20 January 2015

English only

Committee on the Peaceful Uses of Outer Space
Scientific and Technical Subcommittee
Fifty-second session
Vienna, 2-13 February 2015
Item 7 of the provisional agenda*
Space debris

National research on space debris, safety of space objects with nuclear power sources on board and problems relating to their collision with space debris

The present conference room paper contains submission received by the Secretariat from the Space Generation Advisory Council, and includes additional pictures and figures not included in document A/AC.105/C.1/109. The document is issued without formal editing.

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* A/AC.105/C.1/L.341.

V.15-00399 (E)

SPACE GENERATION ADVISORY COUNCIL
IN SUPPORT OF THE UNITED NATIONS PROGRAMME ON SPACE APPLICATIONS

Report on National Research on Space Debris, Safety of Space Objects with Nuclear Power Sources on Board and Problems of their Collision with Space Debris

Authors: Joao Lousada, Andrew Malcolm, Hamed Gamal, Rajendrasing Rajput, Matteo Emanuelli, Ali Nasseri.

October 2014

The Space Debris Situation

Ever since the first satellite was launched in 1957, Earth's orbit has become more crowded. Many nations and commercial enterprises have launched their own spacecraft into orbit around Earth, and many of these are still in orbit. Of the objects in space only 6% are still operational, while almost 60% are fragments produced from explosions and collisions [1]. These uncontrolled fragments along with other pieces of space debris such as discarded rocket bodies and retired satellites, can collide with each other and generate yet more debris. This cycle, popularly known as the 'Kessler syndrome', results in an exponential growth of orbital debris as time progresses, resulting in an ever-increasing risk for operational bodies in orbit [2].

Figure 1 presents the distribution of space debris according to altitude. It presents the spatial density distribution of the cataloged objects on 1 April 2012 (red histogram), and also shows that the space debris 1000 km altitude have more than doubled since the beginning of 2007 (blue histogram). Fragments generated from the anti-satellite test conducted by China in 2007 and the collision between Iridium 33 and Cosmos 2251 in 2009 were major factors in the jump in the number of space debris [2]. Incidents such as the Iridium-Cosmos collision so the important role debris-debris collision can have in changing the space debris environment.

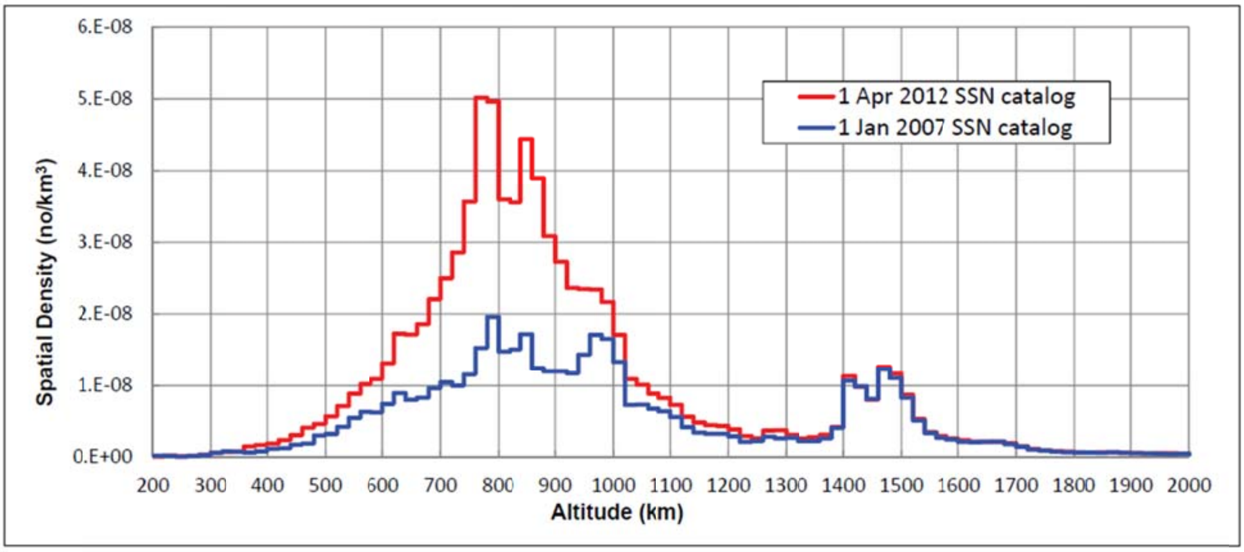

Figure 1: Distribution of space debris according to altitude [2].

