INDEPENDENT SAFETY ASSESSMENT

of the

TOPAZ-II SPACE NUCLEAR REACTOR POWER SYSTEM

United States Department of Energy
Office of Nuclear Energy

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[Revised]
The Independent Safety Assessment described in this study report was performed to assess the safety of the design and launch plans anticipated by the U.S. Department of Defense (DOD) in 1993 for a Russian-built, U.S.-modified, TOPAZ-II space nuclear reactor power system. Its conclusions, and the bases for them, were intended to provide guidance for U.S. Department of Energy (DOE) management in the event that the DOD requested authorization under section 91b. of the Atomic Energy Act of 1954, as amended, for possession and use (including ground testing and launch) of a nuclear-fueled, modified TOPAZ-II.

The scientists and engineers who were engaged to perform this assessment are nationally-known nuclear safety experts in various disciplines. They met with participants in the TOPAZ-II program during the spring and summer of 1993 and produced a report based on their analysis of the proposed TOPAZ-II mission. Their conclusions were confined to the potential impact on public safety and did not include budgetary, reliability, or risk-benefit analyses.

This assessment was sponsored by the Office of Space and Defense Power Systems within the DOE’s Office of Nuclear Energy.

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# U.S. DEPARTMENT OF ENERGY
## INDEPENDENT SAFETY ASSESSMENT OF THE TOPAZ-II SPACE NUCLEAR POWER SYSTEM

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EXECUTIVE SUMMARY

The United States Air Force (USAF), the Ballistic Missile Defense Organization (BMDO) of the U.S. Department of Defense (DOD), and the U.S. Department of Energy (DOE) are involved in a joint research program to develop thermionic space nuclear reactor power systems in the 5-40 kW(e) range for military applications. A part of this program, known as the Thermionic System Evaluation Test (TSET), has been directed toward unfueled reactor testing to support the U.S. design.

In early 1990, the Russian Government offered to sell to the DOD a complete, unfueled, electrically-heated thermionic space nuclear power system. The system consisted of two unfueled TOPAZ-II thermionic reactors, a vacuum test rig, and the control equipment necessary to perform electrically heated tests. DOD elected to purchase the system for the TSET program and obtained the necessary approvals, including DOE authorization under section 91b. of the Atomic Energy Act of 1954, as amended, to acquire the unfueled TOPAZ-II units as utilization facilities for military purposes. The program hardware was delivered by the USAF from Russia in May 1992.

In December 1991, the BMDO proposed to investigate the possibility of purchasing, modifying, fueling, and launching a TOPAZ-II, provided these operations could be done safely and within budget constraints. The proposed launch program, which involved the purchase of four additional unfueled TOPAZ-II reactors, envisioned the testing of electric thrusters in orbit for altitude adjustments, as well as an extensive series of experiments (for which the BMDO sought foreign participation). As part of the program, the purchase of Russian fuel for use in ground testing and launch was considered, subject to DOE agreement.

DOE requirements, established as authorized under the Atomic Energy Act to ensure the safety of utilization facilities or special nuclear material planned for transfer to or acquisition by DOD, call for a pre-authorization assessment. For this purpose, and in anticipation of a DOD request for authorization, an Independent Safety Assessment (ISA) of the Russian TOPAZ-II space nuclear power system, as modified for a U.S. launch, was initiated. To conduct this review, the DOE, through a support services contractor, assembled a panel of independent expert consultants (the "ISA panel"). This panel evaluated the TOPAZ-II system's specific features related to its planned mission, focusing on public health and safety issues. Other considerations, such as safeguards requirements, environmental concerns in space, reliability (except as related to safety), and the likelihood of mission success, were not included in this review.
The assessment process included a review of relevant reference material; three meetings with representatives of the USAF and BMDO, the Nuclear Electric Propulsion Space Test Program (NEPSTP) team (the team of scientists established by the BMDO), and several DOD/DOE contractors; as well as a tour of the U.S. TOPAZ-II installation. During these meetings, discussion topics included the background of the U.S. and Russian nuclear space programs, the U.S. TOPAZ-II program, TOPAZ-II design and testing activities, and ongoing TOPAZ-II safety studies.

The BMDO established several top-level requirements for the NEPSTP’s TOPAZ-II flight program, including three fundamental safety requirements:

- The reactor shall not be operated prior to space deployment, except for low-power testing on the ground, which produces negligible radioactivity.

