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Paradigm Shift in Design for NASA's Space Exploration Initiative: Results from MIT's Spring 2004 Study

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This paper summarizes the findings of a comprehensive study commissioned by NASA's space architect and conducted by graduate students and faculty at MIT during spring 2004. The goal of the study was to broadly analyze implications of NASA's new space exploration initiative at the value, system architecture and vehicle levels. The space exploration system is expected to accomplish a wide variety of defined and undefined mission objectives throughout its lifetime, while doing so with limited resources. As a result, the traditional view of designing an optimal system that satisfies current mission objectives is no longer an effective design approach. A new approach is needed in which the system's lifecycle is considered throughout the design process, and environmental factors such as political and budgetary uncertainty are incorporated alongside more traditional factors such as technology development and scientific interests. To promote a sustainable system design, the first step in the design process is the identification of the true value delivered by the system to its stakeholders. In this paper we argue that the true value of an exploration system is knowledge acquisition, not simply transportation of humans and cargo to planetary surfaces. The new design process is defined and then applied to the space exploration system with decisions and analysis guided by knowledge delivery as the ultimate purpose, resulting in the design of a sustainable exploration system.

I. Nomenclature

LEO = Low Earth Orbit
STS = Space Transportation System
SRM = Solid Rocket Booster
ET = External Tank
EELV = Evolved Expendable Launch Vehicle
DSN = Deep Space Network
COV = Crew Operations Vehicle
HM = Habitation Module
CES = Crew Exploration System
SM = Service Module
MTV = Moon/Mars Transport Vehicle
ML = Mars Lander
LL = Lunar Lander

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MCM = Modern Command Module
SHM = Surface Habitation Module
LL1 = Lunar Lander 1
LL2 = Lunar Lander 2
L1 = Earth-Moon Lagrangian Libration Point 1
MOR = Mars Orbital Rendezvous

I. Introduction

ON January 14, 2004, President George W. Bush presented the nation with a bold new space exploration initiative. NASA has been given the task of developing the program, which will take humans back to the Moon by 2020, to Mars, and beyond. The directive raises two important questions for space system design. First, given the extended life-cycle of the project, how can one architect a space exploration system to accomplish the directive in a sustainable fashion? Second, what measures should be used to evaluate the performance and effectiveness of a sustainable exploration system? The following report, based on the work of the 2004 MIT spring graduate course in Space Systems Design, addresses these questions. In doing so, it presents a method for incorporating sustainability into the conceptual design of a space system, to develop a preliminary exploration system architecture. A new design process methodology is presented and then applied to the problem of designing a space exploration system. In order to develop a sustainable space exploration program and develop tools to evaluate the performance of the system, the primary goal of the system must be identified. This report will argue that the primary purpose of an exploration system is the delivery of knowledge to the stakeholders. Thus, the effectiveness of the system is related to the acquisition, synthesis and delivery of knowledge both in space and on the Earth.

II. Sustainability

In order to design a sustainable space system, the question of what is a sustainable exploration program must first be addressed. To “sustain” means literally: to maintain in existence, to provide for, to support from below. At the programmatic level, an exploration system will be maintained in existence provided that it receives funding, which in turn is contingent on the program meeting the needs of key stakeholders, members of Congress, the Administration, and ultimately the American people. Realistically, however, system designers must recognize that these needs themselves will change. A multi-year, multi-billion dollar program in the US Government must expect to face a great deal of uncertainty with respect to objectives, budget allocations, and technical performance.

In order for an exploration system to be sustainable, it must be able to operate in an environment of considerable uncertainty throughout its life-cycle. Traditional engineering definitions of sustainability are often limited to the physical and technical realms, defining sustainability in terms of physical operation over a long period of time. Space systems, however, are subject to influences from several realms, including policy decisions, budgetary uncertainty, organizational changes and the more traditional technical and supply chain issues that are incorporated into most engineering definitions of sustainability. It is important to recognize that threats to the sustained operation of a space system may not only come from these realms, but from the interactions between them. For example, a policy decision change may mandate a technical change that is responsible for the system’s ultimate failure to survive. Thus, different forms of sustainability may interact with one another and form a cyclic relationship between the policy, organizational, technical and operational realms. Designing for sustainability thus implies identifying various sources of uncertainty, and managing them through up-front system attributes. Various terms have been used to describe such system attributes, including: flexibility, robustness, and extensibility.

While a large complex system must react to changing environments in order to be sustainable, technological aspects of systems can themselves impact the environment. Once in development and operation, a multi-billion-dollar system will mediate political interests, organizational decisions, and technical alternatives, creating potential sources of stability and positive feedback-loops, as well as sources of uncertainty. Early decisions that create high switching costs or large infrastructure sites, can “lock-in” architectural configurations and influence the objectives and development path of later systems. A sustainable design will be one in which, to the greatest extent possible, the dynamics behind political, technical, and financial sources of stability support, rather than hinder, system development and operations.

There are two different sustainability design concepts that may be used to increase the length of a system’s lifecycle. On one extreme is robustness. A robust system is designed to withstand changes in its environment with minimal or no redesign. Unfortunately, this method is limited when designing for extreme uncertainties, since the factors may be unknown. On the other extreme lies flexibility. A flexible system design can adapt and evolve to meet the constraints imposed by the different environments in which it will operate. One element of flexibility that is particularly relevant to the creation of a long-term space exploration infrastructure is extensibility. Extensibility is the capability of a system to evolve or adapt through time such that it is better able to meet the needs of the key stakeholders. Unlike a point design, which is optimal for one point in time only, an extensible system is able to change and evolve in the face of future environmental uncertainty. Often, designing an extensible system will require additional up-front cost, with the goal of reducing the expected cost over the system's life cycle. An extensible space exploration system is one that will continue to deliver knowledge to the stakeholders, even in the face of unfavorable policy, organizational and budgetary changes, while also successfully incorporating most of the benefits of changes in these areas and breakthroughs in the technical realm. Extensible systems are therefore sustainable by their very nature, because of their ability to evolve through time, thus increasing the chances that such systems will remain useful and affordable.

III. Knowledge

In order to design a sustainable and successful exploration system, the primary purpose of the system must be identified. While there are myriad motivations behind exploration, such as national prestige, sovereignty, technical leadership, and inspiration, the primary purpose of any *exploration system* is knowledge acquisition. While mass transport enables exploration, the ultimate success of an expedition depends on the acquisition, communication, and synthesis of visual imagery, scientific data, and human experience to various stakeholders. As knowledge is returned, and perceived as valuable by the various stakeholders, it generates support for further exploration. Figure 1 illustrates how such a system can form a positive feedback loop resulting in sustainable exploration.

