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Lessons from the History of Space Nuclear Development Projects (Presentation)

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LESSONS FROM THE HISTORY OF SPACE NUCLEAR DEVELOPMENT PROJECTS

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Since the beginning of the nuclear and space ages, the United States government has devoted considerable resources to develop technologies that would enable American technological and military superiority in space. The United States began developing nuclear systems for space applications in the years following the World War II. Efforts ranged from the successfully-deployed radioisotope power systems (RPS) enabling missions currently in the outer solar system to fission power systems with yet unrealized potential to unlock new levels of power in space to several failed development efforts of fission systems for space power and propulsion. As the United States government initiates new efforts to develop space nuclear power and propulsion (SNPP) systems for space, it can and should learn from these past efforts. This paper introduces previous SNPP development efforts, with the goal of understanding how those experiences can benefit future development efforts. The first objective is a simple understanding of what we have attempted before, including what has been accomplished and can be built upon. This paper further attempts to describe why these projects failed in an effort to create a more sustainable space technology development environment.

INTRODUCTION

Since the beginning of the nuclear and space ages, the United States government has devoted considerable resources to develop technologies that would enable American technological and military superiority in space. The United States began developing nuclear systems for space applications in the years following World War II. Efforts ranged from the successfully-deployed radioisotope power systems (RPS) enabling missions currently in the outer solar system, to fission power systems with yet unrealized potential to unlock new levels of power in space to several failed development efforts of fission systems for space power and propulsion (Table 1).* As the United States government initiates new efforts to develop space nuclear power and propulsion (SNPP) systems for space, it can and should learn from these past efforts.

This issue brief introduces previous SNPP development efforts, with the goal of understanding how those experiences can benefit future development efforts. The first objective is a first order understanding of what we have attempted before, including what has been accomplished and can be built upon. We also explore why these projects failed in an effort to create a more sustainable space technology development environment.

Name	Years	Approx. Funding [1]†	Today Dollars
SNAP	1955–1973	$850 M [2]	$5.2 B
NERVA	1958-1972	$1.4 B [3]	$8.5 B
SP-100	1982–1994	$420 M ‡	$826 M
SNTP	1987-1992	$139 M [4]	$251 M
JIMO-Prometheus	2003–2005	$463 M	$612 M

Table 1. Previous Space Nuclear Fission Development Programs.

EARLY SNPP DEVELOPMENTS UNDER THE ATOMIC ENERGY COMMISSION

* This table only includes reactors developed within the United States. Reactors such as Topaz II developed abroad are not included in this analysis.

† Then year spending taken from p.9 of: Johns Hopkins Applied Physics Laboratory. 2015. "Nuclear Power Assessment Study: Final Report".

‡ Other sources estimate total program costs could be closer to $1 billion. Demuth, S. 2003. "SP100 Space Reactor Design". Los Alamos National Lab.

EARLY SNPP DEVELOPMENTS UNDER THE ATOMIC ENERGY COMMISSION

Systems for Nuclear Auxiliary Power

Early breakthroughs demonstrating the potential for radioisotope decay in generating electricity, pushed the newly established Atomic Energy Commission (AEC) to develop programs to research the potential of RPS systems for space applications. Early satellites were powered by solar cells. The solar cells used on many early satellites became inefficient, damaged by excess heat energy. Solar power-based systems also struggle in lunar nights or in deep space where there is no sunlight or a corrosive environment [5]. Increasing the power requirements of satellites meant larger solar-cell arrays were needed, complicating launch and assembly processes. RPS provided power comparable with solar arrays, but were able to power the satellites through darkness, deep space, and radiation belts [6]. The size of the units and their long lifetimes garnered the interest of the defense community for military reconnaissance [6]. Encouraged by early innovations showing the potential of atomic energy for space applications led to the Systems for Nuclear Auxiliary Power (SNAP) program within the newly established AEC. SNAP consisted of two system types developed in parallel tracks both managed by the AEC. Odd-numbered SNAP programs developed RPS, and even-numbered SNAP programs focused on fission power systems.

