

Project Humans to Mars

A Look at 60 Years of Mission Studies

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“No one can know what humans will find when they land on Mars – all that can be said with certainty is this: the trip can be made and will be made ... someday.”

(Wernher von Braun, “Can We Get to Mars?,” Collier’s Magazine 133, April 30, 1954, with Cornelius Ryan)

“The Expedition to Mars should be seen as the crowning achievement of a stepwise and often painfully slow development of human spaceflight which may require many decades.”

(Wernher von Braun, 1956, Frankfurt/Germany)

“What seemed to be unrealizable for centuries and yesterday was a daring dream, now becomes a real challenge, but tomorrow an accomplishment. There are no barriers to human thought!”

(Sergei Pavlovich Korolev, 1966, Pravda)

With the dawn of the space age people started to ask seriously whether human flight to Mars could actually be technically accomplished with rocket power. Thus began a time of increasing numbers of ideas, growing over time to a wide, dazzling array of at first unreal-grandiose visions that became progressively more realistic with the steady development of a wealth of practice-based experience. It was a time of unbounded mental engineering creativity, and the excitement of deep-space exploration was thick in the air. I have carried the memory with me until today.

The knowledge base assembled in those six decades provides the foundation for the confidence with which we today can design future Mars exploration ventures with increased sophistication, diminished guesswork, less uncertainty, and reduced risk.

It is interesting and instructive for future developments, how in particular the emerging real infrastructure in space, i.e. facilities, flight systems, technologies, space achievements, in short, the entire “establishment”, more and more dominated and constricted new concept studies, making them become more realistic at the expense of fresher and more innovative, less bounded thinking. That may be unfortunate to some degree, but there really can’t be found much fault in the wisdom of wanting to get

maximum use out of investments made already in new programs of the magnitude of a Mars expedition.

1950-1960

The first techno-scientifically serious investigation of whether and how manned Mars flight is possible with chemical rocket propulsion dated from the moment when the first large liquid-propulsion rocket in the world, the German A4/V-2 missile, had shown that in fact this technology possessed the capability of escaping Earth's gravitational pull and flying outside the atmosphere. Thus was accomplished the step from utopian fantasy to feasible, if still not affordable, reality. The historical study was initiated in the late 1940s in Texas by Wernher von Braun, assisted by his Peenemünde colleagues Krafft Ehrlicke, Hans Friedrich, Josef Jenissen, Joachim Mühlner, Adolf Thiel and Carl Wagner, when the German rocket pioneers after their takeover by the U.S. Army at Fort Bliss began to get bored with launching captured V-2s.

What was special about that epochal work which made Wernher von Braun "without a doubt, the most influential figure in the history of human Mars mission planning"? (*Platoff, NASA/CR-2001-208928*). It delivered the first proof of the feasibility of generously equipped expeditions to the Red Planet using conventional chemical propellants and a large, yet at that time for an undertaking of such magnitude not unreasonable appearing expense. It was an amazing feat of human creativity, because before it there had only been fantastic and – thanks to pioneering spirits like Tsiolkovsky, Oberth and Hohmann – speculative concepts, and von Braun could draw only from those few thinkers, with no existing technical models to build on. The detailed technical and programmatic concept study was published 1952 in German under the title "The Mars Project - Study of an Interplanetary Expedition" by the Frankfurt/Germany publishing house Umschau Verlag, and in 1953 in English as "The Mars Project" by the University of Illinois (Urbana). Not only did it subsequently fertilize the thinking of a generation of Mars planners, who's concepts and designs in the following years gushed forth like a flash flood after a dam break, but it also provided a convincing model study of the necessary detailed methodology for doing such large-scale advanced and preliminary design studies.

With regard to the required resources, people and funding, the "Mars Project" did exceed everything that humankind had undertaken in engineering history up to that point. Developments such as the Manhattan Project's atomic bomb and the B-52 bomber would have been overshadowed by it by far. The most amazing thing of course was the fact that its implementation would not have required any special technical breakthroughs. That is, its conceptualization was based on technologies, processes and methods that either already existed at that time or were predictable in their necessary development. With this, von Braun showed that the tremendous journey was in fact doable if only someone could be found who would pick up its financing – at a magnitude of "ten Berlin airlifts", as Wernher later put it.

He organized the problem in four clearly defined chunks. The first was to build an armada of carrier rockets on the ground that would deliver the elements of the actual

Mars ships to their assembly site at a space station in Earth orbit. This station, a huge wheel-like "Weltraumrad" 75 m in diameter added in a second iteration, circled Earth in a two-hour orbit at 1730 km altitude and 23.5° inclination to the equator. The second step, after successful assembly of the fleet, was the actual journey to Mars and the stationing of the convoy in a 1000-km orbit around the Red Planet. The third phase involved the landing of people and their return to the orbiting ships. When these three steps were successfully accomplished, Phase 4, the fleet's return to Earth, should have posed no particular difficulties.

After the Apollo Program, the Space Shuttle development, the construction of the French/British "chunnel" under the English Channel and the ISS Program, the undertaking of large-scale engineering projects can hardly shake today's humans anymore. But the sheer enormity of von Braun's Mars project even now exceeds the imagination of most people.

Just imagine: In order to transport the total mass of the huge expedition of ten (!) spaceships with a total crew of 70 persons into space, von Braun wanted to build 46 reusable launch vehicles, each with 6400 metric tons take-off mass, about three times heavier than the mighty Saturn V of the 1960s. Of this launch mass, only 39 t payload reached the space station. Each of the ten Mars ships weighed 3720 t fully loaded, as much as a Navy destroyer, thus requiring a total of 950 supply flights by the 46 super-heavy launchers, each of which therefore had to be reusable about 20 times. The assembly time for the ten expeditionary ships was estimated at nine months.

According to the detailed plans, after the arrival of the convoy in the Mars parking orbit three winged 200 t landing vehicles were to deorbit and land to explore the surface. Each carried a payload of 149 t, sufficient to allow a landing expedition of 50 people to stay for more than 400 days. In addition to the daily rations, the cargo included ground vehicles, inflatable rubber houses, heating and propulsion fuels, research tools, construction equipment and the like.

Since nothing was known at first about the suitability of the surface for horizontal landings (strangely enough, preceding reconnaissance using unmanned precursor probes had not been considered), the first lander was to be equipped with skids, to touch down on a (likely) snow-covered polar cap (as we know today there is not much snow on the Red Planet). After a successful landing, the crew of this scout ship had to unload tracked vehicles and make their way to the equatorial zone where they prepared a landing strip on which the other two wheel-equipped machines could land. The landing site would then become the basis for long-range exploration of the planet. Over a year later, the crew would have closed down the Camp and returned to the orbiting fleet in two of their gliders, leaving the third behind. The ascent vehicles would also have been given up, and the ten expedition ships would have returned to Earth and the space station after an absence of two years and 239 days.

Already shortly after publication of his Mars Project, von Braun became strongly concerned about the costs of the undertaking. He realized that he had to reduce the

enormous scale of his vision considerably to match the real circumstances of a USA which had just come out of the Korean War. In a thorough scrub-down revision he pruned the project, recalculated it and published in 1956 a second program proposal which due to better overall planning required only 10% the amount of propellants of the 1952 study, although the basic assumptions for engine performance and structural weight factors were retained unchanged.

