

SPACE REACTOR SAFETY, 1985-1995 LESSONS LEARNED

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Abstract

Space reactor safety activities and decisions have evolved over the last decade. Important safety decisions have been made in the SP-100, Space Exploration Initiative, NEPSTP, SNTP, and Bimodal Space Reactor programs. In addition, international guidance on space reactor safety has been instituted. Space reactor safety decisions and practices have developed in the areas of inadvertent criticality, reentry, radiological release, orbital operation, programmatics, and policy. In general, the lessons learned point out the importance of carefully reviewing previous safety practices for appropriateness to space nuclear programs in general and to the specific mission under consideration.

INTRODUCTION

Safety has been a paramount objective of the U.S. space nuclear program from its inception and will continue to be a key consideration in all future U.S. space nuclear programs. Over the last decade, the United States has sponsored a number of space reactor programs. These programs include the SP-100, Multi-megawatt, Space Exploration Initiative, Nuclear Electric Propulsion Space Test Program (NEPSTP), Space Nuclear Thermal Propulsion (SNTP), and Bimodal Space Reactor programs. A good discussion on space nuclear safety activities during this period has been provided by Sholtis et al. (1994). At present, all space reactor programs leading to space deployment have been canceled; nonetheless, a number of important lessons have been learned from these programs that should be of value for future space reactor programs. These lessons are in the area of safety policy, inadvertent criticality, inadvertent reentry, orbital operation, radiological release, and safety programmatics.

SAFETY POLICY

The space environment creates unique considerations and places unique requirements and constraints on space nuclear systems that are not present for terrestrial nuclear systems. The space environment can present safety advantages as well as safety issues. These unique considerations suggest a safety philosophy and policy specifically tailored to space nuclear activities. The early Radioisotopic Thermoelectric Generator (RTG), SNAP-10A (Otter et al. 1973), and NERVA (Koenig 1986) space nuclear programs identified important safety issues and established safety practices, but they did not create an overarching safety policy (Fig. 1).

During the resurgence of space reactor programs in the early 1980s, the U.S. Department of Energy developed the OSNP-1 document for Nuclear Safety Criteria and Specifications for Space Nuclear Reactors (USDOE 1982). Although this document was never approved as official DOE guidance, it set a precedent of establishing top level safety guidance. The SP-100 space reactor program (USDOE 1991) in turn developed its own safety criteria and specifications based on the groundwork set by OSNP-1. Still later the interagency Nuclear Safety Policy Working Group (NSPWG) was chartered to recommend safety policy, requirements, and guidelines for space nuclear propulsion in support of the Space Exploration Initiative (Marshall et al. 1992a). This interagency team (DOE, DoD, and NASA) carried out an in-depth review of existing nuclear safety policies, regulations, and guidance, and recommended a hierarchy of safety guidance based on an overarching safety policy. The NSPWG recommendations were then adapted to the NEPSTP space reactor program (Marshall et al. 1992b), and the SNTP program (Vest 1993) and later to the Bimodal Space Reactor Program (Kennedy and Jacox 1995).

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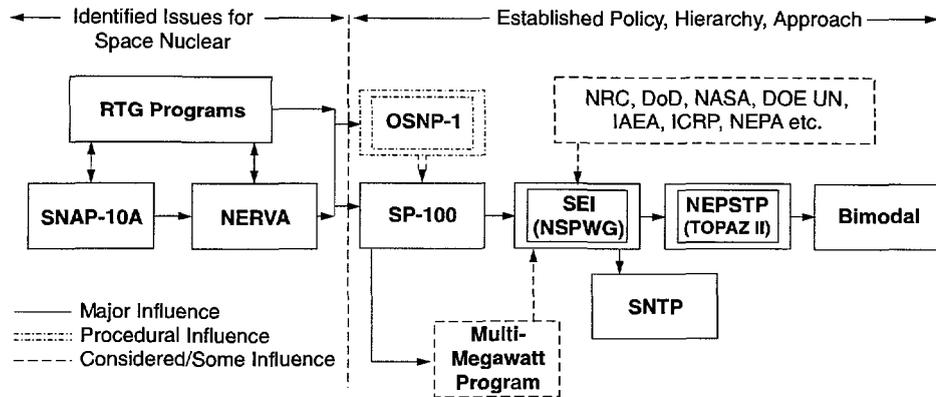


FIGURE 1. The Evolution of U.S. Space Nuclear Policy and Practices.

