

How Propulsion Technology Shaped Beyond-Low-Earth-Orbit Exploration Roadmaps

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This paper provides an overview of launch and in-space propulsion systems 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 propulsion systems. The NASA Roadmap was technology-driving and outlined a specific plan for Martian exploration that would use propulsion technologies developed specifically for the leading missions. The ISP was technology-driven and provided a gradual plan for solar system exploration, implementing technologies as they would be presented.

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 to be revisited in 2011 as the nation will enter the post-Space Shuttle era, see the end of the Constellation Program, and address 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 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 propulsion elements and themes like heavy lift launch vehicles, a space shuttle and nuclear propulsion all play critical roles in both plans. This paper will discuss how assumptions about future propulsion technology shaped each roadmap.

II. Overview of Roadmaps

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

1. 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 presented the plan, completed at Marshall Space Flight Center, 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 concludes that man's first step on Mars will be "no less exciting than Neil Armstrong's first step on the moon."^{*}

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 a 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.

2. Mission 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 braked 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 a 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 as 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.

3. Start and End Points

The NASA Roadmap was created with the moon landing fresh in mind. The primary objective of exploration was the search for extraterrestrial life in our solar system, culminating with a manned Mars landing in 1982 and forecasting a more permanent Martian presence by 1990 (a 20 year timeframe). This progression was seen as a natural extension of the lunar landing. In the words of the NASA Roadmap, "Manned planetary flight provides the opportunity to resolve this universal question [i.e., the possible presence of extraterrestrial life] thus capturing

^{*} W. von Braun, Manned Mars Landing Presentation to the Space Task Group (1969) 25.

international interest and cooperation.[†] To this end, the roadmap outlines a very specific mission profile, destination, and technology development path.

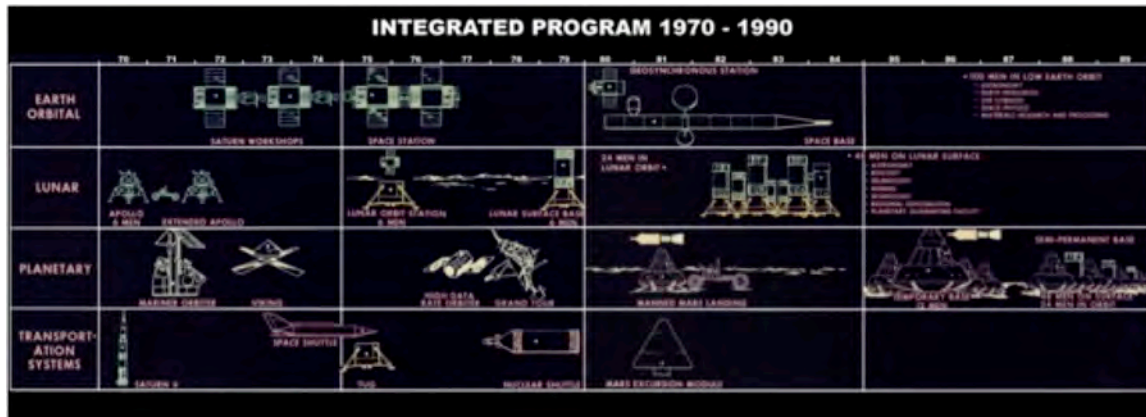


Figure 1. NASA's 1969 Roadmap

The NASA Roadmap had four areas of focus, each with mission-essential milestones.

