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Background on Space Nuclear Power

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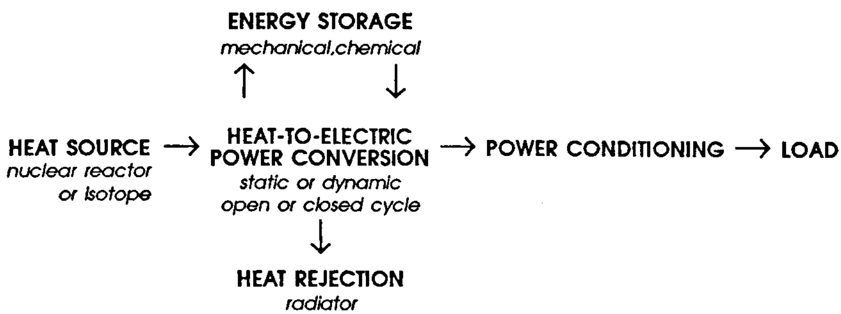
This paper introduces the technology of space nuclear power, reviews the history of its deployment, provides background information on current development programs, and examines the proposed applications of space nuclear power systems.

SPACE POWER CONCEPTUAL DESIGN SUMMARY

A space nuclear power system converts the energy from a nuclear heat source into electricity to power a particular load or application. The elements of this process may be outlined as follows:



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Two basic types of nuclear power supply have been used in space—nuclear reactors and radioisotope sources. In a space nuclear reactor system, the energy source is the heat generated by the controlled fission of uranium. This heat is transferred by a heat-exchange coolant to either a static (for example, thermoelectric) or dynamic (for example, turbine/alternator) conversion system, which transforms it into electricity. This electricity can then be "conditioned" into the form needed by the payload. Waste heat is rejected through a radiator.

In an isotope power supply, the heat is produced by the natural decay of a radioisotope, which in all US–launched systems is plutonium-238.[1] This heat, like that produced by reactors, can be converted to electricity by a static converter or by a dynamic conversion system. And again, this electricity is conditioned to meet payload requirements, and waste heat is radiated away.

Nuclear power supplies offer significant reductions in mass, compared with the alternatives, when power needs exceed several tens of kilowatts for more than several days. Quantitative estimates for the chemical and solar power equivalents to the SP-100 and multi-megawatt space nuclear reactors are listed in table 1. The general applicability of various energy sources, nuclear and non-nuclear, for a range of power and duration requirements is illustrated in figure 1. For all practical purposes, nuclear reactors are required when moderate to high levels of continuous power are required for an extended period.

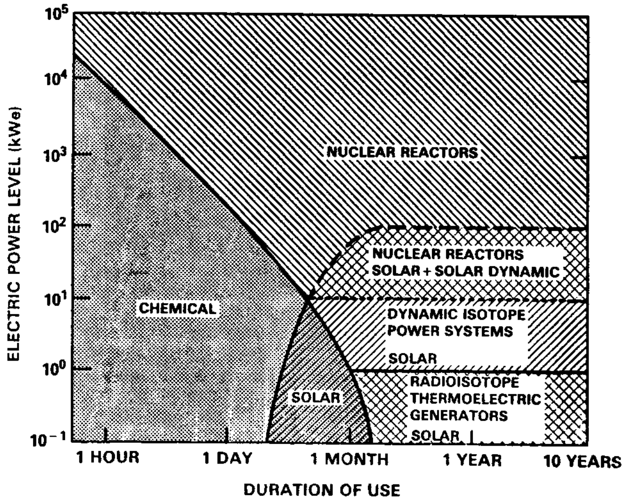

Figure 1: Regimes of Possible Space Power Applicability

Source: DoE

Table 1: Solar and Chemical Power Equivalents of Two Space Reactors

	Nominal projected mass *kg*	Chemical equivalent mass *kg* (1 kWhr/kg)	Solar panel equivalent mass *kg* (10W/kg)	Solar panel equivalent area m^2 (130W/m²)
SP-100 *100 kWe, 7 years*	~5,000	~6×10^6	10,000	750
Multi-megawatt *10 MWe, 1 year*	~50,000	~9×10^7	1×10^6	75,000

HISTORY OF SPACE NUCLEAR POWER

US Programs

The US began to develop small nuclear power sources for use in space in 1955 as part of the SNAP (Systems for Nuclear Auxiliary Power) program.

