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Development of Supersonic Retropropulsion for Future Mars Entry, Descent, and Landing Systems

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Recent studies have concluded that Viking-era entry system deceleration technologies are extremely difficult to scale for progressively larger payloads (tens of metric tons) required for human Mars exploration. Supersonic retropropulsion is one of a few developing technologies that may enable future human-scale Mars entry systems. However, in order to be considered as a viable technology for future missions, supersonic retropropulsion will require significant maturation beyond its current state. This paper proposes major milestones for advancing the component technologies of supersonic retropropulsion such that it can be reliably used on Mars technology demonstration missions to land larger payloads than are currently possible using Viking-based systems. The development roadmap includes technology gates that are achieved through ground-based testing and high-fidelity analysis, culminating with subscale flight testing in Earth's atmosphere that demonstrates stable and controlled flight. The component technologies requiring advancement include large engines (100s of kilonewtons of thrust) capable of throttling and gimbaling, entry vehicle aerodynamics and aerothermodynamics modeling, entry vehicle stability and control methods, reference vehicle systems engineering and analyses, and high-fidelity models for entry trajectory simulations. Finally, a notional schedule is proposed for advancing the technology from suborbital free-flight tests at Earth through larger and more complex system-level technology demonstrations and precursor missions at Mars.

Nomenclature

A	=	reference area, m^2
C_D	=	aerodynamic drag coefficient; $D/q_\infty A$
C_T	=	engine thrust coefficient; $T/q_\infty A$
L/D	=	lift-to-drag ratio
M	=	Mach number
m	=	mass, t
$m/C_D A$	=	ballistic coefficient, kg/m^2
q_∞	=	freestream dynamic pressure; $\rho_\infty V_\infty^2/2$, Pa
T	=	engine thrust, N
V_∞	=	freestream velocity, m/s
ρ_∞	=	freestream density, kg/m^3

I. Introduction

STARTING with the two Viking landers in 1976 and continuing through the successful Mars Science Laboratory [1] (MSL) landing in 2012, NASA and its partners have used similar entry, descent, and landing (EDL) system architectures with evolutionary improvements to deliver robotic science payloads to the surface of Mars. This architecture is based on a rigid blunt-body aeroshell (spherically blunted, 70 deg half-angle cone), a supersonic disk–gap–band parachute, and a subsonic propulsive descent system used in sequence to decelerate the payload in the thin Martian atmosphere. Viking-based systems have delivered robotic payloads to the Martian surface from both orbit (Viking) and direct entry (Mars Pathfinder, Mars Exploration Rovers, Mars Phoenix, and MSL). Table 1 summarizes previous Mars EDL systems developed by the United States that have successfully delivered robotic payloads to the surface of Mars, all of which were less than 1 metric ton (*t*). The MSL system (Fig. 1) used the largest aeroshell (4.5 m diameter), the largest supersonic parachute (21.5 m diameter), a high parachute deployment Mach number (1.7), and the highest aerodynamic lift-to-drag ratio ($L/D = 0.24$) ever attempted at Mars in order to land a 0.9 t rover within 10 km of the targeted landing site. Only minor improvements in landed mass and accuracy beyond MSL are believed to be possible using the same entry system architecture [2].

NASA's long-term Mars human exploration goals will require significant entry system improvements beyond MSL: at least an order of magnitude increase in payload mass (10s of metric tons), four orders of magnitude improvement in landing accuracy (meters), and the capability to land at higher altitudes to reach scientifically interesting sites [2]. The ability of Viking-based entry systems to deliver payloads larger than MSL with higher precision is reaching a practical limit. This limit is largely due to physical constraints on parachute size and materials, deteriorating drag performance at

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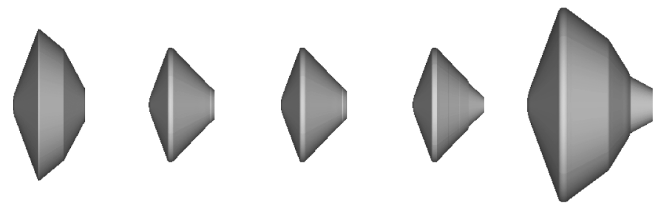
Table 1 Comparison of Mars Viking-based EDL systems [2]

	Viking 1 and 2 (1976)	Pathfinder (1997)	Mars Exploration Rovers (2004)	Phoenix (2007)	MSL (2012)
Aeroshell (to scale)					
Entry type	From orbit	Direct	Direct	Direct	Direct
Aeroshell diameter, m	3.5	2.65	2.65	2.65	4.5
Entry mass, t	0.99	0.58	0.83	0.60	3.15
Ballistic coefficient, kg/m^2	64	63	94	70	135
Relative entry velocity, km/s	4.5	7.6	5.5	5.5	5.9
Hypersonic L/D	0.18	0	0	0	0.24
Parachute diameter, m	16	12.5	14	11.7	21.5
Parachute deployment Mach number	1.1	1.57	1.77	1.65	1.7
Total landed mass, t	0.590	0.360	0.539	0.364	1.7
Lander or rover mass, t	0.244	0.092	0.173	0.167	0.9
Landing site elevation, km	−3.5	−2.5	−1.9/ − 1.4	−3.5	−1.45

increasingly higher deployment Mach numbers, and requirements that exceed the existing flight qualification envelope for both parachute size and deployment conditions. As a result, alternative EDL technologies are needed to enable delivery of the larger payloads needed for human (and advanced robotic) exploration of Mars. A recent study [3] by NASA's EDL Systems Analysis (EDL-SA) team recommended investment in new EDL technologies that include methods for improving entry system performance beyond that possible using Viking-era methods: 1) deployable/inflatable aerodynamic decelerators that reduce ballistic coefficient ($m/C_D A$) via larger cross-sectional area and higher drag coefficient as compared to parachutes; 2) rigid aeroshell shapes that improve L/D; and 3) propulsive deceleration during a larger portion of the EDL trajectory (i.e., supersonic conditions), or supersonic retropropulsion (SRP). NASA's Space Technology Roadmap for EDL [4] specifically mentions SRP as a technology in need of further development to meet long-term Mars exploration goals: "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."

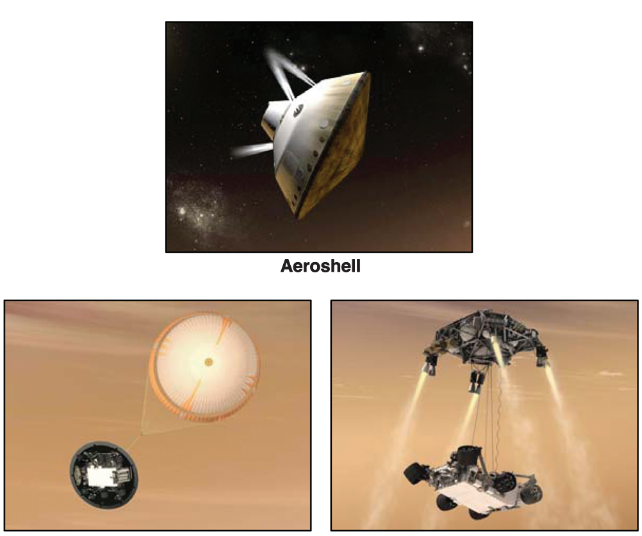


Fig. 1 Mars Science Laboratory EDL system.

As the name implies, SRP involves initiating propulsive deceleration at supersonic Mach numbers by directing engine exhaust into the oncoming freestream flow. The complexity of the interaction between the supersonic freestream and the retropropulsion exhaust flow is illustrated notionally in Fig. 2 for a single SRP jet [5]. For the case shown, the supersonic jet plume terminates in a shock behind the main bow shock, with a contact surface separating the two postshock flows. The location and existence of these features are largely a function of the difference in momentum between the freestream and jet flows. The total effective drag coefficient ($C_{D,\mathrm{total}} = F_{\mathrm{total}}/q_\infty A$, where q_∞ is freestream dynamic pressure and A is reference area) using a system such as that shown in Fig. 2 is derived from the aeroshell's aerodynamic drag ($C_D = D/q_\infty A$) and a propulsive "drag" component provided by the engines (thrust coefficient, $C_T = T/q_\infty A$):

$$C_{D,\mathrm{total}} = C_D + C_T \tag{1}$$

Depending on the entry system mass and deceleration requirements, especially for human-scale payloads, the thrust term in the

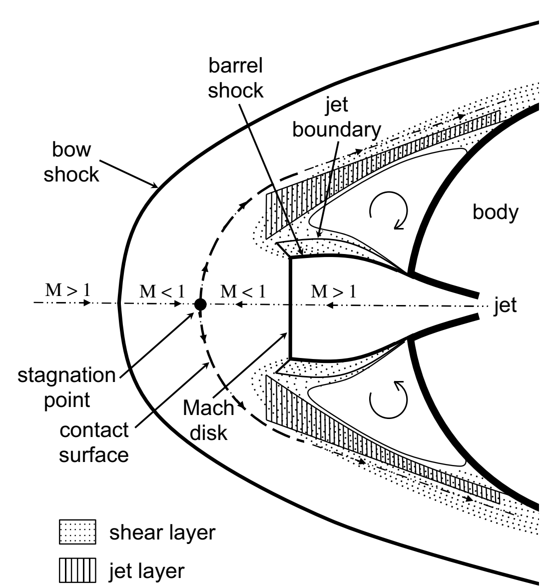


Fig. 2 Interaction between supersonic freestream and exhaust from a single SRP jet [5].

