for all 4 SIAD configurations.

The air volume inside an iso-tensoid is generally larger than the air volume inside a comparable tension cone or attached torus. The air enclosed within an iso-tensoid is partially or completely provided by ram air inlets located on the forward face of the SIAD. It was assumed here that half of the air mass required by fully deployed iso-tensoids would need to be provided by a gas generator system in order to initiate SIAD deployment. The air enclosed within a tension cone and attached torus is provided entirely by a gas generator system. The gas generators used for the Mars Exploration Rover airbag system were used to estimate the quantity and mass of the gas generator system required for each SIAD configuration: the gas generator masses were estimated to be 3.4 kg, 41 kg, 17 kg, and 65 kg for TS-1, TS-2, TS-3, and TS-4, respectively.

A cover panel system is required to protect the stowed SIAD softgoods from the hypersonic thermal environment associated with planetary entry. A spectrum of cover panel systems was considered here. At one end of the spectrum was a "hard cover" system that used a rigid thermal protection system (TPS) over rigid panels similar to the vehicle backshell. At the opposite end of the cover panel system spectrum is the "soft cover," which consists of only a flexible TPS material such as AFRSI. In the middle of the cover panel spectrum are a number of "hybrid" cover panel options that would use some amount of flexible TPS and some amount of rigid structure. A low mass, high speed panel ejection system is considered a significant issue for the implementation of a hard cover system.

Assuming a packing density of 400 kg/m^3 (25 lbs/ft^3) allows for the estimation of the volume required for the stowed SIAD configurations. For SIAD configurations with a softgoods mass below 62 kg, the stowed SIAD can fit within both a straight or curved cover panel envelope with at least a 25mm gap between the SIAD and the cover panel. At a softgoods mass of 112 kg, the stowed SIAD completely fills the volume inside a straight cover panel system but still has a 34mm gap to the curved cover panel system. At 200 kg, the stowed SIAD completely fills the volume inside the cover panel system (Figure 16).

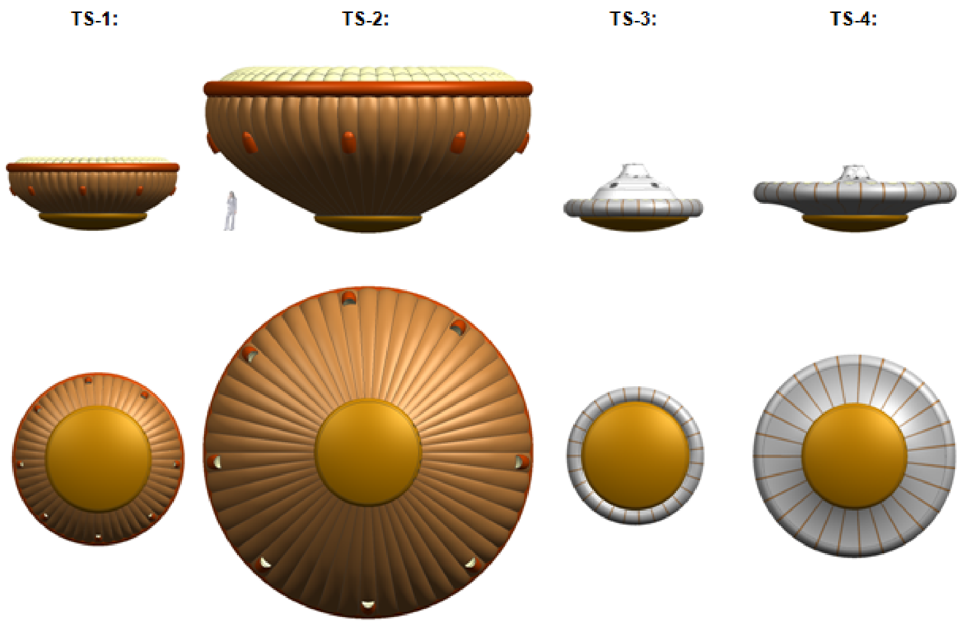


Figure 15. Iso-Tensoid and Tension Cone SIADs

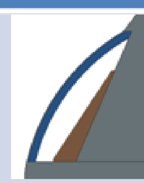
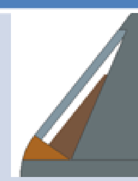
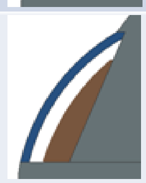
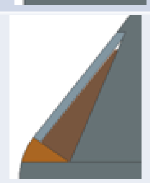
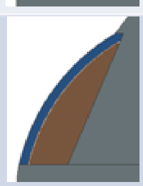
SIAD Mass	SIAD Stowed Density	SIAD Stowed Volume	Curved Cover	Straight Cover	Clearance
62 kg	400 kg/m^3 25 lbs/ft^3	0.156 m^3			Hard:48mm Soft:25mm
112 kg	400 kg/m^3 25 lbs/ft^3	0.281 m^3			Hard:34mm Soft:1mm
200 kg	400 kg/m^3 25 lbs/ft^3	0.503 m^3		X	Hard:1mm Soft: n/a

