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# A Comparison of Transportation Systems for Human Missions to Mars

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**There are many ways to send humans to Mars. Credible technical reports can be traced to the 1950's. More recently, NASA has funded major studies that depict a broad variety of trajectories, technologies, stay times, and costs. Much of this data is still valid with direct application to today's exploration planning. This paper presents results comparing these studies with particular emphasis on the in-space transportation aspects of the mission. Specifically, comparisons are made on propulsion systems used for getting the crew and mission equipment from Earth orbit to Mars orbit, descending and ascending from the surface, and returning to Earth orbit. Areas of comparison for each of these phases include crew size, mission mass, propellant mass, specific impulse, transit time, surface stay time, aerobraking, and others. Data is analyzed to demonstrate either strong trends toward particular technologies or diverging solutions.**

## I. Purpose/Introduction

### A. Purpose

The purpose of this paper is to provide mission planners and analysts with a comparison of in-space transportation characteristics found in key Mars studies.

### B. Introduction

Today, engineers are asked to conduct Mars analysis but have little understanding of the breadth and depth of previous work (see Fig. 1). One annotated bibliography refers to over 243 citations through December, 2000. Studies are available through conventional literature searches; however, others are buried in filing cabinets at NASA Centers and in offices of Aerospace Contractors. The documentation is inconsistent and material comes in many different formats. Some are recorded as formal documents, others as interim study reports. Technical conference papers provide a valuable source of published data, whereas, the latest work is not in the public domain and only available in presentation chart form. Regardless, the work is impressive and because many of the technical and

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planning issues are the same today, it represents an enormous resource for future Mars mission planning. Few engineers have ready access to these studies let alone the time to dig through 1000's of pages for a particular data point. This paper represents the process used to identify key studies, collect the documentation, conduct comparison analyses and present results as they apply to in-space transportation. While the comparisons are useful, it is important to note that because the underlying mission objectives, ground rules, and assumptions vary widely, the results do not represent a true apples-to-apples comparison.

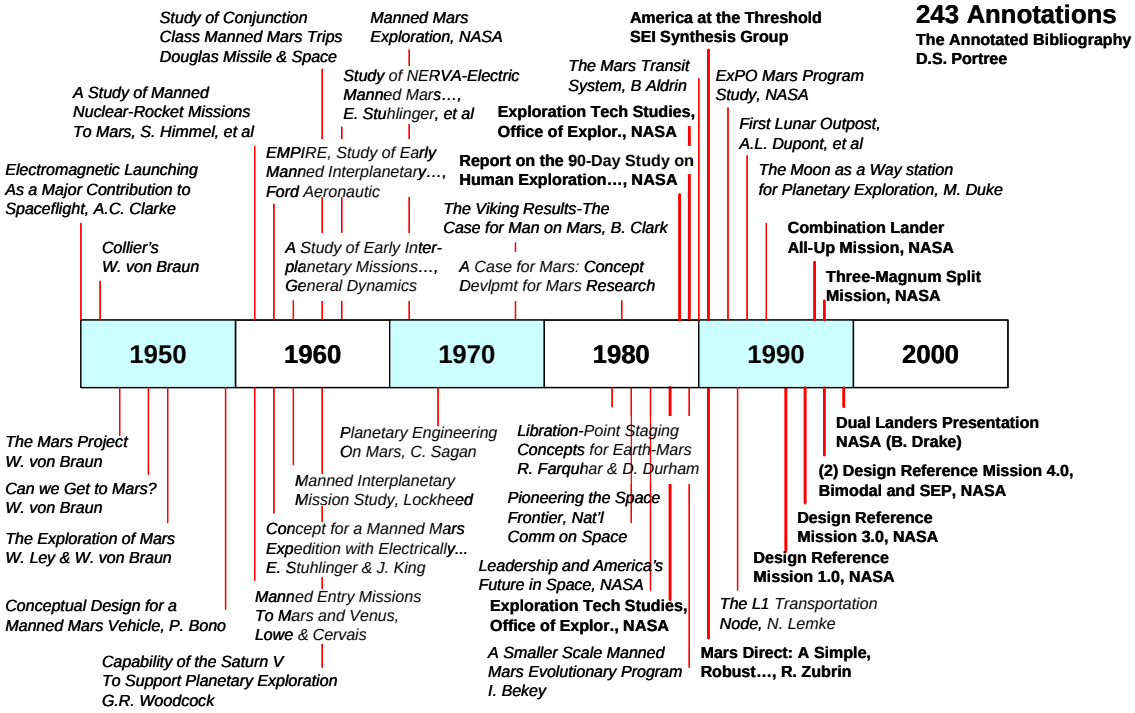



**Figure 1 Timeline for Mars studies (bold type represents selected studies)**

## II. Approach

### A. Survey of Studies, Reports and Technical Papers

The process began with a comprehensive search to identify studies, reports, and technical papers for human missions to Mars. Because there is no single repository of documentation on this subject, this process included research through NASA and contractor technical libraries, internet searches, and copying material from personal collections. A large volume of material was collected both in hard copy and electronic form. For this research, 21 studies were selected for comparison. Some are alternatives created within the same study, but because they represent a different approach, they were compared separately. The rationale for selecting the 21 studies is shown in Fig. 2.

