How Technologies Shaped Beyond-Low-Earth-Orbit Exploration Roadmaps

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This paper provides an overview of key technologies for beyond-LEO human spaceflight for two different space exploration roadmaps: NASA's Roadmap for Solar System Exploration (1970-1990) and Rockwell's Integrated Space Plan (ISP) (1989-2100). Both plans were generated at dynamic points in U.S. space exploration history: the first developed in the midst of a successful Apollo lunar landing program, and the second during the first decade of the Space Shuttle program. The policies, research and development, technologies, funding and support of each era impacted each plan's development and focus on technologies. The NASA Roadmap is technology-driving and outlines a specific plan for Martian exploration that uses technologies developed specifically for the leading missions. The ISP is technology-driven and provided a gradual plan for solar system exploration, implementing technologies as they are developed and defining new missions to make use of those technologies. This paper will discuss how existing technology development efforts and assumptions about future technologies shaped each roadmap. Six key technology areas have been identified: artificial gravity, environmental control and life support systems, radiation shielding, in space resource utilization, Earth-to-orbit propulsion, and beyond-LEO propulsion. How the current and planned developments in each of these areas influenced the design of the roadmaps and how those technologies shaped the proposed development of key infrastructure assets (space stations, launch vehicles, and surface bases) will be reviewed.

I. Introduction

At key points in space exploration history, roadmaps have been used for planning the major elements required for man's next steps into the cosmos, an idea being revisited in 2011 as the nation enters the post-Space Shuttle era, sees the end of the Constellation Program, and addresses the future of human spaceflight. NASA's 1969 Roadmap, developed by the von Braun team, laid aggressive plans for the continuation of NASA human exploration of the solar system following the completion of the Apollo lunar program. The use of Saturn V and Saturn V-derived vehicles would have continued for heavy lift capabilities and a space shuttle would have been developed in the mid-1970s, replacing the Apollo/Saturn IB. In-space elements such as a permanent Mars base and the NERVA-derived nuclear shuttle would have been developed by the early 1980s. The ISP, developed by Rockwell, was created from several long-term NASA plans and spanned over 100 years. A long-range approach to the space program, the ISP was developed during the post-Challenger 1980s and focused on derivations and capabilities of the Space Shuttle as it existed during that time. The ISP had a gradual buildup to exploration capabilities, including interstellar travel, using in-space technologies like Nuclear Electric Propulsion and Mars cyclers. While there are notable differences between the two roadmaps in terms of assumed development times and mission planning, common elements and themes such key technologies and infrastructures would have been required elements for the execution of both plans.

II. NASA's Roadmap for Solar System Exploration (covering years 1970-1990)

A. Historical Context

At the height of the Apollo program, then vice-president Spiro Agnew asked NASA to prepare a plan to go to Mars. Wernher von Braun completed the plan at Marshall Space Flight Center and presented it to NASA Headquarters and the White House. Dated August 4, 1969, this proposed Mars mission was presented shortly after Apollo 11's moon landing.

Sending a man to Mars was viewed as the next logical step for NASA, and the NASA Roadmap included a method for accomplishing this milestone in 1982. The experiences from the Apollo program provided both the technical and programmatic expertise for this endeavor and set a path for manned planetary missions. A manned Mars mission was thought to be no greater challenge than our commitment to go to the moon, a likely result of NASA's recent and significant accomplishments from the Apollo program. This plan concluded that man's first step on Mars will be "no less exciting than Neil Armstrong's first step on the moon.[1]"

A manned Mars landing was viewed as only part of a total exploration program, but missions to Mars were important because Mars likely had similar origins and development as Earth. The most consuming questions for the space program were whether life had ever existed on Mars or could, and manned missions to Mars would allow for the study any indigenous life as well as transplanted life. A Mars mission also provided long-term, post-Apollo focus for NASA, starting it on a sustained path for manned planetary exploration.

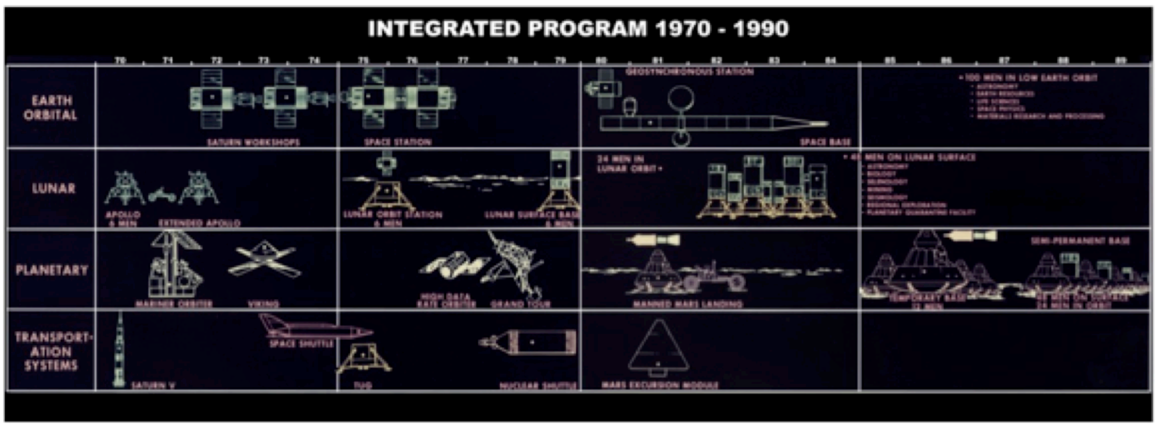

Figure 1. NASA's 1969 Roadmap

B. Roadmap Overview

The proposed mission to Mars would have begun with launches of multiple Saturn V's and space shuttles, assembly of a planetary vehicle in Earth orbit, and departure from Earth orbit. After the 270-day journey, the ship would have been propulsively captured into Martian orbit and remained there for 80 days. During this time, surface exploration would have taken place with Mars Surface Sample Return (MSSR) probes followed by Mars Excursion Modules (MEM) that would have taken three-man landing parties to the surface for 30-60 days. Surface exploration would have included the use of a one-man rover, drilling for water, and potentially the manufacturing of rocket fuel. The return trip would have offered a close encounter with Venus, providing the opportunity to release probes to the planet. At the end of the two-year mission, crew would have returned to Earth via space shuttle. Scientific objectives for a manned Mars mission included the collection of soil and atmosphere samples, the study of terrestrial life forms on Mars, the search for usable resources, and the search for Martian life forms.

The Mars transfer spacecraft and nuclear shuttles would have been launched via Saturn V's, while space shuttles would have launched the crews, expendables and some fuel. The nuclear shuttles would have been launched with half of their propellant and received the remainder from the space shuttle flights. The mission vehicles would have been assembled in Earth orbit, with two nuclear shuttles providing propulsion for Earth departure and one for the remainder of the mission's propulsion. The two nuclear shuttles that would accelerate the planetary ship to trans-Mars injection velocity would return to an Earth orbital space station for reuse after separating from the ship.

The proposed mission recommended the use of two ships due to the long mission duration. While the mission could have been accomplished with just one ship, advantages that would have been provided by two ships included the ability to bring more exploration equipment and the ability for one ship to act as a rescue vehicle in the event of a catastrophe. Vehicles would have consisted of three side-by-side nuclear shuttles with a planetary spacecraft docked to the center shuttle. Each ship could have carried six people for two years or twelve people for an extended period in an emergency. Technical challenges to such a mission included several factors related to the long mission duration including life support and propulsion systems.

Each assembled and fueled vehicle would have weighed 1.6 million pounds before departure, 75% of which (1.2 million pounds) was propellant. Sixty percent of the vehicles' initial weight would have been that of the fuel required for Earth orbit departure. Midcourse corrections and life support would have accounted for weight lost during travel to and from Mars in addition to the release of surface sample return probes, the MEM, and Venus probes. The last of the propellant would have been used in the nuclear stage for braking when the vehicle returned to Earth orbit, and the total weight of the empty vehicle upon return would have been 160,000 pounds, just 10% of its original weight.

