Science & Global Security, 1989, Volume 1, pp.83–92
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Printed in the United States of America

The Military Connection and Environmental Hazards of Space-based Nuclear Power

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The potential dangers associated with space-based nuclear power have alarmed many specialists. There are two principal reasons:

- Space-based nuclear energy sources have been declared to be a key part of the military Strategic Defense Initiative (SDI) program. Even in the absence of current military interest in space nuclear reactors, the existence in space of a considerable number of *civilian* nuclear sources would always provide a temptation for ideas of space militarization.

- Nuclear reactors deployed in near-earth orbits are a potential source of radioactive fallout that would be dangerous for the population of the entire earth. Multi-kilogram plutonium-238 radioisotope thermal generators (RTGs) would also be a dangerous source of radioactive contamination on a global scale.

Below, we consider these objections in more detail.

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This paper was written under the auspices of the Cooperative Research Project on Arms Reductions, a joint project of the Federation of American Scientists and the Committee of Soviet Scientists for Peace and Against the Nuclear Threat

REACTORS AND SDI ELECTRICAL POWER NEEDS

A space-based ballistic-missile defense that used new, so-called "exotic" kill mechanisms (for example, laser beams, particle beams, electromagnetic guns, and so on) would have extremely high electrical power demands.

Consider the three modes of operation for hypothetical space-based battle stations:

- *Housekeeping mode* when stations perform very limited operations and power is required only for cryogenic cooling of sensors, computer operations, etc.

- *Alert mode* when all elements and systems of the station are activated and become ready for attack.

- *Burst mode* when hundreds or thousands of targets might be attacked during a short time (of the order of hundreds of seconds).

Of the activities in these modes, the orientation and maneuvering of the battle station during alert mode appear the most demanding in terms of integrated energy requirements.

Let us assume that the launching sites of the target IBCMs are separated by distances of the order of 50 kilometers, which means an angle of rotation of roughly 0.1 radian for a space station deployed in a 500-kilometer orbit. Targeting time should be rather small—of the order of 0.1 seconds, because of the number of potential targets. The corresponding power requirements P for the orientation maneuver may be determined by a simple formula

$$P = I\dot{\omega}\omega$$

where I is the moment of inertia, ω is the angular speed, and $\dot{\omega}$ is the angular acceleration. For this case, the angular speed would be equal to approximately 1 radian/sec, and the angular acceleration to 10 radian/sec^2.

One does not need to rotate the station as a rigid body: it might be enough, for example, to rotate only a mirror. Let us assume that the mirror radius R would be of the order of 3 meters and the mirror mass m_m would be, say, 10 tonnes. The moment of inertia for such a mirror is

$$I = \tfrac{1}{4}m_m R^2$$

so the corresponding rotational power would be equal to

$$\tfrac{1}{4} \times 10^4 \times 9 \times 1 \times 10 = 0.23 \text{ MW} \qquad (\text{ 1 megawatt} = 1{,}000{,}000 \text{ watts}).$$

This rate of energy consumption could be required for tests during the alert mode.

It is a similarly simple problem to estimate the power requirement for maneuvers to avoid attacks by the offensive side by changing the altitude or inclination of the battle-satellite's orbit. For a change of altitude Δh, the corresponding change in orbital energy is

$$\Delta E = \tfrac{1}{2}m_s g \Delta h$$

(where m_s is the mass of the spacecraft and the gravitational acceleration g is about 10 ms^{-2}). This energy change would be equal to 5 megajoules per tonne per kilometer change in orbit height. (For orbits in a gravitational field the change in total energy per tonne is half the change in potential energy.)

For the case of a change in orbit inclination, the change in energy would be

$$\Delta E = P\Delta P/m_s$$

(where $P = m_s\upsilon$ is the momentum of the satellite, υ is the orbital velocity [7.6 km/sec in a 500-kilometer orbit] and m_s is the satellite mass). From this formula, we obtain

$$\Delta E \approx m_s\upsilon^2\alpha$$

for a small angle of change of orbit inclination α, since for small angles $\Delta P \approx \alpha P$. The corresponding energy consumption is then 1 gigajoule per tonne per degree change in orbital inclination.

Characteristic times for these kinds of evasive maneuvers might be tens of seconds. The corresponding power levels are in the range of 1–10 megawatts electric—or 10–100 megawatts thermal, assuming a 10 percent thermal efficiency.

The alert mode is therefore characterized by power requirements in the range of 1–10 megawatts. The most notable feature of this mode is an absolute unpredictability of switch-on moments, the duration of each operating period, and the total number of such periods. According to some estimates, the total operating time in this mode could be as long as years.

To ensure energy supplies during such a long alert period are not exhausted, nuclear power is the only practical source of energy. Operating at low power, these reactors could also be used as energy sources for the housekeeping mode. (However, if a country did not want others to be aware of all its space nuclear reactors from the outset, it might not use these reactors for the housekeeping mode—keeping them "invisible" and turning them on only at the moment of first alert.)