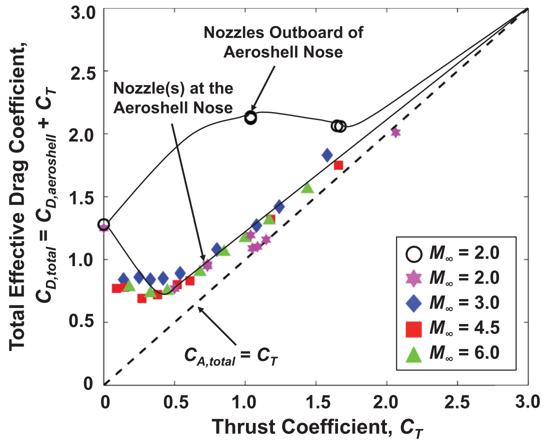


Fig. 3 Experimental wind tunnel data for total effective drag coefficient.

preceding equation is often the dominant contributor to the total effective deceleration. The EDL-SA team considered SRP systems that delivered minimum thrust coefficients above 10, which far exceed the typical blunt-body drag coefficient of about 1.7 at low angles of attack. Previous wind-tunnel studies suggest that the use of retrorockets can at best maintain the native aerodynamic drag of the aeroshell and at worst reduce the aerodynamic drag to nearly zero, depending on the retrorocket configuration and thrust level [6]. In the case where aerodynamic drag is eliminated or is small relative to the propulsive drag term, the total entry vehicle deceleration comes from the engine thrust alone. These trends are illustrated from experimental wind-tunnel data in Fig. 3 [7]. These studies also suggest the latter case (dominant propulsive drag) to be more relevant for flight systems of the scale required for human Mars exploration.

Figure 4 illustrates notional EDL system architectures that were studied by NASA's EDL-SA team [3]. Each architecture contains a sequence of deceleration methods for delivering a human-scale payload (40 t) to the surface of Mars using technologies that have never been flown or demonstrated at the required scale. Architecture 1 was adopted from previous studies as part of the Mars Design Reference Architecture 5.0 (DRA5) [8]. That architecture consists of a rigid, slender aeroshell with improved L/D used for aerocapture and hypersonic deceleration, followed by a SRP phase ending at terminal descent. Three of the remaining seven architectures (2, 3, and 4) also include a SRP phase. The EDL-SA team ranked architecture 1 highest using metrics for safety, performance, and development path. The EDL-SA team completed a parametric SRP sizing and performance analysis to estimate mass fraction and thrust requirements for a 40 t payload scenario. The baseline propulsion system baseline for the EDL-SA study was derived from DRA5 and adjusted to satisfy mission objectives: 1) six liquid oxygen, liquid methane (LO_2/LCH_4) engines, each delivering a maximum thrust of 300 kN; 2) engines capable of throttling down to 20% of full thrust; and 3) two propellant tanks each for the LO_2 (9300 kg total, 8.2 m^3 per tank) and LCH_4 (2670 kg total, 6.1 m^3 per tank).

Given the demonstrated benefits of SRP in the EDL-SA architectures, the study recommended further investment by NASA to begin the maturation of SRP into a viable decelerator technology.

NASA subsequently formed a team within the Exploration Technology Development and Demonstration (ETDD) Program to focus its efforts solely on SRP development for human-scale Mars EDL. Given the desire to advance the technical maturity of SRP, the first task was to construct a high-level SRP technology development roadmap with the following objectives:

1) Assess the current technical maturity of SRP using NASA guidelines.

2) Identify the major component SRP technologies in need of maturation.

3) Determine experimental and analytical achievement gates that are needed to mature SRP into a viable decelerator technology.

4) Develop a notional technology roadmap through Earth-based flight testing in preparation for larger and more complex flight demonstration and qualification programs.

This paper serves two purposes. First, it begins to address the steps needed to mature SRP toward the level needed for human-scale Mars EDL missions. Second, it serves as an introduction to the recent work performed by the ETDD team and others [9–18] toward addressing some of the aforementioned objectives. In addition to this roadmapping effort, the ETDD team also focused its efforts on wind-tunnel testing and computational modeling of SRP fluid dynamics, as well as conceptual design of an Earth-based free-flight test.

The concept of supersonic retropropulsion for Mars EDL predates the Viking missions. A focused technology development effort in the 1960s and 1970s developed SRP to nearly the level of maturity the concept had at the start of the ETDD activities. The eventual selection of a supersonic parachute system and subsonic propulsive terminal descent phase for the Viking landers ended much of the research efforts to develop SRP [7]. Interest in SRP as a supersonic decelerator has resurfaced to address performance gaps in EDL technologies for future missions. Efforts to define requirements and architectures for advanced robotic and human Mars exploration [2,3,5] have identified

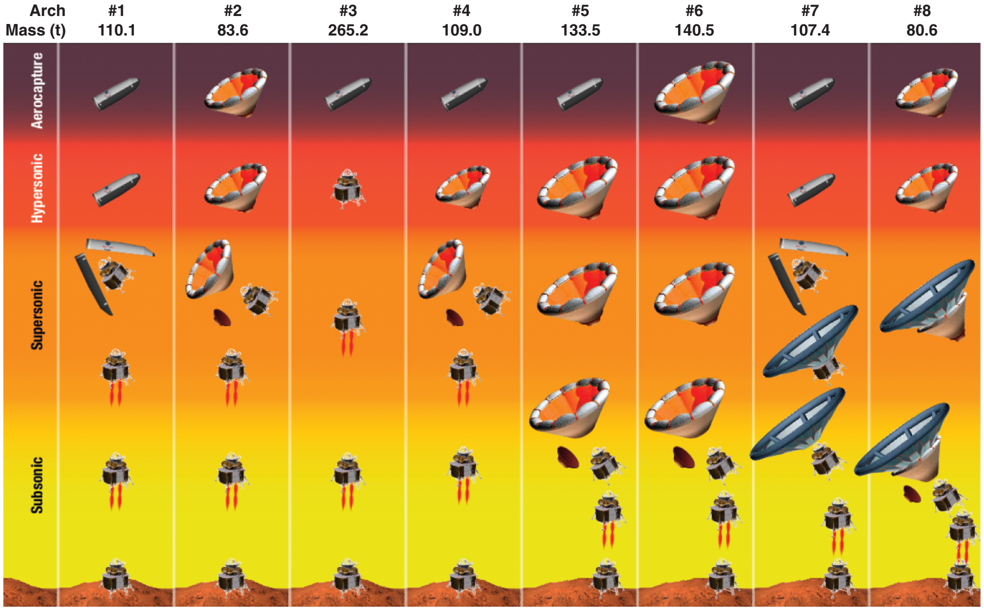


Fig. 4 Architectures for human-scale Mars exploration (arrival mass for 40 t payload).

SRP as a potentially enabling EDL technology, and development efforts within EDL-SA and ETDD teams resumed from where original investigations left off more than 30 years prior.

A substantial number of SRP wind-tunnel tests were completed in the 1960s and early 1970s using small-scale models of blunt bodies with retropropulsion nozzles [7]. The intent of those tests was to understand effects arising from interactions with nozzle thrust that could be potentially advantageous for EDL. While the test conditions and vehicle configurations were limited, the tests demonstrated that SRP aerodynamic/propulsive fluid dynamic interactions significantly alter the aerodynamic characteristics of the vehicle and fundamentally differ from subsonic terminal propulsion. Retropropulsion configuration and thrust coefficient were found to drive the degree of change in the vehicle's aerodynamic characteristics. Simple analytical models were developed from experimental trends, and these models were then used to size and scale SRP systems for prototypical Mars landers [7].

Current objectives of using SRP for advanced robotic and human missions differ in physical scale from those when the concept of SRP was originally formulated. However, extensible trends in static aerodynamics as a function of retropropulsion configuration, freestream conditions, and thrust have been established from this historical work. These trends have been integrated into recent studies [3,19,20] and bounds on SRP initiating and operating conditions, system sizing, and performance have been determined. These studies have demonstrated the potential of SRP technology to increase landed mass at Mars and motivated efforts to increase the fidelity of SRP models through the construction of aerodynamic databases with computational fluid dynamics (CFD) tools.

The significant period of inactivity in SRP development resulted in little published work on CFD simulation of SRP flowfields. Much of the existing work is focused on reducing the overall drag of the vehicle or the severity of the aerothermal environment, rather than augmenting the total effective drag of the vehicle through retropropulsion [7]. However, the similarities between the aerodynamic/propulsive interactions across existing work and SRP flowfields have been useful in extending computational approaches to the SRP problem. CFD analyses that accurately capture SRP aerodynamic/propulsive interactions exist under a very limited range of conditions, and the difficulty in generating a relevant aerodynamic database for systems analysis remains a challenge to maturing SRP technology.

The current maturity of SRP aerodynamics is limited by the existing experimental database. Historical work is limited in terms of retropropulsion configurations, flight-relevant freestream and thrust conditions, and uncertainty in collected data [7]. Additionally, no historical information has been found on the startup of a high-thrust propulsion system directly opposing supersonic flow, controllability of vehicles using SRP, subscale flight testing, or the integration of an SRP system into an EDL architecture. Despite these limitations, the current state-of-the-art for SRP technology includes: 1) systems analysis of integrated vehicles using SRP with experimentally derived models for aerodynamic/propulsive interactions; 2) wind-tunnel testing using cold-gas SRP exhaust simulants to examine aerodynamic/propulsive interactions; and 3) CFD solutions of SRP flowfields anchored to cold-gas wind-tunnel data.

The fidelity of testing and analysis must continue to improve in order to advance SRP beyond the laboratory stage of development. The identification of SRP as a technology with the potential to improve EDL system performance beyond that achievable with Viking-heritage systems has been strongly dependent upon knowledge gained from historical SRP development efforts. The ETDD team partially addressed some of the shortcomings in the current knowledge base, but much work remains for SRP to be considered as a viable decelerator technology option for future flight projects. The following sections discuss how SRP can move beyond reliance on historical efforts and how the ETDD team began this process.