The expedition was now limited to 12 crewmembers: eight in a passenger ship, four in a cargo ship. Each of the two ships had an Earth orbit departure mass of 1,700 t (down from 3,720 t). Its propulsion were 12 engines with hydrazine as fuel and nitric acid as oxidizer, with a total thrust of 360 t. The cargo ship carried a single landing glider of 161 t mass to land nine astronauts on the surface of the planet while the other three remained as "ship keepers" in space. Outbound and return flight paths used semi-elliptical Hohmann trajectories, each lasting 260 days; added to this were about 400 days of Mars staytime. For the return flight, only the passenger ship was used; it provided just enough space and supplies for the 12 expedition members.

Wernher von Braun's vision of 1948-50, published 1952-1953 in the US by several colorfully illustrated articles in Collier's Magazine and on television in 1955-1957 by the Walt Disney Studios, shook an audience of millions awake and even attracted the interest of President Eisenhower in the White House of the post-Korea years. There's no doubt they contributed to the founding of NASA on 1 October 1958 (rather than leaving space exclusively to the military), although the Soviet success with the first two Sputniks gave the final push, followed in 1961 by the flight of Yuri Gagarin, first human in space, which triggered President Kennedy's Apollo Program mandate.

1960-1970

During the 1960s, NASA focused considerable analytical research on the feasibility of Mars missions under various conditions. Until the 1970s, this amounted to more than 40 internal investigations and industry-contracted studies, with a total value of over four million dollars (which today would be of much higher monetary value than back then). Initially, the interest of planning managers was primarily focused on the possibility of "early" planetary flights that directly connected to Apollo and were based on the techniques and systems that supported the lunar landing program. The first series of NASA-funded industry studies, bundled under the acronym EMPIRE (for Early Manned Planetary - Interplanetary Roundtrip Expedition), addressed an extensive, still today exceptionally comprehensive and thorough spate of investigations of planetary flight, creating a solid foundation for all future Mars studies. They focused on the NOVA vehicles, the class of super-heavy launchers envisioned as follow-on to the Saturn vehicles, and on NERVA (Nuclear Engine for Rocket Vehicle Application), the AEC/NASA nuclear thermal engine program, all at the Marshall Space Flight Center (MSFC). Until about 1968, they investigated all conceivable variants of manned Mars missions in numerous variations. By combining all possible trajectories, modes of operation, maneuvers and types of ships they conceptualized an enormous number of "mission modalities" that had to be meticulously analyzed in a broad program to provide

an overview of the best possible mission profiles for manned exploration of Mars. They were analyzed, one after the other, in four successive key classes: Venus Flyby, Mars Flyby, Grand Tour and planetary Stopover.

For presenting all possible flight profiles and trajectories at a time still without today's sophisticated computational power, an extensive series of atlases of contour maps with flight path profiles was created, so-called "shell maps". This is how we used them for advanced planning: Every desired departure date from Earth determines the position of Earth in the Solar System, and every chosen arrival date that of the target planet, the difference between the two dates being of course the flight time. If both endpoints and the flight time are given, then there exist only a few flight path solutions in the two-body model Sun-Spacecraft. Eliminating impractical and otherwise less attractive cases yields a single optimal trajectory for the given conditions. Using the "patched-conics" technique, the so-called hyperbolic excess velocities were then calculated for the departure and arrival points, i.e., the additional velocity required for a spaceship above the (parabolic) Earth escape velocity – which would take it only to the edge of the Earth's gravitational influence, about 575,000 miles away. If these two values are plotted in a chart with the Earth departure date (in the JD- or Julian System) as the X-axis and the planet arrival date on the Y-axis and all points of equal hyperbolic excess velocity are connected, we obtain parametric contour curves that are closed and shell-shaped for small velocities. These graphics maps, which also sometimes included the vehicle-determining launch injection energy C_3 (km^2/sec^2), were of great help to mission planners in the preliminary design of flight profiles.

Trajectories for round trip missions to the Red Planet exist in the two categories of Opposition and Conjunction Class missions, referring to the particular Earth-Sun-Mars constellation in each case. However, in both cases the tours begin at or near Earth-Mars opposition; the difference between the two classes is created only by the position of the two planets during the outbound leg or during the stay on Mars.

Opposition Class missions are of relatively low energy on their outbound leg, close to the ideal minimum-energy Hohmann transfer of 180° central angle, and allow only a short "stopover" at Mars. (Besides the Hohmann ideal, there are Type I and Type II trajectories, the former having a heliocentric transfer angle less than 180° and trip times around 180 days, the latter with central angles greater than 180° and trip times greater than about 275 days.) Because of the shortness of the stay, a low-energy return near the Hohmann ideal is not possible, since this would require a planetary position with Mars ahead of Earth. That's easy to see: With the expedition on its low-energy outward path, the Earth will have overtaken Mars at the time of arrival, and the return flightpath must cut well inside the Earth's orbit, closer to the Sun, to attain a greater angular velocity than Earth in order to catch up with the home planet. Upon arrival, the ship's velocity relative to Earth is then relatively high because of its large radial components.

Thus, besides their advantage of short travel times (400-550 days), the Opposition Class missions have the disadvantage of high speeds at Earth return and corresponding requirements on braking techniques. The simplest solution to this

problem is to allow the expedition to stay on Mars until the next Opposition in order to allow a Hohmann return. In this case, it is a Conjunction Class mission, also called a "Double-Hohmann", with a stay time on Mars of about a year and a total travel time of 900-1100 days. Such missions not only offer a minimum of energy expenditure, i.e. maximum payload capacity, but also the longest residence time at the destination planet. When we have learnt to properly control the problems associated with the extended absence from Earth and the long duration of stay in microgravity in a thorough preparation phase, Conjunction Class missions are offering without doubt the greatest benefit potential for the invested cost for gaining a foothold and doing research in the new world.

Since Earth-Mars distances vary from Opposition to Opposition due to the ellipticity of the Mars orbit, our studies distinguished early on between "favorable" and "unfavorable" Mars missions, depending on their time period. An "unfavorable" time back then was the period 1975-1985, for two reasons: first, the planetary position required significantly more launch energy than in the "favorable" periods, due to the Mars orbit eccentricity; second, the Sun was just in its most active and thus radiation-intensive phase which returns every 11 years. "Favorable" in the more recent past was the period of relatively small planetary distances from 1984-1990, while the oppositions from 1993-1999 had greater distances and therefore were considered unfavorable.

If you don't want to accept the long travel times of the Conjunction Class, a Venus Flyby during the return trip would allow a reduction in flightpath energy and thus Earth arrival speed, because the path is bent stronger and more tangential to the Earth orbit plane. This technique can be used for an average of two thirds of all Mars opportunities. A second technique, first proposed by Krafft Ehrlicke, utilizes a propulsive braking maneuver at perihelion (its closest point to the Sun). Doing the Venus swingby during the outbound leg, the ship will be accelerated such that it arrives at the target before the Opposition. At Mars departure, it is then ahead of Earth, so that a near-Hohmann return is possible. Since the remaining third of the missions, those without Venus swingby during return, would allow this technique, Venus flybys could be included in principle on all Mars flight opportunities.

Our main interest initially was not on landing missions but on Mars flyby missions, because the first EMPIRE studies showed that piloted planetary missions with existing or foreseeable advanced flight systems, ground facilities and experience of the Apollo and post-Apollo programs were only possible for relatively low-energy "free return" flights. In these, the ship performs a flyby at the destination planet, which is calculated such that its trajectory is turned back to Earth under the influence of the planet's gravitational field without complex correction maneuvers, i.e., "free" in the sense of needing no propulsive energy. In addition to this simple type of flyby, the EMPIRE studies also examined more complex variations, including Multi-Planet Flybys and "Powered Flybys," which required thrust maneuvers after the passage.

