Space Reactor Arms Control

OVERVIEW

Joel R. Primack, Nancy E. Abrams, Steven Aftergood, David W. Hafemeister, Daniel O. Hirsch, Robert Mozley, Oleg F. Prilutsky, Stanislav N. Rodionov, and Roald Z. Sagdeev[a]

Unshielded nuclear reactors provide the lightest and most survivable long-lived sources of electric power available to support military satellites. Restricting their use now, before a new generation of larger space reactors is tested and deployed by the US and USSR, could help prevent an arms race in space.

Space nuclear power systems have been used by the United States and the Soviet Union since the 1960s. The Soviet Union has used orbiting nuclear reactors to power more than 30 radar ocean reconnaissance satellites (RORSATs). Two RORSATs have accidentally re-entered and released their radioactivity into the environment, and a third, *Cosmos 1900*, narrowly avoided a similar fate.

The United States is developing much more powerful space reactors, of which the SP-100 is farthest along, primarily to power satellite components of the Strategic Defense Initiative (SDI). A working group associated with the Federation of American Scientists (FAS) and the Committee of Soviet Scientists for Peace and Against the Nuclear Threat (CSS) has been studying a proposed ban on orbiting reactors. A proposal by the FAS/CSS group that includes such a ban is attached in the appendix to the Overview.

The first five papers in this section, all by members of the working group, summarize the technological and historical background to nuclear power in space and show that restrictions on orbiting reactors are verifiable. The final paper, by Rosen and Schnyer of NASA, surveys the civilian uses of nuclear power in space.

The overview is a nontechnical introduction to the issues of space reactor arms control, including the proposed ban on orbiting reactors.

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a. See *Notes and References* for biographical information

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BRIEF HISTORY

The United States launched the first space reactor, SNAP 10A, in 1965. This small (500 watts electric) experimental reactor, like all subsequent space reactors, was fueled by the rare chain-reacting isotope of uranium, uranium-235. It operated for 43 days until an apparent electrical malfunction shut it down. It remains in a 1,300-kilometer orbit.[1]

The Soviet Union has launched at least 33 RORSAT (radar ocean reconnaissance satellite) reactors, of which at least one did not reach orbit. The reactor-powered radar in the RORSATs is used to locate US naval forces;[2] the US uses other methods to achieve similar goals. The RORSATs are placed in very low orbit at an altitude of about 250 kilometers. These low orbits are used apparently because radar effectiveness falls off rapidly with distance—approximately as

$$R^{-4} = (R^{-2} \text{ down}) \times (R^{-2} \text{ back})$$

where R is the distance between source and reflector. Atmospheric drag causes the orbits of even satellites of small cross-section to diminish quickly at such low altitudes. This is why a compact reactor is used for power rather than large solar panels.

When a RORSAT's useful life is over, the reactor is supposed to be boosted to a "nuclear safe" disposal orbit at approximately 950 kilometers. At this altitude, re-entry will not normally occur for several hundred years, by which time most of the radioactivity will have decayed.

Two of the RORSATs have re-entered accidentally when their booster systems apparently failed. *Cosmos 954* re-entered on 24 January 1978, spreading radioactive debris over northern Canada. After the reactor boost system on *Cosmos 1402* failed, a new system was used to eject the fuel core, which disintegrated in the upper atmosphere over the South Atlantic Ocean on 7 February 1983.

Cosmos 1900 ceased to respond to radio commands in April 1988, preventing boost to a disposal orbit. The decay of the *Cosmos 1900* orbit was confirmed by Soviet and American sources on Friday 13 May 1988.[3] On 30 September 1988, shortly before the satellite's expected re-entry, an automatic backup system caused the reactor to be boosted to a high orbit. The reactor aboard *Cosmos 1900* apparently contained about 30 kilograms of highly enriched uranium-235, producing about 75 kilowatts of thermal power and perhaps 5 kilowatts electric.[4,5]

Counting *Cosmos 954*, *1402*, and *1900*, as well as the one or two RORSAT launch failures, the accident rate for RORSATs is about 15 percent. This is comparable to the accident rate of US spacecraft carrying radioactive nuclear power sources.[6]

Soviet reactor experts announced recently that the Soviet Union had launched two experimental reactors of a new design into 800-kilometer orbits (*Cosmos 1818* on 1 February 1987 and *Cosmos 1867* on 10 July 1987).[7] These reactors generate electricity by in-core thermionic devices that are more efficient than the thermoelectric generators (thermocouples) used on the RORSAT reactors. They apparently produce about 10 kilowatts electric.

US SPACE REACTORS AND SDI

The United States built and ground-tested several nuclear reactors as part of the Rover/NERVA program to develop a reactor-powered rocket in the late 1960s and early 1970s. Several reactors for generation of electric power in space were also designed, but until SDI there was little demand for them.[8]

A National Academy study recommended in 1983—before SDI—that a program to develop a 100-kilowatt electric space reactor be funded at an annual level of $10–15 million.[9] Current funding for this reactor program, now called the SP-100, is ten times higher. According to Congressional testimony by a senior DoE official[10]

> ...I would say that, frankly speaking, the major rebirth and driving factor [for the space reactor program] is [President Reagan's] strategic defense initiative. I think if it were not for that, we would be hard pressed to have a sufficient number of defined missions to sustain it at the levels we're talking about today.

