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Powering Space Exploration: U.S. Space Nuclear Power, Public Perceptions, and Outer Planetary Probes

Roger D. Launius*
Smithsonian Institution, Washington, DC 20650

I. Abstract

Since the dawn of the space age more than fifty years ago, the United States has pursued a variety of methods for delivering electrical power to spacecraft in flight. Nuclear power systems are the only ones that have been found acceptable for deep space missions. While these technological systems made possible a myriad of accomplishments in space, especially the successful flights to the outer planets, the details of space nuclear power generation is virtually unknown to even the most knowledgeable observers. What is known, furthermore, is often limited to the often incomplete reporting of controversies over the propriety of using nuclear systems for space power. This essay traces the development of this technology from its origins in the 1960s to the present. It describes the evolution of the systems involved and the decision-making process whereby NASA chose to adopt one approach over another. Finally, it analyzes the public debate over the employment of these technologies for spaceflight.

II. Satellite Power Systems in Summary

Flying in space requires reliable, uninterrupted, stable electrical power, not only for engines to maneuver and navigate but for systems on spacecraft performing a range of functions.[1] One of the critical components of any satellite either in Earth orbit or dispatched elsewhere is the power system that allows the operation of its many systems. There are only four methods of providing the electrical power needed for spacecraft, all of them with positives and negatives. The first method, and the one used on the first spacecraft launched into orbit, was batteries. Their wattage was limited, but even more limited was their longevity. With a few weeks they always ran down and the spacecraft's systems no longer operated. For example, about three weeks after the launch of Sputnik 1 on October 4, 1957, its batteries ran down and it ceased to broadcast telemetry although it remained in orbit for about ninety days after launch.[2] Second, to help resolve that problem NASA pioneered in the 1960s fuel cell technology, which generated more electricity for the size of the cell and had a longer effective life. Even so, fuel cells have an effective life of less than two months.[3] Of course, this may change in the future as NASA pursues more efficient fuel cells for its Constellation program that could have remarkably long lives.[4] Third, photovoltaic solar cells emerged in the 1960s as a useful alternative to batteries and fuel cells. They have a long life measured in years rather than weeks or months, and with additional refinement they have become the critical power generation technology for most spacecraft.[5] They have one important drawback; they require the Sun's powerful light source to be effective. For spacecraft traveling into deep space beyond Mars, where the Sun becomes much less intense, photovoltaic systems up to this point have proven insufficient. This may change in the future as new technologies increase the efficiency of energy collection and power management but past and present capabilities have not allowed their use.[6] Accordingly, when requirements are for short mission times or do not require high power, chemical and/or solar energy may be used effectively to make electricity. But for the generation of high power levels over longer periods of time, especially farther away from the Sun, nuclear energy has thus far been the only way to satisfy mission requirements.

For this reason, as well as others of a more sublime nature, many spacecraft designers have adopted nuclear power technology as a means of powering spacecraft on long deep space missions. As NASA's chief of its nuclear electric power programs remarked in 1962:

> Basically, radioisotopes are of interest because they represent a compact source of power. The energy available in radioisotopes is many orders of magnitude larger that that available in batteries, and thus they constitute a unique, concentrated energy source that may be used for space purposes if design requirements are met. Radioisotope power is inherently reliable. It cannot be turned on or off. There are no moving parts of

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* Senior Curator, Division of Space History, National Air and Space Museum, Smithsonian Institution, P.O. Box 37012, NASM Room 3550, MRC 311, Washington, DC 20013-7012, Voice: 202-633-2428, Fax: 202-786-2947, Cellular: 202-528-3278, E-Mail: launiusr@si.edu, AIAA Associate Member.

> oriented arrays. It will provide heat energy in accordance with the fixed laws of radioactive decay. This heat is absorbed in a device that converts the heat directly into electricity.[7]

There are several types of nuclear power that could be employed, everything from small reactors to nuclear heaters to the dominant technology of radioisotope thermoelectric generators (RTG). In those small space nuclear reactors, energy could be generated through controlled fission of uranium. Creating heat through this process, it is then used to power either a thermoelectric or a dynamic turbine or alternator conversion system. While excess heat would be dissipated through a radiator, electricity generated through this process served to power the spacecraft. These reactors had the capability to generate more than 100 kilowatts (kWe) of electricity, making them much more powerful than other forms of energy generation in space, including RTGs.

The more simple process of allowing the natural decay of an isotope and harnessing its heat to generate electricity with and RTG, however, has become the preferred method for supplying the power needs of American deep space probes but it has also been used on some Earth-orbital and lunar spacecraft. It operates by releasing heat during the decay process of a suitable radioactive material that is then converted into electricity through means of an array of thermocouples, with the outer end of each thermocouple connected to a heat sink. Radioactive decay of the fuel produces heat which flows through the thermocouples to the heat sink; generating electricity in the process. The thermocouples are then connected through a closed loop that feeds an electrical current to the power management system of the spacecraft. Indeed, all U.S.-launched systems have used plutonium-238 for this purpose.[8]

In addition to its longevity, space nuclear power offers a significant saving in terms of mass associated with an individual mission compared to the other possibilities. As policy analyst Steven Aftergood reported: "for all practical purposes, nuclear reactors are required when moderate to high levels of continuous power are required for an extended period."[9] Another observer, admittedly one committed to exploiting space nuclear power much more aggressively than has been done thus far:

> Nuclear power has been used for deep space vehicle for over 40 years. RTGs have been used for spacecraft electrical power since 1961. All RTGs have operated as designed, both in normal operations and accident conditions. RTGs were designed carefully with consideration for the accident environments that might be experienced during every phase of the launch. The design requirement is to protect public and worker health and safety during all phases of operations during launch and accident conditions.[10]

In addition, these systems have provided power ranging from 2.7 Watts on the very early systems to 500 Watts on more recent flights.[11] Even so, while RTGs have been a proven, reliable technology, they have fostered only relatively low power efficiency, only about 7 percent at the beginning of the mission, and researchers have consistently sought to improve on that fact.[12]

Of course, the conversion of heat into electricity as done by an RTG is not a new concept. It was discovered more than 150 years ago by the German Thomas Johann Seebeck, who learned that electric voltage might be produced when two dissimilar but conductive materials were joined in a closed circuit and the two junctions were kept at different temperatures. These junctions gained the name thermocouples, and they generated electricity through the movement of electrons through the interaction of the electrons of the two materials properties. The thermocouples in RTGs, therefore, use heat from the natural decay of radioactive plutonium-238 to heat one material of the thermocouple, while the other remains cold from the temperatures in space, and electricity results from the interactions.[13]

Beginning in the latter 1940s several threads converged to make it possible to develop and use radioisotope thermoelectric generators. First, the Atomic Energy Commission (AEC) began to develop radioisotopes for atomic weapons. This prompted scientific research to understand the nature of the half lives of various isotopes, decay processes, and charge separation. Second, scientists began to experiment with the development of small nuclear power generators for a variety of uses on Earth, especially at the poles and under the seas where scientific instruments could be placed and left alone for months at a time. The first bench test RTGs emerged from the Mound Laboratory (operated for the AEC by the Monsanto Research Corp.) in 1953 and quickly found application in Antarctica to power scientific research stations.[14] Indeed, Mound scientists Kenneth Jordan and John Birden had hit upon the RTG as a possibility almost by accident. They had been frustrated in efforts to use decaying radioactive materials to boil water to drive a steam turbine. They then decided to apply the thermocouple principle to harness heat from decaying isotopes and after working out the calculations quickly built a successful model of an RTG. The Jordon/Birden principle soon became the basis for all radioisotope thermoelectric generators.[15] Third, advances in thermoelectricity and semiconductors for the first time made the type of power source offered by RTGs feasible. As William R. Corliss and Douglas G. Harvey commented about this heady time in a 1964 textbook on the subject: "The right ingredients were present and the dough began to rise."[16]

III. Origins of Nuclear Power Systems for Spaceflight

In the latter part of the 1940s several engineers began to consider the possibility of using nuclear power sources for space exploration. The seminal document in this consideration appeared in 1946 from the newly-established RAND Corporation on a *Preliminary Design of an Experimental World-Circling Spaceship*, exploring the viability of orbital satellites and outlining the technologies necessary for its success.[17] It did not take long for scientists and engineers to graft nuclear power sources onto their considerations and 1947 brought the first publications concerning the subject.[18] By 1949 a full-scale analysis by RAND had sketched out the large-scale use of nuclear power sources for satellites in Earth Orbit.[19] Beginning in 1951, at the Department of Defense's (DoD) request, the AEC sponsored research into nuclear power for spacecraft to support the United States Air Force's (USAF) Project Feedback study, leading to the development of a reconnaissance satellite. By June 1952, as reported in an early classified study of the effort, "preliminary results of the reactor analyses were available; all were favorable to the feasibility of the proposal." This extensive and positive discussion of radioisotopic power for space application led to an exponential growth in interest in isotopic power for space satellites. A year later, in May 1953, USAF Headquarters took the next step by authorizing development work on a nuclear power source for satellites. This research effort led directly to the nuclear power systems used on spacecraft in the early 1960s.[20]

The AEC oversaw this effort, pursuing two related avenues. The first led to a small nuclear reactor and the second to the RTG. Codenamed SNAP for "Systems for Nuclear Auxiliary Power," these systems were numbered with the odd numbers designating RTGs and even numbers for the reactors. For the RTGs, SNAP-1 was built at the Mound Laboratory under Atomic Energy Commission's (AEC) supervision in 1954. It used a thermocouple heated by polonium (Po)-210 for fuel. Exceeding all expectations, SNAP-3, used advanced thermoelectric conversion devices with the first Po-210 fuel capsules; the capsules would soon become a standard in future RTGS. In the reactor arena, the SNAP-2 system used a 50-kw(t) reactor system weighing about 600 pounds employing liquid NaK—a sodium (Na) and potassium (K) alloy—as a coolant to transfer heat through a mercury loop. This reaction, basic chemistry really, produced 3 kw of electricity. This led to the research on two additional space power units, SNAP-8 and SNAP-10, emphasizing a metal hydride reactor technology first used in SNAP-2.[21]

These efforts led to a longstanding record of success in meeting the electrical needs of deep space vehicles while offering both reliable and safe operations. As Richard Engler commented:

> The history of the radioisotope power program is basically a success sto[r]y, although it is certainly not one of linear success. The program was initiated by the AEC under impetus from the Department of Defense but first went public late in that decade as part of the "atoms for peace" movement, with President Eisenhower showing an atomic battery to the world and extolling its peaceful potential uses. Subsequently, while the Defense Department supported mostly test applications of the radioisotopic power devices in space, the program reached its pinnacle of success through uses by the civilian space agency, NASA.