Burst-mode power requirements, despite their magnitude, would not necessarily be well met with nuclear energy.

A hypothetical nuclear reactor for the burst mode would need an electrical power of about one gigawatt and therefore a thermal power of about 10 gigawatts. Design and construction of such powerful rectors for deployment in space is a serious and complicated problem: many aspects of these large pulsed reactors are not understood at this time.

Let us try to estimate the mass of such a powerful reactor. When the power level gets relatively high, the maximum thermal flows inside a reactor's elements—and hence its mass and size—begin to become significant. In the limit, the power/mass ratio depends only on mass. According to Soviet calculations, this limiting ratio is equal to 3–5 kW/kg.[1]

Application of these concepts to very high power levels is not correct, however. For example, a reactor with thermal power of, say, 50 gigawatts would have a mass of 10,000 tonnes. This is clearly absurd. One needs other conceptual approaches to the design of such reactors—the American Physical Society report on directed energy weapons, for example, discussed pulsed reactors with a power/mass ratio of the order of 10–100 kW/kg.[2]

In practice, we believe that the most likely source of energy for the burst mode would be stored energy.

Let us make some estimations of the required amount of stored energy. We have found elsewhere that each shot from an exotic weapon delivers about 100 megajoules.[3] It is assumed that a space station is intended to kill, say, thousands of targets during a hundred seconds. Taking into account inefficiency, possible missed shots and the additional energy consumption for SATKA (Surveillance, Acquisition, Targeting and Kill Assessment) system operations, it would then be necessary to store about 300–500 gigajoules of energy on a space station for operation in the burst mode.

The amount of energy might realistically be available from chemical energy. For example, burning beryllium in an atmosphere of fluorine would deliver about 30 megajoules per kilogram of reagents.[4] If the efficiency of conversion into the electrical energy were about 10 percent, the total mass of the chemicals would be of the order of 100 tonnes.

In summary, space-based defenses would require the design and construction of nuclear reactors for space basing with a thermal power up to 100 megawatts for use mainly in the alert mode and also possibly in the housekeeping mode operating with a much lower power level. This power level is well beyond the present level of space-oriented nuclear reactor technology. If a program to develop such space reactors were authorized, a program of space trials, including full-scale testing, would be required.

ENVIRONMENTAL CONCERNS

Space-based reactors

The testing and deployment of high-powered reactors in low earth orbit might be a source of accidental atmospheric pollution by either nuclear fuel (for example, as a result of launch accident) or fission products.

Suppose that the space reactor nuclear fuel were highly enriched uranium—for example, 97 percent uranium-235 and 3 percent uranium-238. The specific activity of these uranium isotopes is rather low: for uranium-235 it is equal to 2×10^{-6} curies/gram; for uranium-238 it is seven times smaller. Maximum acceptable safe concentrations of uranium isotopes in air are: for uranium-235, 2×10^{-9} grams/liter (4×10^{-15} curies/liter) and for uranium-238, 1×10^{-8} grams/liter (3×10^{-15} curies/liter).[5]

In order to calculate the environmental effects of a launch accident, we must estimate the total mass of uranium in the reactor body. This estimate will depend on the type of reactor. In fast-neutron reactors, the core volume is small, but the mass of uranium-235 is relatively high. In thermal-neutron reactors, the situation is reversed.[6]

The available information on operating and projected space reactors is that the uranium mass is in the range of 30–170 kilograms. We will assume this parameter to be 100 kilograms in order to make further calculations.

Let us calculate the contamination using the above limits on acceptable exposure to uranium-235 and ignoring the small amount of uranium-238. If all the uranium were dispersed uniformly in the form of a fine-grained dust, it could contaminate 5×10^{13} liters—50 cubic kilometers—up to maximum permissible limits. This result is greatly exaggerated, but it shows that a radioactive launch accident would have only a local impact.

Now let us consider the potential hazards associated with re-entry of space nuclear reactors after they have been operating for some time.

The uranium-235 fission process yields a total energy of 203.9 million electron volts (MeV) per fission. A single megawatt of thermal power then corresponds to 3×10^{16} fissions per second.[7] A megawatt-year therefore corresponds to 1×10^{24} fissions (400 grams of uranium-235), and results in the production of 9 grams of strontium-90 (about 2,000 curies), and 14 grams of cesium-137 (also about 2,000 curies). The accumulation inside an operating reactor of biologically dangerous isotopes increases with the time in orbit, increasing the dangers of powerful reactors in low earth orbit.

Consider, for example, the NASA project SP-100, a reactor with a thermal power of about 2 megawatts, designed for a 10-year operation cycle. At the end of this cycle, about 1×10^{5} curies of strontium-90 and cesium-137 would have accumulated. Any accident with such a reactor could result in the fallout of a significant part of these materials. The long-term cancer effects of such an accident could be comparable with the Chernobyl disaster.[8]

Radioisotope Thermal Generators (RTGs)

Isotopes which may be used as energy sources for RTGs are listed in table 1.