The deployment of space-based defenses against strategic missiles (as proposed in SDI) or of antisatellite weapons (ASATs) could involve, among other things, attack with directed-energy weapons (DEWs) such as lasers, orbiting space mirrors (in conjunction with ground-based lasers), particle beams, or hypervelocity guns—missions with large requirements for electric power. The power requirements of such orbiting battle stations can be listed under three headings:

♦ *Housekeeping* under standby conditions, which includes spacecraft inertial stabilization. One major power need is likely to be for cryogenic refrigeration of chemical fuels.

♦ *Alert mode*, when the spacecraft is fully powered and maneuverable. This might occur for many periods of hours or days during tests, exercises, or crises. The total time in alert mode might be as much as a year over the lifetime of the spacecraft.

♦ *Burst mode*, when the weapons are actually firing—possibly on hundreds or thousands of targets in a period of perhaps a few hundred seconds.

It is difficult to discuss the corresponding power requirements in the absence of any specific SDI or ASAT design.

Housekeeping is likely to consume tens to hundreds of kilowatts of electricity over a lifetime of perhaps 10 years, which could be supplied by either solar cells or a nuclear reactor.

Alert mode exercises might involve velocity changes due to rotations or evasive maneuvers of the order of 10 meters per second for lasers, mirrors, or other objects with masses of about a tonne (1,000 kilograms) on timescales of a second, which implies a minimum power requirement of about 100 kilowatts electric. Similar power requirements characterize other alert mode activities.[11] This would probably require reactor power sources, especially if the spacecraft is supposed to be compact and hardened against attack.

In burst mode, the power required to destroy one target each second is likely to be of the order of 1,000 megawatts. If the total number of targets each orbiting battle station is designed to attack is about 100, then allowing a factor of three for misses and an electric conversion efficiency of about 10 percent, about 100 tonnes of high-power-density chemical fuel such as beryllium burning in a fluorine atmosphere (30 megajoules per kilogram) should suffice.

One could use closed-cycle multi-megawatt reactors to power burst mode operations, but they are likely to be extremely heavy, especially in view of the requirement of rapid•energy conversion. However, open-cycle reactors may be competitive with chemical energy sources in energy storage density (energy output per unit mass).[12] The strength of materials limits energy storage in devices such as flywheels and magnets to considerably less than 1 electron volt (eV) per atom, which is probably not competitive in energy density with the best chemical fuels or open-cycle reactors.

Thus, for SDI DEW satellites, reactors are being considered for burst mode, could be useful for housekeeping, and might be essential for alert mode. Former SDI director Lt. Gen. James Abrahamson said that space nuclear reactors will be an essential component of the second phase of SDI, and that without reactors in orbit, "that's going to be a long, long lightcord that goes down to the surface of the Earth."[13]

This is the main justification for the SP-100 project, although its current design power capacity of 2.5 megawatts thermal and 100 kilowatts electric may be too small for many SDI needs: several contracts have recently been granted by the SDIO for the design of multi-megawatt reactors.[14]

Studies by an American Physical Society group and the Congressional Office of Technology Assessment have concurred that reactors are probably necessary for SDI.[15,16] But a recent National Research Council study has concluded that the technological challenges of building launchable multi-megawatt reactors are truly formidable.[17]

Since satellite-based directed energy weapons to attack ICBMs, if they are possible at all, would have relatively short range, DEW battle stations would have to be placed in low earth orbit (LEO—about 400 kilometers), with orbital periods of 1.5–2 hours. In order to have these satellites over enemy ICBM launching sites at all times, many, perhaps hundreds, would be required. That means that many operating nuclear reactors, each many times more powerful than the current RORSAT reactors, would be within sight of almost every point on earth at all times.

ARMS CONTROL ARGUMENTS FOR A BAN ON ORBITING REACTORS

A primary reason for our proposing a ban on orbiting reactors is to restrict the development and deployment of new weapons in space, particularly destabilizing weapons for strategic defense or for anti-satellite applications. Because detection of operating reactors on earth satellites is relatively easy (see below), a ban on orbiting reactors would be among the most easily verifiable ways of supplementing and strengthening the Anti-Ballistic Missile Treaty of 1972.[18]

President Carter proposed a ban on orbiting reactors in the wake of the *Cosmos 954* re-entry in 1978, but it was not accepted by the Soviet Union. In view of the present strong interest of the Soviet government in avoiding an arms race in space, now may be a good time to consider such a ban again.

An FAS delegation was told by the responsible official at the Soviet Foreign Ministry in September 1988[19]

> If the US government were to say to the USSR, let us consider neither of us launching into outer space nuclear power, and such a matter were to be mutual, it would be very seriously considered by the Soviet side.

It could be a good deal for both sides, trading off the US SDI investment in reactors against RORSATs and the larger orbiting reactors reportedly under development in the USSR.[20]

It is possible that an agreement to ban orbiting reactors, if it is achieved, would be part of a larger arms control package. For example, restrictions on ASATs might also be included, particularly since the Soviet RORSATs are the principal near-term target of the US ASAT program.

ENVIRONMENTAL AND NONPROLIFERATION REASONS FOR A BAN

There are many reasons beyond arms control to seek a ban on orbiting reactors:

♦ As *Cosmos 954* and *1402* have already demonstrated, re-entry of reactors can cause radioactive contamination.