Earth Orbital

- (1972) Saturn Workshops
- (1975) Space Station
- (1980) Geosynchronous Station
- (1986) 100 Men in LEO

Lunar

- (1972) Extended Apollo
- (1975) Lunar Orbit Station
- (1979) Lunar Surface Base
- (1980) 24 Men in Lunar Orbit
- (1984) 48 Men on Lunar Surface

Planetary

- (1971) Mariner Orbiter
- (1973) Viking
- (1977) High Data Rate Orbiter
- (1976) Grand Tour
- (1981) Manned Mars Landing
- (1985) Temporary Mars Base
- (1988) Semi-Permanent Mars Base

Transportation Systems

- (1970) Saturn V
- (1973) Space Shuttle
- (1975) Tug
- (1978) Nuclear Shuttle
- (1981) Mars Excursion Module

Milestones in each of the four areas laid the foundation for NASA's manned Mars missions. Work in the Earth Orbital area would have qualified both man and systems for the upcoming long-duration missions. Continued Lunar

[†] Von Braun 3.

missions would have provided additional off-Earth operational experience for missions on the Martian surface, and along with the Planetary orbiter missions of the 1970s would have laid the ground work for the manned Planetary missions. For its Transportation Systems, NASA would have continued to fly the Saturn V for its heavy lift capability, including launching space stations and the Mars missions. A space shuttle would have been developed for transfer of people, equipment, and supplies, replacing the Apollo and Saturn IB. These events would have led up to a Mars landing in the early 1980s. The mission would have required development of a new mission module, space shuttle and tug during the 1970s, all of which would have been the beginning of the 1980s systems that would take us to Mars.

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”[‡] 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 CY1988) 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.

B. Rockwell’s Integrated Space Plan (covering years 1989-2100)

1. Historical Context

Rockwell International flourished in the 1980s during the generation of the Integrated Space Plan (ISP). Reaching its pinnacle in the 1990s, the largest NASA and U.S. defense contractor showed ambition with its roadmap as it envisioned enabling crewed interstellar missions by the end of the twenty-first century.

The Rockwell ISP was developed as a very long-range systematic perspective of the space programs of America and the Western World. The integration of several NASA studies formed the ISP, which spans more than 100 years. Such studies include 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); 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. The National Space Policy defined the critical path of the ISP, which mirrors 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 would evolve to self-sustaining bases. These bases would be highly dependent on in-situ resource utilization (ISRU) 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 required further analysis.

[‡] Von Braun 49.

While the ISP drove toward large-scale human habitation of Mars, expansion into the cosmos would begin 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.