Odd-Numbered SNAP Systems

The first SNAP program worked to use the heat from radioisotope decay and convert it to electrical power, this contract went out to the nuclear division of the Martin Company [7]. The Martin Company developed SNAP 1, using the heat from cerium-144 radioisotope decay to boil water spinning a turbine that generated 500 watts [6]. SNAP 1 demonstrated the feasibility of a turbine concept but was never set into space. Instead, SNAP replaced the turbine power system with more efficient and longer lasting static thermoelectric power conversion systems [7]. The program achieved many firsts for nuclear power in space. The SNAP 3B system provided electrical and thermal power to the Navy’s transit satellite in 1961, the first use of nuclear power in space [7]. SNAP 19B launched in a NASA weather satellite, in 1969, became the first civilian space nuclear system [7][8]. SNAP 27 was used by NASA to power the Apollo Lunar Surface Experiment Packages from 1969–1977 [7].[§]

Even-Numbered SNAP Systems

The first SNAP fission power contract went to Atomics International Division of North American Aviation Inc., which ultimately aimed to develop a fission reactor capable of producing 3 kW electric (kWe) [7]. SNAP 2 technology would be integrated with newer technology to create SNAP 10-A [8].[**] SNAP 10-A, also referred to as SNAPSHOT, was a fission power system made to produce more than 500 W_e of power for a year [8]. Mission demand for fission power systems came and went. The Air Force program requirements that initiated SNAP 10-A development were lost in 1963, when budget cuts shifted Air Force mission requirements. The Joint Committee on Atomic Energy continued SNAP 10-A hoping that its 1965 technology demonstration would promote future demand [9]. The SNAP 10-A demonstration was the first fission power system tested in space, showing the feasibility of remotely operating a liquid-metal-cooled nuclear reactor [10]. Although a voltage failure caused the system to shut down after 43 days (subsequently the vehicle broke up, likely as a result of collision) [11], a twin reactor on the ground successfully operated at over the 500 W_e threshold for over a year [8].

Nuclear Engine for Rocket Vehicle Applications

Since the end of World War II, Nuclear Thermal Propulsion (NTP) has been seen as an enabling technology for civil and military activities in space [12]. With an ISP 2–3 times higher than chemical propellants, along with high power density, NTP had the potential to enable missions to Mars or work as a tug quickly moving satellites from LEO to lunar orbits. As early as 1947, the Air Force researched nuclear propulsion for ICBMs [12]. By 1958, the newly-founded NASA incorporated Nuclear Engine for Rocket Vehicle Applications (NERVA) into its space exploration program.

The NERVA program was managed under the Space Nuclear Propulsion Office (SNPO) established when NASA and AEC signed an MOU in August of 1960 [7]. SNPO was jointly managed by both NASA and the AEC; the director of the office was a NASA employee, and the deputy was from AEC. AEC funded the nuclear components, while NASA provided funding for non-nuclear components.

NERVA Phase 1 began at Los Alamos Scientific Laboratory (LASL). LASL built KIWI reactors to test the feasibility of fuel elements at high temperatures over a sustained period. Based on the prototyping done with KIWI, Aerojet and Westinghouse developed a Nuclear Rocket Experimental Engine System Test (NRX/EST). In 1966, subsystem testing was completed, and NRX

[§] A list of all SNPP systems operated in space can be found in Appendix A.

[**] There was also a SNAP 4, 6, and 8. SNAP 4 and 6 were designed for underwater applications; while SNAP 8 designed for space using a mercury-based Rankine system. For more information see: Bennett. G.L., E.W. Johnson., 2003. “First Flights: Nuclear Power to Advance Space Exploration”.

was operated at full power for two hours and 28 minutes [13]. The NERVA program continued to test and develop engine capabilities of nuclear powered systems. In 1969, SNPO simulated system flight capabilities and functionality operating the engine remotely for 115 minutes [13]. Over a period of almost 20 years, the NERVA program demonstrated a process for ground testing NTP systems, demonstrating 28 full power reactors, ranging in size from 300 MW to 200,000 MW [14].

End of the SNAP and NERVA Programs

At the time the SNAP and NERVA programs were underway, alternatives to SNPP such as solar power and other non-nuclear sources also continued to evolve and become more competitive. Both SNAP and NERVA research under the Nixon Administration was largely defunded [2]. The United States Office of Management and Budget was committed to reducing unnecessary federal expenses within NASA's budget and a NERVA reactor without a mission or even a shuttle to carry the reactor was seen as unnecessary and canceled [15]. SNAP fission programs faced similar challenges and struggled to sustain mission support for any of their programs [16]. In 1973, during congressional joint hearings, the Director of Space Nuclear Systems Division at AEC said: "…distant payoffs did not warrant continued funding of high powered nuclear propulsion and reactor power systems" [7].

