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TOPAZ II PRELIMINARY SAFETY ASSESSMENT

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Abstract

The Strategic Defense Initiative Organization (SDIO) decided to investigate the possibility of launching a Russian Topaz II space nuclear power system. A preliminary 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 safety assessment included a top level event tree, neutronic analysis of normal and accident configurations, an evaluation of temperature coefficients of reactivity, a reentry and disposal analysis, and analysis of postulated launch abort impact accidents, and an analysis of postulated propellant fire and explosion accidents. Based on the assessment, it appears that it will be possible to safely launch the Topaz II system in the U.S. with some possible system modifications. The principal system modifications will probably include design changes to preclude water flooded criticality and to assure intact reentry.

BACKGROUND AND OBJECTIVE

In December 1991, the 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. SDIO's primary concern in launching a 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 Safety Assessment (PSA) from March through August 1992. (SDIO, 1992)

The primary objective of the Topaz II PSA is to provide an adequate safety assessment such that SDIO can 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 to the system. SDIO, the program sponsor, will determine what costs are acceptable. 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 PSA. 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. A more comprehensive safety analysis will be performed during the next phase of the program.

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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 PSA, 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 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.

The nuclear reactor contains 37 single-cell thermionic fuel elements (TFEs), which are fueled by uranium dioxide (UO_2) fuel pellets that are 96% enriched U-235. The TFEs are set within channels in blocks of $\text{ZrH}_{1.85}$ moderator, 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 9 control drums. Each drum contains on its periphery a section of boron carbide (B_4C) neutron poison that is used to control the nuclear reaction by drum rotation. The radiation shield is attached to the lower end of the reactor. The shield consists of lithium hydride (LiH) within a stainless steel shell. The reactor coolant system includes sodium-potassium (NaK) coolant, a single EM pump, stainless steel piping, and a heat rejection radiator. The radiator consists of an inlet and outlet plenum that are 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. Cesium vents to space through a throttle valve at a rate of 0.5 g/day. The Topaz II Instrumentation and Control (I&C) system provides the mechanism for monitoring, controlling, and telemetering power system conditions.

The primary goals of the NEP Space Test Program are (1) demonstrate the feasibility of launching a space nuclear power system in the United States, (2) demonstrate an orbit adjust capability using nuclear electric propulsion, (3) evaluate the in-orbit performance of the Topaz II reactor and selected electric thrusters, and (4) measure, analyze and model the NEP self-induced environment. The secondary goal is to conduct space science and engineering experiments compatible with the primary mission requirements.

The Topaz II flight mission will be launched on a medium class launch vehicle such as an Atlas, Delta, or Titan II. The launch will be to a circular orbit with a 28.5° inclination angle. The altitude of this initial orbit is expected to be in the range of 1000 to 2000 km. Ground based assets will be employed to provide independent confirmation that the vehicle is in an acceptable orbit. The spacecraft and reactor will begin their initial checkout, and operation of the vehicle sensors will commence. The 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 propulsion system will be used to increase the spacecraft altitude only and essentially circular orbits will be maintained. The sensors will be employed to study the effect of the electric propulsion system on the spacecraft. The operation of the electric propulsion system will be suspended periodically during this part of the mission in order to sense the local space environment and determine any residual effects of the propulsion system operation on the spacecraft.

Assuming that the spacecraft has achieved a much higher altitude $\sim 36,000$ km, a second propulsion phase will begin. In this phase, the electric propulsion system will be used to both increase the orbital altitude and decrease the orbital inclination in an optimum fashion. This propulsion phase will be continued as long as possible. 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 less than two years from launch.

SAFETY POLICY AND FUNCTIONAL REQUIREMENTS

Ensuring safety is a paramount objective of the Topaz II Flight Demonstration Program; all program activities shall be conducted in a manner to achieve this objective. The fundamental Topaz II Safety Program philosophy is 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 will be based on applicable regulations, standards, and research.

A hierarchical structure will be used to establish 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. These functional requirements will eventually be used to establish detailed safety specifications and any system modifications that must be made.

The most important safety functional requirements that have been developed are as follows:

- 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. (A sufficiently high orbit is one in which the orbital lifetime is long enough for the fission and activation products to decay to about the level of the actinides.)
- Inadvertent criticality shall be prevented for both normal conditions and credible accident conditions.
- Radiological release from the spacecraft shall not contribute significantly to any local space environment for an extended period of time. ("Significant" means greater than the most appropriate guideline or norm. Extended period of time is understood to mean encompassing the time period of potential future space enterprises in the region of space under consideration.)
- Adequate protection for the reactor system shall be provided during operational life for all normal conditions and credible accident conditions to prevent reactor system disruption or degradation that could preclude safe disposal.
- For any credible reentry accident prior to disposal, the reactor shall reenter essentially intact, or alternatively, shall result in essentially full dispersal of radioactive materials at high altitude.

