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Daedalon: A Revolutionary Morphing Spacecraft Design for Planetary Exploration

Jarret M. Lafleur[*], John R.Olds[†], and Robert D. Braun[†]
Georgia Institute of Technology, Atlanta, Georgia 30332

The product of a study sponsored by the NASA Institute for Advanced Concepts (NIAC), Daedalon is a spacecraft design baselined for Mars which utilizes morphing wing technology to achieve the design objective of a standard, flexible architecture for unmanned planetary exploration. This design encompasses a detailed vehicle mass and power sizing study for the Daedalon lander as well as its cruise stage and entry backshell. A cost estimation and comparison study is also performed, and qualitative functionality comparisons are made between Daedalon and other Mars lander and airplane designs. Quantitative comparisons of gross mass and range are also made, including the results of scaling an existing Mars aerial vehicle design to match Daedalon functionality. Altogether, the Daedalon launch mass is found to be 896 kg for a 12 kg payload capacity. If five such vehicles are produced, it is found that the per-mission cost can be as low as $224 million. Given the necessary morphing wing technology development, it is concluded that the Daedalon design may be a feasible and cost-effective approach to planetary exploration 20-40 years in the future.

Nomenclature

APXS = Alpha Proton X-ray Spectrometer
ARES = Aerial Regional-scale Environmental Survey of Mars
C3 = Measure of trajectory energy (square of hyperbolic excess velocity)
CAD = Computer-Aided Design
C&DH = Command and Data Handling
GNC = Guidance, Navigation, and Control
IMU = Inertial Measurement Unit
I_{sp} = Specific Impulse
MER = Mars Exploration Rover
NIAC = NASA Institute for Advanced Concepts
RAT = Rock Abrasion Tool
SSDL = Georgia Tech Space Systems Design Lab
TES = Thermal Emission Spectrometer
UHF = Ultra High Frequency

I. Introduction

ROBOTIC planetary exploration today consists chiefly of flight-specific vehicle designs. Lessons learned from previous designs are incorporated into future spacecraft, but after years in development, those craft hardly resemble their predecessors. While this may suffice in these early years of planetary exploration, larger-scale operations may require a more standardized and cost-effective approach. Additionally, planetary exploration today is limited to either breadth or depth of scope. Landing spacecraft gather very fine details about their surroundings but have limited range. Orbiting spacecraft have range over an entire planet but limited capacities for gathering fine detail. Daedalon presents the concept of a single vehicle capable of various missions with the ability to enter an atmosphere, take flight to survey a region, and choose the ideal landing site for its given mission.

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[*] Undergraduate Student, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0150, Student Member AIAA.
[†] Associate Professor, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0150, Associate Fellow AIAA.

Daedalon's namesake is the king Daedalion of classical mythology, a man who leaped off the summit of Mount Parnassus only to sprout wings and be transformed into a hawk by Apollo before he could reach the ground below. This tale well illuminates the key technology that Daedalon employs: wing morphing. In order to take flight directly after entering a planetary atmosphere, Daedalon transforms itself from a blunt-body entry spacecraft into an airplane through a form of wing morphing.

While applicable to any planet or moon with an atmosphere, the Daedalon concept was transformed into a vehicle design baselined for Mars as part of a NIAC-sponsored study which ended in May 2004. This paper presents the results of that work, including a system-level mass and power estimation study as well as cost and functionality comparisons between Daedalon and other Mars lander and airplane designs.

II. Baseline Mission

Daedalon begins its journey to Mars in 2025 with a launch aboard a Delta II 7925 expendable launch vehicle. On the cruise to Mars, Daedalon is supported by a cruise stage providing communications, power, and course correction functionality.

On its direct-entry approach to Mars, the Daedalon lander is powered up and released from its cruise stage 5.5 hours before entry interface. Once the most intense period of atmospheric entry passes, Daedalon discards its backshell and remaining heat shield insulation and proceeds to morph its wing into a high-sweep, low-aspect-ratio configuration for about ten minutes of high speed gliding through the Martian atmosphere. This phase of flight involves a continuous morphing of the wing, such that the final low-sweep, high-aspect-ratio configuration allows a 54 minute rocket-powered cruise at Mach 0.7 and 500 m altitude. During the entire flight, Daedalon also surveys the ground in search of the ideal landing site for its given mission. In all, from backshell release to landing, Daedalon can fly a total of 670 km, which is enough to fly the circumference of a 160-km crater (such as Gusev Crater) with enough fuel remaining to fly across the crater in the case that the ideal landing site is one diameter away.

On the approach to its landing site, Daedalon initiates a deep stall at 10 m altitude. Two descent thrusters allow Daedalon to land gently on its wheels. Once landed, Daedalon deploys two solar arrays over its wings and activates its payload. Daedalon then has the ability to rove about the surface on its motorized landing gear.

Figure 1. Daedalon Flight Profile.

III. Vehicle System

The principal task in the investigation of the Daedalon concept was the sizing of the vehicle system, which consists of five major segments: Payload, Daedalon Lander, Backshell, Cruise Stage, and Launch Vehicle. The lander and cruise stage were sized in the most detailed manner, with a parametric sizing spreadsheet taking into account every major system's mass and power budgets. The payload and backshell were sized based on historical data, and the launch vehicle was selected using a spreadsheet-based tool from the Georgia Tech Space Systems Design Lab (SSDL).

A. Payload

Daedalon is designed with a payload bay which can accommodate a number of different types of payloads; indeed, this is one of the fundamental benefits of the Daedalon approach. The goal for this design was, additionally, to accommodate more payload mass than previous vehicles. Fairly early in the development of the sizing spreadsheet, it was realized that Daedalon could not nearly support a payload the size of an entire Mars Exploration Rover (MER), which was an original goal of the system; however, since Daedalon's mission would not depend on the payload roving (since the lander itself could rove), the payload accommodations only needed to include room for mission-specific hardware. Thus, the Daedalon payload only needs to be compared to the science instruments aboard previous Mars rovers.

Unfortunately, mass estimates were not available for all instruments aboard the MERs or the 1997 Sojourner rover. However, from the available data,[1] it was estimated that the MERs hold about 7.9 kg of payload with a normal operating power of 32 W. Similarly, for Sojourner it was estimated that 1.4 kg of payload was carried with an operating power of 2 W. Also, for the purposes of comparison, it is known with certainty that the Sojourner rover as a whole had a mass of 10 kg and power output of 16 W.