II. Technology Development Roadmap

The SRP development roadmap presented here is framed around the advancement of all necessary component technologies and an integrated system using NASA guidelines for measuring technology maturation. NASA's technology readiness level (TRL) [21] scale defines progressive levels of technical maturation, from observation of basic principles (TRL 1) through successful application on a spaceflight mission (TRL 9). Table 2 shows the TRL definitions and descriptions (1 through 6) considered by NASA to be critical for technology advancement. NASA uses TRLs as one method of determining the readiness of a technology for its intended purpose and guiding decisions about funding and risk assessment. To be considered sufficiently mature for incorporation into a NASA flight project, a technology often must first achieve TRL 6, defined as "System/subsystem model or prototype demonstration in a relevant environment (ground or space)," by the project preliminary design review. Achieving TRL 6 would involve the successful testing of a subscale prototype system in Earth's atmosphere as a means to validate and qualify the system for use on a precursor mission at Mars. If SRP is to be used for human exploration missions, robotic precursors at Mars will undoubtedly be required to demonstrate

Table 2 NASA technology readiness levels [21] (1 through 6 shown)

TRL	Definition	Description
1	Basic principles observed and reported	This is the lowest "level" of technology maturation. At this level, scientific research begins to be translated into applied research and development.
2	Technology concept and/or application formulated	Once basic physical principles are observed, then at the next level of maturation, practical applications of those characteristics can be "invented" or identified. At this level, the application is still speculative: there is not experimental proof or detailed analysis to support the conjecture.
3	Analytical and experimental critical function and/or characteristic proof of concept	At this step in the maturation process, active research and development (R&D) is initiated. This must include both analytical studies to set the technology into an appropriate context and laboratory-based studies to physically validate that the analytical predictions are correct. These studies and experiments should constitute "proof-of-concept" validation of the applications/concepts formulated at TRL 2.
4	Component and/or breadboard validation in laboratory environment	Following successful proof-of-concept work, basic technological elements must be integrated to establish that the "pieces" will work together to achieve concept-enabling levels of performance for a component and/or breadboard. This validation must be devised to support the concept that was formulated earlier, and it should be consistent with the requirements of potential system applications. The validation is relatively "low fidelity" compared to the eventual system: it could be composed of ad hoc discrete components in a laboratory.
5	Component and/or breadboard validation in relevant environment	At this TRL, the fidelity of the component and/or breadboard being tested has to increase significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications (component level, subsystem level, or system level) can be tested in a "simulated" or somewhat realistic environment.
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	At TRL 6, a representative model or prototype system or system would be tested in a relevant environment. At this level, if the only "relevant environment" is the environment of space, then the model/prototype must be demonstrated in space. Of course, the demonstration should be successful to represent a true TRL 6. Not all technologies will undergo a TRL 6 demonstration: at this point, the maturation step is driven more by assuring management confidence than by R&D requirements.

successful operation in that environment. At that point, a flight project may take over the focused development and qualification of the technology for its specific purpose through space operations (TRL 9). The roadmap shown here is formulated to develop SRP to TRL 6 to facilitate adoption on a large robotic (greater than 1 t) flight demonstration at Mars. Significant additional development and risk reduction activities beyond what are shown here, and at higher scale and complexity, would be needed to advance SRP for human-scale use.

A. Component Technologies

The use of large engines directed into a supersonic flow opens up numerous technical challenges that have mostly been unaddressed at NASA. Advancement of a number of key technologies is considered to be critical to the maturation of SRP into a method for supersonic deceleration of large-scale entry vehicles. Interactions between the engine plumes, the freestream flow, and the entry vehicle present a number of challenges that will affect the technological advancement and practical application of SRP. These technical challenges, for the purpose of developing the roadmap, have been divided amongst the major components of a SRP system. Table 3 summarizes some of the major technical challenges foreseen in the areas of 1) propulsion; 2) aerodynamics and aerothermodynamics; 3) guidance, navigation, and control (GN&C); 4) systems engineering and analysis; and 5) ground/flight testing [22]. These challenges will need to be addressed and overcome for SRP to achieve TRL 6. Additional challenges are likely to arise as the maturation of SRP continues. The following section describes in more detail the approaches to address these challenges in each of the major technical areas listed in Table 3, along with the necessary advancements to achieve TRL 6.

As with any EDL technology, analytical models and tools will be an important aspect of the technical maturation of SRP. These models will be required to predict, among other things, engine performance, aerodynamic/propulsive interactions, aerothermal effects due to exhaust flow impingement, and structural and thermal loads, as well as simulate entry vehicle configuration and flight mechanics. Many of these models will be required to analytically assess EDL system performance through three-degree-of-freedom (3-DOF) and six-degree-of-freedom (6-DOF) entry trajectory simulations. The fidelity of the models that feed into the trajectory analyses must advance in TRL concurrently with the SRP hardware and must be validated using ground test data when available. ETDD started the process of identifying critical modeling needs for large-scale Mars EDL systems.

The advancement of analysis methods will require several ground-test campaigns in facilities that can achieve environments relevant to conditions expected at Mars. For example, in the case of wind-tunnel aerodynamics testing, relevant environments may mean matching the appropriate combinations of Mach number, jet pressure ratio, and angle of attack. The responsibility for bridging the gap between ground facility limitations and full-scale conditions, such as entry vehicle scale, will fall onto validated CFD tools. One of the primary goals for any of the planned tests, especially in the areas of aerodynamics and engine performance, will be to provide a database that can be used to validate analytical models for application to full-scale Mars conditions. One area that will require significant effort, specifically for SRP, will be the CFD prediction of aerodynamic and propulsive forces and moments that are imparted onto the entry vehicle. These forces and moments will affect both the entry system deceleration, as well as stability and controllability requirements.

Vehicle transitions are not addressed as a SRP technology in this paper. However, the complexity and difficulty of separating a SRP descent stage from a large aerodynamic decelerator at significant freestream dynamic pressure cannot be overstated. For all studies known to the authors, such as EDL-SA, no rigorous analysis has been

Table 3 Major SRP technical challenges

Technology (estimated TRL)	Major challenges	State of the art
Propulsion (TRL 2)	1) Developing large engines (hundreds of kilonewtons) capable of deep throttling 2) Demonstrating engine startup and throttling against supersonic flow 3) Developing methods for long-term cryogenic propellant storage	1) Conceptual engine and propellant tank sizing for a 40 t payload [3] 2) Small-scale engines (hundreds to thousands of newtons) 3) Analysis of long-term propellant storage in space
Aerodynamics and aerothermodynamics (TRL 3)	1) Predicting aerodynamics (static and dynamic forces and moments) and aerothermodynamics (surface heating) 2) Developing validated CFD tools needed to build aerodynamics and aerothermodynamics databases	1) Cold-gas wind-tunnel testing for various jet numbers, Mach numbers, thrust levels, and angles of attack 2) Navier–Stokes CFD solutions showing promising agreement with cold-gas wind-tunnel test data [13–18]
GN&C (TRL 2)	1) Developing algorithms and systems to control and stabilize the entry vehicle in the presence of complex fluid dynamic interactions	1) Simplified control via 3-DOF simulations [3]
Systems engineering and analysis (TRL 2)	1) Defining reference vehicle configurations 2) Configuring SRP engines on full-scale reference entry vehicles to satisfy the required system performance 3) Packaging the propulsion system within the EDL system's volume and mass constraints 4) Developing vehicle transitions before and after the SRP phase of EDL 5) Testing and computationally analyzing ground effects at touchdown 6) Developing and validating high-fidelity models (propulsion, flight mechanics, aerodynamics, aerothermodynamics, GN&C) required for integrated entry trajectory simulations	1) Conceptual vehicle, engine, and propellant tank sizing for a 40 t payload [3] 2) 3-DOF trajectory analysis demonstrating the benefits of SRP
Ground testing (TRL 3)	1) Testing in ground facilities that can achieve relevant environments for engine, aerodynamics, and aerothermodynamics experiments 2) Providing a database for validation of analytical methods (e.g., CFD)	1) Wind-tunnel testing [9–12] 2) Small-scale engine testing 3) Conceptual design of a hot-fire engine test (see next)
Flight testing (TRL 1)	1) Completing stable and controlled instrumented flight tests with as-predicted performance at sufficient scale and complexity to reduce risks for the desired mission infusion scale	1) Conceptual design of suborbital Earth free-flight tests [22]

completed to define how a rigid or flexible aeroshell could be safely separated from the descent stage in a timely manner such that the SRP phase could start without losing excessive altitude. For the EDL-SA studies, a 10–20 s freefall was used as a placeholder for the transition event, depending on the type of aerodynamic decelerator [3]. As reference missions and vehicles are better defined in future studies, more attention should be given to define the sequence of events during transition, to identify the necessary separation mechanisms, and to determine the range of allowable initial conditions (i.e., vehicle attitudes and attitude rates) for the SRP phase. Transition development will undoubtedly require a combination of high-fidelity analyses and tests to screen and mature each concept.

B. Technology Readiness Level Achievement Criteria

As an integrated set of component technologies, SRP has achieved, at a minimum, TRL 2, defined as "Technology concept and/or application formulated." This evaluation is based on work identifying SRP as a decelerator technology for Mars EDL with little data to support that SRP can be successfully developed and implemented for such a purpose at the scale desired. The authors are not aware of any engine tests where startup and steady operation have been demonstrated against a supersonic freestream. Most of the past work related to SRP has focused on subscale wind-tunnel testing with cold-gas jets [7] aimed at understanding the aerodynamic trends and benefits when exhaust is directed into the freestream flow. CFD studies [13–17] have demonstrated promising results when compared to SRP wind-tunnel data, but substantial work remains to fully validate computational methods. Recent architecture studies that include SRP, such as the EDL-SA investigation [3], have used low-fidelity models designed to meet requirements rather than models based on proven performance data from analysis or experiment. Much of the work recently performed within ETDD, including additional wind-tunnel testing and CFD work, may be considered as activities required to achieve TRL 3. The following sections describe in more detail the technical advancements needed in the various components and the methods to be used to advance from the current state to TRL 6. TRLs have been and will be achieved through a combination of analysis, ground tests, and/or flight experiments. Some SRP components are ahead of others in technical maturity, and some will require more investment than others to advance through the remaining levels. The authors' consensus is that large-scale engines (hundreds of kilonewtons of thrust) and GN&C are currently lagging behind in development compared to other areas for human-scale (40 t) payloads. NASA's ETDD began to address some of the technical challenges, specifically in the area of aerodynamic/propulsive interactions, through cold-gas wind-tunnel testing and computational modeling. Those TRL achievements that have already occurred are indicated as such in the following discussion.