♦ Accidental return of an intact reactor to the earth's surface because of a launch failure or re-entry could allow recovery of enough highly enriched uranium-235 to make several fission bombs.

♦ Placing used reactors in "nuclear safe" disposal orbits exacerbates the space debris problem.

♦ Operating orbiting reactors are a source of serious "light pollution" for astronomical observations: they have been interfering with gamma-ray astronomy for several years.

We will briefly take up each issue in turn.

Radioactive contamination

Since unused uranium-235 fuel is not radioactive, the environmental contamination from a launch accident or abort would be minor, assuming that space reactors are carefully designed to prevent a criticality accident at launch and are turned on only after they are in orbit.

Once a reactor is turned on, the accumulation of long-lived radioactive fission products is approximately proportional to its thermal power level multiplied by its operating lifetime. The first generation of SP-100 reactors is designed to operate at about 2.5 megawatts (about 25 times the *Cosmos 1900* reactor's power) for seven years (about 20 times the operating life of a typical RORSAT), so a re-entering SP-100 could contain several hundred times the long-lived radioactivity of a RORSAT reactor.

Since the environmental effects of this radioactivity would depend on whether it is dispersed, where (for example, injection into the upper atmosphere, or a particular surface location), and in what form (for example, size of particles), they are very uncertain. However, they could clearly be serious.[21]

Nuclear proliferation

Current designs call for the SP-100 to be fueled with approximately 200 kilograms of highly enriched uranium-235, 40 times the "formula quantity" for which the US Nuclear Regulatory Commission requires special safeguards. This is enough to construct a formidable arsenal of fission bombs. Although the current SP-100 plans, which call for intact re-entry, would mitigate radioactive contamination, they would exacerbate this security problem.[22]

The Strategic Defense Initiative Organization (SDIO) has responded to concerns about unplanned re-entry of orbiting reactors by proposing an exploratory program called Space Intercept Rescue and Expulsion (SIREN) to consider ideas for retrieving low-orbiting reactors or boosting them to higher orbits. This will not be easy, since unshielded reactors are extremely radioactive, and a reactor that has suffered a malfunction may not even be in one piece. Moreover, a satellite reactor that has had a criticality accident, suffered a collision with another space object, or been attacked by an antisatellite weapon could re-enter before there is time to rescue it.

Space debris

The number of man-made objects orbiting the earth is increasing very rapidly. The US North American Defense System (NORAD) is currently tracking some 6,000 objects larger than 10 centimeters across, and an MIT study recently estimated that there are 48,000 objects larger than 1 centimeter orbiting the earth.[23] Since the relative speed of objects in orbit is about 10 km/s, ten times the speed of a rifle bullet, collision with space debris is a serious threat to satellites, including nuclear reactors. According to Nicholas Johnson[24]

> The destruction of a radioactive satellite by hypervelocity collision not only will make it impossible to dispose of the satellite in the future, but also may create more immediate hazards to manned and unmanned satellites. A hypervelocity collision with a spent Soviet nuclear reactor may produce as many as 10^6 particles with a diameter of 1 millimeter or more.

It is evident that it is in the long run unacceptable to place spent reactors in "nuclear safe" disposal orbits, where they exacerbate the space debris problem.

Light pollution

Astronomers are attempting to detect faint signals from phenomena distant in space and time amid background radiation ("light pollution") that has been growing rapidly near the earth because of activities such as lighting and communications.

Orbiting reactors add significantly to this interference. They are very bright sources of infrared (heat) radiation, since their conversion of heat to electric power is inefficient and most of the heat produced in the reactor must be radiated into space.

Space reactors are also intense sources of neutrons and gamma rays and are essentially unshielded except in the direction of the payload.

NASA has recently revealed that an instrument on the Solar Maximum Mission (SMM) satellite launched in 1980 has seen gamma rays from the RORSATs and has also detected positrons (anti-electrons), which are produced by high-energy reactor gamma rays in the outer reactor casing.[25] Some of these positrons are trapped in the earth's magnetic field, effectively becoming an artificial radiation belt. When another spacecraft passes through this cloud of positrons, the positrons annihilate with electrons in the spacecraft's outer casing, and this produces penetrating gamma rays. A gamma-ray burst experiment aboard the Japanese *Ginga* satellite has also been disabled for about 20 percent of the time by reactor-produced positrons. Positrons from orbiting reactors will also be a serious problem for the Gamma Ray Observatory, a major American astronomical satellite currently scheduled to be launched in 1990, and for other satellites as well.

Space reactors are essentially unregulated

Despite these environmental problems and the accidents that have already occurred, there is essentially no regulatory mechanism for space nuclear power. The United Nations Committee on Peaceful Uses of Outer Space has promulgated several guidelines, but decisions are still largely at the discretion of national governments. Within the US, there is no procedure for licensing of space nuclear reactors, just classified review by an Interagency Nuclear Safety Review Panel composed of representatives of the sponsoring agencies, with only their final Safety Evaluation Report made public. The simplest solution in the present case is a ban on orbiting reactors.