Figure 16. SIAD Cover Options

6.3 Trim Tab

Trim tab mechanical development starts with the assumption that the panel area shall produce a lift/drag value of approximately 0.35. Using CBAERO and CART3D and based on balancing the aerodynamic performance and packaging requirements, a 0.75 m^2 panel area was derived. High and low aspect ratio tabs were included in the analysis, resulting in a 1m long by 0.75 m wide trim tab deployed perpendicular to the vehicle z-axis

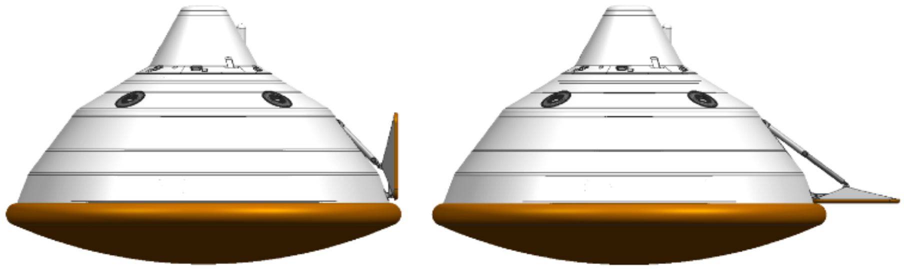


Figure 17. Trim Tab Configuration

The major mechanical subsystems of the trim tab include the trim tab panel and deployment/retraction actuators.

6.3.1 Trim Tab Actuator

The trim tab is deployed exo-atmospherically and remains deployed during entry. The deployment mechanism must be able to deploy the trim tab in less than five minutes and then withstand entry loads. These loads were calculated based on the aerodynamic performance analysis. After entry, the trim tab must retract in 5-10 seconds at Mach 2.5, just before parachute ejection.

Multiple actuation methods were considered including ball screws, hinge actuators, and pneumatic pistons. A dual pneumatic piston system provides feasible mechanical advantage due to attachment point flexibility, reasonable mass estimates, and fast retraction times. Two 63 mm outer diameter pistons will meet the load requirements. For the deployment subsystem designed in this study, a pressurant system must provide 1800 psi prior to deployment. This pressure needs to be maintained for less than 60 minutes.

During launch and after retraction, the trim tab panel will be locked into its stowed configuration. This can be accomplished with a launch lock/retention mechanism incorporated into the pneumatic actuators. During retraction, the actuators will also act as dampers, limiting the retraction speed while still meeting the 5-10 second retraction requirement.

6.3.2 Trim Tab Panel

The panel was designed to withstand structural entry loads. A structural analysis was performance to determine that a M55J carbon fiber face sheet/aluminum honeycomb core panel will withstand the loads determined in the aerodynamic performance analysis, with an estimated mass of 10.5 kg. Due to high thermal loads on the panel, PICA TPS is needed on the exposed panel surface.

The estimated total trim tab system mass is 31.0 kg.

6.4 SABr - Supersonic Air Brake

Technology set seven (TS-7) contains a supersonically deployed aerodynamic braking device coupled with a supersonically deployed ringsail parachute. TS-7 uses EBMs mounted in the heat shield to obtain a prescribed angle of attack during hypersonic and supersonic flight. At Mach 4.5 a Supersonic Aerodynamic Brake, or SABR, is deployed. Immediately prior to parachute deployment at Mach 2.3, the "straighten up and fly right" (SUFR) maneuver is performed to prepare for parachute deployment. SABr panels are retracted simultaneously with parachute inflation so as to maximize overall system aerodynamic stability.

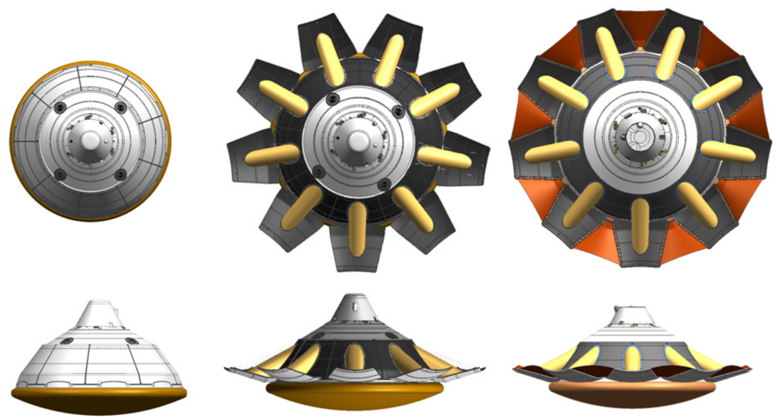


Figure 18. SABr Stowed and Deployed, Unwebbed and Webbed Configurations

The rigid decelerator is comprised of 9 composite articulating panels, 9 inflatable pneumatic actuators, 9 launch locks, and a single manifolded gas generation system. The panels can either be uncoupled, or coupled via fabric webbing, as seen in Figure 18. The Panel Components are shown in Figure 19.