| Study | Options within Study | Acronym | Selection Rationale |
|---|---|---|---|
| **1988/1989 Case Studies** | **5** | **Exp-P, Exp-M, Evo88, Evo89, Exp89** | Agency-wide analysis of exploration options; provide focused program for human exploration of solar system |
| **90 Day Study** | **1** | **90D** | Large integrated NASA/Contractor effort, results well documented, includes design, schedule and cost |
| **Synthesis Study – America at Threshold** | **1** | **Syn** | Chartered by National Space Council – "major study"; Explore Mars & provide significant science return |
| **Mars Direct** | **2** | **MDCh/MDNTR** | Low cost; no orbital rendezvous or assembly; dependent upon ISRU propellant production for return; Chemical and NTR options |
| **Mars Semi-Direct** | **1** | **MSD** | Concept bridge between Mars Direct and Design Reference Mission 1.0; low cost |
| **STCAEM** | **1** | **S-C/A** | Major NASA funded study produced by Boeing in 1991; focus on in-space propulsion |
| **STCAEM NTR** | **1** | **S-NTR** | Major NASA funded study produced by Boeing in 1991; focus on in-space propulsion |
| **STCAEM NEP** | **1** | **S-NEP** | Major NASA funded study produced by Boeing in 1991; only study chosen using Nuclear Electric Propulsion as in-space propulsion |
| **STCAEM SEP** | **1** | **S-SEP** | Major NASA funded study produced by Boeing in 1991; focus on in-space propulsion |
| **DRM 1.0** | **1** | **DRM1** | NASA's "Design Reference Mission" based upon previous studies; good focus on operations and science return |
| **DRM 3.0** | **1** | **DRM3** | Refine DRM 1.0 systems concepts and design; smaller class launch vehicle (80mt);source data from Borowski paper |
| **DRM 4.0** | **2** | **DRM4N/DRM4S** | Refine DRM 3.0; SEP Prop Option; NTR Bimodal "all-propulsive" option; source data from Borowski NTR |
| **Combo Lander** | **2** | **CLA/CLS** | Focus on single Mars lander to transport crew & also support on surface; all-up and split mission scenarios |
| **Dual Lander** | **1** | **DUL** | Follow-on of combo lander study – back to 2 landers; no formal report, presentation charts only |
| **Total Studies** | **21** | | |

**Figure 2 Rationale for study selection**

**B. Rationale for Selecting Key Studies**

Mars studies are complex with many interrelated variables. "An Overview of Recent Coordinated Human Exploration Studies" and "Key Findings from Previous NASA Exploration Mission Studies" are two NASA presentations that provide a good comparison of many of these variables. The analysis discussed in this paper builds upon this work while focusing on the attributes of in-space transportation.

A consideration for selecting key studies was to determine the technological relevance. The first credible study was von Braun's "Das Marsprojekt" of 1952. NASA funded studies from 1963 to 1972. There was very limited study work from 1972 to 1988. All of the basic themes of Mars architectures (except perhaps solar electric propulsion (SEP)) were pioneered in the old studies and repeated in the later studies. Studies that were published from 1988 to the present were chosen to include modern technology development. Also, 1988 was the year that President George H. Bush appointed NASA to form the Mars Office of Exploration, which resulted in plans for a number of reports on manned missions to Mars and the Moon. These reports started a series of credible studies that would be produced over the following ten years.

Another guideline that was used in the selection of key studies was quality and quantity of documentation. There was a strong preference for published studies, in particular those resulting in formal documentation authored by NASA Headquarters. Published reports from NASA funded contractors were also considered an important source of information and, in some cases, a technical society paper was used because it best described the in-space transportation portion of a study. When no other documentation was available, presentations were accepted only because they represented the latest work. Documents were screened for credible concepts that included enough information to be used in comparison. NASA and NASA funded aerospace contractors' studies were chosen because of the consensus process leading to an integrated architecture versus an emphasis on particular technologies.

Presidential support and new approaches to accomplish manned lunar and Mars missions were additional criteria for the selection of the key studies. Also, studies were selected based on the significant benefits produced from new approaches to get to Mars such as split missions (sending the equipment first then the crew) and Venus swingby trajectories (using the gravity of Venus to reduce propulsion system mass).

It is important to note that cost was not a consideration for selecting or comparing key studies. Typically, any cost analysis was based on different assumptions, schedules, and risk. Although cost was not considered for selection it is often related to mass. Most costing models use mass as the primary input for system cost, and thus mission designers typically strive to reduce overall system masses.

### C. Traceability of Data

Early in the process, studies were collected and reviewed. It would be easy to lose track of the source of pertinent data, so a concerted effort was made to trace each piece of data back to a page and volume number within the study. Although time consuming, the benefit of this approach allowed revisits to the source material for verification. Millions, if not hundreds of millions, of dollars of analysis is represented in these reports and having a means of access to this data affords significant cost savings for future mission planners.

### D. Different Ground Rules and Assumptions

It is difficult to compare one study to the next because each study had its own ground rules and assumptions. Some were motivated by scientific objectives and others by "flags and footprints". Some were constrained by schedule, cost, or technology readiness. Others created very large launch vehicles, and some relied on making return propellant on the surface of Mars.

The common primary objective of each study was to safely send and return humans to Mars. The secondary objective varied among the different studies reviewed. Some studies yielded more defined information in specific areas than others. Specific areas included in-space propulsion and operations. In-space propulsion was better defined in Space Transfer Concepts and Analysis for Exploration Missions (STCAEM) reports which yielded four types of in-space propulsion applications using the same ground rules and assumptions. The Design Reference Mission 1.0 focused not only on landing a crew safely on Martian surface but on providing them with the tools to accomplish science and exploration objectives.

Technology advancement was assumed in all Mars studies. Propulsion and in-situ resource utilization (ISRU) for propellant production made a significant difference in architecture studies. Studies assumed different technology development and readiness for the Mars mission in the launch opportunity investigated. Perhaps the greatest assumption in these studies was payload capacity for heavy lift launch vehicles (HLLV). Assumed launch vehicle lift capability ranged from 80 metric tonne (mt) to as large as 240mt across the board. Overall capacity of the launch vehicle affected the transportation system definition which drove the complexity of comparing the studies. By comparison, the Saturn V vehicle had over a 100mt lift.

