SUPERSONIC RETROPROPULSION TECHNOLOGY DEVELOPMENT IN NASA'S ENTRY, DESCENT, AND LANDING PROJECT

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ABSTRACT

NASA's Entry, Descent, and Landing (EDL) space technology roadmap calls for new technologies to achieve human exploration of Mars in the coming decades [1]. One of those technologies, termed Supersonic Retropropulsion (SRP), involves initiation of propulsive deceleration at supersonic Mach numbers. The potential benefits afforded by SRP to improve payload mass and landing precision make the technology attractive for future EDL missions. NASA's EDL project spent two years advancing the technological maturity of SRP for Mars exploration [2-15]. This paper summarizes the technical accomplishments from the project and highlights challenges and recommendations for future SRP technology development programs. These challenges include: developing sufficiently large SRP engines for use on human-scale entry systems; testing and computationally modelling complex and unsteady SRP fluid dynamics; understanding the effects of SRP on entry vehicle stability and controllability; and demonstrating sub-scale SRP entry systems in Earth's atmosphere.

1. Introduction

In August of 2012, NASA's Mars Science Laboratory (MSL) EDL system will deliver the largest payload ever sent to Mars (Curiosity rover, 900 kg = 0.9 metric ton, t) within approximately 10 km of the landing site target [8]. MSL will use the largest aerodynamic decelerators ever built for Mars EDL: a 4.5-m diameter rigid aeroshell and a 21.5-m diameter disk-gap-band supersonic parachute [Fig. 1]. MSL's aerodynamic decelerator system evolved from those previously used by NASA for the successful Viking, Pathfinder, Mars Exploration Rover, and Phoenix missions. It is estimated that a slightly larger payload (~1.1 t) could be safely landed on Mars at 0-km elevation using the MSL EDL system [2].

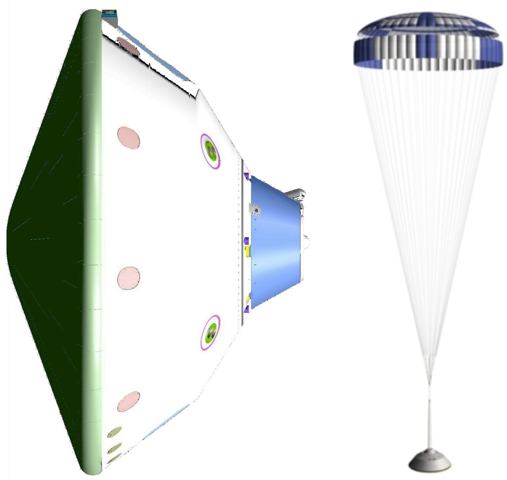

Fig. 1. Mars Science Laboratory (MSL) aerodynamic decelerators: 4.5-m diameter aeroshell (left) and 21.5-m diameter supersonic disk-gap-band parachute (right).

Human exploration of Mars will require new technologies for deceleration of large-scale payloads (10s of metric tons, t) with precision accuracy (within meters of the target). NASA's EDL space technology roadmap (TA09) [1] specifically recommends new deceleration technologies to succeed parachutes, the latter of which do not scale well for human payloads:

> *"As Mars missions approach human class entry masses, the required size of supersonic deployable aerodynamic decelerators renders them impractical…initiation of propulsive deceleration must occur earlier in the descent phase…SRP becomes an enabling technology for human class Mars missions."*

Propulsive deceleration initiated at supersonic Mach numbers, or SRP, is viewed as one technology that may enable payloads of the desired size to land on Mars. Significant advancements are required to bring SRP from its current estimated technology readiness level (TRL) of about 3 (0-9 scale) to the TRL required to implement SRP on an EDL mission (TRL 6) [5] (Fig. 2). Component SRP technology areas in need of attention include: propulsion, aerodynamics and aerothermodynamics, entry vehicle guidance and control, ground testing, and flight-testing at Earth. As described later in this paper, recent investments by NASA have addressed a number of these technical areas.

TRL	Definition	Phase
1	Basic principles observed and reported	Basic Research
2	Technology concept and/or application formulated	
3	***Analytical and experimental critical function and/or characteristic proof-of-concept***	
4	Component and/or breadboard validation in laboratory environment	Focused Technology
5	Component and/or breadboard validation in relevant environment	
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	

Fig. 2. SRP Technology Readiness Levels (currently at approximately TRL 3) [6].