RUSSIAN FLIGHT SAFETY PROGRAM

The Russian flight safety program for the Topaz II power system has not been completed, because a Topaz II system has never been launched. The major emphasis of their safety program has been on ground safety; six Topaz II systems have undergone nuclear ground testing. Nonetheless, a substantial amount of safety information has been obtained that is applicable to the Topaz II flight mission.

One area of concern in assessing the safety of any system is the extent of the quality assurance (QA) program that is employed. A high level of confidence that the system that is actually launched will behave as predicted is essential to making projections about safety. Initial investigations indicate that the Russians now have an extensive QA program for the Topaz II. This program was implemented in the early 1980's when repeated failures; for example, coolant system leaks (including a Loss of Coolant Accident) occurred in their testing program.

Experience that the Russians had with a Loss of Coolant Accident (LOCA) during a nuclear ground test in 1984 indicates that the Topaz II system is robust. The LOCA resulted when a coolant leak occurred at the outlet to the coolant pump. This leak resulted in a loss of flow accident (LOFA) when the pump became vapor bound. The resulting thermal stresses in the moderator block caused significant cracking and hydrogen loss. This resulted in a rapid power drop. Although no extensive post irradiation examination of the fuel has been performed, all of the TFEs were removed from the reactor core, and no visible damage was observed. Also, calculations performed after the accident indicate that the fuel stayed below its melt temperature.

The current QA program appears similar to U.S. QA programs. A goal of the current QA program is to provide sufficient quality assurance to prevent system failures, such as coolant failure accidents for current Topaz II systems. Although the ground test LOCA described above did not result in a radiological hazard, the U.S. Automatic Control System and operating procedures will be designed to preclude continued operation following a LOCA. It should also be emphasized that any credible accident during the on orbit operational phase is expected to result in an insignificant radiological consequence.

The Russians have also performed a large number of system calculations to predict the performance of the Topaz II system under normal and postulated accident conditions. The calculational results indicate acceptable system behavior for the credible accidents that they investigated. An extensive effort has been made to calibrate the systems codes used in these analyses against actual tests.

EVENT TREE ANALYSIS

An event tree analysis of the Topaz II mission was performed to delineate the sequences of events that could potentially result in radiological consequences to the public or the environment. Due to the lack of definitive information regarding the launch vehicle and mission, it was not possible to estimate the probabilities of various, potential accidents. The objective was to provide a framework for a full probabilistic risk assessment of public radiological risks to be conducted in the future.

The event tree developed for the Topaz II mission is structured by mission phases. The mission phases addressed are (1) Pre launch/Launch, (2) Ascent/Orbital Injection, (3) Startup, and (4) On-Orbit Operations, and Disposal.

To assess the potential consequences of the spectrum of scenarios, the large number of source terms that could conceivably arise were grouped together into bins. A total of 26 source term bins have been identified. The magnitude of the consequences depends on such factors as whether or not the reactor has been operated, the duration of the decay period between operation and the accident scenario, whether or not the accident scenario includes a reactor excursion, whether the reactor impacts on water or land, etc.

NEUTRONIC ANALYSIS

A review of Russian neutronics analysis and experimentation has begun. As part of this review a number of independent neutronics calculations have been completed using the MCNP Monte Carlo computer code. Our initial model yielded an eigenvalue, or k_{eff} , of 1.0007 ± 0.0009 , in good agreement with the Russian reported value of 1.0052. This base case represented cold, beginning-of-life conditions with the control drums completely turned out.

MCNP was also used to predict drum worths, isothermal feedback coefficients, and the effects of water flooding on criticality. Drum worth for the revised base case is in good agreement with the Russian values. Calculated isothermal feedback coefficients are also in good agreement with the Russian predictions.

The water flooding calculations were performed with the initial model described above. The calculated results, adjusted for the bias between the calculated and predicted base case, indicate that the flooded and immersed reactor would be \$2.50 supercritical with the reflector in place and the control drums turned in, and \$1.40 supercritical with the reflector segments and drums ejected and water surrounding the core. The beryllium reflector in the shutdown configuration is more reactive than a water reflector. MCNP also predicts a \$4.00 supercritical core (with reflectors off) when flooded internally with water and surrounded with wet sand.

The Russian Topaz II staff are performing water immersed and flooded criticality experiments. Results thus far show their flooded and immersed mock up is \$.30 supercritical with the radial reflector in place and the drums turned in. Measurements with the reflector off are currently in progress. These experiments will serve as benchmarks for our MCNP calculations.

Both the MCNP calculations and the Russian experiments should be regarded as preliminary. Efforts to resolve discrepancies are underway. Furthermore, other potential critical configurations from accidents will be explored. If preliminary indications that the Topaz II will be supercritical when water immersed and flooded are confirmed, some modifications of the Topaz II reactor will be required to conform to our safety policy. Such modifications may be significant if the substantial reactivity additions from water flooding predicted by MCNP are correct. The topic of water flooding criticality is being given a high priority.

