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Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Self-Assembling Transfer Vehicles for Human Mars Missions

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Introduction

OVER the course of a five-year NASA/Boeing Human Mars Missions study, three Mars transfer vehicle design baselines were developed, each configuration reflecting results of the three sequential phases of the study. Favorable attributes incorporated into the final concept, including the capability for on-orbit self-assembly, represent design solutions to configuration deficiencies impacting human Mars spacecraft designs since the vehicle archetype originated in the 1950s. This Note describes this vehicle type. A short historical overview of Mars vehicle development is included as a means of introducing the issues involved in the conceptual development of these very large vehicles. Cost concerns associated with a limited resource Mars program future weighed heavily in vehicle and mission assessments undertaken in Boeing's Space Transfer Concepts and Analysis for Exploration Missions (STCAEM) contract.

Early in the course of the study, nuclear thermal propulsion (NTP) was chosen as the most promising propulsion system for Earth–Mars transfer based on considerations of mission flexibility, performance, crew safety, programmatic resiliency, life cycle cost for multiple missions, and potential for reusability. The NTP concept generally outranked alternative chemical propulsion/aerobrake and electric propulsion (nuclear and solar) concepts. The task of assimilating lessons learned from the extensive array of inputs gathered from presentation sessions, working group meetings, and contract subtasks occurring over the five-year study period (1989–1993) was brought to completion with the final vehicle configuration, which is characterized by its simplified modular design, ease of launch-vehicle packagability, and minimum on-orbit assembly complexity. The primary design drivers for human Mars spacecraft can be classified into several categories, including cost, operability, and mission flexibility. A more specific list would include ease of packaging the component sections of the vehicle into the launch vehicle for delivery to orbit, simplified on-orbit assembly, minimum mass in low Earth orbit, and attenuation of naturally occurring solar and galactic radiation. Adaptability for artificial-g flight may also be important. Launch-vehicle packaging and on-orbit assembly are particularly sensitive to the configuration design. Typically, the large majority of a Mars vehicle's mass is propellant, which for NTP systems would be cryogenic hydrogen, the least dense of liquids. Consequently, NTP Mars vehicles are dominated by large tankage systems.

Historical Overview

In the Mars mission design studies of the 1960s, NTP was almost uniformly selected as the propulsion system of choice for the transfer vehicle. In these designs usually the large hydrogen tanks were to be delivered to orbit separately and attached end to end, with the pressurized tanks themselves serving as structure, carrying the engine thrust loads during the relatively short thrusting periods. Vehicle designs of this period were alike in their multistage, multiengine approach; typically, each stage had a nuclear engine or cluster of engines that was to be jettisoned with the propellant tanks set when they were emptied. This approach was typified in several designs[1–8] of that era, illustrated in Fig. 1. These designs represent the first generation Mars vehicle archetype, which remained essentially unaltered until STCAEM analysts devoted attention to configuration issues in the late 1980s time period of renewed interest in human Mars missions. Serious technical literature describing nuclear reactors for space propulsion began to surface in the late 1940s, with one of the earliest appearing in 1946 as a project Rand publication, "The Use of Atomic Power for Rockets."[9] A series of articles in the *Journal of the British Interplanetary Society*[10] entitled "The Atomic Rocket" followed in 1948. Wernher von Braun's[11] *Das Marsprojekt* study was published in 1949 and eventually gained much popularity when recast in the *Colliers* magazine articles in 1952, in part because of the spectacular spacecraft and planetary scene illustrations of Chesley Bonestell. For this early work von Braun chose chemical (nitric acid and hydrazine propellants) propulsion rather than NTP for the Earth–Mars transfer vehicle.