The NASA Roadmap leveraged heavily on the work done for the Apollo and Saturn V programs. Those programs provided the experience to make a Mars mission both a feasible undertaking and a natural next step for U.S. space exploration. The proposed Mars mission's vehicle design elements, mission planning, and operations were evolutions of those used for Saturn and Apollo, and the proposed nuclear propulsion systems were viewed merely as an evolution of less-efficient chemical propulsion systems. The proposed space stations and lunar base would provide the additional experience necessary for sending both men and equipment on such a long duration mission, and systems from early Mars missions would evolve into a base by the end of the decade.

C. Key Technologies

Commonality and reusability were important factors of the plan, shown in many elements including the shuttle and space tug that would have supported lunar missions and acted as a maneuvering unit at the space station. There were five hardware elements required for the plan: a nuclear shuttle, space shuttle and mission module all required for the program, and the MEM and MSSM that were required for landing missions. The space shuttle was seen as the "key element to future space operations"[1] for its reusability and flexibility in transporting both crew and cargo to orbit. Its role in the plan provided justification for the development of the Space Shuttle Program. The mission module would have served several roles, including acting as a space station, use in lunar orbit, and as a lunar surface base. The 1970s space station would have turned into a space base in the early 1980s that would have supported 100 people and led the way for a geosynchronous station. Later, the reusable nuclear shuttle would have become the primary propulsion system and support lunar missions. The plan concludes in 1990 with a semi-permanent Martian base, 100 humans in LEO, 48 humans on the moon, and 72 humans in the Mars system.

The NASA Roadmap assumed an increase over NASA's Apollo-level budget for the proposed development programs with an initial focus on Earth orbital and lunar programs. Funding priorities would have shifted to planetary missions by 1980 while the Earth orbital and lunar programs' funding would remain constant. An emphasis on component commonality, reuse, and multi-use components was intended to minimize operating costs. The increase in spending in the 1970s developed the mission's programs and by 1990 funding levels returned to those of the Apollo program.

The NASA Roadmap presented a 19-year planning schedule (through calendar year 1988) involving Apollo, lunar, applications, space station, planetary, and shuttle missions. It used a gradual build-up of technologies and mission types to meet a 1982 initial Mars landing and followed that with the build-up to a permanent Mars presence in the 1990s. In addition to the semi-permanent Martian base, the roadmap also concluded with a large (48-person) lunar base, a substantial (100-person) Low Earth Orbit presence, and numerous robotic planetary exploration vehicles.

The roadmap developed by NASA lists several technical challenges of the time, including long-life autonomous systems; long duration cryogenic storage; contamination; reusable and multipurpose space systems; long stay time of man in space and long life reusable nuclear propulsion systems. The technologies required for the proposed missions are assumed to be in existence by the time they are needed, but their developmental details are not discussed in the roadmap. These technologies required to fulfill the Roadmap's goals are discussed below.

1. Artificial Gravity

Extended weightlessness affects space travelers with muscle atrophy, bone loss, and a weakened cardiovascular system. Today these symptoms are managed with exercise and medication, stemming from Soyuz 11's early treadmill experiments to combat the side effects and learn what caused them.[2] While today's methods work for shorter-duration missions to the ISS, which may be measured in months, they may not be ideal when considering a mission to Mars or beyond, which would be measured in years. Since the 1960's, artificial gravity has been proposed as a way to combat these negative side effects of space travel, especially on a long-duration mission to Mars. Methods could include use of a centrifuge[3] or a rotating space station.

> "You can try to treat each of the effects of weightlessness system by system, with certain pills for bone loss and certain exercise regimens for the muscles," said Laurence Young, an aeronautics and astronautics engineer at

> the Massachusetts Institute of Technology. "Or you can treat the root cause of weightlessness by restoring gravity."[4]

The NASA Roadmap mentions the use of artificial gravity, but does not provide much detail in its discussion. At the time of the Roadmap's development, little was known about the effects of weightlessness on an astronaut over a long duration. The Roadmap relied on the planned Saturn Workshops of the early 1970's to provide data on man's ability to withstand months of weightlessness, and the following Space Station to determine man's capabilities for the longer durations required for a trip to Mars. The Roadmap's en route spacecraft had an artificial gravity mode where the two vehicles are docked end-to-end and rotated, as well as an alternative tethered mode. The Roadmap acknowledged the issues of weightlessness and artificial gravity, but also noted the lack of data of the time and pointed to future missions to recommend solutions.

2. Environmental Control and Life Support System

An environmental control and life support system (ECLSS) is an essential part of a space ship's design. The ECLSS provides essential life support functions and a hospitable living environment for crew. For example, the modern space shuttle ECLSS included

> an air revitalization system, water coolant loop systems, atmosphere revitalization pressure control system, active thermal control system, supply water and waste water system, waste collection system and airlock support system. These systems interact[ed] to provide a habitable environment for the flight crew in the crew compartment in addition to cooling or heating various orbiter systems or components.[5]

The NASA Roadmap does not specifically address an ECLSS system, but acknowledges the technical issues of long-duration space travel including long life autonomous systems, long duration cryogenic storage, contamination, long stay time of man in space, and proposes Earth orbit demonstration of manned long life systems. At the time of the Roadmap's development, NASA had already addressed life support systems for the Apollo program. While a mission to Mars and the intermediate steps would have required significantly more from ECLSS systems than the short duration Apollo missions, the basics for the systems were already in existence. NASA would have been able to expand on the Apollo ECLSS systems to complete its missions, likely without having to develop any significant new technologies. While the Roadmap addresses the technical challenges it would face along these lines, ECLSS development was not a primary focus for Roadmap completion.

3. Radiation Shielding

Radiation is a significant issue for beyond-LEO travel, both for humans and electronics. Various shielding methods are available and are broken into categories of passive (methods that absorb radiation, such as metal insulation) and active (methods that deflect radiation, such as an electromagnetic field). Passive shields are the only available option even today in space travel, offering a basic system, but limited by mass allocation. Active shields have very high power requirements, such as nuclear fission or fusion, which carry their own risks.

Since mass is at a premium for space travel, shielding needs to be optimized. Spacecraft structures provide basic shielding, so spacecraft are designed to take advantage of the existing structure before adding any specialized shielding that serves no other function. In addition to transit exposure, surface operations are a major concern for radiation exposure. Destinations such as the moon and Mars, however, offer regolith that can act as a shield with processing as part of ISRU operations.

The concept of magnetic shielding for spacecraft (similar to the protection provided by the Earth's own magnetic field), was introduced during the Apollo days, but as trips to Mars were abandoned, the concept was put aside in favor of more traditional shield designs. While the easiest way to avoid radiation is to use a shield to absorb it, the required passive shielding is very heavy, and limiting for missions. In addition, cosmic rays can interact with shielding and create secondary charged particles, thus compounding the problem. Challenges to a magnetic field solution include the development of a system that can create a magnetic field large enough for a manned spacecraft as well as keeping the system cold enough to maintain its superconductive properties.[6]

Other ways to protect against radiation do not rely on shielding. Improvements in propulsion would reduce transit time. This would mean crew and electronics spend less time in a radiation environment as well as reducing weight and therefore offering more mass for additional shielding. Prediction of radiation events can be used in scheduling missions. Early warning systems can offer a way to minimize entire spacecraft shielding; spacecraft with centralized, heavy shielding for emergencies would offer a more elegant solution than a heavily shielded spacecraft.[7]

NASA's early manned missions were of a fairly short duration; at the time of the Roadmap's development the longest mission was Apollo 7, which lasted 11 days. For these early missions, NASA's spacecraft were not designed with special radiation protection; the modules themselves provided the necessary shielding for astronauts on short-duration missions. This was an aspect of early space missions with a limited mass budget as well as a scientific experiment for measuring the radiation doses experienced on the missions. Apollo missions included dosimeters for the astronauts to measure their exposure. Radiation doses were small and radiation was not an operational problem for the missions.[8]

The NASA Roadmap notes the need for radiation shielding only in its description of the Mission Module's role as both living quarters and radiation shelter, but does not account for the shielding method or required hardware. During 1969 planning, with limited manned space travel experience, NASA simply had to make assumptions about shielding requirements based on the limited knowledge of the effects of radiation on crew and electronics. The assumption would be that designs from that time would use passive shielding, although von Braun thought about electromagnetic shielding in the 1960s, dismissing the idea due to the impracticality of the assumed size of the magnet.[9] Surface operations on the moon and Mars would likely have used regolith as shield material.

