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Soviet Options for a Manned Mars Landing Mission

An Intelligence Assessment

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December 1989
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Soviet Options for a Manned Mars Landing Mission

An Intelligence Assessment

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Soviet Options for a Manned Mars Landing Mission

Scope Note

This paper examines several options that the Soviets are likely to pursue in accomplishing a manned Mars landing mission. It does not cover all available options. They were developed using different scenarios presented by the Soviets at international meetings.

Soviet Options for a Manned Mars Landing Mission

Key Judgments

Information available as of 1 December 1989 was used in this report.

We believe the Soviets are planning for a manned Mars landing mission some time after the year 2000. Although we believe the mission has not been officially funded, the Soviets have invested in the infrastructure and are engaged in the long-lead research and development necessary for its conduct. Clear indications of Soviet intent to perform such a mission include:

- Continuing long-duration flights aboard the Mir space station that have resumed following the recent short-term hiatus in manned activity.
- The probable development of nuclear rocket engines.
- A planned program of unmanned flights to Mars over the next 10 years, despite last year's Phobos failures, giving the Soviets data for an attempted manned mission.
- An increasing number of press releases by Soviet scientists, engineers, and cosmonauts discussing their intent to conduct a manned mission.

The Soviets have several available options in mission profile and spacecraft design to accomplish this mission. Balancing the technical demands of each option with the strengths and weaknesses of their space program leads us to believe the Soviets are most likely to pursue:

- An opposition-class mission profile, where Earth and Mars are near their closest approach at the time of arrival at Mars, with a Venus swing-by—to reduce energy requirements.
- Either nuclear or conventional engines using cryogenic propellants—for efficient spacecraft propulsion.
- Aerobraking into Mars orbit—to reduce the propellant requirement.

Because of the size and mass of the spacecraft, a manned Mars landing mission will require vehicle assembly in low Earth orbit. The Soviets have the Energiya heavy-lift launch vehicle to place the components into low Earth orbit. In addition, they will have a manned space station to support spacecraft assembly and probably a space tug to move large components into position for assembly.

We believe a full-scale, manned Mars landing mission is unlikely without development of an on-orbit cryogenic storage capability and either nuclear engines or aerobraking techniques. If the Soviets use nuclear engines with a liquid hydrogen propellant, it would substantially reduce the number of launch vehicles required to place spacecraft components in low Earth orbit. The use of cryogenics will require the development of advanced on-orbit refrigeration and insulation techniques to maintain the propellants in a liquid state and reduce their loss because of boiloff. Aerobraking into Mars' orbit would reduce the mass of propellants required in low Earth orbit by as much as 55 percent. This would allow the Soviets to use proven conventional engines with liquid oxygen and liquid hydrogen propellants to achieve roughly the same reduction in the number of launch vehicles needed to place spacecraft components in low Earth orbit as with nuclear engine

We believe that, if the Soviets proceed with a manned Mars mission, they will pursue a cooperative effort with the United States to defray some of the high cost. Current Soviet estimates range from 40 to 50 billion US dollars for even the most economical launch opportunity

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Soviet Options for a Manned Mars Landing Mission

Introduction

Recent public statements by Soviet officials have confirmed that the Soviets are continuing research for a possible manned Mars mission. In March 1989, Soviet space scientists attending a space symposium outlined the following long-term Soviet Mars space program:

- The launch of a Mars and lunar-polar orbiter in 1992.
- The launch of two spacecraft to Mars, including an orbiter, atmospheric balloon, and/or soil penetrators, in 1994.
- Mars sample return mission with rover in 1998.
- A manned Mars landing mission—possibly between 2010 and 2015.

The successful completion of unmanned missions will give the Soviets valuable data on spacecraft component on-orbit lifetimes, landing sites on Mars, and command and control of interplanetary spacecraft. Despite the Soviets' recent failure to complete their Phobos mission, we believe that they will apply the lessons learned and pursue a manned Mars mission.