The US has launched a total of 22 spacecraft powered by one or more radioisotope thermal generators (RTGs). In addition, the US has deployed one reactor-powered satellite. A list of these space nuclear power systems is presented in table 2. The sources used in these missions were all quite low power. The most powerful, the SNAP 10A reactor, generated only 500 watts of electricity.

The US space reactor program was shelved in 1973, because no missions then required a space reactor. It was not revived until the start of the SP-100 program, described below.

The most recent US RTG-powered spacecraft was launched in 1977. NASA's *Galileo* voyage to Jupiter is the next RTG-powered mission and as of early 1989 was scheduled for launch in October 1989.

Soviet Programs

The Soviet Union has launched over 30 nuclear reactor powered satellites and several RTG-powered satellites and lunar modules. A list of nuclear powered spacecraft launched by the USSR is presented in table 3.

Space reactors are used by the Soviet Union to power their Radar Ocean Reconnaissance Satellites (RORSATs), which track and target US naval vessels. The altitude of a RORSAT orbit is typically between 270 and 255 kilometers. This low orbit, which enhances the satellite's radar capability, also dictates the use of nuclear power rather than solar panels, since the latter would increase drag and significantly shorten the lifetime of the orbit. In addition, solar-powered spacecraft would require an electrical storage system for operation in the Earth's shadow, adding mass and technical complexity.

At the end of a RORSAT's mission of typically two to three months, the reactor is designed to separate from the satellite and be boosted to a

Table 2: Space Nuclear Power Systems Launched by the US

launch date	Spacecraft	Power source	Mean altitude *km*	Status/ lifetime
29 Jun 1961	Transit 4A	RTG*	930	shut down
15 Nov 1961	Transit 4B	RTG	1,030	nonoperational
28 Sep 1963	Transit-5BN-1	RTG	1,095	9 months
5 Dec 1963	Transit-5BN-2	RTG	1,085	nonoperational
21 Apr 1964	Transit-5BN-3	RTG		aborted
3 Apr 1965	Snapshot	reactor	1,290	43 days
18 May 1968	Nimbus-B-1	RTG		aborted
14 Apr 1969	Nimbus III	RTG	1,100	nonoperational
14 Nov 1969	Apollo 12	RTG		on lunar surface
11 Apr 1970	Apollo 13	RTG		aborted
31 Jan 1971	Apollo 14	RTG		on lunar surface
26 Jul 1971	Apollo 15	RTG		on lunar surface
2 Mar 1972	Pioneer 10	RTG		beyond Pluto
16 Apr 1972	Apollo 16	RTG		on lunar surface
2 Sep 1972	Transit-01-1X	RTG	770	RTG operating
7 Dec 1972	Apollo 17	RTG		on lunar surface
5 Apr 1973	Pioneer 11	RTG		beyond Saturn
20 Aug 1975	Viking 1	RTG		on Mars
9 Sep 1975	Viking 2	RTG		on Mars
14 Mar 1976	LES 8	RTG	35,785	RTGs operating
14 Mar 1976	LES 9	RTG	35,785	RTGs operating
20 Aug 1977	Voyager 2	RTG		beyond Uranus
5 Sep 1977	Voyager 1	RTG		beyond Saturn

* All US RTGs are fueled by plutonium-238; the *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**, 4, October-December 1981, pp.321–342; Nicholas L. Johnson, "Nuclear Power Supplies in Orbit," *Space Policy*, August 1986, pp.223–233. Mean altitude given as of 1 January 1986.