CIVILIAN USES FOR SPACE NUCLEAR REACTORS

Nuclear reactors may well have essential roles to play in space. One relatively near-term use seems especially appropriate: to provide power for a manned lunar base. A reactor would have a considerably lower mass than the energy storage devices necessitated by the 14-day lunar night that occurs at all locations but the lunar poles.[26] A reactor to power a manned lunar base would presumably be buried in the lunar soil for shielding, and it would require pumping of coolant to radiators on the lunar surface. Rather than attempt to use a space reactor design such as SP-100, it would probably be better to design a reactor specifically for this application.

Another civilian space application for which reactors are perhaps essential is powering ambitious spacecraft to explore the outer reaches of the solar system, where solar energy is very faint.

It is important to appreciate that a ban on orbiting reactors would not prevent these nonmilitary projects, because they do not require reactors in earth orbit. (A ban could include a provision allowing testing in earth orbit of space reactors for deep-space applications.)

Figure 1 of the article in this issue by Rosen and Schnyer is a NASA chart of many possible civilian applications for space reactors. Most are on the moon, Mars, or in the outer solar system. However, missions in earth orbit are also suggested to provide power for a space station complex, a materials processing platform, air traffic control radar over the oceans, communications platforms and bases in geosynchronous orbit, and nuclear-electric orbital transfer vehicles. Below we comment briefly on each of the proposed earth-orbit missions.

Space station

Nuclear power is not currently contemplated for the US space station, which is instead to be solar powered by a combination of photovoltaic cells and "solar dynamic" systems (converting heat focused on a collector by mirrors to electricity using a working fluid).

In this application, any weight advantage of nuclear power would be obviated by the need for massive shielding around the nuclear reactor to prevent excessive irradiation of the crew, especially during extravehicular activity and shuttle docking. Neutron shielding (by lithium hydride, for example) is relatively low in mass; but the gamma shielding on all sides of an SP-100 required to make the area safe for nearby human activity would be equivalent to a shell of lead or tungsten about 20 centimeters thick, which would have a mass of about 45,000 kilograms—more than 10 times the mass of the reactor, heat radiator, and supporting systems.

Materials processing platform
That significant demand exists for large-scale materials processing in microgravity remains to be demonstrated. In any case, the heat and electric power requirements for materials processing could be met by solar collectors and photovoltaic or solar dynamic power. The arguments against nuclear power for space stations apply here too, at least for early-generation human-tended facilities.

Ocean Air Traffic Control Radar
Because the effectiveness of radar falls off so rapidly with distance, the radars would have to be placed in low-earth rather than geosynchronous orbit. As a result, many reactor-powered satellites might have to be in orbit in order to have one or two continuously covering each of the major air routes. A much simpler solution would be to require all aircraft to have reliable transponders (which send a return signal that allows them to be located, including information on altitude, etc., whenever they receive an appropriate interrogating signal).

Geosynchronous bases
The roughly 100 kilowatts electric contemplated for this application is available from solar power, by scaling up the photovoltaic systems in present use or utilizing the solar dynamic technologies being developed for LEO space stations.

Orbital transfer vehicles
Electric or magnetic fields can be used to accelerate the ionized rocket propellant to higher velocities than are attainable with chemical reactions, thus requiring less mass of propellant. Because of the limited power of the reactor, such space tugboats would have relatively slow acceleration, but the concept is potentially attractive. However, solar-electric power is a potential alternative to nuclear. It might be worthwhile, as another alternative, to design thermal-propulsion systems in which sunlight concentrated on a tungsten heat collector heats it to a temperature of 3,000 K. The corresponding thermal velocity imparted to hydrogen propellant is about 7 kilometers per second. The specific impulse I_{sp} is a quite respectable 700 seconds, better than the best chemical fuels.[27]

We conclude that alternatives to nuclear reactors for power can be found for all attractive near-term civilian missions in earth orbit. Indeed, according to recent preliminary studies at the Soviet Space Research Institute (IKI), there is good reason to believe that solar energy would be the safest and most reliable power source for missions as far as Mars.[28] It would only be beyond Mars that the sun would become too dim to power spacecraft.

In view of the uncertainty of future developments in technology, it would probably be best to plan to review and, if necessary, renegotiate any restriction on space reactors after a decade or two.

We have also tried to ascertain whether there are any reconnaissance or military intelligence missions that are potentially important for national security that require reactors in earth orbit.

No such mission has been described to us in numerous discussions with experienced active and retired military personnel and prominent scientific staff and advisers. Indeed, several very knowledgeable people have told us that in their opinion the ban on orbiting reactors that we have proposed would not compromise the national security of either side.

VERIFIABILITY OF THE PROPOSED BAN

Several papers below describe the possible verification of a ban on reactors in orbit in considerable technical detail. On the basis of these papers, our conclusion is that such a ban would be verifiable. Space is an exposed environment, and a powerful reactor is essentially impossible to hide.

The most readily detectable signal from an operating reactor is its thermal radiation, largely in the infrared but partly in the visible part of the spectrum. At the design temperature of 800 K, the 100 square meters of heat radiators on SP-100, for example, would have a deep red glow.