1. Propulsion

As shown in Table 3, the major technical challenges for the propulsion subsystem are developing large LO_2/LCH_4 engines with sufficient thrust and throttling capability for human-scale payloads (hundreds of kilonewtons); demonstrating reliable engine startup and throttling against a supersonic flow; and long-term storage of cryogenic propellants during cruise to Mars. Since the testing of large-scale engines and the counterflow supersonic environment are (in general) mutually exclusive, these two challenges must be addressed separately. Consequently, the large engine development effort follows the classic approach of scaling up existing engines, using existing and modified hardware, and then building full-scale prototype engines for ground testing. The reverse supersonic flow startup and throttling effort follows a largely separate path, relying on scaled ground-based testing, CFD analysis, and scaled Earth-based flight testing. The efforts are complementary and are worked in parallel, each providing insight and feedback for the other.

As previously noted, the notional vehicle and propulsion system for a human-scale Mars mission was defined in the EDL-SA study [3] The LO_2/LCH_4 propellant combination was chosen because it is generally considered both space-storable and compatible with in situ resource utilization goals. The ability to produce return mission propellants at Mars significantly reduces both launch mass at Earth and landed mass at Mars. Given an initial vehicle total mass of 62 t after aerocapture and three Earth g initial deceleration for EDL-SA architecture 1, 1.8 MN ($400,000\,\mathrm{lb}_f = 400\,\mathrm{klb}_f$) of initial thrust is required. The final system thrust is throttleable down to about 10% at touchdown. Most large pump-fed engines have a lower throttle limit of about 50% thrust due to the combined effects of injector dynamics, pump and turbine design, engine cooling, and performance dropoff at low throttle levels. A recent demonstration of a modified version of the RL-10 LO_2/LH_2 engine [23] achieved 13% throttling, which suggests the potential for at least one well-characterized engine. Pressure-fed engines are more amenable to wide throttle ranges but are impractical for the large thrust levels needed for a Mars lander. Throttle considerations, along with a desire from the vehicle control team to have engines in multiples of three, led to a notional design of six engines (300 kN each) for the EDL-SA study. Such a cluster could have half of the engines shut down at 40–50% throttle, with the balance throttled up to 100%, to maintain the descent rate. The remaining three engines would throttle down to 20–30% for landing, a reasonable goal for throttle range with many years left to develop such an engine. With half of the engines operating at low throttle, the desired 10% total thrust at shutdown is achieved.

The state of the art for LO_2/LCH_4 propulsion has been driven primarily by recent development efforts funded through ETDD and separate from the SRP investigations. These efforts are all geared toward relatively low thrust and low ΔV missions, e.g., a lunar ascent vehicle. The total technology effort is ongoing at multiple NASA centers and contractors across many separate technology development programs. Overall, the TRL could be considered 5–6 for reaction control system (RCS) and small main engines, and 2–3 for large throttleable main engines. Some of the significant ETDD engine development efforts include a prototype 22 kN (5 klb_f) fixed thrust ascent engine, a 176 kN (40 klb_f) breadboard injector with heat sink chamber, a 44 kN (10 klb_f) workhorse engine, and several 444 N (100 klb_f) RCS thrusters. In addition to the ETDD work, numerous studies have been performed on LO_2/LCH_4 engines, from 44 to 900 kN. In all cases, the goal of a high specific impulse engine will have, by necessity, a large expansion ratio nozzle that will complicate vehicle structural and dynamic interactions with the external flowfield.

To advance the TRL for Mars-appropriate SRP, it will be necessary to perform conceptual design and analysis trades (e.g., conventional nozzles, aerospike) and to prepare candidate designs with adequate detail to define specific test hardware, levels, and durations. TRL 4 is achieved with a full-scale development unit engine using a short sea-level nozzle with demonstration of startup, minimal throttling, and shutdown. As an example, Pratt-Whitney has studied and performed turbopump testing for a 266 kN (60 klb_f) derivative of their RL10 engine, adapted for LCH_4 and renamed the PWR-35M development engine. TRL 5 might then be achieved with altitude testing of a similar or second-generation version. Numerous other engine studies are available in the AIAA and Joint U.S. Army–Navy–NASA–Air Force databases, although relatively little hardware has been built or tested. One promising concept for reducing engine height is an aerospike (or plugless nozzle) solution, although throttling would likely be a challenge with a single large engine. The aerospike concept is generally chosen for its inherently altitude-compensating nozzleless external flowfield, but the elimination of the large nozzle makes it an attractive alternative for a Mars lander mission, albeit with a likely mass penalty.

Demonstrating reliable engine startup and throttling against a supersonic flow is the second major challenge requiring significant development effort to achieve TRL 6. This requirement will be addressed through a combination of analysis, wind-tunnel testing, and flight testing in Earth's atmosphere. Engine startup in a reverse flowfield during Mars entry has at least three major considerations: engine static pressure at startup, the subsequent dynamic pressure/flow environment interacting with the nozzle flow streams, and nozzle stiffness. For the EDL-SA study, the startup pressure in the chamber was calculated to be 5.2 kPa (0.75 psia) at $M_\infty = 3$. This modest pressure is well within the state of the art since both sea level and vacuum starts are common operations. More significant challenges are the dynamic interaction between a large nozzle and the unsteady flowstream around the vehicle at startup, the subsequent dynamic response of the flow stream to mass flow introduced behind the bow shock, and having sufficient nozzle stiffness in the opposing flow. The size of the nozzles (relative to the vehicle) will be much larger than has ever been tested in wind tunnels; placement inside a subsonic region could alleviate the negative effects of shock interactions during startup. Similarly, the mass flow directed into the oncoming flow will be much larger. Another layer of complexity is introduced with multiple nozzles interacting both with each other and with the environment. Achieving TRL 3 will require a Mars-specific CFD analysis and correlation with wind-tunnel test data, generated with a simple cold-gas propulsion system (including both startup and dynamic response). Advancing to TRL 4 will require a more complex and flightlike wind-tunnel test series with a hot-gas propulsion system and another round of analytical model improvement and correlation. TRL 5 will require the aforementioned plus throttling and off-nominal conditions in a simulated Mars environment in a wind tunnel. Finally, Earth-based flight tests will require a propulsion system capable of startup and throttling in relevant conditions to achieve TRL 6.

A secondary challenge related to the propulsion system is cryogenic storage of propellants. A combination of a lightweight linerless composite overwrapped pressure vessel (COPV) with suitable insulation and thermal management will be required to meet the mission timeline. Testing and analysis at NASA Johnson Space Center and within ETDD suggests that propellant boiloff losses can be very small, even without active cooling. The key technology development is the linerless COPV; a long-term thermal storage test would be required to verify performance in a flightlike configuration.

The ETDD team did not specifically address any of the engine development goals via testing or analysis. However, candidate ground facilities have been identified that could potentially serve as a test venue for hot-fire testing of scaled engines. The purpose of such testing would be to understand the transient engine loads during startup and transition to steady-state thrust while being exposed to supersonic counterflow conditions. One of the main challenges will be to pair engines and facilities to match basic fluid dynamic scaling parameters that govern the SRP flowfield: most importantly, Mach number and jet pressure ratio. The desire would be to test existing mature engines (hundreds to thousands of newtons thrust) that serve as suitable scaled versions of engines that are envisioned for a full-scale system. One potential test facility that is experienced with engine testing is NASA John H. Glenn Research Center at Lewis Field's 10-by-10-ft supersonic wind tunnel. Based on preliminary work by the ETDD team, a 1500 N engine appears to be suitable for testing and could be matched with facility conditions to give the desired conditions (Fig. 5). The main challenges to executing the test include selecting an appropriate existing engine for testing; designing the test article to acquire the desired data (force and moment, discrete pressure and temperature, high-speed video); and performing a facility safety assessment for testing in a mode that has not been attempted before.

2. *Aerodynamics and Aerothermodynamics*

The diversity of the flow physics created by the interaction of retropropulsion exhaust plumes and a supersonic external flow poses difficult challenges to entry vehicle aerodynamics (forces and moments) and aerothermodynamics (surface heating) predictions. The SRP system will be used to enhance entry vehicle deceleration and to maintain entry vehicle stability and control in the presence of these interactions, which will likely be unsteady during startup and full-thrust operations. Those same exhaust/flowfield interactions can also cause interference heating to the vehicle surface. Consequently, knowledge of the aerodynamic/propulsive interactions will be critical for entry system performance predictions. Entry trajectory simulations (3- and 6-DOF) will rely heavily on aerodynamic characteristics derived from validated CFD methods and tools. Also, thermal protection system (TPS) design will require CFD input to estimate the effects of plume impingement heating and exhaust flow contamination. While all prior Mars EDL work focused on flying blunt entry vehicles of a well-known shape, the presence of retrorockets changes the effective shape of the vehicle that the flow encounters, which in turn complicates prediction of aerodynamics and aeroheating. This can result in a more complex relationship between the aerodynamic environment, freestream conditions, entry vehicle angle of attack, and engine thrust than exists for a vehicle with no retropropulsion. The aerodynamic/propulsive interactions may also be more prevalent for elongated entry vehicles flying at an angle of attack, where nonaxial forces are higher than they are for blunt geometries. Furthering the predictive capabilities of SRP aerodynamics and aerothermodynamics will require a combination of wind-tunnel testing and CFD validated with test data in an effort to understand these interactions.