Typical of the simple low-energy trajectories envisioned then for the 1975-1980 period were their relatively short outbound flight time (~130-140 days) and long-lasting return

trips, with total flight times of 660-690 days. Already weeks before the "encounter" and also long after it, the target planet was under scientific observation and data gathering. For the then-existing instrument technology of the researchers, passage distances of 300-400 km or less appeared desirable, even though at 1000 km excellent data were expected.

Unlike Mars, which features greatly varying Earth departure velocities during the biennially occurring best flight options, called "launch windows", due to the elliptical shape of its orbit ($e = 0.093$), the delta-V requirements for the considerably less eccentric Venus ($e = 0.00676$) vary only slightly between the windows which are spaced 19.2 month apart. The energy required for about a year-long round trip is only ~80% of the required total delta-V for Mars flybys.

We therefore at first considered a piloted Venus flyby as early interplanetary mission. It required a ship departure IMIEO (Initial Mass in Earth Orbit) of 46 t, which for chemical propulsion called for the use of two Saturn V carriers and orbital refueling of the S-IVB third stage. If instead of the normal S-IVB a new cryogenic RIFT (Reactor in Flight Test) stage with the nuclear-thermal engine called NERVA was used (with exoatmospheric ignition), it would have taken only a single Saturn V for this mission. RIFT was under early development at that time, and MSFC had an actual RIFT Project Office. The Mars flyby would instead have required either a two-stage vehicle of 276 t IMIEO for Earth departure, which presupposed orbital assembly of a chemical S-IVB and a nuclear RIFT, or all-chemical propulsion (flight mass ~500 t) with a new trans-Earth injection stage of the type of the Saturn V S-II second stage.

High-energy Mars flybys were also called "hot" missions, because the trajectory on the way to the target planet cuts into Earth's orbit, i.e. partially enters its interior and thus comes closer to the Sun than Earth. On such flights, we also distinguished between night and day side passages, depending on the locally prevailing lighting condition on the surface below periape (closest point to the planet) during the passage. Low-energy flights, where the Sun distance always remains larger than 1 AU (Astronomical Unit), were called "cool" flights. A typical "cool" mission, which we calculated, would have left the Earth on 14 August 1973 to fly by the Red Planet 100 days later, on 16 November, at a distance of one Mars radius and to arrive back at Earth on 17 May, 1975. (In the real world, in July of that year of course Americans and Russians performed the first joint mission – the Apollo Soyuz Test Project).

Of particular interest were the so-called "Grand Tour" missions or multi-planet flybys of Mars and Venus, which could be flown past both targets in one mission without any major maneuvers on either planet. Earth-Mars constellations favorable for them repeat every 2338 days (6.4 years) but at differing energy requirements (due to the Mars orbit eccentricity). One typical Grand Tour, which we looked at in those days (of the early 60's under von Braun, be it reminded), had only 464 days duration, with the following dates: Earth departure on 11 August 1972, Venus fly-by (1.5 radius distance) on 24 December 1972, Mars flyby on 7 September 1973 and return to Earth on 18 November 1973. A particularly interesting constellation was identified for 1977: A ship launched to

Mars in February with an injection delta-V of 4000 m/s could carry out a first Venus flyby during the outward flight, and a second Venus flyby after the Mars passage on the way back: three planetary passages in a mission of a total duration of 715 days!

By 1967, these studies had progressed far enough for us to choose a preferred model start date to Mars: 5 September 1975. The Mars expeditionary ship, carried to orbit with two Saturn-V vehicles, had to support a delta-V of 4700 m/s for flying past Mars 130 days later on 23 January 1976, with a velocity of 9650 m/s at a distance of 1.25 radii. After performing "en-route" experiments during the outbound flight, the four-person crew was to launch a flurry of orbiters and atmospheric probes several days before the encounter, so that they arrived at their goal before them, to transmit their measurements for the first ten days to the ship racing by and later to Earth. A robotic lander would have photographed the surface and collected soil and atmospheric samples, which then would have been brought up along with the film material to the passing mothership aboard a remote controlled three-stage rocket. In those years, detailed designs were developed even for such ancillary probe devices, as well as for the manned mission module (MMM) and the special Earth return capsule into which the crew had to transfer just before hitting the Earth atmosphere. At the high reentry velocities of 15,000-15,250 m/s the Apollo Command Module, built for lesser speeds, would not have been acceptable.

As next logical step after the early flybys, we thought of piloted planetary stopover and landing missions (the former also including pure Mars orbiting missions without landfall). The studies showed IMIEOs around 1,200-1,400 t for Mars, 500-700 t for Venus for a ship with a crew of eight and a cargo of 46 t. For the more demanding missions, the required systems, techniques, maneuvers, and flight control accuracies exceeded the state-of-the-art of the Saturn/Apollo Program in part quite significantly, by more than a technical "generation". The need to develop new technologies shifted the earliest possible mission date into the 1980s in our then-estimate, with 1984 being particularly attractive for a while.

For stopover missions, a wide spectrum of carrier systems came under detailed investigation: from early versions of the Saturn V and "Post-Saturn" vehicles to giant NOVA super-heavies with payload capacities of 500+ t and more. For the upper stages, nuclear energy was considered necessary, either directly in the form of nuclear rockets (nuclear thermal, NTR) or as an energy source to power electric or ion engines (nuclear electric, NET). In 1964, Lockheed Co. investigated the use of low-thrust electric drives for the manned Mars mission, as proposed by Ernst Stuhlinger, and determined, among other things, that ion engines could be used for all flight phases except for the Mars landing itself. Therefore, in addition to the various combination options with nuclear and chemical propulsion alone, electric propulsion also deserves consideration.

For the systematic evaluation of all possible varieties for each individual mission, three interrelated parameters were varied: the departure mass of the ship in orbit (IMIEO), the starting date and the duration of the mission. For example, if one used a fixed mass as starting value by selecting a specific carrier concept, e.g., about 500 t for certain "post-

Saturn" and NOVA concepts (Saturn V: ~120 t), then the other two values could be "parameterized" (varied). IMIEO determines the choice of the propulsion system for the Earth departure, crew size, life-support system (which in the early flyby missions was still assumed to be "semi-open"), radiation protection, navigational precision, onboard power and the re-entry system. For most of these technologies only approximate empirical projections or intellectually challenging assumptions could be made at that time. There was no experience yet for the psycho-physiological effects of weightlessness that we could expect, so that for safety our designs often included a centrifuge to generate the pressure of "artificial gravity" to the human body during the long journey. Very little was known of the consequences of long confinement in cramped quarters although nuclear submarine experts of the Navy were consulted. In those early study years there were only a few specialists in the world, in West and East alike, whose creativity was equal to the task. For us, foremost among them was Krafft A. Ehricke, a member of the Peenemünde group who had led the development of the high-energy Centaur upper stage for the Atlas rocket at General Dynamics/Astronautics.