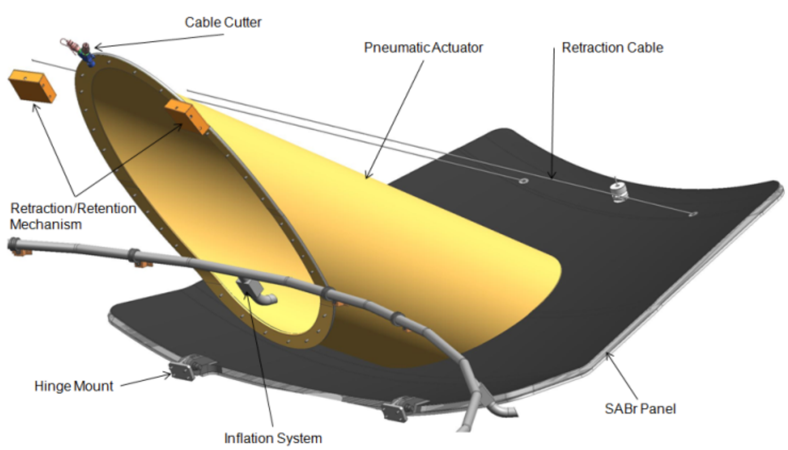


Figure 19. SABr System Components

The unwebbed version provides a projected surface area increase of 1.7x the projected area of the heatshield alone. The webbed version provides a 2.0x increase.

Panel deployment is initiated with the firing of a cable cutter that releases the preloaded launch lock interface. Immediately following is the lighting off of the gas generation system. The gas generation system is a solid fuel combustion gas generator commonly used in the aerospace industry. The combustion gases are manifolded to all 9 panels simultaneously. As the gases flow into the pneumatic actuator, which is a fabric tube, the inflation pressure creates a motive force on the panel. The panel quickly accelerates into the free stream, at which time, the prevailing dynamic pressure applies a counter force on the panel. The gas generation system and all other components in the system have been sized in order to overcome the free stream dynamic pressure and to deploy the panel to its fully deployed position within 1 sec. One second was chosen as the deployment time in order to minimize aerodynamic disturbances to the vehicle.

Immediately prior to, or simultaneous with the parachute mortar firing, an actuated relief valve on the pneumatic actuator is opened. The valve is sized to allow the force of the dynamic pressure on the panels to force the panels closed, while still providing enough resistance to create a viscous damper to eliminate a high speed impact between the panel and the backshell. Once the panel is out of the free stream the retraction cables provide a constant force to guarantee the panels are pulled completely closed and remain closed under the dynamic oscillations of the vehicle experienced during parachute deployment.

By allowing for a panel retraction prior to full parachute deployment, the SABR design allows the parachute 10x trailing distance to be minimized.

TS-7 is a drag system that can be built using existing technology. It can also be tested in existing wind tunnels. TS-7 has an estimated mass of 200 kg.

6.5 SABr with Trim Tab

Technology set eight (TS-8) is hypersonically guided utilizing a SABr panel as a trim tab, a supersonically deployed rigid decelerator (SABr) coupled with a supersonically deployed ringsail parachute. TS-8 deploys a single panel of the SABr system exo-atmospherically in order to trim the vehicle to a specified angle of attack. This eliminates the need for EBMs and the dead mass associated with them. The basic configurations can be seen in Figure 20.

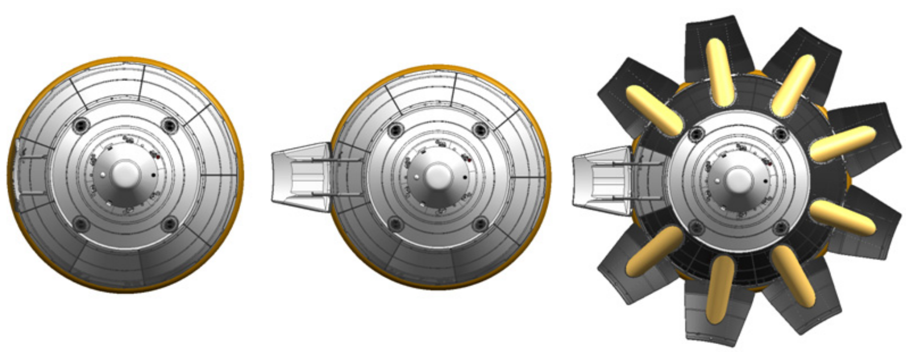


Figure 20. SABr + Trim Tab Configurations

TS-8 utilizes the same pneumatic actuators as seen in TS-5, however the panel is a stronger and stiffer SABr panel. The panel is also equipped with a thicker layer of PICA TPS. This protects the panel against the higher aero-thermal heat rates expected at hypersonic speeds. The details of the pneumatic actuators required can be found in the TS-5 and TS-7 sections.

TS-8 is a combined trim tab and drag system that can be built using existing technology. It can also be tested in existing wind tunnels without the need for a supersonic high altitude flight test. TS-8 has an estimated mass of 211 kg.

7 Cost, Risk and Cross-Cutting Applicability

In addition to the performance and mechanical implementation assessments covered in Sections 5 and 6, cost, risk and cross-cutting applicability were evaluated for each technology and technology set. The results presented in this section and the following section represent an initial cost and risk assessment, and because cost and risk were not evaluated in this study to the degree and depth that were performance and mechanical implementation, these results should be regarded as having a significant level of uncertainty until future work provides clearer definition.

The evaluation process leveraged the collective experience and expertise of the MSL-I Robotic Steering Committee in establishing cost and risk levels. This was accomplished in part via written evaluation inputs from RSC members, as well as by verbal inputs and feedback during reviews and consultations. The RSC written evaluation inputs were compiled and where scored they were averaged, and were used in establishing risk levels as well as influencing the development cost estimation process. Table 3 contains the evaluation criteria definitions and score metrics used in the evaluation process. Detailed scoring results are not presented in this document, however the resulting risk levels are presented.

