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Entry, Descent, and Landing With Propulsive Deceleration

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December 2012

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Entry, Descent, and Landing With Propulsive Deceleration

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Abstract

The future exploration of the Solar System will require innovations in transportation and the use of entry, descent, and landing (EDL) systems at many planetary landing sites. The cost of space missions has always been prohibitive, and using the natural planetary and planet's moons' atmospheres for entry, descent, and landing can reduce the cost, mass, and complexity of these missions. This paper will describe some of the EDL ideas for planetary entry and survey the overall technologies for EDL that may be attractive for future Solar System missions.

Introduction

Entry, descent, and landing are a series of events needed to safely land on the surface of another body in the solar system which possesses an atmosphere. Mars, Venus, the outer planets, and the outer planet moon, Titan, all require technologies that will protect the spacecraft from the high temperatures created during the initial hypersonic entry, and finally slow the vehicle from that hypersonic speed into the supersonic regime, then to subsonic and to the final touchdown. In the outer planet atmospheres, the final landing would be replaced with a buoyancy system such as an airship, balloon, or an aircraft.

Historical Missions

Landing space vehicles on other planetary bodies is a challenge in propulsion, precision control, and guidance. As there is no substantial atmosphere surrounding Earth's Moon, the lunar landings of robotic Surveyor and human Apollo missions used propulsion for the entire descent. The same was true for the successful Luna and Lunakhod flights of the U.S.S.R. For Venus with its dense atmosphere, landing vehicles used aeroshell and parachute combinations, with crushable elements (balsa wood, etc.) to absorb the final landing energy. On Mars, the landing vehicles became more massive and complex (Viking, Pathfinder, Mars Exploration Rovers (MER)), and the since the atmosphere was very thin, the final landing systems was a combination for aeroshell, parachute and retro rockets. To allow landing in more rugged areas of Mars, an additional airbag system was devised for the Pathfinder and MER landers to assure a successful landing in rock strewn sites. Figure 2 depicts the Mars Science Laboratory landing sequence. A rocket powered descent is essential for softly landing a large payload.

Mars

Several EDL configurations are under assessment for Mars. Figure 1 presents the historical comparison of the USA Mars entry capsules (Ref. 1). The typical 70° cone angle for these configurations was selected for high stability and high drag. As the planet's atmosphere is quite thin, the blunt body can provide the needed drag for relatively small payloads of up 1 metric ton. As the mass of the lander vehicle increases, a different set of EDL technologies are required. Based on past studies (Refs. 2 and 3), parachutes are impractical for vehicles with lander masses of over 20 metric tons; the parachutes are too big to deploy effectively and reliably. Therefore, a combination of inflatable decelerators and propulsive deceleration has been suggested. Many past studies have investigated landing on Mars with aerodynamic systems (Refs. 4 to 9). However, the most recent studies imply that the past studies assumptions were too optimistic and are in need of revision to assure success.

Current Planning

The Supersonics Project in the NASA Fundamental Aeronautics Program is supporting research in areas to allow effective design of future High Mass Mars Entry Systems (HMMES). Under HMMES, there are five areas of research: Static Aerodynamic Performance Prediction, Dynamic Performance Evaluation, Computational Fluid-Structures Interaction Methods, Decelerator Testing, and Propulsive deceleration.

Static Aerodynamic Performance Prediction

In this research area, there are efforts to computationally simulate the fluid dynamics of entry vehicles, the interactions of wakes with static parachutes or other decelerators, and the loads on and the performance of the decelerator system. Experimental studies will use these simulations for design improvements.

Dynamic Performance Evaluation

There will also be efforts to develop an integrated conceptual analysis capability for analyzing and comparing potential EDL systems for large payloads. Variable-fidelity discipline analyses, including aerodynamics, trajectory, structures, propulsion, mass estimation, and heat transfer, will be incorporated into a computational tool to allow assessment of various system architectures.