- The reactor shall be designed to remain shut down prior to the system’s achieving a sufficiently high orbit (i.e., an orbit at which re-entry time exceeds that required for fission product decay to insignificant levels).

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

Upon completion of the review described above, and in consideration of the NEPSTP requirements, the ISA panel reached the following conclusions:

- Information available at this stage of program is not sufficient to formulate final conclusions on the safety of the proposed flight program.

- The panel believes it will be very difficult to conclusively demonstrate that inadvertent criticality can be prevented for all credible accident conditions during the launch or for end-of-mission re-entry phases.

- Other than the difficulty described above, there is no information available at this time to suggest that the mission cannot be performed in a safe manner.

- There is adequate information available to conclude that low-power (critical) nuclear experiments can be safely performed, if they are conducted under DOE oversight at a DOE critical facility and existing DOE safety procedures and overview are used.

- Safety aspects relating to transportation of the fuel can be adequately addressed by the use of Nuclear Regulatory Commission (NRC)-licensed containers.

- An additional independent safety review should be performed at a later date after all analyses, experiments, and safety report preparations have been completed.
INTRODUCTION

Background

The United States Air Force (USAF), the Ballistic Missile Defense Organization (BMDO) of the U.S. Department of Defense (DOD), and the U.S. Department of Energy (DOE) are involved in a joint research program to develop thermionic reactor power systems in the 5 to 40 kW(e) range for military space applications. The program is known as the Thermionic Space Nuclear Power Systems Technology Program and is formally organized under a tri-agency Memorandum of Understanding (MOU) among the USAF Systems Command; the DOE's Office of Nuclear Energy; and the Strategic Defense Initiative Organization (SDIO), the predecessor agency to the BMDO. One program element is the ground testing of an unfueled reactor as part of the Thermionic System Evaluation Test (TSET) program, to produce systems-level testing in support of the U.S. thermionic reactor design effort.

During the period of political and governmental change within the former Soviet Union, officials of the Russian space program offered to sell the U.S. DOD a complete, unfueled, electrically-heated system for qualification testing of thermionic space nuclear reactors. This arrangement offered the USAF and the BMDO a way to acquire a turn-key system including two unfueled reactors, a large vacuum test chamber and associated pumps, a thermionic fuel element test rig, and control hardware for unfueled systems-level testing under the TSET program at a potentially attractive cost and schedule. Following a positive recommendation by the Air Force Science Advisory Board, the USAF and BMDO provided funding for acquisition and designated the Phillips Laboratory (PL) at Albuquerque, NM, as the executing agency for reactor systems.

Section 91b. of the Atomic Energy Act, as amended, requires DOE authorization, as directed by the President, for DOD acquisition of utilization facilities for military purposes. The DOE provided 91b. authorization for the purchase of the two unfueled TOPAZ-II reactors on condition that they not be fueled or launched without further DOE authority.

The TSET program hardware was installed in June 1992 in the research park of the University of New Mexico at the New Mexico Engineering Research Institute (NMERI). One of the two unfueled reactors was installed in the vacuum test stand for non-nuclear electrical, mechanical, and thermal tests.

In December of 1991, the BMDO initiated an investigation of a TOPAZ-II flight program, including purchasing, modifying, fueling, and launching a flight-qualified TOPAZ-II reactor from a U.S. launch site. The reactor and the spacecraft vehicle were proposed to be used for demonstration of Nuclear Electric Propulsion (NEP) with an array of electric thrusters. Also, an extensive set of space science experiments was planned. This operation, known originally as Flight TOPAZ, was renamed as the Nuclear Electric Propulsion Space Test Program (NEPSTP).
The NEPSTP has four primary goals:

- To demonstrate the feasibility of launching a space nuclear power system in the U.S.
- To demonstrate an orbit-adjust capability using nuclear electric propulsion.
- To evaluate the in-orbit performance of the TOPAZ-II reactor and selected electric thrusters.
- To measure, analyze, and model the Nuclear Electric Propulsion (NEP) self-induced environment.

NEPSTP's secondary goal is to conduct a space science/engineering mission that is compatible with these primary mission objectives.