Ehricke preferred Mars stopover missions, and his contributions in the EMPIRE studies were seminal, exemplary and tone-setting from the beginning. He strongly urged the use of nuclear power (specific impulse I_{sp} : ~800 sec), allowing Mars round trip missions with stay times of 30-50 days and total flight times around 400-450 days (Venus: 350-400 days). As already von Braun ten years earlier, he also stood firm on the fleet concept for safety, but in the modified form of his "flagship" mode. Here, the convoy consists of a manned spacecraft plus one or two unmanned supply ships with auxiliary vehicles, spare parts and spare propellants, to which the crew could transfer in an emergency. This approach was particularly attractive when nuclear propulsion was used, since the crew could be kept to a single ship and therefore be protected from any possible side radiation from the reactors. The flagship flew always ahead, followed by the less radiation-sensitive freight transporters. The design of entirely modularized and standardized convoy ships provided for easy R&R (removal and replacement) under any conditions. One of Ehricke's ideas was the so-called multiplex spaceship, basically a vehicle bundle which could be separated in the course of the mission.

A typical Mars roundtrip, proposed by Douglas Aircraft Co., was designed for a minimum total delta-V of around 1.44 EMOS (Earth Mean Orbital Speed), to be launched in 1984 for a total flight duration of 880 days, including 40-day Mars staytime. The spacecraft could be launched on a single super-heavy carrier of the "Post-Saturn" class of 21 m diameter (Saturn V: 10 m), but with empty prop tanks. Their filling required two additional logistics flights. Since the spacecraft was designed for lower thrust loads during Earth orbit departure, it had to be surrounded by an exoskeleton-like external structure that served as a micrometeorite shield and was dropped in space from each stage just before engine ignition of the latter.

The minimally required crew size was determined to be six persons, based on the assumption that three would touch down in the Mars Lander and three more would be required to fly the spaceship back home in case of a total loss of the Lander including crew. For the crew, the habitable part of the ship included a special shelter called

"biowell" as protection during the operation of the nuclear engines and from solar flares. Since liquid hydrogen provides good radiation protection, the shelter was located inside the fuel tanks of the fourth stage. For entry into the Earth's atmosphere, Douglas studied both a ballistic capsule of Apollo CM type (only bigger and heavier) and a winged lifting body.

In the Soviet Union, the official planning for the conquest of the Red Planet had been given the name Aelita, after a famous socialist film by Jakov Protazanov in 1924 about Aelita, the Queen of Mars. The first serious Soviet examination of manned Mars flight was made in 1956 by M. Tikhonravov, one of Sergei Pavlovich Korolev's section chiefs at the OKB-1 Design Bureau, closely tailored after von Braun's work of 1948-1950, also based on conventional liquid propellants. At the planned heavy-lift rocket N-1 (Nositel 1)'s payload mass of 75 - 85 t, about 20-25 N-1s would have been required to launch the components of the MPK (Martian Piloted Complex). In fact, Korolev's first draft design of the N-1 in 1956-57 was based on the MPK study. The fact that the payload capability of the N-1 was limited to 75-85 t, versus the Saturn V's 120 t, may have contributed much later to the Soviet's loss of the space race to the Moon.

Later, human landings on Mars based on chemical propulsion, as opposed to flybys, were considered impractical in Russia. The choice was (and is) between nuclear thermal propulsion and nuclear electric drive. The latter was favored by Korolev and thus became the prime candidate for Mars spacecraft. Optionally, the nuclear power source could be replaced by solar energy although it would require vast arrays of photovoltaic panels with diminished efficiency at Mars distance.

Korolev's design of the MPKK (Martian Piloted Cosmic Complex) reached its final configuration by 1964 – after only the fourth design iteration. It consisted of two basic parts, MOK (Martian Orbital Complex) with MPK (Mars Landing Complex) and RRK (Injection Rocket Complex), for the flight of the crew to the Red Planet, landing on its surface and returning to the Earth. Some variants used a heavy interplanetary complex named TMK and an interplanetary rocket complex (MRK), essentially a three-stage N-1 booster, supported by launch complexes and other ground constructions. The MRK would carry the TMK into an Earth orbit in 75-t blocks for assembly.

The MPKK's build-up in orbit was supported by a spherical assembly shack with six or eight docking units. On one side of it was docked the MOK and the MPK, on the other side the RRK in the form of a center module and 4-6 side modules, which launched the MPKK on its flight path to Mars.

Part of the MOK structure was the TMK and the RRB (Injection Rocket Block) for inserting the TMK from the Martian parking orbit onto its return trajectory to Earth, as well as the MPK landing complex with its braking and landing equipment, touchdown rocket and Martian lander with two-stage takeoff rocket and the return capsule.

The assembly in Earth orbit of the 400-500 t complex with 4-5 N-1 rockets was estimated to take a year. All its components would undergo a full cycle of checks and

tests similar to the factory, performed by special brigades of cosmonauts from among skilled experts of OKB-1, the main factory and the launch site. The crews were to be delivered into orbit on "Soyuz"-type spacecraft and housed in the spherical habitation shack. After completing prestart preparations, the assembly crews would return to Earth. The actual Mars crew arrived on the TMK long before the launch and personally conducted preparations and start-up of the closed biological-technical life support system, as well as checkouts of all ship's systems. For the start, they would relocate to the descent module from where all dynamic operations could be controlled.

1970 – 1980

With the growing disillusionment in the long-term perspectives of the space planners after the development of the Saturn V, the EMPIRE era with its tremendous treasure trove of knowledge had to yield to more realistic considerations. When NASA successfully achieved Kennedy's mandate of the manned lunar landing "before the end of the decade" in July 1969, it was already quite clear that our ambitious plans of follow-on steps of continued expansion in space would fall victim to the newly emerged world of "real politics". The Nixon era brought the confrontation with foreign and domestic issues like the Vietnam War, Civil Rights unrest (e.g., Kent State University, Selma etc.), expensive social programs, inflation and the growing disillusionment over militarism, large-scale industrialism, environmental risks. The U.S. Congress increasingly withdrew its favor of more major programs of the style of Apollo, forcing the U.S. and NASA to turn away from the Moon and toward the new priorities.

The change made it clear as day for all parties that their grandiose plans for the development of large "Post-Saturn" and NOVA carriers would remain illusionary for a long time. NASA's Mars studies from the end of the 1960s therefore confined themselves for the time being to the Saturn V in place of the super-large carriers projected earlier. It was joined in 1972 by the Space Shuttle whose development President Nixon approved at that time.

Back in February 1967, the President's Science Advisory Committee (PSAC) had recommended that NASA should study reusable space vehicles, or "more cost-effective ferry systems" which may be expected to include partial or complete recovery and reuse. In 1968, a Boeing study looked at an integrated interplanetary spaceship concept for the entire period of 1975-1990, based on 40 days staytime on Mars for Opposition Class missions, or 500 days for the Conjunction Class. Depending on the selected mission profile and year, the required injection delta-V ranged of from 3565-5080 m/s, for the braking maneuver at Mars from 2120-5300 m/s and for the return launch to Earth 1925-5790 m/s. The atmospheric entry velocities at Earth were between 11.6 and 18.32 km/s; up to about 13.7 km/s, they could be handled by an advanced six-man Apollo capsule. For higher speeds, up to about 19.8 km/s, a newly developed capsule for the hyperbolic entry was required, such as a "bi-conic" body proposed at that time by Lockheed.

As carrier for all missions Boeing chose an enhanced version of the Saturn V, called

Saturn V-25(S)U, with four solid boosters of 3.96 m diameter strapped on its stretched first stage in parallel. The F-1 and J-2 engines were thrust-enhanced versions of the standard units. This Saturn, grown now to a total length of 143.2 m, could carry payloads around 250 t to a 485-km orbit, requiring a new upper stage for circularization. The actual Mars ship consisted of five identical 10 m wide propulsion modules, for which Boeing used the NERVA nuclear engine of 867 kN (88.4 t) thrust, then under development.