## III. Mars Mission Planning

### A. Trajectories

Trajectories employed in each mission dictate different requirements for the mission ranging from launch opportunity dates to requirements for initial mass in low earth orbit (IMLEO). Trajectory options for studies generally fall into two types of trajectory classes: opposition or "short-stay" and conjunction or "long-stay".

The first Mars mission class consists of short stay times (typically 40 days) and round trip mission times ranging from 365-660 days. This is referred to as an opposition class mission, although the exploration community has adopted the more descriptive terminology "short-stay" mission. Most opposition class missions try to use a Venus swingby trajectory as the nominal approach. A swingby maneuver uses a planet's gravity to modify the trajectory change in velocity (delta-v) and reduce trip time. Deep space maneuvers are used when Venus swingbys are not available for specific mission dates/trip times. Trajectory profiles for typical short-stay missions are shown in Fig. 3. This class of mission has high propulsive requirements even when employing a gravity assisted swingby of Venus or performing a deep space maneuver to reduce the total mission energy. Short-stay missions always have one short transit leg, either outbound or inbound, and one long transit leg, the latter requiring close passage by the Sun (0.7 AU or less). After arrival at Mars, rather than wait for a near-optimum return alignment, the spacecraft initiates the return after a brief stay and the return leg cuts well inside the orbit of the Earth to make up for the "negative" alignment of the planets that existed at Mars departure. Distinguishing characteristics of a short-stay mission are: 1) short stay at Mars, 2) short to medium total mission duration, 3) perihelion passage inside the orbit of Venus on either the outbound or inbound legs, and 4) large total energy (propulsion) requirements.

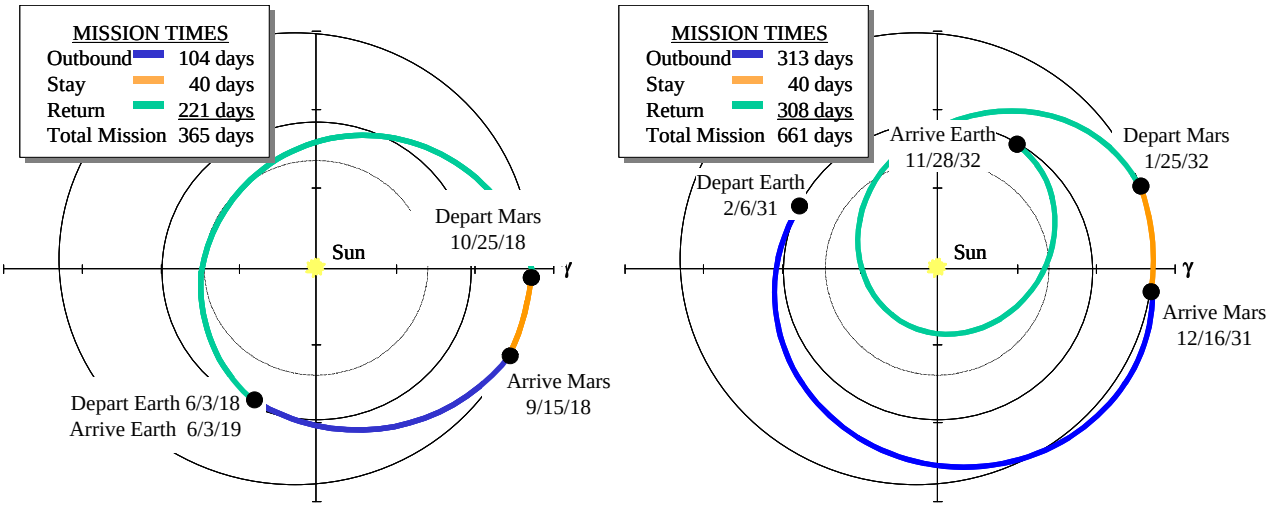



**Figure 3 Short-stay (opposition class) mission profile examples**

The short-stay mission approach has some distinct disadvantages. First, the total energy requirement varies greatly for each mission opportunity to Mars, repeating across the synodic cycle. (The 15 year synodic cycle is the period of time required for the orbital phasing between Earth and Mars to repeat itself). The total energy is also dependent on total round trip mission time and it can vary by as much as 88% across the synodic cycle. For all Mars mission classes, as trip time decreases, the required injection velocity and Mars arrival velocity both increase. This is important because higher total energies require exponentially greater propellant quantities, and higher approach velocities place excessive demand on technology development. In addition, total round trip mission time can be up to 660 days, with only 40 days at Mars. These long periods in deep space environment increase human radiation exposure, as well as physiological degradation due to the weightless environment and human performance issues that must be considered during the mission design process.

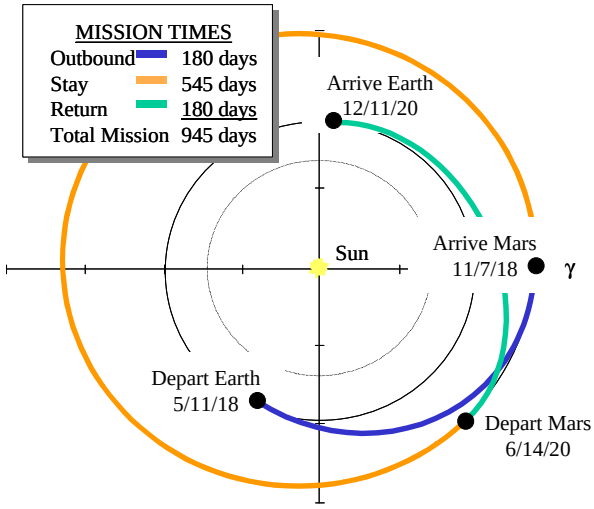



**Figure 4 Trajectory profile for typical fast-transit, long-stay (conjunction class) mission**

The second Mars mission class is typified by long-duration stay-times (as much as 600 days) and long total round trip times (approximately 900 days). This mission type is referred to as conjunction class, although the exploration community has adopted the more descriptive terminology “long-stay” mission. These missions represent global minimum-energy solutions for a given launch opportunity. Unlike short-stay mission approaches, departure

timing is based on a lower energy return. A variation of this long-stay mission has a total round trip time comparable to those of the minimum-energy mission, but the one-way transits are substantially reduced. Distinguishing characteristics of long-stay missions include: 1) long total mission durations, 2) long-stays at Mars, 3) relatively little energy change between opportunities, 4) bounding of both transfer arcs by the orbits of Earth and Mars (closest perihelion passage of 1 AU), and 5) relatively short transits to and from Mars (less than 200 days). The mission flight profile for a typical fast-transit mission is shown in Fig. 4.