Table 3. Evaluation Criteria

Evaluation Criteria	Definition
Significant Development Cost Drivers	Significant drivers to the cost of developing the technology from its current TRL to TRL 6.
Development Risk	Areas of significant risk to successfully developing the technology from its current TRL to TRL 6. Scoring: 1=Low Risk, 2=Medium, 3=High Risk.
Performance Risk	Significant areas of potential risk associated with the performance of the technology. Scoring: 1=Low Risk, 2=Medium, 3=High Risk
Overall Risk	A qualitative assessment of the overall level of risk associated with the technology. Scoring: 1=Low Risk, 2=Medium, 3=High Risk
Cross-Cutting Applicability	The applicability of the technology to other Mars exploration applications and other solar system destinations.

7.1 Development Cost

Given the relative immaturity of understanding of the details of required effort for the development of the MSL-I technologies, two simple approaches were taken to provide an initial estimated development cost. For all technologies except the trim tab, an analogy cost estimation technique was employed[4]. For the trim tab, expert opinion was used to establish a development cost estimate. Because of significant uncertainty in these initial cost estimates, the cost estimations were then used to place the technologies into a development cost space comprised of overlapping domains of $50M, $100M, $150M, $200M and $250M development costs. In this space, a particular technology may be a member of more than one cost domain signifying to first order the level of uncertainty in the present understanding of development cost. Figure 21 shows the placement of the technologies in the development cost domains.

More details about the initial cost estimation process utilizing analogy cost estimation can be found in NASA/TM-2011-216989.

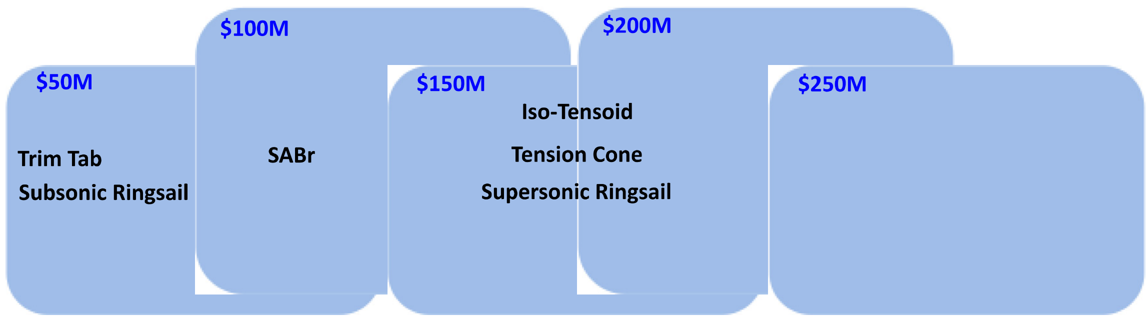


Figure 21. Technology Development Cost Space

7.2 Risk

The MSL-I RSC was asked to evaluate three categories of risk for each MSL-I technology: development, performance and overall risk. These categories are described in Table 3. Because of the uncertainty remaining in understanding of the risk associated with each technology, a detailed assessment of risk is not presented. Instead, broader risk observations resulting from the MSL-I work and derived from the RSC evaluations is presented as a guide to future work.

7.2.1 Development Risk

For the MSL-I study, development risk is defined as the risk inherent in developing a technology from its current TRL to TRL 6. To first order, development risk for the MSL-I technologies is delineated by rigid technologies vs non-rigid technologies, with rigid technologies having lower development risk. In general, the development of rigid structures is a more tractable development problem that leads to the division of development risk groups for the technologies. For inflated SIADs (iso-tensoid & tension cone), which fall into the higher risk category, the risk can be delineated again into smaller more rigid SIADs and larger more flexible SIADs. Because of their quasi-rigid characteristic, small diameter SIADs are assessed to have lower development risk than larger, more flexible SIADs.

7.2.2 Performance Risk

Performance risk is the risk that once developed, a technology will not perform as expected or predicted. As with development cost, non-rigid technologies were also assessed as having higher risk associated with performance, with parachutes assessed as having the most performance risk, iso-tensoids and tension cones being next, followed by the inherently rigid technologies.

7.2.3 Overall Risk

Overall risk is the integration of all the risk associated with a technology. It is not a roll-up of the other risk category assessments, rather the RSC was asked to provide an assessment of the overall risk associated with the MSL-I technologies. As shown in Table 4, the overall risk assessment led to a delineation between technologies assessed as having high overall risk, which included the SABr + trim tab, the iso-tensoid and the tension cone; and those assessed as medium/low overall risk, which included both parachute options, the trim tab and SABr. Table 4 also contains the optimized landed payload performance for each technology and development cost estimation, as presented previously. Additionally, Table 4 contains an *assessment fidelity* rating indicating the level and depth of analysis supporting the result. Optimized performance received the most effort and had the highest fidelity analysis and thus the results receive a medium-high assessment fidelity level. The assessment of both overall risk and development cost were initial efforts in this study and thus are rated as low and medium-low in fidelity, with a corresponding high level of uncertainty in the results.