Apollo missions would continue to utilize RPS technology pioneered in the SNAP program, but no new missions for fission programs would be developed. After SNAP and NERVA were terminated "most of the 1970's was devoted to simply keeping the [space fission] technology alive" [7].

Soon after the end of SNAP and NERVA the AEC was abolished in 1974, its functions were assigned to two new agencies: the Nuclear Regulatory Commission (NRC) and the Energy Research and Development Agency (now the Department of Energy) that would resume SNPP development.

MORE RECENT DEVELOPMENTS IN SNPP

Progress in RPS Technologies

United States Space development efforts have sustained the use of RPS systems first developed during the NERVA program, continuing the use of radioisotope thermoelectric generators (RTGs) and Radioisotope Heater Units (RHU's) as a part of their missions.†† The United States has launched 46 different RTG's providing power for missions including Pioneers 10/11, Voyagers 1/2, Galileo, Ulysses, Cassini, New Horizons, and the Mars Curiosity Rover [2][7][17]. The technology used in these RPS systems has evolved continually, and the United States has successfully developed these systems across multiple missions, administrations, and decades. Unlike RPS programs, fission power and propulsion programs struggled to develop and use nuclear reactors in space. Because RPS technology has successfully sustained demand since the SNAP program, what follows in this brief will focus primarily on fission power and propulsion development programs.‡‡

SP-100 Program

In 1979, the DOE funded a 5 year $2 million dollar a year study for LASL to develop a space reactor concept capable of producing 10-100 kW_e [7]. DOE worked with NASA and DOD to coordinate government research efforts. The initial DOE program was named Space Power Advanced Reactor (SPAR) program but was subsequently renamed SP-100 when OMB funding constraints on DOE forced the program into NASA and DOD budgets [7]. The SP-100 space nuclear reactor was designed to be an orbital power supply for DOD's Strategic Defense Initiative (SDI) [18]. NASA aimed to use the system as a Nuclear Electric Propulsion (NEP) with potential to be a surface power station on Mars [18]. Program development began in 1983, jointly sponsored by DOD's Defense Advanced Research Projects Agency (DARPA), DOE's Office of Nuclear Energy (DOE-NE), and NASA's Office of Aeronautics and Space Technology. A multi-agency steering committee was developed to oversee project development. The steering committee oversaw actions of the program director, who reported to the Strategic Defense Initiative Organization (SDIO) director [19].

The separate demands for reactors forced the program to develop modular components and subsystems [18][19]. The time and money spent developing a system with multiple high levels of functionality and modularity caused delays and cost overruns. At almost ten years into development, the program was thirteen years behind schedule, and cost estimates for component testing alone had increased from ~$500 Million to over $2 billion [20]. Furthermore, the technology developed in the SP-100

†† See Appendix for complete list of RTG's and Fission systems used in space.

‡‡ For details on the evolution of RPS see (McNutt & Ostdeik, 2015) [1].

program failed to develop a system capable of producing the 300 kW originally proposed, and by 1992, power goals had dropped to 5–40 kW [20]. The DOD canceled SP-100 in 1994, because there was no mission pull for the more expensive and lower power system [19][20]. Without the support of the DOD and facing programmatic challenges, support for NASA's missions also began to dissipate and the program was discontinued in 1995.

Project Timberwind and Space Nuclear Thermal Propulsion (SNTP)

In 1982 Grumman pursued an innovative gas cooled reactor concept invented by Dr. James Powell of Brookhaven National Lab (BNL). Grumman worked with B&W and Aerojet using their respective knowledge of reactor fuels and launch components [3]. By 1987, SDIO contracted the Grumman team to continue research on their space-based Particle Bed Reactor (PBR) to serve as a boost phase of an intercept vehicle to disable enemy missiles. Under the SDIO contract, the PBR research was conducted at Sandia National Lab (SNL) and BNL. Within two years, the SDIO program spent $131 Million to conduct preliminary design reviews and PBR key component testing [3].