## B. Propulsion Options

The major propulsion options for human Mars missions are summarized in Fig. 5.

| Propulsion Option | Description | Advantages | Disadvantages |
|---|---|---|---|
| **Chemical** | Conventional cryogenic rocket engines, usually one stage for each major maneuver (TMI, MOI, TEI). Insulated tanks with vapor-cooled shields to reduce boiloff. Start T/W 0.1 to 0.25. Isp ~ 460s. | -Mature technology<br>-High thrust, short burn times<br>-Ballistic interplanetary transfers facilitate implementing artificial gravity | -Low performance leads to high IMLEO except for conjunction profile with long transfer times<br>-Cryogenic with hydrogen, low density, needs heat leak control<br>-Expendable system |
| **Chemical/ Aerocapture** | Same as chemical except aerocapture used for MOI. Large aeroshell needed requiring either intact launch or in-space assembly. Lander may capture separately to simplify configuration. | -Reduces IMLEO by replacing one major maneuver with aerocapture | -Performance still marginal for "hard year" opportunities<br>-Aerocapture risk: TPS/thermal, GN&C<br>-Mars Vhp limited to ~ 6 for safe aerocapture<br>-Expendable system |
| **NTR** | Nuclear thermal rocket engine, hydrogen propellant, Isp ~ 900s. Usually drop tanks utilized for each major maneuver. Insulated tanks as above; start T/W <= 0.1 to reduce nuclear engine size. | -Known technology<br>-Twice the Isp of chemical propulsion reduces IMLEO and sensitivity to opportunity<br>-High thrust, short burn times<br>-Ballistic interplanetary transfers facilitate implementing artificial gravity | -Nuclear costs and risks<br>-Engine test protocols not resolved (how to contain radioactive products)<br>-Cryogenic with hydrogen, low density, needs heat leak control (exacerbated because propellant is all hydrogen)<br>-Expendable system |
| **SEP** | Large (multi-megawatt) solar electric propulsion system, performs all major maneuvers. Isp typically 3000s; MPD or comparable thrusters. | -Known technology with flight experience in small size<br>-High Isp reduces IMLEO and sensitivity<br>-No hydrogen propellant<br>-Reusable system | -Large size may require more space assembly than other options<br>-High-power electric thrusters not mature (TRL 2 - 3)<br>-Achievable power-to-mass ratio may not permit opposition-class profiles |
| **NEP** | Large (multi-megawatt) nuclear electric propulsion system, probably Brayton or liquid metal Rankine power generation, performs all major maneuvers. Isp typically 3000s; MPD or comparable thrusters. | -Known technology (no space experience or experimental prototypes except thermoelectric and thermionic conversion)<br>-High Isp reduces IMLEO and sensitivity<br>-No hydrogen propellant<br>-Potentially reusable system | -Nuclear costs and risks<br>-Large size may require more space assembly than other options<br>-High-power electric thrusters and space-configuration power conversion not mature (TRL 2 - 3)<br>-Achievable power-to-mass ratio may not permit opposition-class profiles |
| **SEP/Chem** | Large SEP "tug" system ~ 1 mega-watt delivers chemical propulsion interplanetary vehicle to highly elliptic Earth orbit (perhaps in major sections with berthing for assembly). Chemical propulsion system departs from this orbit; otherwise same as chemical option. | -Placement in elliptic orbit reduces chemical delta-v by ~ 3 km/s, reducing IMLEO and sensitivity to opportunity<br>-Other advantages same as Chemical Option | -Cost and mission complexity added by use of SEP "tug"<br>-Cryogenic with hydrogen, low density, needs heat leak control<br>-Expendable system |

**Figure 5 Propulsion option advantages and disadvantages**

## C. Mission Approach

Two approaches to mission design were researched: the all-up mission and the split mission. The all-up mission requires both cargo and crew to leave Earth's orbit at the same time. In split mission design, the cargo is flown to Mars prior to crew departure for Mars. The reason for the split mission is to send cargo and perhaps even return propellant on a low-energy trajectory which requires much less propellant.

Another feature of the transportation system is the method of orbit insertion. Studies have proposed both propulsive and aerocapture alternatives. The propulsive option uses the vehicle's propulsion system to reduce the delta-v while aerocapture uses the planet's atmosphere to slow the vehicle down.

In-situ resource utilization is another mission variable. ISRU is another way of saying "live off the land". ISRU can involve propellant production on the surface of Mars or one of its moons, using Martian resources for oxygen production, and/or setting up a habitat on the surface where food can be grown. The type of ISRU employed will determine what the mass requirement for the mission will be, as well as other mission parameters.

Another mission approach was artificial gravity to counter physiological degradation during long periods of weightlessness. This, of course, has a significant impact on the design and location of propulsive elements. Some architectures use artificial gravity but none are included in the list of 21 missions used for this comparison.

## IV. Areas of Comparison and Results

Common areas of comparison (see Fig. 6) were identified so the differences across the Mars studies could be seen. Most areas related directly to the transportation system, but several areas such as crew size were included to provide context and indicator of mission scale.