Computational Fluid-Structures Interaction Methods

This research effort will extend the static aerodynamic calculations of the Dynamic Performance Evaluation element to calculations of the unsteady aerodynamics of a vehicle/decelerator system, and to develop tools for computing the interactions between the fluid mechanics and the structural response of flexible parachutes and other decelerators.

Decelerator Testing

Develop ground and flight test capabilities for evaluations of various supersonic aerodynamic decelerator concepts. This research will focus on inflatable decelerators for the supersonic flight regime and also investigate the hand off from the hypersonic flight speeds to supersonic flight.

Propulsive Deceleration

Investigate novel experimental approaches for using rocket propulsion for decelerating an entry vehicle through the supersonic speed regime in a planetary atmosphere. Under the auspices of Propulsive Deceleration, the elements of the planned experimental and computational program include:

1. Supersonic Aerodynamics About The Nozzles During Ignition,
2. Flow Instabilities During The Ignition Process,
3. Covers For Engines, Including Purge Gases, To Effect Ignition In Vacuum,
4. Large Expansion Ratio Nozzle Effects On Aerodynamics And Ignition Transients (Shock Structure(s) In Nozzle), Heat Transfer In Nozzles, Chambers, and Landing Site,
5. Exhaust Plume Jet And Surface Interactions During Landing,
6. Evaluation of propellant selection and propulsion modes, including O_2/H_2, and O_2/CH^4 (methane), and O_2/CO (carbon monoxide). The effects of in-situ resource utilization (ISRU) on propellant combination selection will be evaluated.

The testing will be conducted in the NASA 1- by 1-Foot Supersonic Wind Tunnel (SWT) on small scale engines to demonstrate techniques for effective ignition and start up transients. A more detailed description of the six areas is provided below.

1. Supersonic aerodynamics about nozzles during ignition:

   We plan to assemble and test fire a subscale rocket engine in a wind tunnel using a relevant Mars environment. The resulting data will be analyzed and correlated with ignition conditions and external flow conditions to create a database on the flow field about the nozzle during entry.

2. Flow instabilities during the ignition process:

   Nozzle flow instabilities during the entry conditions will impact the ignition process. Flow instabilities will be measured to develop a database of nozzle flow stability regimes. The measured nozzle flow instabilities will be analyzed and correlated to the external flow conditions about the nozzle.

3. Engine covers to effect ignition in a vacuum:

   Successful rocket ignition is often affected by vacuum levels. Wind tunnel testing will measure the ignition limits for purged and unpurged engines during entry conditions. The resulting data will define purge gas concentrations required for effective ignition and whether engine covers may be required.

   As the vehicle descends through the atmosphere, the vehicle will decelerate to supersonic speeds. The planned inflatable aerodynamic decelerators are predicted to allow the vehicle to slow to Mach 2 or 3 before the retro propulsion or propulsive deceleration system is ignited. The engines for the deceleration are protected from the entry heating by the main aeroshell, and to be effective, the engines will likely need some extendible nozzle to protrude through the aeroshell.

4. Large expansion ratio nozzle effects (fluid-structure interactions):

   Wind tunnel testing will measure the external aerodynamics and ignition transients (shock structure in the nozzle flow) of large expansion ratio nozzles. Resulting data will be analyzed and correlated with flow instabilities to create a database of external aerodynamics and ignition transients of these large expansion ratio nozzles that can be applied to EDL mission profiles.

   With the potentially large expansion ratio nozzles protruding from the aeroshell, additional heat transfer enhancement will occur due to rocket plume recirculation or base heating (Fig. 4, Ref. 24). Issues associated with improving and enhancing the heat shield, such as shock-shock interactions, where enhanced heat transfer will occur, are to be investigated.