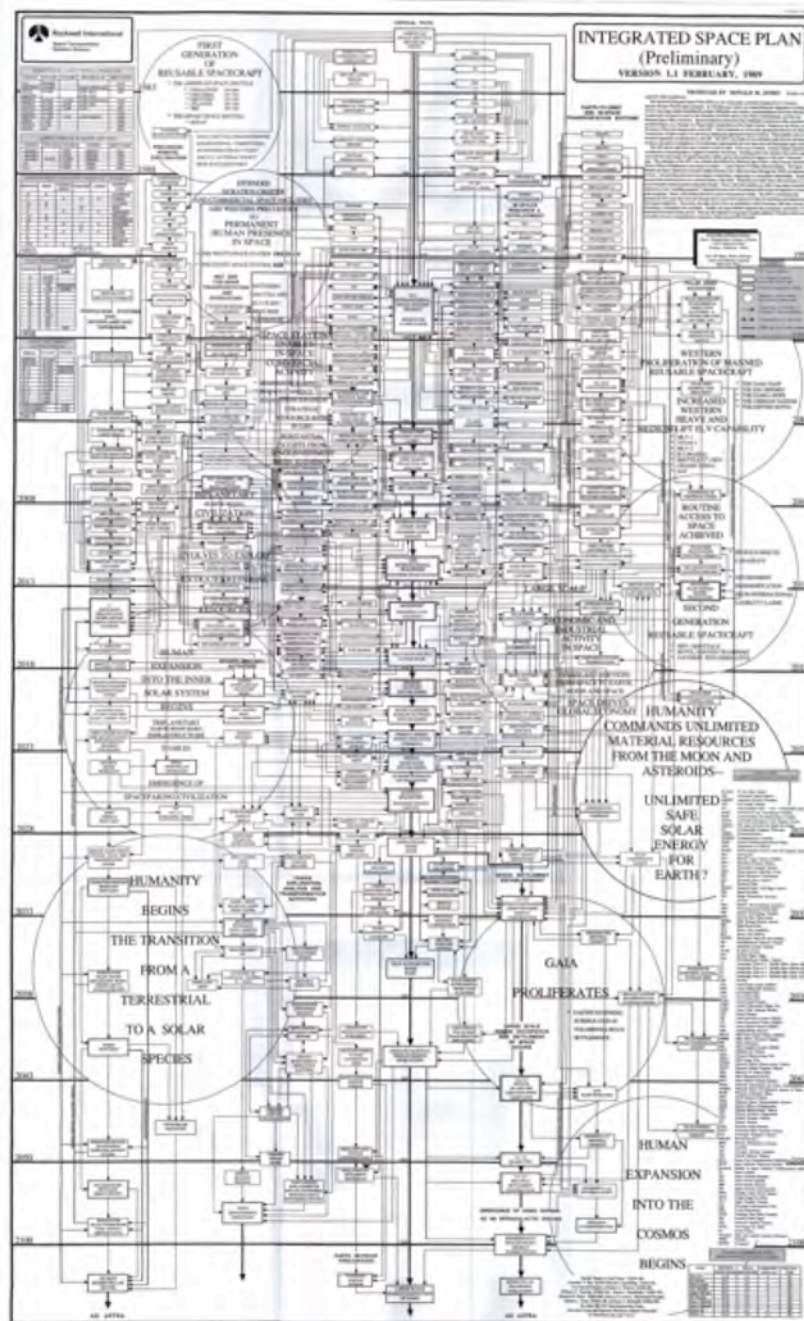


Figure 2. Rockwell's Integrated Space Program

2. Key Factors

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 were offered as a means to more easily implement various in-space transportation nodes, such as GEO cryogenic and hypergolic propellant depots; commercial manned GEO communications platforms; Earth-Moon Lagrange Point 1 (L1) 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.

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

C. Roadmap Contrasts

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. For example, the two roadmaps have very different scientific and technical objectives. The primary objective of the NASA Roadmap was for the search of extraterrestrial life in our solar system, culminating with a manned Mars landing in 1982 and forecasting a more permanent Martian presence by 1990 (a 20 year timeframe). In addition to specific mission/destination objectives, the NASA Roadmap also outlined very specific scientific objectives. These objectives were again related to the potential existence of extraterrestrial life:

- Make geophysical observations
- Collect soil and atmospheric samples
- Study life forms
- Study behavior of terrestrial life forms in Mars environment
- Search for water and usable natural resources

While the ISP had a similar critical path, ending with large-scale human habitation of Mars in 2100, it provides a slightly different (and longer range) method for achieving that goal. The objective of the ISP was not merely to move from spaceflight capabilities of the time (in this case, Shuttle) to a human presence on Mars, but rather to describe the technologies, infrastructure, and missions necessary to transform mankind into a spacefaring

civilization, ready to expand into the cosmos. Unlike the NASA Roadmap, the ISP focused solely on human exploration and expansion with no substantive focus on the search for extraterrestrial life.

The ISP focused on several broad goals and objectives, culminating with the beginning of human exploration into the cosmos. In chronological order, the outlined objectives included:

- Permanent human presence and space
- In-space commercial activity
- Exploitation of extraterrestrial resources
- Routine access to space
- Human expansion into the solar system/spacefaring civilization
- Unlimited material resources from moon, asteroids, and sun
- Replication of Earth's biosphere in voluminous space settlements
- Human expansion into the cosmos

The timescale of the activities involved also varies significantly between the roadmaps. Because of its specific goals and supporting technologies, the NASA Roadmap would accomplish a semi-permanent Martian base and notable off-Earth human presence over the course of 20 years. The Rockwell ISP would only progress to an international lunar base and outpost 20 years into its implementation versus 10 years on the NASA Roadmap. An operational Mars base is not established on the Rockwell ISP until 2029, 40 years into the plan. Part of this difference was driven by the budget assumptions associated with each plan. The NASA Roadmap assumed an Apollo-level budget; the ISP was commercial and concerned with lowest cost.