In-depth technical conceptual development of Mars transfer vehicles began in the later 1950s. Krafft Ehriche led investigations of Mars mission strategies, producing a variety of technical papers on interplanetary flight, including "Calculations on a Manned Nuclear Propelled Space Ship," in 1957 (Ref. 12). Ehriche (with General Dynamics) published more material in the late 1950s and early 1960s and was a study contractor in one of the earliest series of NASA

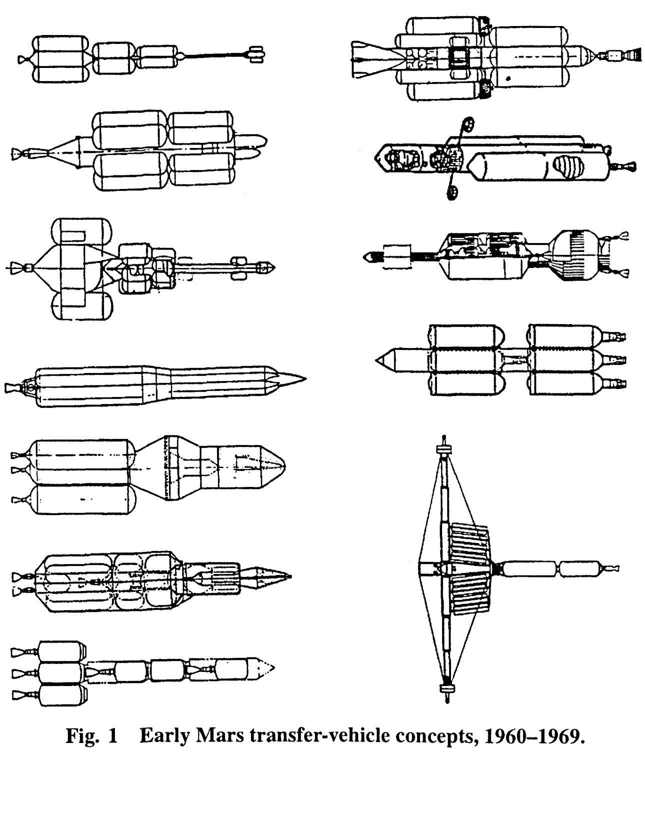

Fig. 1 Early Mars transfer-vehicle concepts, 1960–1969.

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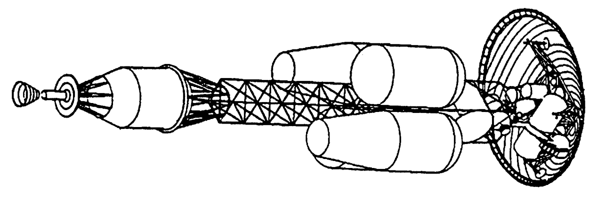
manned Mars mission studies, entitled the "EMPIRE" studies. These studies were sponsored by the NASA Marshall Space Flight Center (MSFC) in Huntsville, Alabama. In 1953, Project ROVER, a joint project of the U.S. Atomic Energy Commission and the U.S. Air Force, was begun to develop nuclear propulsion. This program reached fruition in the mid and late 1960s when the Nuclear Engine for Rocket Vehicle Application (NERVA) series of nuclear thermal engines were built and tested at the Jackass Flats, Nevada, test facility. Engine thrust of up to 1000 kN (225 klbs), burn times of over 1 h in duration, and specific impulses of near 840 s were achieved. At this time von Braun and Earnest Stuhlinger, both at MSFC, were influential advocates of human Mars exploration and of nuclear propulsion (von Braun favored nuclear thermal, whereas Stuhlinger favored nuclear electric). The early EMPIRE studies were followed in the mid and late 1960s by a variety of studies coming out of MSFC, the Manned Space Center (to become NASA Johnson Space Center), the NASA Lewis Research Center (to become NASA John H. Glenn Research Center at Lewis Field), and the NASA Langley Research Center. Comprehensive studies conducted in this period included "Manned Mars Exploration in the Unfavorable (1975–1985) Time Period,"[4] the "Manned Mars and Venus Exploration Study,"[5] "Manned Mars and/or Venus Vehicle Systems Study,"[6] and the "Integrated Manned Interplanetary Spacecraft Concept Definition Study."[1] In 1969 the Space Task Group[13] presented its recommendations[14] to Congress for a manned Mars mission as a follow-on to the Apollo program then in progress. Information presented was based on a NTP manned Mars vehicle flying a short stay time opposition mission profile as the initial Mars mission scenario. (Another NASA sponsored long-range planning study of 1969 came to similar conclusions.[15]) This proposal was rejected; Mars mission planning was soon dropped by NASA, and the NERVA test program was canceled. The last of the in-depth NASA MSFC-sponsored Mars vehicle design studies[16] concluded in 1973. It would be 15 years until further in-depth NASA-sponsored contractor studies would resume. On the 20th anniversary of the first Apollo landing, plans for a renewed program of exploration were announced, which included as a long-range goal a manned mission to Mars to be accomplished within 30 years, by the year 2019. Subsequently, NASA began again with in-depth evaluations of manned Mars missions. The Boeing/MSFC STCAEM study was the most comprehensive of these during this period. During this five-year study, a broad range of mission strategies and vehicle designs were investigated. A significant portion of mission analysis, vehicle design, and cost estimating tasks were conducted utilizing a NTP transfer stage as the baseline Mars vehicle. This first baseline vehicle was frequently refined pursuant to ongoing requirements definition and trade study results.

