IISL.4.-94-850

THE TECHNICAL BASIS FOR REGULATING THE USE OF NUCLEAR POWER SYSTEMS IN NEAR-EARTH SPACE

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Abstract

We review the history and the main applications of nuclear energy in space, and the related safety concerns. These refer to the potential re-entry into the atmosphere of radioactive material, to the interference with space research in high-energy astrophysics, to potentially destabilizing military applications, and to the hazard of disruptive and polluting collisions in Earth orbit. Actually, it has been recently pointed out that most nuclear reactors in space have been disposed at altitudes between 700 and 1050 km, where drag-induced orbit decay is negligible, but the collisional probability with a piece of space debris is significant and is going to increase in the future. The accidental impact breakup of a nuclear reactor, or a future nuclear-electric propulsion spacecraft, may thus pollute a large shell of circumterrestrial space.

These concerns prompted the U.N. General Assembly in 1992 to approve a resolution establishing criteria for a safe use of nuclear power sources in space. However, these criteria were restricted to non-propulsive systems and to current types of technologies and missions. We argue that while a comprehensive ban on space nuclear systems in general appears neither feasible nor desirable, additional "rules of the road" are needed to address current and future safety concerns. In this context, it appears important to make a clear distinction between nuclear systems operating permanently in low Earth orbits and systems launched from or assembled near the Earth but intended to operate in deep interplanetary space. While the former systems should be forbidden (up to a maximum height taking into account the collision hazard), the latter ones may be allowed provided suitable safety measures or devices are put in place. Technologies ensuring reliable verification of such rules are currently available.

Introduction

The exploration of remote solar system bodies or hostile planetary surfaces, as well as the exploitation of space resources, will continue to require nuclear power sources. In fact, extrapolating existing technologies, it is difficult to envisage another reliable system able to provide high electric power (i.e. hundreds or thousands of kW) for long enough periods of time (years); far away from the Sun, where solar panels are not sufficient, nuclear power sources are essentially the only way to obtain energy. Moreover, no power-generating system shares the other advantages inherent in the nuclear sources: compactness, robustness, ability to work quite anywhere in the solar system, whitstanding harsh environments with a high degree of system autonomy.

Nuclear power sources for space applications have been considered as energy sources both for power generation and propulsion. Apart from the ORION project, that was intended to use small nuclear charges sequentially detonated to lift and propel a large spaceship, from 1955 to 1973 the United States were engaged into a comprehensive research program, named Rover, to develop solid-core nuclear rockets.[1] Such rocket motors could provide as much as twice the specific impulse of the best chemical rockets and were seen as the only realistic propulsion system for a manned mission to Mars (a view still shared by many people today).

Besides some active research projects to establish for space applications basic nuclear reactor technology, design concepts and performance limits, the development of nuclear rocket engines was pursued as well. Probably the most known was the NERVA motor, intended to replace the J-2 chemical engines burning liquid hydrogen and oxigen in the upper stages of the Saturn V moonrocket.

The suspension of the Saturn V production on 1969, the quick change of the political climate and the shifting national priorities led to the termination of the Rover program on 1973. However, the re-

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search and development efforts resulted in a technical success and could be at the basis of a renewed interest in nuclear rocket propulsion at the beginning of next century.

In the 1980s the U.S. Strategic Defense Initiative Organization launched a secret effort, code-named Timberwind, to develop a nuclear upper stage that could sharply increase the lifting power of military boosters.[2] But the program was abandoned on 1993.

On June, 1991, it was disclosed that also the former Soviet Union was involved for 30 years in the development of a powerful nuclear-thermal rocket engine to support human missions to Mars. The experimental results were very good, but no application for it is foreseen at present.

Nuclear power sources to provide electric energy for the functioning of a spacecraft have been more successful. Both the United States (since 1961) and the Soviet Union (since 1965) used several nuclear power systems on board of spacecraft. The thermal energy liberated by nuclear processes, such as the decay of radioisotopes or the controlled fission of heavy nuclei in a reactor, may be converted into electrical power. The United States launched 24 spacecraft equipped with radioisotope thermoelectric generators (RTG) and one satellite powered by a thermoelectric nuclear reactor. The Soviet Union, on the other hand, launched only two spacecraft equipped with RTGs, but at least 36 carrying on board nuclear reactors (both thermoelectric and thermionic).

In Earth orbit the United States used the RTG power sources on navigational (6), meteorological (2) and communications (2) satellites. The last launch in low orbit (mean altitude less than 2000 km) took place on 1972, while two spacecraft in geosynchronous orbit were launched by the same booster on 1976. All the other RTGs equipped lunar (6), martian (2) and interplanetary (6) missions. Ulysses, an ESA/NASA probe, was the last to be launched on 1990. The next interplanetary probe that foresees the use of RTGs is the Cassini Saturn Orbiter, whose launch is scheduled in October 1997.