Alpha sources are preferable since the ranges of alpha particles are small, and the energy is released in a small volume. Half-life is an important feature, too, since very short-lived sources would have to be replenished in space. Of course, the availability of a specific isotope must also be taken into account.

All things considered, plutonium-238 is the most attractive energy source for space-based radioisotope thermal generators. This isotope is used in the US *Galileo* and *Ulysses* missions, where more than 10 kilograms of plutonium-238 will provide about 5 kilowatts of thermal power and approximately 1 kilowatt of electrical power.

Below we roughly analyze the worst-case-scenario consequences of a launch accident in which all the plutonium is dispersed as a fine dust over large distances.

The International Council for Radiation Protection (ICRP) has recommended an exposure limit for plutonium-238 of 7×10^{-17} curies/liter. This isotope has a high specific activity of 18 curies/gram, so the corresponding minimum volume over which the plutonium must be dispersed is

$$18/(7 \times 10^{-17}) = 2.6 \times 10^{17} \text{ liters/gram.}$$

Ten kilograms of plutonium-238 could therefore theoretically contaminate

Table 1: Energy Sources for RTGs

Isotope	**Decay type**	**Half-life** *years*	**Power/mass** *W/g*
Polonium-210	α	0.38	141.0
Curium-244	α	0.45	120.0
Cerium-144	β,γ	0.78	26.0
Thorium-228	α	1.90	170.0
Cobalt-60	β,γ	5.25	17.4
Curium-242	α	18.	2.8
Strontium-90	β,γ	28.	0.9
Cesium-137	β,γ	30.	0.4
Plutonium-238	α	89.	0.6

a volume of about 3×10^{21} liters or 3×10^9 cubic kilometers. For comparison, if we take 10 kilometers as the effective thickness of the earth's atmosphere, its volume is equal to

$$10 \times 4\pi \times 6{,}400^2 = 5 \times 10^9 \text{ cubic kilometers}$$

or roughly the maximum contaminated volume. The result for plutonium-238 has not a quantitative, but rather a qualitative meaning: a plutonium-238 accident would be of global consequence.

Similar estimates for some other isotopes for a thermal power level of 5 kilowatts give the following results:

- cobalt-60 would have a contamination volume of 1×10^6 cubic kilometers
- strontium-90 would have a contamination volume of 2×10^7 cubic kilometers.

These volumes are not as large as for the plutonium case but they still imply that the potential consequences would be serious.

For strontium-90, the long-term effects might also be amplified since it enters humans via food, and accumulates in the bones by replacing calcium.

The problem of determining a safety threshold for RTGs (if such a threshold exists) needs more serious investigation. It is evident from the calculations above, however, that RTG launch and deployment in near-earth orbit is dangerous if the probability of accident and dispersal is not near zero.

VERIFICATION

Consider now the detectability by remote sensing methods of an operating space-based nuclear power system.

In principle, space-based nuclear reactors may be detected by neutron and gamma emissions as well as by infrared emission from their heat radiators. A kilowatt of thermal power from a nuclear reactor corresponds per second to 3×10^{13} fissions, which emit 7×10^{13} fast neutrons and 2.5×10^{14} prompt gamma rays (with an average energy of 1 MeV). (Because of the radioactivity of the fission products, the gamma-ray intensity is ultimately doubled.)

By comparison, RTGs are weak emitters of nuclear radiation. A plutonium-238 isotope power source with a thermal power of 1 kilowatt would emit per second:

- 5×10^6 fast neutrons
- 1.5×10^7 gamma-rays with energy of 1 MeV
- 2.7×10^8 gamma-rays with energy of 0.766 MeV
- 1.2×10^{10} gamma-rays with energy of 0.153 MeV.

Isotope power systems are therefore not very strong sources compared with nuclear reactors, and their detectability by nuclear techniques is limited. However, they are just as detectable by their thermal radiation as nuclear reactors with the same power.

The factors affecting detectability are discussed in detail in companion articles in this issue. The general conclusion of these articles is that operating (or recently switched off) space based nuclear reactors may be detected with a great degree of confidence. However, never-operated reactors would be invisible to passive detection methods. Prelaunch inspection could, however, determine the presence of nuclear-reactor-like configurations in the space-launch payloads.

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7. Based on 200 MeV per fission, 1.6×10^{-13} joules per MeV and 1 kilowatt = 1,000 joules per second.

8. *Editor's note*: the Chernobyl accident released an estimated 1–5 megacuries of cesium-137 and perhaps 0.2 megacuries of strontium-90. Tens of thousands of fatal cancers are expected to result. See Christopher Hohenemser, "The Accident of Chernobyl: Health and Environmental Consequences and the Implications for Risk Management," *Annual Reviews of Energy*, **13**, (1988), p.383.