Table 4. MSL-I Technologies Initial Overall Risk Estimates

An initial assessment - further evaluation is needed

Assessment	***Assessment Fidelity***	**Technology** 						
		Trim Tab	**SABr**	**SABr + Trim Tab**	**Iso-Tensoid**	**Tension Cone**	**Supersonic Ringsail**	**Subsonic Ringsail**
Optimized Performance (Paired with Supersonic Ringsail)	***Medium-High***	1.8 km, 1462 kg	4.9 km, 1132 kg	4.8 km, 1256 kg	6.0 km, 1135 kg	6.0 km, 1157 kg	2.9 km, 1309 kg	2.5 km, 1086 kg
Optimized Performance to 0 km (Paired with exisitng MSL DGB)	***Medium-High***	1132 kg	1088 kg	Unavailable	1108 kg	1101 kg	N/A	N/A
Overall Risk	***Low***	Low-Medium	Medium	High	High	High	Medium	Low
Development Cost Estimation	***Low-Medium***	<$50M	$50M-$100M	$50M-$150M	$100M-$200M	$100M-$200M	$100M-$200M	<$50M

7.3 Cross-Cutting Applicability

Cross-cutting applicability is defined as a technology's potential for use beyond the MSL-I DRM including other Mars missions, at other solar system destinations and toward NASA overall exploration objectives. The trim tab is assessed as having potential for use for other Mars missions, including scalability to larger class missions, as well as use at other solar system destinations. SABr is assessed as having limited application beyond the MSL-I DRM due to a high mass penalty when scaling the technology. Application to destinations with thicker atmospheres may also be limited. SABr + trim tab applicability is the combined potential and limits of the individual technologies. Both SIAD technologies are assessed as having minimal cross-cutting applicability. The supersonic ringsail parachute is evaluated as having only robotic mission applications at Mars, with some potential for deployment extraction application on larger Mars vehicles. The subsonic ringsail parachute is assessed as having no application beyond the MSL-I application. Because of the limits of the cross-cutting applicability assessment in this study, it is recommended future studies consider this topic again in more depth.

8 Technology Set Evaluations

Having provided an evaluation of individual technologies in the previous section, this section provides a summary of the overall evaluation by showing how the individual technology evaluations map into the MSL-I Technology Sets.

8.1 Technology Set Development Cost

Because each technology set contains two assessed technologies, the development cost for a technology set is the combined development cost of the two technologies. Two methods were employed to combine the development costs. First, if the development efforts for the two technologies appear to first order to be independent and decoupled, the development costs for the two technologies were simply added, yielding a likely conservative overall development cost. Second, if the technologies both require a supersonic high altitude flight test, it is assumed there would be significant savings by combining the flight test programs, so that 30% of the lowest development cost technology was added to the cost of the other technology development cost. The resulting technology set development cost estimates were used to place the technology into the development cost space described in the previous section. Figure 22 shows were the technology sets fall in the development cost space.

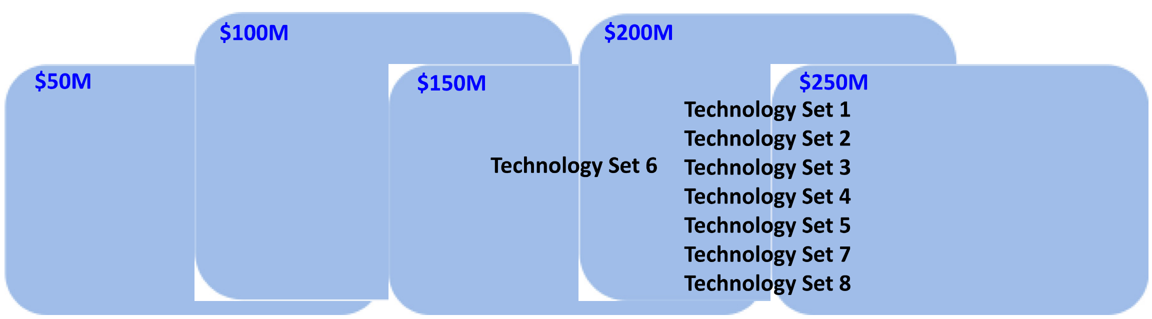


Figure 22. Technology Set Development Cost Space

Because each technology set contains either a SIAD or a supersonic parachute, all technology sets require a supersonic high altitude flight test, which is a primary cost driver, and thus all technology sets are a member of at least the $100M domain and higher. All technology sets except Technology Set 6 occupy the $150M, $200M and $250M domains.

8.2 Technology Set Performance Summary

Figure 23 is a summary of the performance capability of each technology set. Performance is shown in terms of technology set elevation capability vs landed payload mass. The rectangular boxes shown on the elevation capability/landed payload mass plane encompass the performance capability of each technology set. TS-1, TS-3 and TS-7 perform well in delivering to higher elevations. This is because SIADs and SABr provide increased drag area earlier in the supersonic phase. TS-5, the trim tab, delivers the most landed payload mass, followed by TS-6 and TS-7. TS-6 in particular has good landed payload mass performance with just the addition of a supersonic ringsail parachute. TS-2 and TS-4 are the subsonic parachute technology sets and perform least well of all the technology sets. This is because delaying parachute deployment to subsonic conditions forces the growth of companion SIADs that increases structural mass and reduces landed payload mass capability. Shown in the black box is the capability box of the baseline architecture with supersonic DGB parachute. Each technology set label lists the technologies that comprise the technology set.

