A NEW LOOK AT NUCLEAR POWER SOURCES AND SPACE DEBRIS

Nicholas L. Johnson

NASA Johnson Space Center, 2101 NASA Parkway, Mail Code KX, Houston, TX, 77058, USA,
Email: Nicholas.L.Johnson@nasa.gov

ABSTRACT

The last satellite containing a nuclear power source (NPS) and intended for operations in Earth orbit was launched in 1988. However, a renewed interest in radioisotope power systems (RPS) and nuclear propulsion could lead to new NPS in orbit about the Earth. Previous NPS risk assessments, particularly those performed for the Scientific and Technical Subcommittee of the United Nations' Committee on the Peaceful Uses of Outer Space, have employed older space debris environment models. The present paper employs current environment models and examines the potential effects of collisions between NPS satellites and space debris to both the near-Earth space environment and the terrestrial environment. Harmful collisions between NPS and space debris are unlikely on an annual basis, but the long durations of most NPS in Earth orbit lead to significantly higher total collision probabilities. Disposal plans for new spacecraft with NPS designed to remain in Earth orbit should be developed early in the design phase and should be compatible with internationally accepted space debris mitigation guidelines.

1. REVIEW OF NPS IN EARTH ORBIT

The concept of using a nuclear power source (NPS) in Earth orbit for electrical power generation dates back to the 1950's when the potential application of nuclear power for peaceful purposes was at its zenith. In January 1959, US President Eisenhower proudly displayed the "world's first atomic battery", an early model of an RTG (radioisotope thermoelectric generator) (*Atomic Power in Space*, 1987). Just two and a half years later, the first satellite with an NPS, Transit 4A, was launched with a variant of the SNAP-3 RTG (SNAP stood for Systems for Nuclear Auxiliary Power), which continued to provide power for at least 15 years. During the 1960's four additional RTGs were successfully placed in low Earth orbit (LEO) by the US, and two RTGs were deployed on satellites by the former USSR (Bennett, Lombardo, & Rock, 1981; Bennett, Lombardo, & Rock, 1984; Johnson, 1986). The world's first nuclear reactor in space was carried by the US spacecraft OPS 4682 (also known as SNAPSHOT) in 1965. The vehicle's SNAP-10A reactor operated for 43 days until an apparent malfunction on board the satellite shut down the reactor.

Although the NPS of the 1960's proved the utility of these devices for generating electrical power in space, with one exception the systems rapidly fell out of favor for Earth orbital applications at the same time that they proved indispensable for deep space missions, particularly at and beyond the orbit of Mars. Improvements in solar cell technology provided reliable and cost-effective alternatives to the relatively low power RTGs in Earth orbit, and requirements for higher-powered nuclear reactors failed to emerge. Consequently, only one more RTG was inserted into LEO (a Transit-class spacecraft in 1972), and two were inserted into geosynchronous orbits in 1976 (the LES 8 and LES 9 spacecraft).

The one exception was a low altitude Soviet space system officially designated US-A in the former USSR but more popularly known as RORSAT (Radar Ocean Reconnaissance Satellite). A thermoelectric Bouk nuclear reactor was the primary electrical power source for missions lasting up to 135 days in operational orbits near 250 km. At completion of the mission, the NPS along with a solid-rocket propulsion system was designed to be separated from the rest of the spacecraft and boosted into a long-lived storage orbit in the vicinity of 900-1000 km altitude. In 31 missions during the period 1970-1988, this disposal procedure failed twice, resulting in uncontrolled reentries of the NPS. The next-to-last mission in this program experienced a less serious malfunction, resulting in an NPS disposal orbit altitude of about 700 km.

Following the first reentry accident of a RORSAT spacecraft in 1978 (Kosmos 954), the Bouk reactor was redesigned to permit ejection of the fuel rod assembly. This action would reduce the threat of radioactive contamination to people and property on the Earth in any subsequent reentry event, as evidenced during the reentry of Kosmos 1402 in 1983. At least 13 of the 16 RORSATs placed in disposal orbits from 1980 to 1988 demonstrated this fuel rod assembly release capability.