The only nuclear reactor launched in Earth orbit by the United States, on board the spacecraft Snapshot on April 1965, was experimental in nature and was not followed by other flights.[1] The reactor SNAP-10A, placed into a 4000 year lifetime orbit, operated successfully for 43 days, until a series of spurious electronic signals shut down the reactor. Owing to the safety design guidelines, it was impossible to re-activate the SNAP-10A from the ground and it is now definitely quiescent. Hundred years after the launch, the radioactivity level in the core will be less than 0.1 curie and when Snapshot will re-enter in the atmosphere this level will be negligible. SNAP-10A was designed to disperse itself in the upper atmospheric layers.[1]

On the other hand, since 1967 the Soviet Union operated routinely thermoelectric nuclear reactors in very low Earth orbits (altitudes less than 300 Km). The Romashka reactors have equipped at least 34 military spacecraft used for the radar ocean surveillance of Western fleets. At the end of the mission, with a typical duration of a few months, the nuclear reactor was boosted into a 1000-year lifetime orbit and the core separated at the same altitude.

The Soviets also developed a much more sophisticated and capable thermionic nuclear reactor, known as Topaz. After many years of laboratory development, on 1987 Topaz was space qualified in two space missions (Cosmos 1818 and 1867) into a 500-year lifetime orbit. On 1991 Russia offered the Topaz reactors to potential Western customers into a new effort of space technology commercialization. On May 1992 two of them have been purchased by the United States for $13 million, for research and development purposes, and other could follow.[2] In the meantime, the plan to launch in space, by the end of 1995, a Topaz 2 reactor to power an experimental electric propulsion system was cancelled.

As far as the radioisotope thermoelectric generators are concerned, the former Soviet Union launched only two satellites equipped with RTGs on 1965 in two constellations of small tactical communications spacecraft. Two more RTGs were used for thermal control purposes on board the Moon rovers Lunakhod 1 and 2.

Safety Concerns

During the last decade there has been a growing concern over the use of nuclear power sources in space. For instance, it has been proposed to definitely ban nuclear power sources in Earth orbit, and even the launch of interplanetary spacecraft equipped with RTGs (in particular, Galileo and Ulysses) was strongly opposed in the United States by some public organizations for fear of accidents during the ascent or near-Earth phases of the flight. Stronger protests and legal actions may be expected in the future.

Until now, the safety design criteria applied to the space nuclear power systems appear to have well performed in emergency situations. The first incident occurred on 21 April 1964, when the US Navy satellite Transit-5BN-3 failed to achieve the orbital speed and re-entered in the atmosphere. However the SNAP-9A RTG perfomed as designed, burning up completely at an altitude between 45 and 60 km in the Southern Hemisphere.[1]

The second incident occurred on 18 May 1968. The American Nimbus-B1 meteorological satellite, owing to the intentional distruction of the erratic launcher, plunged into the Pacific Ocean about 5 km North of San Miguel Island, off the California coast. The SNAP-19 RTG carried on board was designed to re-enter intact, avoiding the dispersion of the fuel (Pu 238) in the environment. Five months later the generator was recovered intact on the ocean floor at a depth of 90 meters.[1]

The last incident involving a RTG happened on April 1970. The aborted manned Moon mission Apollo-13 carried in the lunar module Aquarius a SNAP-27 fuel capsule to power the scientific instruments to be deployed on the lunar surface. Due to an oxigen tank explosion in the Apollo service module, the Moon landing was suppressed and the lunar module became a lifeboat for the crew, providing energy, oxigen and propulsion to the spaceship. When Apollo-13 approached the Earth aiming to a safe splash down, the lunar module was discarded and re-entered over the South Pacific Ocean at a speed of about 40000 km/h. The fuel capsule was designed to survive intact the re-entry, and in fact the atmospheric monitoring of the impact area showed no release of plutonium-238 oxide. The SNAP-27 capsule probably lies on the floor of the Tonga Trench at a depth larger than 6 km. No adverse environmental effect has been reported up to now.[1]

The next incident involved the Soviet spacecraft Cosmos 954, a radar ocean reconnaissance satellite (RORSAT) equipped with a Romashka nuclear reactor. The standard procedure to boost the reactor into a safe orbit failed and the satellite re-entered over Canada's Northwest Territories on 24 January 1978. Even though no large fuel particle was found in the following field researches, several large fragments producing high radioactivity were recovered from the unpopulated area. Small particles of reactor fuel (uranium-235 dioxide enriched to the 90% level) were probably scattered over 100,000 square kilometers with a negligible impact on the environment. Some 88% of the fuel actually burned up during the re-entry.[1]

Two further incidents involving Soviet RORSATs, Cosmos 1402 on 1983 and Cosmos 1900 on 1988, had a less dramatic outcome, due to design improvements of the safety systems. The reactor of Cosmos 1402 re-entered on the Atlantic Ocean, while that of Cosmos 1900 was finally boosted into a graveyard orbit by a new safety mechanism.[3] In both cases no release of radioactive material in the environment was detected.

The Space Debris Threat

At present the United States Space Command tracks about 7500 objects in Earth orbit with sizes typically larger than 20 cm.[4] About 21% of them are inactive payloads, 16% are spent rocket stages, 12% are operational debris, and 45% are fragments resulting from more than 120 unintentional or deliberate fragmentations. Only 6% of the catalogued objects are active satellites and probes.[4,5]

More than 15500 catalogued space objects have re-entered in the atmosphere since the launch of the first artificial satellite on 1957.[4] However, several investigations indicate the likely presence in space of 2000 additional objects in the 10-20 cm size range and some 30,000 to 70,000 objects in the 1-10 cm range.[5] These untrackable particles constitute a growing hazard for space operations, mainly when large structures (e.g. space stations) and manned vehicles (e.g. space shuttle orbiters) are involved.