   As the EDL vehicle decelerates, the shock structure of the atmospheric flow field will begin interacting violently with the retro propulsion system exhaust plumes. Figure 3 illustrates some of the effects of the rocket—aeroshell flow field. Localized higher than normal heating will occur where these shocks touch the aeroshell and therefore enhanced heat shield designs will be needed to protect the vehicle from these localized hot spots.

5. Heat transfer in nozzles and chambers:

   We plan to measure the nozzle and chamber heat transfer environment during EDL and at landing site conditions. Wind tunnel tests will be conducted to measure these heat transfer conditions over the EDL condition range. Resulting data will be analyzed and correlated to nozzle flow instabilities and the external aerodynamic environment.

6. Evaluation of propellant selection and propulsion modes:

   We will evaluate the use of O_2/H_2 (hydrogen), O_2/CH^4 (methane), and O_2/CO (carbon monoxide) as propellants for EDL propulsive deceleration requirements. The effects of in-situ resource utilization (ISRU) on propellant combination selection will be reviewed.

EDL Links to Other Future Space Missions

Exploration Systems and Space Operations Mission Directorates Benefits

Improved rocket exhaust plume modeling for all space vehicles will be derived from EDL technologies. Detailed studies and experiments focused on the plume effects on vehicle heating during entry and the main engine heating effects during descent and landing will be a major benefit to other space operations program, such as the NASA Crew Exploration Vehicle.

Science Mission Directorate Benefits

With EDL technologies, there will be improved lander protection from rock-strewn surfaces, which will aid precision landing technologies. With effective rocket engine design, EDL technologies can allow for improved payload protection after landing, mitigating dust on spacecraft surfaces. Lunar, Mars, and outer planet moon landing dust mitigation strategies can be investigated. With lunar and Mars missions, dust has been a serious issue in the obscuration of the landing site and potential damage to space suit and rotating components.

The Outer Solar System

Our Outer Solar System is composed of gas giant planets, moons, and many smaller bodies than exciting targets for exploration (Refs. 9 to 25). The Galilean moons of Jupiter have been studied intensively by the Galileo spacecraft, and the implications of these studies imply that oceans of water may exist below these moons' icy surfaces (Refs. 11 to 13). A series of EDL technologies may be used to enter Jupiter's atmosphere, slow a higher payload mass vehicle into orbit, and allow more effective exploration of those moons. At Saturn, Titan is also a fascinating target for exploration, and its relatively thick and cold atmosphere can allow the use of aerocapture and EDL technologies for braking into orbit about Saturn and landing on Titan, or both. With EDL technologies, aerocapture at these outer planets can be accomplished and the planetary landing may also be allowed with the same or a related deceleration system: either propulsive or aerodynamic.

Preliminary designs from past studies have identified the technologies are most attractive for use of EDL for these missions. Other options for atmospheric flight are possible for exploration and exploitation, including flight in planetary atmospheres with advanced fuels (Refs. 9 and 21 to 25). Outer planet mining options using entry and descent techniques have been assessed in References 21 to 23.

Outer Planet Flagship Missions

A series of outer planet flagship missions are also being assessed for selection. These include a Titan orbiter or Titan Balloon (at Saturn), Enceladus mission (at Saturn), Europa mission (at Jupiter), and a Jupiter survey mission. Each of these missions could employ aspects of the EDL technology being developed. Though landing on the outer planets is not an option, using the entry and descent technologies for atmospheric braking and exploration of a planet's atmosphere is an option for future uses of this basic aerodynamic research. Figure 5 (Ref. 25) shows an aerocapture vehicle designed for Neptune called the ellipsled. Its name is derived from the elliptical cross sectional shape and the fact that the spacecraft is stored inside the aeroshell as if it were attached to a sled (or toboggan).