SDIO terminated project Timberwind in 1992, to focus on ground-based intercept systems. That same year, a Senate inquiry led to a Defense Science Board review. Reviewers deemed nuclear propulsion a critical technology for defense application and the project was picked up by the Air Force, changing the project's name to the Space Nuclear Thermal Propulsion (SNTP) program [3]. Presumed peaceful co-existence between the United States and Russia changed the direction of the program objectives from interceptor to lift and rocket capabilities. It was estimated that PBR would increase lift capabilities by 200-400% over chemical propellants [14]. SNTP was not designed for one single mission alone but could be useful for orbit transfers and maneuvers or upper stage launch vehicles.

The Air Force partnered with NASA, which at the time was interested in restarting NTP system development for Mars exploration. The Air Force and NASA looked to build test facilities at Idaho National Lab (INL), Nevada Test Site, or at underground facilities. The DOD programs faced several newer challenges not faced by the AEC-led ones (i.e., SNAP and NERVA). The regulations around testing an NTP had changed since the NERVA program such that the full nuclear system could no longer be tested at NERVA facilities because of the high power densities in the PBR. The new facility also needed to be compliant with stringent safety and environmental standards, standards not relevant during NERVA testing. The SNTP program was cancelled before significant funding could be put towards constructing an NTP test site. In President Clinton's 1993 inauguration speech, he emphasized constraints on federal spending, including "eliminating programs that are no longer needed, such as nuclear power research and development" [7].

JIMO-Prometheus

In 2002, NASA's Nuclear System's Initiative funded the Jupiter Icey Moons Obiter (JIMO) project to enable a scientific exploration mission to the icy moons of Jupiter. In 2003, the Congress funded development of the JIMO NEP reactor under NASA's Office of Space Science that renamed the project Prometheus [21]. Developing the JIMO NEP required expertise that could not be fulfilled by one entity alone. DOE had the authority to license the reactor along with experience using reactors; NASA's Jet Propulsion Laboratory (JPL) had the deep space expertise; NASA's Glenn Research Center and JPL had non-reactor technology development experience; and industry had expertise in large spacecraft development [22]. At the request of the Secretary of Energy, DOE Naval Reactors (DOE-NR) was given the responsibility for the development of Prometheus' space nuclear reactors [22]. In response, the DOE-NR passed responsibility to the newly established Naval Reactor Prime Contract Team to develop the reactors [21]. Developing space reactors within the Navy's Naval Reactors program presented challenges as space nuclear reactors required new designs and capabilities.[§§]

Separate management interactions were costly, and delayed the decision-making process [21]. During phase A of the study, the project spent $128.5 million on mission planning, analysis of alternatives, design, subsystem analyses, conferences, and experimentations [21]. The program grew quickly, and responsibilities became distorted among the different organizations. The JIMO program further tried to address design and subsystem challenges concurrently, drying up funds before the program could successfully test critical components of the NEP system [21].

By 2004, Prometheus had a 5-year budget of $3 billion, surpassing a $1 billion estimate from 2002 [7]. Concerned about the budget, Senators John McCain and Daniel Inouye called for an audit of the Prometheus program. The congressional budget office estimated that the lifetime cost of the system would be $10 billion [7]. Following an analysis of alternatives and considering budgetary restraints, NASA identified return to flight,

[§§] Space nuclear reactors do differ from naval reactors in some substantial ways, most importantly NR had to determine how to get rid of waste heat from the reactors. For submarines and aircraft carriers, oceans help the reactor with excess heat, this process does not apply to space.[19]

Program Name	Furthest Progress Made	Reason for Termination
SNAP RPS Systems	Systems used on 18 different missions	N/A
SNAP Fission System	Flight demonstration (failure after 43 days)	Lack of mission pull
NERVA	28 full system ground tests	Lack of mission pull
SP-100	Reactor design and development	Cost overruns, and insufficient mission pull
SNTP	NTP design with 900 Isp and 20 to 1 thrust to weight ratio	Lack of mission pull, and seen as expensive
JIMO-Prometheus	Systems analysis	Cost overruns before any substantial technology was developed or tested

Table 2. Programs and Rationales for Termination

the International Space Station, and crewed exploration vehicles as more pressing NASA missions [21]. The project was discontinued in October 2005.