2. State of the Art

Initial development of SRP as an EDL technology was completed through exploratory investigations in the 1960s and 1970s. This early work focused on sub-scale wind tunnel testing for the development of an all-propulsive Mars lander configuration [4]. Much of the data were presented as a function of the *thrust coefficient*:

$$C_T = T / \tfrac{1}{2}\rho_\infty V^2_\infty S_{ref} \qquad (1)$$

where T is the SRP nozzle thrust, ρ_∞ and V_∞ are the freestream density and velocity, and S_{ref} is the aerodynamic reference area. The total effective deceleration of an aerodynamic decelerator with SRP is due to the sum of the aerodynamic drag and C_T:

$$C_{D,Total} = C_{D,Aero} + C_T \qquad (2)$$

Previous wind tunnel tests indicated that at C_T levels of ~1 from a single, central jet, the first term on the right side of Eq. (2) vanishes as a result of the SRP flowfield structure shielding the forebody from the freestream flow, thus reducing the surface pressures that contribute to aerodynamic drag. For human-scale EDL systems, C_T levels are expected to be much greater than one [2, 3], so the deceleration is expected to be completely from propulsive forces. The effect of SRP propulsive forces on a full-scale EDL system's stability and controllability is one area in need of further investigation in future technology development efforts. See [4] for a thorough review of past SRP wind tunnel tests, including the test depicted in Fig. 3. The selection and further development of a supersonic parachute for the Mars Viking landers (and all subsequent robotic Mars missions) effectively ended SRP development efforts in the 1970s.

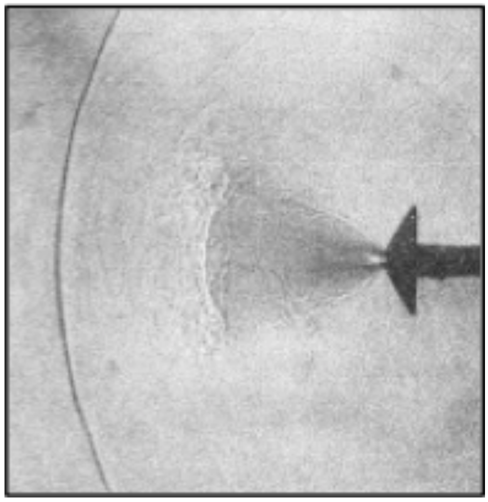

Fig. 3. Wind tunnel testing of a single air jet against a Mach 1.5 freestream [7].

The knowledge base for SRP has recently expanded since interest in high-mass missions to Mars resurfaced in the late-2000s [4, 5]. The potential for SRP to substantially increase landed mass capability at Mars resulted in SRP investment through NASA's EDL Systems Analysis [2, 3] efforts (EDL-SA) and EDL Technology Development Project (EDL-TDP). Both projects advanced the state-of-the-art for SRP in systems analysis, computational fluid dynamics (CFD), and experimental testing. Achievements in these areas represent a preliminary step in addressing the challenges faced in maturing SRP from its current status to a technology with sufficient performance and acceptable risk for Mars EDL.

3. Recent Work

Recent studies by the EDL-SA team demonstrated the potential benefits of SRP for large-scale Mars payload delivery [2, 3]. The baseline architecture was a rigid aeroshell capable of a mid-level lift-to-drag ratio (mid-L/D) at hypersonic Mach numbers (e. g. MSL L/D = 0.24) followed by SRP for supersonic deceleration. Fig. 4 shows a diagram of the EDL sequence for this architecture with notional configurations. The SRP system was required to have 1.8 MN of available thrust to meet the performance requirements. The SRP architecture scored higher than those with inflatable aerodynamic decelerators in the areas of complexity and perceived risk, but additional work is needed to make informed decisions about future investments as these technologies mature.