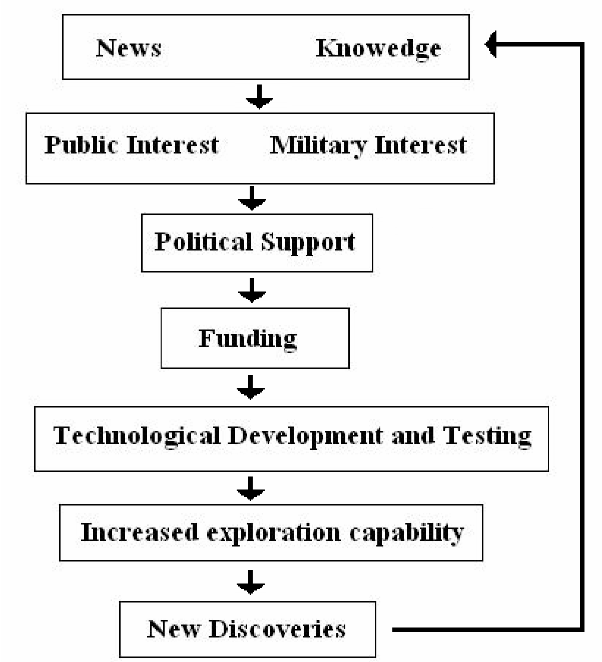


Figure 1. Positive feedback loop for knowledge, technology and support for exploration

Understanding the positive feedback relationship suggests revaluing traditional space system characteristics and trades to account for the demands of knowledge acquisition and delivery. Further, in order to make informed decisions about system capabilities and mission goals, attributes of knowledge must be categorized and valued in accordance with stakeholder needs. System designers must have a firm grasp of the knowledge delivery process, and establish how it will occur at each point in the system's lifecycle.

This report defines five specific types of knowledge and the associated beneficiaries:

1. Scientific knowledge focuses on the description of the universe and the world, which will ultimately generate a better understanding of past and present life. Scientific knowledge is of primary interest to the scientific community.
2. Resource knowledge relates to the existence, location and amount of materials that may be used for in-situ resource utilization. Resource knowledge is of primary interest to the government, private explorers, and commercial enterprises.
3. Operational knowledge relates to the performance of maneuvers and activities during a mission. Operational knowledge is of primary value to NASA and other space faring agencies, and individuals or corporations who may perform future activities in outer space.
4. Technical knowledge relates to the development, testing and operation of new technologies, which will be used in the exploration process. Technical knowledge is of primary interest to technologists and all those who would see the benefits of these technologies applied.
5. Experiential knowledge is gained from sending humans on exploration missions, and is most instrumental in the inspiration of the public and of future generations. Experiential knowledge is of primary interest to the American people, and indeed, to all humanity, who are able to identify with the heroic acts performed by past, present and future NASA astronauts.

The goal of a knowledge transportation system is to allow for knowledge transfer and transportation. Knowledge may be transported through three basic types of knowledge carriers, namely *bits, atoms and human experience*. These may be further divided into several categories, including:

1. Passive bits rely on remote collection, such as a digital image.
2. Active bits rely on direct interaction, such as the use of a Rock Abrasion Tool to determine the composition of a Martian rock.
3. Implied discovery relies on the return of a physical sample (atoms) for a conclusion to be reached with respect to a specific hypothesis, such as analyzing erosion characteristics of a rock to determine the existence of water on Mars.
4. Direct proof requires the transport of a physical sample that directly verifies or refutes a hypothesis, such as the discovery of liquid water flowing on Mars.
5. Human experience requires the direct interaction of humans with that which produces knowledge, such as the experience of the first Martian astronaut seeing, feeling and perhaps even tasting liquid water on Mars. Human experience is that which may be directly perceived through the basic senses.

The process by which knowledge is delivered is a cycle, in which one piece of knowledge fuels a concept for a new exploration mission. This mission is then designed and executed, and if all goes well, data is returned for analysis. The data is then processed and the relevant knowledge is extracted, which in turn fuels another exploration mission.

The knowledge delivery cycle time includes the amount of time required for a mission to be conceived, designed, implemented and executed, in addition to the amount of time that it takes for knowledge to be successfully extracted from data. This research latency, referred to as the Knowledge Delivery Time, must be factored into the mission design, and is as important as the mission design time.

A sustainable knowledge delivery system must recognize that, although news is often instantaneous, net knowledge delivery often takes years. For example, the Hubble Space Telescope did not peak in knowledge delivery (as measured by the publication of papers in scientific journals) for 8 years, as seen in Figure 2. A balance must be sought between allotting sufficient time between missions, such that one mission may take full advantage of its precursor's achievements and maintaining public interest in space exploration by continued achievements. Although, initially, the media will serve this function, it is important to establish other means of information dispersion, as exploration activities become routine and are no longer considered news. Thus, it is important to recognize that the successful establishment of a sustainable knowledge delivery-based exploration system must extend into the realms of socio-political engineering as well as into the more traditional realm of technical engineering.

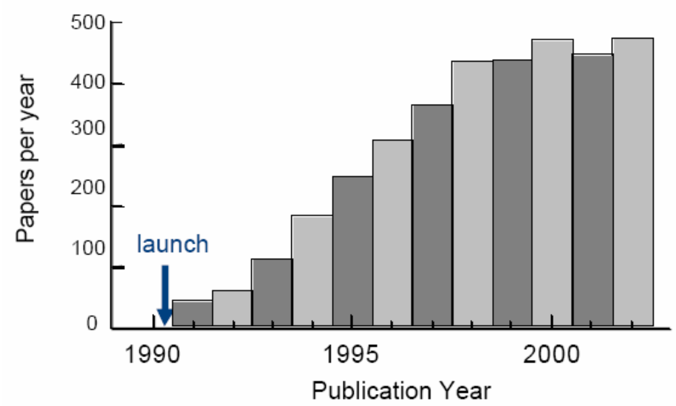


Figure 2. Hubble Space Telescope knowledge throughput[1]

IV. Proposed Design Process

President Bush set forth two major milestones for the new exploration system. The nation will first return humans to the Moon. Lunar missions will be used as a test bed for the second milestone, eventual Martian exploration. This high-level outline suggests a "stepping-stone" strategy that will develop over an extended timeline. In order to meet these objectives, the exploration system must operate through political change, budgetary uncertainty, and technical progress. An underlying goal of a sustainable design process is thus to develop an integrated strategy that can quantify how the system will react to changes in the environment. Rather than create a point design to accomplish a Moon or Mars expedition, various scenarios can be anticipated and addressed during conceptual design and, as importantly, the elements designed (which will likely make the system sub-optimal from a point-design perspective) can be justified quantitatively.

The design process established to create a sustainable space exploration system has five distinct steps:

1. Creation and refinement of individual staged missions, collection of existing studies and evaluation of the capabilities of legacy hardware.