As expected, both roadmaps built on their current environments with the NASA Roadmap displaying a strong reliance on Apollo-era hardware such as the Saturn V and lunar landing/ascent systems ("Except for the effects of the Martian atmosphere, the landing and return to orbit sequence is analogous to the Apollo lunar landing operation utilizing the Lunar Module[§]") while the ISP used the Space Shuttle as its starting point, with a heavy emphasis on reusable spacecraft.

III. Propulsion Systems' Role in Roadmap Development

For any long-term space exploration strategy, decisions about launch systems and in-space propulsion are critical design drivers. As both the NASA and ISP Roadmaps show, critical propulsion-related functions fall into one of three areas:

- Heavy-lift launch
- Crew launch
- Beyond LEO in-space transport

Each roadmap had a different approach to developing and using each of these capabilities. The vehicles and propulsion technologies that existed at the time of each roadmap's development were the driving influences in the selection of propulsion solutions. In the following sections, the approaches taken for each of the critical functions listed above will be compared across the two roadmaps.

A. Heavy-Lift Launch Capabilities

[§] Von Braun 21.

The NASA Roadmap used the Saturn V and its upgraded derivatives³ as a backbone for Earth to Orbit transport. Without any upgrades, the last operational version of the Saturn V (J Series) was capable of placing 125 tons of cargo in a Low Earth Orbit. This cargo could be placed in an approximate 6.5-meter diameter shroud of a length of

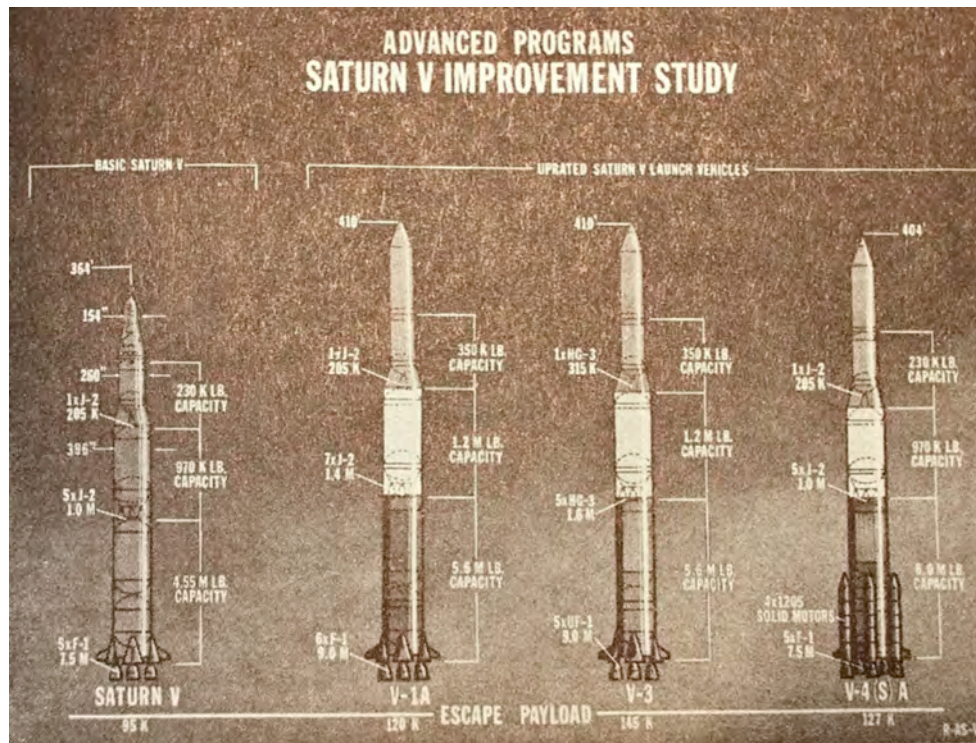


Figure 2. Saturn V and Upgraded Derivatives (image credit: NASA)

20-30** meters long without exceeding the height of the Kennedy Space Center Vertical Assembly Building. Upgrade options to the Saturn V were also being conceptualized at the time that could increase the payload to orbit capability upwards by another 50-75 tons, giving the Saturn system capability to place approximately 200 tons to a LEO orbit or over 100 tons to a GSO orbit. The Apollo team was able to send two people for two days with 100-250 pounds of equipment to the moon with a 125 ton to LEO capability. To accomplish placement of the upgraded infrastructure envisioned in the NASA Roadmap would likely have involved employing several upgrades to the Saturn Heavy-Lift System.