In missions requiring on-orbit assembly, different Mars vehicle elements are launched into Low Earth Orbit (LEO) on separate HLLV launches. Assembly may consist of a "simple" automated rendezvous and dock between elements or it can be much more complex requiring use of a space station or construction facility.

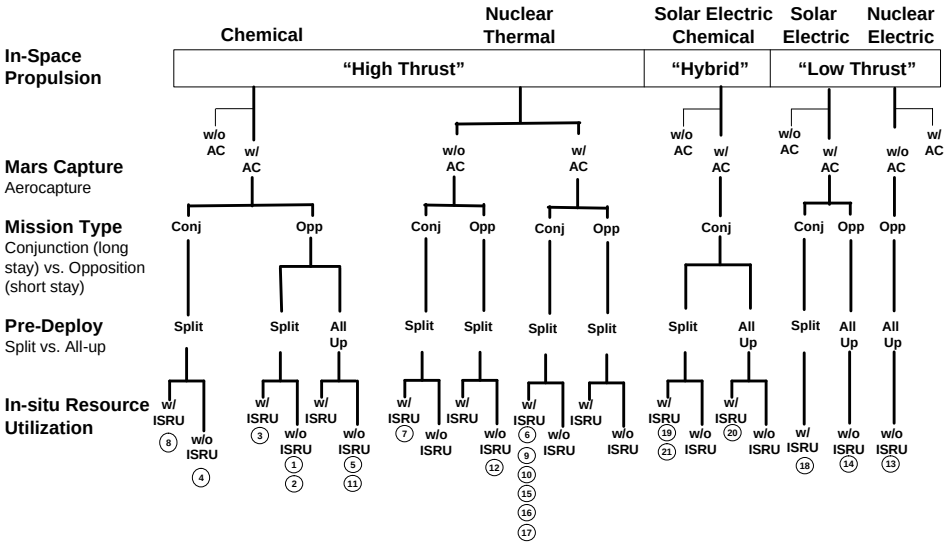



**Figure 6 Mission design options for Mars studies**

Most studies described the type of propellant used for Mars ascent and descent including the dependence on in-situ propellant production.

For this research, a Mars mission is considered to be one round trip from Earth. This is important because some transportation schemes send the cargo ahead with the crew to follow. In this case, all crew and cargo launches required for a single round trip would be book-kept against the mission.

### A. Earth Departure Date

The Earth departure date or launch window opportunity is the first date when a cargo and/or piloted vehicle leaves LEO. In an all-up mission approach, the piloted vehicle with relevant cargo departs LEO and travels to Mars; thus, the mission will be accomplished during the designated opportunity window (i.e. CLA 2011). Alternatively, the split mission requires two Earth departure dates. The cargo departs LEO on the first opportunity and the piloted vehicle follows on the second opportunity (i.e. DRM1 2009/2011).

Mars mission planning is sensitive to the 15 year synodic cycle. Within the synodic period, some launch dates are "easier" than others due to planetary positions at departure and return. The difference between easy and hard mission opportunities has an impact on design of a transportation system. Some studies documented (i.e. DRM1) took a conservative approach of designing to the hardest opportunity year (2009) in the synodic cycle. The philosophy behind this rationale is that excess system capability may be available on the easier departure dates such that additional payload mass in the form of cargo or crew members may be afforded.

Launch opportunities for the 21 studies ranged from 1997 to 2018 for the LEO departures. The latest initial launch refers to the 90-Day Study in 2018. The information shown in Fig. 7 is based on the first crew departure date from LEO and shows the Mars Direct 1997 mission as the earliest. Some studies included multiple departure dates across the entire synodic cycle as part of a process of building a self-sufficient Mars outpost.

| Acronym | Study Title | Acronym | Study Title |
|---|---|---|---|
| Exp-P | (1988) Expedition to Phobos | S-NTR | (1991) STCAEM NTR |
| Exp-M | (1988) Expedition to Mars | S-NEP | (1991) STCAEM NEP |
| Evo88 | (1988) Mars Evolution | S-SEP | (1991) STCAEM SEP |
| Evo89 | (1989) Mars Evolution | DRM1 | (1995) Design Ref Msn 1.0 |
| Exp89 | (1989) Mars Expedition | DRM3 | (1997) Design Ref Msn 3.0 |
| 90D | (1990) 90 Day | DRM4N | (1998) DRM 4.0 Bimodal |
| Syn | (1991) Synthesis | DRM4S | (1998) DRM 4.0 SEP |
| MDCh | (1991) Mars Direct Chem | CLA | (1998) Combo Lander All-Up |
| MDNTR | (1991) Mars Direct NTR | CLS | (1998) Combo Lander Split |
| MSD | (1991) Mars Semi-Direct | DUL | (1999) Dual Landers |
| S-C/A | (1991) STCAEM Cryo/Aero | | |

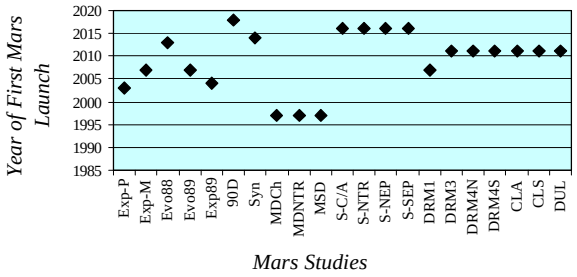
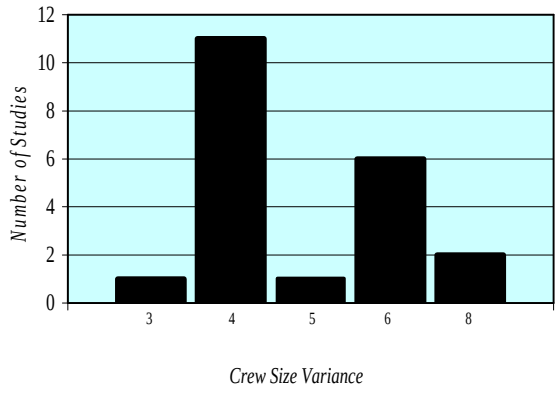