2. Identifying required capabilities (“functional requirements”) for each of the staged missions and existing studies into a matrix aimed at identifying common elements between these missions.
3. Mapping common functional requirements between missions, while also identifying the capabilities (“functions”) provided by each piece of legacy hardware.
4. Analyzing each of the individual staged missions for key trades and options, that may make these missions more extensible in the face of an uncertain environment.
5. Creation and refinement of an integrated baseline strategy that will map the progression of staged missions through time in an extensible manner.

The design process is iterative, and the baseline strategy must be re-evaluated in the face of deviations from the expected environmental conditions. Figure 3 illustrates the design process described.

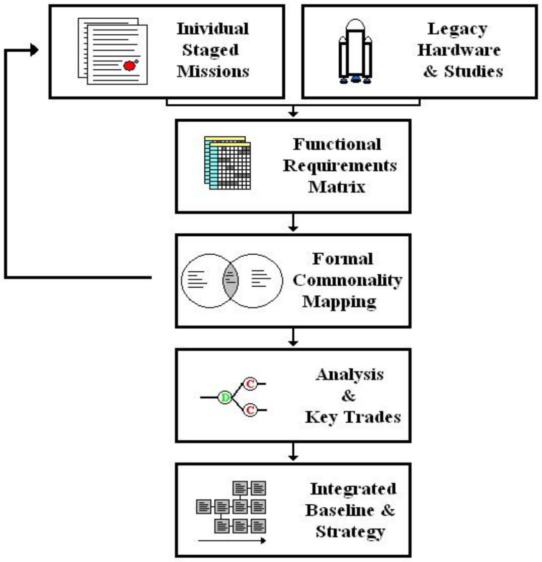


Figure 3. Design Process

The first step in the design process is to examine existing studies and legacy hardware to determine if the desired functionality is already in existence. The prime example in which existing legacy hardware may be used is in the delivery of mass to Low Earth Orbit (LEO). The current Space Transportation System (STS) architecture, including the Space Shuttle, provides an adequate opportunity to take advantage of the heavy-lift capability provided by the shuttle’s External Tank (ET) and Solid Rocket Boosters (SRBs). Several different configurations of legacy hardware were considered, and after calculating the capability of each, the conclusion has been reached that the most technically attractive and cost effective architecture should be built around two launchers. A heavy cargo launcher would be based only on the STS launchers (a shuttle stack in which the shuttle is replaced with a cargo carrier) and possess the capability to lift about 100 metric tons to LEO[2]. It is recommended that a human-rated heavy EELV, such as the Delta IV Heavy be used for transporting crew.

Since knowledge return is the ultimate deliverable, an infrastructure must be developed to transport bits and atoms. Transportation of bits will occur through the use of a communications architecture consisting of a set of satellites, which will augment the capabilities of the existing Deep Space Network (DSN). Transportation of atoms, on the other hand, will occur through an extensible set of baseline forms whose purpose is to deliver mass to and from the Earth. The forms used to execute these missions are as follows: The *Crew Operations Vehicle (COV)* is functionally similar to the Apollo Command Module, capable of transporting and supporting a crew of three for a short duration mission. The *Habitation Module (HM)* is an extensible habitable volume, made up of separable modules. This module can sustain life for long duration missions. When the COV and the HM dock, they form the *Crew Exploration System (CES)*. The *Service Module (SM)* provides the in-space propulsion. In combination with the COV and HM, this module is defined as the *Moon/Mars Transfer Vehicle (MTV)*. The *Mars Landers (ML)* or the *Lunar Landers (LL)* are functionally similar to the Apollo landing module (slightly different forms for Moon and Mars) and capable of transporting three crewmembers from orbit to the surface and back into orbit. In addition to containing the crew during launch and transferring the three crewmembers to the HM in LEO, the *Modern Command Module (MCM)* is functionally similar to the COV, but can return crew back to Earth from LEO at the end of the mission.

Now that the forms have been defined, it is important to outline some of the assumptions that have been made for the mission design, which are as follows:

- The capability to pre-position cargo using solar-electric propulsion systems is extant and available for use.
- Technologies have been developed for the long-term storage of cryogenic chemical fuel.
- Countermeasures exist which may counteract the effects of high doses of radiation.
- Countermeasures exist which may counteract the effects of long-term exposure to a low-gravity environment.
- Advanced space suits are available, which provide astronauts with increased locomotive capability, and allow for increased exposure time to the space environment.

The mission design presented in this paper focuses on an evolution of missions and functional capabilities, first to the Moon and then to Mars. Proceeding with the design process, the mission profiles for both the Moon and Mars missions will now be defined, however, it is important to recognize that each mission profile is not discrete, but rather, represent waypoints in an evolvable continuum of missions that may be attempted while exploring space.

V. Lunar mission baselines

Lunar missions assume the ability to successfully land humans and cargo on the lunar poles and on the far side of the Moon, as well as the ability to land cargo and humans within walking distance of one another. All manned missions assume the use of cryogenic chemical fuel for in-space propulsion.

A. Short-stay Lunar Missions

The primary purpose of a short-stay mission is to re-establish lunar transit capability and serve as a scout for future lunar missions. In this mission profile, a crew operations vehicle (COV) containing the three astronauts is launched into low Earth orbit, docks with a previously launched Lunar Lander (LL), and together, travel to lunar orbit. Once in lunar orbit, two crewmembers transfer to the LL, undock from the COV and descend to an equatorial landing site on the near side of the Moon. The astronauts on the lunar surface will live in the LL for approximately two days and explore the landing site on foot. EVA will have minimal science capabilities since the purpose of this type of mission is a basic technology demonstration. Upon the conclusion of the surface stay, the two astronauts ascend to lunar orbit in the LL and dock with the COV. One astronaut has been left in the COV as a safety measure for the basic technology demonstration; in case a manual docking is required. Then, the astronauts transfer to the COV, undock with the LL, and initiate the return trip. The COV performs a ballistic re-entry, returning the astronauts to Earth. An operational view of this mission is depicted in Figure 9 in the appendix.

B. Medium-stay Lunar Missions

The primary purpose of a medium-stay mission is to perform technological and scientific tests, with the eventual goal of extending these practices to the Martian environment. The main differences between the Short and Medium Stay Missions are: the LL is pre-positioned in lunar orbit using electric propulsion, all astronauts transfer to the LL to descend to the lunar surface, the astronauts stay at a non-equatorial location on the near side of the Moon for one week and exploration activities are aided by an un-pressurized rover. An operational view of this mission is depicted in Figure 10 in the appendix.