The 1989 Rockwell ISP used the Space Shuttle as the initial critical path for space transportation. This roadmap also included a heavy-lift component as a critical need but was not Saturn based (the Saturn system was shut down in the early 1970s). The Shuttle-C, a conceptual cargo variant of the Space Shuttle, was termed on the ISP as the heavy-lift vehicle for Earth to orbit. In order to minimize infrastructure and operational changes, a separate expendable or reusable uncrewed cargo module ('C') would be launched with the space shuttle stack instead of the orbiter. This system would provide between 60-75 tons of payload to a LEO orbit. The payload would fit inside a module that had a 6.5-8.4 meter diameter and was 20-25 meters in length. The 'C' module would have a propulsion module in its aft end similar to the orbiter that could be recovered. A kickstage would have been necessary to move or place payloads beyond Low Earth Orbit with this type of concept. This system at the time was viewed as the most cost effective approach to heavy-lift since it could be introduced into the Crewed Shuttle Operations flow and used all of the shuttle propulsion stack as well.

Both the NASA and ISP Roadmaps envisioned using the existing infrastructure and upgrading from them in order to expeditiously obtain a heavy-lift capability that could begin placing initial pieces of infrastructure for solar system exploration. The Rockwell ISP also included Department of Defense and international launch vehicles for Earth to orbit transport, whereas the NASA Roadmap was a straight evolution of the Apollo infrastructure to a Mars Mission Capability.

** A. Lawrie, *Saturn*, (2005) 301.

B. Crew Launch

For both roadmaps, a “space shuttle” is a critical component to enable crew launch. Both roadmaps envisioned a routine shuttle crew transport to compliment the heavy-lift transport component.

The Space Shuttle crew launch system that we know today was originally envisioned as a partially reusable or fully reusable crewed system that would enable cost savings by flying more frequently and utilizing aircraft-like operations for land landing. This was in contrast to the previous American crewed-systems, including Mercury, Gemini, and Apollo, that performed water splashdowns, and thus required more infrastructure (ships, etc.) that would be cost-prohibitive for a frequently flying system. This section will compare and contrast the role of the Space Shuttle in the two roadmaps. In short, the NASA Roadmap described the shuttle concept in its infancy (a fully reusable system without significant cargo transport capability that would operate in conjunction with the existing Saturn V heavy lift vehicle), while the ISP described an already operational, post-Challenger Space Shuttle system (partially reusable, crew and cargo transportation requirements combined in a single system).

In terms of historical context, the NASA Roadmap space shuttle would have been developed as a follow-on to and replacement for the Apollo Command and Service Module launched on a Saturn IB. The Space Shuttle would be a small fully reusable or partially reusable system designed to ferry crews and limited cargo to and from destinations in low earth orbit. Cargo would be limited and would not necessarily include “payloads” as defined by the Space Transportation System. The space shuttle could be launched on a fully reusable, crewed first stage or be launched on a heritage Saturn derivative booster. In many ways, the space shuttle as envisioned in the NASA Roadmap would have been similar to the winged version of the Orbital Space Plane, a cancelled program from 2003, with the space shuttle being a larger system capable of launching more crew with more cargo.