Initial Configuration (Phase 1)

This early (phase 1 of the study) NTP baseline design represented a break from the Apollo era archetype. Hydrogen tanks were to be delivered, then mated on orbit to attachments on a deployable truss (at that time a deployable truss was baselined for the space station design). This design used only one large engine, which was to be restarted for each major burn. The main propellant tanks, which did not carry the engine thrust loads, were to be jettisoned when empty. The phase 1 design, first presented in Ref. 17, is characterized by its central deployable truss structure and radial placement of propellant tanks around that truss (Fig. 2). The centrally placed truss system provided separation distance between the reactor and transfer habitat module for radiation attenuation. The large propellant tanks were mounted far enough forward on the truss so that each fell within the shadowed region provided by the aft-positioned reactor radiation shield. All tankage, structural hardware, and payload elements were placed within this protected region. Immediately forward of the aft engine/shield section, the aft propellant tank was positioned to supplement the reactor shield as direct-line attenuation. The truss spine was connected to the forward end of this tank and to the crew habitat system at the forward end of the vehicle. Phase 1 divided NTP Mars mission propellant splits of the trans-Mars injection (TMI) and Mars orbit insertion (MOI) allocations into two tanks each, disposed symmetrically about the vehicle axis. After the phase 1 design was



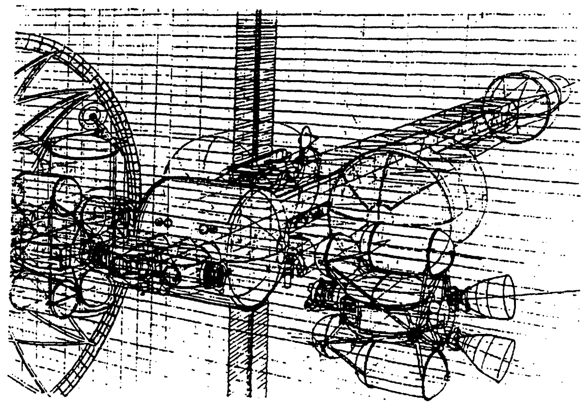


Fig. 2 Phase 1 Boeing STCAEM NTP Mars transfer-vehicle configuration.

