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Preliminary Nuclear Safety Assessment of the NEPST (Topaz II) Space Reactor Program

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ABSTRACT

The United States (US) Strategic Defense Initiative Organization (SDIO) decided to investigate the possibility of launching a Russian Topaz II space nuclear power system. A preliminary nuclear safety assessment was conducted to determine whether or not a space mission could be conducted safely and within budget constraints. As part of this assessment, a safety policy and safety functional requirements were developed to guide both the safety assessment and future Topaz II activities. A review of the Russian flight safety program was conducted and documented. Our preliminary nuclear safety assessment included a number of deterministic analyses, such as; neutronic analysis of normal and accident configurations, an evaluation of temperature coefficients of reactivity, a reentry and disposal analysis, an analysis of postulated launch abort impact accidents, and an analysis of postulated propellant fire and explosion accidents. Based on the assessment to date, it appears that it will be possible to safely launch the Topaz II system in the US with a modification to preclude water flooded criticality. A full scale safety program is now underway.

BACKGROUND AND OBJECTIVE

In December 1991, the US Strategic Defense Initiative Organization (SDIO) decided to investigate the possibility of launching a Russian Topaz II space nuclear power system. The intended application for the Topaz II reactor is the Nuclear Electric Propulsion (NEP) Space Test Mission.. The primary mission goal is to demonstrate and evaluate Nuclear Electric Propulsion technology to establish a capability for future civilian and military missions. SDIO's principal concern in launching Topaz II was whether or not it could be conducted safely and within budget constraints. To assess the safety of the Topaz II, SDIO established a team of twelve scientists and engineers from Sandia National Laboratories (SNL), Los Alamos National Laboratory (LANL), the Air Force Phillips Laboratory (PL), the University of New Mexico (UNM), and Advanced Sciences, Inc. (ASI). This team worked on a preliminary nuclear safety assessment from March through August 1992. (Marshall, et al. 1993)

The primary objective of the Topaz II preliminary nuclear safety assessment was to provide an adequate safety assessment such that SDIO could decide if a full-scale flight program should be initiated. Reasonable assurances are required that the Topaz II system is, or can be, made safe enough to launch in the United States. Since the cost of any modifications needed for safety must not exceed budget constraints, a major ground rule is that only minor modifications can be made

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to the system. If safety cannot be assured at reasonable cost, the program will not be implemented.

An exhaustive safety analysis was not required to meet the primary objective for this assessment. The implicit guideline was to perform an assessment sufficient to identify any important safety deficiencies and to suggest the type of modifications that might be required to eliminate these deficiencies. Consequently, only those analyses were performed that were considered necessary to meet the primary objectives.

The major emphasis of the work was to assess the safety of launch, operation, and system disposal. Ground activities such as transportation, zero-power critical experiments, etc., which must be addressed at a later date, were not seen as activities that would drive the decision on launch approval. Rather, they were seen as activities that could be carried out safely if the proper safety procedures were employed.

In the process of developing the assessment, extensive collaboration between the Topaz II Safety Team and the Russian scientists and engineers responsible for developing the Topaz II power system has taken place. This collaboration provided the Safety Team with a significant amount of useful information.

SYSTEM AND MISSION DESCRIPTION

The Topaz II power system is a 4.5 - 6 kWe space nuclear system that is based on thermionic power conversion. The major subsystems that comprise the power system are (1) the nuclear reactor, which contains the thermionic converters, (2) the radiation shield, (3) the coolant system, (4) the cesium supply system and (5) the instrumentation and control (I&C) system (Fig. 1).

The nuclear reactor contains 37 single-cell thermionic fuel elements (TFEs), which are fueled by uranium dioxide (UO_2) annular fuel pellets that are 96% enriched in U-235. The TFEs are set within channels in blocks of $ZrH_{1.85}$ moderator (Fig. 2), which is canned in stainless steel. The height and diameter of the reactor core are 37.5 cm and 26.0 cm, respectively. The reactor core is surrounded by radial and axial beryllium (Be) reflectors. The radial reflector contains three safety drums and nine control drums. Each drum contains, on its periphery, a borated neutron poison segment that is used to control the nuclear reaction by drum rotation. The radial reflectors are held in place by steel bands. In order to assure shutdown in the event of an accident, the bands can be severed on command and the radial reflectors ejected. The bands will also sever due to impact.