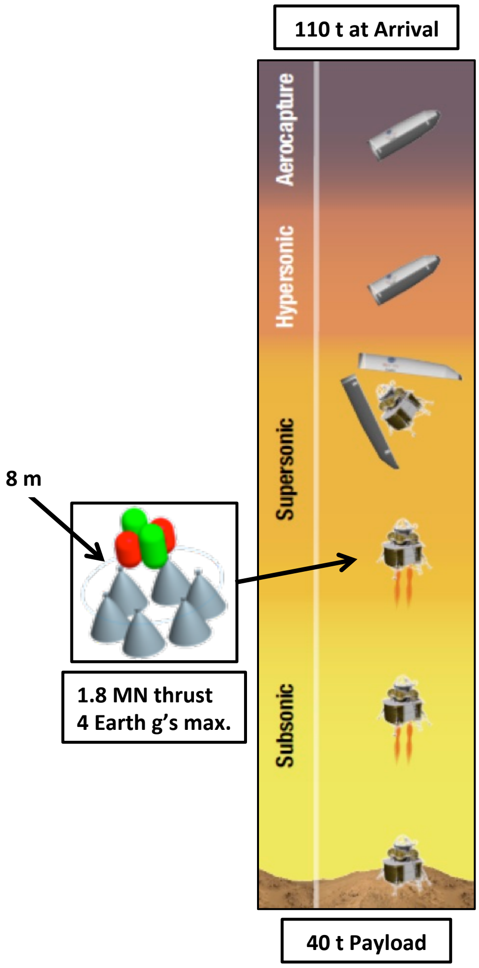

Fig. 4. EDL architecture with SRP (40-t payload) [2].

4. SRP in NASA's EDL Project (2009 to 2011)

The SRP element of the EDL-TDP was started in 2009 to begin addressing technology gaps for SRP [5]. The project proceeded over the course of two years to make significant progress in addressing those gaps through both ground testing and analysis, including:

- Completed a SRP technology roadmap (through TRL 6) [5]
- Conducted the first modern SRP wind tunnel test program (designed specifically for CFD validation) since the early 1970s [9-11]
- Completed the first known uncertainty quantification of NASA wind tunnel test data using Design of Experiments (DOE) methods [12]
- Calibrated industry-standard CFD codes against wind tunnel data and provided lessons learned for grid requirements, turbulence modelling, unsteady solution advancement, and verification & validation [13-16]
- Completed a preliminary analysis (mass, packaging, engine options, concept of operations) for an initial Earth-atmosphere sounding rocket SRP flight test [17]

The following sections describe in more detail the EDL-TDP's major accomplishments and recommendations for future work.

5. Technology Roadmapping

One of the first tasks for the EDL-TDP was to outline roadmaps for the maturation of various EDL technologies, including SRP. The objectives of this task for SRP were to [5]:

- Identify the major component SRP technologies in need of maturation
- Assess the current technical maturity of SRP using NASA guidelines
- Determine the experimental and analytical achievements needed to mature SRP into a viable decelerator technology
- Specify metrics by which to measure the technical advancement of SRP
- Develop a technology maturation schedule

The roadmap also identified the anticipated technical challenges for different component areas of SRP, including propulsion, aerodynamics, guidance and control, ground testing, and flight demonstration. The end product was a six-year schedule with major milestones addressing the challenges in each area, either through ground testing or computational analysis. The first few years in this schedule are focused on ground testing in wind tunnels to investigate SRP fluid dynamics, which the EDL-TDP began addressing, and testing of hot engines in a wind tunnel to demonstrate ignition and operation. Parallel tasks are focused on maturing all models needed to run high-fidelity EDL trajectory simulations, which require models for SRP engine performance, mass, packaging, and aerodynamics. Work on an initial flight test at Earth is initiated in the second year, with launch in the sixth year to reach TRL 6. See [5] for a detailed discussion of the roadmap and recommendations.

