Nuclear Power in Space

The best course for space-borne reactors? Ban them from Earth orbit and use them in deep space, the authors say

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Space nuclear power is a double-edged sword. Although it has played a constructive role in the exploration of space and could continue to do so, it has been burdened by an extensive history of accidents and failures, both Soviet and American. Numerous nuclear-powered spacecraft have released radioactive materials. Spent reactors now in Earth orbit exacerbate the threat posed by orbital debris. And radiation from orbiting reactors has interfered with the operation of other satellites.

In addition, nuclear power in space has in general been a source of international tension because of its role in Soviet and American military space programs. As a result, organizations of both Soviet and American scientists (of which we are members) have proposed banning the use of nuclear power in Earth orbit. Such a ban would reduce the risks associated with nuclear power in space, while permitting its use in those deep-space missions for which nuclear power is essential.

The first nuclear-powered spacecraft was Transit 4A, a navigational satellite launched by the U.S. in 1961. Transit used a radioisotope thermoelectric generator (RTG), which converted heat from decaying plutonium 238 to electricity. The first nuclear accident in space came less than three years later: Transit SBN-3, the fifth RTG-powered craft to be launched, failed to achieve orbit in April 1964. Its power source disintegrated in the atmosphere (as early RTGs were designed to do) at an altitude of about 50 kilometers. Release of its 17,000 curies of plutonium 238 fuel tripled the worldwide inventory of this isotope and increased the total world environmental burden of all plutonium isotopes—mostly from atmospheric testing of nuclear weapons—by about 4 percent. (Current RTGs contain an order of magnitude more radioactive material.)

In 1965 the U.S. launched its first and only space nuclear reactor, the prototype SNAP-10A. (Reactors generate heat by means of a controlled fission chain reaction rather than simple radioactive decay.) The SNAP-10A operated for 43 days; it is still in orbit. Later that same year the U.S.S.R. sent its first RTG-powered satellites into space. It also launched radioisotope-powered Lunokhod lunar modules in 1969 and 1973.

After 1970, however, the Soviet program largely revolved around the Radar Ocean Reconnaissance Satellite (RORSAT), used to monitor U.S. naval forces. The small reactors on board these craft produce about two kilowatts of electricity. Although a RORSAT's power requirements could be met by solar panels, the craft uses a reactor because solar panels would cause too much drag at the RORSAT's typical altitude of around 250 kilometers. The limited range of the craft's radar necessitates the low orbit.

After a lifetime of several months, a RORSAT's reactor is ordinarily boosted to a "disposal orbit" at approximately 950 kilometers, while the body of the spacecraft reenters the atmosphere. The disposal orbit of the reactor guar-
CLEANING UP AFTER RORSAT: a Soviet surveillance satellite (Cosmos 954) reentered the earth's atmosphere over the Northwest Territories in 1978, littering radioactive debris over thousands of square miles. In the photographs above, workers gather both large and small fragments of the satellite and its reactor. Decontamination cost the Canadian government approximately $10 million. Proposed U.S. nuclear-powered spacecraft would produce hundreds of times as much radioactivity.
The Next Step in Space Nuclear Power?

There are two fundamental sources of nuclear power for applications in space: reactors and radioisotope power supplies. Whereas a reactor produces heat through the controlled fission of uranium fuel, a radioisotope thermoelectric generator, or RTG, derives heat simply from the decay of a highly radioactive material. In both cases, the heat is converted to electric power. The RTG is best suited for power requirements of less than a few kilowatts, the reactor for higher power levels.

Although the U.S. has launched only one nuclear reactor into orbit, an ambitious reactor development project has been under way for most of the past decade [see illustration below]. As currently planned, the SP-100 reactor would generate approximately 100 kilowatts of electricity from 2.5 megawatts of thermal power—far more power than any reactor flown to date. It would contain about 190 kilograms of uranium nitride fuel enriched to 96 percent in the fissionable isotope uranium 235.