The radiation shield is attached to the lower end of the reactor and the thermal radiator is located aft of the radiation shield. The radiator consists of an inlet and outlet plenum connected by 78 coolant tubes. Thin copper fins are attached to the outside of the coolant tubes. The cesium supply system provides cesium (Cs) to the TFE interelectrode gap. During operation, the cesium from the reservoir passes through a throttle valve and provides Cs vapor to the Cs plenum, where it is distributed to all of the TFE interelectrode gaps. The Topaz II Instrumentation and Control (I&C) system provides the mechanism for monitoring, controlling and telemetering power system conditions.

Figure 1

Topaz II Space Nuclear Power System

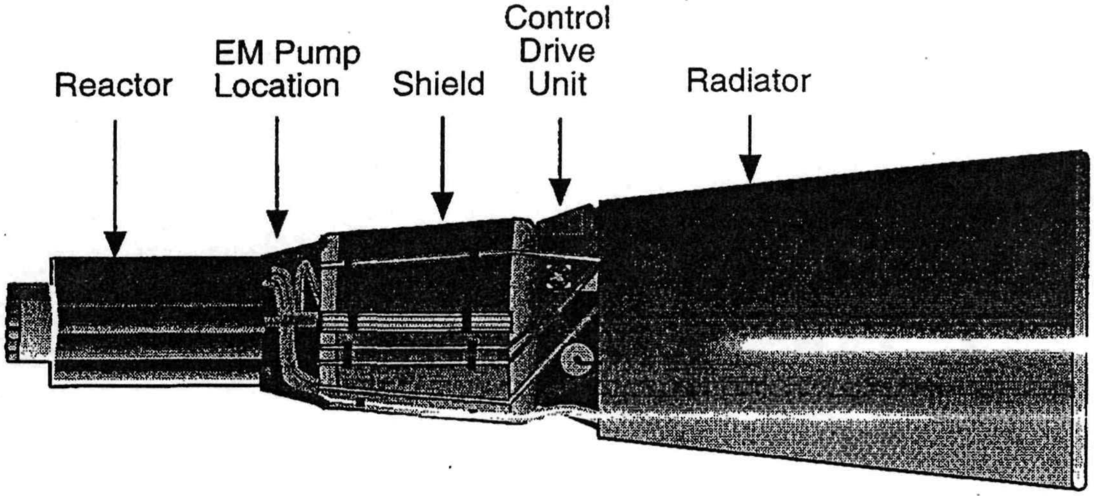
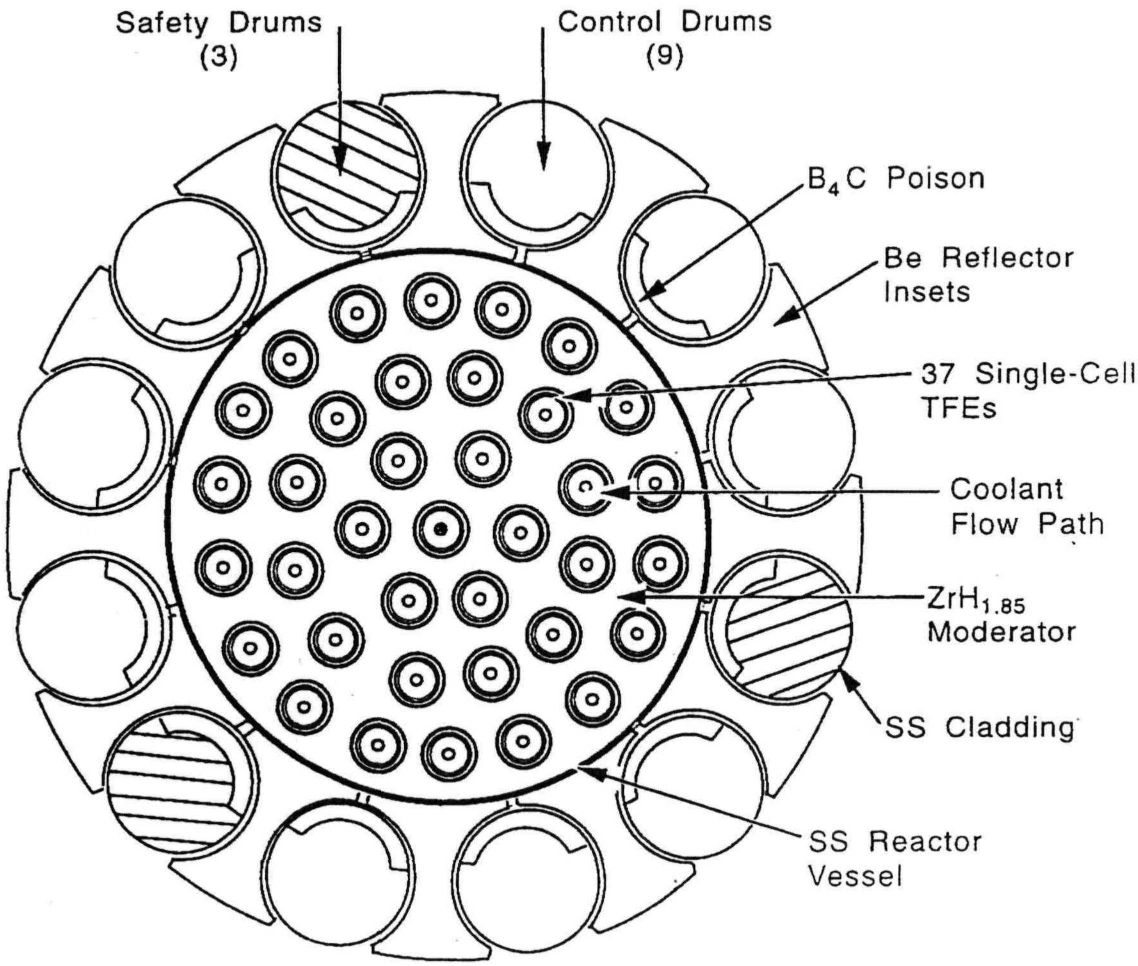