Aerodynamic/propulsive interactions have previously received attention in several flight projects. The interference effects of attitude control jets on aerodynamics were reported for the space shuttle [24]. More recently, the effects of RCS during entry have been predicted for the Mars Phoenix [25], MSL [26], and Orion Crew Exploration Vehicle [27]. For these cases, induced aeroheating and the interaction with the control system authority were based on wind-tunnel testing and CFD predictions. Experimental efforts are often complicated by the need to match scaling and simulation parameters, which for jets may involve external flow, nozzle-local flow, gas compositions, turbulent transition in various regions of the flowfield, as well as the interaction with the model support system. Consequently, wind-tunnel testing is frequently approached as more of a CFD validation effort. Scaling parameters generally reflect objectives of the test, but the order of effects may not be known a priori. Numerical methods are required for analysis of the full-scale flight vehicle. In the case of the listed examples, CFD analysis was completed using the available methods and was found to have difficulty with grid density,

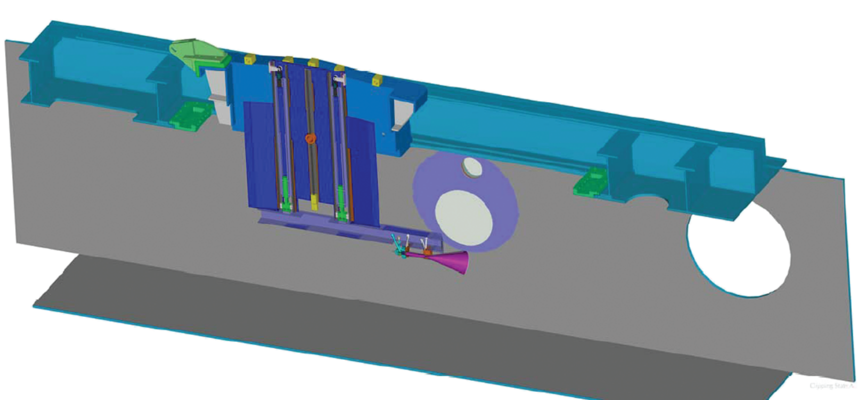


Fig. 5 Concept for hot-fire engine testing (image courtesy of Randy Clapper).

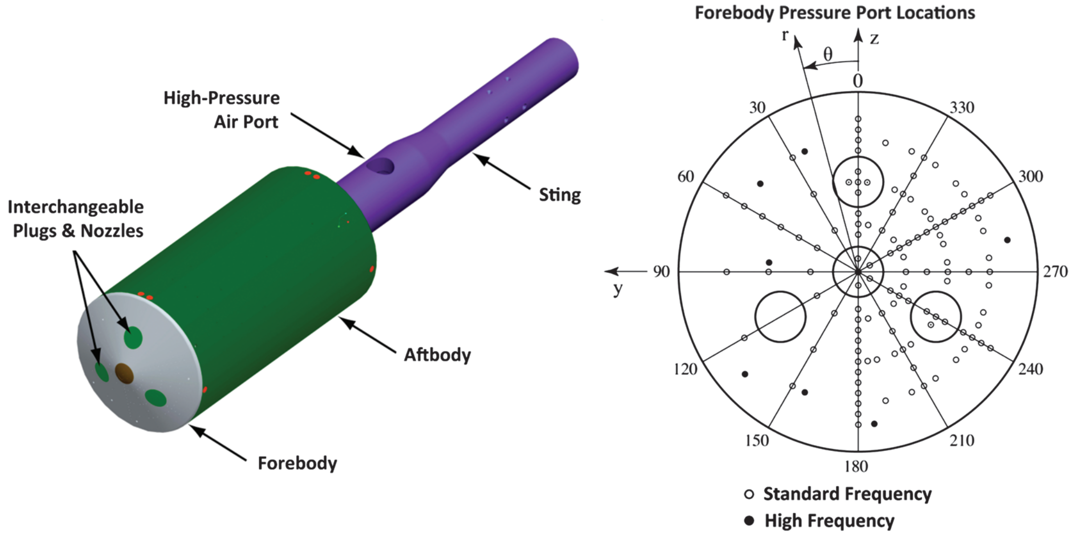


Fig. 6 Wind-tunnel model used for recent cold-gas testing.

appropriate turbulence modeling, and unsteadiness in predicting aerodynamics and aerothermodynamics for such interactions. These challenges appear to be common to SRP and are reflected in the outlook on the technology maturation.

Previous attempts to compare CFD results to historical wind-tunnel tests were hampered by missing data needed to fully characterize the tunnel conditions and sparse quantitative data [7]. The ETDD team addressed some of the required TRL 3 achievement criteria for aero/propulsive interactions by designing and conducting cold-gas testing of a generic model in two separate wind tunnels [9–12]. The model and test matrices were specifically designed using recommended guidelines to collect qualitative (high-speed video) and quantitative (surface pressure) data to provide a source of validation data for CFD tools. Figure 6 illustrates the 6-in.-diam model and forebody instrumentation used for testing in the NASA Langley Research Center 4-by-4-ft Unitary Plan Wind Tunnel and NASA Ames Research Center 9-by-7-ft supersonic wind tunnel. The model was designed to allow blowing of up to four cold-gas air jets over a range of thrust coefficients. The model configuration was not scaled to match a defined full-scale system but rather to provide high-quality data for CFD validation over a range of test conditions (jet configuration, Mach number, and thrust coefficient). The surface pressure instrumentation was densely spaced on the forebody and aftbody (not shown) to provide quantitative data for CFD validation. High-speed video (up to 20,000 frames per second) was also included to better understand the magnitude and frequency of unsteady flowfield oscillations.

It was found during testing that unsteady flow features existed at various scales, frequencies, and magnitudes regardless of the Mach number, thrust coefficient, and nozzle configuration. The various CFD codes employed thus far show promising results in their ability to capture the salient features of SRP flowfields and capture quantitative trends. Figure 7 shows a schlieren image from testing in the NASA Langley Research Center Unitary Plan Wind Tunnel compared to snapshots of unsteady CFD solutions. The conditions were $M_\infty = 4.6$, a single central jet, and $C_T = 2$. The CFD solvers were Data-Parallel Line Relaxation (DPLR), Fully-Unstructured Navier-Stokes (FUN3D), and OVERset grid FLOW (OVERFLOW). The plume geometry and shock standoff distance are reasonably well predicted by each code. However, work is still needed to test scaled versions of full-scale configurations, once they become defined, and to extend CFD codes to flight conditions with chemically reacting, engine exhaust interacting with the freestream and vehicle. The extensibility of CFD to full-scale Mars EDL systems will directly impact margin policies for aerodynamics, GN&C, and TPS. As the CFD analysis matures, one question will be whether or not time-accurate CFD solutions will be needed for full-scale system design, since such solutions are extremely resource-intensive. If unsteady computational analyses are needed to establish time-averaged results for the purposes of vehicle design, the accuracy of unsteady CFD methods must be addressed as part of the technology maturation.

The knowledge and prediction capability of SRP aerodynamics and aerothermodynamics is currently estimated to be at TRL 3 based on recent cold-gas wind-tunnel testing of various geometries and jet configurations [7,9–12] in conjunction with recent assessments of CFD capabilities [13–18]. The achievement of TRL 1 was based on previous wind-tunnel tests that demonstrated SRP's basic physics and aerodynamic trends for single and multiple jets [7]. Advancement through TRL 3 is accomplished with further wind-tunnel testing of generic configurations (e.g., model geometry, and number and arrangement of jets) designed specifically to validate CFD methods. Confidence in CFD must be established in order to

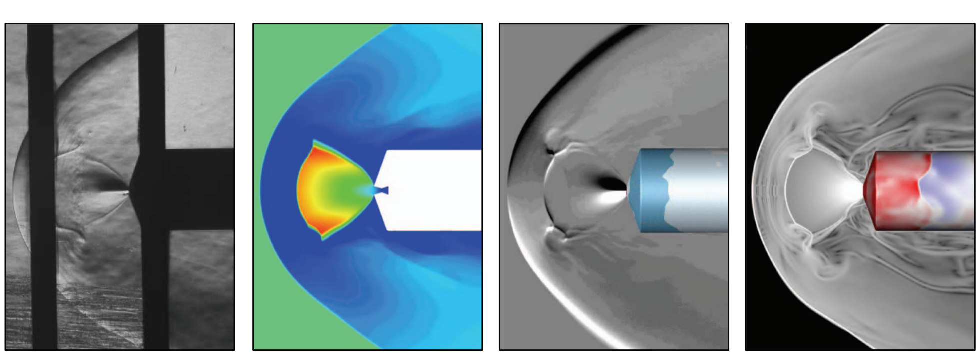


Fig. 7 Schlieren image compared to CFD solutions ($M_\infty = 4.6$, single jet, $C_T = 2$).

support 3- and 6-DOF trajectory simulations that require entry vehicle aerodynamic databases. The databases provide entry vehicle force and moment coefficients as a function of numerous parameters, including Mach number, angle of attack, thrust, and dynamic pressure. TRL 3 is achieved when acceptable CFD accuracy of aerodynamics and aerothermodynamics is demonstrated in comparison to wind-tunnel data. It is believed that recent CFD analysis at wind-tunnel conditions partially satisfies TRL 3 completion. TRL 3 CFD activities should continue with the development of first-order CFD-based Mars vehicle databases and wind-tunnel testing on more representative Mars configurations.

Advancement through TRLs 4, 5, and 6 will be achieved with demonstration of improved fidelity of analysis of increasingly complex physics. Continuing convergence of CFD predictions and ground-test data in terms of aerodynamics and aeroheating is shared among the readiness levels of 4, 5, and 6. Comparison between the numerical predictions and data allows an assessment of the fidelity of aerodynamic and aeroheating predictions for Mars applications. Predictions for the actual flight environment are needed to construct flight simulations and to accurately determine requirements on the propulsion, control, and thermal protection systems. Accurate modeling of the unsteady effects may be required, such as during engine startup and throttling, as well as the unsteady interaction flowfield at a constant angle of attack and with pitching motion. Given that the roadmap includes flight tests in Earth's atmosphere, analysis of expected interactions and postflight analysis showing as-predicted performance are part of the TRL 6 achievement. Extension of CFD to reference flight vehicles will be used to identify any risks not addressed in ground-based and free-flight Earth testing.