4. In-Situ Resource Utilization

In-situ resource utilization (ISRU), the in-place use of resources found on other celestial bodies such as the moon or Mars for space exploration, will play a significant role in extended beyond-LEO travel. The use of in-situ resources will not only provide substantial cost savings by minimizing the amount of supplies necessary to be carried from Earth, but also enable extended beyond-LEO human presence by allowing exploration of much greater distances. In-situ resources can include propellant, life support, construction and energy materials. Each roadmap includes elements of ISRU.

The NASA Roadmap identifies the search for water and usable natural resources in its scientific objectives for its planned manned Mars landing mission in the early 1980s. By 1984, the roadmap proposes 48 men on the lunar surface with activities that include selenology (moon geology), mining, and regional exploration. These objectives list the scientific activities in the search for and research of ISRU resources, but do not propose what to do with the resources that might be found. The NASA Roadmap also plans for 48 men on the lunar surface in 1984 and calls out activities as part of this mission that will contribute to ISRU. Selenology, mining and regional exploration are included as part of the mission profile for this time in the roadmap. The plan's exploration activities include use of a one-man rover, the search for usable resources including drilling for water, and potentially the manufacturing of rocket fuel. While the Roadmap assumes future use of any resources, it does not detail specific plans and leaves the possibilities open.

> Drilling for or locating water will be an early objective on Mars, and its discovery would open many possibilities for utilization of Mars. For example, it might become possible to produce rocket fuel for the return trip on later missions.[1]

The roadmap addresses ISRU as a scientific objective, allowing any scientific discoveries to dictate future ISRU uses.

5. Earth-to-Orbit Propulsion

A critical component of any exploration planning is the method by which crews, cargo, and infrastructure are transported from Earth to orbit. The NASA Roadmap defines crew and cargo launch vehicle development plans based on the requirement for crewed missions to Mars and the existing Saturn technologies from the Apollo program.

The NASA Roadmap bases it initial launch capabilities on the Saturn family of vehicles, specifically, the existing two-stage Saturn V. For the first phases of the plan, the Saturn V would be the primary method of getting large payloads to orbit. Less than a decade into the plan (by the late 1970s), however, the need for a new launch technology is identified. The plan envisions a reusable space shuttle element for transporting people, equipment, and supplies to LEO as an eventual replacement for the Saturn V system for crew and routine supplies.

While the NASA roadmap lacks particular details about the design of the proposed shuttle system, the graphic used in the roadmap presentation is similar to the "Star Clipper," shown below,[10] developed by Lockheed as the LSC-8MX.[11] Lockheed proposed this vehicle during a 1968 Air Force ILRV study as well as during the Phase A portion of the NASA ILRV program.[12] The Star Clipper used a 1.5 stage, partially expendable design with a delta shaped orbiter flanked by two fuel tanks. It was designed to lift 50,000lbs of payload to orbit using 5 engines with 2.33 Mkg of thrust. A critical technology for the development of this type of system was the linear aerospike engine. The orbiter also included a variable geometry wing and an air-breathing engine to allow for flexibility during the landing.[13]

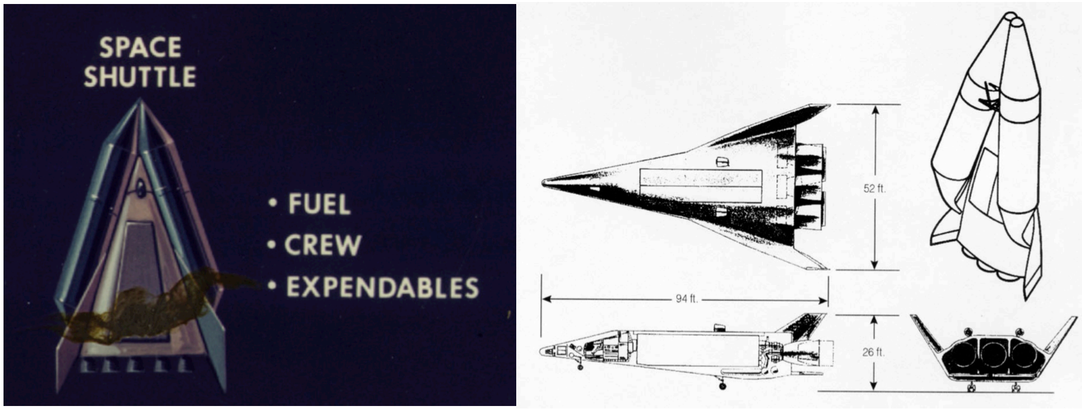

Figure 2. NASA Roadmap Space Shuttle (left), Lockheed Star Clipper Configuration (right)

These performance requirements were in line with known NASA shuttle requirements from that era (1965-1969), specifically those described in the July 1969 Space Shuttle Task Group final report. A vehicle with the Lockheed configuration would fall into the SSTG's definition of a "Class II" vehicle. Class II designs included 1.5 stage vehicles with reusable orbiters and expendable fuel tanks that did not require a separate booster.[12]

Beyond the existing Saturn V and the proposed shuttle system, no additional launch vehicle programs or technologies are referenced in the NASA roadmap. At the time, re-usability of launch systems was deemed a necessary and critical technology in order to make space access more routine and cost effective. The studies of re-usability technologies identified thermal protection and re-entry, blending of aircraft and spacecraft operations, horizontal vehicle and payload processing, and new crew survivability concepts. By the early 1970s, budget trade-offs and additional military mission requirements on the Space Shuttle Program had phased and or compromised some of these key technologies.

6. Beyond-LEO Propulsion

Getting to orbit is only the first step toward accomplishing an exploration mission. Both roadmaps focus on how to get astronauts to destinations within and, in the case of the ISP, beyond the solar system. In both roadmaps, the development of nuclear propulsion technologies is a critical requirement for any beyond-LEO transportation system; however, the type of nuclear propulsion proposed is decidedly different.

The NASA Roadmap is focused almost exclusively on identifying the technologies and mission architecture to support a 1981 manned landing on Mars. The Earth departure phase of the mission involves a 270-day journey to Mars with a 290-day return voyage. Propulsion systems were identified and sized to support those mission requirements. The main component of the architecture is a nuclear propulsion module, which can be combined together on-orbit in sets of three with a planetary spacecraft module to form a "Nuclear Shuttle." Two propulsion modules would be used during the Earth-to-Mars phase of the mission while the remaining module would be used during the return phase. These nuclear modules are assumed to be reusable and would be serviced on-orbit at a space station in the same assembly orbit used to assemble the shuttles at the start of each mission. According to the plan, "the nuclear shuttles which return to Earth orbit will be available for transfer of fuel and supplies to geosynchronous orbit or to lunar orbit." [1]

In July 1969, NASA's Marshall Spaceflight Center chartered a Nuclear Flight System Definition (NFSD) study, which funded three contractors to perform detailed analysis and conceptual design of nuclear rocket stages, both expendable and reusable.[14] The NERVA I engine (Nuclear Engine for Rocket Vehicle Applications) was the central component of the reusable design, called the Reusable Nuclear Shuttle (RNS). The original RNS mission goals included the "delivery of men and materials between lunar/geosynchronous and earth orbit"[15] as well as the "injection of unmanned payloads on planetary intercept trajectories." [15] It was envisioned that the original RNS capabilities would evolve to allow for manned planetary missions such as those in the NASA roadmap.