This technology proved exceptionally quiet for most of its history, until the latter 1970s when concerns about all things nuclear erupted in the public consciousness. This was in part because it involved neither explosive power nor a human built reactor to operate.[22] Even so, it has been discussed at the highest levels of national discourse. President John F. Kennedy in 1961 believed that nuclear power would be used to send Americans in space, while "Nuclear Power will sustain him there."[23]

The possibilities of space nuclear power first entered the public sphere in January 1959 when President Dwight D. Eisenhower posed for a photo op with an RTG in the Oval Office of the White house. It was SNAP-3, the AEC-developed power source that so many involved in the space program pinned their hopes for exploration of the solar system. AEC officials hailed this RTG as a "significant breakthrough," one that was reliable, simple, flexible, safe, and just as importantly they said, "We can tailor the product to fit the customer."[24] In the context of the post-Sputnik high technology competition with the Soviet Union in the latter 1950s, Eisenhower undoubtedly viewed this showing of the first RTG as a useful propaganda device, graphically demonstrating American technological verisimilitude. He emphasized that this nuclear device was not destructive; rather it was a means of supporting peaceful scientific expeditions for ramifications for the positive development of humanity. Accordingly, the SNAP-3 served as a proof-of-concept for Eisenhower's "Atoms for Peace" initiative, a positive use of nuclear technology around the globe. Its small size, inconspicuousness, and non-threatening nature served Eisenhower well in helping to defuse the caustic international confrontations between the U.S. and the Soviet Union.[25]

RTGs have evolved over the last nearly fifty years from the early SNAP systems to the current General Purpose Heat Source (GPHS) system that has flown on a wide range of NASA deep space missions. For instance, the Galileo mission to Jupiter contained two RTGs, while Ulysses had one RTG to power its systems. The GPHS had a thermal power of 4.4 kilowatts and contained a total plutonium mass of 9.4 kilograms.[26] Because of the low wattage of these systems, all space probes flown by NASA have been power constrained. For example, the Cassini spacecraft launched to Saturn in 1997, with power supplied by three GHPS radioisotope thermoelectric generators (RTGs), has the most electrical power onboard any deep space vehicle. But it produced only 900 watts of onboard electrical power at the time launch. When compared to the number of 60 watt light bulbs in a normal home, the power for Cassini palled in comparison. To help resolve this constraint a twin pronged effort has been pursued to (1) enhance the wattage of RTGs, and (2) economize on what may be accomplished with a limited amount of electricity.[27]

This has led to a coordinated R&D effort, under the direction of the AEC (later renamed the Department of Energy) and NASA, over many years to advance technology along a broad range of space power areas.

Basic Research:

- Photovoltaic energy conversion
- Chemical energy conversion
- Therma1 (nuclear) energy conversion
- Power management
- Thermal management

Focused Research:

- Space nuclear power
- Surface power and thermal management
- Earth orbiting platform power and thermal management
- Deep space probe power and thermal management
- Laser power beaming
- Mobile surface power systems

As Gary L. Bennett, the dean of space nuclear power at NASA, and Ronald C. Cull remarked in the context of NASA's Space Exploration Initiative (SEI) in 1991: "The ongoing NASA research and technology program in space energy conversion provides a foundation from which to build the focused technology programs to meet the SEI power requirements. An augmented program focusing on space nuclear power, high capacity power, surface power and thermal management, Earth orbiting platform power and thermal management, spacecraft power and thermal management for deep-space vehicles, laser power beaming, and mobile surface systems power has been defined to develop the specific focused technologies for SEI applications."[28]

IV. Space Nuclear Power and the Early Satellite Efforts

The application of nuclear power to spaceflight really began in the 1950s when the Navy through its contractor, the Applied Physics Laboratory (APL) of the Johns Hopkins University, developed first RTGs for space applications. Specifically, Transit, the first navigation satellite, flew an RTG in 1965. Intended as a method of ensuring the capability of the inertial navigation systems of the U.S. Navy's Polaris ballistic missile submarines, the Transit system promised 80-100 meter accuracy. Accordingly, it supported one/third of the nation's strategic triad in enabling targeting and ensuring the deterrent threat posed to the Soviet Union was real.[29] It originated on March 18, 1958, when the APL's Frank T. McClure wrote two memoranda to APL Director Ralph E. Gibson: "Yesterday I spent an hour with Dr. [William H.] Guier and Dr. [George C.] Weiffenbach discussing the work they and their colleagues have been doing on Doppler tracking of satellites. The principal problem facing them was the determination of the direction which this work should take in the future. During this discussion it occurred to me that their work provided a basis for a relatively simple and perhaps quite accurate navigation system." Most importantly, McClure noted, it offered the solution to a vexing problem of genuine military significance during the cold war.[30]

The first Transit satellite, Transit 1A, took off from the Space Operations Center at Cape Canaveral, Florida, on September 17, 1959, but failed during launch. A second satellite, Transit 1B, was launched on April 13, 1960, and operated for 89 days. There followed a succession of Transit satellites, with a general development of greater capability and longevity interspersed with failures of missions. A vexing issue was how to maximize the spacecraft's useful service life on orbit, the best that the Navy could achieve seemed to be about a year with batteries and solar arrays.[31] RTGs offered a ready alternative. As John Dassoulas of APL recalled: "I had been looking into the possibilities of isotopic power since we first began the Transit program. We had a five-year goal for the life of the operational Transit, and we weren't confident that the hermetic seals on batteries would hold up for five years."[32]

Dassoulas attended a space technology symposium in 1959 that prompted his conversion to the belief that nuclear space power had real potential for Transit. By happenstance he sat on the airplane back to Washington, D.C., near Col. G.M. Anderson of the Atomic Energy Commission (AEC). Their conversation led to a visit to the Martin Nuclear Division in Baltimore to learn more about the RTG program then underway. While the bench test RTGs at Martin used polonium (Po-210) as a fuel source, with its relatively short half life of 138 days, it led to longer-lived systems using plutonium (Pu-238) as the isotope of choice for the heat source. As two veterans of this project recalled:

> As word spread about a possible flight opportunity many proposals, including some not so credible ones, were put forward. It was clear to those working the spacecraft design that most of these proposals had not been developed with the entire system in mind. One alternative scheme proposed 90Sr as the isotope of choice; however it involved implementing a shield of mercury around the SNAP device (to protect the workers) that could presumably be drained off prior to launch. This would have imposed significant design constraints in safety, reliability and weight that were clearly unacceptable. It should be noted that none of these suggestions came from the SNAP office of the AEC.

In the end the Transit 4A and 4B satellites were provided with SNAP-3B power sources from the AEC. Both satellites also used solar cells supplying 35 W at the start of the mission as well as the RTG.[33]

An early and persistent issue in the use of nuclear power sources for spacecraft was the issue of safety. It took time and energy to acquire approval to launch these nuclear systems, however. The first tests to assure the safety of RTGs for Transit spacecraft were conducted in the fall of 1960 and the DoD formally requested that the AEC initiate a program in February 1961 "to provide two plutonium-238 isotope-fueled generators for TRANSIT satellites to be launched in June and July."[34] A detailed safety analysis conducted under AEC auspices in March 1961 focused on potential hazards that might result from launch or re-entry failures. It concluded that because of the shielding developed for the RTG and the nature of the system itself "that if the radioisotope generator considered is launched in the trajectory proposed for Transit vehicles, it will not produce a significant radiation hazard."[35]

The AEC's Glenn Seaborg proved a persistent advocate for this mission. He officially asked the president on May 6, 1961, to approve the launch, citing the findings of a hazards study that "any danger to the public is extremely unlikely." He added, "I call this to your attention since this first application of a nuclear auxiliary power source in space is likely to have a wide public impact."[36] The Department of State resisted this launch, in no small part because of its international implications, but the DoD and the AEC persisted and eventually succeeded in obtaining approval. Before the Transit launch there had been no AEC protocol for delivery of Pu-238 for the integration tests; AEC officials hand carried the RTG to the Applied Physics Laboratory in the trunk of a private automobile. Security stood guard over the system, and engineers completed their integration tests as quickly as possible. Thereafter, they delivered the RTG to Martin Nuclear in Baltimore where it underwent shipment to Cape Canaveral.[37]

As this took place, the public learned of the impending launch of a nuclear-power plant and organized a protest. Picking up on the high-level discussions inside the Kennedy administration, on May 16, 1961, the *New York Times* broke the story, suggesting that the "problem confronting the Administration...is not so much a technical decision as one of diplomatic, political and psychological considerations."[38] Three days later the *New York Times* pressed the issue, highlighting concerns from State Department officials "that in event of an unsuccessful launching, the satellite, with its radioactive parcel, could fall on Cuba or some other Latin-American country." They feared, in the politically charged involvement over the failed Bay of Pigs invasion of Cuba that this would add fuel to any international incident that might result. Some even expressed concern that other nations might "take offense about having radioactive materials flown over their territory."[39]