As propulsion systems for Mars spacecraft, in the early 70s, three main classes were investigated, as already some ten years earlier: chemical, nuclear and electric. Main criteria for system selection were the state of the existing technology and the likelihood of its availability before the end of the century. The chemical systems, for which the Shuttle Main Engine (SSME), then under development, was the fleet leader, preferably used liquid oxygen/liquid hydrogen as propellants, with a specific impulse of 460-465 s and a thrust-to-engine weight ratio of 35-75. In the case of nuclear fission propulsion, hydrogen was chosen as drive medium, with an Isp of 800-1000 s for "conventional" hard-core and 1500-3000 s for more advanced gas-core nuclear reactor systems, and thrust-to-weight ratios of 3 - 4 for the former, 1-10 for the latter. For the electrical drive, we distinguished between solar energy and nuclear energy systems for the generation of the necessary on-board electricity and opted for mercury as fuel, with a specific impulse of ~3000 s and a thrust-to-weight ratio of 0.0001 (indicative of the extremely low micro-thrust forces typical for this technique).

For the spaceship designs with chemical and nuclear propulsion, modular designs were consistently chosen as in the earlier proposals of Ehrcke, von Braun and others, because overall ship's mass can be reduced consecutively by dropping empty propellant tanks,- dead mass. All in all, the studies yielded a basic set of conclusions which substantially enriched our knowledge about the feasibility of manned Mars exploration. It was shown, for example, that the Venus Swingby and Conjunction Class missions were vastly superior to all other mission modalities for practical reasons under the then-current assumptions.

Furthermore: The implementation of planetary manned missions requires a heavy lift vehicle for the cargo transport from the earth's surface. The suitability of a propulsion system for the Mars mission is directly related to its characteristic Isp, and only secondarily to its mass ratio. Also, with regard to the necessary IMIEO masses and travel times for the 1980-1999 period, the high- and low-thrust nuclear engines were far superior to the chemical engines. Compared to all-chemical propulsion, which required an IMIEO around 1,180 t up to the end of the 1990s for Conjunction missions, this figure dropped to 680 t for hard-core and to 454 t of gas-core nuclear reactor drives.

Even after the sobering lessons of the Apollo developments, Wernher von Braun at end of the 1960s still remained firmly convinced that a manned Mars landing could take place as an integral part of a total space exploration program in the course of the 1980s. The Mars studies which we conducted under his top leadership as the first lunar landing moved closer, notably the Boeing study, provided the material for a plan that he

presented on August 4, 1969 to the President's Space Task Group (STG) under Lee DuBridge and then to the U.S. Congress. The cost of the overall program in his estimate was around \$4 billion (1969 value) for 1971, to rise thereafter to \$7-8 billion annually and to return to ~\$6 billion in 1976. Other features of the integrated program, which George E. Mueller, the then-chief of Manned Space Flight, strongly supported, had a near-Earth space station, the Space Shuttle, unmanned planetary research including a "Grand Tour" deep-space probe mission to the outer planets, taking advantage of an approaching special planetary constellation (which later spawned the Voyager Project), and a "balanced" program of practical applications, scientific research and lunar exploration. The period for the Mars mission was set by von Braun in November 1981 as the departure date and August 1983 for the return. The Mars landing itself was to take place in August 1982.

In his concept, the expedition was to be carried out by two identical ships, for safety, assembled in Earth orbit from components delivered by two-stage Saturn Vs. The Space Shuttle delivered propellant, cargo, consumables and crews. Besides the four propulsion stages for the main flight phases, the actual Mars ship consisted of two elements, the Mission Module (MM) and a Mars Lander (Mars Excursion Module, MEM). For the Opposition Class missions it had a typical length of 25 m without the propulsion stages, a Saturn-V compatible diameter of 10 m and a mass of 128 t, including all consumables. The MM part was a pressure cell; its front "hangar" remained exposed to the space vacuum. Here were located the MEM, which was accessed through an airlock from the crew cabin, as well as unmanned probes for dropping during the Venus passage.

The MEM was an Apollo-type ballistic entry capsule for the aerodynamic braking in the Martian atmosphere. For touchdown, it deployed landing legs. It contained a small laboratory, a rover vehicle and enough reserves to supply four crewmembers for about two months before they returned in the ascent stage of the MEM to the two persons that had remained in the MM in the elliptical parking orbit. For landing and ascent the MEM therefore possessed two separate propulsion systems with storable chemical propellants. The external structure and laboratory of the MEM remained on the surface, and after the crew had transferred to the orbiting MM, the ascent stage was jettisoned. The estimated total MEM mass was about 45-50 t. Earlier studies, based on models of a denser Martian atmosphere of the pre-Viking years, had yielded a minimum diameter of a ballistic Apollo-like MEM of about 8.5 m, while a nonballistic lifting body MEM would have had a length of 5.8 m and a cross-sectional width of 4.5 m. In preliminary plans of Conjunction class missions, a second MEM was included due to the longer staytime on Mars. The MEM design allowed for landing by a single pilot and the capability to bring the entire stranded crew back to the ship.

For the duration of the outbound and return trips, the MM provided the six crew members with living quarters, control center, laboratory experiment and radiation bunker in a "shirt sleeve" environment. Although laid out for six persons and two years, in an emergency, if one of the ships dropped out en route, the other could also support twelve for a longer period of time. At the end of the trip it braked itself with the fourth stage into

an elliptical Earth orbit, from which the crew returned to Earth via Space Shuttle, thus making a high-speed entry capsule unnecessary. A typical MM had a thin heat and meteorite shield surrounding a pressure cell of 10 m diameter and about 9 m in length. Its mass: 64 t.

The Mars expedition's IMIEO, dependent on the propulsion system and the chosen start year, was between 410 and 2270 t. Given the payload capacity of the Saturn V of about 120 t, a number of these carriers would have been necessary to carry the components of the expedition into space. For manned flights and possibly the delivery of propellant tanks in its 4.5 x 18 m cargo bay, the Space Shuttle was considered, or an unmanned heavy cargo carrier version derived from it. In von Braun's mission concept each of the ships, with a mass of about 726 tons (of which 544 tons, or about 75%, were propellants), consisted of three nuclear modules staged in parallel, each with one tank and one engine, and the planetary part in front of the center module. The two outer engine modules formed the first stage for the injection into the Mars transfer orbit. After their burnout, they were to separate and return with appropriate retro maneuvers under remote control to Earth orbit for reuse. The Mars ship, then only of 306 t mass, continued on its voyage.

After a flight of 270 days, the ships settled into an elliptical parking orbit and launched one of the MEM Landers with a three-man crew for 30-60 days on the surface. After 80 days staytime in Mars orbit, the two ships would have started back home on 28 October 1982, on a trajectory which led past Venus on 28 February 1983. When the ships arrived at Earth on 14 August 1983, each of them was down to 73 t.

But the high-flying plans would again remain in cloud cuckoo-land. As we know, the changed priorities of the United States of the 1970s did not let von Braun's integrated approach become reality. Instead of accepting the STG's recommendations of 1969, President Nixon cut the space budget in February 1970 to \$3.5 billion; in January 1972 it amounted to only \$3.4 billion, and in January 1973 it was slashed to \$3.1 billion, which represented approximately 60% of the above mentioned STG recommendations (including a 29% value loss due to inflation). Thus, the actual NASA budget during the years of Shuttle development was less than for the STG-calculated minimum level for a program scenario without manned flights.

