Chapter 7: The Case for Mars

> We didn't know all of the people who finally did speak . . . until they called us! Somehow they heard about the conference, through the flyers we sent around and from word of mouth, and they volunteered. It really was a Mars Underground! (Christopher McKay, 1981)[1]

Columbia

Columbia, the first Space Shuttle, lifted off from Pad 39A at Kennedy Space Center on 12 April 1981, with Commander John Young and Pilot Robert Crippen on board for a two-day test flight. Nearly 12 years before, the Apollo 11 CSM Columbia had left the same pad atop a Saturn V at the start of the first Moon landing mission. For Shuttle flights, the twin Complex 39 pads were trimmed back and heavily modified. Designated STS-1, it was the first U.S. piloted space flight since the joint United States-Soviet Apollo-Soyuz mission in July 1975.

At launch, the 2,050-metric-ton Shuttle "stack" consisted of the delta-winged orbiter Columbia and twin 45.4-meter-long Solid Rocket Boosters (SRBs) attached to a 47.4-meter-long expendable External Tank (ET). Columbia measured 37.2 meters long with a wingspan of 23.8 meters. Seconds before planned liftoff, the three Space Shuttle Main Engines (SSMEs) in the orbiter's tail ignited in rapid sequence, drawing liquid hydrogen and liquid oxygen propellants from the ET. Then, at T-0, the two SRBs lit up. Unlike the Saturn V, which climbed slowly during first-stage operation, Columbia leapt from the launch pad. Also unlike the Saturn V engines, the SRBs could not be turned off once they ignited, making abort impossible until they exhausted their propellants and separated. This was not considered a major risk—SRBs, used since the 1950s, were considered a mature technology.

Two minutes into STS-1, the SRBs separated and fell into the Atlantic for recovery and reuse. Columbia's SSMEs, the world's first reusable large rocket engines, continued pushing the orbiter and ET toward space. Eight and one-half minutes after launch, the SSMEs shut down and the ET separated. Young and Crippen fired Columbia's twin Orbiter Maneuvering System (OMS) engines to complete orbital insertion while the ET tumbled and reentered, then opened the long doors covering Columbia's 18.3-meter by 4.6-meter payload bay. The payload bay was the orbiter's raison d'être. Maximum payload to low-Earth orbit was about 30 metric tons, though center of gravity and landing weight constraints restricted this to some degree. The payload bay could carry satellites for release into orbit or a European-built pressurized laboratory module called Spacelab. The Space Shuttle orbiter was also the only space vehicle that could rendezvous with a satellite and capture it for repair or return to Earth—it could return about 15 metric tons to Earth in its payload bay. NASA hoped to use the Space Shuttle to launch components for an Earth-orbiting space station and other vehicles, such as aerobraking Orbital Transfer Vehicles (OTVs) based at the station.

On 14 April Young and Crippen fired Columbia's OMS engines for about two minutes to begin reentry. The STS-1 reentry had almost nothing in common with previous piloted reentries. Columbia's heat shield did not ablate—that is, burn away—to protect it from the friction heat of reentry. Instead, in the interest of reusability, Columbia relied on more than 24,000 individually milled spun-glass tiles to shield its aluminum skin.

After a pair of close-timed sonic booms—they would become a Space Shuttle trademark—Columbia glided to a touchdown on the wide dry lake bed at Edwards Air Force Base, California. Future landings would occur on a runway seven kilometers from the Complex 39 Shuttle pads at KSC.[2]

NASA heralded the flight as the start of a new era of routine, inexpensive space access that might spawn industry off Earth. An ebullient Young told reporters, "We're not really too far—the human race isn't—from going to the stars."[3]

The Case for Mars

The Mars buffs who were gathered in Boulder, Colorado, for the first Case for Mars conference, just two weeks after the first Shuttle flight, would have settled for NASA's setting its sights on Mars—never mind the stars. Fueled by the Viking discoveries, would-be Mars explorers dared look beyond the Space Shuttle. They hoped that Mars ship propellants and components might soon be manifested as Shuttle payloads. They also saw in the Shuttle and in the Space Station Program (expected soon to follow) sources of hardware for Mars ship parts, much as planners in the 1960s envisioned using Apollo hardware for piloted Mars flybys.