**Figure 7 Study legend and Earth departure dates for chosen Mars studies**

## B. Crew Size

Human missions to Mars are more complex than the robotic missions. Increased system reliability along with adequate consumables and travel accommodations will drive the mission design and transportation system. After departure from LEO, the crew is committed to the Mars journey without re-supply from Earth. As a result, trade-offs are usually made between cost and comfort, as well as performance and risk. Few studies presented material on the relationship between crew size and mission assurance. Crew size determines mass of the habitat and the corresponding space transportation system as well. STCAEM performed an analysis and concluded seven or eight was the minimum crew size to have an adequate skill/training mix with allowance for one disabled crew person.

Many studies concentrated on an optimal skill mix for choosing crew members while others were concerned with the overall mission cost. Requirements for the crew size and composition of the crew would require considerable effort for future studies. Operational tasks would need to be well-defined along with safety and risk considerations. Crew dynamics would also be an important consideration. Figure 8 shows the variance in crew size from three crew members to as many as eight.

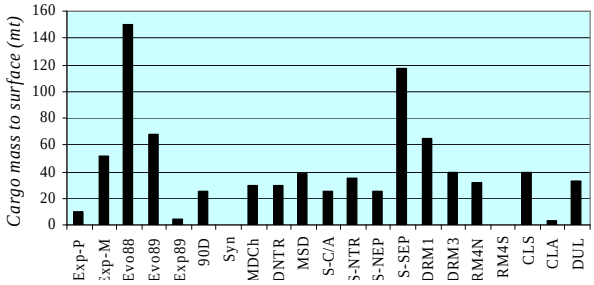



| Study | Crew Size | Study | Crew Size |
|---|---|---|---|
| Exp-P | 4 | S-NTR | 4 |
| Exp-M | 8 | S-NEP | 4 |
| Evo88 | 8 | S-SEP | 4 |
| Evo89 | 5 | DRM1 | 6 |
| Exp89 | 3 | DRM3 | 6 |
| 90D | 4 | DRM4N | 6 |
| Syn | 6 | DRM4S | 6 |
| MDCh | 4 | CLA | 4 |
| MDNTR | 4 | CLS | 4 |
| MSD | 4 | DUL | 6 |
| S-C/A | 4 | | |

**Figure 8 Crew size variance for chosen Mars studies**

### C. Cargo Mass to Surface

Missions were compared for cargo that reached the surface of the planet. (See Fig. 9.) Mars Evolution (1988) delivered the greatest amount of cargo while Combination Lander All-up (1998) delivered the least. Payload cargo mass is the amount of cargo delivered to the surface of Mars by the transportation system on a single opportunity from Earth. This cargo may consist of consumables such as crew supplies and food, power systems, and possibly a surface habitat. Generally, cargo remains on the planet surface as a building block for a Mars outpost.




*No data found for Synthesis Study & DRM4S

**Figure 9 Cargo mass payload to Mars surface**

### D. Split/All-Up Mission Approach

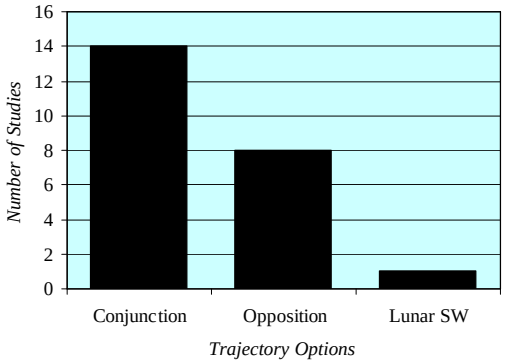
A split mission sends cargo ahead of the crew. Launches occur at sequential launch opportunities (i.e. 2009/2011). In contrast, the all-up mission approach includes both cargo and crew on the same flight opportunity.

Of the 21 studies researched, 5 used the all-up mission approach. The remaining use variations on split mission approach.

All-up mission design involves less risk because the crew is not separated from their cargo. Split missions generally provide for redundant consumables and/or abort options in the event that the piloted mission is unable to rendezvous with their cargo on the Mars surface.

### E. Trip Time and Trajectory

A trip is the time it takes for a flight, either cargo or manned, to complete a mission. Mars missions include an outbound leg and inbound leg. Nested in between the outbound and inbound legs is the Mars surface stay time in which the crew performs exploration and science.




| Conjunction | Opposition | Lunar Swingby |
|---|---|---|
| Evo88-in | Exp-P | S-NEP |
| Evo89 | Exp-M | S-SEP |
| 90D | Evo88-out | |
| Syn | Exp89 | |
| MDCh | S-C/A | |
| MDNTR | S-NTR | |
| MSD | S-NEP | |
| DRM1 | S-SEP | |
| DRM3 | | |
| DRM4N | | |
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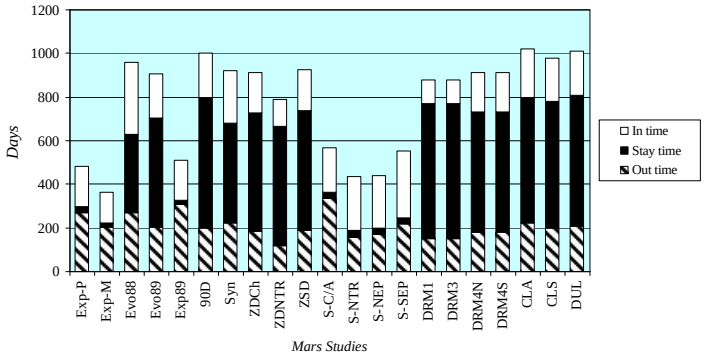



**Figure 10 Trajectory selections and Mars mission trip time**

Most opposition class missions try to use Venus swingby's; deep space maneuvers are used when Venus swingbys are not available for specific mission dates and associated trip times. The STCAEM Nuclear Electric Propulsion (NEP) opposition trajectory includes a lunar swingby leg.