The NERVA I engine, while a technologically intensive project, had been under development at NASA and the Atomic Energy Commission since 1961[16] and supports the assertion that the NASA roadmap focus was on the use of technologies that either existed at the time, or were currently under development. During the 1960s, NASA used the Rover/NERVA program as the primary engine for development of nuclear rocket technologies. "The principal research thrust…was directed to the development of reactor fuel and reactor systems that would operate with hydrogen at temperatures above 2200K."[16] Other research emphasis areas included safety and reliability, the propellant feed system, and the nozzle and engine control systems. In addition to the baseline design (a hydrogen-cooled graphite reactor), several other higher-risk, higher-performance options were also included such as liquid and gas core reactors.[16] The goal of the NERVA development program was to design an engine that could be applied to a variety of space missions, including the NASA roadmap's Mars mission scenario. The Rover/NERVA program was considered a highly successful, mission-oriented, technology development program that culminated with a "successful demonstration of a ground test engine system."[16]

D. Key Infrastructures

Technologies, such as those described above, necessitate infrastructure that can support and supply the proposed missions. In addition, existing infrastructure and assets are required to support the development of many of these critical technologies. For example, a permanent (or long-duration) human presence in LEO is essential for collecting vital information to support the development of required radiation shielding and ECLSS systems. For most exploration architectures, three major infrastructure components are required to support development and implementation of the technologies that drive human exploration: space stations, launch vehicles, and surface bases. By examining the role of these infrastructures in the exploration roadmaps, we can see how technology either drives or is driven by these infrastructure requirements.

1. Space Stations

A space station is an example of a specific infrastructure, with the capability to support technologies such as artificial gravity, multipurpose space systems and addressing the concern of humans on long-duration stays. Following Apollo, NASA deemed manned exploration of the planets the next frontier of the space industry, as presented to the Space Task Group in 1969. In fact, this declaration was the first of many that attempted to ignite enthusiasm within NASA for a follow-on program: landing men on Mars in 1982.

In describing the 1981 Mars Landing Mission Profile, The NASA Roadmap depicts the 'Mars ship' or spacecraft that would travel to Mars as a multi-use facility, intended in part to be a manned laboratory in space permitting temporal and spatial experiments in such an environment. The spacecraft would serve as such a space station while en route to Mars, and with this 270-day journey from Earth, the station's experiments and measurements will be of prime scientific importance. The forward compartment would be an unpressurized area, which would house the Mars Excursion Module, an airlock and robotic probes. Aft of the airlock would be the Mission Module, which serves as the living quarters, experimental laboratory space and radiation shelter. At the aft end of the mission module, Mars surface samples would be received and analyzed upon arrival to the spacecraft. The purpose of such a space station would be to demonstrate the capabilities of humans for the longer periods required for the manned Mars landing mission. During the nine months the spacecraft would be en route to Mars, the crew would perform experimental activities (e.g. solar wind measurements and solar/planetary observations) and biological monitoring.

The facility put in orbit by 1975 would have evolved into a Space Base by the early 1980s that will have the capacity to support up to 100 people. However, as this infrastructure would help to employ new technologies, technologies such as nuclear propulsion would be necessary for culmination of such a geosynchronous, multi-disciplinary station.

2. Launch Vehicles

The ultimate goal of the NASA Roadmap was to land on the Martian surface. Existing infrastructure from the Saturn V program was to play a key role in supporting the launch requirements of this mission. This existing infrastructure included facilities for manufacturing, vehicle assembly and processing, and ground and flight operations. In addition to the Saturn infrastructure, the roadmap proposes the development of a new space shuttle system for ferrying crews to and from LEO (in conjunction with a permanent space station, described above). Drs. Mueller and Von Braun, among others, communicated the need for a reusable Space Shuttle and how it was viewed as "the first step in achieving the capability to assemble a Mars ship in Earth orbit."[1] The space shuttles would not only transport crew, but also would deliver fuel for the nuclear shuttles and other expendables.

3. Surface Bases

The Manned Mars Landing mission proposed to the Space Task Group assumes two Mars Excursion Modules (MEMs), which would be carried to the surface from each orbiting spacecraft. The MEM consists of ascent and descent stages, with the latter serving as the living quarters and laboratory for the 30-60 day stay (per MEM) on the Mars surface. The ascent stage contains the control center and houses the three-man crew during entry, descent, landing and ascent. A one-person rover would also be stored in the descent stage until it would be needed for surface mobility. In this sortie mission, all descent stage equipment is left on the Martian surface, though no infrastructure would be established beyond this. It was the expectation of The NASA Roadmap, that a temporary base would be established by the end of the decade of the eighties with experience gained from early Mars missions. Unlike the space station and launch infrastructures that can serve as test-beds and technology development drivers, the development of the surface bases will be driven by the currently available technologies.

III. Rockwell's Integrated Space Plan (covering years 1989-2100)

A. Historical Context

Rockwell International flourished in the 1980s during the time it developed the Integrated Space Plan[17] for NASA. Reaching its pinnacle in the 1990s, the largest NASA and U.S. defense contractor showed ambition with its ISP as it envisioned a transformation from an Earth-restricted species to interstellar traversing humans. Rockwell was also the prime contractor for the development and operations of the National Space Transportation System or Space Shuttle.

The Rockwell Integrated Space Plan was developed as a very long-range systematic perspective of the space programs of America and the Western World for the next 100+ years. It was the result of the integration of several NASA, including the Pathfinder case studies; the Ride report to the NASA Administrator (i.e. Mission to Planet Earth, Exploration of the Solar System, Outpost on the Moon and Humans to Mars); and recommendations from the National Commission on Space's report to the President and the National Space Policy Directive (1988). These integral pieces culminate to a cohesive interpretation of enabling technologies and proposed objectives to reach beyond our solar system. As mentioned in the ISP itself, the National Space Policy defined the ISP's critical path, which mirrors the NASA Office of Exploration case study 4 scenario from 1988: Lunar Outpost to Early Mars Evolution.

This scenario included development of a sustained human presence beyond LEO with early emplacements of outposts on the moon and Mars, which evolve to self-sustaining bases. These bases would be highly dependent on in-situ resource utilization and be supported by advanced technologies (e.g. electric propulsion, nuclear surface power). The findings of this case study revealed that reliance on the large number of high technology elements imposed significant program risk; development of nuclear electric propulsion by 2007 (first Mars cargo flight) was much too aggressive; ISRU including propellant production and storage provided large mission leverage, and human performance for long duration missions requires further analysis.

While the ISP drives towards large-scale human habitation of Mars, expansion into the cosmos begins around 2050, fostered by technologies and achievements that are not destination specific. Plateaus of human achievement are listed below and chronicled to capture the summation of individual element implementation.

B. Roadmap Overview

The ISP was not intended to be a definitive plan for the development of space, but rather a compilation of evolutionary opportunities for near-term and long-range space activities. Initially, the Space Shuttle and ISS were integral elements to enable future activities such as in-space commerce and biosphere research. Beyond these qualifying elements, the critical path of the ISP was sequenced as follows:

(1995) US/International Space Station Project & Mission for Planet Earth
(2003) Lunar Orbit Staging Facility
(2004) Return to Moon; Core Sample Collection and analyses
(2007) Lunar Outpost Established
(2009) International Lunar Base expanded Lunar Outpost
(2012) LEO International Spaceport (expanded space station)
(2015) Moonport (Lunar Orbit Staging Facility Expanded)
(2017) Self-supporting Lunar base
(2019) Phobos Outpost established
(2021) Mars Landing Human Outpost Established
(2023) Phobos/Deimos Mining Operations Commence
(2024) Initial Mars Base established
(2026) Martian Spaceport (expanded Phobos facility)
(2029) Operational Mars Base
(2036) Self-Supporting Mars Base
(2042) Initiate Martian Terraforming Operations
(2100) Large Scale Human Habitation of Mars

International partnerships with Europe, Japan and Russia are offered as a means to more easily implement various in-space transportation nodes, such as GEO cryogenic and hypergolic propellant depots; commercially available manned GEO communications platforms; Earth-Moon Lagrange Point 1 arrival-departure spaceports; Lunar Orbit Staging Facility storage depots; Phobos and Martian spaceports and skyhooks. These deep-space nodes would lend themselves to space settlement establishments.