The Soviets also have stated publicly that the long-term effects of weightlessness on humans must be fully understood before a manned mission to Mars can be accomplished. Soviet cosmonauts have been in space continuously for up to 366 days. Vladimir Titov, crew commander, and Musa Manarov, flight engineer, were on board the Mir space station from 21 December 1987 through 21 December 1988. (They exceeded the previous 326-day record, held by Yury Romanenko, on 11 November 1988 and became the fourth and fifth cosmonauts to accumulate more than a year in space.) We believe that the Soviets will attempt a manned mission of 18 months or longer within the next few years. Continued long-duration stays in space by Soviet cosmonauts (not required for space-station operations) and planned unmanned missions to Mars are our strongest indicators of continuing Soviet plans for a manned Mars mission.

Planning for a Manned Mars Mission

Planning for a manned mission to Mars is a complex undertaking. Basic mission requirements include:

- Definition of mission goals.
- Selection of a launch date (dictated by orbital mechanics).
- Selection of the type of propulsion used.
- Determination of spacecraft trajectory.
- Design of the spacecraft.
- Selection of amount and type of scientific equipment carried on the spacecraft.

Changes to any of these requirements could change the mission profile.

Assumptions Considered for a Manned Mars Mission

An article in the 1985 edition of the *Encyclopedia of Cosmonautics* characterized a manned Mars mission as lasting one and a half to two years and using nuclear engines and liquid hydrogen propellant, with a specific impulse (Isp)[1] of 836 seconds (sec) and a total mass on orbit of 1,000 to 1,500 metric tons. Our

[1] Figure of merit expressed in seconds. Increasing Isp improves the propulsion system's ability to produce additional thrust for every pound of propellant burned.

assumptions were based in part on this article. Additional assumptions were taken from US concepts for a manned Mars mission:

- Crew of five or six.[1]
- Mars spacecraft assembled in and departing from low Earth orbit with space station support.
- Nuclear engines using liquid hydrogen propellant (Isp 836 sec) or conventional engines using liquid oxygen and liquid hydrogen propellants (Isp 450 sec).
- Venus swing-by to reduce energy requirements.
- Mission module, to remain in Mars orbit, with a weight of 54,000 kg, plus 6,800 kg return weight for Earth reentry module.
- Mars excursion module to transport Mars landing crew and equipment to and from Mars surface. The module's weight will be 60,000 kg, plus an additional 4,500 kg for nuclear shielding.
- Required velocities achieved by three propulsion stages.
- Stage structure factor for nuclear engines using liquid hydrogen is 20 percent; conventional engines using liquid oxygen and liquid hydrogen is 9 percent.
- Elliptic capture orbit at Mars and Earth.

Mars Mission Opportunities

Opportunities for direct flights to and from Mars occur near the Earth-Mars opposition, approximately every 26 months. Two general classes of direct round trip mission profiles to Mars are available:

- Opposition-class mission—where Earth and Mars are near their closest approach at the time of arrival at Mars, with a short stopover time at Mars.
- Conjunction-class mission—where Earth and Mars are farthest apart at the time of arrival at Mars, with a long stopover time at Mars.

Because of the eccentricity of Mars' orbit, the mission profile changes from one opposition to the next. The mission profile variation is cyclic, and the pattern repeats every 15 years or every seven oppositions. The relative positions of Earth and Mars for a short stopover time at Mars (30 to 60 days) require excessive energy for the spacecraft propulsion stages to perform a direct round trip mission. To reduce the energy requirement for an opposition-class mission, the gravity field of Venus can be used either en route to Mars for an outbound swing-by or en route to Earth for an inbound swing-by. Total mission time for an opposition-class mission will vary from approximately 550 to 740 days. Energy requirements can be reduced for a conjunction-class mission because low-energy, near-Hohmann-type (minimum energy) transfers can be used on the outbound and inbound trip by extending the staytime at Mars appropriately (340 to 550 days). Total mission time for a conjunction-class mission will vary from approximately 950 to 1,000 days.

There are a wide range of mission options available; for the purposes of this paper, we will assume a Soviet manned Mars mission with a 60-day staytime on the surface of Mars and will use an opposition-class mission profile with a Venus swing-by to reduce total energy requirements (see figure 1). Data considering conventional and nuclear propulsion, including the effects of aerobraking at Mars and Earth, are presented. The total on-orbit mass of the Mars spacecraft and the number of launch vehicles required to place the necessary components for it in low Earth orbit are determined for each case.