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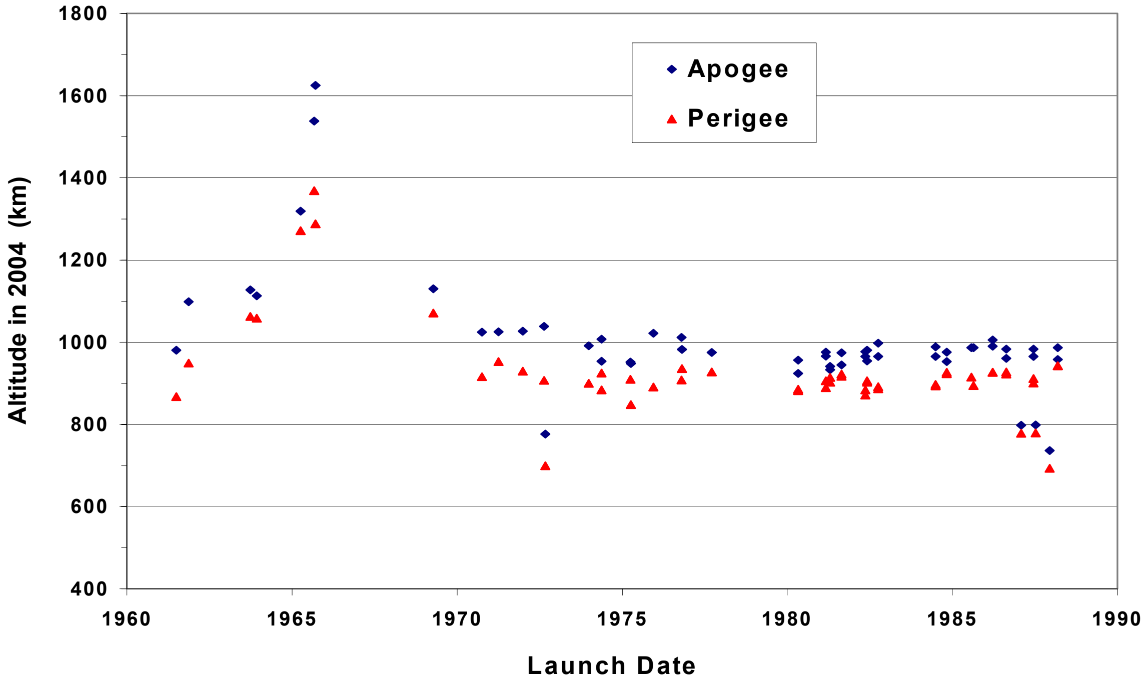

Figure 1. A total of 53 NPS-related objects currently reside in low Earth orbit.

In 1987 two Soviet spacecraft, Kosmos 1818 and Kosmos 1867, carrying Topaz thermionic reactors, were inserted into 800 km high orbits for testing. However, this new NPS design was never adopted for an operational space program and did not exhibit the ability to eject the fuel rod assembly.

Fig. 1 depicts the current apogees and perigees for all eight RTGs, 13 fuel cores, and 32 nuclear reactors (one SNAP-10A, two Topaz, and 29 Bouk) known to still be circling the Earth in low altitude orbits.

2. THE NEAR-EARTH SPACE DEBRIS ENVIRONMENT AND COLLISION RISKS

Space debris includes both natural meteoroids and artificial, i.e., man-made, orbital debris. At altitudes between 700 km and 1700 km, the regime pertinent to the present investigation, the flux of orbital debris greater than 1 mm is one or more magnitudes greater than the flux of meteoroids of the same size. Consequently, the risk of collision between spacecraft with NPS and the space debris environment is dominated by the orbital debris population. The effects of collisions by meteoroids and orbital debris of the same size are more complex to differentiate due to the typically higher velocities and lower densities of meteoroids.

The large (>10 cm) orbital debris population primarily consists of derelict intact spacecraft and launch vehicle orbital stages, mission-related debris, and debris from the fragmentation of spacecraft or launch vehicle orbital stages. Collisions with these debris are often sufficient to cause catastrophic damage to a spacecraft. Collisions with smaller debris (1 mm – 10 cm) can lead to damage of various severity, depending upon spacecraft construction, debris size, and impact location.

The overall vulnerabilities of satellites with NPS can be different than those of other, more conventionally-powered spacecraft. The payload section of an NPS-equipped satellite is often similar to other satellites and can be susceptible to serious physical damage by debris as small as 1 cm and less severe, but potentially mission-ending, damage by debris as small as 1 mm. RTGs and nuclear reactor housings are typically of a rugged construction and less vulnerable to small debris impacts. On the other hand, radiators can be very vulnerable to small particles, which can be a significant design challenge for nuclear reactors which require large amounts of radiator surface area.

Unlike the meteoroid environment which is relatively unchanged from one year to the next and is altitude independent except for very low altitudes (Earth shadowing), the orbital debris environment can be highly dynamic and at altitudes above 700 km exhibits a general increasing trend with time. Since the 1990's, the Russian Federation has provided estimates of the probability of collision between space debris and Soviet NPS to the Scientific and Technical Subcommittee of the United Nations' Committee on the Peaceful Uses of

Outer Space. In a 1996 report, the annual collision probability of an NPS in a typical RORSAT storage orbit with a 5 mm particle was 0.03 (Untitled working paper, 1996). Five years later a more detailed risk assessment, using a 1993 Russian space debris environment model, was submitted at the UN (Collisions between nuclear power sources, 2001) and two months later was presented at the Third European Conference on Space Debris (Grinberg et al., 2001). For example, the annual probability of the destruction of a RORSAT fuel rod assembly by collision with a particle 2.2 cm or larger was calculated to be about 0.01%.