The general policy statement that evolved is as follows:

Ensuring safety is a paramount objective of any space nuclear program; all program activities shall be conducted in a manner to achieve this objective. The fundamental safety philosophy shall be to assure risk levels are as low as reasonably achievable. In conjunction with this philosophy, stringent design and operational safety requirements shall be established and met for all program activities to ensure the protection of individuals and the environment. These requirements shall be based on applicable regulations, standards, and research.

A comprehensive safety and protection program shall be established. It shall include continual monitoring and evaluation of safety performance and shall provide for independent safety oversight. Clear lines of authority, responsibility, and communication shall be established and maintained. Furthermore, program management shall foster a safety consciousness among all program participants and throughout all aspects of the space nuclear program.

The safety policy outlined above has a number of advantages and has been recommended as a general safety policy for U.S. space nuclear systems (Marshall 1992). This policy provides guiding principles that are generally applicable to any space nuclear program. Once the basic mission is defined, the guiding principles provide the basis for developing appropriate safety requirements applicable to the specific mission. In all of the most recent space nuclear safety programs, care has been taken to ensure that top level safety requirements specify the safety function to be achieved and not the manner in which it should be achieved. Lower level prescriptive requirements should only be established while the mission and design are being defined.

In the earlier versions of this safety policy, space environment and safeguards issues were also addressed. Although these issues are important, they must be treated by a separate set of requirements in separate documents. This clear distinction is necessary to avoid confusion of safety issues and standards with non-safety issues and standards.

INADVERTENT CRITICALITY

Although the SNAP-10A space reactor program did not rule out credible inadvertent criticality accidents, every space reactor program thereafter has prohibited such accidents. The basic safety requirement is:

- *Inadvertent criticality shall be prevented for both normal conditions and credible accident conditions.*

Some reviewers have argued that this requirement is too constraining. They argued that the requirement should be that the consequences from any inadvertent criticality accident should be small. Several problems are presented by changing the currently established practice of preventing credible inadvertent criticality accidents. First, the suggested change would require a detailed safety analysis for a very broad range of potential accidents to demonstrate low consequences. This observation was countered by the argument that an inadvertent criticality would result in explosive dispersion, shutting the reactor down permanently with a very small radiological release. Hence, a single worst-case accident analysis is all that is required. Unfortunately, this type of “benign” self-destruction is only one of many credible scenarios and usually does not represent a worst case. For some concepts, explosive self-destruction is not even a credible scenario. Second, allowing inadvertent criticality accidents requires resolution of the unresolved (and some would say unresolvable) issue of an acceptable dose from an accident. In addition, the probability of human proximity to the postulated accident must be assessed and defended. Furthermore, public acceptance of a “safe” criticality accident is much more difficult to achieve than an approach that simply precludes credible criticality accidents. Finally, United Nations (UN) Principle-3 (UN 1990) was developed to address space reactor safety issues and the United States has agreed to follow its guidance. UN Principle-3 does not permit credible criticality accidents.

In conclusion, prohibiting credible criticality accidents is still the recommended safety practice. Program developers should establish a list of potential credible accidents and take design and operational measures to ensure that inadvertent criticality does not occur under any of these credible scenarios. (At this time, a probability of $>10^{-6}$ /year is considered credible.)

REENTRY

The early U.S. RTG and space reactor programs adopted a practice of designing space nuclear systems that would break apart and disperse upon an inadvertent reentry accident. After the inadvertent reentry of the SNAP-9A RTG in 1964, a decision was made to design RTGs for intact reentry. This same practice was adopted by the SP-100 program because operation in low Earth orbit was considered for some potential missions. The original safety requirements for the NEPSTP space reactor program, consequently, specified intact inadvertent reentry.

The primary concern for these RTG and SP-100 programs was the possibility of “radiologically hot” reentry involving systems with many thousands of curies of activity. The practice of intact reentry was chosen because widespread radiologically hot material presents a greater safety and environmental risk than an intact system that can be recovered. The NEPSTP mission, however, did not require low Earth orbit operation and would be launched “radiologically cold” (<2 Ci). As a consequence, radiologically hot reentry was determined to be a noncredible accident. After much debate, a decision was made to require intact reentry only for radiologically hot systems. A review of accident scenarios demonstrated that this new requirement reduced radiological risk while removing an unnecessary design constraint (Marshall and Haskin 1994). This approach was favorably received by all independent safety review teams.