C. Extended-stay Lunar Missions

The primary purpose of an extended-stay mission is to establish semi-permanent habitation capabilities on the lunar surface. The main differences between the Medium and Extended Stay missions are: a separate surface habitation module (SHM) is pre-positioned on the lunar surface using electric propulsion for transit and cryogenic fuel for descent, a MCM and COV are used to launch six astronauts into LEO, a HM is used to transit to the moon, two LL's transport the crew to the surface, the astronauts stay at a pole or far side of the Moon location for six months, aerobraking is used to re-establish LEO upon return from the moon, and the crew returns to Earth using the COV and the MCM left in LEO. An operational view of this mission is depicted in Figure 11 in the appendix.

The semi-permanent base allows for extensive science capabilities, possibly including but not limited to Moon-based observatories, greenhouse technology demonstrations for closed-loop life support, and nuclear power production. A habitable, pressurized rover for overnight field trips will aid surface mobility.

Individual staged lunar missions are aimed at the eventual establishment of a lunar habitation capability and the use of in-situ resources. In attempting lunar missions, valuable knowledge will be gained that may be applied to the eventual accomplishment of successful Mars missions. Thus, the Moon is used to reach Mars in what is commonly referred to as a "stepping-stone" approach. The Martian individual staged missions are aimed at exploiting this similarity.

VI. Mars mission baselines

Assumptions made in performing the Martian missions include a crew size of six people, the use of solar-electric propulsion for pre-positioning, the existence of life-support and radiation-shielding technologies, and the use of a Martian Orbital Rendezvous (MOR) mission strategy, similar to the Lunar Orbital Rendezvous strategy used by the Apollo missions. All manned missions assume the use of cryogenic chemical propellant.

It is important to realize that a Martian mission is significantly different from a lunar mission, if only for the disparity in the time scales and distances involved. Furthermore, Mars has an atmosphere, implying that lunar landing and habitation technologies will not be directly transferable to Mars. It is primarily for this reason, that a mission to one of the Martian moons, Phobos or Deimos, is proposed. This mission would effectively serve to decouple the test of Martian transfer technologies from the Martian landing and surface habitation technologies. In addition, landing on a Martian moon would have significant knowledge return-related benefits. For example, inspection of the Martian moons could provide information on planetary science and evolution and potential sources of water ice[3]. Significant operational knowledge is to be gained from performing operations with a Martian moon. Since they are asteroid-sized, and hypothesized to be captured asteroids, these missions would prove invaluable in providing asteroid rendezvous experience that could be extended to other asteroid missions. More generally, the ability to rendezvous with a planet's moon may prove to be advantageous in future missions to the outer planets, whose moons are locations of interest. The ability to establish a human presence on a Martian moon implies that a tele-robotic presence may be established on Mars with a minimal communications delay. Finally, a landing upon a Martian moon will serve to build the public's confidence in NASA's Mars exploration activities, since it will demonstrate a successful extension of lunar mission technology to another celestial body.

Even if a mission to the Martian moons is not undertaken, Martian missions will proceed in a three-tiered structure similar to that used for the Moon missions.

A. Short-Stay Mars Missions

The primary purpose of a Short-stay mission is to establish a human presence on Mars. This mission is the shortest Mars mission possible in terms of total mission duration; it is composed of approximately 600 days transit time and 60 days surface stay[4]. The crew travels to Mars via an opposition class free-return trajectory with a Venus fly-by in the Mars Transfer Vehicle (MTV), which is composed of a habitation module (HM) and a crew operations vehicle (COV). Upon arrival at Mars, the MTV aerocaptures into Martian orbit and performs a rendezvous with two pre-positioned Mars landing vehicles (ML1 and ML2). Three crewmembers descend to the Martian surface in each landing module, which allows flexible timing for each landing, with the second being contingent on the success of the first. The landing is achieved using a heat shield for atmospheric entry after which parachutes are deployed to slow the spacecraft and a final powered touchdown is made to increase crew control and minimize risk. The crew remains on the surface for approximately 60 days and during this time, lives in a pre-positioned surface habitat that could be extended by an inflatable module if more volume is required. During the stay, the crew will explore the Martian surface, using EVA suits and an un-pressurized rover. In addition to the surface habitat, the un-pressurized rover and additional surface equipment will be pre-positioned. At the end of the surface stay, the crew returns to Mars orbit in the two landing modules and docks with the MTV. The MTV docks with the pre-positioned return propellant module (SM2) and executes a trans-Earth injection maneuver. Entry back into low Earth orbit (LEO) is achieved via aerocapture, and the MTV docks with the two Modern Command Modules (MCM1 and MCM2) in succession allowing the crew to transfer into their Earth reentry vehicles. An operational view of this mission is depicted in Figure 12 in the appendix.

B. Extended-stay Mars Missions

The primary purpose of the extended-stay mission is extensive exploration of Mars. For this mission, the crew travels to Mars in the MTV via a fast transfer conjunction class trajectory, which allows for a longer surface stay, has only a slight increase in mission duration, and does not require a Venus fly-by. In most respects the mission architecture is the same as for the short-stay mission. One exception is the use of in-situ propellant to fuel the Mars ascent. Assuming the option of in-situ propellant production (ISPP) during a short-stay mission is employed, and successfully demonstrated, the ascent propellant for the landing modules will be provided in-situ using the Sabatier process. The functional test of ISPP at this stage will act as a stepping-stone towards the eventual goal of using ISPP to fuel the entire return journey to Earth. Another principal distinction between extended and short-stay missions is the length of surface stay. For an extended-stay, the crew surface habitation module will need to be considerably larger, and therefore either an inflatable module or an additional habitation module will be pre-positioned. In addition, the increased surface stay will allow the crew to explore a large area, and therefore, although not a requirement, two pressurized rovers, capable of ranges on the order of 500km is a recommended option for the long-stay mission. An operational view of this mission is depicted in Figure 13 in the appendix.

In addition to the large-scale physical exploration of the Martian surface, the crew will have the opportunity to conduct longer, more advanced scientific experiments, such as small-scale agriculture development. The construction of an inflatable greenhouse prototype is one option for the extended-stay mission, and could serve to supplement the crew's food supply for both the surface stay and Earth return trip.