Accordingly, the DoD reconfigured Transit-4A to fly without the RTG, reluctantly accepting a lesser capability on orbit. The story differs on how the approval finally came down to fly the RTG on Transit-4A. Some believed that it was the culmination of a month-long set of internal negotiations between the DoD and State Department to proceed with the June 1961 launch of Transit-4A; with final approval clearing the spacecraft for launch on May 23, 1961.[40] Others claimed that it only contained the RTG because of the intervention of President John F. Kennedy, who personally gave an approval to proceed during a small dinner party in which Glenn Seaborg pled the case for the mission. Regardless, about two days before the scheduled lift-off, a military team flew the STG from Baltimore to Patrick Air Force Base in Florida where the launch team destacked the payload and inserted the SNAP-3 system. The vehicle then launched on June 29, 1961, from Launch Complex 17 and operated for fifteen years until the satellite was finally shut down. Transit-4B followed on November 15, 1961, and operated until June 1962 when a thermoelectric converter in the power unit failed. The satellite ceased communications on August 2, 1962, but there were some reports of picking up telemetry from it as late as 1971.[41]

The launch of Transit-4A made headlines. The *New York Journal American* offered a positive story. It reported: "The successful orbiting of the nuclear device...gives American scientists a significant lead over Russia in the race to harness atomic power for space exploration."[42] Previous concerns voiced by officials from the State Department withered with the success of this flight, and serious inter-governmental opposition never found traction thereafter. By October Glenn Seaborg was promoting the use of atomic power as the logical technology to power spacecraft. He asserted:

> The presence of the “atomic battery” in the satellite is a symbol of a “marriage” that was bound to occur—between Space and the Atom. We have known for some time that the two were made for each other. No one would be tempted, at the present time, to abandon other sources of energy for space. However, the atom has made greater strides toward coming of age for space application in the past few years than many of us could have hoped. The day is not far off when atomic energy will be available in many different packages for practical use in space vehicles.[43]

At the same time he lobbied with Vice President Lyndon B. Johnson, the chair of the Space Council, for greater use of space nuclear power. He argued that the success of the first mission could be replicated over and over, providing efficient power systems for spacecraft.[44]

The initial successes prompted the development of the Transit 5B series of satellites containing nuclear power sources. Launched atop Thor Able-Star rockets, Transit 5BN-1 reached orbit on September 28, 1963, but it achieved gravity-gradient stabilization upside down, which limited its signal output to the ground. Transit 5BN-2 was launched on December 5, 1963, with an RTG power source and operated for approximately one year. The last RTG-powered navigation satellite, Transit 5BN-3, was launched on April 12, 1964, but failed to achieve orbit and its failure prompted widespread concern. As a U.S. GAO report noted in the latter 1990s: “In 1964, a TRANSIT 5BN-3 navigational satellite malfunctioned. Its single RTG, which contained 2.2 pounds of plutonium fuel, burned up during reentry into Earth’s atmosphere. This RTG was intended to burn up in the atmosphere in the event of a reentry.”[45]

It did, and this sent shock waves through the world community. The Atomic Energy Commission tried to assuage the public’s fears, reporting that “From previous safety analysis and tests it had been concluded the re-entry will cause the plutonium-238 fuel to burn up into particles of about one millionth of an inch in diameter. These particles will be widely dispersed...and would not constitute a health hazard.”[46] This proved too optimistic. One study concluded that “a worldwide soil sampling program carried out in 1970 showed SNAP-9A debris present at all continents and at all latitudes.”[47] As reported in *New Scientist*, within a decade after its reentry atmospheric measurements “showed that about 5 per cent of its plutonium-238 remained in the atmosphere. The activity of the release is about 10 per cent of that of plutonium-239 released in all tests of nuclear weapons in the atmosphere up to now. It is the main source of plutonium-238 in the environment.”[48] NASA’s economic impact statement conducted in advance of the Cassini space launch in 1996, added:

> Since 1964, essentially all of the SNAP-9A release has been deposited on the Earth’s surface. About 25 percent ... of that release was deposited in the northern latitudes, with the remaining 75 percent settling in the southern hemisphere....The release into the atmosphere was consistent with the RTG design philosophy of the time. (Subsequent RTGs, including the RTGs on the Cassini spacecraft, have been designed to contain the Pu-238 fuel to the maximum extent possible, recognizing that there are mass and configuration requirements relative to the spacecraft and its mission that must be considered with the design and configuration of the power source and its related safety requirements.)[49]

Such reports, and the concerns that they engendered led both to the development of a very rigorous test and safety program and the restriction of space nuclear power to only those missions for which it was absolutely critical.

Its immediate result was to prompt the Navy to rely thereafter on solar power satellites because of the many high-level approvals necessary launch a nuclear power system and the safety hazard inherent in failure. Of the six objectives for this series of satellites listed below, only three were fully met, 3, 4, and 5, while the remainder were at best partially resolved:

1) Provide a means by which US Navy ships may navigate anywhere in the world.
2) Demonstrate satisfactory operation of all satellite subsystems.
3) Demonstrate satisfactory operation and potential long life capability of the SNAP 9-A power supply.
4) Improve our understanding of the effects of ionospheric refraction on radio waves.
5) Demonstrate satisfactory operation of the satellite-borne data injection memory system.
6) Increase knowledge of the earth’s shape and gravitational field.

Each of these satellites contained a SNAP-9A power source: a cylinder 30.48 cm in diameter by 20.32 cm high with four radiating fins, weighing 12.3 kg. They provided, when working correctly, 25 W at 6V for a projected satellite lifetime of five years in space.[50]

At the same time, The U.S. military flew one nuclear reactor in space, solely as a test program, in the middle part of the 1960s. Designated SNAPSHOT, this mission was launched from Vandenberg Air Force Base, California, on April 3, 1965, with the SNAP-10A reactor. A heritage project based on earlier SNAP reactors, the 435-kg system produced 500 We of energy for one year. Precautions abounded for this test, for example, the reactor was not started until in the spacecraft reached orbit. The test was successful until 43 days into the mission when a voltage regulator on the carrier vehicle, an Agena upper stage, failed and the test had to be terminated.[51] Thereafter, as Canadian nuclear policy analyst Michael Bein commented: “The only U.S. satellite thus far to carry a nuclear fission reactor failed in 1965 after 43 days aloft and was subsequently boosted into a 4000-year orbit in order that its radioactivity might have time to decay to safer levels before it descends to earth. Injection into higher orbit is the method of reactor ‘disposal’ preferred by both the American and Soviet programs.”[52]

V. Space Nuclear Power at High Tide

The period between the flights of the Transit navsats and the flights of NASA’s outer planetary probes, Voyagers 1 and 2, in the latter 1970s may best be characterized as the high tide of space nuclear power. During that time NASA flew no fewer than 14 RTGs, and the Department of Defense (DoD) operated another 11, while the Soviet Union launched 20 on various spacecraft. These included RTGs on the Apollo lunar missions, the flights of Pioneers 10 and 11, the Viking missions to Mars, and the so-called “Grand Tour” of the solar system made by Voyagers 1 and 2. Throughout this period, furthermore, the technology evolved and became increasingly capable. Table 1 depicts the total number of RTG used by the United States for space missions to the present.

Table 1

U.S. Spacecraft Using Radioisotope Systems

Spacecraft	*Power Source*	*No. RTGs**	*Mission Type*	*Launch Date*	*Status*
Transit 4A	SNAP-3	1	Navigational	6/29/1961	Currently in orbit
Transit 4B	SNAP-3	1	Navigational	11/15/1961	Currently in orbit
Transit 5BN-1	SNAP-9A	1	Navigational	9/28/1963	Currently in Orbit
Transit 5BN-2	SNAP-9A	1	Navigational	12/5/1963	Currently in Orbit
Transit 5BN-3	SNAP-9A	1	Navigational	4/12/1964	Aborted; Burned up
Nimbus B-1	SNAP-19	2	Meteorological	5/18/1968	Aborted; Retrieved
Nimbus III	SNAP-19	2	Meteorological	4/14/1969	Currently in Orbit
Apollo 11	ALRHU	Heater	Lunar	7/16/1969	On Lunar surface
Apollo 12	SNAP-27	1	Lunar/ALSEP	11/14/1969	On Lunar surface
Apollo 13	SNAP-27	1	Lunar/ALSEP	4/11/1970	Aborted in Pacific
Apollo 14	SNAP-27	1	Lunar/ALSEP	1/31/1971	On Lunar surface
Apollo 15	SNAP-27	1	Lunar/ALSEP	7/26/1971	On Lunar surface
Pioneer 10	SNAP-19	4	Planetary	3/2/1972	Heliopause
Apollo 16	SNAP-27	1	Lunar/ALSEP	4/16/1972	On Lunar surface
Triad-01-1X	Transit-RTG	1	Navigational	9/2/1972	Currently in Orbit
Apollo 17	SNAP-27	1	Lunar/ALSEP	12/7/1972	On Lunar surface
Pioneer 11	SNAP-19	4	Planetary	4/5/1973	Heliopause
Viking 1	SNAP-19	2	Mars Lander	8/20/1975	On Martian surface
Viking 2	SNAP-19	2	Mars Lander	9/9/1975	On Martian surface
LES 8, LES 9	MHW-RTG	2, 2	Communication	3/14/1976	Currently in Orbit
Voyager 2	MHW-RTG	3	Planetary	8/20/1977	Heliopause
Voyager 1	MHW-RTG	3	Planetary	9/5/1977	Heliopause
Galileo	GPHS-RTG	2	Planetary	10/18/1989	Intentionally deorbited into Jupiter
Ulysses	GPHS-RTG	1	Planetary	10/6/1990	Sun’s polar regions
Mars Pathfinder	LWRHU	Heater	Mars Lander	12/4/1996	Operated on Mars
Cassini	GPHS-RTG	3	Planetary	10/15/1997	Operating at Saturn
New Horizons	GPHS-RTG	1	Planetary	1/19/2006	Enroute to Pluto

*All U.S. RTGs are fueled by plutonium-238; Snapshot reactor was fueled by uranium-235.