Although the atmosphere is opaque to most infrared radiation, there are "transparency windows" that allow detection from the ground or from an infrared telescope on an airplane. Even with the Air Force Maui Optical Station (AMOS) equipment, which no longer represents state-of-the-art technology, an operating reactor could be rapidly detected far beyond geosynchronous altitude (40,000 kilometers).[29]

Although infrared verification is perhaps adequate by itself, detection of nuclear emissions would confirm that a detected infrared source is actually a reactor. As noted above, it was recently revealed that the mature technology represented by the US Solar Maximum Mission Gamma Ray Spectrometer has routinely detected gamma rays and positrons from RORSATs, and we have calculated that the more sensitive detectors soon to be available such as the Compton Telescope (COMPTEL) on the Gamma Ray Observatory will reliably detect even a shielded reactor.[30]

If desired, in addition to the small number of sensitive gamma-ray detectors on satellites in orbit for astronomical purposes, a number of light and inexpensive gamma-ray detectors could be placed on spacecraft in a variety of orbits specifically to monitor compliance with a ban on reactors in earth orbit.

Neutrons from a reactor can also be detected in principle at distances of many thousands of kilometers by appropriately designed detectors.[31]

Detecting reactors that are placed in orbit but never turned on would be much more difficult than detecting operating or recently operating reactors. The best way to counter such a "breakout" threat would probably be to inspect space payloads before launch. But until high-powered reactors have been thoroughly tested in space, it is extremely unlikely that billions of dollars or rubles would be spent launching them with the associated equipment that they are supposed to power. As we have discussed, the tests could be detected.

ALTERNATIVE REGIMES FOR REGULATING REACTORS IN SPACE

There are different approaches to restrictions on space reactors that might be considered in negotiations between our respective governments. We include here a brief discussion of four alternative versions of a ban on orbiting reactors. They are summarized in the table.

Before describing these four regimes, however, we begin by summarizing the basic arguments against reactors in orbit that these alternatives attempt to address:

♦ Reactors are probably essential to power the "alert modes" of certain categories of space-based weapons, including several varieties of antiballistic missile weapons.

♦ About 15 percent of past space reactors have been involved in accidents or failures. If orbiting reactors re-enter, they can cause environmental contamination and, if they do not disintegrate on re-entry, they can present anyone able to salvage them with enough uranium-235 for several nuclear weapons.

♦ "Nuclear safe" orbits are not really safe. There are already thousands of pieces of space debris orbiting the earth, endangering satellites and astronauts, and contributing to a planetary halo of debris whose creation our descendants will doubtless regret.

Table 1: Alternative Regimes for Regulating Reactors in Space

	I Ban all space reactors for 15 years	II Ban orbital reactors; Testing OK for deep space	III Ban reactors in low orbit[*]; permit only civilian uses above	IV Ban reactors in low orbit only
Bans RORSATS	yes	yes	yes	yes
Constrains SDI	yes	yes	yes	?
Eliminates breakout threat	yes	no	no	no
Prevents reactor re-entry	yes	yes[†]	yes[†]	yes[†]
Avoids orbital debris	yes	most	no	no
Reactors OK for moon and deep space	[‡]	yes	yes	yes
Protects gamma-ray astronomy	yes	largely	no	no
Legally clear	yes	?	no	yes

* Low orbit means orbits less than 800-kilometer altitudes
† Except for collisions
‡ No lunar or deep-space missions using reactors are planned for this period

Alternative I: BAN ALL SPACE REACTORS FOR A DEFINED PERIOD

This regime has the virtues of comprehensiveness and simplicity. It would prevent breakout (sudden abrogation of an arms control treaty causing a serious military threat) by allowing no exceptions for reactors for lunar and outer solar-system missions—or for the testing of the latter category of reactors in earth orbit. To strengthen the protection against breakout, such a ban might also exclude tests in space of major components of space reactor systems such as heat radiators.

After the defined period—say 15 years—the agreement would be up for renegotiation if necessary. This would allow for consideration of political or technological developments.

The potential problem with this proposal is that it may be too comprehensive. While dragnet measures may succeed in eliminating their targets, they may also eliminate more than they need to.

Alternative II: BAN ORBITAL REACTORS; ALLOW TESTING FOR LUNAR AND DEEP-SPACE APPLICATIONS

This is the version of a space reactor ban included in the FAS/CSS proposal (see appendix).[32] But it might permit a reactor tested in orbit under the guise of a deep-space probe to provide the technological basis for a breakout from the ban of reactor-powered space weapons.

Although both (I) and (II) prevent civilian uses of reactors in orbit, it is unclear whether such uses exist. One possible way of dealing with this uncertainty would be to make the ban renegotiable after 10–15 years, since such uses will not be occurring in this period anyway.

Alternative III: BAN REACTORS IN LOW (< 800 km) ORBIT; PERMIT ONLY CIVILIAN USES ABOVE

Although this regime deals with some of the environmental problems, it is based on the "nuclear safe" orbit idea that we find dubious, it would permit orbiting reactors that could seriously hamper gamma-ray astronomy, and it does not adequately address the arms control concerns.[33]

Alternative IV: **BAN REACTORS IN LOW ORBIT ONLY**

This alternative addresses primarily the environmental issue. It is simpler than (III), since it does not require agreement as to what functions are appropriate for high orbit, but it does not prevent any military uses of higher orbits, including Strategic Defense.

Both alternatives (I) and (II) would effectively address the arms control objectives of a ban on orbiting reactors.