Currently, the debris field in Low Earth Orbit (LEO) is not stable. Simulations have shown that even without any future launches the debris field will slowly grow [3]. However, this is an optimistic and unrealistic scenario, since space launches are not expected to stop any time soon. With regular launch rates and no mitigation measures, the quantity of debris in orbit is likely to grow exponentially [2], [4], [5].

Figure 2 shows the distribution of the top 500 massive space debris according to the inclination and altitude of their orbits [3]. It presents the apogee altitude (crosses) and perigee altitude (open circles) versus inclination distributions of the existing LEO rocket bodies and spacecraft that have the highest mass and collision probability products. These objects are the most likely objects for catastrophic collisions that can increase the number of space debris in low earth orbit, as was previously seen in the Iridium 33 and Cosmos 2251 case.

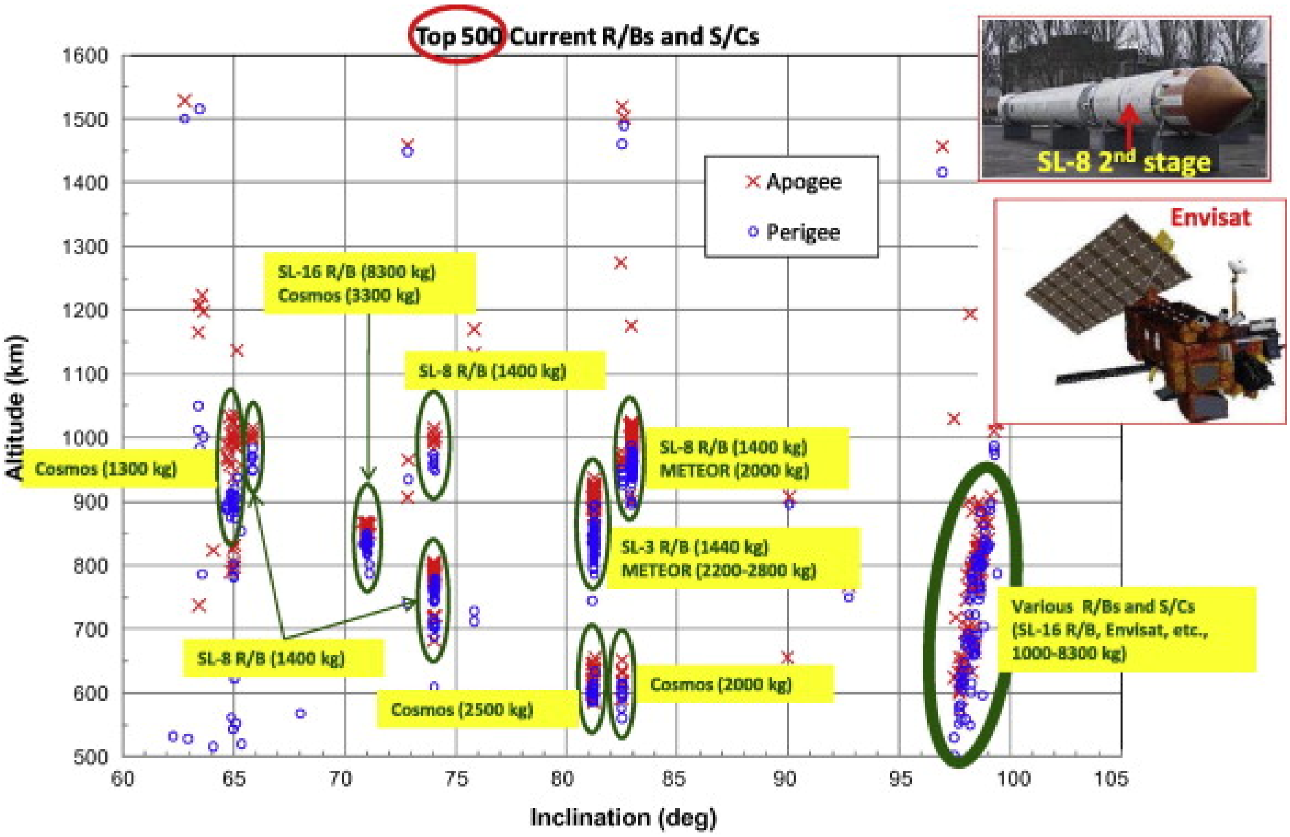

Figure 2: Distribution of space debris according to inclination and altitude of orbit [3].

Spacecraft carrying Nuclear Power Technology

There are three general scenarios to consider with respect to nuclear-powered spacecraft:

1) The spacecraft is equipped with a Radioisotope Thermal Generators (RTG) for onboard power and instrument heating (e.g. deep space probes);

2) The spacecraft is nuclear-powered and uses the derived energy to power the spacecraft, including the launch phase (e.g. Project Rover/Nuclear Engine for Rocket Vehicle Applications (NERVA));

3) The spacecraft is designed to use nuclear technology for propulsion, however does not employ this for launch, merely carrying the nuclear fuel into orbit. Nuclear propulsion will only be used once the spacecraft is in orbit.