Table 3: Nuclear Powered Spacecraft Launched by the USSR

launch date	**Spacecraft**	**Power source**	**Mean altitude** *km*	**Lifetime**
3 Sep 1965	Cosmos 84	RTG*	1,500	
18 Sep 1965	Cosmos 90	RTG	1,500	
27 Dec 1967	Cosmos 198	reactor	920	1 day
22 Mar 1968	Cosmos 209	reactor	905	1 day
25 Jan 1969	possible RORSAT launch failure			
23 Sep 1969	Cosmos 300	RTG	re-entered	
22 Oct 1969	Cosmos 305	RTG	re-entered	
3 Oct 1970	Cosmos 367	reactor	970	1 day
1 Apr 1971	Cosmos 402	reactor	990	1 day
25 Dec 1971	Cosmos 469	reactor	980	9 days
21 Aug 1972	Cosmos 516	reactor	975	32 days
25 Apr 1973	RORSAT launch failure			
27 Dec 1973	Cosmos 626	reactor	945	45 days
15 May 1974	Cosmos 651	reactor	920	71 days
17 May 1974	Cosmos 654	reactor	965	74 days
2 Apr 1975	Cosmos 723	reactor	930	43 days
7 Apr 1975	Cosmos 724	reactor	900	65 days
12 Dec 1975	Cosmos 785	reactor	955	1 day
17 Oct 1976	Cosmos 860	reactor	960	24 days
21 Oct 1976	Cosmos 861	reactor	960	60 days
16 Sep 1977	Cosmos 952	reactor	950	21 days
18 Sep 1977	Cosmos 954	reactor	re-entered	~43 days
29 Apr 1980	Cosmos 1176	reactor	920	134 days
5 Mar 1981	Cosmos 1249	reactor	940	105 days
21 Apr 1981	Cosmos 1266	reactor	930	8 days
24 Aug 1981	Cosmos 1299	reactor	945	12 days
14 May 1982	Cosmos 1365	reactor	930	135 days
1 Jun 1982	Cosmos 1372	reactor	945	70 days
30 Aug 1982	Cosmos 1402	reactor	re-entered	120 days
2 Oct 1982	Cosmos 1412	reactor	945	39 days
29 Jun 1984	Cosmos 1579	reactor	945	90 days
31 Oct 1984	Cosmos 1607	reactor	950	93 days
1 Aug 1985	Cosmos 1670	reactor	950	83 days
23 Aug 1985	Cosmos 1677	reactor	940	60 days
21 Mar 1986	Cosmos 1736	reactor	950	92 days
20 Aug 1986	Cosmos 1771	reactor	950	56 days
1 Feb 1987	Cosmos 1818	reactor	800	~6 months
18 Jun 1987	Cosmos 1860	reactor	950	40 days
10 Jul 1987	Cosmos 1867	reactor	800	~1 year
12 Dec 1987	Cosmos 1900	reactor	720	~124 days
14 Mar 1988	Cosmos 1932	reactor	965	66 days

* The RTGs are believed to be fueled by polonium-210, which has a half-life of 138.39 days.

Source: Nicholas L. Johnson, "Nuclear Power Supplies in Orbit," *Space Policy*, August 1986, pp.227, 228. Revised and updated by personal communication with Johnson, 24 June 1988. Mean altitude is given as of 1 January 1986 for pre-1986 launches. *Cosmos 1818* and *Cosmos 1867* are believed to be flight tests of a new Topaz-type reactor.

higher, long-lived orbit of about 950 kilometers. Booster failure resulted in the premature re-entry of the reactor aboard *Cosmos 954* in 1978, which scattered radioactive debris over northwest Canada.

Following that incident, the system was redesigned to expel the reactor core from the reactor at the end of the mission to facilitate disintegration in the high atmosphere in the event of re-entry. This was the case when *Cosmos 1402* re-entered in 1983. Even when boosting is successful, the reactor core is still ejected once the higher orbit is attained.