In preparation to carry out this program, the BMDO initially contacted the Interagency Nuclear Safety Review Panel (INSRP) coordinators, representing the National Aeronautics and Space Administration (NASA), the USAF, and the DOE. INSRP is charged with evaluating the risk associated with launch of special nuclear material by reviewing the safety analyses provided by the launching agency. [For clarification, the INSRP has no relation to the 91b. decision process, but is a separate function required by a Presidential Directive issued in December 1977.]

To provide a preliminary evaluation of the TOPAZ-II space nuclear power system's safety, the BMDO established a team of scientists for NEPSTP from the New Mexico Strategic Alliance, a coalition of interested parties comprised of the USAF Phillips Laboratory, Sandia National Laboratory, Los Alamos National Laboratory, and the University of New Mexico/NMERI. The objective of the NEPSTP team was to identify any important safety deficiencies and suggest those modifications that might be required to correct such deficiencies. [The team was not charged with performing the type of thorough safety analysis considered suitable for a formal Preliminary Safety Analysis Report (PSAR).] In the process of developing this preliminary evaluation, considerable contact and collaboration took place between NEPSTP personnel and Russian engineers responsible for developing the TOPAZ-II system.

The preliminary evaluation document, called the *NEPSTP Preliminary Nuclear Safety Assessment*, or NEPSTP PSA, was issued in November 1992. Tentative conclusions based on that evaluation were that, in order to meet U.S. guidelines for a U.S.-based launch, the TOPAZ-II reactor system would require modification to:

- assure that inadvertent criticality could not occur during any mission phase;
- assure intact re-entry of the reactor system with use of a re-entry shield; and
- employ a U.S.-designed automatic control system with the ability to shut down the reactor during the operational phase.
Work on the preliminary design of these and other modifications was undertaken at the Phillips Laboratory and at Johns Hopkins University’s Applied Physics Laboratory, which was designated as the spacecraft executing agency. [Following issuance of the NEPSTP PSA, a re-examination of the need for the re-entry shield was initiated.]

During this time, NEPSTP staff scientists began work on a high-level safety functional requirements document for providing guidance to the team and for use in evaluating the need and efficacy of the modifications. The resulting *NEPSTP Nuclear Safety Policy, Functional Requirements and Safety Guidelines Document* was published as NEPSTP/T-002 dated April 28, 1993. It was modeled on an earlier interagency (DOD, NASA, DOE) study effort conducted for the Space Exploration Initiative, documented as NASA Technical Memorandum 10575.

Top-level safety requirements called for in NEPSTP/T-002 were:

- The reactor shall not be operated prior to space deployment, except for low-power testing on the ground, from which negligible radioactivity is produced.
- The reactor shall be designed to remain shut down prior to the system’s achieving a sufficiently high orbit.
- Inadvertent criticality shall be prevented for both normal conditions and credible accident conditions.

**The Mission Scenario**

The intended mission profile for the launch of a fueled TOPAZ-II space nuclear reactor power system calls for initial launch into a circular orbit at 5,250 km altitude. The orbit was originally intended to be 1,600 km; the altitude was raised, however, after objections from astronomers concerning gamma radiations from the reactor and their potential interference with the orbiting Gamma Ray Observatory.

Once in a verified circular orbit, TOPAZ-II would be given a ground command to start up and attain its rated thermal power of approximately 115 kW(th); at this rating, nominal electrical power production is about 6 kW(e). The on-board ion propulsion thrusters would be turned on for a 1,000-hour testing of each of several types furnished by different countries. The thrusters would deliver thrust along the vehicle velocity vector, slowly raising the orbital altitude from 5,250 km to 40,000 km in 2.25 years. The reactor system’s projected (design) life is three years. The reactor system is described in more detail in Appendix D.

**Procurement of Nuclear Fuel: The Approvals and Acquisition Process**

While considerable information can be gained from the unfueled TOPAZ-II reactors as a result of electrical heating, particularly concerning system testing of the thermionic elements,
flight testing cannot be undertaken without the actual nuclear fuel designed for the space reactor system. Each reactor is designed to be fueled with 27 kg of uranium, fabricated as UO$_2$ annular pellets and enriched to 96 percent in the fissionable U$^{235}$ isotope.

During the production phase of the TOPAZ-II space nuclear power systems in the former Soviet Union, a total of 26 unfueled units were fabricated to varying degrees of quality assurance for different purposes (thermal and mechanical testing, vibration, and flight). Two units were ground-tested with nuclear fuel, and fuel sufficient for two more units was fabricated for flight purposes; however, no TOPAZ-II units were ever launched. [Earlier Russian launches of space nuclear reactors were of a different design.]