Figure 2

Top View of Topaz II Reactor



The Topaz II flight mission will be launched to a circular orbit with a 28.5° inclination angle. The altitude of this initial orbit is expected to be in the range of 5000 km. Ground based assets will be employed to provide independent confirmation that the vehicle is in an acceptable orbit. The spacecraft and reactor will then begin their initial checkout and operation will commence. Sensors will be employed to determine both the ambient environment and the interactions of the nuclear power supply with the spacecraft. After several days in space, operation of the low thrust electric propulsion system will be used to slowly increase the spacecraft altitude.

When all mission objectives are satisfied, the reactor will be shut down and any remaining propellants will be vented. The total mission duration is expected to be approximately years from launch.

SAFETY POLICY AND FUNCTIONAL REQUIREMENTS

A hierarchical structure will be used for the Topaz II safety program. At the top of the hierarchy are the existing government policies and mandatory requirements. At the next level is the Topaz II safety policy. The safety policy establishes the importance and priority placed on safety and provides the overall guiding principles for the development and implementation of an effective space nuclear safety program. The safety functional requirements, which fall below policy in the hierarchical structure, delineate the specific safety functions required of the system or program. This is the level of detail that currently exists in the safety program. Functional requirements have been developed for reactor startup, inadvertent criticality, radiological release during routine operation, disposal, reentry and safeguards.

The Topaz II Nuclear Safety Policy statement is presented below:

Topaz II Nuclear Safety Policy Statement

Ensuring safety is a paramount objective of the Topaz II space nuclear program; all program activities shall be conducted in a manner to achieve this objective. This fundamental program safety philosophy shall be to reduce risks to levels 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 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 Topaz II program.