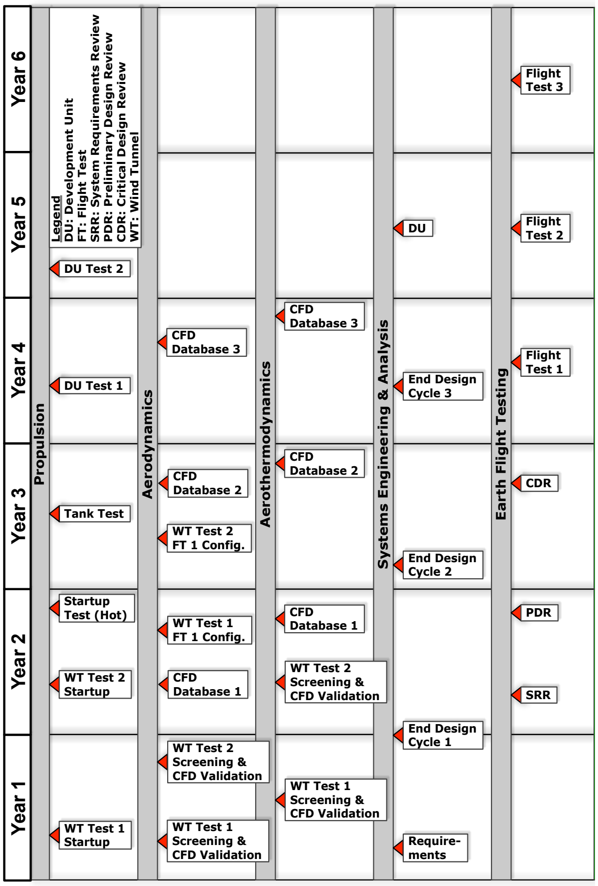

Fig. 5. SRP Technology Roadmap from TRL ~2-3 to TRL 6 [5].

6. Wind Tunnel Testing

Wind tunnel testing from the 1960s and 1970s identified some of the basic fluid dynamics features and aerodynamic trends for SRP in a laboratory environment. However, no continuous test program was ever established in order to anchor the analytical methods needed to predict full-scale system performance [4]. The EDL-TDP made it a priority to conduct wind tunnel tests with densely instrumented models to provide sufficient data to begin evaluating the prediction capabilities of CFD codes for SRP.

The EDL-TDP conducted SRP tests [9-12] in two of NASA's supersonic wind tunnels: the Langley 4-Foot by 4-Foot Unitary Plan Wind Tunnel and the Ames 9-Foot by 7-Foot Supersonic Wind Tunnel. The same model was tested in each tunnel using high-pressure air as the SRP exhaust simulant (Fig. 6). The Langley test also included provisions to estimate the uncertainty in the recorded surface pressure measurements [12].

The test data served two purposes: (1) to better understand the general characteristics of SRP fluid dynamics for a range of thrust coefficients and jet count, and (2) to provide data against which CFD codes can be validated. The test matrix and data products were as follows:

- 5-in diameter model
- 0-4 jets with high-pressure air
- Freestream Mach number (M_∞) = 1.8 to 4.6
- Angle of attack (α) = -8 to +20 deg
- $C_{T,total}$ = 0 to ~10
- 167 ESP surface pressure ports (118 on forebody, 49 on aftbody), 7 Kulite high-frequency pressure ports (forebody only)
- High-speed video (up to 20,000 frames per second)

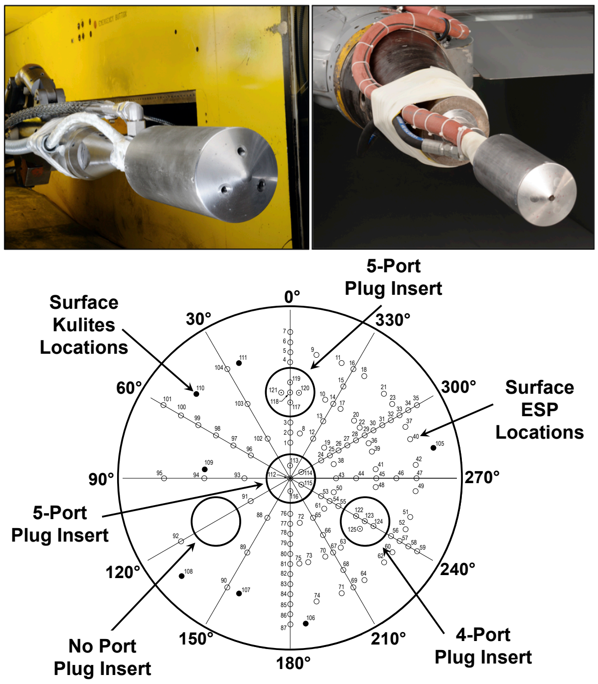

Fig. 6. SRP model in the NASA Langley 4x4-Foot (top left) and Ames 9x7-Foot (top right) supersonic wind tunnels. Nozzle and forebody surface pressure instrumentation layout (bottom) [9-12].

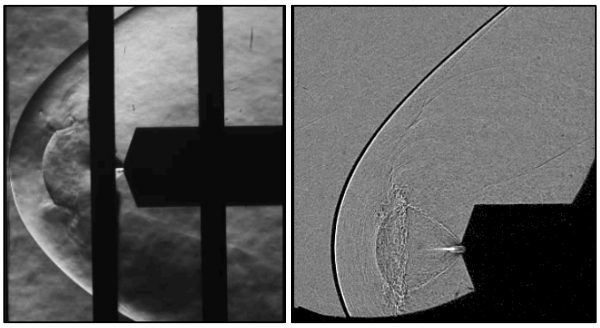

Fig. 7. Flowfield images from the NASA Langley (left, Mach 4.6) and NASA Ames (right, Mach 2.4) wind tunnel tests (one jet, $C_T = 2$, $\alpha = 0$) [9-11].