The Russian Government has offered the fuel for two flight units, as well as an additional four unfueled TOPAZ-II reactor units, to the DOD. The four additional units include two built to flight standards (the ones initially acquired by the U.S. were not). The two flight units are the ones proposed for launch (i.e., one would be the flight unit and the second would serve as backup).

The DOE was asked by the USAF to provide a 91b. authorization for the purchase, importation, and utilization of the four additional units; this action was taken by DOE on April 23, 1993. As before, the authorization covered ground testing only, without special nuclear material, so a safety assessment was not required.

The BMDO, after considering the option of U.S. fabrication of fuel for TOPAZ-II, concluded that purchase of the Russian-made, flight-qualified fuel was preferable to domestic fabrication. This ISA was undertaken to enable DOE to fulfill its responsibilities under section 91b. of the Atomic Energy Act, in anticipation of a DOD request that DOE authorize its use of a nuclear-fueled TOPAZ-II reactor in ground testing and launch into orbit (a military purpose).

Other approval processes must be undertaken, such as those related to an Environmental Impact Statement, for fueling and launch of the TOPAZ-II (including fuel transportation) and to obtain approval by the National Security Council and the Office of Science and Technology Policy for importation of the fuel. Such processes are not part of this ISA review.
STATUTORY AUTHORITY FOR THE
DOD AUTHORIZATION REQUEST

The U.S. DOD is charged by law with defining, designing, developing, launching, operating, and providing overall program management for the Nation's military spacecraft and space-related military facilities, including the development of non-nuclear subsystems, integration of nuclear and non-nuclear subsystems, and mission safety.

The U.S. DOE, as the successor agency to the Atomic Energy Commission (AEC), is charged with development of nuclear technologies and systems by the Atomic Energy Act of 1954, as amended (Public Law 83-703), and by successor legislation which transferred authority and function from the AEC to the Energy Research and Development Administration (ERDA) and finally, to the DOE (Public Laws 93-438 and 95-91).

The Atomic Energy Act precludes organizations other than the DOE from acquiring, possessing, or using utilization facilities, including nuclear reactors, unless licensed by the Nuclear Regulatory Commission (NRC). Under section 91b. of the Act, however, the President may direct the DOE to authorize DOD to manufacture, produce, or acquire any utilization facility for military purposes. This authorization applies only to the DOD and the DOE role is independent of the funding source for such acquisitions. Under National Security Council Decision Memorandum (NSDM) 182 and DOE Delegation Order 0204-122, the DOE Assistant Secretary for Nuclear Energy (now the Director of the Office of Nuclear Energy) holds continuing authority to authorize DOD’s acquisition of utilization facilities under section 91b.

Where DOE has granted a section 91b. authorization, the responsibility for identifying and resolving health and safety issues related to the use of the utilization facilities remains with the DOD. By a Presidential Directive of September 23, 1961, however, comment and concurrence must be obtained from the DOE on the adequacy of the safety of utilization facilities design; preparation or amendment of safety standards, procedures, or instructions relating to location and operation; and the use of special nuclear materials.
THE INDEPENDENT SAFETY ASSESSMENT PROCESS

A DOE Independent Safety Assessment was begun in spring 1993 to provide timely support for the decision-making process related to granting of a 91b. authorization for the conduct of critical experiments and the launch of a fueled TOPAZ-II system. The Office of Management and Budget held discussions with DOE to encourage this activity and to assist in providing funding for the study from other DOE programs.

The DOE anticipated the safety review would be conducted in two phases: (1) a thorough safety evaluation and assessment of the TOPAZ-II system design; and (2) subsequent review, nearer the launch date, to assess the Air Force's preparedness pertaining to safeguards and security, training, operational safety, emergency planning, and related matters. This ISA study addresses Phase 1 of the review.

The first phase of the assessment was further divided into two activities. The first activity was intended to be an intensive, short-term review of existing and developed information, with a near-term ending to accommodate the USAF schedule to obtain fuel and launch the system by December 1995 (a date which has since been extended). The second activity would be an in-depth follow-on study by a DOE laboratory or a DOE contractor, if assurance of safety could not be ascertained or if gaps in the available knowledge were apparent.