Eighteen flight Safety Functional Requirements have been established. Some of the more important Safety Functional Requirements are presented below:

- The reactor shall not be operated prior to space deployment, except for low-power testing on the ground, for which negligible radioactivity is produced.
- The reactor shall be designed to remain shut down prior to the system achieving a sufficiently high orbit.
- Inadvertent criticality shall be prevented for both normal conditions and credible accident conditions.
- Spacecraft radiological release to the space environment shall not result in a significant adverse effect on other space enterprises.
- Radiological release from the spacecraft shall have an insignificant effect on Earth.
- The consequence on Earth of a radiological release from an accident in space shall be insignificant.
- On-orbit disposal shall be limited to sufficiently high orbits.
- For any credible radiologically hot reentry accident, the reactor shall reenter essentially intact, or alternatively, shall result in essentially full dispersal of radioactive materials at high altitude.
- Planned radiologically hot reentry shall be precluded from mission profiles.

A sufficiently high orbit is an orbit in which the orbital lifetime is long enough to allow for the decay of fission and activation products to approximately the level of the actinides (approximately the level of activity at launch). Radiologically hot refers to the situation in which fission and activation products have not decayed to about the level of the actinides, and radiologically cold refers to the situation in which they have decayed to this level.

SAFETY PROGRAM

A safety program structure is under development. A design nuclear safety team has been established and is aggressively addressing all important safety issues. This team performs the mainline nuclear safety function, including detailed deterministic safety analysis, detailed probabilistic risk assessments, and the development and defense of Safety Analysis Reports. A Project Safety Team is now forming to provide safety oversight for the Topaz II project office. In addition, an Independent Nuclear Safety Advisory Committee is being formed to provide top level advice to the NEPST program. This team of Advisors meets quarterly with the design safety team and is entirely independent of the NEPST program. The Department of Energy is now forming its own safety oversight team to provide an independent safety review in conformance with their safety responsibilities. In addition to all of these safety teams, an executive order requires a safety review by an Interagency Nuclear Safety Review Panel (INSRP). The Design Safety Team will submit a Preliminary, Updated, and Final Safety Analysis Report (PSAR, USAF, and FSAR) to INSRP during the progress of the program. INSRP will review these reports and other safety analysis and conduct their own independent risk assessment for the mission. This risk assessment is passed on to the Office of Science and Technology Policy and the National Security Council for review and then on to the Executive Office of the President for launch approval.

SAFETY ASSESSMENT

After the completion of the preliminary nuclear safety assessment, it was concluded that it would be possible to safely launch the Topaz II system with a design modification. Based on this conclusion a full scale safety program was initiated. The safety assessment presented in this paper is primarily the result of our preliminary nuclear safety assessment.

The preliminary safety assessment focused on potential show-stoppers. Since Topaz II will contain essentially fresh uranium fuel when launched, the system will be radiologically cold (~2 curies vs ~3×10^5 curies for the Galilleo radioisotopic source) and the risk from a postulated disruption accident is very low. Furthermore, any postulated accident occurring in space during the operational phase is expected to have an insignificant and probably undetectable effect on Earth. Lastly, the NEPST mission assures that any postulated reentry of the reactor system will be radiologically cold for all credible scenarios. Based on this perspective, the preliminary safety assessment was directed primarily toward potential preoperational inadvertent criticality accidents.

(a) Flooding/Immersion Criticality
An accident scenario can be postulated in which the reactor system fails to achieve orbit and subsequently impacts the Earth's surface. It is then assumed reactor barriers are disrupted, the core is immersed in water, and water floods the core through the disrupted barriers. Since Topaz II is an undermoderated reactor, the addition of water to reactor void and coolant channel regions will increase moderation in the core and could result in an inadvertent criticality. In addition, immersion in water or wet sand could affect neutron reflection and also insert positive reactivity. The MCNP Monte Carlo neutronics code was used to explore these postulated accident scenarios.. The results of this accident analysis for the original (unmodified) Topaz II is presented in Table 1a.

Table 1a
Topaz II Excess Reactivity for Postulated Flooding Accident
Original Design

Reflectors*	Flood	Immerse	Excess Reactivity ($)
on/Drums 0°	water	water	+3.46
on/Drums 0°	water	wet sand	+4.00
OFF	water	water	+1.20
OFF	water	wet sand	+4.78