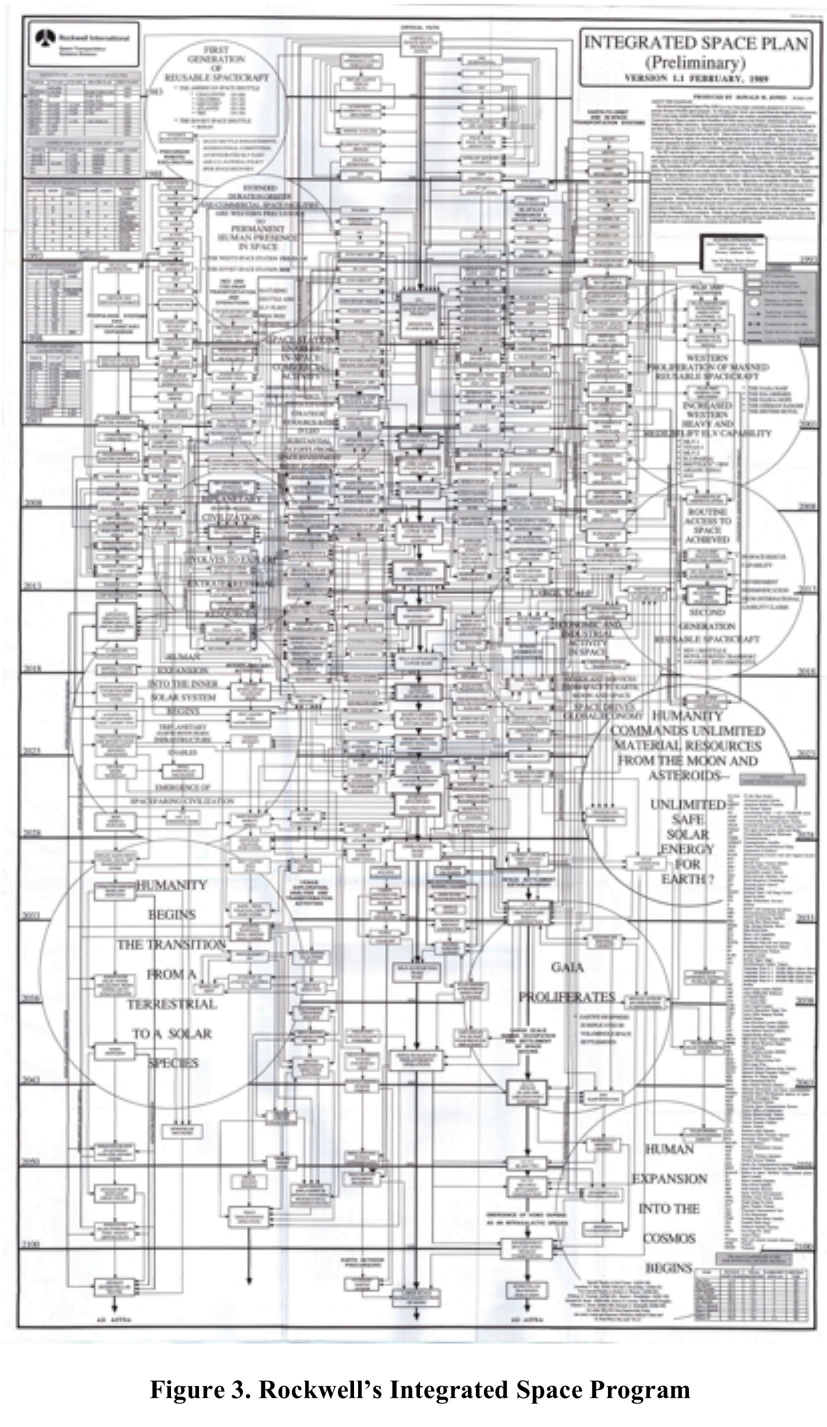

Figure 3. Rockwell's Integrated Space Program

The ISP provides a roadmap until just beyond the year 2100, when large scale human habitation of Mars is pervasive; humans tour the outer solar system via antimatter propulsion; best candidate stars for interstellar exploration are identified and the emergence of homo sapiens as an intragalactic species is the next logical step.

The need to employ technologies within the Rockwell roadmap is different than the singular need captured by the NASA Roadmap – landing on Mars. Von Braun and others presented a case for landing on Mars using specific launch vehicles and spacecraft. The Integrated Space Plan shows a multitude of options for a plethora of missions and milestones beyond a Martian settlement. Key technologies are discussed below.

C. Key Technologies

Due in part to its longer time scale and evolutionary nature, technology development and insertion activities play a much different role in the ISP than they do in the NASA roadmap. Where the NASA roadmap focuses on leveraging existing technology with limited insertion of new technologies only as needed for the specific mission goal, the ISP focuses on identifying key technologies that are either currently under development or envisioned as being development in the future, and then describing the missions and infrastructures that would be supported by this technology development plan. For example, the focus on single-stage-to-orbit launch vehicle technology development was seen as critical for developing a fleet of vehicles capable of meeting launch rate and turn-around requirements to support a wide variety of missions. The same six technologies as discussed earlier will be described as they pertain to the development efforts described in the ISP.

1. Artificial Gravity

Several technologies required for space travel, such as artificial gravity, do not make an appearance in the ISP. A spacecraft that provides artificial gravity is designed to provide some sort of spinning function, whether it is the entire spacecraft or smaller centrifuges used internally for shorter durations. There were no new technologies that would need to be developed to provide artificial gravity with the exception of some yet unimagined technology that could not have been included in the plan at the point of the ISP's development. To spin a spacecraft or not was a design decision that would be implemented at the time of a spacecraft's development and was an unnecessary detail to be included for elements of the ISP.

2. Environmental Control and Life Support System

The ISP lays out major milestones in its progression of life support systems. With its goals of large-scale human habitation of Mars and interstellar traversing world ships, the ISP relies heavily upon major advances in ECLSS, but provides little detail into the required technologies and major advancements. The ISP includes a partially closed component CELSS (Closed Ecological Life-Support System) in 1998, a CELSS around 2005, and a near closed ECLSS around 2015.

The ISP was published pre-ISS, so life support system assumptions would have been made on experiences with programs like Skylab and the Space Shuttle. The ISP places life support system work under "In-Space Research & Development," an indicator of both the ISP's heavy reliance on future technology development to meet its long-term goals and of the acknowledgement that much of the development needed for this area would need to be done in space.

It is assumed that the ISP starts with a basic ECLSS, similar to what is used today on the International Space Station[18] and shown below. Today's ISS ECLSS, a physicochemical system, provides basic life support for crew on the ISS, but is completely dependent upon regular resupply from Earth.

The ultimate goal of any ECLSS is to be a self-sustaining closed-loop system, or a CELSS, "that can regenerate all of the water, air, and food without adding anything to the system after startup"[19,20] Based on the ISP's goals for enabling human expansion into the cosmos, the CELSS definition describes the desired life support system solution for the ISP.

> A CELSS is, in theory, a completely-closed system wherein continuous waste-recycling and regenerative systems provide 100 percent of the food, water, and breathable atmosphere in a psychologically-acceptable human environment. In practice, a completely-closed system is not possible, because some loss of resources (such as leakage of oxygen and water out of the habitat) is inevitable. The goal, then, of CELSS is to approach, as closely as possible, a condition of self-reliance for humans on the Moon, where a minimum re-supply from Earth is necessary.[Error! Bookmark not defined.]

While a completely closed system is today only theoretical, the technology advances expected by the ISP would enable interstellar traveling world ships around 2100, which would be well beyond the reach of lunar or Martian bases and could not be dependent upon resupply from the Earth's system. The ships that fall between today's systems and the interstellar ships of 2100 would make progressive steps toward becoming independent systems, and each generation would rely less on resupply from Earth or future planetary bases. The technologies that follow today's ISS ECLSS would fill this gap.