The 1981 Case for Mars conference provided the first public forum for Mars planning since the 1960s. The conference crystallized around an informal seminar based on NASA's 1976 study The Habitability of Mars, organized by Christopher McKay, a University of Colorado at Boulder astro-geophysics Ph.D. candidate. The seminar brought together Mars enthusiasts from Boulder and around the country. The "Mars Underground," as they light-heartedly called themselves, decided in the spring of 1980 that the time was ripe for a conference on Mars exploration.[4]

The Case for Mars conference drew its name from the title of Benton Clark's 1978 Mars ISRU paper (see chapter 6). Clark took part in the conference, along with about 300 other engineers, scientists, and enthusiasts.[5] It was the largest gathering of would-be Mars explorers since the 1963 Symposium on the Manned Exploration of Mars.

The conference was in part a brain-storming session—an opportunity to take stock of ideas on how to explore Mars. Among the concepts presented was S. Fred Singer's "PH-D Proposal," which drew upon Shuttle-related technology expected to exist in 1990.[6] Singer's scenario had staying power—he was still writing about it in the spring of 2000.[7]

Singer's $10-billion expedition would use Deimos, Mars' outer moon, as a base of operations for exploring the Martian system. It was similar to the 1960s piloted flyby and orbiter missions in how it minimized spacecraft weight. None of the six to eight astronauts would land on Mars, though a sample-return lander would bring up a "grab sample" from the planet and two astronauts would visit Phobos, Mars' inner moon. The astronauts would remote-control between 10 and 20 Mars surface rovers during their two-to-six-month stay in the Martian system. At Deimos' orbital distance, round-trip radio travel time would be only one-fifth of a second.

Two astronauts would be "medical scientists" who would study human reactions to weightlessness, radiation, and isolation throughout the expedition. They would minimize risk to the crew from these long-duration space flight hazards by continually monitoring their health; data they gathered would also minimize risk for future Mars landing expeditions.

Singer's expedition would rely on solar-electric thrusters, using electricity from a large solar array to ionize and electrostatically expel argon gas. As described in chapter 2, electric propulsion thrusters produce constant low-thrust acceleration while using very little propellant. Singer assumed that the solar array would be available in high-Earth orbit in 1990 as part of a pre-existing Shuttle-launched cislunar infrastructure. The cost of the solar array was thus not included in Singer's expedition cost estimate.

At the start of the PH-D Proposal expedition, the unpiloted solar-electric propulsion system would spiral out from Earth, slowly gaining speed. Several weeks later, as it was about to escape Earth orbit, the piloted Phobos-Deimos craft would catch up, using chemical rockets, and dock. This technique minimized risk to crew by reducing the amount of time they had to spend in weightlessness and by speeding them through the Van Allen Radiation Belts. The solar-electric propulsion system would accelerate the spacecraft until expedition mid-point; then its thrusters would be turned to point in the direction of travel. The spacecraft would then decelerate until it was captured into orbit by Mars' gravity.

The 1990-91 target launch date would allow Singer's expedition to take advantage of a Venus flyby opportunity to gain speed and change course without using propellant. Total expedition duration would be "something less than two years." Electric propulsion plus Venus flyby plus postponing the piloted Mars landing until a later expedition would reduce spacecraft weight at Earth-orbit departure to about 300 tons.

The Planetary Society

In 1983, The Planetary Society, a non-profit space advocacy organization with about 100,000 members, commissioned the most detailed piloted Mars mission study since 1971. The organization did this because, as Society president Carl Sagan and executive director Louis Friedman wrote in their foreword to the study report, "since Apollo, there have been, in the United States at least, almost no serious studies of manned (or womanned) voyages to other worlds, despite the fact that enormous technological advances have been made since those early lunar landings."[8] Writing in the Society's member magazine, The Planetary Report, Friedman explained that "we funded [the study] because it is important to have solid technical evidence to back us in our advocacy of new goals . . . ."[9] The nine-month study, "a labor of love" performed at a "bargain basement price" by Science Applications International Corporation (SAIC), was completed in September 1984.[10]

SAIC's Mars mission design resembled MSC's 1963 Flyby-Rendezvous mode. Eighteen Space Shuttle launches would deliver more than 160 metric tons of spacecraft components to Earth orbit. The four-person crew would travel to Mars in a 121-metric-ton Outbound Vehicle consisting of four "sub-vehicles." These were the 38-metric-ton Interplanetary Vehicle, the 19-metric-ton Mars Orbiter, the 54-metric-ton Mars Lander, and the 10-metric-ton Mars Departure Vehicle.