Sources: Gary L. Bennett, James J. Lombardo, and Bernard J. Rock, “Development and Use of Nuclear Power Sources for Space Applications,” *Journal of the Astronautical Sciences* 29 (October-December 1981): pp. 321-42; Nicholas L. Johnson, “Nuclear Power Supplies in Orbit,” *Space Policy*, August 1986, pp.223-33; Gary L. Bennett, “Space Nuclear Power: Opening the Final Frontier,” AIAA 2006-4191, p. 2, presentation at 4th International Energy

Conversion Engineering Conference and Exhibit (IECEC), San Diego, CA, June 26-29, 2006, copy in possession of author.

Viewing the efforts of the Department of Defense, NASA officials determined that RTGs—although the possible use of reactors for space power was rejected—would be helpful in its planetary exploration program. For example, as reported in the Atomic Energy Commission's SNAP Fact Sheet: "NASA's inquiries about using RTGs for Project Surveyor—the unmanned soft lunar exploration program—had led to work at the AEC on SNAP-11. This devise, to be filled with curium-242, would weigh 30 pounds, and would provide a minimum of 18.6 watts of power continuously for 90-day lunar missions."[53] While NASA chose to forego RTG usage for Surveyor, it adopted it for the Apollo lunar landing program. It had a willing partner in Glenn Seaborg and the AEG. A report advocating the use of RTGs emerged from the AEG in February 1964, emphasizing the appropriateness of space nuclear power for extended and deep space missions because the "performance of ambitious space missions will require amounts of reliable power so large that they can be achieved only from nuclear systems."[54] A similar report from NASA's Jet Propulsion Laboratory in 1964 advocated the employment of RTGs to power deep space probes where solar power would be insufficient to meet the needs of the spacecraft.[55] In June 1965 NASA and the AEG reached agreement on the establishment of a joint Space Nuclear Systems Division. Harry Finger, the senior official working on space nuclear issues, emphasized the need "to develop systems that bracket as broad a range of potential mission uses as possible, and parallel with this, continue to push the technology into more advanced areas in order to try to improve the performance and life capability of these systems."[56]

Even with this impetus, it took five years after the loss of Transit 5BN-3 for another RTG to reach orbit, and the effort to achieve it was slow and prickly. As never before, NASA weighed in to ensure the safety of the RTGs from any conceivable accident. The AEG were willing accomplices, of course, and all took seriously this charge. The management structure evolved to carry out this mission. First, the two organizations used the joint office to coordinate all efforts, giving it both authority and responsibility to conduct the program effectively and safely. Like the larger Apollo program, the joint office pursued RTG efforts with the same top down leadership style that was so successful elsewhere, emphasizing configuration control and project management as the only trued means of achieving acceptable results.This centralization of design, engineering, procurement, testing, construction, manufacturing, spare parts, logistics, training, and operations worked well. This approach was lauded in the November 1968 issue of *Science* magazine, the publication of the American Association for the Advancement of Science:

> In terms of numbers of dollars or of men, NASA has not been our largest national undertaking, but in terms of complexity, rate of growth, and technological sophistication it has been unique....It may turn out that [the space program's] most valuable spin-off of all will be human rather than technological: better knowledge of how to plan, coordinate, and monitor the multitudinous and varied activities of the organizations required to accomplish great social undertakings.[57]

Finger employed the same approach in building and flying the RTGs used in the Apollo program and other missions of NASA. The AEC's Bernard Rock reflected on this approach to overseeing the RTG program and its influence on other activities of his organization: "My background was technical, but I soon saw how important management was in the NASA scheme of things and I sensed that this concern with management was correct. I went out and enrolled in some courses in engineering administration….Apollo was many orders of magnitude greater in size and complexity than" other AEG programs and it was successful largely because of its rigorous management.[58]

The SNAP-27 RTG became the power supply for the Apollo Lunar Surface Experiments Package that was left on the Moon by all Apollo missions but the first one. This was largely because of the scientific objectives of the Apollo program. Of course, the reasons for undertaking Apollo had little do with furthering scientific understanding. Its impetus rested almost solely on cold war rivalries and the desire to demonstrate technological verisimilitude to the peoples of all the nations of the world. Even so, a great deal of good scientific knowledge emerged from the exercise as scientists gained entrée to the program and maximized the scientific return on this investment. They succeeded in having established at each of the landing sites a self-contained experiments package that would measure, record, and send data back to Earth on a variety of factors, seismic occurrences, surface vibrations, responses of the Moon to fluctuations in solar and terrestrial magnetic fields, and changes in the low concentrations of gas in the virtually non-existent lunar atmosphere.[59]

Ongoing debates about the size and mass of experiments, as well as their power requirements, roiled the mission planning efforts throughout the middle 1960s. The scientists agreed that the first investigations should relate to geology (especially sample collection), geochemistry, and geophysics. They also agreed that the early landings should focus on returning as many diverse lunar rock and soil samples as feasible, deployment of long-lasting surface instruments, and geological exploration of immediate the landing areas by each crew. These could be expanded later to include surveys of the whole moon and detailed studies of specific sites in the equatorial belt.[60]

The scientific "geeks" exploited this opportunity to place more than 50 experiments on the various Apollo missions, and in the case of the last landing mission, to have one of their own, Harrison Schmitt, undertake field work on the Moon. The science packages deployed on the Moon included the following types of experiments:

- *Soil Mechanics Investigation* studied the properties of the lunar soil (Apollo 11, 12, 14, 15, 16, and 17).
- *Solar Wind Composition Experiment* collected samples of the solar wind for analysis on Earth (Apollo 11, 12, 14, 15, and 16).
- *Passive Seismic Experiment* detected lunar "moonquakes" and provided information about the internal structure of the Moon (Apollo 11, 12, 14, 15, and 16).
- *Laser Ranging Retroreflector* measured very precisely the distance between the Earth and Moon (Apollo 11, 14, and 15).
- *Lunar Dust Detector* studied the effects of lunar dust on the operation of the experiment package (Apollo 11, 12, 14, and 15).
- *Lunar Surface Magnetometer* measured the strength of the Moon's magnetic field (Apollo 11, 12, 15, and 16).
- *Lunar Portable Magnetometer* measured the strength of the Moon's magnetic field (Apollo 14 and 16).
- *Cold Cathode Gauge* measured the abundance of gases in the lunar atmosphere (Apollo 12, 14, and 15).
- *Suprathermal Ion Detector Experiment* studied the lunar ionosphere (Apollo 12, 14, and 15).
- *Solar Wind Spectrometer* measured the composition of the solar wind (Apollo 12 and 15).
- *Active Seismic Experiment* provided information about the structure of the upper 100 meters of the lunar regolith (Apollo 14 and 16).
- *Charged Particle Lunar Environment Experiment* measured plasmas around the Moon (Apollo 14).
- *S-Band Transponder Experiment* measured regional variations in the Moon's gravitational acceleration (Apollo 14, 15, 16, and 17).
- *Bistatic Radar Experiment* measured scattering of radar waves from the lunar surface (Apollo 14).
- *Heat Flow Experiment* measured the amount of heat coming out of the Moon (Apollo 15, 16, and 17).
- *Metric and Panoramic cameras* provided systematic photography of the lunar surface (Apollo 15, 16, and 17).
- *Laser Altimeter* measured the heights of lunar surface features (Apollo 15, 16, and 17).
- *X-ray Fluorescence Spectrometer Experiment* measured the composition of the lunar surface (Apollo 15, 16, and 17).
- *Gamma-ray Spectrometer Experiment* measured the composition of the lunar surface (Apollo 15, 16, and 17).
- *Alpha Particle Spectrometer Experiment* measured radon emission from the lunar surface (Apollo 15, 16, and 17).
- *Orbital Mass Spectrometer Experiment* measured the composition of the lunar atmosphere (Apollo 15, 16, and 17).
- *Bistatic Radar Experiment* measured the scattering of radar waves from the lunar surface (Apollo 15, 16, and 17).
- *Subsatellite* measured regional variations in the Moon's gravitational acceleration and magnetic field and the distribution of charged particles around the Moon (Apollo 15, 16, and 17).
- *Far Ultraviolet Camera/Spectrograph* took pictures and spectra of astronomical objects in ultraviolet light (Apollo 16).
- *Cosmic Ray Detector* measured very high energy cosmic rays from the Sun and other parts of our galaxy (Apollo 16 and 17).
- *Active Seismic Experiment* provided information about the structure of the upper 100 meters of the lunar regolith (Apollo 16 and 17).
- *Lunar Surface Magnetometer* measured how the strength of the Moon's magnetic field varied with time (Apollo 16).
- *Traverse Gravimeter Experiment* measured how the Moon's gravitational acceleration varied at different locations near the landing site, which helped to measure the thickness of the basalt layer in this region (Apollo 17).