In 1978, one year after Wernher von Braun's death, a NASA study team reviewed his Mars plans of 1969 in light of the meanwhile emerged technical and political developments. In August, about nine years after his presentation to the U.S. Congress, the team came out with a version tailored to the changed circumstances, which were especially marked by the new Space Shuttle and the abandonment of the old Saturn V. In its rationale in support of manned Mars exploration, the team made the following points: Of all the planets of the Sun, Mars offered besides Earth the least inhospitable environmental conditions; it was a sought-after scientific study object that held great attraction for people all the way back to antiquity. The development of a manned Mars mission as a goal for humankind is demanding enough to require international cooperation with all its benefits, and it challenges science and technology to such an

extent that it can become a new engine of economy and trigger a host of fresh technological pushes. The establishment of a Camp after the first landings opens up the potential for future growth to a synodic Base (i.e., served every 2.13 years based on Earth/Mars positional periodicity) with increasing self-sufficiency through the use of local raw materials, called ISRU (In-Situ Resource Utilization), including for the production of oxygen and fuel. ISRU, proposed by NASA engineers first in the 1960s, would definitely require a nuclear reactor on the surface as power plant.

The Saturn V is no more since 1972. Thus, the 1978 study called for a heavy lift derivative of the Shuttle for the transportation of cargo which also could carry the manned modules as defined in the 1969 Saturn V study. It also noted that the use of newer standards of reliability (fault tolerance) would probably result in lighter and less complex systems. Whether long-term tests in orbit are really needed in order to achieve the required high functional systems reliability for the Mars mission was drawn into question; however, in today's atmosphere of heightened safety awareness in space it definitely will again be regarded as unquestionable. Nevertheless, space station-based test and demonstration flights in Earth orbit were seen in 1978 as essential to develop orbital assembly, long-term storage of cryogenic fluids such as liquid hydrogen, and other less mature or still absent technologies. Von Braun's requirement of a minimum crew size of six per expeditionary ship could be maintained unless new scientific requirements necessitate additional mission experts. The crew quarters should definitely be reconfigured due to our newly gained knowledge of human factors and man/machine division of roles as well as the accommodation of a mixed male/female crew (the participation of women, incredible as it may seem today, in 1969 was not even up for debate!).

With regard to the scientific research objectives of the Mars mission, NASA's recommendations in 1978 were: (1) Of great importance is the retrieval of soil samples in original, pristine condition. (2) Soil samples are needed from both the volcanic and the temperate zones as well as from the polar caps. (3) Of particular importance will be samples from subsurface layers. (4) During the unpowered flight phases, research focus of life sciences should be on the people (male and female, group dynamics, etc.). (5) The possibility of human intervention in the course of the mission upgrades the value of the research program considerably due to the observational and selective powers of humans. (6) Besides the automatic sample retrieval, automatic instruments and recording equipment typified by the ALSEP (Apollo Lunar Surface Experiment Package) stations of the Apollo lunar landings should continue to work after the departure of the crews. (7) To prevent forward and back contamination, the Mars Program will face special restrictions due to much more stringent quarantine conditions than Apollo.

1978 was also the year in which the scientist Fred Singer proposed an alternative concept of a manned flight to the Mars moons Phobos and Deimos, as the former Peenemünde member Ernst Steinhoff did 16 years earlier (1962). Reaching them would require significantly less energy than the landing on the Martian surface. The extremely weak gravity of the two dwarfs can be an advantage: One wouldn't "land" on Phobos and Deimos, but only berth on them like on an asteroid. Phobos' nearness to

Mars (6,000 km) could make the moonlet a possible site for an early base camp, a natural "space station" in Mars orbit.

Singer's plan provided for a single expedition ship with a crew of six. For departure from geostationary earth orbit at 35,870 km altitude, the braking and start maneuvers at Deimos and for braking at Earth arrival it used chemical propulsion, and as cruise engine a solar-electric propulsion module of two megawatts power. The ship would spend two to four months on Deimos, during which two researchers visit the moon Phobos. The assembly of the Phobos-Deimos expedition, called "Ph.D." mission for short, needed about 40 Shuttle flights and a corresponding number of flights of a reusable upper stage (since the Shuttle cannot reach geosynchronous orbit). The possible existence of a near-Earth space station like the ISS was not considered in Singer's scenario which also in other aspects reflected more wishful thinking than realism.

1980 – 1990

After the begin of the "operational phase" of the Space Shuttle Program on July 4, 1982, NASA's Mars studies initially simmered on a low flame until the ad hoc National Commission on Space (NCOS), established in 1985 by U.S. President Ronald Reagan and headed by Thomas O. Paine, former NASA Administrator of the Apollo years, moved the Red Planet back into focus in the context of a top-level examination of new U.S. space ventures over the span of the next five decades. Its final report, "Pioneering the Space Frontier", published in May 1986 in an atmosphere charged with the reverberations of the Challenger disaster, presented a "manifesto", still valid today, for a long-term civilian space program which considered scientific exploration of the cosmos, exploitation of near space, and exploration, search for indigenous resources and human settlement in the Solar System as equally important.

For Mars, the report drafted an ambitious, optimistic and in some aspects fantastic scenario, during which people build permanent base camps in the new world. Research flights from Earth, beginning in the decade after 2000 and becoming routine during the early 21st Century, would be supported in this vision by a range of cargo and crew transportation systems, with Mars travelers changing several times between them as they make their way from the transfer station in Earth orbit, the Spaceport, to the spaceport in Mars orbit and from there to the landing site. Starting from the Base Camp, which would include a warehouse with stocks of supplies and equipment, the expedition members then go by their specific tasks: geological studies with their new brought-in instruments, research trips in vehicles that stayed based on Mars, or atmospheric and geographical studies with remote controlled unmanned drones or piloted flying machines.

In the wake of the Challenger loss, the task of the Space Commission was anything but easy. But as much as its final report may have lacked in realism, it strongly confirmed for NASA that human space flight indeed reaches for other worlds in the cosmos, as

pioneers like Tsiolkovsky, Tsander, Oberth, Goddard, von Braun, Korolev and Ehricke once had been pushing for in their unshakable idealism and optimism.

The next step for NASA was to differentiate the wide-ranging future dimensions of the Paine Commission into more concrete plans. Administrator James Fletcher in 1986 assigned the 36-year-old astronaut Sally Ride, America's first woman in space, to this task. She organized a study group (to which I belonged), and its widely-watched surveys in a no-nonsense report entitled "Leadership and America's Future in Space" in August 1987 enumerated a range of concepts of the future in space which offered four alternative long-term initiatives: Mission to Planet Earth, Unmanned Exploration of the Solar System, Outposts on the Moon, and human development of Mars. Ride did not chose to select one single program at the expense of the other three, but presented instead four specific sample programs that would catalyze and accelerate the discussion of the goals, objectives and individually required efforts of the civil space program.

Sally Ride's "Humans to Mars" program followed in broad strokes the path blazed by the NCOS: Shortly after the begin of the 21st Century astronauts were to land on Mars (first landing: 2005) and build up human presence to an outpost on the planet within a decade, with three successive missions. Sally Ride also reached the basic understanding that a robust, efficient space transportation system, including a heavy lift vehicle requiring significant investment, would be the most important prerequisite for such a program. The near-Earth space station played also a key role for her since it permits the critical life science research and development of medical technology during the preparatory years and represents the test bed for life support systems, propulsion, radiation protection, automation, remote control and expert systems. Added to this would be the newly developed systems in orbit for storing massive amounts of propellants and assembly of large transport ships.