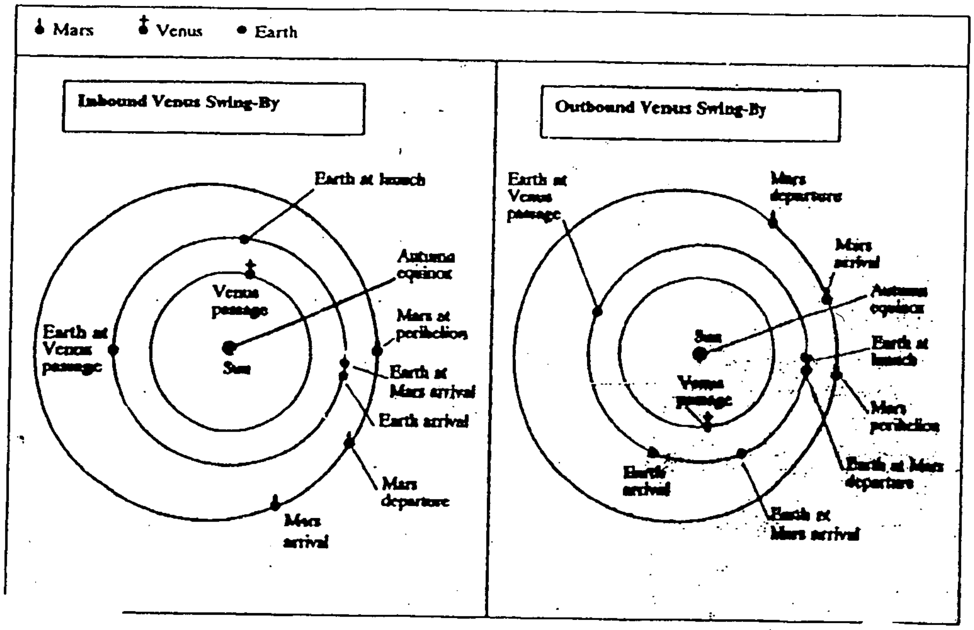
Mars Spacecraft Mass—An Estimate

There are major factors for determining spacecraft mass on orbit. These include the propulsion system, spacecraft design, launch opportunity, and crew size. We calculated the total mass required on orbit for the Soviet Mars spacecraft assuming three propulsion stages were used to conduct the mission from low Earth orbit.[4] The propulsion options we examined were:

- Conventional engines using liquid oxygen and liquid hydrogen in all three stages.

[1] A crew of six was determined to be the optimum size required to conduct a manned Mars mission. Although the crew size could be reduced, it is unlikely that a mission would be conducted with fewer than five members. A crew probably would consist of at least a commander, a pilot, a flight engineer, and two mission specialists—one of whom might be a physician. We believe that at least three crewmembers would go to and from the surface of Mars in an excursion module while the other two to three crewmembers would remain in orbit around Mars in a mission modul

Figure 1
Typical Mission Profiles For a 60-Day Stopover at Mars



- Nuclear engines using liquid hydrogen in all three stages.
- Nuclear engines using liquid hydrogen in the first and second stages, and conventional engines using liquid oxygen and liquid hydrogen in the third stage.

For each option, calculations were made for:

- All-propulsive maneuvers for all phases, including Mars entry and Earth reentry.
- Aerobrake at Earth reentry, with remaining maneuvers propulsive.
- Aerobrake at Mars entry, with remaining maneuvers propulsive.
- Aerobrake at Mars entry and Earth reentry, with remaining maneuvers propulsive.

We selected two launch opportunities—the years 2001 and 2007—for an opposition-class mission for our calculations. The dates represent the approximate minimum- and maximum-energy requirements for selected future opposition-class, Venus swing-by launch opportunities (see appendix).