Further design changes were disclosed in 1988 that included automated boost systems.[2] These are triggered by one of three failures: a loss of attitude control, reactor depressurization, or disruptions in the electrical system. The first of these apparently triggered the last-minute boost of *Cosmos 1900* in 1988.

Published details of Soviet space nuclear power programs are sparse and sometimes contradictory.[3] In 1988, however, the Soviets issued information on the *Cosmos 1900* reactor:[4]

> The reactor's core consists of 37 cylindrical heat-releasing elements with facing beryllium reflectors. A uranium-molybdenum alloy with 90 percent uranium-235 enrichment is used as nuclear fuel (total weight 31.1 kilograms)....

Also, judging from an analysis of the *Cosmos 954* debris, these Soviet space reactors operate on fast neutrons.

Soviet officials recently disclosed that two new "Topaz" reactors were flight-tested in 1987–88.[5] The tests were performed at a power level of 10 kilowatts electric at orbits of about 800 kilometers altitude and with an operating time of 6 months and 1 year respectively. The satellites bearing the Topaz reactors have been tentatively identified by Western observers as *Cosmos 1818* and *Cosmos 1867*.[6]

SPACE NUCLEAR POWER ACCIDENTS AND FAILURES

A remarkably large fraction—about 15 percent—of all US and Soviet nuclear powered space missions have ended in accidents, launch aborts, or other failures. These incidents are briefly described below in chronological order:[7]

♦ 1964

When the US *Transit-5BN-3* navigational satellite failed to achieve orbit on 21 April, its SNAP 9A RTG power source disintegrated in the atmosphere (as it was designed to do in case of re-entry) at an altitude of about 50 kilometers. Release of its 17,000 curies of plutonium-238 tripled the worldwide environmental inventory of plutonium-238 and increased the total world environmental burden (measured in curies) from all plutonium isotopes (mostly fallout from atmospheric nuclear weapons testing) by about 4 percent.[8]

♦ 1968

On 18 May, the US *Nimbus-B-1* meteorological satellite was aborted following a launch failure, and fell into the Pacific Ocean just off the California coast. Five months later, its two SNAP 19A RTGs were retrieved intact.

♦ 1969

A Soviet launch failure occurred on 25 January that may have involved a nuclear powered RORSAT.

♦ 1969

On 23 September and 22 October the USSR launched unmanned probes to the moon. Both achieved earth orbit, but re-entered the atmosphere a few days later. According to various sources, one or both of them carried a polonium-210 heat source. Measurable amounts of radioactivity were detected in the atmosphere following re-entry.[9]

♦ 1970

A US moon mission, *Apollo 13*, was aborted in April. Its jettisoned lunar lander fell into the Pacific Ocean. The SNAP 27 plutonium power supply has never been recovered, but atmospheric sampling detected no release of radioactivity, and the RTG is assumed to have remained intact.

♦ 1973

On 25 April a Soviet nuclear powered RORSAT fell into the Pacific Ocean after a launch failure.

♦ 1978
In one of the most serious accidents involving space nuclear power, the Soviet *Cosmos 954* re-entered the atmosphere on 24 January, spreading thousands of pieces of radioactive debris over more than 100,000 square kilometers of northwest Canada.[10] A few fragments were highly radioactive (gamma radiation as high as 500 roentgens per hour near contact).

♦ 1983
The jettisoned reactor core from *Cosmos 1402* re-entered the atmosphere on 7 February, where it disintegrated and was dispersed.[11]

♦ 1988
Radio contact with *Cosmos 1900* was lost in April, preventing a directed boost of the satellite to a high-altitude disposal orbit. Backup systems were finally activated on September 30, just days before anticipated re-entry, and the on-board reactor was boosted to a higher orbit.[12]

CURRENT US SPACE NUCLEAR POWER PROGRAMS

SP-100

The US has several space nuclear power development programs under way. The SP-100 reactor is the cornerstone of this effort. Its design is still under revision, but many of the important design parameters have been determined, at least tentatively, and these are presented in table 4. The SP-100 System Configuration is illustrated in figure 2. A more detailed view of the reactor itself is portrayed in figure 3. The gamma and neutron radiation profiles of a preliminary SP-100 design are summarized in table 5.