Table 1. Available MER Payload Data.[1] *Note: Other payloads were carried for which no mass or power data were available.*

Instrument	Mass (kg)	Power Consumption (W)
Mini-TES	2.10	*Not Available*
Mössbauer Spectrometer	0.55	2.0
Rock Abrasion Tool (RAT)	0.75	30.0
Pancam	0.54	*Not Available*

Table 2. Available Sojourner Payload Data.[1] *Note: Other payloads were carried for which no mass or power data were available.*

Instrument	Mass (kg)	Power Consumption (W)
APXS	0.57	0.30
Cameras	0.12	4.20

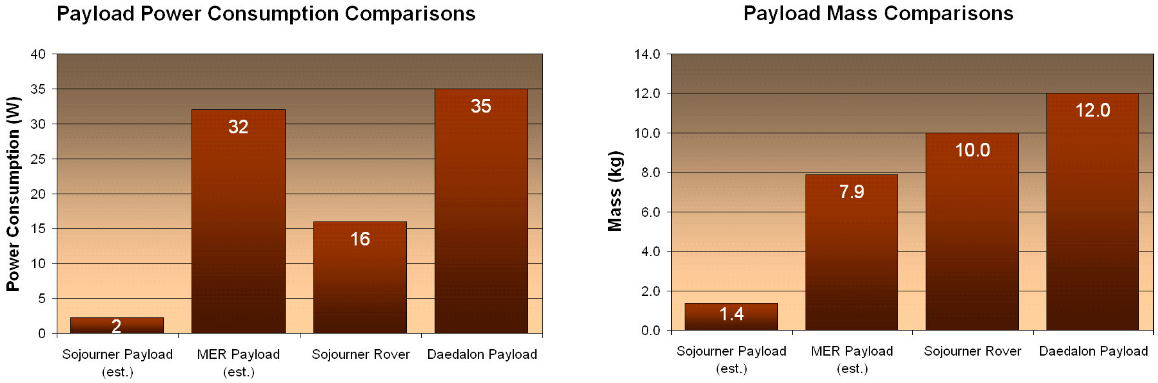


Figure 2. Payload Comparisons.

As can be seen from Fig. 2 above, Daedalon can conceivably fill the payload needs of any Sojourner- or MER-class mission. Additionally, from Fig. 3 it is evident that Daedalon can even hold a Sojourner-class rover as a payload if the desired mission requires finer roving control than Daedalon can provide on its own.

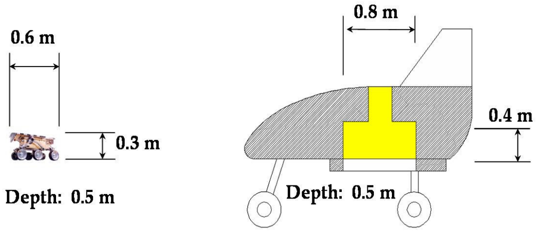


Figure 3. Daedalon Payload Bay and Sojourner Rover

One final note on the payload is that, as will be seen in Table 4, the payload is assumed to perform in a dormant mode during the journey from Earth and during the nighttime on Mars in which it is only allotted 5.3 W. Once the flight phase begins, the payload is allotted the full 35 W, which means that the payload can perform at full power during flight, offering advantages if an atmospheric sciences package, for example, were to fly as a payload.

B. Daedalon Lander

The Daedalon lander and cruise stage were sized system by system through a combination of mass estimating relationships and hardware mass and power specifications. This part of the project drew heavily from Ref. 2 and the expertise of the SSDL. For clarity, this paper details the vehicle system by system, but it should be noted that the entire process for sizing the vehicle was iterative based on the parametric spreadsheet developed.

Overall, the lander has a dry mass of 138 kg (including 25% dry mass margin). When loaded with 101 kg of propellant and pressurant and 12 kg of payload, the entire system has a mass of 250 kg (see Table 3). The vehicle has a peak power consumption of 226 W during flight and a dormant power consumption of 30 W during nighttime on Mars and during the cruise from Earth to Mars. In Fig. 4, key dimensions of the Daedalon lander are given.

1. Propulsion System

The Daedalon lander's propulsion system is composed of two major components: the cruise propulsion system and the descent propulsion system. During the 54 minute low-speed cruise, the lander consumes 90.7 kg of monopropellant hydrazine fuel through the use of two 36 N thrusters (with an I_{sp} of 235 s) mounted on the sides of the craft at the rear of the propulsion pods.

The thrusters were chosen based on thrust specifications[2] which matched the estimated steady-state drag on the vehicle. Drag itself was estimated through the use of a lift-to-drag ratio vs. lift coefficient curve from experimental data obtained from the NASA Dryden Mini-Sniffer craft,[3] which operated at altitudes in Earth's atmosphere bearing similarity to aerodynamic conditions in the atmosphere of Mars. This resulted in an assumed lift-to-drag ratio of 14.6. Steady and level flight was assumed, and total drag on the vehicle was found to be 64 N. The two 36 N thrusters selected provided the closest match.

The descent propulsion system consists of two nadir-mounted thrusters which fire during the last seconds of flight after the craft has gone into a deep stall in preparation for landing.[‡] These two 444 N thrusters (with an I_{sp} of 235 s) use a total of 0.2 kg monopropellant hydrazine to allow a soft landing on Mars. The thrusters were chosen from specifications[2] based on the thrust needed (i.e. the weight of the vehicle on Mars), and the required fuel was calculated from the 8.6 m/s ΔV necessary to halt the fall of the craft from 10 m altitude.

The cruise and descent propulsion systems have several components in common, including propellant and pressurant tanks and the propellant and helium pressurant within them.

In total, propulsion system hardware amounts to 12.5 kg in mass, and fuel and pressurant combine to a mass of 100.6 kg. Power consumption was estimated at 5 W per thruster while firing.[2]

Table 3. Lander Mass Breakdown.

	Mass (kg)
Spacecraft Systems	
Propulsion	12.5
Communications	4.3
GNC	3.6
C&DH	3.2
Thermal	5.0
Power	47.9
Structure & Mech.	33.8
Dry Mass Margin	27.5
Dry Mass	*137.7*
Propellant	90.9
Prop. Reserves & Residuals	9.1
Pressurant	0.7
Payload	12.0
Gross Mass	**250.4**

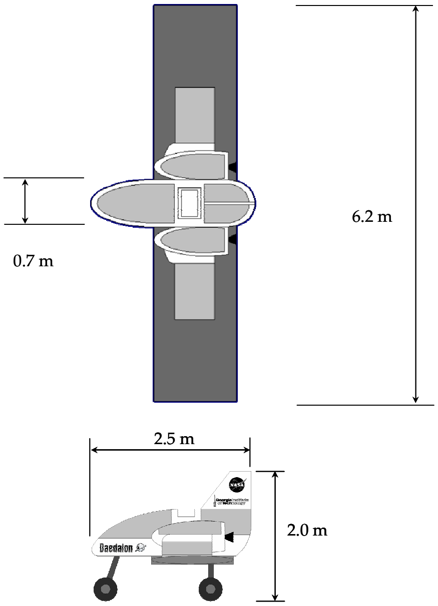


Figure 4. Daedalon Lander Dimensions (landed configuration).