The entire reactor is intended to weigh approximately 3,000 kilograms, a mass-to-power ratio of 30 kilograms per kilowatt. Except for a small "shadow shield," which helps to protect the payload from the intense radiation emitted during operation, the SP-100 is designed to be unshielded.

The reactor would be cooled by liquid lithium metal, which would flow through pipes to thermoelectric cells—circuits containing junctions between dissimilar metals that can transform a temperature difference into a voltage difference. These cells would convert about 4 percent of the reactor-generated heat into electricity. The considerable waste heat would be ejected through a set of radiator panels with a surface area of around 100 square meters.

Nearly every component of the SP-100 design extrapolates beyond existing technological experience, making it uncertain whether the program will be able to achieve its goals. Moreover, the reactor has been designed in the absence of a proposed mission, and so any specific application is likely to require substantial revision.

Flight-testing of the SP-100 will not be possible before the turn of the century; cost estimates for the test alone exceed $1 billion, a discouragingly large sum. Furthermore, as the program moves toward its second decade, a specific mission for the SP-100 has still not been defined.

antees that it will not reenter the atmosphere for several hundred years, by which time most of its radioactivity will have decayed.

Between 1970 and 1988 the Soviets deployed 31 RORSATs. The jettisoned reactors from 29 of these systems are still in orbit, along with hundreds of kilograms of radioactive fuel. Two have reentered accidentally. Cosmos 954 fell to the earth on January 24, 1978, spreading radioactive debris over thousands of square miles of northwestern Canada. U.S. President Jimmy Carter immediately proposed a ban on orbiting nuclear-powered satellites, but the U.S.S.R. did not respond.

After the Cosmos 954 incident, the Soviet Union introduced a backup fuel-core ejection system, so that in the event of accidental reentry, the fuel would disintegrate in the atmosphere. This measure increases the total population that may eventually be exposed to radiation, but it minimizes the exposure received by any single person. In 1983 the fuel core on board Cosmos 1402 at least partially disintegrated in the upper atmosphere over the South Atlantic Ocean.

Another RORSAT, Cosmos 1900, ceased to respond to radio commands in April 1988. Days before its anticipated reentry, however, an automated backup booster system was successfully activated, and the reactor was lifted to a high orbit. The Soviet Union has not launched any additional RORSATs (or other space nuclear power systems) since then.

In 1987 the Soviets flight-tested the Topaz, a next-generation reactor. One flew on board Cosmos 1818 and operated for six months; the other, on board Cosmos 1867, operated for a year. Each generated about 10 kilowatts of electricity. The Soviets have since offered Topaz reactors for sale to Western nations, and the U.S. government has purchased an unfueled version for ground testing and development.

It is possible to detect a learning curve in the history of nuclear power in space. The identical type of accident has never happened twice. Designers have learned such obvious lessons as encapsulating RTG power sources so that they can withstand most launch failures and accidental reentries. Reactors, too, have been redesigned to improve safety. Nevertheless, the power levels, operating lifetimes and radioactive payloads of current and projected space nuclear power systems have also increased significantly. Future accidents could therefore have unacceptable consequences.
But accidental reentry is not the only danger that space nuclear power holds. Even those reactors that are launched or later boosted into a long-lived orbit present hazards because they could collide with orbital debris. Although it is unlikely at present, a collision between a nuclear reactor and one of the thousands of sizable objects traveling at a relative velocity of 10 kilometers per second could yield an abundance of radioactive fragments. Many of them would be driven into the lower orbits utilized by manned spacecraft and back into the earth's atmosphere within a few years. Unfortunately, most of the spent nuclear power supplies in orbit now reside in those parts of space near the earth that are most densely populated with debris.

Furthermore, even while they are operating safely, reactors can disrupt the operation of other satellites. To minimize mass and cost, orbiting reactors are largely unshielded. They thus produce strong emissions of radiation that can make it difficult for astronomical satellites to detect signals from distant sources. This phenomenon (which was kept secret by the U.S. government until 1988) has already significantly interfered with the work of orbiting gamma-ray detection systems such as that on board the National Aeronautics and Space Administration's Solar Maximum Mission.