Mass for the different options for all-propulsive maneuvers ranges from approximately 745,000 kg to 2,745,000 kg. Aerobraking at Mars could reduce the mass requirement by 15 to 55 percent, depending on the propulsion option and launch date chosen. In fact, aerobraking at Mars would have a major impact on the number of launch vehicles required to place Mars

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Total Mass on Orbit and Number of Launch Vehicles Required *(By launch year)*

	Conventional Engines with Liquid Oxygen and Liquid Hydrogen		Nuclear Engines with Liquid Hydrogen		Nuclear Engines with Liquid Hydrogen (Third-Stage Conventional Engines with Liquid Oxygen and Liquid Hydrogen)	
	Mass *(kilograms)*	Launch Vehicles	Mass *(kilograms)*	Launch Vehicles	Mass *(kilograms)*	Launch Vehicles
All-Propulsive						
2001	1,274,940	17	792,211	16	744,378	15
2007	2,745,115	35	1,320,521	28	1,234,491	26
Aerobrake Earth						
2001	1,211,238	16	715,364	14	715,364	14
2007	2,607,569	33	1,186,308	25	1,186,308	25
Aerobrake Mars						
2001	964,676	13	674,256	13	638,789	13
2007	1,268,705	17	807,741	16	762,443	15
Aerobrake Mars and Earth						
2001	924,104	12	617,283	12	617,283	12
2007	1,214,683	16	737,073	15	737,073	15

Note: The number of launch vehicles required to place components in low Earth orbit was calculated by assuming that the HLLV has a 100,000-kilogram payload capacity. Assuming a propellant tank 7 meters in diameter and 20 meters tall, the volume would be sufficient to carry only 50,000 kgs of liquid hydrogen (because of its density). The same size tank would easily carry the full 100,000 kilograms of liquid oxygen. The mixture ratio (mass) for liquid oxygen and liquid hydrogen propellants is normally 6:1, and that ratio was used to determine launch vehicle requirements.

spacecraft components in low Earth orbit, especially during launch opportunities with higher energy requirements (see table). The number of launch vehicles required for all-propulsive maneuvers ranges from 15 to 35. Aerobraking at Mars, however, reduces launch vehicle requirements to a low of 13 and a high of 17 for any propulsion option chosen at any launch opportunity. This significant reduction would make proven conventional engines with liquid oxygen and liquid hydrogen an attractive option, eliminating the need for nuclear engines and reducing the radiation shielding for crew protection.

Calculations for crews of six and three were performed and analyzed to determine the impact on total spacecraft mass. Depending on the launch opportunity and propulsion system selected, a reduction in crew size from six to three would produce a savings of 5 to 20 percent of the total spacecraft mass required in low Earth orbit. This would result in a savings of one to seven launch vehicles. By selecting only favorable launch opportunities, the savings in launch vehicles becomes one to three. These resultant savings were considered minimal when compared to the advantages afforded by the larger crew and are not further discussed in this paper.

At least several months would be required to orbit all the necessary components for a Mars spacecraft, assuming a 30-day turnaround time for each launchpad.

Manned Mars Mission Requirements

A Soviet manned Mars mission will involve the development of key technologies. These technologies are of two types—those that will be required for the Soviets to conduct a manned mission and those that will enhance the Soviet ability to conduct the mission.

Key Technologies Required for a Manned Mars Mission

The required key technologies are:

- Heavy-lift launch vehicle (HLLV).
- Space station on orbit.
- Space cryogenics.
- On-orbit shelf life of spacecraft components.
- Life sciences and support.
- Orbital maneuvering vehicle (OMV

Heavy-Lift Launch Vehicle. An HLLV will be required to place propellants and spacecraft components in low Earth orbit. The Soviets successfully launched an Energiya HLLV in May 1987 and November 1988. The vehicle is capable of placing a 100,000-kilogram payload in low Earth orbit and should be fully operational by the mid-1990s.

Space Station on Orbit. To support assembly of the Mars spacecraft, a space station on orbit will be required. The Mir modular space station now is on orbit and could support the construction of a Mars spacecraft. The Soviets already have announced Mir-2, a larger modular space station, which we expect to be launched in the 1994 to 1996 time frame.