The DOE panel that performed the first activity of the assessment was assembled from three sources. First, the DOE assigned a DOE task leader with experience in the conceptual design of space nuclear power systems, as well as critical experiment systems. Next, five nuclear expert consultants were contacted and agreed to serve. Finally, to provide this ISA panel with a knowledgeable source on space launches and space nuclear power sources, the Air Force provided its space power system safety expert as a panel member. [The ISA panel's membership and resumes are provided in Appendix A.] In addition, technical and document production support, as well as the administration of the consultants' contracts, were provided by DOE support services contractors.

Assessment Work Scope

The ISA panel was given the following assignment:

"Provide, through independent assessment of the TOPAZ-II space nuclear reactor:

- Evaluation of the safety in design of the reactor, including any analyses and tests needed to produce reliable and convincing safety assessments;

- Evaluation of proposed modifications in design or function of components to meet U.S. safety standards;

- Examination of safety procedures and recommendations on safety and safeguards risks associated with the flight demonstration;"
• Recommendations for safe operation of the reactor, including orbital parameters for minimizing operational risk of re-entry; and

• Examination of recommendations for safe disposal of the spent reactor core."

The product of the ISA panel was intended to be a DOE document drawn from the expert opinions of the independent consultants, DOE technical staff, and DOE support contractors to:

• Assess the safety design adequacy of the TOPAZ-II for fueling, launch, operation, and ultimate disposal in accordance with U.S. safety standards;

• Make recommendations for needed additional analysis, modeling, or data;

• Assess the quality of key data used in important safety analyses; and

• Recommend any quality audit checks of the original engineering design/data/criteria.

This ISA report is the final product of this phase of the DOE’s Independent Safety Assessment of this reactor power system.

Conduct of Review

The process was initiated by assembling a bibliography of reference material relevant to the safety assessment (e.g., safety analyses for the U.S. space reactor known as SNAP-10A; the NEPSTP PSA; radiological risk analyses for the U.S. SP-100 reactor program; evolving U.S. space nuclear safety philosophy; safety analyses for radioisotope thermoelectric generators; etc.), and by making these available to the panelists prior to the first meeting. [See Appendix C for a complete list of these references.]

A series of three two-day working meetings were held with DOD representatives, including the USAF and the BMDO, as well as several DOD/DOE contractors. Provision was made for recording the minutes of each meeting and transcribing them for the use and study of individual panelists.

The first meeting was held in Washington, DC, on May 20-21, 1993. It served as a general introduction to space nuclear power systems for most of the panel and introduced the panelists to the TOPAZ-II safety assessment work being performed by the NEPSTP staff. Additional presentations were made on Air Force range safety; launch abort practices; past U.S. and Russian launches and accidents; and principles of thermionic devices. A description of the modifications to TOPAZ-II judged necessary before a U.S. launch was also presented (e.g., the mechanical device design for preventing inadvertent criticality or "Anti-Criticality Device" and modifications to the automatic control system).
The second meeting was held at the NMERI facility in Albuquerque, NM, on June 10-11, 1993, a location which made it possible to interact with more of the NEPSTP staff. This meeting introduced the panelists to the TOPAZ-II units already purchased by the BMDO, which were undergoing electrical, mechanical, vibrational, and other non-nuclear testing at the facility. Additional neutronics, safety planning, and Probabilistic Risk Assessment (PRA) planning were also presented, and the process of acquiring Russian documentation on fabrication, quality assurance, and Russian critical experiments, both by visits and by direct contact with the Russian engineers, was described by Los Alamos National Laboratory (LANL) staff. This second meeting was important because it led to a realization that the status of the safety analysis would not support a detailed safety evaluation at this time.

Meeting number three was held July 27-28, 1993, at Annapolis, MD. The agenda was prepared by the NEPSTP staff and was primarily aimed at demonstrating that orbital events occurring in a "sufficiently high orbit" (SHO) would not result in a hazard to the Earth's population. The panel arranged for Dr. William Ailor of the Aerospace Corporation, an expert in re-entry phenomena, to be present for the meeting, and his advice was used by the panel in reaching its conclusions. Following the meeting, the panel met in executive session to discuss its tentative conclusions and report.

ASSESSMENT CONCLUSIONS

Scope

This assessment covers only the NEPSTP mission, as defined. It is restricted to the TOPAZ-II reactor (as proposed for modification) and to those launch conditions and parameters necessary to launch the reactor into the SHO required to attain the BMDO program objectives.