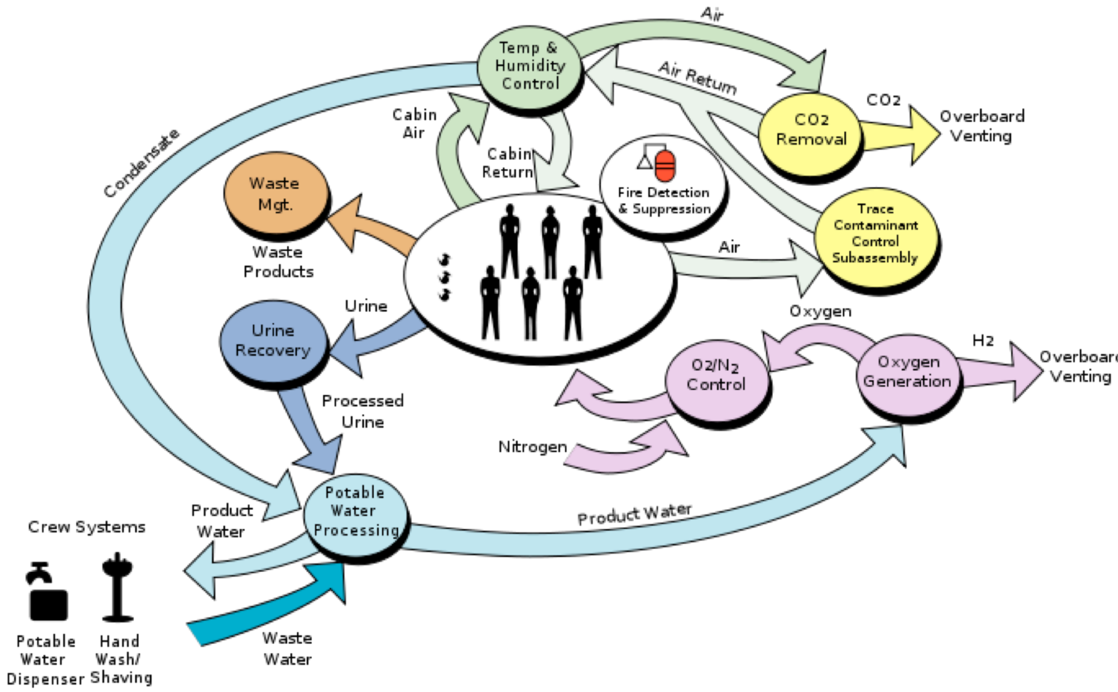

Figure 4. ISS ECLSS

3. *Radiation Shielding*

At the time the ISP was written in 1989, the U.S. had experience with only limited duration manned space flight. Space Shuttle missions lasted a week or less, and the longest NASA manned missions were its three Skylab missions, the longest of which was Skylab 4 at 84 days.[21] From measurements on the Skylab missions, it was determined that "the Skylab 4 crewman could fly a mission comparable to one 84-day Skylab 4 mission per year for 50 years before exceeding these [established] career limits"[22] based on exposure limits set by the National Academy of Science. These measurements, however, were based on data from missions in LEO, and do not take into account beyond-LEO travel.

The ISP does not provide any detail about the methods of radiation shielding that would be used for its missions. For missions early in the ISP, the lack of information for shielding methods would be explained by the lack of new or expected technologies; passive shielding methods were the only methods available, so the ISP's spacecraft would have implemented those existing methods. It would have made assumptions based on Skylab and Space Shuttle missions and used similar shielding for the early LEO missions. As the ISP progressed, especially as it planned for the transformation of humanity from a terrestrial to a solar species, it likely did so with the assumption that not yet imagined technologies would be available; its lack of detail on radiation shielding methods are due to a lack of knowledge about future technologies.

Methods for protection of the large ships required for solar system expansion could include the aforementioned early warning systems and areas shielded for emergencies. While such areas would not be practical on a 2000 timeframe space station with limited area, a large ship intended for universe exploration in 2040 would be designed with significantly more room and the ability to include heavily shielded emergency areas in the center of the ship. There would also be potential for biological or pharmaceutical methods to counteract the effects of radiation, as well as astronaut selection based on advances in biomarkers that could determine an individual's susceptibility to the effects of radiation.

4. In-Situ Resource Utilization

The Rockwell Roadmap, with its focus on expansion over an extended period, relies heavily on ISRU. The plan has many ISRU related milestones, including an in-situ lunar liquid oxygen (LLOX) pilot production unit in 2008 that was likely based on the assumption of the time that water or other forms of oxygen would be discovered, which didn't happen until later[23]. It progresses to the use of solar energy for greenhouses and solar furnaces by 2020, mining operations shortly thereafter, and indigenous resource construction in 2034. This progression of ISRU capabilities demonstrates the Roadmap's assumptions that significant technology leaps would make extended travel beyond LEO a reality. Much like ECLSS, ISRU would be a notable requirement for extended space travel because it would not be feasible to bring along all necessities.

5. Earth-to-Orbit Propulsion

The ISP Earth-to-Orbit capabilities begin with the U.S. Space Shuttle and focuses on the evolution of that system via new technologies to an eventual capability for fleets of SSTO Aerospace Plans to lift people to LEO and a simultaneous heavy lift launch vehicle capability to get cargo to orbit. Having these capabilities is seen as an enabler of a variety of mission classes and exploration opportunities.

UNITED STATES LAUNCH VEHICLE CAPABILITIES				
VEHICLE	# TO LEO	# TO GEO	GEO-CIRCULAR	FIRST FLIGHT
ALS	200,000			1998
SHUTTLE C	150,000		20,000 (CENTAUR)	1994
SPACE SHUTTLE	55,000		5,500 (IUS) 6,500 (TOS)	1981
TITAN 4	40,000	12,500	10,000 (CENTAUR)	1989
TITAN 3	33,000	8,600	4,200 (IUS)	1965
ATLAS 2	14,400	5,200	2,500	1991
ATLAS 1	12,300			1959
DELTA 2	11,100	3,190	1,350 (PAM-D)	1988
DELTA	7,800			1960
TITAN 2	5,500			1965
SCOUT	475			1961

LAUNCH VEHICLES OF EUROPE AND JAPAN				
VEHICLE	# TO LEO	# TO GEO	COUNTRY	FIRST FLIGHT
ARIANE 3		5,690	EUROPE	1984
ARIANE 4		9,260	EUROPE	1988
ARIANE 5	46,000	14,960	EUROPE	1996
H-1		2,300	JAPAN	1986
H-2		9,000	JAPAN	1992

Figure 5. ISP summary of existing launch vehicle capabilities at the time of plan development.

Earth-to-Orbit Transportation systems in the ISP begins with what is available in the late 1980s (Ariane 3 and 4, Titan 2) and include the NSTS (Space Shuttle), and the LOFT-1 (Launch Operations Flight Test 1) of the pathfinder for the E Prime commercial launch vehicle. It then looks ahead to planned launch vehicles such as the Delta II, Titan III, Titan IV, Pegasus, Japanese H-2. Technologies are introduced in the early 1990s timeframe which include the advanced second source SRB and LRB which enables the NASA Shuttle-C/Shuttle-Derived Heavy Lift Capability. The Shuttle-C would make maximum use of the existing shuttle systems by using the same type of external tank, solid rocket boosters, and main engines as the crewed space shuttle, requiring very few technology advances. Other future vehicles include the Ariane 5, and the DOD Advanced Launch System-NASA/DOD Heavy Lift Vehicle. The ALS was seen as combining advanced technologies and innovative management and design approaches to reduce system cost. Several approaches for this system were considered, ranging from a liquid core with up to six strap-on liquid engines to a technologically challenging, winged, fully reusable booster.

The Rockwell ISP highlights the winged, reusable, single-stage-to-orbit aerospace plane as a critical capability for enabling a permanent orbital presence in LEO and developing the necessary infrastructure for exploration. In addition to the ALS efforts, planned orbital planes such as the X-30 National Aerospace Plane, European Hermes, the Japanese H-II Hope aerospace plane and SSTO Aerospace Plane, the German TSTO Sanger Aerospace Plane, British SSTO Horizontal Take-off and Landing Aerospace Plane, and the American Shuttle II are all listed in the plan as vehicles that will pave the way for Earth-to-orbit Aerospace Plane Passenger Transport Vehicle Fleet Operations by 2008. The development of this technology could enable a variety of missions such as an International Spaceport in LEO and a DOD Polar-Orbiting Space Station.