Space Cryogenics. Advanced refrigeration and insulation techniques will be required to prevent excess loss of cryogenic propellants caused by boiloff. Handling and storage of these propellants also is a major problem because no in-flight refueling capability is envisioned during the mission. The Soviets have some experience with liquid oxygen and liquid hydrogen in their HLLV. These propellants, however, will have to be stored for up to two or three years for a manned Mars missio

On-Orbit Shelf Life of Spacecraft Components. The Soviets have more than five years of experience with the Salyut 6 and 7 space stations. Salyut 7 remains on orbit, providing additional lifetime data, and additional experience will be gained with the Mir space station. The Soviets have demonstrated increased lifetime with their manned spacecraft by having crews on board to repair and replace component

Life Sciences and Support. Long-duration flights aboard Soviet space stations are providing much of the data necessary to make continual improvements in the life science areas. The harmful effects of weightlessness continue to be a major concern. Soviet cosmonauts have performed continuous spaceflight in excess of a year. We believe that the Soviets will increase the duration of space station mannings in increments to a period of two years. One or more two-year missions may be needed to fully understand the medical requirements for a manned Mars mission. According to Soviet open sources, readaptation to a gravity field normally takes place within several days, but, in some cases, several weeks may be required. However, the ability of a cosmonaut to perform tasks unaided by a ground crew immediately after long exposure to weightlessness is questionable. Control of bone-calcium loss on long-duration missions also is not well understood by US or Soviet researchers and is a major issue requiring further stud

Orbital Maneuvering Vehicle. An OMV, also known as a space tug, will be required to move large components of the Mars spacecraft into place for assembly following delivery to the space station orbit. The Soviets have used a propulsion module to accomplish approach and docking of the Kvant space station module with Mir. A similar vehicle may be intended for use as an OMV .

Key Technologies That Will Enhance a Manned Mars Mission

Key technologies that will enhance Soviet efforts to conduct a manned Mars mission are:

- Aerobraking.
- Nuclear propulsion.
- Closed ecological system.
- Artificial gravity

Aerobraking. Aerobraking involves using a planet's atmosphere to dissipate an entry vehicle's energy and reduce its speed. Aerobraking can be used to change orbit or to descend to a planet's surface instead of using propulsive maneuvers. An entry vehicle is enclosed within a heatshield (that could be shaped like the US Apollo or Soviet Soyuz entry modules) that provides a relatively low lift-to-drag ratio. The entry vehicle's energy then would be dissipated through ablation of the heatshiel

Aerobraking into Mars orbit would reduce the mass of propellants required in low Earth orbit by as much as 55 percent (see figure 2).

The Soviets have stated that they intend to use aerobraking on their unmanned missions, and they do have some experience with aerobraking on earlier Mars missions. The Mars 2, Mars 3, and Mars 6 lander missions used an aeroshell braking device, although it did not generate any lift.

Nuclear Propulsion. Nuclear engines using liquid hydrogen propellant could provide almost twice the Isp of conventional engines using a liquid oxygen and liquid hydrogen mixture. The increased Isp would reduce the amount of propellant and the total mass required on orbit. A nuclear engine also could provide electrical power for the Mars spacecraft during the missior

The Soviets may be testing advanced reactors to be used as power and propulsion plants for future space missions