The completed test campaign was exploratory in nature and was focused on providing CFD validation data for a limited range of configurations. Future work is recommended to expand the experimental database to include additional configurations (nozzle size and placement) that are more representative of Mars configurations, either for precursor or human missions, and Earth flight test geometries. For example, the SRP configuration in Fig. 4 shows nozzles that cover the majority of the vehicle base, with little aerodynamic surface. Also, tests with direct force and moment measurement would also be extremely valuable to better understand the effects of unsteady SRP fluid dynamics on entry vehicle stability and controllability.

7. Computational Fluid Dynamics Modelling

One of the primary purposes of SRP wind tunnel testing was to provide data against which Navier-Stokes CFD codes can be validated for SRP applications. Design of full-scale Mars EDL systems with SRP will depend on CFD methods to predict the aerodynamic and aerothermodynamic effects on the entry vehicle during the SRP deceleration phase.

The EDL-TDP started the process of anchoring NASA-developed CFD codes for SRP using the wind tunnel data from the two tests described in Section 6. To date, the computational work has been primarily accomplished using three codes: Data Parallel Line Relaxation (DPLR, structured), Fully Unstructured Navier-Stokes Three-Dimensional (FUN3D, unstructured), and the OVERset grid FLOW solver (OVERFLOW, overset structured). The codes have been compared to surface pressure data and high-speed video from each of the tests for select cases in order to ascertain their ability to capture the flowfield structure (steady and unsteady) and match the recorded surface pressure data [13-16]. Thus far, the codes have been able to capture the primary fluid dynamic structures across the range of C_T values tested.

One of the first cases examined using each code was a single-jet case from the NASA Langley wind tunnel test at Mach 4.6 freestream conditions (Fig. 8). Each code was able to reproduce the general shape of the SRP jet structure, as well as capture the frequency of the vortex shedding from the intersection of the shock structures in the jet. The predictions for forebody surface pressure are shown in Fig. 9, with each code also capturing the qualitative distribution and demonstrating varying degrees of quantitative agreement. Subsequent CFD cases from the two NASA wind tunnel tests have also shown promising results for each code across a range of nozzle configurations and thrust coefficients.

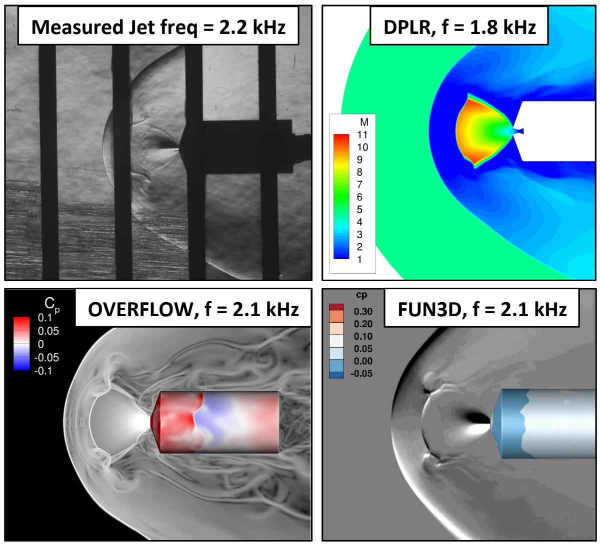

Fig. 8. Schlieren image and CFD flowfields from Run 165 in the NASA Langley tunnel at Mach 4.6 (one jet, $C_T = 2$, $\alpha = 0$) [13]. The frequency of the jet vortex shedding is noted in each frame [9-11].