To make the matter worse, any collision between orbiting debris may generate a cloud of many more objects, with a consequent dramatic increase in the collision probability for the remaining objects. This is a typical exponential growth process, that may easily get out of control. It has been estimated that we are already in a situation where, even for zero launch rate of new spacecraft, the amount of space debris will continue to grow, eventually creating a "debris belt" (or better, "swarm", as it will not be confined near the equatorial plane) around the Earth, which will make impossible to carry out any prolonged activity in the corresponding region.[6] Another estimate puts the population needed for the setting-in of a chain reaction at about 2 or 3 times the current debris population, a situation that could be reached within 50-100 years at the present rate of space activity.[7]

Unfortunately, most nuclear reactors used in space have been disposed in orbit with altitudes between 700 and 1050 km, were the collision probability with a piece of space junk is largest. The breakup of a nuclear reactor could be triggered by a "projectile" of the order of only 1 centimeter in size, and would produce thousands of sizeable radioactive debris; at the beginning they would be confined in a narrow "ring" around the original orbit, but within a few years they would be dispersed by natural perturbing forces over a large volume of space. Such "pollution" will not be short-lived, since above a 700 km height the atmospheric drag force is so small that the corresponding removal time for the fragments exceeds a few centuries.

A space debris shell or belt around the Earth could also be a hazard for spaceships in transit. Nuclear electric propulsion (NEP) is being considered for Moon and Mars missions. Due to the low thrust-to-weight ratio, spacecraft equipped with NEP will travel along a spiral trajectory that very gradually expands until the escape velocity is finally achieved (after weeks or months since the launch). Some preliminary estimates have shown that the collision hazard may become significant for a large nuclear spaceship after 2015, in particular if the spiral trajectory starts below an altitude of 1100 km.[8]

The Regulation of Nuclear Power Systems in Space

In the past, several reasons have been put forward to support a ban on the operation of nuclear power systems in Earth orbit:

- No near-term civilian applications are envisaged;
- The highly radioactive core of activated nuclear reactors, as well as the toxicity of the plutonium used in RTGs, represent a potential hazard for the Earth environment in case of accidental re-entry into the atmosphere;
- The collision of a small piece of artificial debris with a space nuclear power system could generate a cloud of radioactive fragments, soon dispersed by the perturbations over a large volume of space;

- The radiation (gamma rays and positrons) emitted by unshielded nuclear reactors in Earth orbit may "blind" the instruments of space observatories devoted to research in gamma-ray astronomy, disrupting the study of this unique window over the most violent phenomena occurring in the universe;

- The possible military use of nuclear power systems in Earth orbit could stimulate an arms race.

However, a comprehensive ban on space nuclear systems in general could jeopardize important medium- and long-term projects and possibly slow down the progress of a potentially promising technology.

On 1992, the General Assembly of the United Nations approved a Resolution ("Principles Relevant to the Use of Nuclear Power Sources in Outher Space"; 47/68) establishing guidelines and criteria for a safer use of nuclear power sources in space.[9] The set of principles endorsed "applies to nuclear power sources in outer space devoted to the generation of electric power on board space objects for non-propulsive purposes".

This Resolution is very important because fills a gap in the international law on a critical topic. However it addresses nuclear power sources having "characteristics generally comparable to those of systems used and mission performed at the time of the adoption of the Principles." But much more capable systems could be developed in the near future and the use of nuclear devices for propulsion is recommended for some new space missions.

Therefore, some additional rules could be needed to lessen the safety concerns while taking into account the difference between a nuclear power system operating in a low Earth orbit and a system launched or assembled near the Earth to operate in interplanetary space or far enough from the Earth.

Possible measures to be considered include the following:

- No nuclear power system should be operated in low Earth orbit (maximum height to be defined): in this region of space only the transit of spacecraft carrying nuclear systems will be permitted;

- Spacecraft carrying on board nuclear power systems could be assembled in low Earth orbit, provided that their final destinations lie outside the forbidden region and an accidental release of radioactive material in the Earth environment could be prevented by safety mechanisms or procedures;

- The orbits available for an extended stay and operation of space nuclear systems should lie at such altitudes that the interference with experiments dealing with gamma-ray astronomy would be reduced below a threshold to be fixed;

- Nuclear devices used for propulsion might be activated in low Earth orbit, only provided that the transit time is maintained below a given ceiling and safety devices are in place to avoid the accidental contamination of the environment.

Were such "rules of the road" implemented, the safety of nuclear systems operations in space and the confidence of the public at large on this issue would certainly increase. At the same time, the possibility of carrying out interplanetary missions requiring nuclear systems would be preserved, as well as the option to assemble large nuclear spaceships in low Earth orbit and to develop new space nuclear technologies in higher and safer orbits.

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