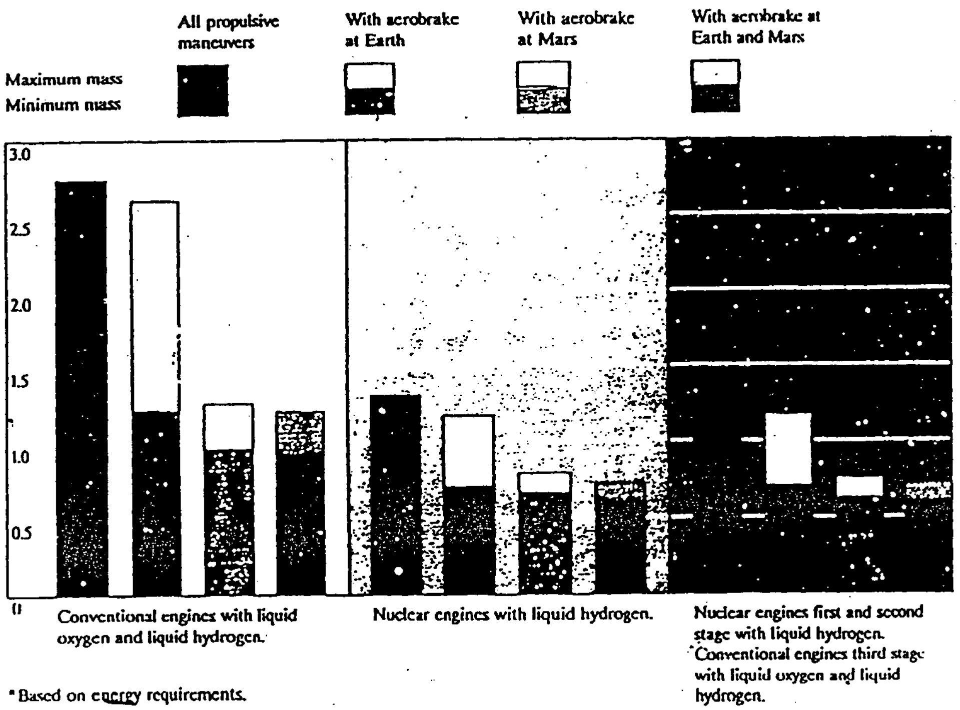
At a US conference held earlier this year on space nuclear power systems, a Soviet scientist presented a paper discussing nuclear electric propulsion (NEP) as one of several options being investigated by the Soviets for use on a Mars mission for electrical power and propulsion. NEP would provide a higher Isp, but with lower thrust levels. NEP engines would probably be designed to burn continuously, and the comparative round trip transit times for a Mars mission would increase significantly, making NEP engine use less desirable for early manned missions

Closed Ecological System. A closed ecological system could provide life-support consumables (oxygen, food, and water), thereby eliminating some of the mass of expendable consumables. A closed system will have minimal impact on the total number of launch vehicles required to support a mission, however, because the mass of expendable consumables constitutes only a small fraction of the total mass required. Soviet scientists at the Institute of Biophysics are working on closed ecological systems and have stated that these systems will be used on future space station

Artificial Gravity. The long-duration effects of weightlessness are not fully understood, and countermeasures are continually being implemented to reduce the period of readaptation to gravity. The gravity of Mars is about one-third that of Earth's, and scientists generally believe that humans would be unable to adapt rapidly to its gravitational field following long periods of weightlessness en route. The Soviets are investigating the possible use of artificial gravity. There are differences of opinion in the Soviet Union, just as there are in the United States, on the benefits and engineering trade-offs required to incorporate an artificial gravity field on the Mars spacecraft

Figure 2
Range of Total Mass Required in Low Earth Orbit[a]

Mass in low Earth orbit in million kilograms



[a] Based on energy requirements.

Soviet Investment

The most economical launch opportunities for a manned Mars mission most likely will cost from 40 to 50 billion US dollars. These figures assume the supporting infrastructure is already in place. The Soviets will have made a major resource investment before committing themselves to a launch, including:

- A fully operational, permanently manned space station.
- [redacted]
- Full development costs for their HLLV.
- Development of modules that could be used for a Mars spacecraft.

Because of budgetary constraints and increasing debates on allocation of future resources for the Soviet space systems, it is too early to know if the Soviets will go ahead with a manned Mars landing mission. We project, however, that the overall manned space effort will remain robust, at least for the next five years as the Soviets add new modules to the Mir space station and as the shuttle orbiter becomes operational. In the middle-to-late 1990s, the cost of manned space activities could increase if the Soviets proceed with plans for a follow-on space station.

Soviet space scientists and officials have been trying to deflect Soviet criticism of the enormous expense of space activities by stressing the economic benefits to the national economy. For example, the Soviets claim that an upcoming Mir module will produce profits that will pay for the project many times over. Other claimed benefits from the space station include increased agricultural production, enhanced reforestation programs, and increased harvest by fishing fleets.