3. Guidance, Navigation, and Control

The current vision for human-scale Mars EDL is for the SRP engines to be used starting at supersonic conditions through terminal descent and touchdown. The GN&C requirements and capabilities for SRP are immature at this time due to a lack of experience with this type of flight concept. The flowfield complexity and dynamic interactions between the exhaust plumes, freestream, and entry vehicle will challenge GN&C algorithms and systems designed for stability and control. Historically, experience gained from powered lunar landings during the Apollo program demonstrated the importance of factoring human design aspects early into the GN&C trade space. Considerations such as viewing, terrain clearance, and lighting will drive trajectory design considerations and assist selection of GN&C sensors and avionics. Tolerance to stochastic powered flight transients and accommodating precision landing and contingency flight (abort-to-orbit, abort-to-landing, target redesignation, and hover hop) requirements will drive propulsion system trades (engine throttle rate and range), fuel tank loading margins, and control system selection and sizing. Therefore, a comprehensive approach to develop and understand the physics and interactions of the SRP system will be necessary to properly anchor the analytical and numerical approximations used to formulate the GN&C system.

The TRL 1 achievement criteria for GN&C is to successfully implement SRP into 3-DOF trajectory simulations to show the expected cost/benefit. This task has been completed by the EDL-SA task [3], at the Georgia Institute of Technology [19,20], showing the need for SRP at Mars. Achievement criteria for TRL 2 place more emphasis on the utilization and understanding of different SRP flight concepts, including but not limited to gimbaled engines, differential throttling, and RCS control. The reasons for developing multiple concepts early on are that the SRP GN&C system will need to leverage various options available to accommodate deviations from the nominal design.

As SRP knowledge improves, so will the driving requirements for GN&C system selection and operation, such that by TRL 3, the GN&C is better suited to handle the expected flight environments. The achievement criteria for TRL 3 are to understand the various interactions of avionics and sensors with the GN&C system in 3- and 6-DOF simulation environments. A selection of avionics systems may themselves affect the final trajectory shaping due to limitations in sensor scanning operation. Target redesignation, hazard detection and avoidance, crew interaction, and manual control capability requirements will also help to define the GN&C avionics support subsystems.

The achievement criteria for TRL 4 require the GN&C to react in real time to perturbations in a 6-DOF simulation environment such that a robust system can be tuned for a variety of flight conditions. The challenge expected here is that aerodynamic interactions during the SRP phase will be rapid and chaotic, possibly requiring the GN&C system to react more quickly than systems designed for previous NASA missions. This learning curve will need to be overcome by extensive validation and verification of the analytic and numerical models used to determine the SRP perturbations.

The achievement criteria for TRLs 5 and 6 focus largely on the validation and verification of GN&C models used in planning and execution of Earth atmosphere flight tests, as described next. The verification and validation of the GN&C models will use a combined process of testing, analyses, and inspection of data supplied by wind tunnels, material testing, hardware and software testing of subscale and scale flight models, and demonstrations to ensure the system performs adequately for a human-rated system throughout all expected flight conditions. The initial development phase for GN&C models will establish a set of requirements that insures the correct system is built and is verifiable. The flight-test progression proposed here ensures that an integrated closed-loop GN&C system is built to the requirement specifications and provides a safe, stable, and fuel-optimal response to entry vehicle perturbations caused by SRP aerodynamic/propulsive interactions. Acceptable margins will need to be defined and understood relative to the flight-test data correlation. An adequate validation and verification program will enable the SRP GN&C to be capable of designing to the conditions that will constitute the SRP flight concepts used by various missions.

GN&C analyses will initially be used to show theoretical compliance to requirements and establish that the technical and program risk versus benefit trade provides a cost and schedule-effective solution. Analyses by similarity will also be used when it can be shown that an article is similar in design, manufacture, and use to an equivalent or more stringent previously qualified GN&C hardware or software component. Similarity analyses must be supplemented if the desired component is integrated into a larger assembly of divergent character than the original qualified use (for example, a powered lunar guidance algorithm applied for atmospheric Mars entry). The final product will be an integrated GN&C system qualified to meet all mission, performance, and lifecycle human-rated SRP program requirements.

4. Systems Engineering and Analysis

The systems engineering and analysis technology area is focused on the definition of requirements, entry vehicle configuration development, and demonstration of SRP performance for full-scale reference EDL systems. As given in Table 3, the major technical challenges for the integration of a flight system using SRP are 1) ensuring that the vehicle can be packaged within the volume and mass constraints of the EDL system; 2) developing high-fidelity EDL models for the SRP system; and 3) performing verification and validation activities to ensure performance of the integrated SRP system. These activities include a combination of ground and flight tests, augmented with analytical modeling using validated tools. The TRL achievement criteria for the integrated system are based upon a progression of increasingly higher-fidelity and integrated subsystem demonstrations, culminating in a fully integrated, flightlike vehicle configuration. At each level, it is implied that the system-level analyses are updated to include models reflecting the best information available from each subsystem by incorporating new test and analysis results. Necessary subsystem models include aerodynamic and aerothermodynamic databases, models for propulsion system performance and sizing, and GN&C algorithms. TRL 6 is the target development level for adoption on a robotic-scale flight demonstration project at Mars, and accordingly, is the terminus for the integrated systems roadmap presented next.

TRLs 1 and 2 have been largely satisfied through the use of 3-DOF trajectory simulations to define top-level requirements, estimate operational envelopes, and demonstrate the potential benefits of SRP for Mars EDL [3,19,20]. Theoretical models have been used to perform first-order sizing with acceptable volume and mass margins for a notional EDL system and to demonstrate system sensitivities to SRP performance. Achievement of TRL 3 will require increased analysis fidelity in subsystem modeling and integrated system analysis to demonstrate full-scale vehicle performance with model uncertainties and acceptable packaging margins (system mass, volume, and mass distribution) using 3- and 6-DOF simulations.

The achievement criteria for TRL 4 are concerned with the direct integration of SRP subsystems and subsequent integration of the SRP components into a full-scale vehicle. It is recommended that one or more reference vehicle configurations are selected with preliminary mechanical designs completed for the integrated SRP system and aeroshell structure. Simulation capability will be extended to 6-DOF Monte Carlo analysis and will include off-nominal operating conditions, as well as models for transients during SRP engine startup, throttling, and shutdown. Acceptable margins must be demonstrated on mass, volume, and critical hardware clearances.

Achievement of TRL 5 will require moving beyond simulations to operation under relevant environmental conditions and is likely to be the most intensive stage in maturing SRP into a viable decelerator technology. Individual subsystems will be brought together at the integrated system level, and ground testing of flightlike systems and flight testing of subscale configurations at Earth will be initiated. All critical systems and interfaces for the "best" vehicle configuration will be sized and packaged in mechanical detail. Acceptable performance with all uncertainties (e.g., landing accuracy and altitude, timeline) and acceptable margins for the integrated system (e.g., aerodynamic, thermal, and structural) will be demonstrated using 6-DOF Monte Carlo analyses and validated computational models. A subscale hot-fire test of a flightlike propulsion system and controller will be conducted, with simulated flight dynamics, through initiation, dynamic throttling, and shutdown. Preliminary requirements for a series of subscale atmospheric flight tests at Earth will be defined, with supporting simulation and modeling capabilities developed. Multiple flight tests will be conducted as part of achieving TRL 5, as described next. These flight tests follow the rationale of progressively increasing the level of subsystem integration toward a fully integrated vehicle configuration. TRL 5 will be achieved after postflight analysis agrees acceptably with measured flight-test data.

Achievement of TRL 6 will require successful demonstration of an EDL system using SRP under relevant environmental conditions. EDL trajectory simulation "stress cases" will be developed to demonstrate the survivability of the vehicle to off-nominal conditions. Integrated thermal and structural analysis will demonstrate system tolerance to thermal conditions during the SRP burn duration (e.g., plume impingement and engine soak back). More complex flight tests at Earth will be conducted using throttled engines and closed-loop GN&C from engine startup through simulated landing, with postflight analysis completed and agreeing acceptably with measured flight-test data. Achievement of TRL 6 will indicate that the performance and integration of SRP, as part of a flight-relevant EDL system, have been acceptably verified and validated through simulation and testing and that SRP has been matured into a viable technology option for robotic-scale flight demonstration at Mars.

5. *Flight Testing*

The SRP roadmap presented here is based on an aggressive schedule for advancing SRP through TRL 6, with a goal of completing subscale Earth atmosphere flight tests before larger demonstrations at Earth and Mars (greater than 1 t). It is expected that flight tests will be critical to advancing SRP through TRLs 5 and 6 where integrated system performance must be demonstrated in a relevant environment. Early flight testing will play a critical role in accurately understanding the integration and performance of SRP component technologies in a dynamic environment, which is difficult, if not impossible, to simulate in a wind tunnel or model with CFD. Flight tests will serve to validate high-fidelity analytical models and confirm subscale data from ground-based testing.

Depending on the level of acceptable risk, the use of SRP on a precursor robotic-scale Mars mission may require Earth-based qualification flights. Before a qualification flight test, multiple subscale flight tests throughout the development cycle are planned to rapidly increase the knowledge base for SRP performance and dynamic vehicle behavior. Three flight tests are proposed to mature integrated SRP technology through TRLs 5 and 6 that feed into demonstrations at larger scales with increasingly flightlike systems. The top-level progression of initial flight-test architectures is conceived to be the following:

1) Flight test 1 includes a single nonthrottled engine and a passively stabilized entry vehicle.

2) Flight test 2 included multiple throttled engines in a passively stabilized entry vehicle.

3) Flight test 3 includes multiple throttled engines and closed loop GN&C.