FISSION PRODUCT RELEASE

Prior to the NSPWG study, operational fission product release was either not addressed by safety requirements (SNAP-10A and NERVA) or very restrictive rules were applied (zero-release for SP-100). After scrutinizing this issue, the NSPWG decided that no established guidance existed and a conservative functional safety requirement could ensure protection without establishing unnecessary constraints. The most recent version of these requirements is as follows:

- *Radiological release from the spacecraft shall have an insignificant effect on Earth.*
- *The consequence on Earth of a radiological release from any credible accident in space shall be insignificant.*

The term “insignificant” means much less than the value specified by the U.S. Environmental Protection Agency (EPA) limitations for radiological environmental contamination of U.S. territory.

OPERATIONAL SAFETY

Although operational accidents are a dominant consideration for terrestrial reactors, they do not generally present a significant risk for space reactors that are operated only in a sufficiently high orbit. As a consequence, many of the prescriptive safety requirements established for terrestrial reactor systems are often inappropriate for space reactor systems. Functional safety requirements for radiological release and for inadvertent reentry are more appropriate for space reactors.

The positive delayed temperature coefficient of reactivity for the TOPAZ-II reactor (NEPSTP program), for example, originally caused some concern. Positive reactivity coefficients present concerns for terrestrial reactors because of their potential for exacerbating certain operational accidents. For terrestrial reactors, postulated operational accidents can have serious consequences. For space reactors in high orbit, however, the consequences of even severe accidents can often be demonstrated to have no significant radiological impact on Earth. Furthermore, the very long time delay for positive feedback (minutes) for the TOPAZ-II reactor meant that a “runaway” accident due to positive feedback should not occur. The positive feedback coefficient, in fact, presents some safety advantages since the cold excess reactivity can be quite small (0.65). The potential for a prompt critical explosive disassembly due to a pre-launch inadvertent startup can therefore be significantly reduced. This is an important safety advantage because space reactor risks are typically dominated by accident scenarios taking place within the Earth’s biosphere; and an explosive disassembly before launch could aerosolize and disperse low-level radioactive material into the atmosphere.

PROGRAMMATIC

A number of programmatic processes were established and are described in the references. A few points are worth highlighting, and are presented below:

- Safety programs should be open to scrutiny and plans should be established for public interaction.

For example, a prominent space nuclear critic from the Federation of American Scientists (FAS) was invited to review and comment on the NSPWG meeting minutes. His participation was valuable to the effort and resulted in a favorable assessment of the NSPWG recommendations from the FAS (Isbell 1991).

- Safety issues should be addressed at a top level as early as possible.

Identifying and addressing safety issues at an early stage is preferable to making safety modifications after the system is developed. Safety modifications after system development can be costly, may affect reliability, and may not result in the most desirable safety approach.

- Prescriptive safety rules should be established only after the design concept and mission details are developed.

Prescriptive safety rules that dictate how a safety function should be achieved can, if established too early, result in designs that are costly, overly constraining, and possibly counterproductive to safety. For example, the prescriptive requirement of intact reentry for the NEPSTP program was found to result in additional safety issues (Marshall and Haskins 1994).

- Early and frequent coordination with safety team, design team, and safety review groups is recommended.

Biweekly safety team meetings, early and frequent meetings with the Interagency Nuclear Safety Review Panel (INSRP) and regular communication with all program groups proved to be valuable in the NEPSTP program (Marshall et al.1994).

SUMMARY AND CONCLUSIONS

A number of important lessons relating to space reactor safety have been learned over the last decade. In general, these lessons learned point out the importance of carefully reviewing previous safety practices for appropriateness to space nuclear programs in general and to the specific mission under consideration.

Important specific lessons include the following:

1. Use a hierarchical safety guidance structure. Develop prescriptive safety requirements only after mission details are known and the design concept is chosen.
2. For most missions, inadvertent criticality should be precluded for all credible accident conditions.
3. Intact reentry, in most cases, should only be required for missions where inadvertent radiologically hot reentry is credible.
4. Fission product release and operational safety concerns should be based on the potential radiological impact on Earth.
5. Safety programs should be open to public scrutiny and plans should be established for public interaction.

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