Cooperation With the United States on a Mars Mission

The Soviets may seek to cooperate with the United States, which is considering a manned Mars mission, to defray some of the expense of such a mission. Soviet scientists now are pursuing such a cooperative effort; if the United States decides not to participate because of technology transfer considerations or for other reasons, the Soviets are likely to implement a manned Mars mission on their own. They would probably attempt to gain greater cooperation and financial support from France and perhaps other nations that have flown or participated in cooperative efforts on Soviet space station

Future Indicators for a Soviet Mission

Future developments that would indicate continued progress toward realizing the mission include:
- Development and use of aerobrake techniques.
- Advanced refrigeration and insulation on upcoming unmanned space missions.
- Assembly of a Mars spacecraft prototype in low Earth orbit.
- A flight to Mars of an unmanned prototype.
- The possible flight testing of a nuclear engine

A manned Mars mission most likely could not take place before the year 2000 because of the time required to develop aerobrake techniques, nuclear engines, advanced on-orbit refrigeration, improved insulation techniques, a fully operational HLLV, and possibly a closed-cycle, life-support system. If the Soviets are successful in developing aerobraking techniques, the most likely option would be to use proven conventional engines with liquid oxygen and liquid hydrogen propellants. Without aerobraking, nuclear engines probably would be used in the mission to reduce the number of launch vehicles required. Without aerobraking or nuclear engines, and a cryogenic on-orbit storage capability, we believe it is unlikely that a full-scale manned Mars landing mission could be accomplished. Using storable propellants, which have lower Isps, would require a prohibitive mass on orbit. Such use probably would make a manned mission nearly impossible, especially during launch opportunities necessitating higher energy requirements.

Appendix

Mars Stopover Mission With Venus Swing-By

Mission Opportunity	Earth-Mars Opposition	Leave Earth	Pass Venus	Arrive Mars	Leave Mars	Pass Venus	Arrive Earth	Outbound Trip (Days)	Mars Stop-over (Days)	Inbound Trip (Days)	Total Mission (Days)
2001 Inbound	13 June 2001	28 Mar 2001		30 Sept 2001	29 Nov 2001	11 June 2002	24 Nov 2002	186	60	360	606
2003 Outbound	29 Aug 2003	24 Aug 2002	23 Dec 2002	22 June 2003	21 Aug 2003		25 Apr 2004	302	60	248	610
2005 Outbound	9 Nov 2005	8 June 2004	21 Nov 2004	15 May 2005	14 July 2005		29 Mar 2006	341	60	258	659
2007 Inbound	26 Dec 2007	7 Sept 2007		7 Mar 2008	6 May 2008	8 Oct 2008	18 Mar 2009	182	60	316	558
2010 Double	29 Jan 2010	23 Jan 2009	1 June 2009	31 Dec 2009	1 Mar 2010	25 Aug 2010	29 Jan 2011	342	60	334	736
2012 Outbound	5 Mar 2012	28 Nov 2010	8 May 2011	8 Oct 2011	7 Dec 2011		8 Sept 2012	314	60	276	650
2014 Inbound	8 Apr 2014	22 Nov 2013		19 Aug 2014	18 Oct 2014	2 Mar 2015	18 Aug 2015	270	60	304	634
2016 Inbound	21 May 2016	10 Nov 2015		27 July 2016	25 Sept 2016	22 Mar 2017	9 June 2017	260	60	257	577
2018 Outbound	26 July 2018	11 Apr 2017	11 Sept 2017	21 Mar 2018	20 May 2018		9 Jan 2019	344	60	234	638
2020 Inbound	19 Oct 2020	10 June 2020		13 Dec 2020	11 Feb 2021	11 Aug 2021	25 Jan 2022	186	60	348	594
2022 Outbound	9 Dec 2022	31 Oct 2021	28 Mar 2022	29 Aug 2022	28 Oct 2022		29 July 2023	302	60	274	636
2025 Outbound	19 Jun 2025	9 Sept 2023	18 Feb 2024	3 Jul 2024	1 Sept 2024		25 May 2025	298	60	256	614
2027 Inbound	19 Feb 2027	2 Nov 2026		29 May 2027	28 July 2027	12 Dec 2027	25 May 2028	208	60	302	570
2029 Double	24 Mar 2029	26 Mar 2028	25 Aug 2028	15 Mar 2029	14 May 2029	28 Oct 2029	1 Apr 2030	354	60	322	736
2031 Outbound	3 May 2031	29 Jun 2030	11 July 2030	18 Jan 2031	19 Mar 2031		14 Nov 2031	354	60	240	654

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