The proposed SP-100 has a power level of 2.3 megawatts thermal, which is converted thermoelectrically into 100 kilowatts electric. The mass-to-power objective for the reactor is 30 kg/kWe. The actual estimated weight of the reference design is about 4,600 kilograms, or 46 kg/kWe. The reactor subsystem, including reactor vessel and shielding, is quite small, occupying roughly a cubic meter in volume. The SP-100 as a whole, however, is considerably less compact, with an overall length of about 25 meters and a radiator panel surface area of about 100 square meters.

Table 4: Selected SP-100 Design Parameters

Thermal power	2.3 megawatts
Electric power	100 kilowatts
Operational lifetime	7 years full power over a 10-year period
Fuel	uranium nitride
Fuel mass	~190 kilograms
Fuel enrichment	89–97 percent uranium-235
Energy conversion	thermoelectric
Radiator area	106 square meters
Radiator temperature	~800 kelvins
Reactor vessel diameter	35 centimeters
Neutron shield	lithium hydride
Gamma shield	tungsten
Total shield mass	1,000 kilograms

Based on proceedings of the SP-100 Project Integration Meeting, 19–21 July 1988, Long Beach, California.

Table 5: SP-100 Radiation Profile

	Core center	**Unshielded reactor surface**	**Shield surface**	**Payload surface*** (~23 meters)
Fast neutrons *(n/cm^2 over 7 years)*	$\sim 1 \times 10^{23}$	$\sim 3 \times 10^{21}$	$\sim 3 \times 10^{15}$	4×10^{12}
Fast neutron flux *(n/cm^2-sec)*	5×10^{14}	$\sim 1.3 \times 10^{13}$	$\sim 1.3 \times 10^{7}$	2×10^{4}
Gamma *(rads over 7 yrs)*	$\sim 1 \times 10^{13}$	$\sim 5 \times 10^{11}$	$\sim 2 \times 10^{8}$	5×10^{5}
Gamma *(rads/sec)*	4.5×10^{4}	$\sim 2.3 \times 10^{3}$	$\sim 9 \times 10^{-1}$	2.3×10^{-3}

Neutron attenuation by shield:	7.5×10^{5}
Gamma attenuation factor by tungsten:	70
by lithium hydride:	50
Total gamma attenuation by shield:	3.5×10^{3}

* These estimates include neutron and gamma attenuation due to the separation distance involved as well as to shielding. Based on General Electric's *SP-100 Ground Engineering System Baseline Design Study*, 1984, pp.3–28.