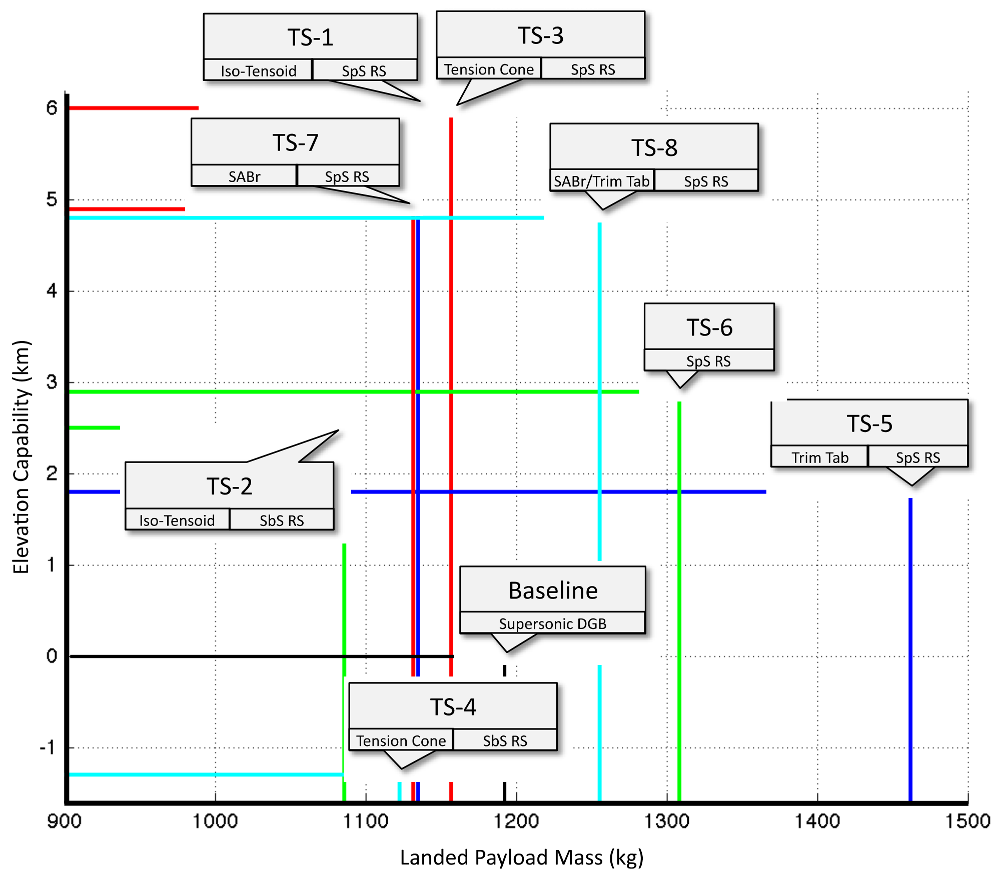


Figure 23. Technology Set Evaluation Summary

9 Conclusion

The purpose of the MSL-I study is to examine enabling technologies that incrementally improve performance of the MSL EDL system while minimizing change to the MSL EDL architecture for missions on or before 2024. Assessed purely on performance, those technologies that increase aeroshell drag earlier in the supersonic phase, such as the SIADs and the SABr, enable landing

MSL class payloads at elevations as high as 6 km. The trim tab technology was shown to deliver the most mass, while the replacement of a supersonic DGB parachute with a supersonic ringsail parachute also provided better mass capability over MSL performance. The study also shows that a subsonic ringsail parachute, when combined with SIAD technology, provides the least incremental improvement. In general, the development cost of the technologies is driven significantly by the cost of a supersonic high altitude flight test program. The SIAD technologies and the supersonic ringsail parachute require this test program and thus were estimated as \$100M to \$200M developments. Because all technology sets examined by the MSL-I study included either a SIAD or a supersonic parachute, the cost domains occupied by the technology sets range from \$100M and higher, with all but TS-6 occupying the \$150M, \$200M and \$250M domains. To first order, overall risk associated with the technologies was established to be a function of technology rigidity with rigid technologies being assessed as having less inherent risk than flexible technologies.

The MSL-I study provides an initial assessment of the seven technologies. Because it is an initial assessment, it is a challenge to derive specific technology investment recommendations given that there remains performance, cost and risk uncertainty. However two initial conclusions are possible. First, the marginal performance of the subsonic ringsail technology sets eliminates the subsonic ringsail as a technology worth pursuing for robotic Mars missions. Second, the performance enhancement provided by the supersonic ringsail parachute across all other technology sets warrants continued development of this technology. Although not included as an assessed technology, development of a higher performing bi-propellant descent engine was identified during the study as a possible high leverage technology that should be considered along side, and possibly instead of, the supersonic ringsail parachute. To further the process of understanding the benefits of each technology, it is recommended that future work include the establishment of Pre-Phase A study teams to fill the in the performance, mechanical integration, cost and risk knowledge gaps for the SIAD, SABr, trim tab and supersonic ringsail technologies.

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Appendix A: Ground Rules & Assumptions

EDL-SA Ground Rules and Assumptions

This section lists the Ground Rules and Assumptions (GR&A) as employed in the EDL-SA Study.