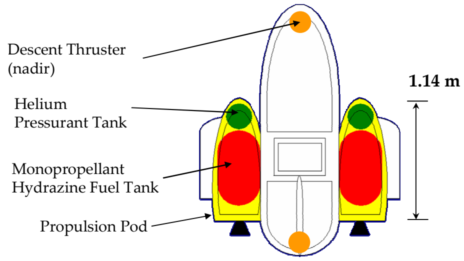


Figure 5. Lander Propulsion System.

[‡] The use of a deep stall to facilitate the landing of a Mars airplane is not a new idea; see also Ref. 4.

2. *Power System*

The Daedalon lander draws its power primarily from solar arrays; however, during the flight phase of the mission, the lander requires more power than its complement of body-mounted solar panels can provide. The lander must also maintain a level of power during the Martian night. To accomodate these needs, the lander's power system also consists of a 670 W-hr NiH_2 battery. The final components of the power system are power control units, converters, and wiring.

One issue in estimating mass for the power system arose as the design began to close. It was realized that the power system was disproportionately large because the same power consumption number was used to size all components. To solve the problem, four power modes were identified: Dormant, Pre-Entry, Flight, and Post-Flight.

The Dormant power mode accounts for housekeeping power necessary during the nighttime on Mars and during the cruise from Earth to Mars. The Pre-Entry mode is used during the 5.5 hr period between the backshell's release from the cruise stage and entry into Mars' atmosphere. The Flight mode is used during the low-speed cruise, and once landed, Daedalon transitions into the Post-Flight mode for surface operations. Table 4 shows a system-level breakdown of power consumption in each of the modes. Note that the power consumption of the power system accounts for losses due to conversion and wire resistance.

Table 4. Lander Power Modes. *All figures in watts.*

	Dormant	Pre-Entry	Flight	Post-Flight
Spacecraft Systems				
Propulsion	0.0	0.0	10.0	0.0
Communications	0.0	0.0	2.8	2.8
GNC	0.0	21.0	52.0	32.0
C&DH	8.0	20.0	20.0	20.0
Thermal	4.3	4.3	4.3	4.3
Power	7.5	22.5	56.4	47.8
Structure & Mech.	0.0	0.0	7.0	18.0
Margin	4.9	16.9	38.1	31.2
Subtotal	*24.7*	*84.7*	*190.5*	*156.1*
Propellant	0.0	0.0	0.0	0.0
Prop. Reserves & Residuals	0.0	0.0	0.0	0.0
Pressurant	0.0	0.0	0.0	0.0
Payload	5.3	5.3	35.0	35.0
Total Consumption	**30.0**	**90.0**	**225.5**	**191.1**

In total, the power system accounts for 47.9 kg of the lander's mass. Most mass estimating relationships for this system were either taken directly from Ref. 2 or, where appropriate, modified to reflect reduced sunlight intensity at the surface of Mars.

To size the battery, the necessary capacity was estimated for the period from backshell release to landing as well as for the nighttime dormant stage. The greater of these two numbers was the former, resulting in the 670 W-hr battery capacity.

The solar arrays were sized based on the Post-Flight power mode. It was found from the Daedalon CAD model that 1.5 m² of solar panels could be placed on the lander's fuselage and propulsion pods. To complete the 2.5 m² solar array area necessary on the surface of Mars, two 0.5 m² arrays are deployed over the wings upon landing. All arrays and panels consist of 15% efficient GaAs photovoltaic cells. Note also that the body-mounted solar panels contribute a significant amount to the power in the Flight power mode, which helps limit the mass of the power system.

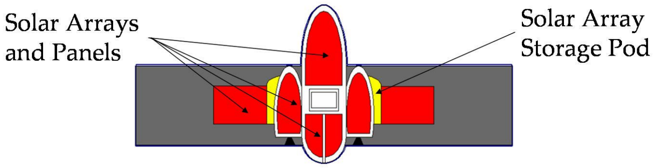


Figure 6. Daedalon Lander Solar Arrays and Panels (landed configuration).

3. Structures and Mechanisms

The structures and mechanisms category is extensive for the Daedalon lander. This system includes the morphing wing, vertical tail, fuselage, propulsion pods, landing gear and landing gear wheel motors, and pressurant and tanks for the morphing wing and landing gear.

The sizing of Daedalon's morphing wing was the most challenging aspect of the design. Significant research was performed on current concepts, although technical papers, articles, and contacts revealed that morphing wing concepts today are diverse and not fully developed. However, enough data was available to make an educated estimate of the morphing wing's mass.

The approach to sizing the morphing wing was to first determine wing parameters at three points during flight: Deployment, High-Speed Flight, and Low-Speed Flight. Lift coefficients and flight speeds were estimated for the high- and low-speed design points based on earlier documented Mars airplane investigations. These pieces of information, combined with atmospheric density[5] and the vehicle weight on Mars, allowed the planform area of the wing to be estimated. This, in turn, allowed a basic wing mass to be estimated based on empirical wing mass estimation equations. Parameters for these high- and low-speed wing design points are listed in Table 5. Note that the driver for the wing basic structure mass is the low-speed configuration because of its large span and planform area. Since the morphing wing was sized for the largest basic structure mass, this low-speed 4.66 kg mass was used.

Table 5. Morphing Wing Design Points.

	Vehicle Weight	Atmospheric Density	Flight Speed	Mach No.	C_L	Planform Area	Wing Basic Structure Mass
High-Speed	932 N	0.0083 kg/m^3	342 m/s	1.5	0.4	4.8 m^2	1.87 kg
Low-Speed	932 N	0.0150 kg/m^3	142 m/s	0.7	0.8	7.8 m^2	4.66 kg

The next step in sizing the morphing wing was to estimate the morphing penalty to be added to the wing basic structure. One of the initial thoughts for this was to use a process similar to that proposed in Ref. 6. In this approach, a 5 lb/ft^2 (24 kg/m^2) penalty was added based on the area change of the morphing wing. However, this approach was found to be ill-suited to the Daedalon concept. As it was intended for military applications on Earth, it was unclear whether the estimate could be scaled for Mars.