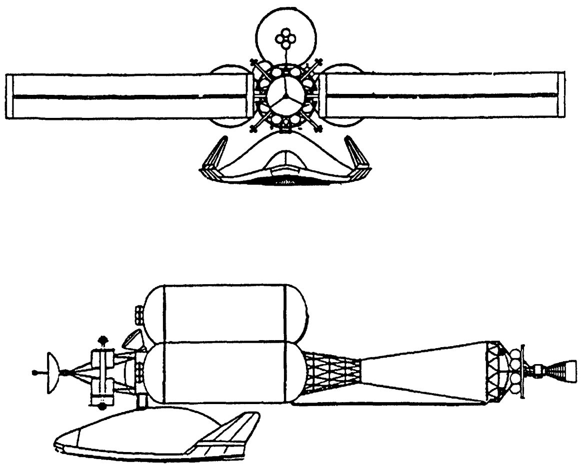


Fig. 3 Phase 2 Boeing STCAEM NTP Mars transfer-vehicle configuration.

developed, it became the baseline for subsequent analysis, not only for the STCAEM contract, but for several other concurrent studies being done by other contractors for NASA John H. Glenn Research Center at Lewis Field and MSFC. A painting of this phase 1 vehicle appeared on the cover of *Aviation Week* magazine on 18 March 1991.

Interim Configuration (Phase 2)

The make-up and integration of the truss structure and positioning of the tanks constituted the principle differences between the phase 1, 2, and 3 configurations. Basically the phase 2 period changes involved sizing to support the Synthesis Group Report[18] mission architectures and the incorporation of a lifting body shaped, high lift-to-drag Mars lander aeroshell. Subsequent phase 3 period improvements specifically addressed launch-vehicle packaging and on-orbit assembly in more detail. These two issues had by this time become the highest priority design challenges because of their influence on mission cost. After phase 1 subsequent efforts focused on the reference mission outlined in the Synthesis Report. The phase 2 period vehicle (Fig. 3) was characterized by conical sections of circular truss, conically shaped aft tank (slim portion forward), and its asymmetrical placement of the high lift-to-drag Mars excursion vehicle.[19] Three identical forward hydrogen tanks were used, two lateral tanks (port and starboard) exclusively for TMI propellant and a dorsal tank for the remainder of TMI but primarily for MOI (about 90% of the tank volume). The ventral side of the vehicle was thus left free for integration of the large excursion vehicle.

Final Configuration (Phase 3)

Critiques of the phase 1 and 2 vehicles principally revolved around inefficiencies associated with launch-vehicle packaging and on-orbit assembly. Difficulties in these areas were ameliorated in the final phase 3 configuration (Fig. 4), which was conceived from the outset to reduce on-orbit assembly tasks to a minimum. This design is characterized by its more modular in-line integrated truss/tank elements and its self-assembly capability. Simplification was achieved by eliminating the requirement for any tank-to-propellant line or tank-to-truss connection assembly operations on-orbit. Phase 3 vehicle tanks are preintegrated with propellant lines, tank gas pressurant lines, and other hardware into a standardized tank/truss module as a single preassembled unit for packaging into the launch vehicle and berthing on-orbit. On-orbit assembly dedicated hardware and tasks are reduced over those of the phase 1 or 2 configurations because the phase 3 design was configured to act as its own assembly platform. A *core* transfer vehicle would consist of two integrated element modules. The first element consists of a transfer habitat module integrated onto a forward-spine rigid truss structure section. Also integrated into this element is a folded solar array power system (aft of the crew habitat) and a reaction control system (RCS). A Mars excursion vehicle (lander) is attached directly onto the crew habitat, allowing the crew to occupy both the transfer habitat and the ascent stage capsule during their outbound journey. The second core element consists of a engine, radiation shield, and cylindrical aft propellant tank and RCS all integrated onto an aft truss structure section. These two elements would be identical for all missions, regardless of opportunity year. Subsequent Earth-to-orbit flights would deliver the necessary TMI and MOI propellant tank/structural modules; each would consist of a large propellant tank preintegrated with propellant lines onto a structural truss section. These are joined in between the forward habitat element and the aft engine/tank element. For each noncore tankage module a truss runs atop the propellant tanks to which they are connected; the noncore tanks are to be jettisoned (by truss-mounted release mechanisms) after use to reduce mass for subsequent burns. Tank modules would have the maximum diameter that the launch-vehicle payload bay would allow. Variations in mission delta velocity (dV) or payload requirement for different missions would show up as variations in propellant load, which would be easily accommodated by altering the length of the noncore TMI and MOI tanks that would be supplied for such missions; i.e., vehicles flying more difficult missions (higher dV) would only differ in total length. The two core modules would be common for all missions. A lunar transfer version of the vehicle would utilize the same two core modules, though with a smaller crew habitat, a smaller lander (requiring no aeroshell), and a single, translunar injection tank element, rather than the two or three tank elements required for Mars missions.