The Interplanetary Vehicle, which would provide one-quarter of Earth's gravity by spinning three times each minute, would include pressurized crew modules based on Spacelab modules. The Mars Orbiter, the Mars Departure Vehicle, and the conical, two-stage Mars Lander were together designated the Mars Exploration Vehicle (MEV). The MEV would include a 54-meter-diameter aerobrake. The crew would return from Mars in the 43-metric-ton Earth Return Vehicle (ERV), which resembled the Interplanetary Vehicle except in that it would include a conical 4.4-metric-ton Earth-return capsule nested in a 13-meter-diameter aerobrake. Of these vehicles, only the MEV would have to slow down and enter Mars orbit. This, plus extensive use of aerobraking, would reduce the amount of propellant required to carry out SAIC's Mars expedition, which in turn would reduce spacecraft weight.

The unpiloted ERV would depart Earth orbit on 5 June 2003, using three large OTVs stacked together, each carrying over 27 metric tons of propellants. The SAIC team assumed that reusable space-based OTVs would be available in Earth orbit as part of NASA's Space Station Program. The expense of developing, launching, and operating the OTVs was thus not counted in the cost of the expedition. OTV 1 would fire its engines at perigee, increasing its apogee distance, then separate. OTV 2 would repeat this procedure. OTV 3's perigee burn would place the ERV on course for Mars. This series of maneuvers would require about six hours.

The crew would depart Earth in the Outbound Vehicle ten days later, on 15 June 2003. Because it was nearly three times heavier than the ERV, the Outbound Vehicle would need perigee burns by seven OTVs over about two days to achieve a Mars-bound trajectory.

On 24 December 2003, the crew would near Mars in the Outbound Vehicle, board and undock the MEV, and aerobrake into Mars orbit. The abandoned Interplanetary Vehicle would fly past Mars into solar orbit. Three of the four crew would enter the Mars Lander and descend to the surface, which they would explore using a pressurized rover. On 23 January 2004, after a month on Mars, the surface crew would lift off in the Mars Lander ascent stage with 400 kilograms of rock samples to rejoin their colleague aboard the Mars Orbiter.

The ERV, meanwhile, would approach Mars on a flyby trajectory. The crew would board the Mars Departure Vehicle, abandon the Mars Lander ascent stage and Mars Orbiter, and leave Mars orbit in pursuit of the ERV. Rendezvous and docking would occur while the ERV was outbound from Mars. Friedman noted that "[b]ecause the orbit doesn't close around Mars, the crew has only a chance at one precise time, to rendezvous with the return vehicle. Although this is risky, SAIC analysis found it acceptable compared to other mission risks. (However, some of us at The Planetary Society wonder if the crew will feel the same way!)"[11]

Eighteen months later, on 5 June 2006, the crew would board the Earth-return capsule and separate from the ERV. They would aerobrake in Earth's atmosphere while the abandoned ERV flew past Earth into solar orbit.

The SAIC team estimated the cost of their Mars expedition at $38.5 billion in 1984 dollars, of which $14.3 billion would be spent on Mars spacecraft hardware, $2 billion would pay for Shuttle launches, and $18.5 billion would be spent on operations. Friedman pointed out that, over a decade, this cost averaged about $4 billion annually, or about 60 percent of NASA's approximately $7-billion FY 1984 budget.[12]

Space Station

Traditionally, space stations have been envisioned as having multiple functions, not least of which was as an assembly and servicing base—a spaceport—for spacecraft, including those bound for Mars. In 1978, as Space Shuttle development moved into its final stages, NASA's Johnson Space Center (JSC) (as MSC was renamed in 1973) began planning a Shuttle-launched modular space station called the Space Operations Center (SOC). A space shipyard, the SOC was the most important station concept in the years 1978 through 1982—the period immediately before gaining approval for a station became a realistic goal for NASA.[13]

An internal NASA presentation in May 1981—one month after STS-1—described the SOC as the central element of a "space operations system" that would include the Space Shuttle, OTVs for moving objects assembled at the SOC to orbits beyond the Shuttle's altitude limit, and Manned OTVs for transporting astronauts on satellite service calls.[14] A JSC press release in early 1982 referred to the SOC as a "space base and marshaling yard for large and complex payloads" providing "garage space for reusable cryogenic stages."[15]