Atmospheric Mining in the Outer Solar System

Mining of the outer planet atmospheres is a special case of planetary resource utilization. Reference 23 summarizes the nature of the gases in the outer planet atmospheres. While there are enormous caches of fuel in those atmospheres, the gravity of the planets makes for a high energy set of maneuvers to enter orbit, enter the atmosphere, persist there for the mining operation, and emerge from the atmosphere with the mined fuel. Therefore, specially designed space and aerospace vehicle vehicles will be needed to wrest the gases from the powerful gravity wells of these giant planets. To reduce the orbit insertion delta-V, previous mission studies and planetary missions have typically placed their space vehicles into highly elliptical orbits. Often, flybys of the planets moons are used to pump (or increase the energy of) the orbit and allow a full tour of the system of moons about the gas giants. Attaining a low orbit about the gas giants takes a fairly high delta-V, a value that is often beyond most previously studied mission capabilities.

Atmospheric mining of the outer planets will require a number of spacecraft and many complex maneuvers to wrest fuels from their powerful gravity wells. Several different mining scenarios were investigated: cruisers, balloons, and scoopers. Given the complexity of the missions discussed and the delta-V required for mining, the cruiser- and balloon-borne mining scenarios are the most promising for future study.

Cruisers have the advantage of operating in the atmosphere at subsonic speeds, which eases the liquefaction requirements for mining. Also, the stresses on the vehicle seem the most benign of all of the mining vehicles. The cruiser idea may be the most attractive scenario for the longer term missions. The cruiser will likely use the planetary atmosphere for fuel (for a nuclear "airbreathing" engine) and capture and liquefy the needed gases from the atmosphere as well. The cruiser may exit the atmosphere and be refitted or resupplied (with delivery capsules, other consumables, replacement units, etc.) from orbital assets.

Balloons have been proposed in the past as viable mining platforms. However, the lifetime of balloon systems, especially higher temperature balloons, will be a limiting factor in balloon-borne mining scenario. Shorter life missions will be more suited to the balloon miner. Typical balloon lifetime for Earth exploration is usually in the 10's to perhaps 100 hr. While a fascinating option, the scooper miners will likely be used for short and limited forays into the atmosphere.

The EDL research will be important in allowing these mining vehicles to enter and re-enter the atmospheres of the outer planets. Entry into the outer planet atmospheres will require specialized developments as the temperatures there are cryogenic and special protection will be required from the hydrogen and helium atmospheric gases.

Mining the planets will likely unlock new capabilities to explore and exploit the solar system. The initial steps in pursuing in-situ resource utilization will allow new visions for energy sources for Earth, solar systems spacecraft, and perhaps humankind's first step into interstellar space. The technologies for entry and descent can lead the way.

Concluding Remarks

Entry, descent, and landing technologies are under development for the high mass Mars Entry system (HMMES). Many investigations of aerodynamic deceleration for the outer planets have been conducted as well. The challenges for EDL are numerous, especially for inflatable decelerator and the interactions that will occur with propulsive deceleration retro propulsion. The high velocities involved in entry and descent will require high temperature materials that are flexible for folding into a small volume, but reliable when they are deployed to their full diameter.

Many exciting possibilities are foreseen for outer planet exploration and exploitation. The resources of the outer planets may allow fueling of nuclear fusion vehicles and other power plants that may be the engine for all of Earth's energy. Wresting fuels such as hydrogen and helium 3 from the gas giant planets may be a critical element of outer planet exploration and also flight to the nearby stars.

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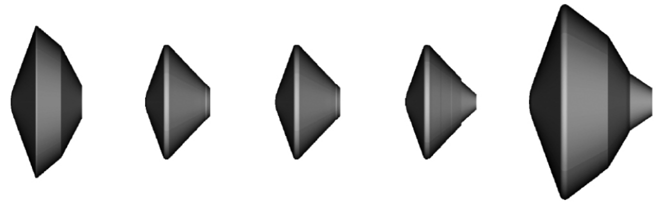