CONCLUSION

Most people are shocked to learn that there are already more than thirty nuclear reactors constantly orbiting over our heads, including deactivated but still radioactive reactors that have been boosted to a dumping altitude at which they join thousands of other pieces of space-age debris all orbiting at 25,000 kilometers per hour. A collision with any substantial chunk of this debris could knock pieces of a spent reactor out of orbit and down to earth long before its scheduled re-entry hundreds of years from now.

An agreement to stop putting reactors in orbit would eliminate this threat, and have very substantial arms control benefits as well. It would stop the Soviet RORSATs, and thereby eliminate a principal US incentive to develop ASATs. And it would significantly constrain SDI.

SDI is an elusive target for arms controllers. Bans on many of its components could be difficult to verify. But space-based SDI battle stations may have an arms-control Achilles heel in the reactors that are probably required to power them.

A ban on reactors in earth orbit may therefore be an important contribution to the prevention of a space arms race.

Space is the largest arena for human endeavors, and one that is only beginning to be militarized and polluted. It has long been recognized that nuclear power has dangers that require regulation. We believe that the time is now ripe for an agreement to ban nuclear reactors from orbit.

ACKNOWLEDGMENTS

The authors have had useful discussions about the material in this paper with many people, in particular Lew Allen, Sidney Drell, Richard Garwin, Fred Lamb, Tom Morgan, W.K.H. Panofsky, John Pike, Ted Postol, Robert Rosen, Ted Taylor, Alexei Vasiliev, and Roy Woodruff. Lisa Ensman did a preliminary study of infrared verification. We also thank Roland Finston, Yuri Petrov, and Alexander I. Shlyakhter for their studies of the consequences of environmental contamination from radioactive releases from space nuclear power sources.

APPENDIX: THE MAY 1988 PROPOSAL BY THE FAS AND CSS

The proposal which we put forward on behalf of our two organizations (after two joint workshops) to ban nuclear power in earth orbit grows out of our efforts to prevent both the radioactive contamination of the earth's surface and the extension of the arms race into space. In particular, this agreement would prevent the use of reactors in earth orbit by either side for any purpose—whether offensive or defensive, including the use of reactors to power surveillance satellites.

The use of nuclear power in space is still at an early stage but already there have been accidents which have caused worldwide concern.

An agreement to ban nuclear reactors from orbit would be a major barrier to any future arms race in space since nuclear reactors are compact sources of large quantities of power necessary for many military purposes. Meanwhile, as far as civilian activities are concerned, solar energy collectors and fuel cells will be a more convenient and safer source of energy in earth orbit for the foreseeable future. Energy sources powered by quantities of radioisotopes below an agreed safe threshold could also be permitted for these purposes.

The ban on reactors in orbit would not prevent the use of nuclear power for deep space scientific or exploratory missions with associated very limited tests under agreed safeguards of such deep-space reactors in earth orbit.

Verification of a ban on nuclear power in orbit would be relatively straightforward because an operating (or even recently operating) nuclear power source would emit large amounts of detectable infrared, gamma and neutron radiation.

We therefore call for an international agreement to ban nuclear power in orbit and our two organizations plan to continue to work on the technical aspects of this ban in the context of our five-year Joint Verification Project.

Roald Sagdeev
chairman
Committee of Soviet Scientists for Peace and Against the Nuclear Threat

Frank von Hippel
chairman of the research arm of the Federation of American Scientists

13 May 1988

NOTES AND REFERENCES

Joel R. Primack
Department of Physics, University of California Santa Cruz, Santa Cruz, CA 95064

Nancy E. Abrams
Attorney, mediator, and writer, 101 Lance Court, Santa Cruz, CA 95065

Steven Aftergood
Executive director, Committee to Bridge the Gap, 1637 Butler Avenue, Los Angeles, CA 90025

David W. Hafemeister
Center for International Security and Arms Control, Stanford University, and Physics Department, California Polytechnic State University, San Luis Obispo, CA 93407

Daniel O. Hirsch
Federation of American Scientists, 307 Massachusetts Avenue NE, Washington, DC 20009

Robert Mozley
Stanford Linear Accelerator Center, Stanford, CA 94309

Oleg F. Prilutsky, Stanislav N. Rodionov, and Roald Sagdeev
Institute of Space Research of the USSR Academy of Sciences, Profsoyuznaia 88, 117810 Moscow, USSR

1. The United States has also used radioisotope thermal generators (RTGs), which generate electricity from the decay heat of their radioactive fuel plutonium-238, on 22 spacecraft launched between 1961 and the late 1970s. Several of these have suffered accidents, including one, SNAP 9A, whose plutonium was dispersed globally when it failed to attain orbit. The Soviet Union has also used a few RTGs. We do not discuss RTGs further in this overview, since current plans call for their use only for probes to the outer planets. See Steven Aftergood, "Background on Space Nuclear Power," *Science & Global Security*, this issue, for more details about the history and technology of the US and Soviet space nuclear power programs, including RTGs.

2. US Department of Defense, *Soviet Military Power* (Washington DC: US Government Printing Office, 1987), p.53. The US Navy has a variety of ways of countering the RORSATs, including deceptive sailing procedures, decoys that project false radar images, and jamming; see, for example, Paul B. Stares, "Anti-Satellite Arms Control in a Broader Security Perspective," in Joseph S. Nye, Jr., and James A. Schear, eds., *Seeking Stability in Space: Anti-Satellite Weapons and the Evolving Space Regime* (University Press of America, 1987), p.117.