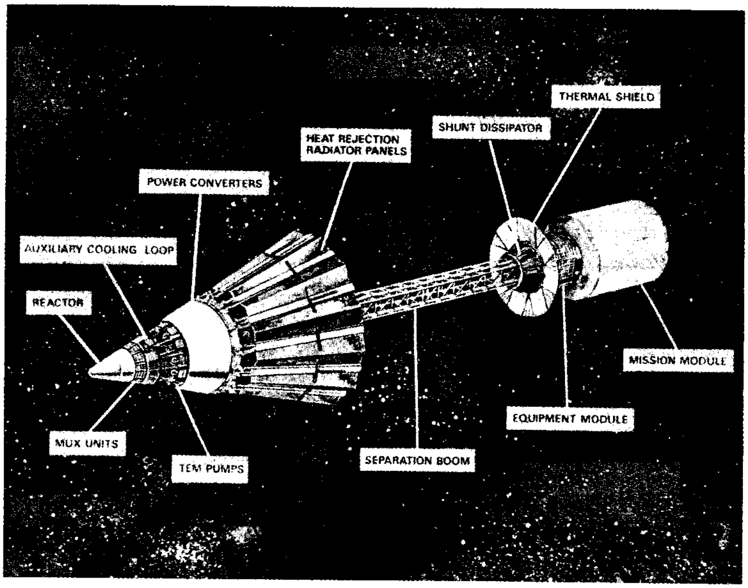

Figure 2: SP-100 Deployed Configuration

Source: Jet Propulsion Lab

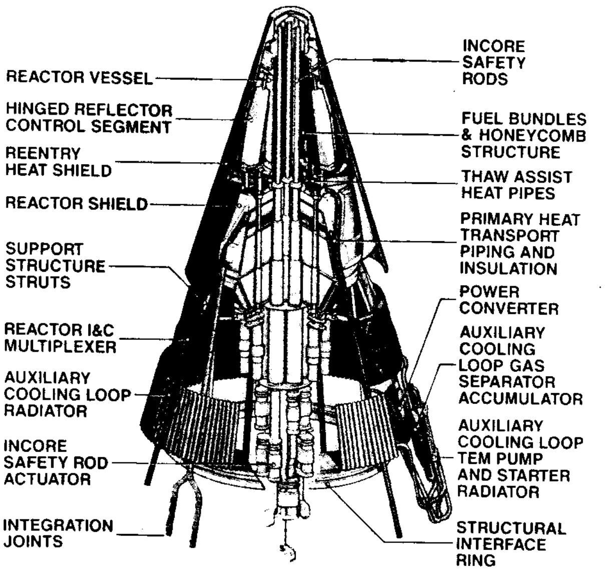

Figure 3: SP-100 Reactor Power Assembly

Source: Jet Propulsion Lab

The SP-100 design concept could be downscaled to about 10 kilowatts electric or upscaled to about 1 megawatt electric. Above 1 megawatt electric it would be unacceptably heavy; therefore this concept is not suitable for multi-megawatt applications.

Multi-megawatt Reactors

The US Department of Energy is also investigating the feasibility of developing space nuclear reactors with power levels above 1 megawatt electric in its Multimegawatt (MMW) Program. Budget limitations will probably push design concept selection beyond 1991, and final development of a MMW reactor beyond the year 2000.

More than a dozen MMW system concepts have been proposed, but many major feasibility issues remain to be resolved. The Department of Energy has subdivided the multi-megawatt reactor requirements into three categories:[13]

- Tens of megawatts, open cycle (working fluid vented)
- Tens of megawatts, closed cycle
- Hundreds of megawatts for hundreds of seconds, open or closed cycle.

Isotope Power Systems

The isotope power systems are divided into radioisotope thermal generators (RTGs), which use thermoelectric conversion, and dynamic isotope power systems (DIPS), which employ dynamic energy conversion. Both systems use plutonium-238 as the radioisotope heat source.

RTGs have evolved over the last 30 or so years from the early SNAP systems up to today's General Purpose Heat Source (GPHS), which is intended to be used aboard NASA's *Galileo* (two RTGs) and *Ulysses* (one RTG) missions. The GPHS will have a thermal power of 4.4 kilowatts and will contain a total plutonium mass of 9.4 kilograms.[14]

Radioisotope heat sources are also used in small quantities to provide thermal energy to critical spacecraft components that might be adversely affected by low temperatures. The *Galileo* mission to Jupiter would use about 130 such Light-Weight Radioisotope Heater Units (LWRHU) (1 watt thermal per unit) in addition to its two GPHS RTGs.[15]

A DIPS would provide electric power in the range 1–10 kilowatts electric. Above about 1 kilowatt, RTGs are no longer acceptably low in mass. Above 10 kilowatts, the mass of a DIPS power supply becomes excessive, and a small nuclear reactor becomes the preferred option.