The phase 1 vehicle utilized a single 333-kN (75-klbf) NTP engine for all burns. Later, a dual engine system was baselined to allow for an engine out margin. Phase 3 analysis utilized three lower thrust 111-kN-class (25-klbf) engines clustered together. At this point in the study, it was becoming obvious that smaller, lower thrust NTP engines would be easier to ground test and would have a broader range of applications to other missions.[20,21] An artificial gravity environment for the crew could be attained by spinning the vehicle about its c.g. to produce a centrifugal effect at the vehicle ends. Vehicle rotational speed would be limited by adverse Coriolis effects on the crew, to about four revolutions per minute.

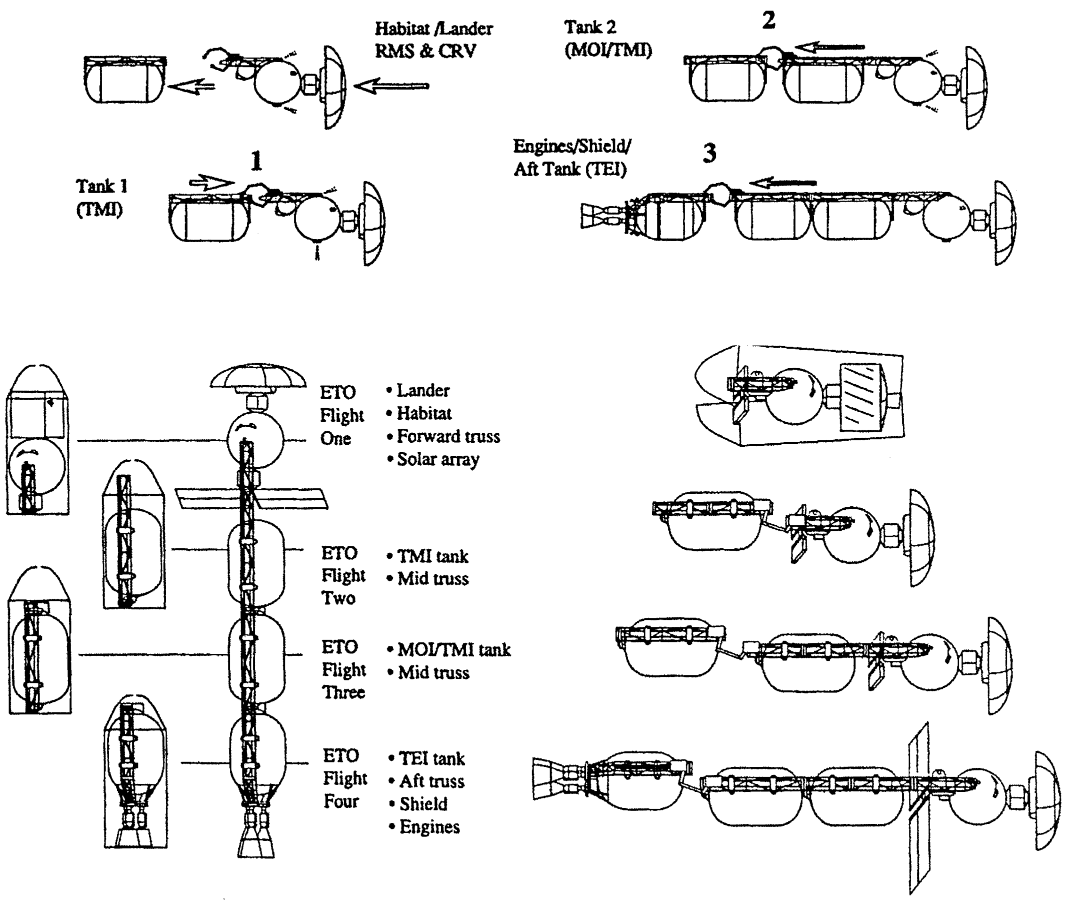


Fig. 4 Phase 3 vehicle configuration: launch-vehicle packaging and on-orbit assembly.

Launch and Assembly

Once on-orbit the modular elements would be attached end to end. At the front and aft ends of each element are interfaces where propellant, gas pressurant, communication, and power lines would be joined. All subsystems, propellant lines, etc. are preintegrated and located on the structural truss to which the tank is attached. Positioned above the truss are one or more remote manipulator system (RMS) arm units that can transverse the length of the truss for the purpose of joining sections together. RMS units traveling across the truss top have access to these subsystems for joining, inspection, repair, or change out; they could accommodate suited personnel to facilitate these operations if required. Assembly consists of attaching the common tank/truss elements at their end-to-end interconnect points as shown in Fig. 4. Rather than sending up to orbit a separate platform prior to the delivery of the spacecraft components, a RMS operates from the first element delivered to orbit. The forward habitat/truss element segment acts as the assembly platform for the remaining elements. Utilizing its RCS, the forward element would translate to within RMS arm capture distance of the second co-orbiting element. Moving along the top rails of the rigid truss section, the autonomous (or crew-assisted) RMS would capture and pull to an aligned position the second element and connect the two at their end-to-end interconnects. In addition to the structural connection of the truss sections, this first interface would connect communication and power lines. Once joined, secured, and inspected, the RMS would then move onto the second element, travel the length of its truss rail, reaching the unconnected end where again the RCS would be used to maneuver