These flight tests will be designed to match relevant scaling parameters and expected conditions on Mars, with a primary focus on Mach number and dynamic pressure. The first flight test will allow the system to achieve TRL 5 by demonstrating SRP performance in a relevant environment. Based on data from this first test, the following tests will have more flightlike characteristics such as engine throttling and control, which will mature the technology to TRL 6. The specific number of flight tests at this scale will ultimately depend on the desired complexity of the test article and the aggressiveness of the technology maturation schedule needed to satisfy future mission capabilities. After each test, it is imperative that high-fidelity simulations and reconstructed data are shown to agree within acceptable margins as an indication of risk reduction for follow-on flights. Flight-test schedule and cost will benefit greatly from the use of existing mature engines that can be integrated into the test platform and meet test requirements.

At the present time, two potential venues have been identified for SRP flight tests at Earth [22]. One candidate is a sounding rocket platform, which has been used for the Inflatable Re-Entry Vehicle Experiment Program [28]. The other platform candidate is a balloon-launched and rocket-accelerated platform similar to that used for Viking parachute testing [29] and for the upcoming Low Density Supersonic Decelerator [30] flight tests. Each of these venues, as well as other potential platforms, will be considered and evaluated based on the ability to meet specific requirements for each test. The mission concept of operations for the sounding rocket SRP test is shown in Fig. 8. In this concept, the SRP test article is stacked atop a two-stage rocket for the launch/ascent and coast phases. Before reentry, the first two stages are separated, and a nose cone, which protects the payload during ascent, is jettisoned. The test phase begins upon reentry when the SRP system is ignited. The details of the test sequence and duration, including initiation and termination conditions, must be developed to capture the relevant flight conditions governing SRP. Mach number and dynamic pressure will most likely factor into defining the test conditions envelope, with consideration for thrust based on the selected engines.

The balloon-launched SRP test concept is divided into five mission phases: loft, boost, coast, test, and descent. The concept of operations for this platform is shown in Fig. 9. During the loft phase, the test article is suspended beneath a large balloon. Upon achieving an acceptable staging condition (altitude, position, and azimuth), the test article is released from the balloon. This marks the transition from the loft phase to the boost phase. The boost phase begins with 1 s of freefall during which spinup motors are used to stabilize the test article before ignition of the boost propulsion system. Once spinup is complete, the boost propulsion system is initiated to bring the test article to the desired test conditions. A brief coast phase follows burnout of the boost motors. This quiescent period allows for any residual thrust transients to die out. Following the coast phase, the test phase is initiated by igniting the test propulsion system. The descent phase follows conclusion of the test phase. Depending on the need for recovery, combined with range safety considerations, the test article would either descend safely under parachute or continue unguided to the surface. In either case, all data would be transmitted before impact.

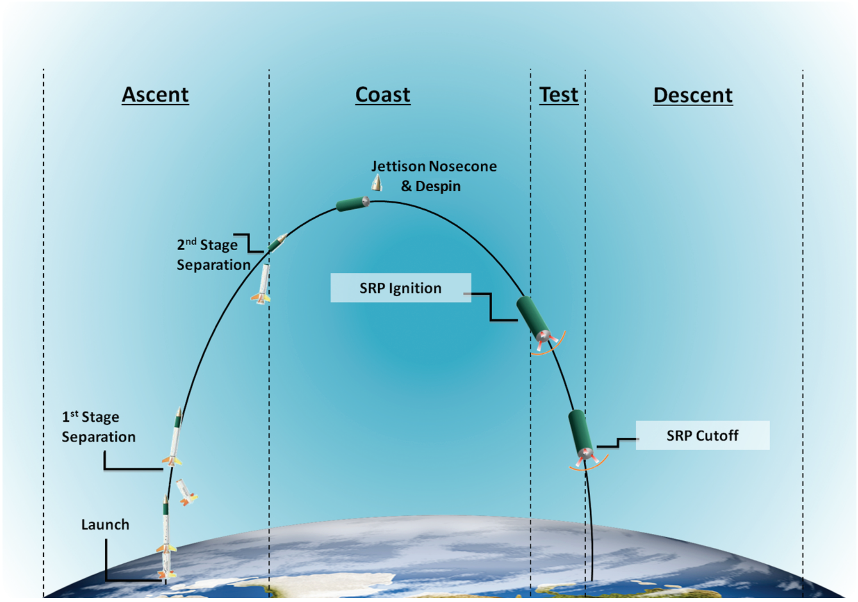


Fig. 8 Concept of operations for a sounding rocket SRP test [22].

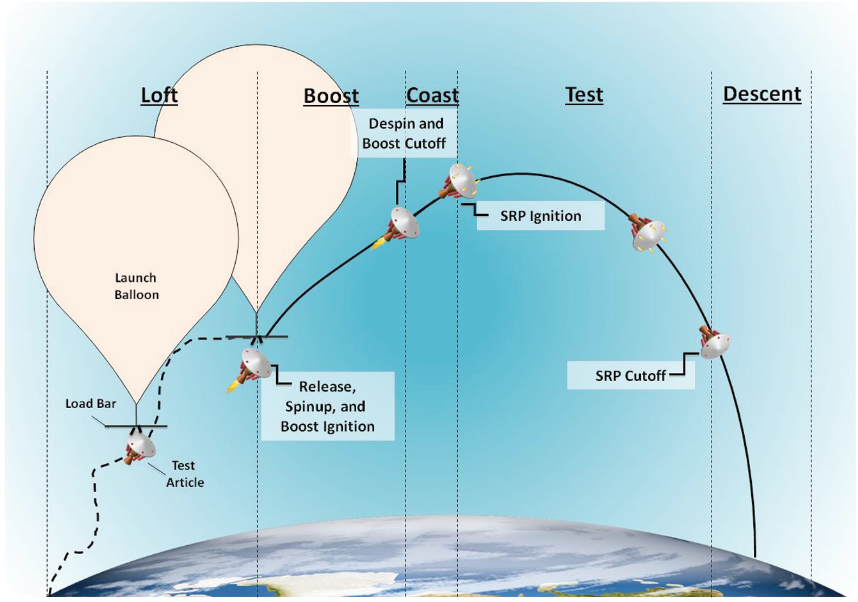


Fig. 9 Concept of operations for a balloon-launched SRP test [22].

Preliminary concept exploration to examine the capabilities of each launch platform has been performed; the test durations, projected development times, and test article diameters are compared in Table 4. In general, the BLST platform is more capable in terms of vehicle scale, system mass, instrument accommodation, test duration, and trajectory flexibility. However, this increased performance is significantly more expensive and requires a longer development cycle. In contrast, a sounding rocket test could be performed at a comparatively lower cost and on a compressed schedule, subject to a possible reduction of flexibility in test article and trajectory design.

ETDD also investigated a sounding rocket platform for executing the first of several free-flight tests in Earth's atmosphere. The concept focused on a single-engine test article with options for thrust level (thousands of newtons) and propellant. Notional packaging concepts were developed for existing liquid and solid engines, all of which resulted in a slender test article (Fig. 10). Consequently, one of the main challenges will be to ensure test article stability with minimal need for closed-loop control on the first flight test. As larger test platforms are developed with sufficient volume for multiple engines, closed-loop control can be developed for a higher-fidelity demonstration of SRP needed to satisfy TRL 6.

Detailed test requirements for each of the flight tests must be developed before the test venues can be adequately traded against each other. Key requirements include target trajectory envelopes (e.g., Mach number and dynamic pressure) and test durations, allowable trajectory dispersions, desired propellant combinations and thrust profiles, flight configuration definitions, required test data and associated instrumentation, ground support requirements, and range safety considerations. As these requirements are developed, the

Table 4 Comparison between potential SRP flight-test venues [22]

	Sounding rocket	Balloon plus rocket assist
Test duration, s	12–16	>100
Development time, months	18–24	18–36
Test article diameter, m	≤0.43 m	Variable, up to ~4 m

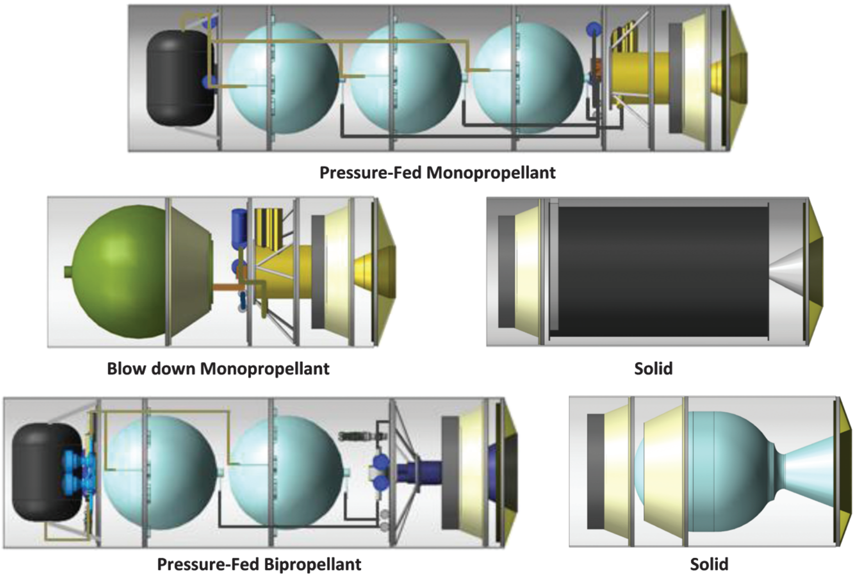


Fig. 10 Concepts for a single-engine sounding rocket test article.

ability of each platform to meet them can be determined. A progressive flight-test series is envisioned, where each flight test relies heavily on, and adapts minimally from, the design of the previous flight test. As such, a single, unifying test venue across all three tests is desirable. This desire must be traded against cost, schedule, and the ability of each venue to meet the specific requirements for each flight test.