After his first year in office, during which NASA took deep cuts, President Ronald Reagan came to see the political benefits of being identified with a successful space program. On 4 July 1982, Columbia returned from space at the end of mission STS-4. Reagan was on hand amid fluttering American flags to declare the Shuttle operational. He spoke of establishing a more permanent presence in space, but withheld a clear mandate to build a space station until his 25 January 1984 State of the Union address. When he did, he emphasized its laboratory function:

> We can follow our dreams to distant stars, living and working in space for peaceful economic and scientific gain. Tonight I am directing NASA to develop a permanently manned Space Station and to do it within a decade. The Space Station would permit quantum leaps in our research in science, communications, in metals and in life-saving medicines which can only be manufactured in space . . . .[16]

The lab function was emphasized partly to keep the Station's estimated cost as close to $8 billion as possible.[17] As we have seen, Mars planners early in the 1980s assumed that OTVs and other Earth-orbit infrastructure applicable to Mars exploration would soon become available. With the spaceport role de-emphasized and the lab role moved to the fore, the justification for OTVs was largely removed, and the ability to assemble other Earth-orbit infrastructure, such as Singer's solar array, was made forfeit. Assembling the Space Station itself would provide some experience with application to Mars ship assembly. However, it would provide little experience with handling tankage and propellants in space, both crucial to building a Mars ship.

Soviets to Mars

In the early 1980s, such NASA advanced planning as existed focused more on the Moon than on Mars. The revival in NASA Mars interest owes much to geologist and Apollo 17 Moonwalker Harrison Schmitt, and to the Agency's lunar base studies, which had never receded to the same degree as its Mars studies. Schmitt was concerned about an on-going Soviet space buildup, which saw long stays by cosmonauts aboard Salyut space stations and development of a Soviet shuttle and heavy-lift rocket, as well as plans for ambitious robotic Mars missions.[18] Schmitt also concentrated on Mars because he had asked children, the future space explorers, about returning to the Moon and found that they were not interested because people had already been there.[19]

Schmitt had attempted to promote Mars exploration in the late 1970s while serving as Republican U.S. Senator from New Mexico. Following Viking's success, he had put forward a bill calling for the U.S. to develop the capability to establish a settlement on Mars by 2010. His "Chronicles Plan" excited momentary interest in President Jimmy Carter's White House, inducing NASA Administrator Robert Frosch to activate a small NASA study team. The team's July 1978 workshop at Wallops Island, Virginia, produced nothing new. In fact, the consensus was that "past work [from the 1960s] should not be updated unless serious consideration is being given to conducting a manned Mars mission prior to the year 2000."[20] In short, NASA was too busy working on the Space Shuttle in 1978 to think about Mars.

Schmitt renewed his Mars efforts in 1983 by contacting Paul Keaton of LANL during a meeting held in the run-up to the 1984 Lunar Bases and Space Activities of the 21st Century conference, held at the National Academy of Sciences in Washington, DC.[21] As seen in Chapter 5, LANL was involved in space flight before NASA was created through its work on nuclear rockets. At the lunar base conference, Schmitt presented a paper on his "Mars 2000 Millennium Project," which he hoped would "mobilize the energies and imaginations of young people who are already looking beyond Earth orbit and the [M]oon."[22] He also made contact with NASA engineers and scientists interested in exploring Mars as well as the Moon.[23]

Schmitt then pressed for a study to give the President the option to send humans to Mars should he desire to respond to the Soviet buildup. LANL partnered with NASA to conduct the Manned Mars Mission (MMM) study during 1984 and 1985. The effort culminated in the joint NASA-LANL MMM workshop at NASA Marshall (10-14 June 1985).[24] The workshop published three volumes of proceedings in 1986.[25]