C. Extended-stay + Infrastructure Mars Missions

The primary purpose of this mission is the development of a semi-permanent infrastructure on Mars, for either further scientific research, or as a testing ground for further exploration. The aim of the mission is to use in-situ resources as much as possible – to provide return fuel, to generate power, to develop sustainable agriculture, to enable closed loop life support and so on. The initial architecture will follow the proven MOR architecture for a long-stay conjunction class mission, but assuming previous attempts at ISPP generation and fuelled ascent have been successful, it is likely that the architecture will move towards something similar in style to Mars Direct[5]. The eventual outcome of this transition would be that the MTV would travel directly to the surface of Mars without orbital rendezvous, and would ascend from the Martian surface using ISPP fuel directly into a trans-Earth injection, significantly reducing the Initial Mass in LEO (IMLEO). Extensive exploration will be provided by pre-positioned pressurized transport vehicles. The Environmental Control and Life Support System will be designed to achieve as close to 100% closure as possible, and the crew will derive most of their power from ISPP. Agricultural facilities such as inflatable greenhouses will be installed to provide or supplement the crew's food supply. The crew habitat will take the form of multiple inflatable modules as well as pre-positioned HM's sent direct from Earth. The extended-stay mission with infrastructure will provide a test bed for further exploration technology development, and it is also possible that the ISPP facilities will allow Mars to serve as a way station for vehicles traveling to more remote destinations.

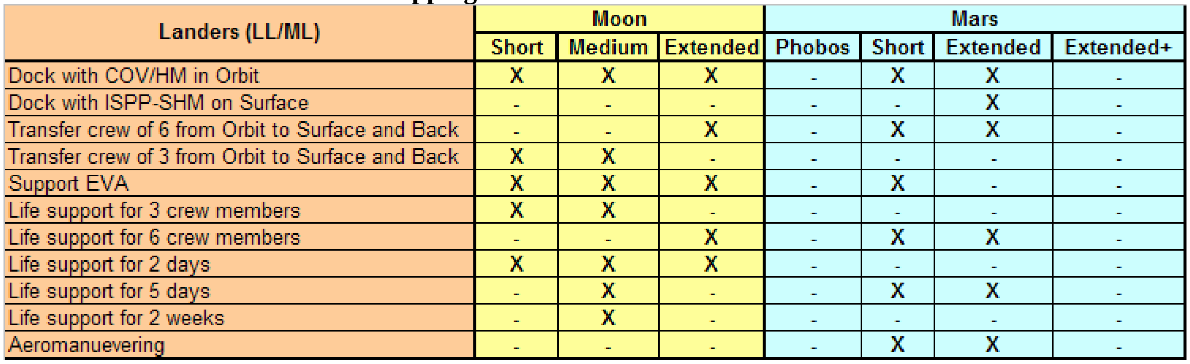
VII. Form/Function Mapping

Following the definition of individual staged missions, the next step in the design process is to map the functional commonality between these missions using a functional mapping matrix. The goal of this mapping is to enhance system sustainability through the development of extensible elements between missions. This process consists of three steps: the identification of required functions for each mission, the mapping of these required functions to specific forms, and the identification of opportunities to maintain commonality across missions.

Requirements were specified for the three Moon missions and the four Mars Missions. Basic forms were selected and the functions were discussed for each form. Each mission was considered independently, which allows functional traits of each form to be easily evaluated and ranked in comparison to other functions for the entire set of mission objectives. When the form does not capture a function, a decision must be made as to whether or not extending the functionality of a form to include higher-level requirements is justified or whether an additional form should be developed to serve the functional requirements flow down from the Mars and Moon mission objectives.

An example of the application of this method may be found in the landing module design process. Table 1 demonstrates common landing module functional requirements between mission profiles.

Table 1. Lander Form/Function Mapping



Landers (LL/ML)	Moon			Mars			
	Short	Medium	Extended	Phobos	Short	Extended	Extended+
Dock with COV/HM in Orbit	X	X	X	-	X	X	-
Dock with ISPP-SHM on Surface	-	-	-	-	-	X	-
Transfer crew of 6 from Orbit to Surface and Back	-	-	X	-	X	X	-
Transfer crew of 3 from Orbit to Surface and Back	X	X	-	-	-	-	-
Support EVA	X	X	X	-	X	-	-
Life support for 3 crew members	X	X	-	-	-	-	-
Life support for 6 crew members	-	-	X	-	X	X	-
Life support for 2 days	X	X	X	-	-	-	-
Life support for 5 days	-	X	-	-	X	X	-
Life support for 2 weeks	-	X	-	-	-	-	-
Aeromanuevering	-	-	-	-	X	X	-

Upon comparison, it is clear that common functions are shared. When common functions exist, incorporating extensibility into the design will benefit the overall group of missions to the Moon and Mars. In the above example, the landing module must dock with the COV or the COV/HM in both lunar and Martian orbit. The landing module must also deliver a crew of 6 to the surface for all of the Mars missions and some of the Moon missions. If two identical landing modules are chosen instead of a single, larger landing module, the impact of this decision can be evaluated by determining if the new option satisfies the functional requirements. If all of the functions are deemed satisfied, only then was the impact of the decision not critical. As can be expected, a wide range of requirements exists for the landing modules, but many of these requirements are specified by only one of the seven missions, making it difficult to justify changing the baseline form, since the landing modules must be highly reliable. Therefore, when considering extensibility of such a device, it may be beneficial to target the landing module design for the most difficult landing mission, thereby ensuring a robust, if over-designed form for the other missions.

Designing a non-optimal form now, such that it may be utilized in a different manner or location in the future, stands as one of the cornerstones of extensibility.

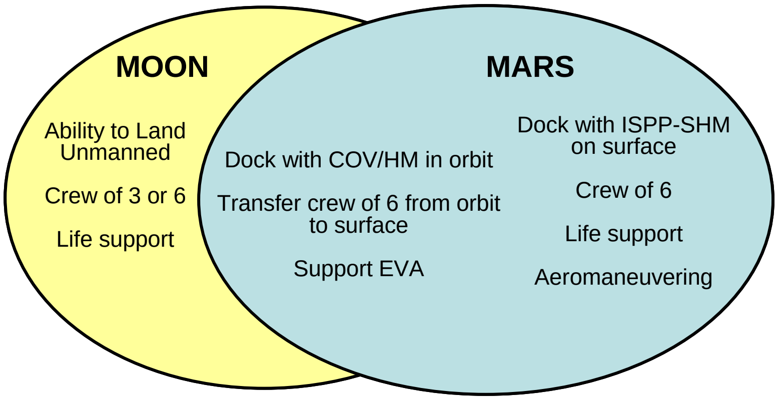


Figure 4. Lander Venn Diagram

Once common functional elements have been identified, the next step in the design process is to maximize commonality between forms. When considering and comparing multiple forms, three degrees of commonality between components may be observed; components may be common, similar or different. In the landing module example presented above, an example of a common component is the crew compartment, which will remain the same between missions and serve to demonstrate components that may be used as legacy hardware. Similar components are the propulsion modules, which must be adaptable and operable both in the Martian and lunar environments. Finally, different components, such as the parachute, deployable landing structure or heat shield, in the Martian example, are components that should be modularized such that they may be added or removed as needed.