The Space Shuttle as it existed in the ISP was the cornerstone of the space exploration architecture. This is not surprising given that the ISP was developed by Rockwell, the prime contractor for the Space Shuttle Orbiter. At this point, the Space Shuttle was already considered a mature system. It had replaced almost all other expendable systems in the United States, although this situation was rapidly changing following the Challenger accident. The ISP Space Shuttle architecture design was a result of steep budget cuts in the 1970s coupled with significant requirements coming from the Air Force in the NASA/USAF partnership. The fully reusable first stage no longer existed and was replaced with strap-on reusable solid rocket boosters and an expendable external tank. The significant performance requirements of the Space Shuttle Main Engine (SSME) had driven costs, which had driven reusability, which had driven robustness and margin, which had further driven performance and cost. With few other launch vehicles remaining operational in the United States, the ISP Space Shuttle also became a payload launcher.

The NASA Roadmap space shuttle would have started flying in the 1970s, replacing the Apollo Command and Service Module for flights to Earth orbital, Saturn-derived Space Stations, such as Skylab and its successors, and later to exploration missions departing Earth orbit. Upgraded over time, it might have first been flown with a Saturn-derived expendable booster, and later flown with a fully reusable first stage. Due to a lack of missions driving cross range requirements, it would have significantly simpler and smaller aerodynamic surfaces.

The ISP Space Shuttle would continue to fly indefinitely. The USAF version of the Space Shuttle would launch out of Vandenberg, with the NASA version continuing to launch out of Kennedy Space Center. The Space Shuttle would eventually be replaced by a more advanced Space Shuttle II after 2003. In addition, it would fly with multiple other reusable systems including HOPE, HERMES, SANGER, HOTOL and NASP and expendable systems such as Advanced Launch System (ALS). While the EELV program can be traced to its roots in ALS, none of these other programs came to fruition. Also planned was the heavy lift cargo version of the Space Shuttle, the Shuttle-C, coming online in the early 1990s. Shuttle-C would have represented the first time the United States had a heavy lift capability since it cancelled Saturn V at the end of the Apollo Program. Shuttle-C would have provided roughly half of the mass to orbit as Saturn V.

The NASA Roadmap space shuttle was intended to compliment the existing fleet of Saturn launch vehicles. Saturn would continue to be updated to launch space stations and exploration missions. The Space Shuttle would be used to frequently and inexpensively ferry crew to and from Earth orbit. It is assumed that there was no military involvement in the development of the Space Shuttle in this scenario, so the requirements would have been similar to the NASA Orbital Space Plane program. The NASA Roadmap Space Shuttle was never intended to be a heavy lifter or an only-lifter.

The ISP Space Shuttle completely replaced the Saturn family as the NASA launch capability, and inherited almost all other United States payloads. The Challenger accident in 1986 reaffirmed the need for expendable launch systems, which would eventually manifest as the EELV Program. The ISP Space Shuttle was developed jointly with the USAF, and so many systems/capabilities on the Space Shuttle were driven by USAF requirements.

C. Beyond-LEO Propulsion

Advanced propulsion has been identified repeatedly as a key for beyond-LEO exploration. Original advanced propulsion was Nuclear Thermal, which saw extensive development work during the 1950s and 60s. No further development work had been done since cancellation of Apollo and budget cuts of the 1970s. As such, the two roadmaps take different approaches to advanced propulsion.

The NASA Roadmap was pursuing Nuclear Thermal Propulsion (NTP) as a baseline for post-Apollo Mars missions. These missions would make use of a “Nuclear Shuttle” that would provide reusable Trans-Mars injection capability, as well as Mars orbital insertion, Trans-Earth injection and potentially Earth-orbit insertion. Hardware for NTP was relatively well understood at the time, and well into ground testing, including hot-fire. Challenging technical issues remained in making the test system into an operational system. Issues included radiation and long-duration materials considerations. Historical indications are that these challenges were surmountable, and that continued development of this system would have resulted in an 800-900 ISP high-thrust propulsion system suitable for both upper stage and in-space propulsion. The NASA Roadmap only covers exploration to Mars. This hardware would not have been suitable for beyond-Mars exploration, which would require propulsion systems with significantly higher specific impulse, but NTP would have been suitable for increasing payload to orbit and providing for getting to Mars and back in the early 1980s.