Further research resulted in the final approach to morphing wing sizing. Based on Ref. 7, information from the SSDL and Georgia Tech Aerospace Systems Design Lab, and pressurant and pressurant tank equations,[2] the approach of telescoping and rotating spars and wing skin was utilized. In this approach, the morphing wing operates via morphing spars which have the ability to rotate and telescope. The wing does not have a stretching skin, but rather one which telescopes with the spars. The spar system consists of 6 spanwise spars, 2 spars along the longitudinal axis, and 4 small spars extending downward from the vehicle to support the wing while it is supporting the heat shield insulator (note that the heat shield insulation mass is accounted for in the backshell budget, since it is released and is not carried during flight). Thus, the total mass of the wing is made up of a basic structure, a penalty including the mass of the actuators that allow wing sweep changes, and finally the mass of the morphing spars themselves along with the pressurant tanks and helium pressurant to allow the spars to telescope. Power required by the wing is small because of the use of pressurant to telescope the wing: 7 W are allotted for in-flight wing morphing.

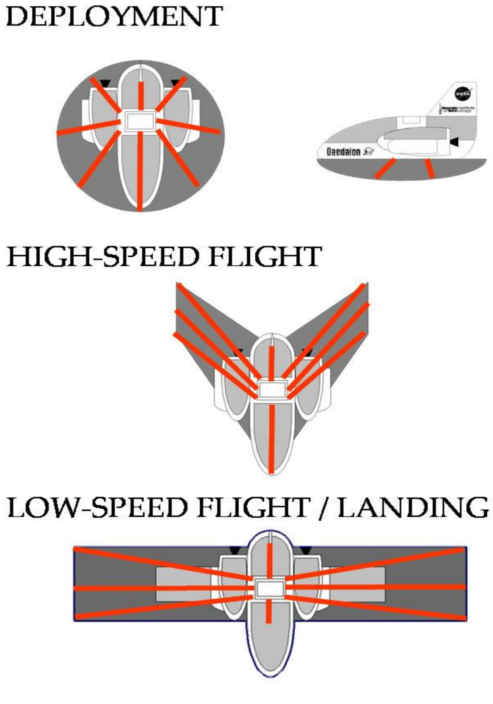


Figure 7. Morphing Wing Spar Structure.

The sizing of the fuselage, propulsion pods, and empennage was fairly straightforward. The dimensions for all components were gathered from the two-dimensional Daedalon CAD model, and all components were sized using appropriate empirical mass estimation equations.

The final component of the structures and mechanisms aboard the Daedalon lander is the landing gear. This includes the wheels and struts on which the lander alights following its deep stall and propulsive descent. Landing gear basic structural mass was estimated using an empirical mass relationship based on vehicle landed mass, resulting in a mass of 2.1 kg. Added to this were 0.2 kg of dedicated pressurant tanks and helium pressurant to inflate the wheels just before landing. Also added were 6.7 kg in motors to allow roving. Specifically, each of the three motors is capable of delivering 37.3 N-m torque, which is meant to allow the 0.37 m diameter wheels to roll over obstacles just over 0.09 m high. The power budget for the motors is a total of 18 W for nominal roving.

In total, structures and mechanisms aboard Daedalon account for 33.8 kg mass.

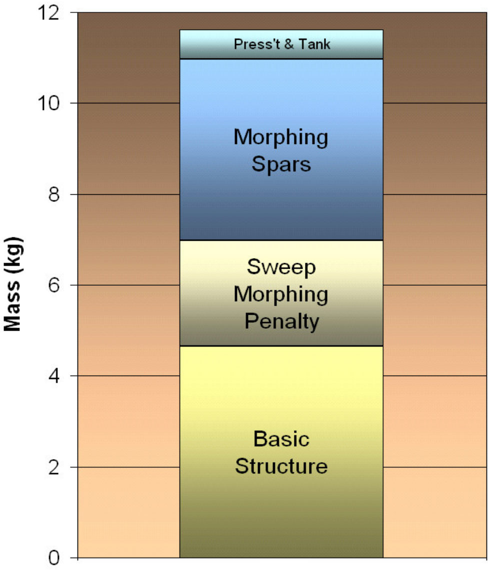


Figure 8. Morphing Wing Mass Breakdown.

4. *Guidance, Navigation, and Control System*

The guidance, navigation, and control (GNC) system aboard the Daedalon lander consists of an inertial measurement unit (IMU), radar equipment, flight sensors, servos, and two navigation cameras. This equipment is designed to aid Daedalon in its flight phase as it autonomously searches for the optimum landing site. This equipment also, however, allows navigation once the vehicle lands and begins roving. Note that the computers enabling these navigation devices to be used are accounted for under the command and data handling system.

Masses for items in the GNC system were estimated based on Ref. 8, plus contingency for an increase in vehicle complexity. The power budget was based upon Ref. 2 and upon inputs contributed by the SSDL. In total, the GNC system contributes a mass of 3.6 kg to the lander's total mass. During the Dormant power mode, none of the GNC equipment is turned on. Once separated from the cruise stage, the IMU, sensors, and servos are powered on, and during flight all equipment is operational. For the Post-Landing power mode, the radar is nominally powered off.

5. *Command and Data Handling System*

The command and data handling (C&DH) system aboard the Daedalon lander is defined to include all on-board computers. Based on Ref. 2 and inputs from the SSDL, the system's mass was estimated at 3.2 kg, with a powered-up consumption of 20 W. During the Dormant power mode, it was estimated that housekeeping functionality would be fulfilled by powering the computers at 40% of nominal power.

6. *Communications System*

The Daedalon lander communication system allows 512 kbps UHF communications with an orbiting relay satellite. During flight, this satellite is the Daedalon cruise stage. However, since the cruise stage is on a flyby trajectory, the lander will depend on an existing satellite for transmissions to and from Earth once landed. The on-board equipment, which includes a transponder, power amplifier, diplexer, whip antenna, and cable harness, has a total mass of 4.3 kg. The power requirements for the communications system were estimated based on Eq. (1) (here, P represents power, G represents gain in dB, and L represents a loss factor).

$$P_{received} = \frac{P_{transmitted} G_{transmitter} G_{receiver}}{L_{space} L_{atmospheric}} \tag{1}$$

To attain an acceptable signal-to-noise ratio between Daedalon and the relay satellite of 11.8 dB, the Daedalon lander transmits at a power of 2.8 W. The communication system is assumed to operate at full power during flight and during nominal landing operations. It is turned off entirely for the Dormant and Pre-Entry power modes (for Pre-Entry, communication is handled by backshell systems).

7. *Thermal Control System*

The Daedalon lander thermal control system maintains proper temperatures for the Daedalon craft throughout the mission. For the purposes of power consumption, it is assumed to be fully powered at all times. Based on Ref. 2, the thermal system was estimated to account for 5.0 kg. The system is powered at 4.3 W for all power modes.