The Ride report especially emphasized that NASA should not undertake the Mars program with the revolutionary quick-fix and politics-driven rivalry behavior of the prematurely ended Apollo Program, but more evolutionary. In no case should it be under the time pressures of the 1960s since this makes it difficult to carry out a program that not only provides a strong foundation to build on, but also develops enough momentum to stay viable beyond the first manned missions. As von Braun saw it already clearly in his classic study of 1950, our long-term goal should not be the first landing on Mars, but its settlement. Besides the actual landing, a comprehensive understanding of the requirements and implications of the construction and permanent maintenance of a permanent base on another world is just as important. We must therefore choose a strategy of natural evolution and mental preparation, which leads step by step in an orderly, nonprecipitative but swift and inexorable manner to Mars. President Reagan's successor George Bush (sr.), who wanted to put his own stamp on NASA's long-term plans of the Reagan era and simultaneously do something for the "victims" of the demise of Reagan's "Strategic Defense Initiative" (SDI) and the Defense industry, announced on 20 July 1989, exactly 20 years after the first lunar landing, his course-setting "Space Exploration Initiative" (SEI). In it he mandated, at least for the

U.S., the main features of human exploration of space: “First, for the coming decade—for the 1990s—Space Station Freedom, our critical next step in all our space endeavors. And next—for the new century—back to the Moon. Back to the future. And this time, back to stay. And then, a journey into tomorrow, a journey to another planet—a manned mission to Mars.” Each step should lay the groundwork for the next.

The National Space Council (NSC), established three months earlier in response to a Congressional request for a coordinated development process of the National Space Policy and a strategy for monitoring its execution, was commissioned by Bush for the continuation of the program. To make SEI economically acceptable, Bush sought an evolving lunar and Mars program which began with small, unmanned exploration projects and culminated in human expeditions. As seen by the NSC, the key to that was a radical reshuffling of top management at NASA and a starkly simplified, cost-effective project management and procurement system. In terms of its costs, schedules, complexity and risks, the Space Exploration Initiative was based on the latest preliminary analyses of NASA, which in 1989 had put together, in a 90-Day Study, five different “Reference Programs”, which now provided a concrete framework for the SEI mission.

The Reference Programs included a wide range of different strategies with differing program objectives, time and schedule plans, technologies and required resources. Each of them had a specific area of emphasis: (1) a “balanced” and fast-track program, (2) the earliest-possible Mars landing, (3) a program with a limited supply from Earth, (4) a program tailored around the development of the space station (then called “Freedom”), and (5) a smaller-scale program.

Again, it was found that the current “mixed” space carrier fleet of Space Shuttle plus expendable rockets was not sufficient to carry out an exploration program. For a lunar station, you need a launch vehicle for about 60 t payload, for the Mars landing around 140 t, which both form a perfect compromise between two alternatives: on the one hand many starts of smaller and cheaper payload carrier with high assembly requirements in space, and on the other hand a few starts of larger and more expensive systems with reduced assembly complexity. The use of these new carriers also requires new ground equipment.

The 90-Day Study developed a solid “end-to-end” (begin-to-end) strategy for the establishment of permanent lunar and Mars outposts and thus provided a mechanism for the logical evolution of the successive elements and objectives of the initiative, beginning with a preparatory phase of robotic exploration to obtain timely scientific and technical data before executing manned missions. This was followed by the development of permanent, largely self-sufficient bases on the Moon and Mars in the form of three progressive development stages: emplacement, consolidation and operation.

The Emplacement Phase deals with the provision of simple living accommodations, supply of ground support equipment and scientific instruments and preparation for

future more complex sensor networks and surface operations through prototype testing. Manned traverses could be carried out within a few dozen kilometers while unmanned rovers would be deployed for longer research excursions. The subsequent Consolidation Phase further extends human presence, making the crew familiar with the conditions of living and working in a planetary environment. To strengthen the outpost, an in situ erectable habitat would be assembled to win additional residential volume, and the manned trips are now covering hundreds of miles from the Base. Objectives of the Operations Phase finally are the routine use of locally existing raw materials and the realization of a Martian living and working style of minimal dependence on Earth. In this way, according to the SEI roadmap, by 2025 we would have had a permanently inhabited station on Mars, besides a Lunar Outpost, as well as the knowledge base and experience for further exploration into the Solar System by human researchers.

The report of the study was published in November 1989. In December 1989, Vice President Quayle, by now grasping the true extent and complexity of the SEI program, charged NASA to include the public in the search for new "Space Exploration Alternatives" and to cast a wide net in the USA for the most imaginative new ideas. Needed were innovative proposals for mission/system concepts and advanced technologies that could improve costs, schedules and services of the Bush initiative. The thousands of proposals in this so-called "SEI Outreach Program" that had come in by mid-1990, were evaluated by the RAND Corporation under NASA contract. The majority were ideas for space propulsion, followed by mission concepts, life support systems, structures and materials, space and ground power units, space processing and manufacturing, system design and analysis, automation and robotics, communications, ground systems and simulation and information systems. A special committee of selected experts under former Apollo astronaut Thomas Stafford, the "Synthesis Group", distilled them into a number of recommendations in terms of technology developments, near-term milestones and four prime alternative exploration "architectures": Mars exploration, Science focus on Moon and Mars, a permanent manned Lunar Station, evolving eventually to manned Mars Exploration and exploitation of raw materials of the universe.

1990 – 2000

The Synthesis results were published in May 1991 in a report entitled "America at the Threshold". Given the thoroughness with which NASA had already plowed the field of interplanetary exploration and the lack of expertise (apart from science fiction notions) which most of the idea donors had brought to the task, it wasn't surprising that the synthesis work did not yield any spectacular practical-realistic new ideas which would have made the Mars project less complex or cheaper.

As far-sighted as George Bush's policy statement with the SEI roadmap may have been, it was not linked to any automatic obligation to fund the massive program, whose cost, spread over 30 years, were estimated at \$400-500 billion. In the contrary: From the very start, it was controversial and weakly received by a bipartisan U.S. Congress, and even NASA, loaded down with more pressing priorities, did not view it with

uninhibited enthusiasm. In mid-June of 1990, a House panel eliminated all funds for SEI from the FY 1991 NASA budget,- its first defeat. With the takeover of the White House by the Democrats under Bill Clinton, SEI at the end of 1992 completely lost the political ground under its feet, and in 1993 the Congress totally zeroed its funding. With this, SEI was dead, at least as an official government directive.

NASA-internally, SEI did not entirely disappear: it mutated. Out of the lunar station architecture of the Stafford Synthesis Group emerged FLO (First Lunar Outpost) which in 1992 was extended by the NASA Headquarters Office of Exploration under Michael Griffin to a follow-on Mars expedition, in the hope that through hardware commonality the costs savings for both programs could be realized. In 1993, this new effort produced the first DRM (Design Reference Mission) of a Mars expedition. It baselined a heavy-lift vehicle with 240 t payload capability to low Earth orbit, 100 t to Mars orbit and 60 t to Mars surface, it required no assembly in Earth orbit, no space station, and no lunar outpost. Its crew of six would rely early on on ISRU on Mars, to minimize mass launched to the planet. ISRU-produced propellants (methane and oxygen) would power the Mars Ascent Vehicle (MAV) during its climb to Mars orbit for rendezvous and docking with the orbiting Earth Return Vehicle (ERV). Cargo and habitat structures would be carried to Mars ahead of the manned flight by three heavy-lift rockets, each with a nuclear propulsion upper stage and an unmanned spacecraft, delivering the ERV, the Habitat, and cargo.