Mission outbound times were 80 days (Mars Direct) to 335 days (STCAEM Cryo/Aero). In general, inbound times were the same or somewhat quicker. Of the studies surveyed, the 90-Day Study had the longest duration stay of 600 days. Figure 10 shows the trajectory options and mission trip times.

### F. In-Situ Resource Utilization

For transportation studies, ISRU translates into propellant made from the atmosphere or soil. Since propellant is a large portion of overall mission mass, ISRU provides an attractive option to transporting return propellant. Many studies assumed that ISRU would be a developed and available technology when the mission took place.

For many studies, ISRU utilization was viewed as necessary for mission success. A clear two-thirds of the studies incorporated ISRU in their mission design.

Many of the studies viewed ISRU as a technology requirement that would, at a minimum, produce propellant using seed-hydrogen from Earth. The hydrogen would catalytically react with Martian $CO_2$ to produce methane and water eliminating the need to store cryogenic hydrogen. The methane and water would be stored and liquefied then chemically combined to produce a methane/oxygen bipropellant.[8] This bipropellant would be used to refuel a Mars ascent vehicle upon departure.

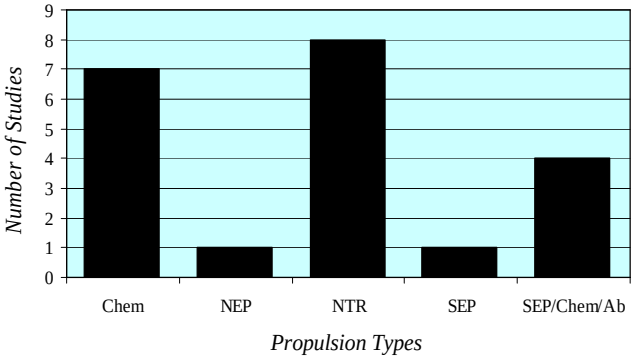
The Mars Direct Study is 100% dependent upon ISRU propellant production. Some of the other studies view ISRU as a technology development that would be a critical component especially for a long-term Mars outpost establishment. Its greatest potential is to provide self-sufficiency, providing greater resources for a broader range of transportation, habitation, life sciences, construction, energy production and other long term activities. [5]

### G. Propulsion Type

The types of propulsion used in the 21 studies were Chemical, Nuclear Thermal Rocket (NTR), Nuclear Electric, Solar Electric or a hybrid of Solar Electric and Chemical using an aerobrake (Ab) referred to as SEP/Chem/Ab. (See Fig. 11.)

Almost an even split occurs between Chemical propulsion (7 studies) and NTR propulsion (8 studies). The remaining 6 studies used SEP with a chemical stage for Trans-Mars Injection (TMI) with only one study using NEP.

Mars studies tend to be transportation studies. The selection of propulsion systems includes important trades that compares key parameters, such as trip time and radiation exposure. The danger of radiation from an NTR or NEP was traded with the benefits of a fast-transit trajectory. Faster trips decrease the danger of crew exposure to in-space radiation caused by solar particle events and galactic cosmic radiation. On the other hand, chemical propulsion is generally slower with added exposure to in-space radiation. Figure 5 presents advantages and disadvantages for using different types of propulsion.




| Chem | NEP | NTR | SEP | SEP/Chem/Ab |
|---|---|---|---|---|
| Exp-P | S-NEP | 90D | S-SEP | DRM4S |
| Exp-M | | Syn | | CLA |
| Evo88 | | MDNTR | | CLS |
| Evo89 | | MSD | | DUL |
| Exp89 | | S-NTR | | |
| S-C/A | | DRM1 | | |
| MDCh | | DRM3 | | |
| | | DRM4N | | |

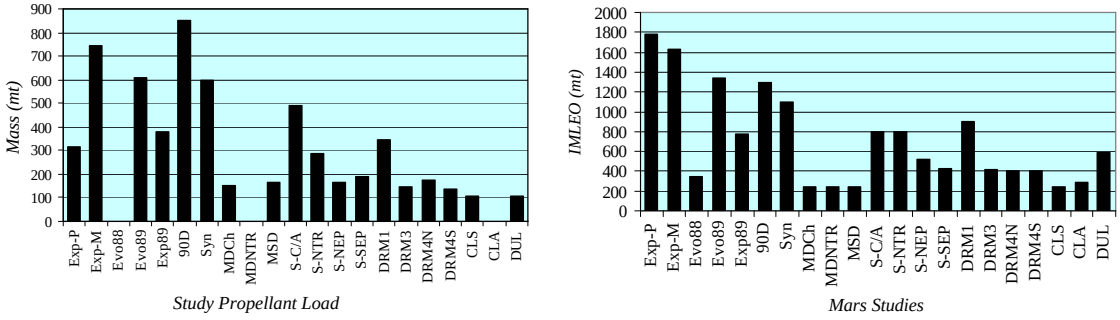
**Figure 11 Mars study propulsion selection**

### H. Propellant Load

The propellant load is the amount of propellant required to perform a complete mission (includes cargo flights and one manned flight). Propellant is the largest item contributing to the overall mission mass in LEO. Reduction in propellant mass is assumed to reduce overall mission cost. Figure 12 shows the amount of propellant required for each Mars mission and the corresponding overall mission mass. The propellant load is a significant contributor to

IMLEO. No propellant mass numbers were found for Mars Direct NTR, Lunar Outposts/Mars Evolution (1988), or the Combination Lander All-up studies.