Conclusions reached in this assessment only consider the safety aspects of the program as related to public health. Other matters, such as safeguards and security of special nuclear material and space environmental issues, were not addressed. In addition, this assessment does not address reliability (except as it may impact safety), mission success, or cost/benefit considerations. This assessment and its concomitant conclusions with respect to the safety of storage, shipment, and critical experiments are further based on the assumption that DOE or NRC-licensed practices will be followed in the performance of this program for storage, shipment, and critical experiments.

Special Circumstances of Review

The panel recognizes that space nuclear reactors, because of their intended application and mode of operation, cannot be designed with reactor safety features common to commercial nuclear power reactors. In addition, the TOPAZ-II reactor incorporates different safety design features than current U.S.-designed space reactors and was built to earlier and different criteria and standards than would be employed in current designs.
However, there are compensatory features which tend to offset these differences. These include reactor operation only in orbit; a low reactor power and resulting low inventory of fission products; and the orbital mechanics, which keep the reactor in a disposal-in-place orbit until long after the fission products have decayed to an insignificant level. The panel considers that the latter feature, that of the sufficiently high orbit, is a necessary condition to the safety of the TOPAZ-II mission. This feature provides the necessary protection to the public from any on-orbit accidents.

General Conclusions

• Information available at this stage of the program is not sufficient to formulate final conclusions on the safety of the proposed flight program.

• The panel believes it will be very difficult to conclusively demonstrate that inadvertent criticality can be prevented for all credible accident conditions during the launch or for end-of-mission re-entry phases.

• Other than the difficulty described above, there is no information available at this time to suggest that the mission cannot be performed in a safe manner.

• There is adequate information available to conclude that low-power (critical) nuclear experiments can be safely performed, if they are conducted under DOE oversight at a DOE critical facility and existing DOE safety procedures and overview are used.

• Safety aspects related to transportation of the fuel can be adequately addressed by the use of NRC-licensed shipping containers.

• An additional independent safety review should be performed at a later date after all analyses, experiments, and safety report preparations have been completed.

As stated earlier, these conclusions are based on the panel’s evaluation of public health and safety considerations.

The panel also determined that the safety analyses being conducted by the NEPSTP team are in an early stage, and that criteria have not been established by the program in the form of requirements with numerical assignments for design margins, design limits, or performance margins similar to those established for terrestrial reactor power plants. The panel reviewed the documentation and guidelines promulgated and found only statements such as "ALARA [As Low As Reasonably Achievable] guidelines," "being very reliable," or "being not credible." These statements are not criteria and cannot be rigorously evaluated as objectives. The panel recommends that, where applicable, rigorous criteria be developed and applied.
For discussion purposes the panel divided the safety aspects of the Topaz II's mission into four phases:

**Phase I:** All pre-orbital activities including fuel transportation, low-power critical experiments, and core assembly at the launch site.

**Phase II:** Actual launch operations until stable orbit is established, including potential launch accidents and re-entry into the atmosphere before reaching orbit.

**Phase III:** Orbital reactor operations at or above the sufficiently high orbit. [Note: Usually (and as planned for this mission), the minimum acceptable orbit at which operations are begun is well above the SHO.]

**Phase IV:** Final shutdown and disposition by disposal in or above SHO, including the potential of re-entry of irradiated fuel into the biosphere as a result of mishaps in orbit.

For Phase I, safety considerations include assurance that fuel shipments will be made using NRC-licensed containers; that critical experiments performed will be done at a DOE critical experiments facility with expanded instrumentation and control in accordance with existing DOE requirements (including DOE reviews and oversight); and that operations at the launch site will be performed by trained personnel in accordance with written procedures which were developed using standard DOE and commercial safety practices, procedures, and regulations.

For Phase II, the primary safety consideration presented by the NEPSTP team was the prevention of criticality until the nuclear fuel reaches the minimum acceptable orbit (above the SHO). Studies will be performed to demonstrate that inadvertent criticality will not occur during this phase. Launch accidents such as fire, explosion, and impact will be included. Design modifications to the reactor are underway to ensure that prevention of inadvertent criticality is achieved for intact fuel through addition of an Anti-Criticality Device (ACD). Other studies will be performed to assess the impact of fuel re-arrangement. In addition, studies were reported that showed that dispersal of un-irradiated uranium fuel from a launch abort accident will not constitute a health hazard to the public.