- *Lunar Neutron Probe* measured the penetration of neutrons into the lunar regolith, which helped to measure the overturn rate of the regolith (Apollo 17).
- *Surface Electrical Properties* measured the propagation of electrical waves through the lunar crust (Apollo 17).
- *Lunar Seismic Profiling Experiment* provided information about the structure of the upper kilometer of the lunar crust (Apollo 17).
- *Lunar Atmospheric Composition Experiment* measured the composition of the Moon's tenuous atmosphere (Apollo 17).
- *Lunar Ejecta and Meteorites experiment* measured the impact of small meteorites on the Moon (Apollo 17).
- *Lunar Surface Gravimeter* attempted to detect gravity waves (Apollo 17).
- *Apollo Lunar Sounder Experiment* used radar to study the structure of the upper kilometer of the lunar crust (Apollo 17).
- *Ultraviolet Spectrometer Experiment* studied the composition of the lunar atmosphere (Apollo 17).
- *Infrared Radiometer* measured the cooling of the Moon's surface at night as a way to determine the physical properties of the lunar soil (Apollo 17).

Collectively, these experiments yielded more than 10,000 scientific papers and a major reinterpretation of the origins and evolution of the Moon.[61]

The Bendix Aerospace Systems Division developed the Apollo Lunar Surface Experiments Package (ALSEP) to support these activities, to be powered by a Pu-238 fueled, 75-watt isotopic power unit built by General Electric. This later had to be downsized to 50-watts, and ultimately the SNAP-27 was only useful once armed by an astronaut during an EVA. It would, therefore, provide power on the Moon throughout the long (14-Earth-day) lunar night for the ALSEP but could not be used on non-astronaut missions.[62] All but Apollo 11 used the SNAP-27, and that first mission used a smaller, nuclear heating unit. George E. Mueller, NASA's Associate Administrator for Manned Space flight, explained why:

> We have sharpened the focus on some of the problems involved. The first landing mission represents a large step from orbital operations…The 1/6 g lunar surface environment will be a new experience. We cannot simulate it completely on Earth. We find that we simply do not have as much metabolic data as we would like in order to predict with high confidence, rates in a 1/6 g environment. Only educated guesses are possible on the difficulties the astronaut will have in maneuvering on the surface or the time it will take him to accomplish assigned tasks….The decision not to carry ALSEP on the first mission is due to the time necessary for deployment and not to any concern of operating with the RTG. You have the strongest advance assurance I can give that ALSEP will be carried on the second mission. I also foresee significant RTG use in the future as lunar exploration progresses.[63]

The first use of the RTG on Apollo 12 proved a moment of truth for its proponents. Not that they were concerned for the safety of the astronauts, all precautions taken, but the crew had trouble deploying the system. Astronaut Alan Bean easily deployed the ALSEP as intended but he could not activate the RTG. As mission commander Pete Conrad relayed to Mission Control: "It really gets you mad, Houston,...Al put the tool on, screwed it all the way down and the fuel element would not come out of the kit. He's taking the tool off and working it again." Al Bean added, "I tell you what worries me, Pete. If I pull on it too hard, it's a very delicate lock mechanism...Just get the feeling that it's hot and swelled in there or something. It doesn't want to come out....Come out of there, rascal." Bean used a common technique when frustrated by a mechanical device, he got a hammer. That sent the RTG staff into a spin, but his light taps were sufficient to dislodge the fuel capsule and activate the RTG. The SNAP-27 then began to produce the power for the ALSEP as intended and operated thereafter without any problem. The first use of an RTG on a human mission was successful.[64]

In no small measure because of the ability of the ALSEP for sustained operation, the Apollo program proved one of the most significant scientific expeditions ever undertaken. Lunar geologist Don Wilhelms commented on the state of knowledge about the Moon resulting from Apollo in his outstanding 1993 recollection, *To a Rocky Moon*:

> I think that to a first approximation we can summarize the geologic style of the Moon very simply. Primary and secondary impacts, helped by a little lava and minor faulting, have created almost the entire range of lunar landforms. The cosmic impact catastrophes have alternated with gentle volcanic extrusions and an occasion fire fountain originating deep in the Moon's interior. Horizontal plate motions like those of Earth are unknown on the Moon. Vertical motions are more important, but only in the settling of the mare mascons and in the rise of crater floors that are not loaded with mare basalt. The Moon's face has been molded by the rise of basaltic

> magmas into receptacles dug in plagioclase-rich terra material by impacts. The Moon is neither cosmic exotica nor a little Earth.[65]

As reported in *Science* in 1973, "Man's knowledge of the moon has been dramatically transformed during the brief 3½ years between the first and last Apollo landing."[66]

The only other difficulty with the RTG's used in the Apollo program came as a result of the failure of Apollo 13, and the near-loss of the crew. Like its sister missions, Apollo 13 had an ALSEP on the Lunar Module powered by an RTG that would have been left on the Moon had the mission not been aborted. As it was, the Lunar Module returned to Earth with the capsule and crew and was jettisoned over the Pacific Ocean prior to the crew's reentry into the atmosphere. It was targeted for the Tonga Trench, one of the deepest points in the Pacific, and all evidence suggests that the RTG impacted the ocean as intact. Crews trolled the area in search of debris, measuring radioactivity in the area. They found none. Everyone involved in the investigation agreed that the Lunar Module had broken up on re-entry, as anticipated, but that the graphite-encased plutonium-238 fuel cask survived the breakup and went down intact to more than 20,000 feet in the depths of the Tonga Trench. Some RTG insiders went on television to reassure the public that no one was in danger from the RTG. Even so, there was not much public outcry. One AEG engineer close to the program recalled that he only received two questions about this potential safety issue; he assured them that there was no reason for concern. The AEG issued a statement about two weeks after the Apollo 13 mission indicating that "Air sampling over the predicted impact area of the SNAP-27 fuel cask freed from the Apollo 13 lunar module showed no traces of radiation above that already present in the atmosphere. The absence of additional radiation indicates that the cask containing the plutonium fuel survived as designed the heat of re-entry, impacted in the South Pacific intact and sank to the ocean bottom."[67] Some anti-nuclear power activists never accepted this conclusion, but no compelling evidence to the contrary has ever been brought forward.

VI. Space Nuclear Power and Outer Planetary Exploration

A major shift in the use of space nuclear power came with the decision of NASA to pursue outer planetary exploration. In the early 1960s several scientists realized that once every 176 years both the Earth and all the giant planets of the Solar System gather on one side of the Sun, making possible close-up observation of all the planets in the outer solar system (with the exception of Pluto) in a single flight. This geometric line-up made possible close-up observation of all the planets in a "Grand Tour." Moreover, the flyby of each planet would bend the spacecraft's flight path and increase its velocity enough to deliver it to the next destination. This would occur through a complicated process known as "gravity assist," something like a slingshot effect, whereby the flight time to Neptune could be reduced from 30 to 12 years. Such a configuration was due to occur in the late 1970s, and it led to one of the most significant space probe efforts undertaken by the U.S.[68]

For such a lengthy mission NASA would need a long-lasting power source. Solar power would not work because of the distance from the sun and the logical, perhaps the only realistic, answer was to use RTGs to generate power on the spacecraft. To prepare the way for a more extensive "Grand Tour," NASA conceived Pioneer 10 and Pioneer 11 as outer solar system probes stripped bare through successive budgetary constraints that forced a somewhat less ambitious effort than originally intended. Both were small, nuclear-powered, spin-stabilized spacecraft that Atlas-Centaur launched. Pioneer 10 was launched on March 3, 1972. It arrived at Jupiter on the night of December 3, 1973, and although many were concerned that the spacecraft might be damaged by intense radiation discovered in Jupiter's orbital plane, the spacecraft survived, transmitted data about the planet, and continued on its way out of the solar system, away from the center of the Milky Way galaxy.

In 1973 NASA launched Pioneer 11, providing scientists with their first close-up view of Jupiter. The close approach and the spacecraft's speed of 107,373 mph, by far the fastest ever reached by an object launched from Earth, hurled Pioneer 11 1.5 billion miles across the solar system toward Saturn, encountering the planet's south pole within 26,600 miles of its cloud tops in December 1974. In 1979 Pioneer 11 again encountered Saturn, this time closing to within 13,000 miles of the planet, where it discovered two new moonlets and a new ring, and charted the magnetosphere, its magnetic field, its climate and temperatures, and the general structure of Saturn's interior. In 1990 Pioneer 11 officially departed the solar system by passing beyond Pluto and headed into interstellar space toward the center of the Milky Way galaxy. Pioneer 11 ended its mission 30 September 1995, when the last transmission from the spacecraft was received.[69]

Earth received Pioneer 10's last, very weak signal on January 22, 2003. The last time a Pioneer 10 contact actually returned telemetry data was April 27, 2002. At last contact, Pioneer 10 was 7.6 billion miles from Earth, or eighty-two times the nominal distance between the Sun and the Earth. At that distance, it takes more than eleven hours and twenty minutes for the radio signal, traveling at the speed of light, to reach the Earth. It will continue to coast silently as a ghost ship into interstellar space, heading generally for the red star Aldebaran, which forms the eye of the constellation Taurus (The Bull). Aldebaran is about sixty-eight light years away. It will take Pioneer 10 more than two million years to reach it. "From Ames Research Center and the Pioneer Project, we send our thanks to the many people at the Deep Space Network (DSN) and the Jet Propulsion Laboratory (JPL), who made it possible to hear the spacecraft signal for this long," said Pioneer 10 Flight Director David Lozier at the time of the last contact.[70]

Both Pioneer 10 and 11 were remarkable space probes, stretching from a 30-month design life cycle into a mission of more than 20 years and returning useful data not just about the Jovian planets of the solar system but also about some of the mysteries of the interstellar universe.[71] The program, perhaps this is an understatement, was a huge success. Such success would not have resulted without the four RTG's on each spacecraft providing power. Each Pioneer spacecraft employed four SNAP-19 generators as the sole power source mounted in tandem pairs on extendable booms 120 degrees apart. As stated in the SNAP-19 final report:

> For this first all nuclear power application in outer space, each RTG is required to produce 30 watts at high probability (0.995) at Jovian encounter which is specified to occur up to 36 months after delivery to NASA. This performance is to be achieved in accord with the constraints of 38 to 42.5 watts at delivery and a maximum weight of 30.5 pounds. The flight time through the asteroid belt and up to encounter with Jupiter is between 20 and 30 months. Thus, the 36 month specification includes six months operation (most with RTG output shorted) prior to launch and the maximum travel time.