DIPS proponents point out that DIPS has a lower infrared signature (less heat radiated: see below), lower radar signature (it is compact), and a lower nuclear signature (neutron or gamma emission) compared with fission reactors.[16]

However, a single 6-kWe DIPS system would require a rather stunning 53 kilograms of plutonium-238.[17] This is about two and a half times the amount of fallout of all plutonium isotopes (measured in curies) from all atmospheric nuclear weapons tests.

MILITARY APPLICATIONS OF SPACE NUCLEAR POWER[18]

The applications of current and proposed space nuclear power supplies, particularly in earth orbit, are predominantly military.

As noted above, the Soviet Union uses nuclear reactors to power reconnaissance satellites that track and target US naval vessels.[19]

In the US, the various space nuclear power programs are driven by the Strategic Defense Initiative, with its development of high-powered space weapons and associated orbiting platforms. Without SDI, there would be little US demand in the near term for most of the space nuclear power supplies now being developed.

Because the architecture of a Strategic Defense System is far from being finally determined, it is impossible to define the precise role of nuclear power in the ultimate system. But there is a broad consensus among the Strategic Defense Initiative Organization, the Department of Energy, the American Physical Society (APS) Study Group on Directed Energy Weapons, and the Office of Technology Assessment that nuclear power reactors in space are likely to be an essential component of the later phases of SDI—those that would employ directed energy weapons.

Members of the APS Panel explained that even[20]

> a few tens of kilowatts of electrical power necessitates nuclear power reactors for two reasons. First is survivability: The large area needed for solar cells would make a satellite very vulnerable to actions of the offense. Second is

reliability: The long expected stay in orbit could reduce the availability of power [from solar cells] because of the radiation damage that occurs over 10-year time scales....

SDI officials have divided their power needs into three categories: housekeeping (or baseload), alert mode, and burst mode. Housekeeping would require from several up to about 100 kilowatts electric of continuous power for various maintenance and control functions, such as surveillance, communication, data processing, attitude control, and refrigeration, throughout the life of the system. The alert mode would be engaged at a time of impending conflict and, according to the SDI Organization, could require as much as 10 megawatts of electricity for up to a total of perhaps one year over the entire mission lifetime. The burst mode, involving the actual pulsing of a directed energy weapon, could require hundreds of megawatts or more for tens to hundreds of seconds. Preliminary estimates of power requirements for specific SDI systems are presented in table 6.

Table 6: Estimated Average Power Requirements for Space Assets *kW*

Mode of operation	Base	Alert	Burst
Boost surveillance and tracking satellite	4–10	4–10	4–10
Space surveillance and tracking satellite	5–15	5–15	15–50
Laser radar (Ladar)	15–20	15–20	50–100
Ladar imager	15–20	15–20	100–500
Laser illumination	5–10	5–10	50–100
Doppler ladar	15–20	15–20	300–600
Space-based interceptor carrier	2–30	4–50	10–100
Chemical laser	50–100	100–150	100–200
Fighting mirror	10–50	10–50	20–100
Neutral particle beam/ Space-based free electron laser	20–120	1,000–10,000	1×10^5–5×10^5
Electromagnetic launcher (railgun)	20–120	1,000–10,000	2×10^5–5×10^6

Source: Strategic Defense Initiative Organization. Reprinted in *SDI: Technology, Survivability, and Software* (Washington DC: US Congress, Office of Technology Assessment, OTA-ISC-353, May 1988), p.142.

NOTES AND REFERENCES

1. Production-grade plutonium-238 actually consists of about 83 percent plutonium-238, 15 percent plutonium-239, and small amounts of other plutonium isotopes. The half-life of plutonium-238 is 87.8 years.

2. See the testimony of Daniel Hirsch in "Cosmos 1900 and the Future of Space Nuclear Power," hearings before the Committee on Energy and Natural Resources, United States Senate, 13 September 1988. See also T.M. Foley, "Soviet Nuclear-Powered Satellite Expected to Reenter Within 30 Days," *Aviation Week & Space Technology*, 19 September 1988, p.20.