Scenarios 2 and 3 differ basically in the launch phase and are considered in the following section.

Scenario 1 is the most common and has been used mostly in deep-space missions. The energy which solar arrays can derive from sunlight decreases in accordance with the inverse square law, therefore as the distance from the sun increases the power available to a spacecraft using solar power diminishes. Nuclear technology provides a reliable source of heat and energy for spacecraft systems beyond the point where solar arrays, for all practical purposes, become ineffective. An RTG, basically, uses the natural decay of radioactive material (usually Pu-238) to convert the heat released by this natural decay into electrical power, using the Seebeck effect [6]. It should be noted that this is not a fission reaction.

Missions such as the Mars Science Laboratory (Curiosity Rover) and solar system probes, such as Voyager 1, 2 and Pioneer 10, 11, have utilized RTGs for reliable power and thermal management.

Some accidents involving nuclear powered spacecraft have been reported in the past, with the first one occurring in 1964 when the TRANSIT 5BN-3 navigational satellite performed an uncontrolled reentry into the Earth's atmosphere after a hardware malfunction. The satellite completely burned up in the upper atmosphere as it was designed to [7] but the long term effects on the human population are hard to determine. Such a re-entry results in increased loading of radionuclides in the upper atmosphere, which can in time spiral down to sea-level. As the half-life of the RTG material is typically long (thousands of years), it is possible that eventual harm was caused to the public and environment.

Two other well-known incidents involving nuclear powered spacecraft were the Apollo 13 mission which re-entered the atmosphere with a fully RTG onboard functional and the Cosmos-954 Radar Ocean Reconnaissance Satellite (RORSAT) uncontrolled re-entry and crash into an unpopulated area of the Northwest Territories of Canada. RORSAT was designed to burn up upon re-entry but failed to do so and a significant amount of nuclear material reached Earth. The RTG from the Apollo 13 mission plunged into the South Pacific, where it remains up to date. It survived the re-entry and impact and no released radiation was detected.

These accidents led to changes in the design of nuclear power systems as a part of space systems. These are now designed to withstand re-entry and impacts in order to reach the ground intact and, most importantly, not to release any radioactive material. It is noted that the RTG from Apollo 13 had already been designed in such a way, which demonstrated the validity of this approach [8].

Launch

Launch is considered the most critical phase of a mission involving nuclear powered spacecraft and also the mission phase with the highest potential threat to the general population.

At this point it is also important to introduce the concept of "criticality". Essentially, it is the point in a nuclear core where fission is initiated and by-products will start to accumulate. Prior to criticality, there are no by-products present in the nuclear fuel. The fuel is relatively benign in comparison to the by-products, as it is typically an alpha radiation emitter and only poses a significant risk to human health if ingested. However, once criticality is achieved, fission by-products start to accumulate in the system. These pose a much greater hazard to human health as a significant part of those by-products are beta- and gamma-emitters, which may cause damage to humans from external exposure alone.

Scenario 2 requires criticality to be achieved before launch and uses the heat derived from a nuclear reaction to power the ascent of the spacecraft. This was investigated and tested in the mid-20th century in the Rover/NERVA programme [9], however any failure of the rocket could potentially result in the release of fission by-products. In comparison, Scenario 3 assumes that the spacecraft is launched into orbit via conventional propulsion methods. It is obvious that the release of any nuclear material, either before or after criticality is achieved, is undesirable. However, in order to limit the severity of any potential consequences, a nuclear reactor should ideally not achieve criticality until it is safely in orbit.

Earth orbit missions and the debris impact hazard

An impact involving space debris must be considered catastrophic as a worst-case, given the significant energies involved. Further, the worst-case example would be a breach of core containment, resulting in fission products being released into space; in the case of an RTG, it is assumed the collision results in the RTG being destroyed and scattered as particulate. This is not necessarily a concern to the public or Earth’s environment, depending upon where in orbit the collision occurs; as long as atmospheric drag is not a factor and the orbit can be considered stable, it can generally be assumed that the nuclear material will stay aloft. However it is also possible that the collision will impart sufficient energy to some debris to move it into an orbit where atmospheric drag becomes a factor, either from the initial impact or from the resultant secondary impacts at a later time.

Given what we know of how orbital debris will spread into a shell around the orbital focus at the orbit’s altitude, the model would effectively be a band of radiation at a certain orbital altitude.