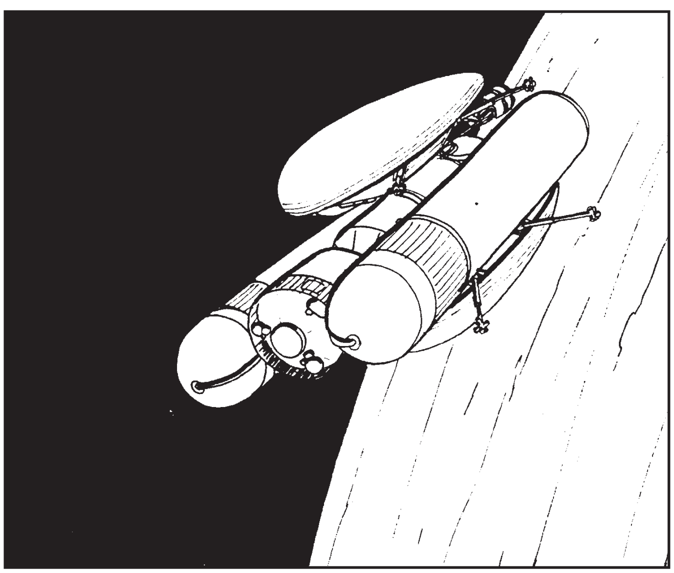

Figure 18—In 1985, NASA's Johnson Space Center responded to suspected Soviet Mars plans by proposing a U.S. Mars flyby using Space Station and lunar base hardware then planned for the 1990s. Here the flyby spacecraft orbits Earth before setting out for Mars. ("Concept for a Manned Mars Flyby," Barney Roberts, Manned Mars Missions: Working Group Papers, NASA M002, NASA/Los Alamos National Laboratories, Huntsville, Alabama/Los Alamos, New Mexico, June 1986, Vol. 1, p. 210.)

Especially noteworthy, given Schmitt's primary rationale for the MMM workshop, was a JSC plan for a piloted Mars flyby based on technology expected to exist in the 1990s as part of the Space Station Program. This aimed at countering a possible Soviet piloted Mars flyby mission.

In April 1985, at Schmitt's request, the CIA prepared an analysis of possible Soviet space moves. The analysis cited "[p]ublic comments in 1982 by the Soviet S[cience] & T[echnology] Attaché assigned to Washington and in 1984 by the President of the Soviet Academy of Science," which suggested that "the Soviets have confidence in their ability to conduct such a mission." The CIA then predicted that " . . . they will choose a one-year flyby as their first step."[26]

The analysis cited current and future indicators pointing to Soviet piloted Mars exploration. These included continuing work on a heavy-lift rocket "capable of placing into low-earth orbit about five times the payload of the present largest Soviet space launch vehicle, thereby significantly reducing the number of launch vehicles required."[27] The "strongest current indicator," however, was "the long-duration stays in space by cosmonauts" aboard Salyut space stations. Potential future indicators included "a cosmonaut stay in low-earth orbit of one year duration . . . [and] space tests of a nuclear propulsion system . . . ."[28] The CIA guessed that the first Soviet Mars flyby might occur as early as 1992, in time for the 500th anniversary of Columbus's arrival in the Americas.[29]

The JSC flyby plan for countering this possible Soviet move was prepared by Barney Roberts, who performed lunar base studies in the JSC Engineering Directorate.[30] Roberts' year-long Mars flyby mission would begin with orbital assembly at the Space Station. Shuttles would deliver two expendable strap-on propellant tanks and an 18-ton Mission Module to the Station. The latter would dock with a 6-ton Command Module (not to be confused with the Apollo CM) and two 5.75-ton OTVs assumed to be in space already as part of the Space Station Program. Shuttle-derived heavy-lift rockets would then deliver 221 tons of liquid hydrogen/liquid oxygen propellants. The propellants would be loaded into the strap-on and OTV tanks just prior to departure for Mars. Spacecraft weight at Earth-orbit departure would come to 358 tons.

At the proper time, the OTV engines would ignite and burn for about one hour to put the flyby craft on course for Mars. This would empty the strap-on tanks, but Roberts advised retaining them to provide additional meteoroid and radiation shielding for the crew modules. After a six-month Earth-Mars transfer, the flyby spacecraft would spend two and one-half hours within about 20,000 miles of Mars. Closest approach would occur 160 nautical miles above the Martian surface with the flyby craft moving at 5 miles per second.

As Earth grew from a bright star to a distant disk, the astronauts would discard the strap-on tanks, then undock one OTV and redock it to the Command Module. They would enter the Command Module and discard the Mission Module and the second OTV. The OTV/Command Module combination would slow to a manageable reentry speed using the OTV's engines, aerobrake to Earth-orbital speed, then dock at the Space Station.