General Ground Rules and Assumptions

The ground rules and assumptions applicable to both robotic studies are

- Mass growth allowances and margins will be applied to all technologies and systems as described below:

    In developing mass estimates, three separate estimates should be provided. These are:

    Current Best Estimate (CBE) Mass: This mass constitutes an assessment of the most recent baseline design including factors of safety or various knockdown factors. The estimate does not include any mass growth allowance.

    Maximum Expected Value (MEV) Mass: This constitutes the CBE mass with the addition of mass growth allowance (MGA), where mass growth allowance consists of the predicted changes to the CBE based on an assessment of the design maturity.

    MEV Mass = Current Best Estimate + Mass Growth Allowance

    Allocated Mass: The allocated mass is the MEV mass with the addition of system margin.

    Allocated Mass = MEV Mass + System Margin

    The total mass growth allowance does not include any TRL-based augmentation.

    In the case of the MSL-I study, the JPL mass margin policy will be applied. The JPL policy addresses both a mass growth allowance for each component (to achieve individual MEV's estimates) as well as a total system/vehicle margin (to achieve the total allocated mass estimate). Other than a slightly different calculation for computing the total allocated mass, the JPL policy is essentially the same as the standard NASA policy. At the component level, the margin practice will be per the AIAA standard document S-120-2006. The total system allocated mass will be defined per the JPL mass margin policy as follows:

    Allocated Mass = CBE / (1 – System Margin %)

    The system margin % to be used will be 30% per the recommended value in JPL-D-17868.

- Subsystem performance parameters (e.g., engine Isp, engine T/W, vehicle inert mass fraction) are to be based upon historical data and trends.
- The atmosphere model used for this study will be MarsGRAM 2005.
- Turbulent flow onset will be estimated using the $Re\theta = 200$ criterion. For $Re\theta > 200$, the entire forebody will be considered to be turbulent.
- POST2 will be used for simulations.
- Representative guidance algorithms will be developed. Theoretical guidance algorithms will also be used.
- Vertical velocity at touchdown will be <= 1 m/s.
- On-orbit assembly will not be considered.
- Landed altitude capability will be a minimum of 0 km above MOLA.
- Landing site altitude sensitivities will be evaluated for -1 km MOLA to 2.5 km MOLA.

- Entry date: October 15, 2025.

MSL-I Ground Rules and Assumptions

The following ground rules and assumptions are applicable to the MSL-I Study

- The launch vehicle is the Atlas V-551.
- Interplanetary mission design will be direct to entry (e.g. no aero/propulsion capture into a Mars parking orbit).
- Entry vehicle will have a 4.7 m maximum diameter (to fit Atlas V fairing), with an Apollo forebody shape, and scaled elements as necessary for g-load, heat load, chute inflation loads, payload mass, etc.
- The descent stage thrust to weight will be greater than 2.7 for all cases studied
- Descent & landing phase mission design will be a scaled version MSL descent stage with skycrane.
- All selected technologies considered capable of achieving sufficient TRL in time to support a 2024 launch.
- The following timeline margin will be enforced for all EDL simulations: >= 15 s from heatshield jettison to radar lock and >= 15 s from radar lock to backshell jettison; both margins are 3 sigma low values.
- The simulation is allowed to optimize several parameters. The parameters include but are not limited to:
    - the size of the drag device,
    - entry state
    - bank angle and/or cg control location,
    - heading alignment velocity
    - deploy Mach numbers
    - bank reversals
    - lift-to-drag ratio
    - powered descent initiation
- In the landed payload/site elevation trade, the landed payload (at 0 km MOLA) is the objective, and the sensitivity is that of landed payload to site elevation.
- The constructed EDL architecture should seek to minimize deviation from the current MSL EDL architecture.
- EDL architectures should be comprised of technologies that individually cost ~$200M or less to mature to sufficient TRL.
- The launch opportunity will be 2024 to support the MSR lander.

Appendix B: Initial Technology List

Table 5. Criterion of Selection Definitions

Criterion	Definition
Development Time	The technology must be capable of being matured to TRL 6 in time for a 2024 launch opportunity
DRM/GR&A	The technology must be in line with MSL-I DRM and GR&A
Cost	The technology must be capable of being matured to TRL 6 at a cost less than $200M
Flight System Technology	The technology must be a vehicle based technology (e.g. no database upgrades or precursor probes)
EDL-SA Scope	The Technology must be within the general EDL-SA Scope
Technology Relevance	The technology should address an area of need (i.e. not seek to improve upon a system or instrument that is already capable of meeting mission needs out to 2024)
FY10 Scope	Insufficient time for adequate analysis, e.g. required model fidelity prohibitive for FY10

Table 6. Initial Technology List

Red = Eliminated during first reduction Orange = Eliminated during final reduction