This report added: "The fuel is in the form of pucks, about two inches in diameter and 0.2 inch thick, of plutonium moly cermet (PMC). Eighteen pucks comprise a complete fuel stack for the capsule."[72] The spacecraft also had a dozen radioisotope heater units (RHUs), each generating 1 W, to heat components in space. They were strategically placed in the Thruster Cluster Assembly, near the Sun sensor, and at the magnetometer. There was no problem with the long-term power capabilities of these RTGs. As one account of the mission noted, "The spacecraft continued to make valuable scientific investigations in the outer regions of the solar system until routine tracking of the probe was stopped on March 31, 1997, for budgetary reasons, and NASA formally decommissioned it."[73]

Meantime, NASA technicians prepared to launch what became known as the Voyager probes. Even though the four-planet mission was known to be possible, it soon became too expensive to build a spacecraft that could go the distance, carry the instruments needed, and last long enough to accomplish such an extended mission. Thus, the two Voyager spacecraft were funded to conduct intensive flyby studies only of Jupiter and Saturn, in effect repeating on a more elaborate scale the flights of the two Pioneers. Nonetheless, the engineers designed as much longevity into the two Voyagers as the $865 million budget would allow. NASA launched them from the Kennedy Space Center, Florida: Voyager 2 lifted off on August 20, 1977, and Voyager 1 entered space on a faster, shorter trajectory on September 5, 1977. The three RTGs on the two Voyagers each weighed 56 kilograms, had a diameter of 42.2 cm, and a length of 114 cm. Like the SNAP-27 that served as a power source on the moon during the Apollo mission, this RTG consisted of a cylindrical fuel supply surrounded by rings of thermocouples. Again, there were cooling fins attached to the cold shoes of the thermocouples. Using Plutonium-238 as the fuel source, as in previous missions, these elements were shaped to that each pellet produced approximately 250 watts of thermal power. The fuel modules were encased in a heat and impact resistant shell designed to prevent a vehicle accident from releasing plutonium. The testing on this power source showed that the RTG containers would remain intact even in a launch vehicle explosion or a reentry accident.[74] As the mission progressed, having successfully accomplished all its objectives at Jupiter and Saturn by December 1980, additional flybys of the two outermost giant planets, Uranus and Neptune, proved possible—and irresistible—to mission scientists. Accordingly, as the two spacecraft flew across the solar system, remote-control reprogramming was used to redirect the Voyagers for the greater mission. Eventually Voyager 1 and Voyager 2 explored all the giant outer planets, 48 of their moons, and the unique systems of rings and magnetic fields those planets possess.[75]

The two spacecraft returned information to Earth that has revolutionized solar system science, helping resolve some key questions while raising intriguing new ones about the origin and evolution of the planets. The two Voyagers took well over 100,000 images of the outer planets, rings, and satellites, as well as millions of magnetic, chemical spectra, and radiation measurements. They discovered rings around Jupiter, volcanoes on Io, shepherding satellites in Saturn's rings, new moons around Uranus and Neptune, and geysers on Triton. The last imaging sequence was Voyager 1's portrait of most of the solar system, showing Earth and six other planets as sparks in a dark sky lit by a single bright star, the Sun. Now traveling out of the solar system, in the early twenty-first century Voyager 2 has reached the heliopause and sent back the first information ever received from the outer boundary of our solar neighborhood. It revealed that at a distance of 83.7 astronomical units the spacecraft had five encounters with the termination shock, something unexpected as it passed into interstellar space.[76] The Voyagers are expected to return scientific data until about 2010 since communications will be maintained until their nuclear power sources can no longer supply enough electrical energy to power critical subsystems. Originally built to explore Jupiter and

Saturn, today Voyager 1 is farther from Earth than any other human-made object and speeding outward at more than 38,000 miles per hour. Both spacecraft carry phonograph records (primitive DVDs) which contain sounds and images portraying the diversity of life and culture on Earth. Perhaps 40,000 years from now when the Voyager spacecraft come within the vicinity of nearby stars, these records will be discovered and played by an intelligent alien being, if such exist. On April 22, 1978 on the television program *Saturday Night Live*, comedian Steve Martin breathlessly announced that extraterrestrials had found the record and sent back the message, "Send more Chuck Berry."[77] Again, such success would not have resulted without the RTG's on each spacecraft providing electrical power.

One observer has called the 1970s the "golden age" of planetary science, perhaps a bit of an overstatement but appropriate in certain ways in part because of the power capabilities of RTGs placed on planetary probes.[78] Virtually every year of the decade brought the launch of at least one major planetary probe, and the start of several others that were not launched until the late 1980s.[79] Indeed, 12 planetary probes launched during the 1970s visited all of the planets of the Solar System save Pluto, some landing on such bodies as Mars. The Solar System exploration program of the 1970s was the stuff of legend and myth in some measure, because of its success. Yet, it was also much more. It represented a rich harvest of knowledge about Earth's neighboring planets, a transformation of our understanding of the Solar System's origin and evolution, and a demonstration of what might be accomplished using limited resources when focusing on scientific goals rather than large human spaceflight programs aimed at buttressing American prestige.[80]

VII. Reconsideration and Retrenchment

From the very first conceptionalization of space nuclear power engineers worried about its safety. Even more than nuclear reactor power plants and submarines powered by nuclear reactors, the challenges of ensuring the safety of individuals in the event of an consumed the designers and builders of RTGs. The AEC used plutonium-238 as the fuel of choice for RTGs primarily because it emitted "alpha" particles, known to be the least penetrating type of radiation, incapable of supporting a chain reaction, and sustaining a long half-life. This meant that the danger to living organisms rested with ingesting radioactive particles contained in the atmosphere should the capsule containing the fuel be breached in an explosion on launch or during a reentry. The key to safety, therefore, rested on redoubling efforts to ensure successful launches and hardening the containers in the event of catastrophe. Extensive and ongoing tests by the AEC/DOE on a successive generation of plutonium-238 fuel capsules served to lessen this danger, to the extent that nuclear space power's advocates have argued that it had little risk. As one statement from an engineering firm working on this technology stated: "The potential hazard is essentially zero. The fuel modules are unlikely to be breeched in any accident, but even if all of the coatings and containers were to fail, there is little chance that any person would consume enough material to cause any health consequences. Plutonium oxide is a dense and relatively non-reactive material; it is most likely that it would rapidly fall out of the air and sink to the bottom of the ocean."[81] The Atomic Energy Commission, later DOE, also enforced a rigorous process of reviews and approvals to obtain permission to launch an RTG on a mission. Its regulators forever questioned every aspect of the construction of the hardware, the safety of the transporting and handling, the placement of the RTGs on the spacecraft, the reliability of the launch vehicles, and the conduct of the mission as a whole.[82]

For the first decade and a half of space nuclear power the public, even though it had an interest in the risk RTGs and space nuclear reactors portended, did not register serious misgivings about the use of this technology in space. This changed rather dramatically in the later 1970s in response to two incidents, one directly bearing on space operations and the other a dramatic ground accident. On January 24, 1978, the Soviet Cosmos 954 re-entered the atmosphere, spreading thousands of pieces of radioactive debris over more than 100,000 square kilometers of northwest Canada. A few of the recovered fragments showed a high degree of radioactivity. "The Cosmos 954 reactor included 110 lbs. of highly enriched uranium 235," according the *Time* story reporting on the incident. "This is a long-lived fuel whose 'half-life'—the time it takes for half the material to lose its radioactivity—is an astonishing 713 million years."[83] These reports U.S. President Jimmy Carter, himself a nuclear engineer, to propose a moratorium on the use of nuclear power for spaceflight. "If we cannot evolve those fail-safe methods, then I think there ought to be a total prohibition against [nuclear-powered] earth-orbiting satellites," he said. A permanent ban, of course, did not take place, but what did result was a more strict control regime that emerged in the aftermath of the accident, recompense for the government of Canada and its citizens, and delay of more than a decade in the launch of RTGs on U.S. space probes, and then exclusively for outer planetary missions.[84]

The Cosmos 954 incident raised the consciousness of the public about the potential hazards of nuclear power in space. Couple this with the public's intense reaction to the serious accident at Unit 2 of the Three Mile Island nuclear power plant in Pennsylvania in March 1979, and support for the use nuclear power in any setting quickly eroded. By October 1981, according to one study, a majority of Americans opposed nuclear power for the first time since the advent of the atomic age: “in fact, over the last four surveys spanning 7 years [through 1988], opposition has exceeded support by a margin of about 2:1, a complete flipflop from the earliest Harris survey.”[85] The significance of the Three Mile Island accident to public perceptions of risk tied to the technology cannot be overestimated. While most analysts had believed prior to that accident that public perceptions of risk were related to serious loss of life and destruction property, this accident defied the model. “Despite the fact that not a single person died, and few if any latent cancer fatalities are expected,” wrote Paul Slovic in *Science* magazine, “no other accident in our history has produced such costly societal impacts.” It stampeded the public toward more costly and arguably more environmentally destructive power sources. It made virtually impossible the continuation of the nuclear power capability of the nation and the advancement of that technology. “It may even have led to a more hostile view of other complex technologies, such as chemical manufacturing and genetic engineering,” Slovic added. This increasing public concern was not mirrored in the scientific and technical communities, which contended as a [86] For the next two decades this opposition to nuclear power would be manifested in direct confrontation with antinuclear activist on all launches of spacecraft using RTGs for onboard power.