Roberts found (as had planners in the 1960s) that Earth return was the most problematical phase of the flyby mission because the OTV would hit Earth's atmosphere at 55,000 feet per second, producing friction heating beyond the planned limits of the OTV heat shields. In addition, the crew would experience "exorbitant" deceleration levels after spending a year in weightlessness.

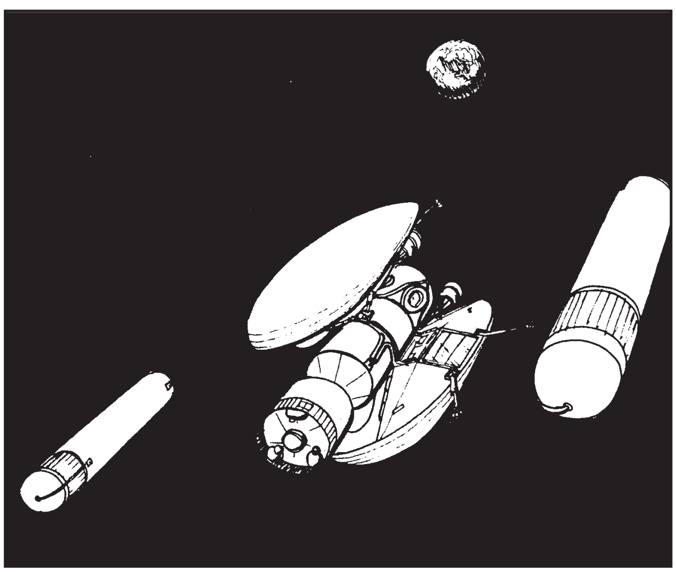

Figure 19—During return to Earth the flyby spacecraft discards empty propellant tanks, revealing cylindrical Command and Mission Modules between twin almond-shaped Orbital Transfer Vehicles. ("Concept for a Manned Mars Flyby," Barney Roberts, Manned Mars Missions: Working Group Papers, NASA M002, NASA/Los Alamos National Laboratories, Huntsville, Alabama/Los Alamos, New Mexico, June 1986, Vol. 1, p. 210.)

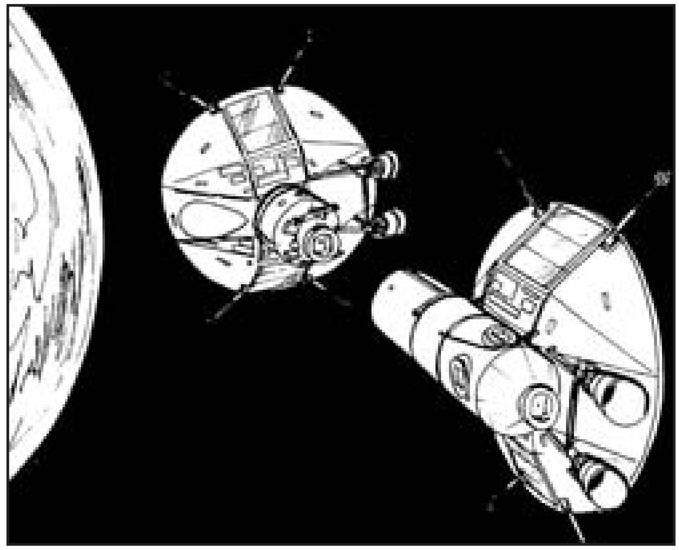

Figure 20—The flyby crew prepares to aerobrake in Earth's atmosphere. As Earth grows from a bright star to a disk, they undock the Command Module and one Orbital Transfer Vehicle, abandoning the second Orbital Transfer Vehicle and their home for the previous year, the Mission Module. ("Concept for a Manned Mars Flyby," Barney Roberts, Manned Mars Missions: Working Group Papers, NASA M002, NASA/Los Alamos National Laboratories, Huntsville, Alabama/Los Alamos, New Mexico, June 1986, Vol. 1, p. 213.)