	Viking 1/2	Pathfinder	MER A/B	Phoenix	MSL
Diameter, m	3.5	2.65	2.65	2.65	4.5
Entry mass, kg	930	585	840	602	>3000
Landed mass, kg	603	360	539	364	>1700
Landing altitude, km	–3.5	–1.5	–1.3	–3.5	–1.0
Landing ellipse, km	420x200	100x50	80x20	75x20	<10x10
Relative entry velocity, km/s	4.5/4.42	7.6	5.5	5.9	>5.5
Relative entry FPA, deg	–17.6	–13.8	–11.5	–13	–15.2
m/C_DS_{ref}, kg/m^2	64	62	90	65	>140
Turbulent at peak heating?	No	No	No	No	Yes
Peak heat flux, W/cm^2	24	115	54	56	>200
Peak surface pressure, atm	0.10	0.20	0.10	0.12	>0.3
Heatshield TPS material	SLA-561V	SLA-561V	SLA-561V	SLA-561V	SLA-561V
Backshield TPS material	None	SLA-561S	SLA-561S	SLA-561S	SLA-561S
Hypersonic α, deg	–11	0	0	0	–16
Hypersonic L/D	0.18	0	0	0	0.24
Control	3-axis	Spinning	Spinning	3-axis	3-axis
Guidance	No	No	No	No	Yes

Figure 1.—Mars EDL aeroshell comparison (Ref. 1).

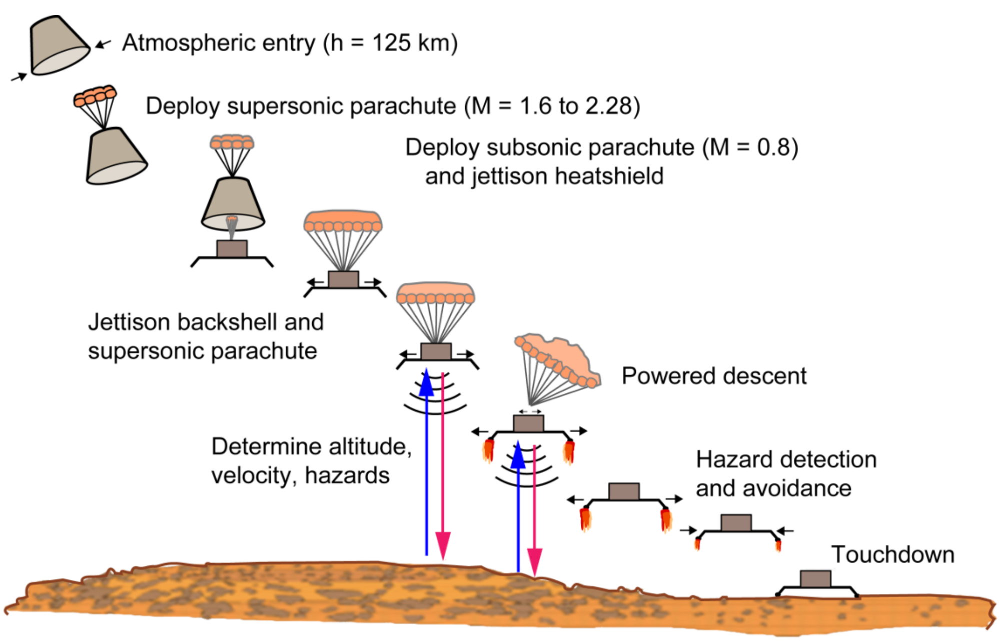


Figure 2.—Mars Science Laboratory EDL sequence (Ref. 2).