The current NASA assessment of the orbital debris environment is known as ORDEM2000 (Liou et al., 2002). For RORSAT storage orbits, the ORDEM2000 model yields a lower debris flux than the Russian 1993 model in the important 2-8 cm size regime. The collision risk to a spacecraft can be calculated using ORDEM2000 and knowledge of the average cross-sectional area of the vehicle of interest. For example, the average cross-sectional area of Kosmos 1818 (excluding appendages) is approximately 10 m^2. In its orbit of 800 km altitude with an inclination of 65 deg, the chance of a collision with a 1 mm particle during 2005 is almost certain. Although the chance for a similar collision with a 1 cm particle is only about 0.04% per year, since the orbital lifetime of the spacecraft is on the order of 400 years (Nazarenko et al., 1996), it is highly likely that the vehicle will be struck by such a particle before reentry, given the expected growth of the debris environment, even under optimistic scenarios.

The main remnant of a RORSAT in its disposal orbit has an average cross-sectional area of about two-thirds that of Kosmos 1818, but the flux of 1 cm particles at 950 km (same 65 deg inclination) is two-thirds greater than at 800 km. Therefore, the annual collision probability is the same, 0.04%. However, since 28 RORSATs reside in the general 900-1000 km altitude regime (one RORSAT is at a lower altitude), the chance of any RORSAT being struck in 2005 is about 1%. Hence, even without the observed growth of the orbital debris population at this altitude, the chance that any RORSAT will be struck by a 1 cm particle within the next few decades is significant. Furthermore, the orbital decay times for these RORSATs are typically in excess of 1000 years, suggesting the possibility of multiple 1 cm debris impacts for each vehicle and the likelihood of impacts by even larger debris.

The consequences of collisions between debris and satellites carrying NPS can be both immediate and long-term. If the spacecraft is operational, a collision with even small debris could disrupt or terminate the mission. The NPS itself usually represents a small part of the cross-sectional area of the vehicle, but the associated radiator can represent a very significant portion of the exposed area. The puncture of a radiator coolant tube could lead to degradation in power output (assuming that the NPS system has multiple coolant loops to ensure that a single puncture did not render the entire system useless). A debris impact with a critical spacecraft support system (e.g., power, communications, attitude control) could also result in loss of control of the vehicle. This situation, in turn, could prevent any active disposal plans, such as a maneuver to a higher storage orbit.

A collision with large debris could result in a major fragmentation of the spacecraft, resulting in the creation of numerous new debris thrown into orbits spanning altitudes over hundreds of kilometers. Unless the NPS sustained a direct hit, the NPS (RTG or reactor) would likely remain intact, although coolant might be lost (see discussion below on secondary consequences of coolant loss). In a worst case scenario wherein the NPS is the site of the impact, the creation of radioactive orbital debris is possible, although in general such debris would pose no greater risk to other resident space objects than normal orbital debris. In the long term, such debris would typically be more thoroughly consumed during eventual reentry, reducing risks to people on Earth, even if the debris is initially thrown into lower altitudes which results in more rapid orbital decay.

3. DISPOSAL OF NPS

The proper disposal of space NPS has been a subject of considerable debate for more than 40 years. From the onset of the use of NPS for missions in Earth orbit, reducing risks from inadvertent and premature reentry of radioactive materials has been a high priority. To this end, both the US and the former USSR chose either to insert NPS-equipped satellites directly into orbits from which natural decay would take decades to thousands of years or, in the case of the RORSATs, to maneuver the NPS into long-lived storage orbits at the end of the spacecraft mission.

No new NPS have been launched on Earth orbital missions since 1988, despite considerable work in the US and the former USSR on new nuclear reactors for space during the 1980’s and early 1990’s. However, some countries are now considering or beginning the development of new NPS which might be used for Earth orbital missions or might remain in Earth orbit for months or years before departing on deep space missions. In light of these undertakings and of the widespread adoption of space debris mitigation guidelines, a re-examination of desirable attributes for NPS disposal orbits is warranted.

The designed storage orbits for the Soviet Bouk and Topaz reactors now coincide with some of the highest concentrations of space debris in Earth orbit. Fig. 2 compares the 900-1000 km disposal regime for the Bouk reactors with LEO spatial density levels in the year 2005 for objects 10 cm and greater.