TEMPERATURE COEFFICIENT OF REACTIVITY

The Topaz II reactor possesses a significant prompt negative temperature coefficient of reactivity. This feature provides for mitigation of reactivity excursion accidents.

The Topaz II also possesses a delayed positive coefficient of reactivity. The delayed positive feedback effect is due primarily to moderator heating. As moderator temperature increases, fewer parasitic neutron captures occur in the moderator and more neutron captures occur in the fuel resulting in a reactivity increase. Because of the large heat capacity of the moderator and the large thermal resistances in the core, the time constant for moderator heating is very large (on the order of five minutes or more). Over this long time scale adequate time is available to control any delayed feedback effects.

Testing and analysis indicate that the Topaz II prompt negative feedback and delayed positive feedback provides for a controllable reactor for normal operations. Preliminary calculations also indicate that the prompt negative feedback effect helps mitigate reactivity insertion accidents and any positive feedback effects are sufficiently slow to assure shutdown by control drum rotation or reflector ejection.

The delayed positive reactivity feedback for Topaz II carries an important safety advantage. The safety advantage is due to the low cold excess reactivity for Topaz II (\$0.65) made possible by delayed positive feedback effect. Because the cold excess reactivity at the beginning-of-life (BOL) is less than \$1.00, prompt critical excursions and disassembly accidents by control system action are probably precluded prior to launch. Space reactor safety risks are typically dominated by postulated accidents within Earth's biosphere; consequently, a delayed positive feedback coefficient can provide a safety advantage.

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 was a worst case calculation, because of the simplifying assumptions that were made. 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 conservative 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, reentry tests performed on SNAP-10A, and the experience of the Cosmos 954 reentry, it appears that the Topaz II may break up on reentry. However, this result is not conclusive. It is possible that the Topaz II will reenter in a radiation shield-first configuration, in which case the reactor would most likely remain completely intact. Also, it would be possible to modify the Topaz II system to add a reentry shield to ensure intact reentry, if that is the desired result. A substantial amount of analysis and possibly testing will be performed to address this issue.

COMPACTION ANALYSIS

Compaction analyses were performed on the Topaz II to determine the type of deformation that could be expected for various accident scenarios. Since the accident scenarios have not been fully developed, a parametric approach was taken in performing these calculations. For an impact velocity of 300 m/s, which is the terminal velocity for a free fall, the amount of deformation becomes significant. If the radial reflector is not present at impact, the deformation of the core increases. For the case of the reactor falling into water on its side at a 300 m/s terminal velocity, core compaction resulting from water impact is negligible. The neutronic significance of Topaz II core deformation will be determined at a later date; however, core deformation alone is not expected to result in a criticality accident.

LAUNCH PAD EXPLOSION/FIRE ANALYSIS

A launch pad explosion analysis was performed to determine the amount of core deformation that could be expected from a propellant explosion. The analysis shows that no core deformation is expected to occur. An analysis of the effects of explosive fragment impact and the effect of shutdown devices is planned.

Heat transfer calculations for the reactor involved in a propellant fire were performed for both liquid and solid propellants. For the case of a liquid propellant fire, which has a flame temperature of about 2727°C (3000 K) and duration of 20 seconds, the temperatures in the reactor core are dependent on whether or not the radial reflector retention band is in place or not; much higher temperatures are reached in the core if the retention bands fail. However, in either case, the temperature of the UO₂ fuel in the outer TFE ring remains below 527°C (800 K), which is significantly lower than its operating temperature.

For the case of a solid propellant fire, which has a flame temperature of 3227°C (3500 K) and has a duration of 120 seconds, the temperatures within the core are significantly higher than for a liquid fire. The reactor vessel as well as a significant amount of the moderator could be expected to melt. The temperature in the outer fuel ring would reach temperatures of 1527°C to 2527°C (1800 K to 2800 K), which are below the melt temperature of UO₂. Although the potential for eutectic formation has not been explored, no scenarios have been identified that would result in a criticality accident from the effects of a propellant fire from fuel relocation or loss of absorbing materials.

DISPOSAL

Calculations of the radioactive inventory at the end of orbital lifetime were performed assuming reactor shutdown at several points along the electric propulsion altitude versus time profile. These preliminary calculations indicate that core activity at the time of reentry will have decayed down to the actinide level (a few tenths of a curie) for all possible scenarios.

CONCLUSIONS

Based on the Flight Safety Team's understanding of the Topaz II system at this time, it appears that it will be possible to launch the Topaz II system in the U.S. if modifications meet SDIO's criteria for minor modifications. The principal system modifications will probably include modifications to preclude water flooded criticality and to ensure intact reentry.

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