VIII. Direct Resistance to the Use of RTGs: The Galileo and Cassini Missions

After the Three Mile Island accident the use of RTGs in space missions met direct opposition from the antinuclear community. Five missions have been flown employing nuclear material since that accident—Galileo (1989), Ulysses (1990), Mars Pathfinder (1996), Cassini (1997), and New Horizons (2006)—and all of them received some form of public opposition. Also, with the loss of Challenger in a fiery explosion on January 28, 1986, any probe with nuclear material to be deployed from the Space Shuttle received serious scrutiny from the public.

It was the Galileo and Cassini missions that most concerned antinuclear activists and efforts to stop both launches took extravagant turns. On October 18, 1989, NASA’s Galileo spacecraft, again with RTGs to provide onboard power, began a gravity-assisted journey to Jupiter, where it sent a probe into the atmosphere and observed the planet and its satellites for several years beginning in December 1995. Jupiter was of great interest to scientists because it appeared to contain material in an original state left over from the formation of the solar system, and the mission was designed to investigate the chemical composition and physical state of Jupiter’s atmosphere and satellites. A mission in the planning since the latter 1970s to be deployed from the shuttle, after Challenger government officials and the public joined to force a review of what was proposed for Galileo. Representative Edward Markey (D-MA) persuaded the Department of Energy to release its risk analysis of the Galileo and Ulysses mission launches, and found the disturbing conclusion that launch failures on those flights could result in between 202 and 386 cancer deaths, more than quintuple the national average. The proposed use of the Centaur liquid hydrogen/liquid oxygen upper stage attached to the space probe as the vehicle that would propel Galileo and Ulysses the shuttle’s cargo bay on their journeys elsewhere ensured that an explosion on launch would be more destructive than ever experienced before. The post-Challenger shuttle accident probability estimates and the high-volatility of the Centaur upper stages persuaded NASA Administrator James C. Fletcher to scrap plans to use Centaurs from the payload bay. This led to a reconsideration of the manner in which NASA would send Galileo on its way beyond Earth orbit. An inertial upper stage (IUS), though much less powerful than the Centaur, was called upon to do the job of sending the spacecraft to Jupiter, but it would require the use of complex orbital mechanics, including flyby gravity assists of Venus and Earth to reach Jupiter. The same took place with Ulysses, a mission dedicated to solar astronomy, which deployed in 1990.[87]

NASA also considered replacing the two RTGs contained on the spacecraft with solar arrays because of the political issues associated with launched a nuclear-powered satellite in an environment of considerable public opposition. The project team eventually rejected this replacement because of several technical factors. As the study team reported for the alternate Galileo power system noted: “In view of the insurmountable mass and schedule difficulties associated with a solar retrofit of Galileo, the study team concluded that the only alternative to an RTG-powered Galileo mission would be to cancel the Galileo mission and design a completely new, solar-powered spacecraft for the late 1990’s.” Based on this conclusion, NASA pursued and eventually received permission to deploy the RTG-powered Galileo spacecraft from the payload bay of the Space Shuttle in 1989.[88]

The space agency’s environmental impact statement analyzed the physical hazards of the mission. As in all such space missions, the launch sequence held the most potential hazard to living things on the Earth’s surface. “An intensive analysis of the proposed action indicates that the possible health and environmental consequences of launch or mission anomalies pose small risks,” it concluded.

> The accident estimated to be most probable would pose very small health risks and very small probability of detectable environmental contamination. The maximum credible accident (having a probability of one in 10

> million) would be an accidental reentry into the Earth's atmosphere during a planned VEEGA flyby, releasing Pu238 upon impact with the ground. The very low probability "maximum case" would lead to an increase of an estimated 9.8 cancer fatalities over a 70-year period among a population of 83,000 persons, which normally would have an estimated 16,000 cancer fatalities over the same period.[89]

Antinuclear groups filed lawsuits to prevent the launch, alleging that the spacecraft's two RTGs posed an unacceptable risk to the residents of Florida and making a connection to the Challenger space shuttle accident in 1986 as an unacceptable worst case scenario with nuclear material aboard. Such a potent carcinogen as plutonium-238, they argued, would render large areas of Florida uninhabitable and infect the bones and lungs of millions of people along the coast. Encased in hardened graphite containers, NASA's engineers insisted that the risk was minimal, even in a Challenger-like explosion. Tests on those containers, they argued, had absorbed shocks and concussions more than 10 times as severe as a rocket explosion. The antinuclear activists refused to accept these arguments, noting that 3 of 22 U.S. missions with nuclear material aboard had failed and the nation should not take that chance again, and there the matter rested until adjudicated.

A centerpiece of antinuclear concern—and this may have been one of the driving forces in catalyzing opposition to the launch—was the unique mission profile of the Galileo probe. Because of Galileo's deployment from the Space Shuttle, it would only be able to reach Jupiter using a gravity assist trajectory that required it to pass close to Venus and have two swings past Earth before slingshoting it to Jupiter. This Venus-Earth-Earth-Gravity Assist (VEEGA) mission profile was ingenious in many ways; and it allowed Galileo to encounter many interesting objects in space, including Venus, asteroid 243 Ida, and asteroid 951 Gaspra.[90] Concerned not only about the explosion of the Space Shuttle Challenger in 1986 and the possibility of such an accident with nuclear material aboard but also with this VEEGA trajectory, antinuclear activists redoubled efforts to prohibit the launch. What if the trajectory calculations were slightly off? The possibility for Galileo's uncontrolled reentry into the Earth's atmosphere on one of its flybys only added to larger concerns about the use of nuclear power in space. Protesters had a point, Carl Sagan, allowed. Although a strong supporter of the Galileo mission, and he weighed in with this opinion before the launch in 1989, while also allowing that "there is nothing absurd about either side of this argument."[91]

The lawsuit that went before Judge Oliver Gasch in the U.S. District Court in the District of Columbia argued that NASA had violated the National Environmental Protection Act (NEPA) by failing to fully document the launch dangers in its environmental impact statement. Just two days before the scheduled launch on October 12, 1998, Judge Gasch rendered his decision on this case, ruling that NASA had fulfilled the letter of the law concerning NEPA and that the launch could move forward. "The court will not substitute its own judgment regarding the merits of the proposed action for that of the government agencies," he wrote. "NEPA itself does not mandate particular results, but simply prescribes the necessary process." Having followed the NEPA process, Gasch noted, NASA had appropriately discharged its responsibilities under the law, rejecting the plaintiff's request for a restraining order and directing that NASA continue the Galileo launch on the Space Shuttle. In so doing, NASA finally received permission to proceed but just as this took place the launch had to be delayed because of a technical malfunction on the shuttle.[92] Delaying the launch allowed the antinuclear opposition time to file an appeal, but this appeal was rejected on October 16 by the U.S. Circuit Court of Appeals. Prepared at Kennedy Space Center for protests at the launch rescheduled for October 18—and there were several incidents in the days leading up to launch day—the shuttle finally took off with Galileo in its payload bay. It deployed without further incident once in Earth orbit and began its lengthy journey to Jupiter.[93]

Because of a unique orbital inclination Galileo passed both Venus and Earth and made the first close flyby of asteroid Gaspra in 1991, providing scientific data on all before reaching Jupiter in 1995. Until 2003 Galileo continued to transmit scientific measurements back to Earth for analysis. Galileo's mission has led to a reinterpretation of understanding about Jupiter, its moons, and the outer Solar System. A short list of Galileo's most important discoveries includes the following:

- Evidence for liquid water ocean under Europa's surface, one of the moons of Jupiter.
- The discovery of a satellite (Dactyl) circling the asteroid Ida.
- Discovery of an intense interplanetary dust storm (the most intense ever observed).
- Discovery of an intense new radiation belt approximately 31,000 miles above Jupiter's cloud tops.
- Detection of Jovian wind speeds in excess of 400 mph.
- Far less water was detected in Jupiter's atmosphere than estimated from earlier Voyager observations and from models of the Comet Shoemaker-Levy 9 impact.
- Far less lightning activity (about 10 percent of that found in an equal area on Earth) than anticipated. The individual lightning events, however, are about ten times stronger on Jupiter than the Earth.

- Helium abundance in Jupiter is very nearly the same as its abundance in the Sun (24 percent compared to 25 percent).
- Extensive resurfacing of Io's surface due to continuing volcanic activity since the Voyagers flew by in 1979.
- Preliminary data support the tentative identification of intrinsic magnetic fields for Jupiter's moons, Io and Ganymede.