C. Backshell

The third component of the Daedalon system is the backshell, which provides aerodynamic stability for the lander during atmospheric entry. It also provides communication between the Daedalon lander and cruise stage until lander separation. The backshell is fairly typical of historical Mars lander backshells, and was thus estimated based on data from the Mars Exploration Rover, Pathfinder, and proposed ARES[9] missions. This was made simpler since the Daedalon vehicle's entry diameter was designed to match previous backshell diameters of 2.65 m. Averaging historical data and subtracting mass for unnecessary ground radar and retro rockets yielded a Daedalon backshell mass of 250 kg (with 25% dry mass margin included).

Also accounted for in the backshell category was the heat shield insulation. While actually part of the Daedalon lander, the insulation is accounted for in this category to avoid complications which would have arisen since it is not carried throughout the lander's flight. The insulation used is SLA-561, with a typical thickness of 1.9 cm for Mars entry. The insulation is placed on the bottom surface of the lander's morphing wing for entry and is then discarded after entry so that the wing can morph into a high-speed flight configuration. In total, the insulation covers a total area of 6.1 m² and has a mass of 31 kg.

D. Cruise Stage

The function of Daedalon's cruise stage is to support the Daedalon lander on the cruise from Earth to Mars by providing communications, power, and course correction functionality. Like the Daedalon lander, the cruise stage was sized system by system through a combination of mass estimating relationships and hardware mass and power specifications. While the cruise stage is detailed here system by system, it should be noted that the entire process for sizing the vehicle was iterative based on the parametric spreadsheet developed.

Overall, the cruise stage has a dry mass of 291 kg (including 25% dry mass margin). When loaded with 55 kg propellant and pressurant and 549 kg of payload (i.e. the backshell, backshell adapter, lander, and payload), the entire Daedalon system has a mass of 896 kg (see Table 6 and Fig. 9). The vehicle has a nominal power consumption of 367 W after trans-planetary injection and a lower power consumption of 232 W before that time to limit battery usage during the launch phase. The cruise stage has a diameter of 2.65 m, identical to that of the backshell.

Table 6. Cruise Stage Mass Breakdown.

	Mass (kg)
Spacecraft Systems	
Propulsion	5.9
Communications	26.6
GNC	18.8
C&DH	25.0
Thermal	20.9
Power	85.3
Structure & Mech.	50.6
Dry Mass Margin	58.3
Dry Mass	*291.4*
Propellant	50.0
Prop. Reserves & Residuals	5.0
Pressurant	0.3
Payload	549.4
Gross Mass	**896.1**

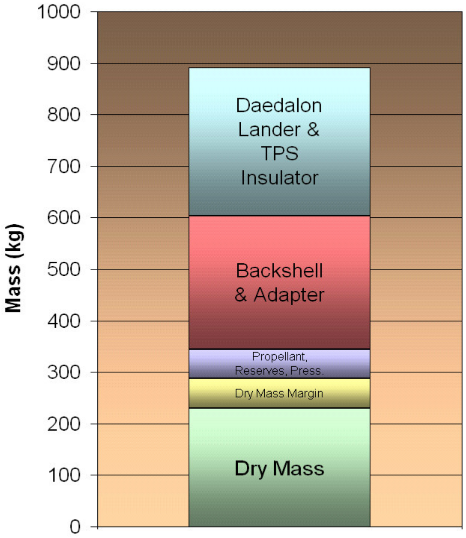


Figure 9. Cruise Stage Gross Mass Breakdown.

1. *Propulsion System*

After receiving its final boost from the Delta II 7925 launch vehicle, Daedalon has the ability to maneuver and make course corrections through the cruise stage propulsion system. The system consists of twelve 13 N thrusters (with an I_{sp} of 225 s) which can provide a total of 130 m/s ΔV. This is equal to the ΔV capability of the 1997 Pathfinder mission.[10]

In total, the cruise stage carries 50.0 kg monopropellant hydrazine fuel, 5.0 kg fuel reserves and residuals, and 0.3 kg helium pressurant. The total mass of the two fuel tanks is 1.7 kg, and the total mass of the two pressurant tanks is 1.8 kg. Power consumption was estimated at approximately 5 W per thruster while firing.[2] Nominal power requirements for the propulsion system assume six thrusters firing plus 5% contingency, resulting in 31.5 W.

In total, propulsion system hardware amounts to 5.9 kg in mass, and fuel and pressurant combine to a mass of 55.3 kg.

2. *Power System*

The Daedalon cruise stage draws power primarily from its deployable solar array; however, during the phase of the mission between launch and trans-planetary injection, the vehicle requires battery power since the array is stowed. To account for this, the cruise stage's power system also consists of a 1160 W-hr NiH_2 battery. The final components of the power system are power control units, converters, and wiring.

As with the Daedalon lander power system design, it was realized that the power system was disproportionately large because the same power consumption number was used to size all components. To solve the problem, two power modes were identified: Pre-Injection and Post-Injection. Table 7 shows a system-level breakdown of power consumption for each mode. Note that the power consumption for the power system accounts for losses due to conversion and wire resistance.

In total, the system accounts for 85.3 kg of the cruise stage's mass. Most mass estimating relationships for this system were either taken directly from Ref. 2 or, where appropriate, modified to reflect reduced sunlight intensity in Mars orbit.

Since practically the entire journey from Earth to Mars will be in sunlight, the on-board battery only needed to be sized based on the power required between launch and trans-planetary injection (i.e. while the solar array is stowed). It was estimated that the Pre-Injection power mode would be applicable to a period of 5 hours, resulting in a required battery capacity of 1160 W-hrs. It was also considered that battery power may be needed to communicate with Earth if the craft makes its flyby partially in the shadow of Mars; however, the length of this period would not drive battery capacity, particularly since the flight of the Daedalon lander is assumed to occur during the Martian day.

The solar arrays were sized for the Post-Injection power mode level. This required a total solar array area of 4.2 m^2 with the use of 15% efficient GaAs photovoltaic cells. Since the area could not be accommodated on the body of the craft, a deployable solar array was used.

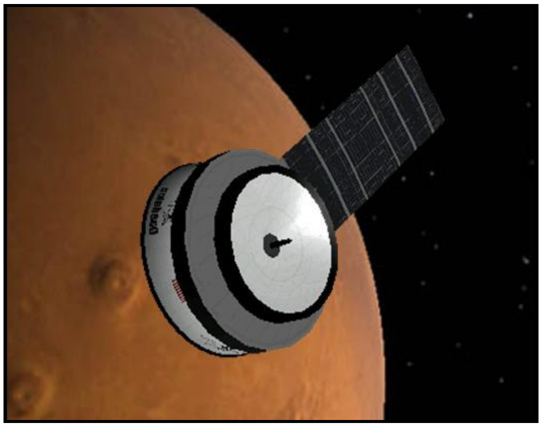


Figure 10. Cruise Stage prior to Backshell Release.