Although many simplifying assumptions were required to analyze a transportation system in this framework, the advantage of this method is evident when considering the impacts of a decision to exclude a certain function from an element of form. The Venn diagram in Figure 4 highlights the functions that were not captured by the baseline mission architecture for the landing module, and must be integrated into the design. In doing so, it is important to recognize a fundamental engineering tension that exists between point-design optimality and extensibility. A form that is designed purely with optimality in mind is restricted to the point design for which it was originally conceived. This makes the creative use and extension of such technology difficult. On the other hand, a form designed with only extensibility in mind will become “spread thin”, and unable to perform the functions required of it at certain stages or missions. Thus, a compromise must be struck between these two extremes.

VIII. Analysis

Once commonality has been identified between missions, key trades may be identified within different mission architectures, so that these trades may be exploited depending upon the needs of the stakeholders. One such trade to be considered is the use of a reusable system. In theory, a reusable system requires a larger initial cost than the associated expendable system, but savings may be gained from not having to fully rebuild the system after each use. Opportunities for reusability within the space exploration infrastructure include reusable landing modules and planetary cyclers. Reusable systems are beneficial if there is a sufficient mission frequency. The Space Shuttle provides an example of a reusable system, which, due to under-estimations of its turn-around time between flights and its maintenance and re-verification costs, costs significantly more per flight than originally intended. Thus, when designing for reusability, it is necessary to consider the effects of environmental change upon the system. In the case of the Shuttle, changes in policy and unanticipated technical and operational problems undermined the value of a reusable system.

The study conducted for this report analyzed existing legacy hardware to determine what combination of materials would provide the best support to a sustainable exploration system. However, an important question that must be addressed is whether the use of legacy hardware for Earth to orbit operations provides the best solution. Due to the enormous cost of maintaining the operational abilities of a system that will be under-utilized for over a decade, and the age of the system, especially for shuttle-derived hardware, the use of legacy hardware may not provide the most affordable solution. Although technological uncertainty exists, there is the potential for new developments with current technologies, and the cost of a new development program should be analyzed and compared to the cost of maintaining operations for legacy hardware before the decision to reuse existing hardware is made.

Another trade to be considered is the use of the Earth Moon Lagrangian Libration point 1 (L1) as a trans-lunar stopping point. The benefits of utilizing L1 include the ability to reach a landing site at any lunar latitude; however this maneuver requires an additional delta-V of about 11%. On the other hand, a mission may go directly into a lunar equatorial orbit and then execute a burn to achieve the required orbital inclination change, which also requires additional delta-V. The trade studies indicate that more delta-V is spent executing this inclination change than is spent stopping at L1, if the desired inclination is greater than 39 degrees from the equatorial plane.

This report assumes that all human in-space transportation was provided by cryogenic chemical propellant; however, the use of nuclear propulsion would significantly reduce the IMLEO, as seen in Figure 5. Thus, it is necessary to trade the cost and risk of developing a new propulsion technology with the mass benefits obtained. In addition, this trade must be re-evaluated at different points along the mission development to determine if at a later time, the result changes.

One of the most important design decisions that may be found in each of the individual staged missions is the use of orbital rendezvous as means to reduce IMLEO, especially for Mars missions. Figure 6 demonstrates the significant mass savings to be gained from using the Mars Orbital Rendezvous (MOR) mission architecture over a mission that goes directly to the Martian surface and the returns. The addition of pre-positioned elements may further reduce the IMLEO to less than 500,000 kg.

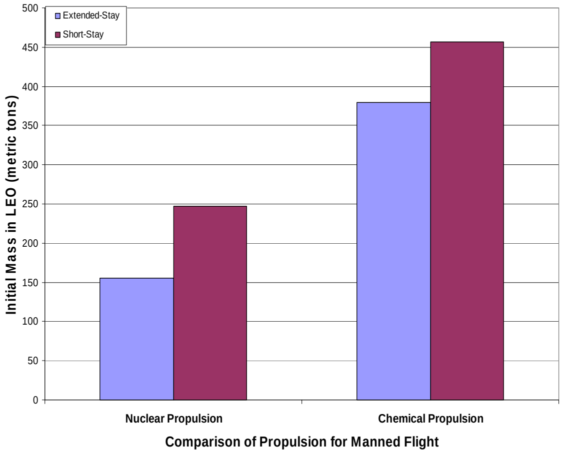


Figure 5. Comparison of nuclear and chemical propulsion for manned Mars missions

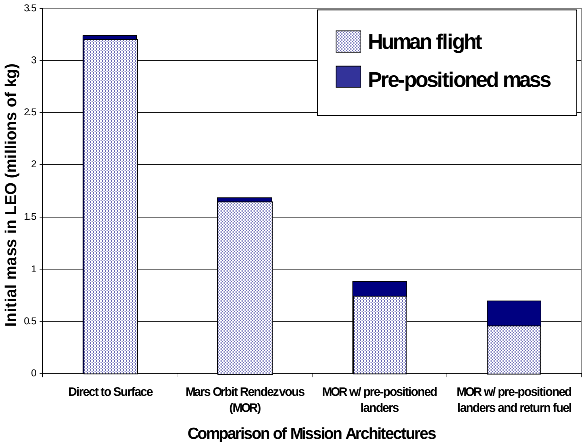


Figure 6. Comparison of Mars mission architectures

IX. Evaluation of an Integrated Baseline Architecture

Once individual staged missions have been designed, compared and elaborated upon, an integrated baseline may be defined. This baseline combines all the individual missions and utilizes their common elements to form a strategy by which sustained space exploration may be achieved. Figure 7 is a schematic for this baseline.

The baseline strategy presented by this report is as follows:

Lunar missions are expected to occur in the near future. The primary purpose of these missions is to re-establish the capability of the Apollo missions and to serve as lunar “scouts”, which will search for location information, perhaps regarding possible resources that may be exploited on the moon. Prior to the first of these missions, unmanned robotic probes may be sent to a number of promising landing sites, until a decision to study particular locations is made.

Initial missions will evolve towards larger endeavors aimed at the generation of scientific and technical knowledge, including resource evaluation of the more promising sites found on the short-stay missions. Astronauts participating in these missions will perform large scale scientific experiments and exploration. In addition, the astronauts will operate the first in-situ propellant production facilities, which will increase in size and importance as the technology demonstrations succeed. Enablers, such as an un-pressurized rover that is designed to carry astronauts to locations beyond their operational walking radius, will eventually be introduced.