The flight team for Galileo ceased operations February 2003 after a final playback of scientific data from the robotic explorer's tape recorder. The team prepared commands for the spacecraft's onboard computer to manage the remainder of its life. Galileo coasted for the next seven months before taking a September 21, 2003, plunge into Jupiter's atmosphere as a means of ensuring that its nuclear propellant did not cause any mischief in the future, thereby ending what turned out to be a remarkably successful mission.[94]

The Cassini space probe—the largest interplanetary probe ever launched, weighing 6.3 tons, and extending 22 feet in length—was a joint NASA, European Space Agency (ESA), and Italian Space Agency (ASI) mission to study Saturn and its rings, moons, and magnetic environment. Launched on October 17, 1997, atop a Titan IV rocket from Cape Canaveral, Florida, it required three RTGs with 72 lbs of plutonium 238 to power a wide array of scientific instruments at Saturn. Like Galileo, although without the Space Shuttle as the Earth launch vehicle, Cassini would require gravity assist to reach Saturn in 6.7 years. It followed a Venus-Venus-Earth-Jupiter Gravity Assist (VVEJGA) trajectory that energized the antinuclear community as had nothing since the Galileo launch. Cassini's three general purpose heat source (GPHS) RTGs and 117 lightweight radioisotope heater units (RHU) provided the necessary electrical power to operate its 19 instruments and maintain the temperatures of critical components and the Huygens probe that was destined for deployment by parachute onto the surface of Titan, Saturn's largest moon. Those three RTGs provided 888 W of electrical power at mission beginning, but would still generate 596 W after 16 years of operation. As always, Cassini's RTGs were tested extensively to ensure that they could withstand any conceived destructive force associated with the flight. Also as had been the practice for many years independent safety analyses by General Electric, Lockheed Martin, and other technical organizations considered possible results from pre-launch fires and explosions, launch accidents, and spacecraft crashes and uncontrolled reentry. Three major reports resulted from those efforts, with the final prepared one year in advance of the projected launch.[95]

This material, along with additional studies by the Department of Energy and NASA, went to an independent Interagency Nuclear Safety Review Panel responsible for judging whether or not to recommend a decision in favor or launch to the President of the United States. As a GAO audit of the Cassini mission documented:

> The processes used by NASA to assess the safety and environmental risks associated with the Cassini mission reflected the extensive analysis and evaluation requirements established in federal laws, regulations, and executive branch policies. For example, DOE designed and tested the RTGs to withstand likely accidents while preventing or minimizing the release of the RTG's plutonium dioxide fuel, and a DOE administrative order required the agency to estimate the safety risks associated with the RTGs used for the Cassini mission. Also, federal regulations implementing the National Environmental Policy Act of 1969 required NASA to assess the environmental and public health impacts of potential accidents during the Cassini mission that could cause plutonium dioxide to be released from the spacecraft's RTGs or heater units. In addition, a directive issued by the Executive Office of the President requires an ad hoc interagency Nuclear Safety Review Panel. This panel is supported by technical experts from NASA, other federal agencies, national laboratories, and academia to review the nuclear safety analyses prepared for the Cassini mission. After completion of the interagency review process, NASA requested and was given nuclear launch safety approval by the Office of Science and Technology Policy, within the Office of the President, to launch the Cassini spacecraft.[96]

This detailed and involved process led to the conclusion that while risk could not be eliminated entirely that the chances of any breech of the plutonium-238 container was exceptionally low. The estimated health effect of an accident was that over a 50-year period not one more person would die of cancer caused by radiation exposure than if there were no accident. These analyses also found that during Cassini's Earth encounter there was less than a one in a million chance that the vehicle would accidentally reenter Earth's atmosphere.[97]

None of this review convinced the antinuclear community and it mobilized to prohibit the Cassini launch. The well-organized STOP CASSINI! campaign rested its opposition on a different set of charges than had the earlier Galileo protest; it claimed that NASA's technical risk assessment omitted, neglected, or underestimated the welfare of the public as a whole. Accepting, as the Galileo opponents had not, that NASA had fulfilled the letter of law, this protest asserted that the government as a whole had to be redirected away from the use of nuclear power or weaponry in any form whatsoever. Sociologist Jürgen Habermas has suggested that when the "instrumental rationality" of the bureaucratic state intrudes too precipitously into the "lifeworld" of its citizenry, they rise up in some form to correct its course or to cast it off altogether. The "lifeworld" is evident in the ways in which language creates the contexts of interpretations of everyday circumstances, decisions, and actions. He argues that the "lifeworld" is "represented by a culturally transmitted and linguistically organized stock of interpretive patterns."[98] The STOP CASSINI! campaign represented an effort to exile nuclear material from the "lifeworld" of modern America, as their expressions of discontent demonstrated, and they could obtain no resolution from the "instrumental rationality" residing in the state. They took direct action and justified it without a tinge of conscience as necessary for the greater good.

Opponents of Cassini organized a rally of about 1,500 participants at Cape Canaveral, Florida, in May 1997 with several prominent disarmament leaders speaking. They received publicity from CNN and the NBC local affiliate, as well as print journalists and radio stations. They argued for greater involvement in choosing the technologies used on spacecraft, specifically nuclear power issues. They tried to sensitize the public to dangers from the use of nuclear power for space exploration, and addressed not only environmental risks but also the motives behind the reason for using nuclear power. One protester commented:

> The military has made an unholy alliance with NASA in its quest for space domination. Now people-power and a commitment to compassion and conscience must be brought into an area where it is not wanted and where it is lacking. There must be resistance to the U.S. push to weaponize and nuclearize space…a renegade government spending massive amounts of money to weaponize and nuclearize space, and at the same time saying that no money is available for schools and other social needs. This issue is not about losing our democracy—we have lost it."

The STOP CASSINI! protest received news reporting from many of the major U.S. news outlets, and the Internet buzzed with discussion of its efforts to end the Cassini mission. It deserved credit for gaining the attention of several members of Congress, who demanded additional analysis from NASA and the DOE. Courtroom proceedings, in comparison to Galileo, were virtually non-existent.

When Cassini launched safely on October 14, 1997, the press gave credit to the protesters for forcing NASA to reconsider its use of nuclear power in space and to undertake more extensive testing and verification of systems. A vigil outside the main gate of Kennedy Space Center by the STOP CASSINI! campaign was peaceful. It had raised important questions about this technology and its meaning for society. As one scholar noted, NASA responded poorly to this challenge in terms of public communication. It believed that more information would resolve the crisis, but there is little reason to believe that this would be the case as the protest had more to do with ideology and values than with assessments of objective knowledge.[99]

In the end the Cassini mission has been conducted with stunning success. Cassini is the first spacecraft to orbit Saturn, beginning July 1, 2004, and to send a probe (Huygens) to the surface of Saturn's moon Titan on January 15, 2005. But even before its Saturnian encounter, the Cassini mission advanced science by finding individual storm cells of upwelling bright-white clouds in dark "belts" in Jupiter's atmosphere, and by conducting a radio signal experiment on October 10, 2003, that supported Einstein's theory of general relativity. At Saturn, Cassini has discovered three new moons (Methone, Pallene and Polydeuces), observed water ice geysers erupting from the south pole of the moon Enceladus, obtained images appearing to show lakes of liquid hydrocarbon (such as methane and ethane) in Titan's northern latitudes, and discovered a storm at the south pole of Saturn with a distinct eye wall. Cassini, like Galileo at Jupiter, has demonstrated that icy moons orbiting gas giant planets are potential refuges of life, and attractive destinations for a new era of robotic planetary exploration.[100]

IX. Conclusion

The use of radioisotope thermoelectric generators to power spacecraft to the outer planets has proven a boon to the space program in the first fifty years of its history. Yet, use of this technology invites opposition because of the danger inherent in any launch or reentry to the atmosphere. There have been failures in the past, duly taken notice of by the public, and in each instance refinements and additional requirements to ensure future safety have resulted. This is as it should be. The issue had receded from the public's consciousness by 2006—in no small measure because of the success of the safety program, the efforts to ensure public understanding of how mission surety was undertaken, and the rarity of the use of RTGs—that the New Horizons spacecraft launched to Pluto and the Kuiper Belt in the outer solar system did not receive much public opposition. From a societal perspective, however, the protests to past launches raised important questions that remain at the center of the debate. As scholar Victoria Friedensen commented:

1. NASA provided inadequate assessment that did not include multi-failure mode testing and had inadequate explanations of the risk.

2. The risk to the citizens and visitors to the region around the Kennedy Space Center, while low in probability, had very high consequence. Nor was the liability to be born by NASA alone—the public would bear the costs of the consequences. NASA was not perceived as trustworthy enough to prevent accidents.
3. The risk to the global population was untenable for a scientific project. The protestors did not feel that the United States was truly responsible for the lives and well-being of all humans. No one asked global consent before increasing global risk.
4. The potential destructive capabilities that humans have created on Earth must not be carried into the future or onto other planets. The protestors based their opposition on strictly moral, strictly future terms and objected to NASA's counter proposition. An incommensurability of world views fueled the controversy.[101]

Such concerns are entirely appropriate and require additional consideration in the future as humanity seeks to extend its presence throughout the solar system. The story of RTGs and space nuclear power, therefore, is one of technological advance and concern from certain segments of society that the consequences of that technological advance might be too great a burden for the public to bear.

Physician and policy analyst Daniel Sarewitz points up the problem in the larger framework of U.S. government science and technology decision-making:

> At present, most citizens have only two options for involving themselves in decision making about science and technology—the diffuse mechanisms of voting, and the direct but often unmediated local action that is commonly associated with not-in-my-backyard sentiments. A middle ground that enhances opportunities for public participation, while also providing mechanisms for technical input and open dialogue between scientists and the laity remains to be defined…It does depend on the creation of avenues by which the public judgment can be brought to bear on important issues of science and technology policy, and on granting the public a stake in decision-making processes. The policy goal is not to substitute "common sense" for technical knowledge but to allow democratic dialogue to play its appropriate role in decision making that is inevitably dominated not by authoritative data but by subjective criteria and social norms.[102]

Advancing the future of nuclear power for space exploration remains a task not without difficulties. In the aftermath of the controversies over Galileo and Cassini, without significant social input and conscientious efforts to involve a broad constituency more aggressive efforts will probably have considerable difficulty getting past the stage of paper studies. As it stands at present the continued use of nuclear power for spacecraft must remain, to adopt a phrase concerning the legality of abortion offered by President Bill Clinton, "safe, legal, and rare."

X. Notes

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