Table 7. Cruise Stage Power Modes. *All figures in watts.*

	Pre-Injection	**Post-Injection**
Spacecraft Systems		
Propulsion	0.0	31.5
Communications	45.3	60.4
GNC	18.2	53.2
C&DH	25.0	25.0
Thermal	15.0	15.0
Power	58.0	84.0
Structure & Mech.	0.0	0.0
Margin	40.4	67.4
Subtotal	*201.7*	*336.8*
Propellant	0.0	0.0
Prop. Reserves & Residuals	0.0	0.0
Pressurant	0.0	0.0
Payload	30.0	30.0
Total Consumption	**231.7**	**366.7**

3. *Structures and Mechanisms*

The structure of the Daedalon cruise stage includes all elements to support the craft's loads. Since the cruise stage is quite standard (unlike, for example, the Daedalon lander), the structural mass of the system was estimated based on historical satellite structural mass averages. In total, structures and mechanisms account for 50.6 kg.

4. *Guidance, Navigation, and Control System*

The guidance, navigation, and control (GNC) system aboard the cruise stage consists of an inertial measurement unit (IMU) as well as several attitude sensors (such as sun and star sensors). Note that the computers enabling these navigation devices to be used are accounted for under the command and data handling system.

In total, the GNC system contributes 18.8 kg to the vehicle's total mass. During the Pre-Injection power mode, only the IMU and sun sensor are assumed to be powered on. Once the solar array is deployed after trans-planetary injection, the entire GNC system can be powered on.

5. *Command and Data Handling System*

The command and data handling (C&DH) system aboard the Daedalon cruise stage includes all on-board computers. The system's mass was estimated at 25.0 kg, with a powered-up consumption of 25 W. The on-board computers are fully powered for both of the cruise stage's power modes.

6. *Communications System*

The Daedalon cruise stage communication system is somewhat more complex than the lander's communication system since the cruise stage communicates with both the lander and Earth. The cruise stage utilizes a 2 m dish for UHF communications with the lander and 8 GHz X-band communications with NASA's Deep Space Network. The on-board equipment, which includes transponders, filters, switches, and the antenna dish, has a total mass of 26.6 kg. The power requirements for the communications system were estimated in the same manner as they were for the lander's communications system through the use of relationships between communications system gain, loss factors, and transmission power. In this case, dish size considerations were also included.

The maximum communication power was found to be required for communication with Earth: To attain an acceptable signal-to-noise ratio of 7.5 dB, the Daedalon cruise stage transmits to Earth at a power of 60.4 W. Communication occurs either to Earth or to the lander, but never both at the same time; thus, the 60.4 W transmission power is used as the communication system's Post-Injection power requirement. During the Pre-Injection power mode of operations, the communication system is assumed to operate at 75% of this power, or at 45.3 W due to its proximity to Earth.

7. *Thermal Control System*

The Daedalon cruise stage thermal control system maintains proper temperatures for the craft throughout the mission. For the purposes of power consumption, it is assumed to be fully powered at all times. Based on historical relationships for satellite systems,[2] this thermal system was estimated to account for 20.9 kg of vehicle dry weight. The system is powered at 15.0 W for all power modes.

E. Launch Vehicle

The launch vehicle for Daedalon was selected using an SSDL-developed launch vehicle selection tool.[11] The parameters of system mass, vehicle diameter, and required C3 were inputs, and the spreadsheet optimized to find the lowest-costing U.S. expendable launch vehicle capable of meeting the performance specifications. System mass and vehicle diameter had already been set at 896 kg and 2.65 m, respectively, and a C3 of 14 km²/s² was used based on 2025 Mars launch opportunity data.

The American launch vehicle which can most economically meet these requirements is the Delta II 7925. This rocket has a fairing diameter of 2.9 m and a payload capacity of 940 kg for a C3 of 14 km²/s², matching the Daedalon system requirements quite well. This rocket has also established a history of successful Mars launches, including Pathfinder and the Spirit MER (Opportunity was launched on a Delta II 7925H). A single launch on a Delta II 7925 costs $57.1 million (2004 est.).

IV. Design Evaluation and Comparison

As mentioned in this paper's introduction, the premise of Daedalon is that such a versatile system can enable gains in planetary probe standardization, information acquisition, and efficiency. The final aspect of this project was to compare the capabilities of Daedalon to those of other Mars exploration vehicles in attempt to quantify those gains. In the following pages, measures of cost, functionality, and flexibility demonstrate that the Daedalon concept does have the potential to change the way Mars is explored.

A. Cost Estimation and Comparison

With the design described above, it is possible to estimate the cost of the Daedalon system. Used in this process were NASA Johnson Space Center cost estimation tools.[12] Inputs into the Spacecraft/Vehicle Level model include system dry mass and number and type of craft to build. Investment cost outputs can then be used as inputs into the Mission Operations model to obtain operations cost estimates. Launch vehicle costs were derived based on Delta II 7925 launch costs. In all cases, dollar amounts were converted to 2004 dollars. Also note that the numbers presented here assume that necessary technologies (e.g. the morphing wing) have already been developed to a high level.

As is common to most cost models, system dry mass was the prime cost driver. In the case of Daedalon, the system dry mass is 720 kg. Based on the cost models used, it was estimated that to fly a single Daedalon mission (as was done with the Pathfinder mission) would cost $643 million. This falls between the Pathfinder cost of $299 million and the MER program cost of $820 million (for two missions). However, the concept of Daedalon, a vehicle that is not mission-specific and is capable of flying a wide variety of missions to Mars, is indeed best suited to flying many missions. Creating a Daedalon vehicle to fly just once would fail to exploit these advantages. Thus, further cost analysis considered multiple production vehicles.

Table 8. Single Mission Cost.

Development	$495 million
Production	$75 million
Launch	$57 million
Operations	$16 million
Total Cost	$643 million

When one looks at increasing the number of production vehicles, total program cost inevitably increases (see Fig. 11). At the same time, however, the cost per vehicle decreases. While operations and launch costs essentially scale linearly, development costs are constant and the production cost per vehicle decreases as more vehicles are built. Thus, significant changes in per-vehicle cost can be seen as one moves from one vehicle to two vehicles, though these changes in per-vehicle cost become smaller as the number of vehicles increases.