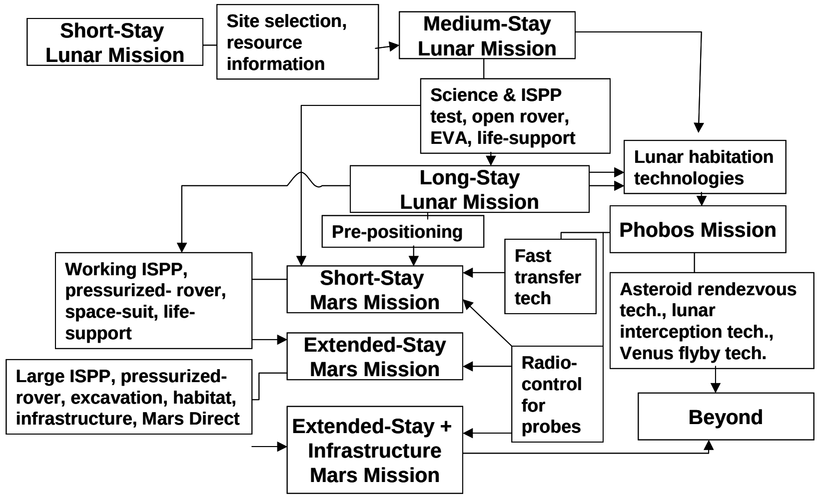


Figure 7. Integrated Baseline

Assuming usable in-situ resources are available for extraction; one primary site will be chosen for a future semi-permanent lunar base to establish lunar habitation technology and enable exploration of the far side of the moon. Over time, the number of astronauts on the moon during a given mission will increase from three to six, and these astronauts will gain experience in living in non-Earth environments for increasingly long periods of time. Astronauts participating in the later missions will be tasked with operating larger-scale in-situ propellant production facilities, with the eventual goal of creating a largely self-sustained semi-permanent base. To this end, an independent power source is necessary to survive the lunar night and a rescue vehicle would be stored in an easily accessible location, if unforeseen circumstances require an escape to Earth. These missions will continue until the first Mars mission is undertaken, at which point the semi-permanent base may be turned over to international partners or the commercial sector for further development.

The primary purpose of the Mars short-stay missions is to demonstrate the ability of mankind to survive on the surface of Mars for short periods of time. These missions nominally require pre-positioning of cargo on the Martian surface, assuming the technology has been successfully demonstrated on the Moon and it is extensible to the Martian environment. Prior to the first missions, unmanned robotic probes may be sent to a number of promising landing sites, as scouts, and as a demonstration of pre-positioning technology for Mars. In addition, a manned mission to the Martian moons may be used to demonstrate interplanetary transit abilities. All Mars mission require habitat modules for the transit and surface stays, which can be an extension of those developed for the extended-stay lunar missions. As in some of the lunar missions, Martian missions will possess un-pressurized rovers to aid in exploration. These missions will be used to test and verify in-situ resource production and utilization facilities for use on Mars. The first Martian missions will occur, usually in different locations, until a decision is made to study particular locations in more depth and for a longer period of time.

Upon finding an ideal long-term site, Martian exploration will continue with longer-stay, shorter-transfer missions to minimize the effects of microgravity. The primary purpose of these missions is to test and develop longer-term habitation facilities, new space-suit concepts, and alternative propulsion and in-situ propellant production concepts. Later missions will be able to take advantage of these capabilities for refueling, for life-support & agriculture, and to explore Mars in a more comprehensive manner. Exploration activities will be aided by the introduction of pressurized rovers for long-term excursions. As these missions progress, humans will establish a semi-permanent infrastructure on Mars to be used for science, operations research, or as a test bed for the next destination, and these missions will have the capability to be self-sustained based upon in-situ resource production, thus reducing mass in LEO as much as possible. To this end, the transit characteristics of later missions will evolve from a MOR class mission to a Mars Direct mission.

It is important to recognize that the integrated baseline architecture carries with it implicit assumptions about the state of the present and future environment. These assumptions about the environment constitute the scenario in which the system is designed to operate nominally. Due to the high degree of uncertainty surrounding these assumptions, it is necessary that the system be able to adapt to changing environmental factors. Scenario planning is used to identify architectural options and trades that will make the system more adaptable or robust to changing environmental conditions. Thus seven extreme changes in the system's operating environment were selected as scenarios against which the baseline system's performance could be evaluated. The performance of the baseline strategy against these scenarios serves to demonstrate the degree to which this strategy is sustainable and extensible in the face of drastic change.

The seven scenarios, and their associated trades, are listed below:

1. Space Race II: A foreign power challenges American leadership in space by making public feasible claims of the establishment of a lunar base and a Martian human mission. NASA budget receives a resultant increase.
   Trade: To what degree should extensibility be designed into the space exploration system at the cost of optimality or schedule?
2. Launch System Failure: NASA's primary launch vehicle is destroyed during operation. All usage of that particular vehicle ceases. American astronauts are required to find another method to leave and return to Earth as soon as possible.
   Trade: Should a second launch vehicle be designed as a preventative measure? If so, will it be done internationally or within a competitive structure?
3. Dawn of the Nuclear Propulsion Age: Nuclear propulsion technology emerges as a viable replacement to chemical propulsion.
   Trade: To what degree should a subsystem in the space exploration architecture be modular?
4. Asteroid Strike: A near Earth asteroid impacts the Earth's atmosphere. The US government allocates approximately 4% of the total yearly US budget between NASA and the DoD for the development of an early warning system, and to explore the possibilities of destroying or diverting asteroids on Earth impact trajectories.
   Trade: Should a mission to the Martian moons be attempted for developing asteroid operational knowledge?
5. Lunar Water World: An American expedition to the moon discovers reserves of resources at the Lunar Poles, allowing for the large-scale extraction of hydrogen, oxygen and water ice.
   Trade: Should L1 be used to access the lunar poles?
6. Following discoveries of microbial fossils on Mars, unmanned probes find strong evidence of one-celled life currently existing in the Martian subsurface soil.
   Trade: To what degree should the Moon be used as a test bed for Mars?
7. NASA Policy Change: NASA is directed to cease all exploration activities. The exploration budge is cut due to lack of public interest
   Trade: To what degree should NASA maintain public awareness activities?

In order to effectively evaluate these trades, it is necessary to develop a rigorous method by which to evaluate different architectural choices. This report presents several econometric tools to accomplish this. One approach is to define a closed "best design" that attempts to account for every possible change; however this option is restricted to current projections of future events. This report suggests a second approach that defines a strategy that will evolve to accommodate changing environmental conditions. This approach chooses the best way to proceed in the future, while preserving as many open options as possible. Decisions, which would otherwise be made at the outset, are delayed such that, when the final choice is required, it is made in an environment of decreased uncertainty. Figure 8 is a schematic representation of the decisions and trades that need to be made relative to the life of the program.