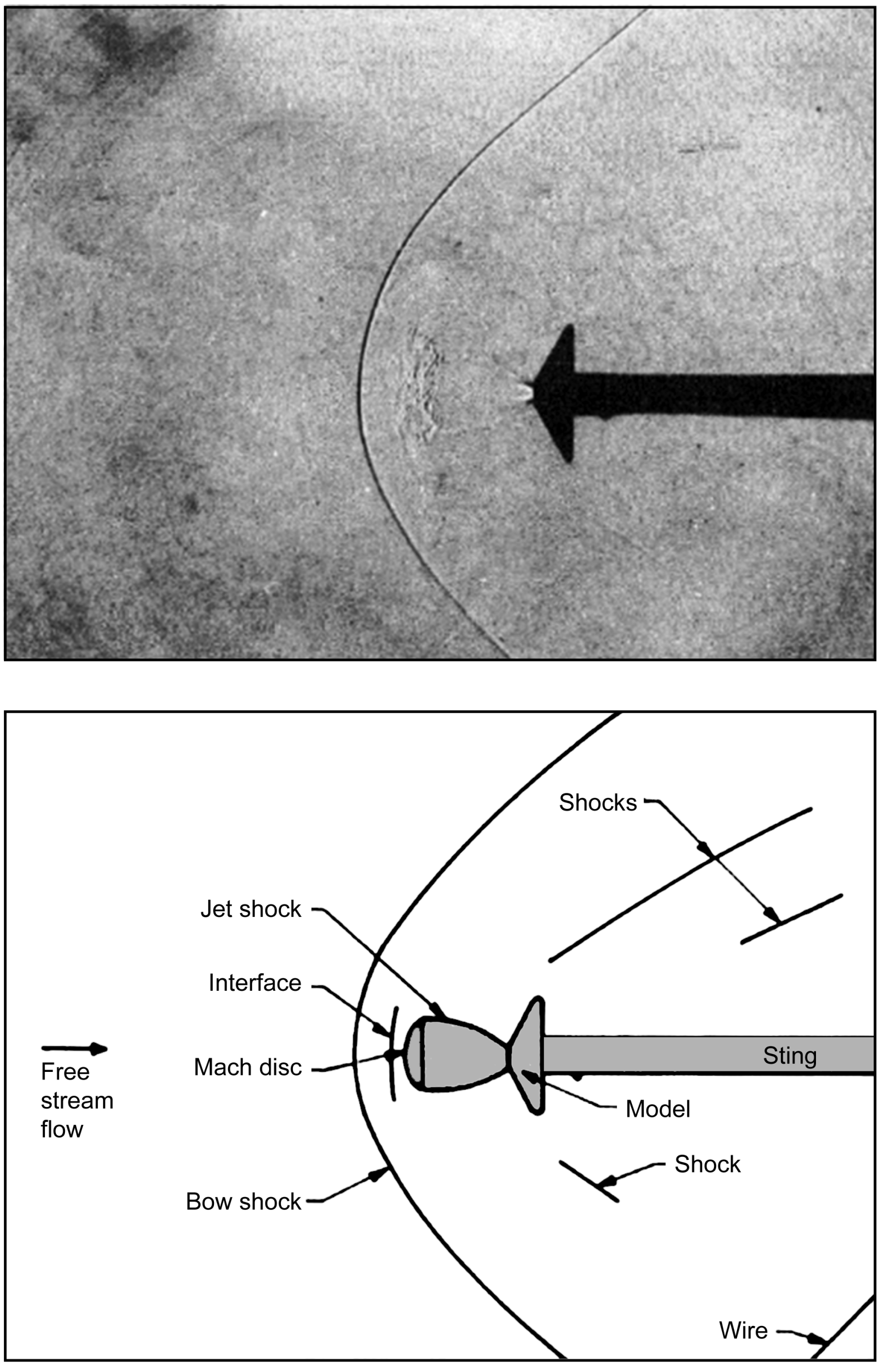
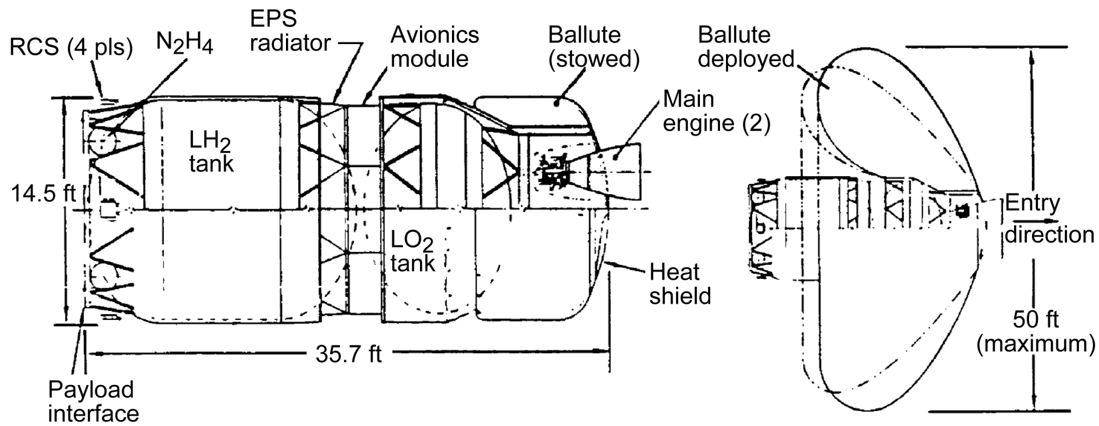