C. Development Roadmap

After identifying the various TRL achievement criteria for each SRP component technology, the ETDD team developed a roadmap in response to NASA's new emphasis on Mars technology demonstration projects. Figure 11 shows a notional roadmap of the major methods needed to mature SRP in preparation for use on a robotic-scale (greater than 1 t) precursor demonstration mission at

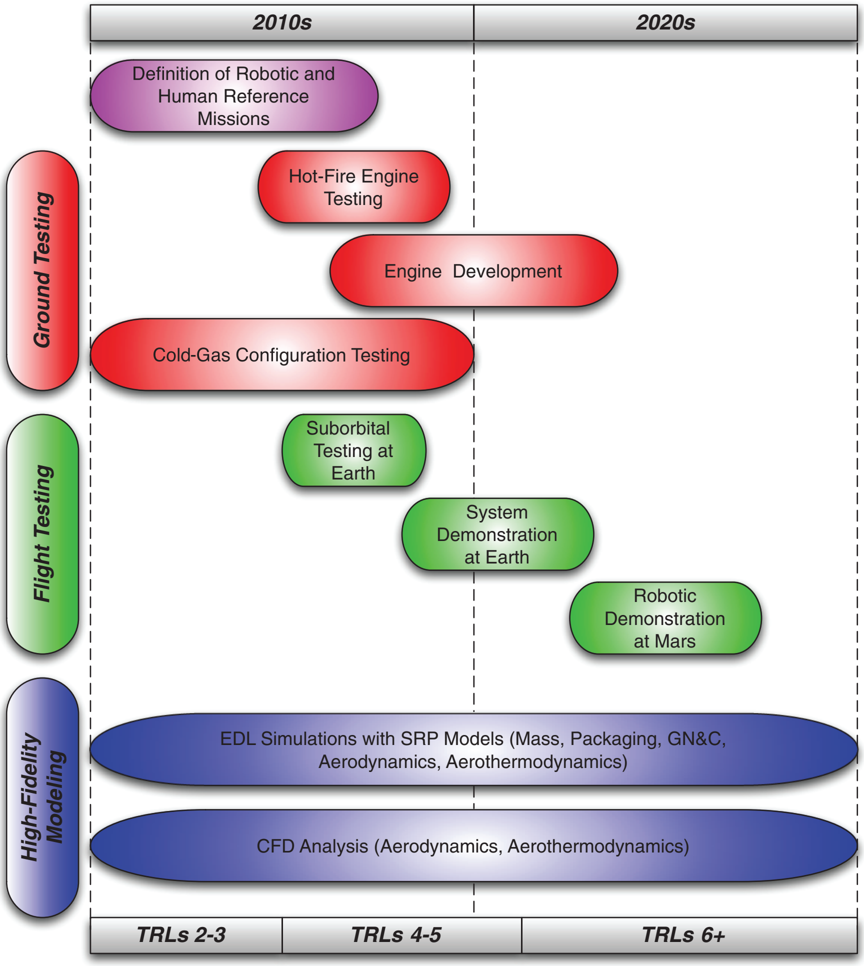


Fig. 11 Notional roadmap through robotic demonstration at Mars.

Mars in the next decade. The current rationale is that multiple Earth-based flight tests must be achieved three to four years before adoption on a Mars flight demonstration project. The timing and sequence of events shown in Fig. 11 are flexible and can be tailored to NASA's technology investments.

The roadmap focuses on the major testing and analysis tasks envisioned for the various technology components through TRLs 5 and 6. The timing of the TRL progression shown in Fig. 11 is notional and reflects an overall assessment of how technical maturity should progress. First and foremost, more definition must be given to full-scale payloads in order to size the descent stage and propulsion system. This exercise will allow proper sizing of the propulsion system, including the number and size of SRP engines needed to meet EDL requirements. Methods for EDL transitions before and after the SRP phase must also be developed for specific configurations. In parallel, hot-fire engine testing in a supersonic flow must be conducted to demonstrate successful startup and throttling using available ground facilities capable of such testing. It is expected that existing, mature, subscale engines can be selected from various vendors for initial hot-fire testing. The use of existing engines will expedite the testing and analysis to inform high-fidelity analytical models. It is desirable to include hot-fire tests of engines that are candidates for Earth free-flight testing. Large-scale engine development specifically for Mars missions must be initiated to address current gaps in thrust and throttling capabilities.

Cold-gas wind-tunnel testing and CFD modeling on specific configurations must progress in parallel with hardware development. Mature CFD analysis will be needed to bridge the gap between wind-tunnel facility capabilities and full-scale Mars conditions. Early work by the ETDD team on a generic wind-tunnel configuration showed promising qualitative and quantitative results. It is recommended that the initial work focus on additional wind-tunnel testing and/or CFD analysis, including aerothermodynamics, on configurations identified for Earth flight-testing and full-scale Mars systems. At each step, CFD must be shown to predict aerodynamics and aerothermodynamics with acceptable accuracy.

The system-level EDL analysis would clearly define performance requirements for full-scale Mars systems. All models required to support 3- and 6-DOF entry trajectory analyses (e.g., mass, aerodynamics, GN&C) must be developed and updated using the best available test data. Design cycles are envisioned during which model complexity increases for a narrowing set of SRP configurations, resulting in a best vehicle design. Each design cycle will require aerodynamic and aerothermodynamic databases derived from wind-tunnel data and CFD analysis to support entry flight system performance and TPS design.

Achievement of TRLs 5 and 6 will require Earth flight testing of gradually more complex SRP systems. Possible venues for such tests include sounding rockets or balloons with rocket assist. The Earth flight-test program reflects the current thinking that the first demonstration at Mars will have a payload at least as large as MSL's. The first fight test is envisioned as focusing more on successful engine startup and achieving the predicted ΔV with a passively stabilized vehicle. Additional tests at Earth add multiple throttled engines and possibly closed-loop GN&C, respectively, both of which will be required on a full-scale vehicle. Each flight-test vehicle will need to be instrumented sufficiently to validate the performance models. Also, the final flight-test vehicle will need to be of sufficient size to reduce scalability risks for Mars application. The flight-test phase of SRP development is likely to make up a large percentage of the total development schedule and cost. Depending on the risk posture for the intended first-use EDL mission, a larger flight demonstration program at higher Earth altitudes (e.g., from orbit) and at Mars may follow the initial suborbital Earth flight-test campaign. These additional flight tests would use larger and more Mars-relevant EDL systems than would the sounding rocket or balloon platform to demonstrate successful SRP performance at larger scales and with transitions. It is estimated that a demonstration at Mars could occur in the middle of the 2020s assuming that the recommended Earth flight-test program is completed near the end of the current decade.

The successful development of SRP for Mars EDL cannot be accomplished without the continued use and development of high-fidelity tools that are regularly validated with available test data. The areas that will require high-fidelity modeling will be determined by the models that are required to simulate the EDL performance of all flight test, precursor demonstration, and eventual Mars mission entry systems. SRP will require mature validated model for mass, packaging, and engine performance in order to simulate the entire EDL sequence, including transition into SRP and touchdown. As with recent Mars robotic EDL systems, high-fidelity trajectory simulations will require the usual aerodynamics, aerothermodynamics, and GN&C models specifically developed for systems with SRP. Each flight test at Earth or Mars must be sufficiently instrumented to show that the vehicle's predicted performance compares within acceptable bounds to the measured performance. Finally, the NASA effort to mature SRP for use on large-scale Mars EDL systems would benefit greatly from any leverage gained from developments at non-NASA entities (commercial or defense) that are also maturing SRP, for example as a means to retrieve and reuse launch vehicle stages [31]. Any chance to collaborate with partners outside of NASA should be pursued in order to reduce development costs, address potential risks, and compress development schedules.

III. Conclusions

Mars atmospheric entry systems based on those used for the Viking missions in the 1970s (blunt aeroshell and supersonic parachute) have approached their practical limit of landed payload mass with the recent Mars Science Laboratory Curiosity rover (less than 1 metric ton). Consequently, NASA is investing in revolutionary entry system technologies that will allow the human exploration of Mars with larger payloads (tens of metric tons), improved landing accuracy, and higher landing site altitudes. Supersonic retropropulsion using chemical rockets is one deceleration technology that is viewed by NASA as enabling for human-scale Mars missions. NASA last considered supersonic retropropulsion as a candidate entry system technology in the 1970s before the Viking missions, focusing on the aerodynamic trends and benefits via subscale wind-tunnel tests.

NASA's renewed interest in supersonic retropropulsion has led to initial investments focusing on performance requirements and parametric sizing analyses that indicate the potential benefits for human-scale payloads. The Exploration Technology Development and Demonstration Program defined options for how to advance the various supersonic retropropulsion technology components (propulsion, aerodynamics and aerothermodynamics, flight mechanics, integrated vehicle engineering and analysis) beyond their current state and how to demonstrate prototype system performance through Earth-based flight tests. Toward these goals, the NASA team identified analytical and experimental achievement criteria for supersonic retropropulsion required for technology maturation. Technologies requiring significant investment and technical advancement for supersonic retropropulsion include: high-thrust engines (hundreds of kilonewtons) capable of starting and throttling against a supersonic flow; computational fluid dynamics 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, transitions); and high-fidelity trajectory simulations. Significant improvements in modeling capabilities, especially in the area of aerodynamic/propulsive interactions, will be needed to predict full-scale vehicle performance and show acceptable margins with confidence.

Multiple ground-test campaigns will be needed to demonstrate the required engine performance and provide data for model validation. To begin flight demonstrations at Mars in the next 10 years, it is recommended that NASA invest early in engine ground tests that demonstrate acceptable performance in a supersonic opposing flow and subscale wind-tunnel tests that provide data for model validation exercises across a range of parameters (Mach number, jet pressure ratio) and engine/vehicle configurations. Concurrently, integrated vehicle level analyses will be needed to define the expected supersonic retropropulsion operating conditions and demonstrate acceptable performance margins. Finally, a series of Earth-based flight tests is needed to advance supersonic retropropulsion 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 Earth flight test will incorporate multiple engines and a closed-loop control system on a sufficiently large vehicle and at relevant conditions prior to Mars robotic demonstration and human mission missions.

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