The gamma rays emitted by orbiting reactors do not just outshine distant supernovas or black holes; in addition, the more energetic gamma rays interact with the outer shell of the reactor to produce streams of electrons and positrons. These charged particles are trapped in the earth's magnetic field, forming a temporary radiation belt. When another spacecraft passes through such a cloud, the positrons annihilate electrons in the spacecraft's skin, producing penetrating gamma rays that can overload the spacecraft's detectors.

These brief interruptions of astronomical observations afflicted the Solar Maximum Mission spacecraft an average of eight times a day for much of 1987 and early 1988, when the Topaz reactors were operating. Similar interference with the gamma-ray burst detector on board the Japanese GINGA satellite effectively blinded it during about a fifth of the same period.

NASA is endeavoring to limit the threat from orbiting reactors to its $500-million Gamma Ray Observatory mission, launched in April of this year. One proposed safeguard involves simply shutting off the gamma-ray burst trigger at times when it might be subject to interference. This strategy assumes, however, that only one or two low-power reactors, in predictable orbits, will be operating at any given time. If the number and operating power of orbiting reactors increase, the ability to conduct X- and gamma-ray observations from near-Earth platforms will be severely restricted.

Finally, orbiting reactors and RTGs pose not only environmental risks but political ones as well. From the first U.S. RTG-powered navigation and commu-
nations satellites through 20 years of RÖRSA Ts, military requirements have often guided space nuclear power development, particularly when near-term civilian applications have been lacking. For instance, when the Strategic Defense Initiative was announced in 1983, the considerable power requirements of space-based missile defense appeared to provide a rationale for the SP-100, a proposed U.S. reactor that otherwise had no obvious application [see box on page 44].

So what good purpose is there for nuclear power in space? We believe that a useful distinction can be drawn between nuclear power in Earth orbit and in deep space. Many environmental hazards of space nuclear power vanish when an RTG or reactor is bound for another planet. Furthermore, deep-space applications are exclusively civilian and scientific or exploratory. (We include lunar missions in the deep-space category, even though the moon is, strictly speaking, in Earth orbit.)

During the past two decades, RTGs have made a major contribution to planetary exploration. The Mars probes, Viking 1 and 2, relied on nuclear power, as did the Pioneer 10 and 11 and Voyager 1 and 2 missions to the outer planets and the Galileo mission to Jupiter launched in October 1989. Ulysses, launched in October 1990 to explore the sun’s polar regions, brought the U.S. total of nuclear-powered spacecraft to 25.

Indeed, the feasibility of many future space missions may depend on nuclear power sources. They are unaffected by their distance from the sun or by natural planetary radiation belts. Although solar panels or chemical power sources might hypothetically generate hundreds of kilowatts for a long period, the mass and volume of these systems would far exceed those of an equivalent reactor.

Nuclear power is essential, in particular, for missions to the outer planets. Beyond the orbit of Jupiter, the incident solar flux is less than 4 percent of the amount that reaches Earth, making solar power utterly impractical.

Eventually reactors not only may power spacecraft systems, they also may propel the craft. Various forms of nuclear propulsion are now under consideration as part of the U.S. Space Exploration Initiative. A reactor can heat a propellant directly or produce electricity to drive various kinds of thrusters. The U.S. conducted extensive ground-based tests of nuclear rockets in the 1960s, and both the U.S. and the Soviet Union have tested electric propulsion systems in space.

The availability of such advanced power and propulsion systems would increase the scientific return of future space missions. It would also reduce the need to wait years or decades for a favorable planetary alignment. These technologies would make possible such ambitious missions as the Thousand Astronomical Unit (TAU) program, for example, a 50-year voyage into nearby interstellar space. An electric propulsion system driven by a one-megawatt reactor could carry TAU far beyond the limits of our solar system, making possible unprecedented observations of the galaxy.