In the 1960s, planners proposed a Venus flyby to reduce reentry speed without using propellant, but Roberts did not mention this possibility. He proposed instead to slow the OTV and Command Module to 35,000 feet per second using the former's engines. Adding this burn would nearly double spacecraft weight at Earth-orbit departure. Roberts calculated that, assuming the Space Shuttle-derived heavy-lift rocket could deliver cargo to Earth orbit at a cost of $500 per pound, Earth-braking propellant would add $250 million to mission costs.[31]

Interplanetary Infrastructure

Some Mars planners envisioned the NASA Space Station in low-Earth orbit as merely the first in a series of stations in logical places serving as Mars transportation infrastructure, much like trails, canals, railways, and coaling stations formed transportation infrastructure in bygone days. They looked ahead to solar-orbiting space stations, known as cyclers, traveling a regular path between Earth and Mars, and to spaceports at the Lagrange gravitational equilibrium points. Apollo 11 Lunar Module Pilot Buzz Aldrin, the second man on the Moon, described cyclers in a popular-audience article in Air & Space Smithsonian magazine in 1989:

> Like an oceanliner on a regular trade route, the Cycler would glide perpetually along its beautifully predictable orbit, arriving and departing with clock-like regularity. By plying the solar system's gravitational "trade winds" it will carry mankind on the next great age of exploration . . . . For roughly the same cost as getting humans safely to Mars via conventional expendable rocketry (because the problems to be solved would be largely the same), the Cycler system would provide a reusable infrastructure for travel between Earth and Mars far into the future.[32]

In the 1960s, Massachusetts Institute of Technology professor Walter Hollister and others studied "periodic" orbits related to Crocco flyby orbits but indefinitely repeating. A space station in such an orbit would cycle "forever" between Earth and the target planet. In January 1971, Hollister and his student, Charles Rall, described an Earth-Mars transport system in which at least four cycling periodic-orbit stations would operate simultaneously, permitting opportunities every 26 months for 6-month transfers between Earth and Mars.[33]

As the large periodic-orbit station flew past Earth or Mars, small "rendezvous shuttle vehicles" would race out to meet it and drop off crews and supplies for the interplanetary transfer. After several Mars voyages, the cycler approach would yield a dramatic reduction in spacecraft mass over the MOR mission mode because the cycler would only need to burn propellants to leave Earth orbit once; after that, only the small shuttles would need to burn propellants to speed up and slow down at Earth and Mars.

The Case for Mars II conference (10-14 July 1984) included a workshop that planned "a permanent Mars research base using year 2000 technology" as a "precursor to eventual colonization." The Case for Mars II workshop took advantage of the long-term weight-minimization inherent in cyclers and Mars ISRU. The Boulder Center for Science and Policy published a JPL-funded report on the workshop results in April 1986.[34]

The Case for Mars had begun to gather steam. Participants in the second conference included Harrison Schmitt with a paper on his Mars 2000 project, Benton Clark, and Christopher McKay, who had earned his Ph.D. and gone to work at NASA Ames. Former NASA Administrator Tom Paine presented a timeline of Mars exploration spanning 1985 to 2085. It predicted, among other things, a lunar population in the thousands in the 2025-2035 decade and a Martian population of 50,000 in the 2055-2065 decade.[35] Barney Roberts, Michael Duke, and lunar scientist Wendell Mendell presented a paper called "Lunar Base: A Stepping Stone to Mars,"[36] while NASA Space Station manager Humboldt Mandell presented a paper called "Space Station: The First Step."[37]

In the Case for Mars II plan, the cycler's Earth-Mars leg lasted six months, followed by a Mars-Earth leg lasting 20 to 30 months. Each crew would spend two years on Mars, and new crews would leave Earth every two years. The first crew would leave Earth in 2007 and return in 2012; the second crew would depart in 2009 and return in 2014; and so on. This schedule would require at least two cyclers. As Hollister and Rall proposed, small Crew Shuttle vehicles would transfer crews to and from the passing cycler. The Crew Shuttles were envisioned as two-stage biconic vehicles designed for aerobraking at Earth and Mars. Their proposed shape was derived from ballistic missile warhead research.

A heavy-lift rocket capable of launching at least 75 metric tons, possibly based on Shuttle hardware, would place cycler components, some based on Shuttle and Space Station hardware, into Earth orbit for assembly. The 1984 Case for Mars plan called for cycler assembly at the low-Earth orbit Space Station; in a subsequent version, a dedicated assembly facility was proposed. The first Mars expedition would require 24 heavy-lift rocket launches and 20 Shuttle launches.