AoA and Drag Control	Elimination Rationale
CG Control	Priority
Propulsion Aids	Technology Relevance & Cost
Extend equilibrium glide	
Aerodynamic body flaps	
Structurally supported fabric system	Cost and Development Time
Alternate Entry Geometries	**Elimination Rationale**
Elipsled	DRM/GR&A & Technology Relevance
Rigid Deployable (in space)	Cost and Development Time
Morphing entry body (time varying geometry)	Cost and Development Time
Apollo shape	
Optimization for drag/lift/packaging/heating/stability	
Aeroshell shape/CG management coupling	
Wings	DRM/GR&A & Technology Relevance
Asymmetry Options	Priority
Alternate heatshield geometries	
Improved Inertial and Atmospheric Relative Knowledge (onboard vs. external)	**Elimination Rationale**
Mach Sensor	Priority
Extend MEDLI MEADS system/feedback loop	
Higher precision/accuracy/reliability IMU	EDL-SA Scope
Improved wind estimation (pre entry estimation)	Flight System Technology
Landing Beacons	Flight System Technology

ALHAT	
Precursor atmospheric scouts	Flight System Technology
Real-time atmospheric sensing (on-board), FADS	Cost
Reduce delivery state dispersion (nav knowledge)	Priority
Improved feed forward engineering datasets	Flight System Technology
Improved transition triggers	Priority
Improved Terrain Relative Knowledge	**Elimination Rationale**
High precision IMU	Technology Relevance
ALHAT	
Terrain relative sensing at higher altitudes	Priority
TPS Improvments	**Elimination Rationale**
Phase Change materials for heatload offset	DRM/GR&A
IADs	
2018 SIAD	
Asymmetric burble (inflatable body flap)	Cost
Towable/trailing ballute	Cost
Heat pulse IAD	Cost & DRM/GR&A
SHADI/HHIAD/LHIAD/SIAD	Cost
Tension cone/stacked toroid/iso-tensoid	Redundant
Staged IADs (both for drag and AoA modulation	Drag
Inflatable body flaps for AoA management	Cost
Deformable IADs for steering	Cost
Inflation concepts - Ram air vs. GG vs. etc	
Improved Parachutes	**Elimination Rationale**
Steerable parachutes	Cost
Larger and/or faster parachutes	
Alternate trailing drag device	Covered by other technologies
Propulsive Augmentation	**Elimination Rationale**
Supersonic Retropropulsion	Anything but simple eliminated due to cost
Enter parking orbit first (propulsive and aero capture approach)	DRM/GR&A
Ram jet engine	cost
Propulsive targeting correction	DRM/GR&A
Phase Change materials for RCS	DRM/GR&A
All propulsive option	DRM/GR&A
Rocket copter/gyrocopter	DRM/GR&A
Improved Staging (Mechanisms and Triggers)	**Elimination Rationale**

Improved staging (obliteration of separated bodies, higher HS sep, tractor rockets, etc.)	Priority
General System Improvements	**Elimination Rationale**
Higher landed velocity allowable	Flight System Technology
Higher precision IMU	Technology Relevance
Terrforming to increase atmospheric density	Cost & Flight System Technology
Propellant depot in Mars orbit	Cost & DRM/GR&A
Reduced Entry mass (light-weighting)	EDL-SA Scope
Reduce Delivery State Dispersions (nav knowledge)	Flight System Technology
Improved Data Fusion / Computation Power	EDL-SA Scope
Smart Descent Stage	EDL-SA Scope
Land at Night	Flight System Technology
Policy Changes	Flight System Technology
Improved guidance algorithms	**Elimination Rationale**
Upgrade Apollo	
NPC	
Entry from Orbit	DRM/GR&A
Skip Entry	Technology Relevance
Propulsive Targeting	

Appendix C: Abbreviations, Acronyms and Symbols List

AFRSI	Advanced Flexible Reusable Surface Insulation
ALHAT	Autonomous Landing and Hazard Avoidance Technology
AoA	Angle of Attack
BIP	Backshell Interface Plate
CAD	Computer Aided Design
CdA	Coefficient of Drag Time Area
DGB	Disk Gap Band
DRM	Design Reference Mission
EBM	Entry Balance Mass
EDL	Entry Descent and Landing
EDL-SA	Entry, Descent and Landing Systems Analysis
FY10	Fiscal Year 2010
GR&A	Ground Rules and Assumptions
IAD	Inflatable Aerodynamic Decelerators
L/D	Lift Over Drag
MER	Mars Exploration Rovers
MOLA	Mars Orbiter Laser Altimeter
MSL	Mars Science Laboratory
MSL-I	Mars Science Laboratory Improvement
NASA	National Aeronautics and Space Administration
OML	Outer Mold Line
PICA	Phenolic Impregnated Carbon Ablator
RSC	Robotic Steering Committee
SIAD	Supersonic Inflatable Aerodynamic Decelerator
SABr	Supersonic Aerobrake
SPTT	Subsonic Parachute Technology Task
SUFR	Straighten Up and Fly Right
TPS	Thermal Protection System
TRL	Technology Readiness Level
TS	Technology Set

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14. ABSTRACT

NASA senior management commissioned the Entry, Descent and Landing Systems Analysis (EDL-SA) Study in 2008 to identify and roadmap Entry, Descent and Landing (EDL) technology investments needed to develop technologies to successfully land large payloads at Mars for both robotic and human-scale missions. This report summarizes the work the Mars Science Laboratory Improvement (MSL-I) team carried out as part of Phase 2 of the study in 2010. The MSL-I study assessed seven Mars EDL technologies selected for their near-term potential to incrementally improve the performance of the Mars Science Laboratory EDL system. The assessment was made based on landed mass performance, mechanical implementation, cost, risk and cross-cutting applicatbility.

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