A nuclear reactor might be used to meet the power needs of a permanent lunar colony if one were ever established. Reactors weigh far less than the systems that would be needed to store solar energy during the 14-day lunar night. Alternatively, a base could be located at the north or south lunar pole, where there is continuous sunlight. One energy-intensive activity that would probably require a reactor is the production of propellant from lunar soil.

NASA is considering using a nuclear rocket to propel a manned mission to Mars. Doing so could perhaps reduce by half the mass that would have to be boosted into orbit from the earth’s surface. Of course, the technical feasibility and the scientific value of such a mission are two distinct questions.

The development of any nuclear rocket would have to be carried out very carefully to minimize the environmental risk of an accident near the earth. Recent disclosures indicate that the U.S. Department of Defense is in fact working on such a rocket, but with imperfect attention to safety.

The highly classified project, code-named Timberwind, is funded through the SDI. Timberwind was reportedly intended to boost massive space weapons into orbit on short notice, although the Defense Science Board concluded in 1990 that the nuclear rocket proj-

NUCLEAR-POWERED SPACECRAFT successfully deployed in Earth orbit by the U.S. and U.S.S.R. are estimated to number 42. (Two are in distant orbits not shown above.) All the spacecraft, or their jettisoned power supplies, are now in orbits high enough so that they will not reenter the earth’s atmosphere until their radioactivity has substantially decayed. Most of them, however, orbit in a region populated with space debris. A collision could send a large number of radioactive fragments along trajectories that would reenter the atmosphere in a few years.

COSMOS 954
IMPACT AREA
NEPTUNE'S MOON TRITON was photographed by the nuclear-powered Voyager 2 spacecraft. The complex structure of Triton's surface has forced substantial revisions of theories of planetary geology. Radioactive power sources have been used on board several of the most scientifically productive space missions, including the Viking, Pioneer and Voyager probes.

ect was more likely to benefit deep-space propulsion. Preliminary testing of the fuel was carried out at Sandia National Laboratories in the late 1980s. The Timberwind reactor would operate at or near the melting temperature of its nuclear fuel, prompting concerns about the release of radioactive fission products.

SDI has proposed a suborbital flight test of Timberwind within the atmosphere near Antarctica. Such testing would violate accepted nuclear safety standards. Indeed, United Nations guidelines prohibit the operation of reactors on board spacecraft that have not achieved either a stable Earth orbit or an interplanetary trajectory.

In view of the various dangers they present, we favor an international agreement to ban nuclear reactors and RTGs from Earth orbit. This readily verifiable measure would eliminate many environmental hazards, enhance international stability and help to protect the space environment; it would also preserve the possibility of using nuclear power for scientific and exploratory missions in deep space.

Since space nuclear reactors possess a variety of distinguishing characteristics, an international agreement to prohibit them in orbit could be verified with confidence. In the first place, space reactors necessarily radiate large amounts of waste heat. They therefore give off a strong infrared signal that can be easily detected. Soviet RORSATs have been observed with a satellite-watching telescope at the Air Force Maui Optical Station on Mount Haleakula. An operating SP-100 reactor would be readily detectable at geosynchronous orbit or even beyond.

Operating reactors also emit strong gamma and neutron radiation signals that are easy to spot. Indeed, the type of gamma-ray interference that has disrupted scientific missions is uniquely produced by orbiting reactors and is a highly reliable, though unwelcome, sign of their presence.

It is true that a nation planning to "break out" of an arms-control treaty could conceivably place reactors in orbit without activating them, thus making the violation much more difficult to detect. But until large reactors have been thoroughly tested in space, they are unlikely to be covertly deployed.

Nuclear power has greatly enhanced space exploration. But it has also demonstrated the potential to produce significant environmental damage. Even if it is wisely controlled, nuclear power in space is likely to remain a challenging and costly technology.

FURTHER READING