Table 1b
Modified Design

OFF	water	wet sand	-4.40

*Drums at 0° refers to poison segments turned toward core

The results show that for radial reflectors on and off, water flooded and reflection by water or wet sand, the reactor is predicted to be significantly supercritical. This observation resulted in a study of potential design modifications to prevent water flooding criticality. The Topaz II fuel element design features allow relatively easy access to the assembled reactor power system. This feature permits testing of the entire power system using electrical heaters to simulate the fuel and permits fuel loading at the last stage of pre-launch operations. This feature also permits relatively unobtrusive modifications to prevent water flooding criticality. An approach would be to insert neutron poison rods within the central cavity of the annular fuel pellets. The poison rods would only be withdrawn after a safe orbit is achieved. A second, "fuel-out," approach would be to remove the fuel pellets from the central four TFEs to reduce the core reactivity. For this approach the fuel would be inserted into the core only after a safe orbit is achieved. A neutronic analysis indicated that both of these approaches would assure water flooding/reflection subcriticality. The "fuel-out" approach, however, has been selected as the baseline "modified approach." As can be seen in Table 1b, for the worst case scenario of water flooding and sand reflection, the reactor will be subcritical by more than $4.00. This approach should assure that the requirement for no inadvertent criticality is achieved for postulated water flooding accidents.

(b) Impact, Explosions and Fires

An analysis was also carried out to determine if an Earth impact or propellant explosion accident could induce an inadvertent criticality. Based on this analysis the distortion of the core from impact and explosions should not result in an inadvertent criticality, even if the central four TFEs were loaded with fuel. Very preliminary liquid and solid propellant fire accident analyses were carried out for Topaz II. This preliminary analysis did not show any fuel melting that could result in a reconfiguration criticality accident; however, more detailed analysis will be required.

(c) Accidental Startup

Calculations have been performed for a highly improbable startup Reactivity Initiating Accident (RIA). The preliminary analysis suggests that the temperature coefficients of reactivity for Topaz II provide controllable operation with important safety advantages. The prompt negative temperature coefficient for Topaz II helps mitigate postulated RIAs and promote stable control. The very delayed positive temperature coefficient for Topaz II does not present any control or safety concerns and it allows an initial cold excess reactivity of less than $1.00, thus virtually precluding a prompt disassembly accident during groundtesting startups.

(d) Reentry Analysis

A preliminary reentry analysis on the Topaz II system was performed in order to estimate the status of the power system after such an event. This calculation used some simplifying assumptions. Specifically, an orbital decay scenario was analyzed, which results in the maximum integrated heating of the power system. Also, it was assumed that the system would fly in a stable, reactor first configuration up to the point that the reactor separates from the rest of the system. This results in maximum melting of the upper head of the reactor. Finally, it is assumed that the reflector retaining bands fail at an altitude of 100 km, and so maximum heating of the side of the reactor vessel occurs.

Based on these assumptions, the reentry analysis shows that at 672 seconds into the reentry scenario, when the system is at an altitude of 59 km, complete melt-through of the three stainless steel plates on the top of the reactor has occurred. Ten seconds later the reactor separates from the rest of the power system because the six support legs that hold it to the shield have melted through. At this point it is assumed that the reactor begins a random tumble and spin (RTS). During the RTS portion of the reentry, some melting of the vessel bottom and side walls occurs before the speed of the reactor is reduced to levels that do not support significant aerothermal heating.

Based on this analysis it appears that Topaz II may break up on reentry. By proper selection of mission parameters, however, it can be assured that a radiologically hot reentry can be made a non-credible event. Consequently, the safety requirement for any credible radiologically hot reentry accident will be satisfied.

(e) Disposal
Calculation of the radioactive inventory as a function of time after shutdown shows that the reactor will be radiologically cold after about 400 years. The orbital lifetime is predicted to be millions of years; consequently, the requirement for on-orbit disposal is easily achieved.

CONCLUSIONS

Based on the Topaz II Flight Safety Team's understanding at this time, it appears that it will be possible to safely launch the Topaz II system in the US with a design modification to assure water flooding subcriticality. The safety team is now aggressively pursuing the next phase of the safety analysis. This analysis includes detailed deterministic analysis of all important safety issues, detailed Probabilistic Risk Assessments, appropriate safety testing, development of Safety Analysis Reports and other safety activities.

Reference

A.C. Marshall, et. al., Topaz II Preliminary Safety Assessment, 10th Symposium on Space Nuclear Power and Propulsion, Albuquerque, NM 1993.

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