If we describe the design architecture by a vector of the different decisions used, it is possible to apply Utility Theory to analyze each vector and more specifically, the scenarios and associated trades. In doing so, one can explore how the present baseline reacts to a change in the operating environment, and how appropriate decisions taken at points throughout the system's lifecycle could buy some insurance against negative scenarios, or increased payoffs in the case of positives ones. This analysis is the basis of Real Options theory. The tool proposed to acquire the utility values is called the Analytical Deliberative Process, and is a formal framework that helps a group of people to argue and discuss a set of measures that may sometimes be in opposition. By assessing the different performance metrics for each architecture vector, it is possible to get a measure of the net utility for the stakeholders. As time passes, both decision points and chance points are encountered. Unanticipated chance points will effect the operation of the baseline architecture and thus an understanding of each of these points is central to the analysis.

One defining attribute of a sustainable system is its long expected life cycle. Thus, predicting the circumstances under which the system will operate throughout its life cycle becomes difficult as uncertainty increases with an extended timeline. An exploration system must incorporate subsystems in the technical, political and commercial domains, which each have significant uncertainty. As a result, the system must be capable of adapting to unexpected situations, should they arise, without significantly reducing the system's operational utility. The value of the analysis tools presented is that they allow for the design of a system in an environment of high uncertainty.

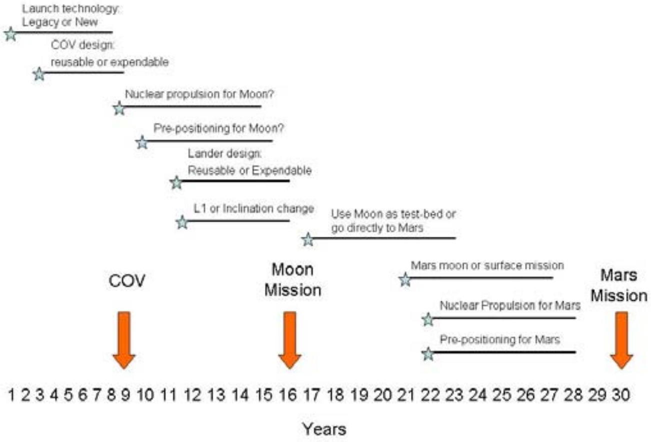


Figure 8. Schematic representation of decision points and milestones

X. Conclusion

A new design methodology must be developed to meet the goals of the new space exploration initiative. This new methodology should account for sustainability and evaluate designs based on knowledge. While the proposed design method is certainly not the only solution, it is intended to be a starting point for further improvement, and ultimately, a catalyst that enables NASA and the nation to move into the next era of space exploration in a sustained and consistent fashion. In conclusion, the following two recommendations are made to NASA:

- Incorporate sustainability into the conceptual design of a space system architecture by using an iterative process that identifies and maximizes commonality across multiple mission scenarios. Tools such as real options analysis, scenario planning, and decision analysis should be used to maximize expected value delivery over the entire system's life-cycle.
- NASA must view the acquisition, transfer, synthesis and communication of knowledge as the primary product of the exploration program. The most important value-added deliverable for an exploration system is knowledge, and therefore attributes of knowledge should be valued in important system trades.

For more detailed information on the results presented, please access the full report, available at http://web.mit.edu/spacearchitects/1689report.htm.

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Appendix

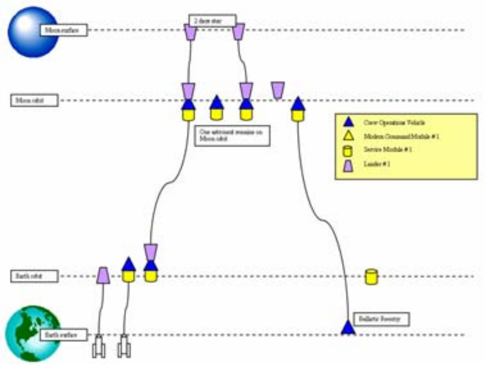

Figure 9. Operational view of short-stay lunar mission

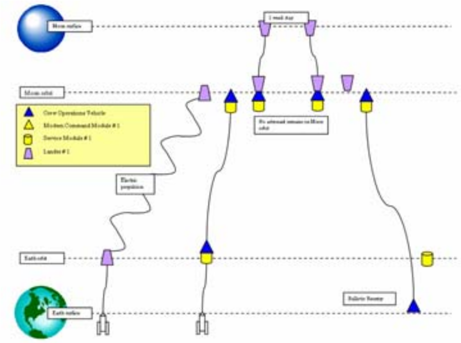

Figure 10. Operational view of medium-stay lunar mission

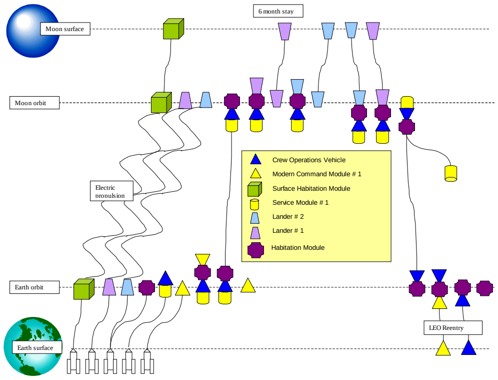

Figure 11. Operational view of extended-stay lunar mission

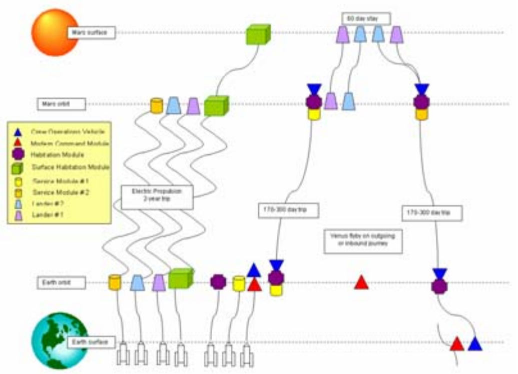

Figure 12. Operational view of short-stay Mars mission

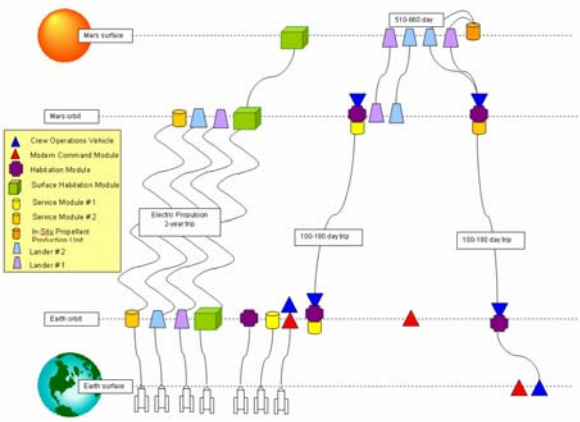

Figure 13. Operational view of extended-stay Mars mission