The NASA Shuttle II concept was examined during a series of trade studies conducted at NASA Langley between 1986 and 1988[24]. These studies identified several critical technologies considered essential for the development of a new TSTO space plane. These included new engines to replace the SSME, such as the STME (Space Transportation Main Engine) and STBE (Space Transportation Booster Engine). The Shuttle II design[24] included 6 methane-fueled STBEs on the booster and 5 hydrogen fueled STME-type engines for the orbiter.

Engine parameter	STME type	STBE type
Vacuum thrust, lb	311 500	359 500
Vacuum I_{sp}, sec	441	369
Weight, lb	4030	3770
Area ratio	60	55
Flow rate, lb/sec	706.3	974
Propellants	LOX/LH_2	$LOX/CH_4/LH_2$
Mixture ratio (inlet)	6.0	3.47

Figure 6. Characteristics of the proposed STME and STBE engines for Shuttle II.

In addition to new engines, a number of other technology needs were identified for the Shuttle II baseline configuration. These included the following[25]:

- Reusable aluminum cryogenic tanks composite structures
- Advanced durable thermal protection system
- Advanced carbon-carbon for high temperature areas
- Common cryogenic propellant
- OMS and RCS systems with no hypergolic propellants
- Electromechanical actuators
- Fault-tolerant subystems with built-in test equipment
- Autonomous flight systems with adaptive flight control
- Advanced avionics control-configured design

Most of these technologies would be essential for the development of fully reusable SSTO vehicles.

6. Beyond-LEO Propulsion

While the NASA roadmap keeps its focus primarily on existing and developing technologies and planned technology development efforts, the ISP roadmap looks forward to potential mission-enabling propulsion technologies both on the near horizon and also those still considered to be decades into the future. Technologies mentioned in the plan include the following:

- Solar Sail - 1993
- Centaur Deep Space Capability - 1995
- Solar Powered Electric Propulsion - 2003
- Nuclear Powered Electric Propulsion - 2005
- Earth-Mars Injection Capability (Chemical) - 2007
- Ion-drive Engine Technology - 2025
- High Energy-Density Matter (HEDM) Chemical Propulsion - 2027
- Anti-Matter Enriched Propellant Propulsion - 2030
- Fusion Propulsion - 2040
- Nuclear-Pulsed Propulsion (Orion Concept) – 2100

These technologies are seen as enabling a wide variety of mission options ranging from near-Earth asteroid exploration (solar sails) and comet sample return (SEP) to interstellar exploration (ion-drive) and human interstellar travel (fusion and anti-matter). Beyond-LEO propulsion is also viewed as a critical component in developing the necessary infrastructure for exploration. For example, a chemical-based Earth-Mars injection capability would support the trans-Mars injection maneuver for very large payloads and enables the development of an integrated Mars transfer vehicle and a Martian cycling spacecraft.

At the time the ISP roadmap was created, NASA was funding technology developments in several of the early areas listed such as solar sails and modified upper stages to support deep space missions. Solar and nuclear electric propulsion were also considered critical technologies and by the early 1990s, NASA was developing and testing electric propulsion systems to support deep space missions[26]. Simultaneously, NASA was researching advanced cryogenic hydrogen-oxygen engines capable of supporting both lunar transfer and Mars transfer and excursion[27].

It is notable that the one major beyond-LEO propulsion technology development proposed in the NASA roadmap, the nuclear thermal propulsion system, is not listed on the ISP roadmap. The reasons for the exclusion of NTP from the roadmap are not clear. In contrast to the ISP roadmap, the 1989 NASA 90-day Study on Human Exploration of the Moon and Mars identified nuclear thermal propulsion as one of eight critical technology areas and specifically mentions the dramatic decrease in travel time to Mars that an NTP-based system would offer[27]. The same study notes, however, that at the time there were no significant U.S. programs performing research or development in the areas of nuclear thermal rocket propulsion.

D. Key Infrastructures

Unlike the NASA roadmap, the ISP focuses on how new technologies can lead to the development of the infrastructure required for exploration and how that infrastructure evolves in response to the availability of new technology. The same three infrastructure areas and their roles in the ISP roadmap are discussed below.

1. Space Stations

Within the Integrated Space Plan, Rockwell indicated its desire to use space stations in various capacities spanning several decades. With established space stations, experiments and laboratories could exist in a self-sustaining environment instead of relying upon the launch vehicle and its manifest.

The Space Shuttle was intended to support the critical path of the ISP during the initial stages, which led directly to the development of the International Space Station (ISS) project in 1998. From this designated “In-Space Transportation Node,” Rockwell envisioned co-orbiting low inclination platforms, furthering the structure of the station via solar arrays, additional international space station modules and DoD space station elements and activities. Other goals that ISS was meant to fulfill included space harboring/servicing/tending and a LEO propellant depot leading to deep space and planetary mission deployment. The critical path of the ISP was significantly enhanced by the production of the ISS. Following its construction, the space station would enable in-space commercial activity, a lunar orbit staging/facility and ultimately the establishment of a lunar outpost in 2008. At the time of the ISP’s publishing, the reference inclination of the proposed Space Station was at 28.5 deg as opposed to the current inclination of 51.6 deg.

Using their respective modules on the ISS as a platform, the Europeans began the construction of an autonomous space station in 2004, while the DoD was expected to have developed a low inclination space station around the same time.

An expanded version of the ISS was dubbed the “LEO International Spaceport,” which would be supported by several launchers. In order to achieve routine access to space, another key “in-space transportation node” was considered to be the DoD Earth-Polar Orbiting Manned Space Station planned for 2013. This would lead to a Polar Orbit Manned Space Station soon thereafter, followed by Polar Orbiting Radiation Hardened Habitats closer to 2050. Near-Earth space stations are predominant within the first two decades of the roadmap, then they seemingly transition to more permanent bases. A decade or so after the last manned stations have begun operations, solar powered space stations begin to orbit Venus, leading to resource extraction and atmospheric research.

Also, around 2019, space station CELSS would be available (Controlled Ecological Life Support System), which sets the stage for the Phobos Outpost being established.

2. Launch Vehicles

Earth-to-orbit and in-space transportation systems are paramount to the success of several milestones listed on Rockwell’s ISP. While the critical path is dependent upon the space shuttle initially, a maturing shuttle and ELV fleet spur free enterprise around 1995. In order to complement the lift capability needed for the initial in-space infrastructure, the development of a pure cargo derived Shuttle (Shuttle –C) was proposed as the heavy-lift backbone as opposed to the Saturn V of the NASA Roadmap. The Shuttle-C used a strong-back cargo carrier faring for 70-100t deployment of large in-space systems. The engines were either separated and recovered or end-of-life SSMEs that were used and expended. Various Shuttle C concepts were studied for several years and an outgrowth of those studies led to the Space Transportation Main Engine and the Advanced Solid Rocket Motor development program.

The majority of launch vehicle capabilities come from the United States, Europe, Japan, the Soviet Union and China. In 2003, there is an increased western heavy and medium lift ELV capability that becomes apparent, followed by second generation reusable spacecraft like a Japanese SSTO derivative and the NDV (National Aerospace Plan Derived Vehicle). However, shortly after the publishing of this roadmap the National Aerospace Plane program was cancelled as the hypersonic propulsion and structures technology necessary to make the concept viable were deemed not mature enough.

In addition to launch vehicles, the ISP also mentions Martian ad Venusian cycling spaceship launches, initiating the manned interplanetary spaceflight and Earth-Mars/Venus cycling spaceship transportation system. Cycling Spaceships are meant to ease the human expansion into the inner solar system.