SUMMARY AND RECOMMENDATIONS

Despite several starts, fission power and propulsion systems have failed to achieve even flight demonstration since the 1965 flight of the SNAP 10-A. Many of the failed SNPP programs lacked a clear or immediate need for their use. Even SNAP 10-A was flown without a use. NERVA was cancelled because NTP was not considered a critical technology for going to the Moon, and Mars was not an immediate concern. Due to cost overruns and scheduling delays by the time the SP-100 system could have been tested, the threat posed by the Soviet Union had subsided, the lower power capabilities did not suit the intended system requirements, and other technology was seen as being more effective. SNTP was terminated due to budget concerns. SNPP programs represent a large investment into technology for future missions in space. Without mission pull, these programs became political liabilities and were cut. These reasons for fission reactor programs' failure, summarized in Table 2, have followed a vicious cycle: power and propulsion programs through United States history have not been able to demonstrate capabilities because they have lacked mission pull. However, researchers have also argued that the reason they lacked mission pull was because previous missions were cancelled before they were able to demonstrate their technical capabilities (Figure 1) [16].

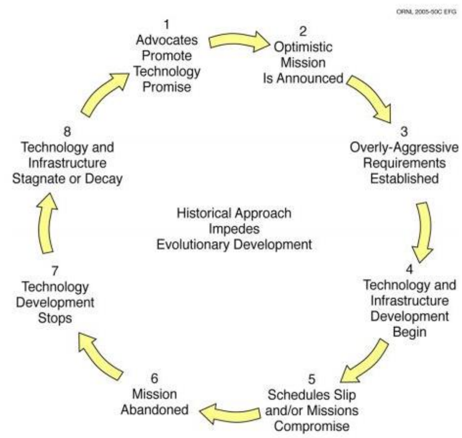

Fig. 1: Space fission power and propulsion development cycle as illustrated by (Greene, 2005) [17].

The United States' experiences developing fission systems and RPS systems have been very different. Some lessons can be drawn from the successes of RPS development, in particular:

1. Allowing the technology to evolve over time, while increasing performance incrementally as greater confidence is gained by flying systems;
2. Focusing on simplicity and technology availability over performance to minimize development cost, risk, and schedule;
3. Exercising of the national infrastructure to ensure the system can be designed, manufactured, tested and launched;
4. Ensuring initial utilization of the system in a non-mission critical application to demonstrate its function and utility; and
5. Once the system is proven, gradually introducing improvements that make the system more beneficial for a greater range of missions.

APPENDIX

Power Source	**Spacecraft**	**Launch Year**	**Average Power (We)**	**Total Initial Spacecraft Power (We)**
SNAP-3	TRANSIT-4A	1961	2.7	2.7
SNAP-3	TRANSIT-4B	1961	2.7	2.7
SNAP-9	TRANSIT-5BN-1	1963	25.2	25.2
SNAP-9	TRANSIT-5BN-2	1963	26.8	26.8
SNAP-9	TRANSIT-5BN-3	1964	25	25
SNAP 10-A	SNAPSHOT	1965	500	500
SNAP-19	NIMBUS B-1	1968	28	56
SNAP-19	NIMBUS III	1969	28.2	56.4
SNAP-27	APOLLO 12	1969	73.6	73.6
SNAP-27	APOLLO 13	1970	73	73
SNAP-27	APOLLO 14	1971	72.5	72.5
SNAP-27	APOLLO 15	1971	74.7	74.7
SNAP-19	PIONEER 10	1972	40.7	162.8
SNAP-27	APOLLO 16	1972	70.9	70.9
TRANSIT-RTG	TRAID-01-1X	1972	35.6	35.6
SNAP-27	APOLLO 17	1972	75.4	75.4
SNAP-19	PIONEER 11	1973	39.9	159.6
SNAP-19	VIKING 1	1975	42.3	84.6
SNAP-19	VIKING 2	1975	43.1	86.2
MHW-RTG	LES 8	1976	153.7	307.4
MHW-RTG	LES 9	1976	154.2	308.4
MHW-RTG	VOYAGER 2	1977	159.2	477.6
MHW-RTG	VOYAGER 1	1977	156.7	470.1
GPHS-RTG	Galileo	1989	288.4	576.8
GPHS-RTG	Ulysses	1990	283	283
GPHS-RTG	Cassini	1997	295.7	887
GPHS-RTG	New Horizons	2006	249.6	249.6
MMRTG	Curiosity	2011	113	113
MMRTG[23]	Perseverance	2020	~110	~110

Table 3. Listing of Nuclear Systems Launched by the United States into Space.