The Human Expedition to Phobos published in 1988 yielded the greatest IMLEO as compared to the other studies. Mars Direct scenarios came in at the lowest IMLEO essentially 7.4 times less than Human Expedition to Phobos. It should be noted that the main goal of the Mars Direct scenario was low cost hence low IMLEO. It should be observed that the degree of design optimism varies widely among the studies and one should be cautious about drawing too many conclusions from IMLEO comparisons.




*Propellant Load numbers for MDNTR, CLA, and Evo88 not found.

**Figure 12 Propellant Mass and IMLEO for One Mars Mission**

## I. Aeroassist at Mars Descent to Mars Surface

Aerocapture uses the atmosphere for deceleration thus avoiding additional propellant. Most of these studies use aerocapture and aerobraking interchangeably. Since then, aerobraking has come to mean the slow process of gradually circularizing a parking orbit by repeated skims of the upper atmosphere.

Some studies used an aerobrake for capture into Mars orbit and for the Mars descent maneuver. Others used the descent lander propulsion and parachutes. Still, 5 studies of the 21 studies used all-propulsive capture into Mars orbit while 16 employed the use of aeroassist.

## J. Heavy Lift Launch Capability and Number of Launches per Mission

All studies use a HLLV to place Mars mission elements into LEO. The lift capability of the launch vehicle determines the number of launches. The DRM1 mission had a launch vehicle size of 240mt intended to avoid in-space assembly. Each element was directly launched into LEO, and following system checkout, proceeded with the outbound leg of the journey to Mars. Other studies chose smaller, HLLV's and more in-space assembly (i.e. STCAEM NEP). Results comparing the size of the HLLV and the number of launches per mission are presented in Fig. 13.

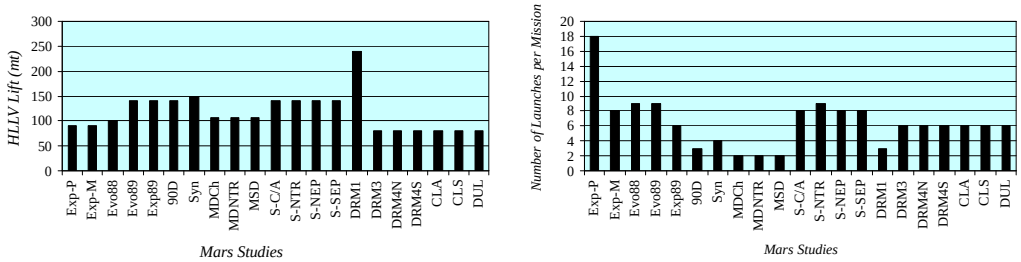



**Figure 13 Assumed Mars launch vehicle capability and number of launches for one Mars mission**

## K. Summary

In summary, there are many ways to conduct a Mars mission as seen throughout this paper. The common areas of comparison among the researched Mars studies reveal differences in mission approach, as well as in ground rules and assumptions. The comparisons are presented not to select a favored scheme, but to show the extensive work that has been done and to create an enormous resource for future Mars mission planning.

**Supporting Personnel**

| | |
|---|---|
| Mary Ellen Harris | SAIC Library (Archives) |
| Ben Donahue | Boeing (Mars Studies + Archives) |
| Vance Houston | NASA MSFC Archives |

**Acronyms and Abbreviations**

| | |
|---|---|
| 90D | Report of the 90-Day Study on Human Exploration of the Moon and Mars |
| CLA | Combination Lander All-Up |
| CLS | Combination Lander Split |
| delta v | delta velocity; change in velocity |
| DRM | Design Reference Mission |
| DRM1 | Design Reference Mission version 1.0 |
| DRM3 | Design Reference Mission version 3.0 |
| DRM4N | Design Reference Mission version 4.0 – NTR Bimodal "all propulsive option" |
| DRM4S | Design Reference Mission version 4.0 – SEP option |
| DUL | Dual Landers Presentation |
| ETO | Earth To Orbit |
| Evo88 | Exploration Studies Technical Report: Lunar Outpost to Early Mars Evolution (Case Study 4) |
| Evo89 | Exploration Studies Technical Report: Mars Evolution Case Study |
| Exp89 | Exploration Studies Technical Report: Mars Expedition Case Study |
| Exp-M | Exploration Studies Technical Report: Human Expedition to Mars (Case Study 2) |
| Exp-P | Exploration Studies Technical Report: Human Expedition to Phobos (Case Study 1) |
| HEO | High Earth Orbit |
| HLLV | Heavy-lift Launch Vehicle |
| IMLEO | Initial Mass in Low Earth Orbit |
| ISRU | In-situ Resource Utilization |
| LEO | Low Earth Orbit |
| L2 | Libration Point 2 |
| MDCh | Mars Direct Study: Chemical Propulsion option |
| MDNTR | Mars Direct Study: Nuclear Thermal Rocket option |
| MSD | Mars Semi Direct Study |
| NEP | Nuclear Electric Propulsion |
| NTR | Nuclear Thermal Rocket |
| RCS | Reaction Control System |
| S-C/A | Space Transfer Concepts and Analysis for Exploration Missions, Volume 2: Cryo/Aerobrake Vehicle |
| SEP | Solar Electric Propulsion |
| S-NEP | Space Transfer Concepts and Analysis for Exploration Missions, Volume 5: Nuclear Electric Propulsion Vehicle |
| S-NTR | Space Transfer Concepts and Analysis for Exploration Missions, Volume 3: Nuclear Thermal Rocket Vehicle |
| S-SEP | Space Transfer Concepts and Analysis for Exploration Missions, Volume 4: Solar Electric Propulsion Vehicle |
| STCAEM | Space Transfer Concepts and Analysis for Exploration Missions |
| Syn | Synthesis Group Study – "America at the Threshold" |
| TMI | Trans-Mars Injection |

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