3. Surface Bases

There are three highlighted cases of space settlement captured in Rockwell's ISP: a lunar base, a Martian base, and the settlement of other entities in space such as Phobos and L4/L5. The lunar outpost established in 2005 was the first surface base that Rockwell mentions in the ISP. This would have led to the international lunar base in less than five years time. A self-supporting lunar base followed, assuming indigenous resource habitat construction and a secure fiber-optic multibase communication network. Only shortly after a base would be established on the Moon, a Phobos outpost is established followed by a human outpost on Mars. This outpost would become an established Mars base in 2023, while the Phobos facility would be simultaneously expanded. The Mars base then would become operational in 2028. From the operational Mars base, two branches of space settlement are assumed in the ISP: the L4/L5 earth-Moon Libration point and the furthering of a self-supporting Mars base in 2035. The ISP suggests that large-scale human occupation and settlement of space begins shortly thereafter as Earth's biosphere is replicated in voluminous space settlements. It takes approximately a decade for small Martian settlements to proliferate. These three cited bases are listed as key enabling programs, but there is an unmanned station on Venus that is listed as more of a periphery program. Venus terraforming operations would follow this unmanned station close to 2080.

IV. Conclusions

Both roadmaps provide both a vision and an implementation path for future human exploration within the context of the technical capabilities of the time at which they were created. While there are many similarities in the phased approach to exploration proposed by both plans, there are several notable contrasts from selected approaches and scientific objectives to mission timeframes and overall goals. Most importantly for this discussion, the two roadmaps take very different approaches toward technology and the way technologies should either drive or be driven by exploration agendas.

In the NASA Roadmap, the mission and the existing infrastructure drives the technologies. With the ultimate goal of a human mission to Mars and a desired timeframe within which to accomplish that mission, schedule and mission goals drove the development of required technologies. A notable side effect of this is the heavy reliance of the NASA Roadmap on the maximum reuse of existing technologies and systems and the carefully planned evolution of necessary technologies to meet schedule requirements. NASA, a government-funded agency, developed its Roadmap at the height of Apollo excitement and with strong assumptions about the level of funding it would receive. NASA's Roadmap was part of a coordinated national exploration program, and had specific goals and an associated timeline that required the development of mission-specific technologies.

In the Rockwell ISP, the opposite is true. For this plan, technologies drive the missions and infrastructures that are described. The ISP is based on the continual development, testing, and flight of new technologies to allow for missions of greater and greater complexity and challenge. Without a coordinated destination goal or fixed timeframe (lack of a national exploration roadmap), the ISP is focused on identifying technology goals and outlining development paths and missions to make use of those technologies. It sees technologies as the key enabler for transforming mankind into a spacefaring civilization. While Rockwell, a commercial entity, emphasized reusability with its Space Shuttle derivations, it did not include budget assumptions with its ISP. At the time of the ISP's development there was no coordinated national exploration roadmap, resulting in a plan that was not goal oriented, focused, or date-driven.

Each roadmap was a product of its time and environment with its own merits, planning for future human space exploration both in short and long term. The six technology development efforts that were discussed in this paper, and the associated assumptions about future technologies, influenced each of the roadmaps and shaped development of key infrastructure.

V. Acknowledgments

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VI. References

[1] Von Braun, W., Manned Mars Landing Presentation to the Space Task Group (1969) 25, 3, 49, 27, 2.
[2] Zimmerman, R., *Leaving Earth*, 2003, Joseph Henry Press, Washington DC, 2003, pp. 37-40.
[3] Bettex, M., "The Pull of Artificial Gravity," *MIT News*, 15 April, 2010, URL: http://web.mit.edu/newsoffice/2010/artificial-gravity-0415.html [cited 3 August 2011].
[4] Hsu, J., "Artificial gravity could solve space problems," *MSNBC*, 12 May 2010, URL: http://www.msnbc.msn.com/id/37120546/ns/technology_and_science-space/t/artificial-gravity-could-solve-space-problems/ [cited 5 August 2011]
[5] "Environmental Control and Life Support System," *NSTS Shuttle Reference Manual (1988)*, URL: http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/sts_eclss.html [cited 26 July 2011]
[6] Atkinson, N., "Magnetic Shielding for Spacecraft," *The Space Review,* URL: http://www.thespacereview.com/article/308/1 [24 January 2005, cited 11 July 2011].
[7] Levine, J.S, Schild, R. E., *The Human Mission to Mars. Colonizing the Red Planet*, Cosmology Science Publishers, Cambridge, MA, 2010, pp. 833-836.
[8] English, R. A., Benson, R. E., Bailey, V., Barnes, C. M., *Apollo Experience Report – Protection Against Radiation*, NASA Technical Note D-7080. March 1973, p. 3, 1.
[9] Crisijones, "Solar Radiation Shielding for Space Flight," *The Crisis Jones Report*, URL: http://crisisjones.wordpress.com/2011/05/02/solar-radiation-shielding-for-space-flight/ [2 May 2011, cited 14 August 2011].
[10] Heppenheimer, T.A., *The Space Shuttle Decision*, NASA, Washington, D.C., 1999, Chap 2.
[11] Miller, R., *The Dream Machines: A Pictorial History of the Spaceship in Art, Science, and Literature*, Krieger, Malabar, 1993, pp. 507-508.
[12] Jenkins, D.R., *Space Shuttle: The History of Developing the National Space Transportation System*, Walsworth, Marceline, 1992, pp. 56, 49.
[13] Wade, M., "Starclipper," *Encyclopedia Astronautica*, URL: http://www.astronautix.com/lvs/staipper.htm [cited 29 July 2011].
[14] Portree, D.S., "Nuclear Flight System Definition studies (1971)," *Beyond Apollo (blog)*, URL: http://beyondapollo.blogspot.com/2009/02/in-july-1969-as-apollo-11-brought.html [February, 2009, cited 19 August 2011].
[15] Jusak, A.R., *SD 71-466-4 Nuclear Flight System Definition Study, Phase III Final Report, Volume II Concept and Feasibility Analysis, Part C Systems Engineering Documentation,* North American Rockwell, 1971, page 10-9.
[16] Robbins, W.H., Finger, H.B., *An Historical Perspective of the NERVA Nuclear Rocket Engine Technology Program*, NASA Contractor Report 187154/AIAA-91-3451, 1991, p. 2, 1, 10.
[17] Jones, R. M., "Integrated Space Plan (Preliminary)," Rockwell International, PUB 3547-H, 1981.
[18] "Breathing Easy on the Space Station," *NASA Science News*, URL: http://science1.nasa.gov/science-news/science-at-nasa/2000/ast13nov_1/ [cited 12 July 2011].
[19] Green, M., "Biospherics," *Henkimaa*, 12 October 2009, URL: http://www.henkimaa.com/2009/10/12/biospherics/ [cited 21 July 2011].
[20] Schrunk, D., Sharpe, B., Cooper, B.L., Thangavelu, M., *The Moon: Resources, Future Development and Settlement*, 2nd ed., Praxis, Chichester, UK, 2007, p.102.
[21] Ryba, J., "Skylab, America's First Space Station, *NASA.gov*, URL: http://www.nasa.gov/mission_pages/skylab/missions/skylab_manned.html [17 November 2005, cited 15 August 2011].
[22] Bailey, V.J., Hoffman, R. A., English, R. A. II, "Biomedical Results from Skylab," *NASA.gov*, URL: http://lsda.jsc.nasa.gov/books/skylab/Ch09.htm [28 February 2002, cited 15 August 2011].
[23] "Ice discovered on the Moon," *BBC News*, URL: http://news.bbc.co.uk/2/hi/science/nature/62489.stm [5 March 1998, cited 15 August 2011].

[24] Stanley, D.O., et al, *Parametric Trade Studies on a Shuttle II Launch System Architecture*, NASA Technical Paper 3059, 1991, pp. 1-2, 5.
[25] "Shuttle II," *Aerospace Guide*, URL: http://www.aerospaceguide.net/ShuttleII.html [cited 17 August 2011].
[26] "NASA Technology Summary: Solar Electric Propulsion," NASA Marshall Spaceflight Center, (FS-2005-05-62-MSFC, May 2005).
[27] Report of the 90-Day Study on the Human Exploration of the Moon and Mars (NASA-TM-102999, November 1989), pp. 8-7, 8-5.