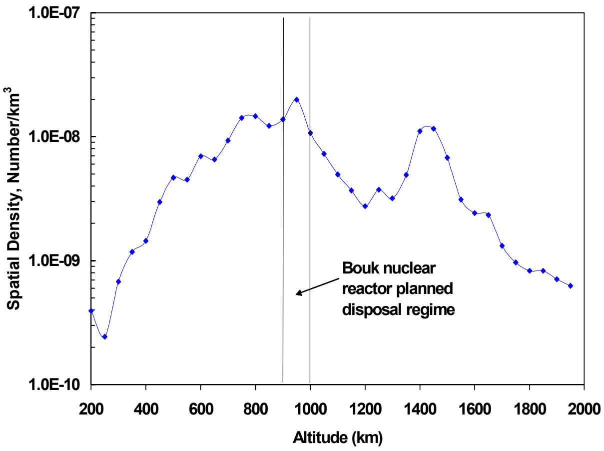

Figure 2. The disposal orbits of the Bouk reactors coincide with the region of highest spatial density in LEO.

Moreover, space debris mitigation guidelines from the US, Russia, Japan, Europe, and the Inter-Agency Space Debris Coordination Committee (IADC) recommend that no space system be left in a long-lived orbit in LEO (*Space Debris Mitigation Guidelines*, 2002). The *US Government Orbital Debris Mitigation Standard Practices* (2000), like NASA Safety Standard 1740.14 from which it was derived (*Guidelines and Assessment Procedures for Limiting Orbital Debris*, 1995), specifically allows for the use of storage orbits above 2000 km in cases where direct retrieval, controlled reentry, or a postmission orbital lifetime of less than 25 years is either impractical or undesirable. Logically, then, storage orbits for future NPS might be found above LEO. The lack of clarity on this subject has been highlighted at recent meetings of the Scientific and Technical Subcommittee of the United Nations' Committee on the Peaceful Uses of Outer Space.

In the case of nuclear reactors, another issue should also be addressed. During observations of the orbital debris environment by NASA in the 1990's an unexpectedly dense population of small particles was found in orbits near altitudes of 900-1000 km altitude and with inclinations of 65 degrees. More than 100,000 particles between 5 mm and 5 cm are now believed to be in this regime, along with even larger particles. Fig. 3 depicts the high concentration of NaK droplets between 600 and 1000 km at inclinations of approximately 65 degrees.

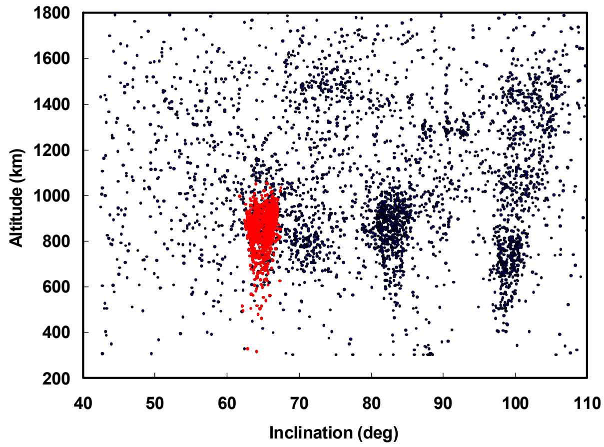

Figure 3. NaK coolant droplets are easily identified in this summary of detections by the Haystack radar in 2003.

As indicated above, particles of this size are potentially hazardous to almost all operational spacecraft. Detailed investigations found the source of these debris to be the sodium potassium primary loop coolant of Bouk reactors which ejected their fuel rod assemblies between 1980 and 1988 (Kessler et al., 1997). Some of these debris are now being officially entered into the US Satellite Catalog, with 47 objects assigned specific satellite numbers as of January 2005. Not only should the removal of fuel rod assemblies from their reactors be reconsidered if coolant leakage would result, but also the vulnerability of radiators containing slowly-evaporating secondary loop coolant should be reduced (Grinberg et al., 1997). An examination of the debris population in the SNAPSHOT storage orbit does not reveal evidence of any leakage of its sodium-potassium coolant via radiator punctures.

4. SUMMARY

The number of NPS-equipped spacecraft in LEO remains small in comparison with the general satellite population, and the near-term risks to these NPS are similarly remote. Unfortunately, the population of small particles in one region of space has been significantly increased due to the release of reactor coolant, thereby increasing collision risks for other spacecraft. The design and mission profiles of future spacecraft carrying NPS should more carefully consider the effects of the NPS on the near-Earth environment as well as the effects of the environment on the NPS. Postmission disposal strategies should be compliant with both nuclear safety directives and internationally accepted guidelines for orbital debris mitigation.

5. AUTHOR'S NOTE

The conclusions presented in this paper are those of the author and do not represent a position of NASA or the U.S. Government.

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