If five Daedalon vehicles are assumed, the total program cost reaches $1.12 billion. However, the cost per vehicle drops dramatically to $224 million, which is less than the cost of the Mars Pathfinder mission. As will be shown, Daedalon is also significantly more functional than past Mars landers and rovers.

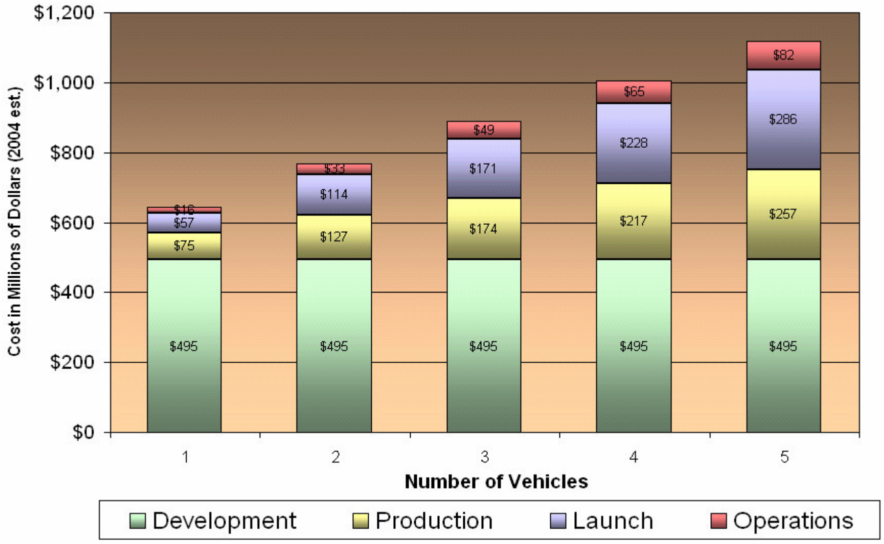


Figure 11. Daedalon Program Cost vs. Number of Production Vehicles.

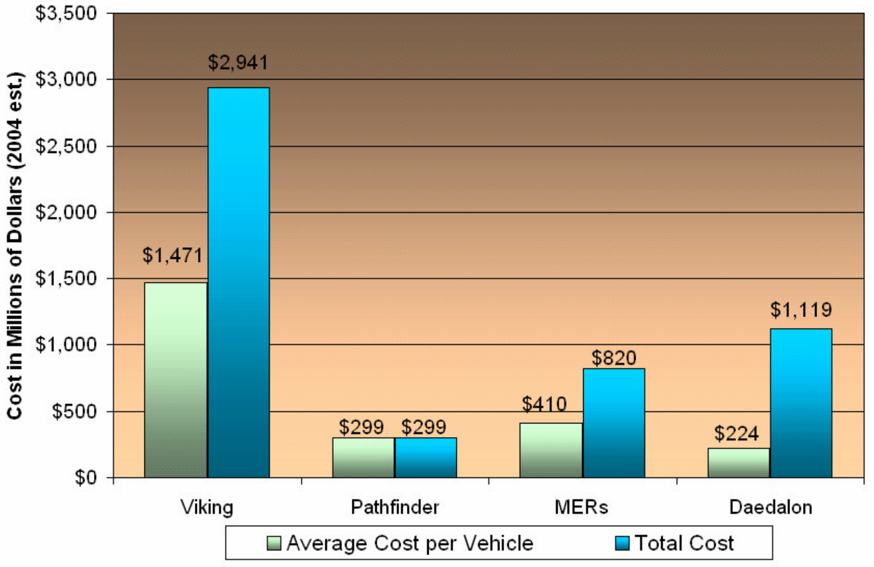
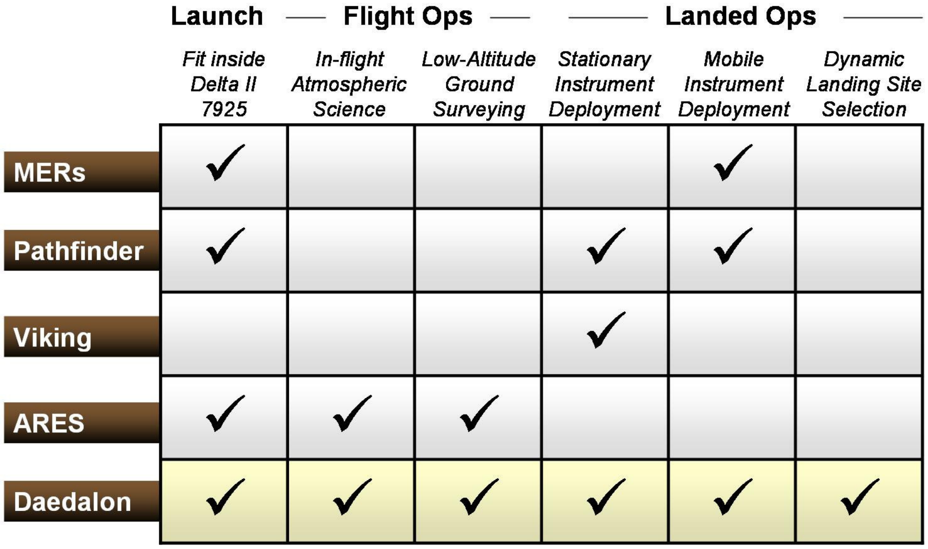


Figure 12. Comparison of Program Costs. *Five Daedalon production vehicles are assumed.*

B. Functionality Comparison

Figure 13 compares functional aspects of past Mars missions which have entered (or been proposed to enter) the Martian atmosphere. The two successful Mars rover programs are listed, as well as Viking, which is representative of a stationary lander. The proposed Mars airplane ARES[9] is also listed in part to represent airplane concepts for Mars. Finally, Daedalon is listed. Check marks indicate achieved (for past missions) or achievable (for future missions) functionality in a given category.



	Launch	Flight Ops		Landed Ops		
	Fit inside Delta II 7925	*In-flight Atmospheric Science*	*Low-Altitude Ground Surveying*	*Stationary Instrument Deployment*	*Mobile Instrument Deployment*	*Dynamic Landing Site Selection*
MERs	✓				✓	
Pathfinder	✓			✓	✓	
Viking				✓		
ARES	✓	✓	✓			
Daedalon	✓	✓	✓	✓	✓	✓

Figure 13. Mars Mission Functionality Comparison.

Launch. The Delta II 7925 has become a fairly common option for Mars missions in recent years. The ability to fit inside a Delta II 7925 is mainly meant as a measure of vehicle size and thus cost. The Viking orbiters and landers were quite massive and were launched aboard a 3700 kg capacity Titan IIIE.