Note: Information within this table was compiled by (INL, 2015, P.184-185).[7]

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ABBREVIATIONS

AEC:	Atomic Energy Commission
BNL:	Brookhaven National Lab
DARPA:	Defense Advanced Research Projects Agency
DOE-NE:	Department of Energy Office of Nuclear Energy
DOE-NR:	Department of Energy Office of Naval Reactors
IDA:	Institute for Defense Analyses
INL:	Idaho National Lab
JIMO:	Jupiter Icey Moons Orbiter
JPL:	Jet Propulsion Lab
kWe:	Kilowatts electric
LASL:	Los Alamos Scientific Laboratory
NEP:	Nuclear Electric Propulsion
NERVA:	Nuclear Engine for Rocket Vehicle Applications

NRC: Nuclear Regulatory Commission
NRX/EST: Nuclear Rocket Experimental Engine System Test
NTP: Nuclear Thermal Propulsion
PBR : Particle Bed Reactor
RPS : Radioisotope Power Systems
RHU: Radioisotope Heater Unit
RTG: Radioisotope Thermoelectric Generator
SDI: Strategic Defense Initiative
SDIO: Strategic Defense Initiative Organization
SNAP: Systems for Nuclear Auxiliary Power
SNL: Sandia National Lab
SNPO: Space Nuclear Propulsion Office
SNPP: Space Nuclear Power and Propulsion
SNTP: Space Nuclear Thermal Propulsion
STPI: Science and Technology Policy Institute

The History of United States Space Nuclear Development Projects

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Presentation Overview

1. Introduction to Space Nuclear Power and Propulsion
2. Historical Progress
3. Challenges
4. Cross-cutting themes
5. Paths Forward

Why Space Nuclear Power and Propulsion?

Power: High density power source even through darkness, deep space, and radiation belts

1. Radioisotope Power Systems (RPS)
2. Fission Power Systems (FPS)

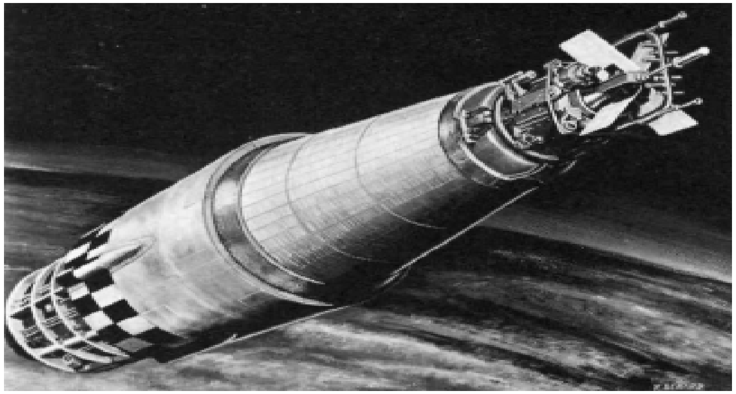
Propulsion: Higher ISP compared with Chemical

1. Nuclear Electric Propulsion (NEP)
2. Nuclear Thermal Propulsion (NTP)

The Early Success: SNAP and NERVA

SNAP (1955-73)

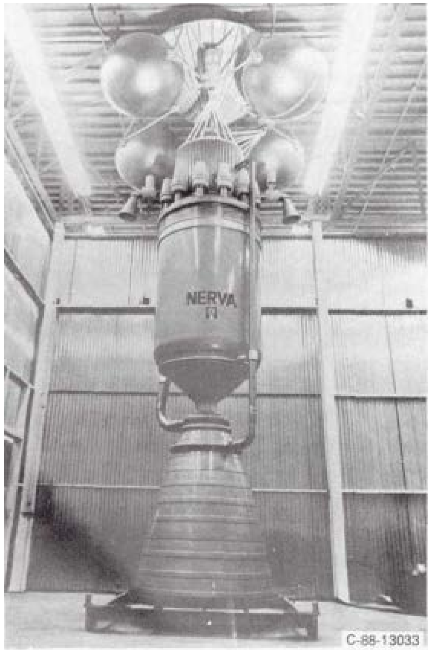
- SNAP 3B: Powered Navy transit satellite (first space nuclear system)
- SNAP 27: Used by NASA to power the Apollo Lunar Surface Experiment Packages from 1969–1977
- SNAP 10-A: First fission system in space