The ISP did not assume any advanced propulsion capabilities until the turn of the century, with Solar Powered electric propulsion coming online around 2003. Note that this was approximately a twenty-five year delay from advanced propulsion in the NASA Roadmap. However, the ISP assumed a rapid debut of new propulsion technologies throughout the twenty-first century. Solar electric propulsion would be used for a variety of robotic missions in the first decade of the twenty-first century, including Mars aeronomy, comet sample return, and main-belt asteroid exploration. Solar electric propulsion would evolve to Nuclear electric propulsion, which would be used to power an Earth-Mars Electric Cargo Vehicle (ECV) as well as robotic missions to the outer planets. It is assumed that this technology would be used in the Martian Cycling spaceship, which would be launched from L1 in 2018, with a following second cyler launching around 2020. Ion-drive technology and advanced chemical propulsion followed, with antimatter-enriched propellant propulsion coming online by 2030. Very high specific impulse propulsion would have allowed human exploration of the outer solar system to commence in the late 2030s with missions to the Jovian system. Fusion propulsion availability by 2040 would have allowed human exploration of the Saturnian system by 2050. Availability of nuclear-pulsed propulsion in the 2050s would have allowed exploration of the Uranus/Neptune/Pluto systems by 2060, and encouraged human travel beyond the Sol system after 2100. Note that arguably one of the highest TRL systems (nuclear-pulsed propulsion) is not developed in the ISP until the 2050s. This is nearly one hundred years after the start of its initial development during Project Orion in the 1950s and well after much more advanced systems involving fusion and antimatter occur in the ISP, and may have to do with the idea of such a system being more palatable if used in deep space and not with the proximity of the Earth’s surface.

Conclusions

Both the 1969 NASA Roadmap and the Rockwell ISP plan for the use of similar propulsive technologies with different focuses and at different times. For heavy-lift capabilities, the ISP proposed the Space Shuttle derivative for cargo, whereas the NASA Roadmap would have leveraged existing Saturn V and its derivatives and used existing KSC facilities and upgrading systems. While both roadmaps required the use of a space shuttle for routine crew launch, the NASA Roadmap only proposed a shuttle as a crew compliment to heavy-lift capabilities as opposed to the ISP’s critical path Space Shuttle that would lift both crew and cargo. NASA’s shuttle concept was in its earliest stages and would have been developed as a follow on to Apollo programs in order to compliment the Saturn fleet with its first launches on a Saturn derived booster. It was never intended for heavy-lift as in the ISP. Performance, cost, reusability, and design requirements drove the ISP’s development. Because of those driving factors, in addition to Rockwell’s role in the shuttle of the 1980s, the company made logical use of its operational shuttle system in mapping out the future of human space exploration and the Space Shuttle became its crew and cargo launch vehicle. NASA’s Roadmap proposed NTP for travel to Mars, a technology in development at the time that would have been suitable for the intended missions to Mars but not for travel beyond. The ISP’s beyond-LEO plans included significant travel after the Mars missions, but planned for later development of new propulsion technologies.

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. The NASA Roadmap had specific goals and an associated timeline that required the development of mission-specific technologies. The plan relied on advanced propulsion and required development of a nuclear shuttle in just eight years. The Roadmap was technology-driving; with specific goals and dates it detailed the necessary technologies and timeline for the nation's next steps in human space exploration. While NASA's aggressive schedule drove the development of propulsion technologies, it was these focused propulsive elements that drove the missions forward, and therefore drove the plan forward. The propulsion technologies to establish off-Earth human presence did not exist at the beginning of the plan, but their role in the plan necessitated their development. NASA's Roadmap was part of a coordinated national exploration program. Rockwell, a commercial entity, emphasized reusability with its Space Shuttle derivations, but did not include budget assumptions with its ISP. The ISP, with its broader goals and timeline, was not as heavily dependent upon advanced propulsion early in the plan and assumed new technologies would present themselves rather than requiring their development by a certain time. The ISP, unlike the NASA Roadmap, was technology-driven; assuming new technologies would be presented in the future and finding uses for them to further human space exploration. 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.

Acknowledgments

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