3. R. Townsend Reese and Charles P. Vick, "Soviet Nuclear Powered Satellites," *Journal of the British Interplanetary Society*, **36**, 1983, pp.457–462, is interesting, though it contains inconsistencies. Nicholas L. Johnson, "Nuclear Power Supplies in Orbit," *Space Policy*, August 1986, pp.223–233, is extremely informative, as is Johnson's annual *Soviet Year in Space* (Colorado Springs, Colorado: Teledyne Brown Engineering).

4. Report by the USSR State Committee for the Use of Atomic Energy, submitted to the International Atomic Energy Agency, reprinted in a telegram from the US Mission in Vienna, Austria, to the US Secretary of State, 27 September 1988.

5. William J. Broad, "Russians Disclose Satellites Carry New Reactor Type," *New York Times*, 15 January 1989, p.A1; "Nuclear Power Plant for Space Vehicles Developed," Tass News Agency, 5 January 1989.

6. Personal communication, Nicholas Johnson, 24 June 1988.

7. Further information and source citations may be found in S. Aftergood, "Nuclear Space Mishaps and Star Wars," *Bulletin of the Atomic Scientists*, October 1986, pp.40–43.

8. E.P. Hardy, P.W. Krey, and H.L. Volchok, "Global Inventory and Distribution of Fallout Plutonium," *Nature*, 16 February 1973, p.444.

9. Johnson, 1986, p.227; William J. Broad, "Satellite's Fuel Core Falls 'Harmlessly'," *New York Times*, 8 February 1983, pp.C1,C2.

10. W.K. Gummer et al., *Cosmos 954: The Occurrence and Nature of Recovered Debris*, (Hull, Quebec: Canadian Government Publishing Center, INFO-0006, May 1980), p.11.

11. Robert Leifer et al., "Detection of Uranium from Cosmos-1402 in the Stratosphere," *Science*, 238, 23 October 1987, pp.512–3.

12. William J. Broad, "Soviet Nuclear Powered Satellite Expected to Hit Earth in Summer," *New York Times*, 14 May 1988; William Harwood, "Crippled Soviet Satellite Fires Reactor into 'Graveyard' Orbit," *Washington Post* (UPI), 2 October 1988, p.A6.

13. Philip J. Klass, "Technical, Political Concerns Impede Space Nuclear Power," *Aviation Week & Space Technology*, 1 February 1988, p.59.

14. Gary L. Bennett et al., "The General Purpose Heat Source Radioisotope Thermoelectric Generator: Power for the Galileo and Ulysses Missions," *Proceedings of the 21st Intersociety Energy Conversion Engineering Conference*, volume 3, August 1986, pp.1999–2011.

15. *Light-Weight Radioisotope Heater Unit Safety Analysis Report*, Report MLM-3293, October 1985.

16. Gary L. Bennett and James J. Lombardo, "Technology Development of Dynamic Isotope Power Systems for Space Applications," *Proceedings of the 22nd Intersociety Energy Conversion Engineering Conference*, volume 1, August 1987, pp.366–372. DIPS has recently been redesignated as TECS (Turbine Energy Conversion System).

17. Assuming 20 percent conversion efficiency, and 0.56 Wth/gram plutonium-238.

18. For further information on applications, see S. Aftergood, "Towards a Ban on Nuclear Power in Earth Orbit," *Space Policy*, February 1989, pp.25–40.

19. Nicholas L. Johnson, *The Soviet Year in Space 1985* (Colorado Springs, Colorado: Teledyne Brown Engineering, 1985), p.39; see also US Department of Defense, *Soviet Military Power 1985*, p.53; and *Aviation Week & Space Technology*, 26 August 1985, p.23.

20. "Debate on APS Directed-Energy Weapons Study," *Physics Today*, November 1987, pp.52–53.