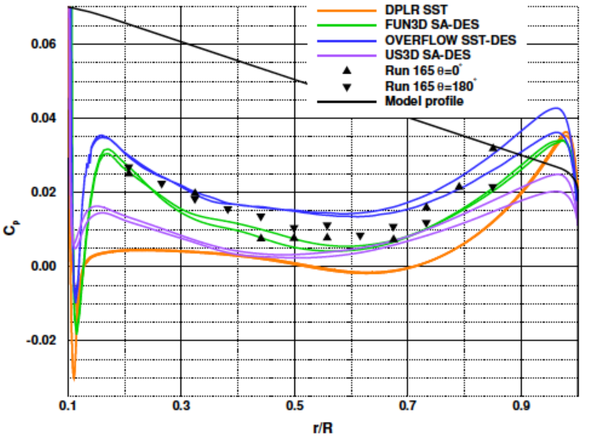

Fig. 9. Forebody surface pressure data and CFD predictions from Run 165 in the NASA Langley wind tunnel at Mach 4.6 (one jet, C_T = 2, α = 0) [14]. Nozzle lip is located at r/R = 0.1.

Future advancement of CFD for SRP would involve more comparisons to the available wind tunnel test data across a larger range of thrust coefficients and at non-zero angle of attack. Additional unsteadiness modelling would be warranted since it appears to be driven by differences in numerical dissipation schemes employed in the various codes. One method of understanding this effect would be to refine the grids and determine the change in unsteadiness. A second method would be to apply a "low dissipation" scheme i. e. laminar solution, to inform the effect of turbulence modelling on the level of unsteadiness. Also, the use of common grids and turbulence models would help understand code-to-code difference. Finally, wind tunnel tests with direct force and moment measurements would provide additional data for CFD validation with respect to SRP fluid dynamics.

8. Earth Flight Test Concept

A prototype SRP system must be demonstrated in a relevant operating environment to reach sufficient technical maturity per TRL guidelines (i.e. satisfy TRL 6) and be ready for implementation on a Mars mission. The EDL-TDP developed a concept for such an initial flight test using a sounding rocket platform [17]. It is expected that, depending on the scale of an eventual Mars precursor mission, more than one SRP flight test will be necessary to sufficiently show as-predicted performance and to reduce risks to a satisfactory level.

The objectives of the study were to: (1) determine if a typical sounding rocket trajectory is a viable option for an initial fight test; (2) select potential options for the SRP propulsion system; and (3) begin notional packaging of the engine and propellant tank(s) into a sounding rocket payload envelope. The constraints imposed were a minimum C_T of 5 and SRP initiation at Mach 3.5. The launch vehicle selected was the Terrier-Improved Orion rocket with a 17-in payload diameter. The concept of operations is shown in Fig. 10.

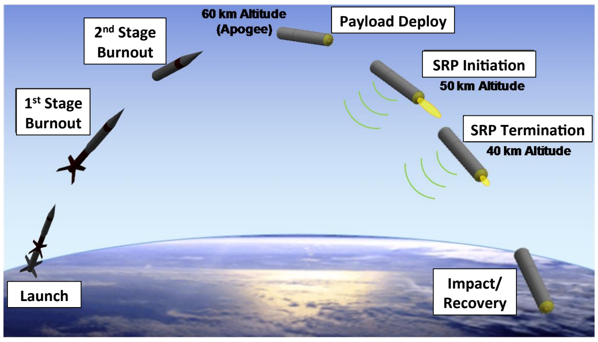

Fig. 10. Concept of operations for an initial sounding rocket SRP flight test [17].

In the course of the analysis, it was determined that a sounding rocket platform appears to provide the necessary conditions for the test. Several engine and propellant options were identified, all using off-the-shelf hardware. These options ranged from pressure-fed and blow-down liquid propellant systems to solid rocket motors (SRM). Each of the engine and propellant tank systems were packaged into the Terrier-Improved Orion payload bay, with the test article length strongly dependent on the amount of required propellant. Fig. 11 illustrates the packaging of each system within the sounding rocket, as well as the general layout of the test article.