Figure 3.—Retrorocket flow into oncoming supersonic free stream for atmospheric entry (Ref. 3). Single nozzle 60° aeroshell model with blunt flow interaction, $M_\infty = 2.0$, $C_T = 1.1$



<u>Unique features</u>

- Ballute
  - Nextel/CS 105
  - 1500 °F backwall
  - Turndown ratio = 1.5
  - 1 use
- Heat shield–RSI
  - 20 uses
- No initial on-orbit assembly

<u>Stage weight summary, lb</u>

- Dry 9,189
- Main property 63,890 [1]
- Other fluids 1,061
- Startburn 74,140

[1] For manned GEO sortie (7.5K R.T.) or 20K GEO delivery

Figure 4.—Space based aerobraking orbital transfer vehicle with inflatable ballute (Ref. 24).

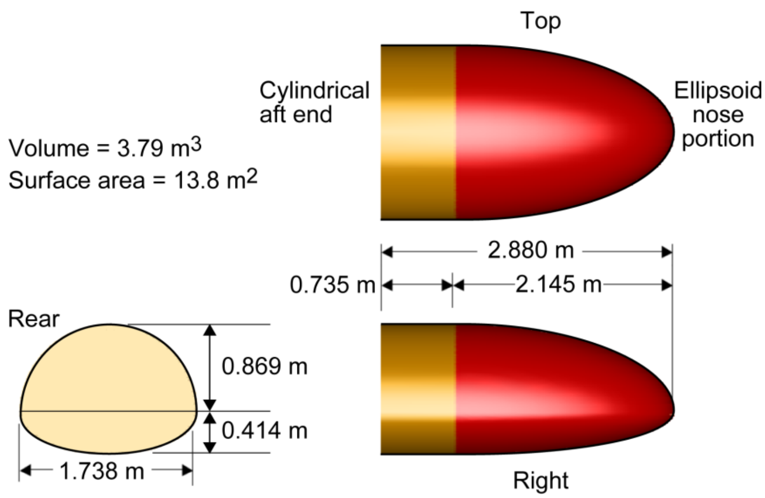


Figure 5.—Ellipsled geometry (Ref. 25).

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The future exploration of the Solar System will require innovations in transportation and the use of entry, descent, and landing (EDL) systems at many planetary landing sites. The cost of space missions has always been prohibitive, and using the natural planetary and planet's moons' atmospheres for entry, descent, and landing can reduce the cost, mass, and complexity of these missions. This paper will describe some of the EDL ideas for planetary entry and survey the overall technologies for EDL that may be attractive for future Solar System missions.

15. SUBJECT TERMS
Planetary entry; Propulsion; Rocket engines; Fluid mechanics; Retrorocket; in situe resource utilization

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