3. See, for example, William J. Broad, *New York Times*, 14 May 1988, p.2; Kathy Sawyer, *Washington Post*, 14 May 1988, p.A3.

4. *Pravda*, 29 September 1988; and 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 to the US Secretary of State, 27 September 1988).

5. Bart W. Bartram and Richard W. Englehart, *A Pre-Boost Risk Assessment of Cosmos 1900*, NUS-5148, prepared for the Office of Special Applications, US Department of Energy, 17 October 1988, under contract DE-AC01-87NE32134.

6. See Aftergood, this issue.

7. William J. Broad, "Russians Disclose Satellites Carry New Reactor Type," *New York Times*, 15 January 1989, p.1; N.N. Ponomarev-Stepnoi, "Nuclear Energy in Space," and G.M. Griaznov et al., "Thermionic Reactors for Space Nuclear Power," paper presented at the sixth Symposium on Space Nuclear Power Systems, Albuquerque, New Mexico, 9–12 January 1989.

8. See, for example, Joseph A. Angelo, Jr., and David Buden, *Space Nuclear Power* (Malabar, Florida: Orbit Book Co., 1985).

9. Committee on Advanced Nuclear Systems, Energy Engineering Board, Commission on Engineering and Technical Systems, National Research Council, *Advanced Nuclear Systems for Portable Power in Space* (Washington DC: National Academy Press, 1983), p.37.

10. Testimony of James W. Vaughan, Jr., then DoE Acting Assistant Secretary for Nuclear Energy, in "Space Nuclear Power, Conversion, and Energy Storage for the Nineties and Beyond," *Hearings before the Subcommittee on Energy Research and Production*, Committee on Science and Technology, US House of Representatives, October 1985, p.68.

11. See Oleg F. Prilutsky and Stanislav N. Rodionov, "The Military Connection and Environmental Hazards of Space-based Nuclear Power," *Science and Global Security*, this issue.

12. American Physical Society Study, "Science and Technology of Directed Energy Weapons," *Reviews of Modern Physics*, 59, no.3, part II, chapter 8 (July 1987). See also the paper by Prilutsky and Rodionov below. In closed-cycle reactors the coolant is recirculated; in open-cycle reactors it is discarded after the energy is converted to electricity. Reactor-powered rockets are an example of an open-cycle design. Pollution of the local environment is obviously a potential problem with open-cycle chemical engines or nuclear reactors.

13. B. Spice, "SDI Looks to Nuclear Power," *Albuquerque Journal*, 12 January 1988, p.A1.

14. See Aftergood, this issue.

15. In *Rev. Mod. Phys.* See note 12.

16. *SDI: Technology, Survivability, and Software* (Washington DC: US Government Printing Office, May 1988), OTA-ISC-353, p.155.

17. Committee on Advanced Nuclear Systems, Energy Engineering Board, Commission on Engineering and Technical Systems, National Research Council, *Advanced Power Sources for Space Missions* (Washington DC: National Academy Press, 1989). Summarized in William J. Broad, "New Flaws Found on Missile Shield," *New York Times*, 19 January 1989.

18. See John E. Pike, "Goals of the ABM Treaty," *Federation of American Scientists Public Interest Report*, 40, No. 7 (September 1987).

19. The FAS delegation consisted of Nancy Abrams, Daniel Hirsch, John Pike, and Joel Primack, accompanied by Elena Loshchenkova of the CSS; the Soviet official was Boris Majorsky; the meeting took place on 8 September 1988. This meeting was further described in Daniel Hirsch's testimony on 13 September 1988 before the Committee on Energy and Natural Resources, US Senate.

20. TASS statement, 17 October 1988, quoted in "Soviets See Increased Use of Nuclear Power in Space," *Aerospace Daily*, 18 October 1988, p.82. See also note 7 above.

21. Two sets of calculations on re-entry consequences have been performed as part of the FAS-CSS space nuclear power study. Estimates prepared for the study by Yuri V. Petrov and Alexander I. Shlyakhter of the Reactor Design Bureau of the Leningrad Nuclear Physics Institute and Stanislav Rodionov of the Soviet Space Research Institute (*Possible Ecological Consequences of Nuclear-Powered Satellite Re-entry*, November 1988, available from the Committee of Soviet Scientists, Moscow) assumed "worst case" conditions: low-altitude injection of radioactive materials from an SP-100-class reactor over a large agricultural region, with the contaminated food consumed. They conclude: "under unfavorable conditions the long-term radiation consequences may be comparable to the corresponding effects of the Chernobyl accident."

The second calculation, by Roland Finston, chief of Health Physics and Radiation Safety at Stanford University assumes high-altitude disintegration of the reactor core, resulting in global dispersal of the injected radioactive material. The calculation was scaled to the UNSCEAR (United Nations Scientific Committee on

the Effects of Atomic Radiation) analysis of fallout from atmospheric weapons tests (*Ionizing Radiation: Sources and Biological Effects*, UNSCEAR, 1982 Report to the General Assembly, Annex E [New York: United Nations, 1982]). Finston estimates consequences under these circumstances two to three orders of magnitude lower than the estimates obtained using worst-case assumptions.