Flight Ops. The ability to conduct atmospheric science at high altitudes as well as survey the ground from an altitude between ground level and orbit are both abilities unique to Mars aerial vehicles. While flying in search of a landing site, Daedalon can also fulfill these goals depending on the payload it is carrying. Further, if a potential payload does not require a landing, Daedalon may still be an attractive $224 million or less alternative to developing an entirely new Mars aerial vehicle.

Landed Ops. This category is divided into the subcategories of stationary instrument deployment, mobile instrument deployment, and dynamic landing site selection. As a lander, Daedalon can deploy its instruments and simply remain at the landing site or leave instruments at selected points along its roving path. As a rover, Daedalon can carry instruments and devices best suited to searching the surface of Mars for given data. Finally, unlike any Mars lander or airplane design in the past, Daedalon offers the ability to immediately reap the benefits of low-altitude ground surveying by actually landing at the site that looks most promising from the air.

C. System Mass Comparison

As is partially evident from its cost, the Daedalon lander is more massive and more complex than any mobile vehicle that has been sent to Mars to date. However, as shown earlier, it is far more functional. There is undoubtedly a mass savings because Daedalon integrates entry, flight, landing, and roving abilities into a single vehicle. This is difficult to quantify, though, because no previous design has sought to accomplish all four elements using the same vehicle.

In an attempt to quantify this design integration mass savings, this study was able to use an existing parametric model of an ARES airplane to match Daedalon's basic mission functionality. Super-ARES, as it will be called, is an ARES craft which could fly the same distance as Daedalon,

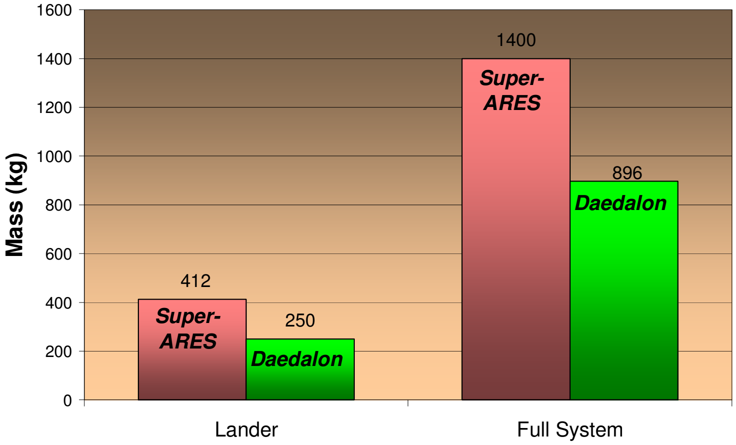


Figure 14. Design Integration Mass Savings. *Note that this Super-ARES design is functionally equivalent to Daedalon. However, it requires a >5 m payload fairing.*

crash-land on Mars, and then deploy a 138 kg rover with a payload capacity equivalent to Daedalon's.

The results of this analysis are shown in Fig. 14. The Super-ARES airplane and lander has a mass 162 kg more than the Daedalon lander, and the Super-ARES system has a gross mass 504 kg greater than the Daedalon system. Further, Super-ARES could not actually launch on any vehicle in production today because it would require a launch fairing diameter greater than 5 m. Clearly Daedalon's design integration strategy has advantages.

D. Range Comparison

Finally, a comparison was made between Daedalon and the Mars Exploration Rovers in terms of vehicle range at or below an altitude of 500 m. This metric is intended as an indicator of the amount of detail that can be acquired by each craft at a given time.

The distance that the MERs traveled below 500 m was estimated to be about 0.6 km before settling to a stop on the surface of Mars. Following that, the rovers were designed to travel about 0.9 km on Mars' surface, resulting in a total design range of 1.5 km. In contrast, Daedalon flies for a distance of 463.4 km while at 500 m or lower and then has the ability to rove, likely at least another 0.6 km. The sum of these distances gives a range for Daedalon of 464.0 km. This information is displayed in Table 9. One additional note to this information is that the first 0.6 km of the MERs' range has little scientific value since it primarily consists of falling to and bouncing on the surface of Mars. Further, if Daedalon's payload has the ability to roam farther than the lander carries it, Daedalon's effective range is increased for this metric.

Table 9. Dollars per Kilometer Comparison.

	Est. Range at or below 500 m	Mission Cost	Dollars Spent per Kilometer Travelled
MER	1.5 km	$410 million	$273 million
Daedalon	464.0 km	$224 million	$483,000

The metric of dollars per kilometer displayed in Table 9 is not meant as a deciding metric; however, it is meant to indicate the flexibility and scope that the Daedalon design can allow for future Mars exploration. With the current rover approach, one is very limited by where the rover happens to finish bouncing and rolling over the Martian surface. With the ability to survey a large area at low altitudes and high resolution and then finally land and rove at the ideal landing site, scientific gain per mission will be increased. While that increase in scientific gain is difficult to quantify, it is quite certain that any such increase will decrease overall costs in the long run.

V. Conclusion

Is the Daedalon design presented here feasible? The obvious technology driver for this design is the morphing wing. Virtually all other technologies used for the vehicle have already been used or will be available in the near-term. Based on the information encountered during the course of this project, there is still a very long way to go before morphing wings have the potential to be operational. However, if one looks at work being done by DARPA, the Morphing Aircraft Structures Program seeks to "ultimately design, build, and demonstrate a seamless, aerodynamically efficient, aerial vehicle capable of radical shape change."[13] The goals of the program include 200% changes in aspect ratio, 50% changes in wing planform area, 5° changes in wing twist, and 20° changes in sweep. While Daedalon's morphing wing requirements lie outside of this range, accomplishment of these goals may indicate that morphing on the order of Daedalon's is not far in the future.

Note, though, that in the broadest sense, the Daedalon concept is not about morphing wings as much as it is about the idea to use a standard vehicle for planetary exploration. Such a vehicle must provide substantial flexibility, which necessitates the integration of entry, flight, landing, and roving functionality. Since the ability to fly and the ability to land are both integrated, in-flight selection of a landing site may be easily enabled. The morphing wing is used in order to integrate entry with flight functionality, at the same time increasing aerodynamic efficiency and avoiding typical Mars airplane wing packaging constraints.

Given the necessary morphing wing technology development, the baseline Daedalon design is a feasible and cost-effective approach to exploring Mars. Still, while the morphing wing is one technology which would enable the necessary functional integration, others may exist and should be explored. The benefits of a system such as Daedalon are significant and present a cost-effective and flexible exploration architecture for a future of expanded study of the solar system.

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