ISRU would supply the Case for Mars II base with many consumables, including propellant. "Mars is abundantly endowed with all the resources necessary to sustain life," the report stated, adding that "propellant production on the surface of Mars is critical to reducing the cost of the program" because it "reduces the Earth launch weight by almost an order of magnitude."[38] Each Crew Shuttle would require 150 tons of Mars ISRU-manufactured carbon monoxide/oxygen propellant to catch up with the passing Earth-bound cycler. The Case for Mars II workshop proposed that an automated probe should test ISRU propellant production on Mars before the Mars base program began.

Lagrangia

Like the cycler concepts, the notion of siting infrastructure at the Lagrange points dates to the 1960s. Its theoretical roots, however, date to 1772. In that year, French mathematician Joseph Lagrange noted that gravitational equilibrium points exist in isolated two-body systems.

Lagrange points exist in space—for example, in the two-body Earth-Moon system. In theory, an object placed at one of these points will remain as if nesting in a little cup of space-time. In practice, Lagrange points in space are unstable or quasi-stable because planets and moons do not exist as isolated two-body systems. In the case of the Earth-Moon system, the Sun's gravitational pull introduces instability. Objects placed at the Earth-Moon Lagrange points thus tend to move in "halo orbits" around the Lagrange point and require modest station keeping to avoid eventual ejection.

Robert Farquhar, an engineer at NASA's Goddard Space Flight Center in Greenbelt, Maryland, first wrote about using the Lagrange equilibrium points of the Earth-Moon system in the late 1960s.[39] For the NASA MMM workshop in June 1985, Farquhar teamed up with David Dunham of Computer Sciences Corporation to propose using Lagrange points as "stepping stones" for Mars exploration.[40]

Farquhar and Dunham envisioned a large, reusable Interplanetary Shuttle Vehicle (ISV) in halo orbit about the quasi-stable Earth-Sun Lagrange 1 point, 1.5 million kilometers in toward the Sun. A Mars transport spacecraft parked there would be gravitationally bound to Earth much more weakly than if parked in low-Earth orbit. A mere propulsive burp would suffice to nudge the ISV out of halo orbit; then gravity-assist swingbys of the Moon and Earth would place it on course for Mars with little additional propellant expenditure. This meant, of course, that the amount of propellant that would need to be launched from Earth was minimized. To save even more propellant, the ISV might park at the Mars-Sun Lagrange 1 point, about 1 million kilometers Sunward from Mars, and send the crew to the Martian surface using small shuttle vehicles.

Farquhar and Dunham pointed out that an automated spacecraft had already left Earth-Sun Lagrange 1 on an interplanetary trajectory. The International Sun-Earth Explorer-3 spacecraft had entered Earth-Sun Lagrange 1 halo orbit on 20 November 1978. After completing its primary mission it was maneuvered during 1984 through a series of Earth and Moon swingbys to place it on course for Comet Giacobinni-Zinner. Farquhar supervised the effort. The maneuvers consumed less than 75 kilograms of propellant. Renamed the International Comet Explorer, the spacecraft successfully flew past Giacobinni-Zinner, 73 million kilometers from Earth, on 11 September 1985.

Paul Keaton elaborated on Farquhar and Dunham's MMM paper in a "tutorial" paper published in August 1985. He wrote that "[a]n evolutionary manned space program will put outposts along routes with economic, scientific, and political importance" to serve as "'filling stations' for [making and] storing rocket fuel" and "transportation depots for connecting with flights to other destinations."[41]

The first outpost would, of course, be NASA's planned Space Station in low-Earth orbit, where Earth's magnetic field would help protect travelers from galactic cosmic rays and solar flare radiation, and medical researchers would learn about the effects of long-term weightlessness on the human body. Keaton then looked beyond Earth orbit for the next outpost site. He proposed placing it in halo orbit around the Earth-Moon Lagrange 2 point, 64,500 kilometers behind the Moon, or at Farquhar's Earth-Sun Lagrange 1 site. He wrote,

> [f]or the settlement of space, a Lagrange equilibrium point between the Sun and Earth has the nearly ideal physical characteristics of a transportation depot . . . . Lagrange point halo orbits are the present standard by which any alternative concept for a transportation depot must be gauged.[42]

Cyclers and Lagrange point spaceports—infrastructure spanning worlds—imply large-scale permanent space operations and long-term commitment to building space civilization. Such grandiose visions are not widely shared outside of a subset of the small community of would-be Mars explorers, as will be seen in the next chapter.