However, it should also be noted that the UNSCEAR risk factors may be too low by an order of magnitude (David Hoffman and Edward Radford, *A Review of the Carcinogenic Effects of Low-Dose Ionizing Radiation* [Philadelphia: Three Mile Island Public Health Fund, 1985], p.124) and that larger reactors than the SP-100 (for example, multi-megawatt reactors) operating for comparable or longer periods would have correspondingly larger fission product inventories.

Of course, if a reactor were to survive re-entry and landing intact, then there would be no widespread radioactive contamination.

Both the Soviet analysts and Finston note that atmospheric dispersal of plutonium-238 from a Dynamic Isotope Power Source (DIPS), a radioisotope thermal generator designed for SDI applications (see Aftergood, this issue), could cause extremely serious consequences (this is also discussed in Prilutsky and Rodionov, this issue).

22. NASA/SDIO/DoE, "SP-100 Ground Engineering System Safety Program Plan," 3 November 1986. Quoted in Committee on Advanced Space Technology, *Space Technology to Meet Future Needs* (Washington DC, 1987), pp.87–89.

23. M. Mitchell Waldrop, "Taking Back the Night," *Science*, **241**, p.1288 (9 September 1988). See also Nicholas L. Johnson and Darren S. McKnight, *Artificial Space Debris* (Malabar, Florida: Orbit Book Co., 1987).

24. Nicholas L. Johnson, "Nuclear Power Supplies in Orbit," *Space Policy*, **2**, p.223 (1986).

25. Arthur J. Reetz, Gamma Ray Observatory program manager, *Transient Gamma Ray Events*, NASA Memo, 29 August 1988. Additional information in this paragraph is from talks by Ed Chupp and James Kurfess at a Conference on High Resolution Gamma Ray Cosmology at UCLA, 4 October 1988, and from remarks by R. Stephen White during the discussion to the effect that his group had seen gamma rays from orbiting reactors using a balloon-borne detector.

This material is discussed in detail in T. O'Neill et al., "Observations of Nuclear Reactors on Satellites with a Balloon-Borne Gamma-Ray Telescope," *Science*, **244**, p.451 (1989); E. Rieger et al., "Man-Made Transients Observed by the Gamma-Ray Spectrometer on the Solar Maximum Mission Satellite," *Science*, **244**, p.441 (1989); and G. Share et al., "Geomagnetic Origin for Transient Particle Events from Nuclear-Reactor Powered Satellites," *Science*, **244**, p.444 (1989). See Joel R. Primack, Philip Pinto, and Oleg F. Prilutsky, "Detection of Space Reactors by their Gamma-ray and Positron Emissions," *Science & Global Security*, this issue, and Oleg F. Prilutsky and N. Fomenkova, "The Effect of Nuclear Reactors in Space on High-energy Astrophysics," (available from the CSS, Moscow) for more details. See also news reports; for example, Marcia Barinaga, "Orbiting Nuclear Reactors Still a Problem for Astronomers," *Nature*, **336**, 17 November 1988, p.192; William J. Broad, "Radiation from Soviet Nuclear Reactors in Space Hampers US Satellite," *New York Times*, 17 November 1988; M. Mitchell Waldrop, "Space Reactors Hinder Gamma-Ray Astronomy," *Science*, **242**, 25 November 1988, p.1119; Sandi Doughton-Evans "Space Nukes Might End Gamma Study," *Los Alamos Monitor*, 1 February 1989, pp.1,6.

26. Alan Friedlander and Kevin Cole, "Power Requirements for Lunar Base Scenarios," *Symposium on Lunar Bases and Space Activities in the 21st Century*, April 1988, paper LBS-88-211. Eagle Engineering, Inc., *Conceptual Design of a Lunar Base Solar Power Plant*, report to NASA, 14 August 1988.

27. Specific impulse is the number of kilograms of thrust per kilogram per second of propellant flow, approximately equal to v/g where v is the propellant velocity and g is the acceleration of gravity at the earth's surface.

28. These studies were also mentioned in the statement of Roald Sagdeev, submitted to the hearings on space nuclear power, 13 September 1988, before the Committee on Energy and Natural Resources, US Senate.

29. See David W. Hafemeister, "Infrared Monitoring of Nuclear Power in Space," *Science & Global Security*, this issue.

30. See Primack, Pinto, and Prilutsky, this issue.

31. See Robert Mozley, *Detection of Orbiting Nuclear Reactors by Neutron Emissions*, 28 November 1988, unpublished report available from the Federation of American Scientists.

32. The FAS/CSS proposal of 13 May 1988 was for a ban on nuclear power in earth orbit, including both reactors and radioisotope generators (other than those powered by quantities of radioisotopes below an agreed safe level).

33. The UN Committee on Peaceful Uses of Outer Space (COPUOS) prefers this solution because the committee limits its mission to "peaceful" uses of outer space and leaves arms control considerations to the Committee on Disarmament. COPUOS further does not question the need for civilian reactors in orbit but focuses on how to improve safety.

Canada, a leader in this movement, has taken the position that further safety measures are needed, and that technology can permit additional procedures such as retrieval.

The requirement inherent in this alternative of defining both an appropriate orbital limit and appropriate functions for nuclear-powered satellites creates serious legal problems. No consensus has ever been reached in COPUOS on these definitions.