Source: (Corliss, 1971)

NERVA (1958-72)

- Demonstrated process for ground testing NTP systems
- 28 full power demonstrations
- sizes from 300 MW to 200,000 MW



Source: (Robbins & Finger, 1991)

Other Attempts at Space Nuclear Power and Propulsion

- SP-100 (1982-1994)
  - General purpose space reactor
  - DOE, NASA, DOD
- SNTP (1987-1992)
  - NTP for DOD missions
  - DOD
- JIMO-Prometheus (2003-2005)
  - NEP for scientific exploration of Jupiter's Moons
  - NASA, DOE


Illustration of Prometheus' Nuclear Propulsion
Source: NASA-JPL, 2004

Reasons for Cancelling

Table 1. Previous Space Nuclear Fission Development Programs

Name	Goal(s)	Lead Agency	Years	Approx. Funding*	Today Dollars
SNAP	Development of compact, light-weight, reliable atomic electric devices (both fission reactor and radioisotope systems) for space	AEC	1955–1973	$850 M**	$5.2 B
NERVA	Development of NTP Systems	AEC and NASA	1958-1972	$1.4 B***	$8.5 B
SP-100	General purpose space reactor from 5–1,000 kW_e	NASA and DOD	1982–1994	$420 M****	$826 M
SNTP	Particle Bed Reactor (PBR) 1,000 kWe	DOD	1987-1992	$139 M*****	$251 M
JIMO-Prometheus	Build a 200-kWe reactor for an ion thruster to Jupiter's icy moons	NASA and DOE	2003–2005	$463 M	$612 M

* Then year dollars. Taken from p.9 of: Johns Hopkins Applied Physics Laboratory. 2015. *Nuclear Power Assessment Study: Final Report.*

** Source: Voss, S.S., 1984. "SNAP Reactor Overview". *Air Force Weapons Laboratory.*

*** Source: Haslett. R.A., 1995. "Space Nuclear Thermal Propulsion Program Final Report". *Phillips Laboratory*.

**** Other sources estimate total program costs could be closer to $1 billion. Demuth, S. 2003. "SP100 Space Reactor Design". Los Alamos National Lab.

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"…distant payoffs did not warrant continued funding of high powered nuclear propulsion and reactor power systems."
– (Director of Space Nuclear Systems Division at AEC, 1973)

Reasons for Cancelling (Cont.)

Table 2. Previous Space Nuclear Programs and Reason for Termination

Program Name	Furthest Progress Made	Reason for Termination
SNAP RPS Systems	Systems used on 18 different missions	N/A
SNAP Fission System	Flight demonstration (failure after 43 days)	Lack of mission pull
NERVA	28 full system ground tests	Lack of mission pull
SP-100	Reactor design and development	Cost overruns, and insufficient mission pull
SNTP	NTP design with 900 Isp and 20 to 1 thrust to weight ratio	Lack of mission pull, and seen as expensive
JIMO-Prometheus	Systems analysis	Cost overruns before any substantial technology was developed or tested

Challenges not discussed: fuel type and geopolitics; safety and environmental reviews; and fuel supply

Fission's Path Forward

1. Mission must be compelling
2. Mission focus is critical
3. Limit technical risk impacts early in program
4. Focus on incremental development

Thank you for listening!

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14. ABSTRACT
This paper will be presented at the 71st International Astronautical Congress: The CyberSpace Edition, October 12-14, 2020. Since the beginning of the nuclear and space ages, the United States government has devoted considerable resources to develop technologies that would enable American technological and military superiority in space. The United States began developing nuclear systems for space applications in the years following the World War II. Efforts ranged from the successfully-deployed radioisotope power systems (RPS) enabling missions currently in the outer solar system to fission power systems with yet unrealized potential to unlock new levels of power in space to several failed development efforts of fission systems for space power and propulsion. As the United States government initiates new efforts to develop space nuclear power and propulsion (SNPP) systems for space, it can and should learn from these past efforts. This paper introduces previous SNPP development efforts, with the goal of understanding how those experiences can benefit future development efforts. The first objective is a simple understanding of what we have attempted before, including what has been accomplished and can be built upon. This paper further attempts to describe why these projects failed in an effort to create a more sustainable space technology development environment.

15. SUBJECT TERMS
history; space nuclear power and propulsion (SNPP); space technology development

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