the two connected modules near enough to the third element to repeat the capture and connection process. For the second-to-third element connection the interface consists of propellant and gas pressurant line quick-connect devices in addition to power and communication connections. This process is repeated for the fourth, aft element, completing the assembly. The number of connection operations would always be one less than the number of elements delivered to orbit; i.e., for a four-element Mars vehicle, three capture operations would be required, and for a three-element Lunar vehicle, two would be required. Furthermore, once the vehicle has completed a mission and returned to Earth orbit, its two reusable core elements (habitat and propulsion) could be rejoined to new noncore tankage modules and a new landing craft on-orbit, allowing for the economical second use of the expensive habitat and propulsion modules.[22]

Conclusion

After five years of detailed study, this phase 3 configuration became the preferred vehicle type for human Mars missions because of its modular design, ease of launch vehicle packagability, ease of on-orbit assembly, and minimal reassembly requirements for subsequent reuse.

Acknowledgment

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Effects of Shock Wave Impingement on Supersonic Film Cooling

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Introduction

FILM cooling, especially in combination with regenerative cooling, is a promising way to protect the engine wall of a scramjet. The effect of the interaction between a shock wave and a coolant flow on cooling efficiency becomes important in supersonic flow. Therefore, many experiments[1–3] on such interactions have been conducted recently. Compared with the case without shock impingement, however, theoretical or numerical studies on film cooling with shock impingement have been insufficient, and so the mechanism of the interaction and the degree of its influence on the cooling efficiency are not well understood. To increase understanding, the effect of shock impingement on film cooling and the change of the flowfield were numerically investigated. Moreover, the effect of an increase in the injection Mach number of the coolant was investigated as a way to reduce its influence.

Numerical Method

Two-dimensional compressible Navier–Stokes equations in generalized curvilinear coordinates for multispecies were solved with a k-ε low Reynolds number turbulent model[4] in which the eddy viscosity did not become zero when flow separation occurred.

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