NASA's Mars studies received new impetus when in August 1996 NASA, Stanford University and McGill University scientists announced the discovery of possible fossilized microorganisms in a Martian meteorite, ALH 84001. Among else, it fostered the reestablishment of an Exploration Office at JSC, as well as a call by the NASA HQ Human Exploration & Development of Space (HEDS) Enterprise and Space Science Enterprise for joint planning toward landing humans on Mars.

In the following years, the 1993 DRM underwent a number of iterations in response to externally perceived realities. The first consisted of a "scrubbing", to minimize spacecraft mass in order to reduce cost to a (it was hoped) politically more acceptable level. Published in 1997 as DRM 3.0, a subscale of the former DRM 1.0, it featured reduced structural masses, among else by employing lighter-weight composite materials, getting rid of the backup Habitat module/lander and abandoning the heavy-lift vehicle, launching the nuclear (NTR) stages singly on a Shuttle-derived rocket of 75 t orbital capability, to be assembled with the spacecraft in Earth orbit. A total of six of these carriers were required for the Mars first launch opportunity on a Conjunction Class mission, followed by six more one synodic period (26 months) later. ISRU was to be used.

2001 – 2011

Alternative designs kept popping up in subsequent years, first a DRM 4.0 in 1998. Then, on January 14, 2004, President George W. Bush (jr.) requested NASA to develop a new Exploration Program, articulated in the NASA Authorization Act of 2005. The

newly established NASA Exploration Systems Mission first conducted a series of studies by the Lunar Architecture Team (LAT), then in 2007 commissioned the Mars Architecture Working Group (MAWG) to develop a new Mars design reference mission, published in 2009 as Design Reference Architecture 5 (DRA 5.0), based on a heavy-lift vehicle called Ares V for cargo transport and a smaller Ares I for crew transport in a new Apollo-type capsule called Orion. Both NTR and chemical/aerocapture options were covered. For the latter option, DRA 5.0 baselined a Conjunction Class mission with seven Ares V launches assembling the first two MTVs (Mars Transfer Vehicles) with five RL10-B2 engines for hauling hardware to Mars in a trip of about 350 days. Earth orbit assembly time: 170 days. After their successful arrival and proof of ISRU production capability, three more Ares Vs and one manned Ares I with the Orion capsule would follow about 26 months later, assembling the Crew Vehicle in orbit (120 days). Its outbound trip would take 180 days, as would its return trip, with a staytime of 500 days in between.

Meanwhile in the East, in 1990 and 1991, Soviet space designer Yuri Semyonov of RKK-Energia compared notes with U.S. Mars supporters at space conferences in Montreal and Houston. To some Americans, the Soviet heavy lift rocket Energia, developed under Glushko, seemed like an ideal way to help cement cooperation between the two countries in developing a joint Mars expedition program. Semyonov and his space station expert Leonid Gorshkov published a Mars expedition report in 1991 baselining solar-electric propulsion for their spacecraft, launched to Earth orbit by five Energia vehicles, to deliver a two-man lander to the Mars surface.. The proposed solar-electric driven spaceship would have a mass of 350-400 t, compared to ~800 t for nuclear-thermal propulsion. To generate 7.6 megawatts of power at Earth's distance from the Sun and 3.5 MW at Mars, a pair of solar panels of 40,000 square meters would be required. The electric drive thrusters first used lithium as propellant, then xenon (Hall-type thrusters). Today, Russian and U.S. planners both are focusing on xenon or bismuth as propellants of choice.

Current Russian designs consider bismuth as most attractive, due to its high density, low cost, condensability at room temperature, low ionization potential and high atomic mass. The Mars expedition would have an IMEO of ~700 t and carry a crew of 6 on a mission totaling about 700 days, with 1 month on Mars (and orbit) without ISRU. The propulsion system would entail 20 Hall thrusters of 1.1 m (~43 in.) diameter each, plus 4 for redundancy or spares, in two pods of 12 thrusters each. With a thrust of about 7-8 N (1.6-1.8 lbf) per thruster, total interplanetary stage thrust would be 140 –160 N (31.5-36 lbf).

In the U.S. today, the Ares I has bitten the dust, but a heavy-lift vehicle (name still TBD) has been approved for preliminary development study. Orion is still alive, and NASA-supported COTS (Commercial Orbital Transportation Services) efforts are underway to provide a crewed launcher, to take the place vacated by Ares I, besides the stalwart Soyuz.

CONCLUSIONS

In looking back over 60 years of manned Mars Mission studies, what can we see? The view shows first of all that by necessity near-term oriented politicians are ill-suited for deciding on such a forward looking complex of questions, but visionary political leaders are necessary and will again raise our sights to more distant vistas. The demise of SEI and its mutations since has not removed Mars from NASA's field of view, especially that of its advanced planners who on the one hand see NASA's undisputed leadership and impetus-setting role in space science and space exploration as a moral obligation to future human generations, and who on the other hand realize how crucial for U.S. economy and strengths in aerospace and other key industries it is to force technological advances which in turn provide new development momentum. Manned Mars provides such forces. NASA internal study teams, as well as research groups at universities and technical institutes are therefore applying even now renewed enthusiasm to advanced planning of evolving Mars exploration.

What in previous Mars flight scenarios of the von Braun and post-von Braun era still played no particular role has become, since the NCOS study, the Ride Report, the 90-Day Study, a *conditio sine qua non* of Mars exploration by humans: the reconnaissance phase by robotic precursors. Starting with smaller international exploration projects like NASA's MGS, Pathfinder, Spirit, Opportunity, Curiosity, and other international projects, a vanguard of robotic scouting probes have started swarming out in this phase of exploration to study the Martian surface and atmosphere and later to reconnoiter for suitable landing and base-construction sites. Design data and criteria that are currently still lacking, will be determined by these scouts for the subsequent manned systems, along with environmental analyses to develop a basis for in-situ research by humans, prospecting for indigenous resources, and trying out new technologies and operational concepts for future manned missions.

For safety and economy, Mars flights by humans will continue to be sectioned off in the classic mission phases of von Braun's "Mars Project" of 1950: Ascent to the assembly site (space station), flight to Mars, Mars parking orbit & landing, ascent with rendezvous, return to Earth and landing. Brought piecemeal into Earth orbit by a heavy lift carrier, currently under preliminary design, the spacecraft will be assembled there, loaded, checked out, counted down and launched. For personnel and cargo transport between Earth and Mars orbits, typically a main stage will be used with the crew compartment, lander with surface module, and Earth return vehicle with a jettisonable injection stage with several engines and, if necessary, additional drop tanks. A large brake shield will allow aerodynamic capture and braking in the Martian atmosphere and later on return to Earth.

When will we be ready for Project Humans to Mars? In addition to the socio-political and financial readiness, it will require the development of specific technologies such as aerobraking, cryogenic fuel storage and equipment, nuclear thermal and nuclear electric propulsion systems, photovoltaic and nuclear energy sources for the Base operation, closed-cycle life support systems, automatic information systems, scientific instruments,

EVA systems, surface rovers and much more. Not in the least, it also requires substantial work on and in the present-day ISS which has evolved from relatively modest beginnings to a powerful and sophisticated international world-class research facility.

All in all, to be able to conduct the Mars expedition in all its phases with a high degree of mission success probability, a technological capacity will be required which today is still far from accessible to us. But its mastery will open incredible new possibilities for tomorrow's humankind.

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