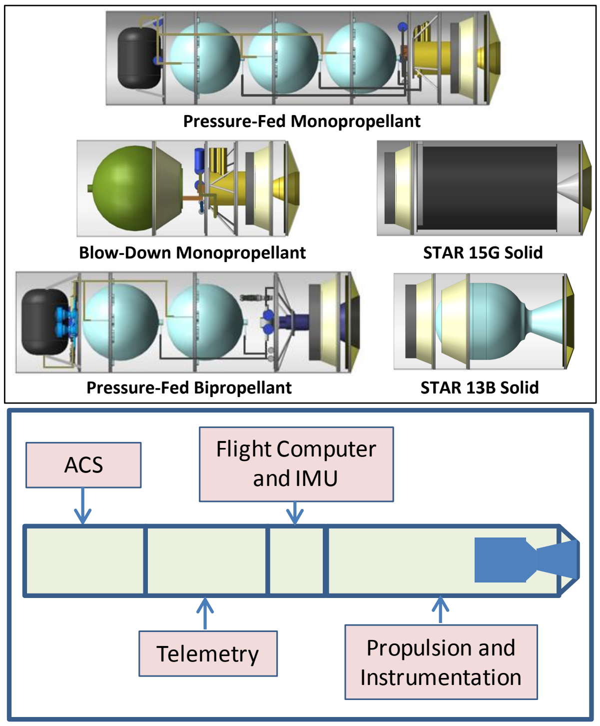

Fig. 11. Engine/propellant packaging (top) and test article layout (bottom) [17].

Work remains to develop the sounding rocket flight test concept to a level suitable for proposal. Complete test requirements must be written to define specific test objectives, including success criteria, on-board instrumentation, and data telemetry. Additionally, trades of the required engine performance, test duration, and initiation and operating conditions must be completed to down-select engines or identify other candidate SRP propulsion systems. The trades will need to be supported by high-fidelity trajectory simulation tools with mature SRP performance, mass properties, packaging, and aerodynamics models. One area that would need to be addressed is whether passive or active methods are needed to stabilize and control the entry vehicle during SRP, given that the initial geometries are fairly slender with unknown mass properties and stability characteristics.

This proof-of-concept flight test has been defined by the SRP technology roadmap to be the first of a series of three, progressively integrated and complex flight tests [5]. The investments recommended in Sections 5 – 7, including prototype propulsion hardware development, all support the design and execution of the flight testing required to mature SRP to TRL 6.

9. Summary and Recommendations

Mars EDL systems based on those used for the Viking missions in the 1970s (blunt aeroshell and supersonic parachute) are nearing their physical limits for landed payload mass with the upcoming Mars Science Laboratory mission (landing in August 2012, ~1 metric ton payload). Consequently, NASA is investing in revolutionary entry system technologies that will enable future robotic and human exploration of Mars (payloads up to 10s of metric tons), improved landing accuracy, and higher landing site altitudes. Supersonic Retropropulsion (SRP) is one deceleration technology viewed by NASA as beneficial for advanced robotic missions and as enabling for human-scale missions to the surface of Mars.

NASA's renewed interest in SRP led to initial investments focusing on performance requirements and parametric sizing analyses that demonstrate the potential benefits of SRP for human-scale payloads. Through the EDL Technology Development Program, definitions were developed for how best to advance the various SRP technology components (propulsion, aerodynamics/aerothermodynamics, flight mechanics, integrated vehicle engineering/analysis) beyond their current state and how to demonstrate prototype system performance through Earth-based flight tests. Towards these goals, the EDL-TDP team has identified analytical and experimental achievement criteria for SRP based on NASA guidelines for technology maturation. Technologies requiring significant investment and technical advancement for SRP include: high-thrust engines (100s of kN) capable of starting and throttling against a supersonic flow, CFD tools for predicting aerodynamics and aerothermodynamics validated with wind tunnel data, algorithms for maintaining entry vehicle stability and control, entry vehicle design (packaging, structural, thermal), and trajectory simulations. Significant improvements in modelling capabilities, especially in the area of aerodynamic-propulsive interactions, will be needed to predict full-scale vehicle performance and demonstrate acceptable margins with confidence.

Multiple ground test campaigns will be needed to demonstrate the required engine performance and provide additional data for CFD and aerodynamics model validation. In order to begin SRP flight demonstrations at Mars in the next 10 years, it is recommended that NASA begin investing now in engine tests to demonstrate acceptable performance in a supersonic opposing flow and sub-scale wind tunnel tests to provide additional data for CFD validation exercises across a range of parameters (operating conditions, thrust coefficient) and flight-relevant configurations. An integrated vehicle level analysis will be needed to define the expected SRP operating conditions and demonstrate acceptable margins, in parallel with the CFD and ground testing. Finally, a series of Earth-based flight tests is needed to advance SRP to a level where the risks are acceptably reduced and system performance is demonstrated to be scalable to Mars conditions as predicted by validated models. The expectation is that the final flight test at Earth will incorporate multiple SRP engines and a closed-loop control system on an entry vehicle of sufficient scale that performs in conditions of relevance to those at Mars. Proposals for a flight test program must be developed to determine the investment level needed for accelerated development of SRP for robotic-scale Mars missions.

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