This would not pose a significant direct threat to astronauts or spacecraft, although anyone carrying out an EVA at the altitude in question may face direct health hazards. Therefore, it is likely that a collision resulting in nuclear material being released into orbit would lead to restrictions on where Extra Vehicular Activities (EVAs) can be carried out. However, the reputational issues need to also to be considered, as the general public tends to distrust nuclear technology. An incident of this nature could effectively lead to the premature termination of future and current nuclear spacecraft programmes. Thus the resultant consequences of such an incident are severe, even if not immediately a health hazard.

The likelihood of a collision with debris also needs to be assessed. Studies have been carried out to assess the size and quantity of debris in orbit, and it is relatively easy to model the probability of a debris impact per year on this basis. The overall probability is generally low (in the order of 10^{-5} per year, according to data from [2]). However, when paired with the severe consequences mentioned above, the overall risk ranking can be considered as high and should drive any engineering programme towards embodying significant safeguards to prevent a release of radionuclides should a collision occur.

Disposal

The spacecraft’s disposal after mission completion also needs to be taken into account. What happens to the critical core?

The simplest answer is to move the spacecraft into a safe “graveyard” orbit and leave it there. This would lead to a further increase in the number of space debris objects in orbit and, consequently, increases the risk of space debris impact for future missions. Moreover, impacts with the dead nuclear powered space system can have other consequences such as leak of radioactive material in space.

A more long-term sustainable solution is controlled re-entry of the space system. This will require the spacecraft and, specifically, the nuclear components to be designed to withstand the high temperatures, stresses and impact loads of the re-entry process. This has been done previously with RTG systems used in planetary exploration, but might drive the costs of the spacecraft up.

The case of active nuclear reactors (and their fission-by products) presents a much more challenging task as it is still not clear whether a reactor capable of withstanding re-entry can actually be manufactured. The risk associated with moving used cores into a “graveyard” orbit, selected specifically for disposal of nuclear powered spacecraft taking into account the probability of future collisions, would be lower than re-entry with a used nuclear core. This “graveyard” orbit needs to be selected with the aim to minimise space debris collision and reduce future hazards.

Deep Space exploration missions

The use of nuclear powered spacecraft for deep space exploration is somewhat more sensible than for Earth orbit missions. The increased efficiency of RTGs over solar arrays as the distance from the Sun increases, support the use of nuclear power. While deep space missions pose the same hazard on launch, they spend less time in Earth’s vicinity. Consequently, space debris impact hazards for them are lower.

However, this will depend upon the mission profile. If the spacecraft were to depart from Earth on a direct transfer orbit to its destination (which is rarely the case) and an accident were to occur, the resultant radioactive debris would remain on an orbit that could eventually intercept the Earth’s orbit, ultimately resulting in radioactive debris entering Earth's vicinity.

Conclusion

The use of nuclear power for spacecraft has enabled several important missions in the past (particularly for deep space exploration) and it can continue to do so as long as the necessary safety measures are undertaken. For this, the Space Generation Advisory Council recommends that:

- If a spacecraft will use a nuclear core, it shall carry it to orbit and start the fission reaction only in orbit, as opposed to using nuclear propulsion as a means to reach orbit.

- For all spacecraft using nuclear power, special emphasis shall be placed on the robustness and sturdiness of the nuclear power system. It shall be protected against debris impacts, re-entry stresses, and extreme temperatures.

- Deep space missions carrying nuclear power systems shall use non-direct transfer orbits if possible.

- Upon reaching their end of life, all spacecraft in low Earth’s orbit using an RTG system shall be re-entered in a controlled manner and assuring the intact survival of the nuclear power system.

- Upon reaching their end of life, all spacecraft using nuclear reactors or using an RTG in geosynchronous orbit, shall be transferred to a “graveyard” orbit. This graveyard orbit should be selected in such a way as to assure stability (i.e. do not decay or present a collision hazard) for the duration of the nuclear fuel’s half-life or until the radiation emitted does not pose a hazard for human populations.

- For every mission considering nuclear power, there shall be an independent nuclear safety panel (similar to the USA’s Interagency Nuclear Safety Review Panel (INSRP)) to assure that all safety procedures are followed

- Safety efforts must focus on planning and prevention rather than investigation of accidents.

About The Space Generation Advisory Council

The Space Generation Advisory Council (SGAC) is an international non-profit organization dedicated to students and young professionals in the space sector. It represents the views of the next generation of space leaders to the UN and other space organizations.

Having been created in the United Nations (UN) environment (UNISPACE III), our work with the UN, particularly the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS), is of central importance to our mission. The SGAC works to give regular input to the work of the Committee and to act as a conduit for the opinions of our members.

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