Based on these considerations, the panel believes that these criteria provide an adequate basis for assurance that the Phase I and Phase II operations can be carried out safely. However, based on its review, the panel considers it will be extremely difficult to show that criticality is not credible as a result of the potential launch accidents that can be postulated. In particular, the panel considers that, even if the ACD can prevent inadvertent criticality for those cases where core geometry is maintained, it will be difficult to show that core geometry is maintained during launch pad fires, explosions, or re-entry impact. In addition, the subject of criticality prevention for post-mission re-entry, during which the ACD will not be available, has been addressed in only a preliminary way.
In view of the emphasis placed on prevention of inadvertent criticality, the panel considers that the analytical tools should be validated by a series of experiments to include fire effects, impact, explosion, and other launch-abort simulations. These experiments should be made as close to full scale as possible. This suggestion is consistent with past practices on SNAP-10A and on shipping casks.

The panel considers that deterministic methods may not be able to demonstrate the BMDO criterion of preventing inadvertent criticality. In this case an acceptance criterion must be established by some other means, such as a probabilistic risk assessment that might consider a low number such as $10^4$ or less per launch to be appropriate.

The panel's general conclusion is that it will be difficult to adequately demonstrate the prevention-of-inadvertent-criticality requirement, although it is possible that public safety could be demonstrated without this requirement.

In addition, planned analytical activities to further refine dispersion analyses on unirradiated fuel should be pursued with increasingly sophisticated tools and documented. Based upon studies to date, this dispersal is not judged by the NEPSTP team to be a significant hazard for a launch accident. Similarly, more thorough study of the dispersal of toxic materials (i.e., beryllium) must be undertaken although it is also not expected to be a problem.

For Phase III, studies to date have shown that, with the possible exception of radioactive particulate matter of 1-2 microns in size, orbital activities or occurrences do not present a hazard to Earth. For small particles the "resonance effect" of solar radiation pressure must be evaluated. Preliminary studies indicate that this phenomenon does not represent a hazard to public health.

The panel concurs with the BMDO that, if an SHO orbit is selected that assures long-term decay prior to re-entry (an orbital lifetime of thousands of years), and if reactor startup does not occur until that orbit is achieved, reactor accidents in orbit do not require consideration as a potential public health hazard. This conclusion is partially based on analysis that shows the resonance effect to be minimal. The panel does recommend that this resonance effect study be expanded and formalized and that an acceptance criterion for public health effects from small radioactive particles be promulgated based on existing standards. A detailed study will be required to show that radiological exposure requirements are not exceeded.

For Phase IV, orbits at or greater than SHO will assure time for radioactive decay prior to re-entry. Various accident scenarios, including the possibility of micrometeoroids and debris in orbit impacting the space vehicle, release of on-board propellants or misdirected thrusters have been evaluated to determine the likelihood of early re-entry. Analysis has confirmed that, with the exception of misdirected thrusters, there is no credible accident mechanism that could result in a significant reduction in the time for re-entry. Redundant design features preclude early re-entry as a result of misdirected thrusters. The panel believes that these studies should be formalized and that the scenario for a meteorite/debris impact or misdirected thrusters should be included in a formal probabilistic risk assessment.
In conclusion the panel believes that, with the exception of supporting the requirement of no criticality prior to achieving SHO, the safety of the TOPAZ-II mission could be demonstrated. Additional studies and experiments are required to address the launch criticality issue. In addition, the preliminary studies performed to date should be refined and carefully documented. It is recommended that the DOE perform an additional safety review of the mission after the issuance of the FSAR.
APPENDICES
APPENDIX A

Panelists and Resumes

Robert S. Brodsky

Mr. Brodsky is President and Founder of Nuclear Power Technology, Inc., a consulting firm specializing in all aspects of nuclear power application, including design, safety, operation, maintenance, and management. The firm’s activities are primarily associated with commercial electric utilities; however, consulting services are also provided to the Department of Energy (DOE). Recent activities include serving on corporate nuclear safety boards for five nuclear power plants and participation in diagnostic and enhancement activities at other nuclear power plants. Recent DOE activities include participation in a Peer Review Group for the DOE Plutonium Disposition Study and as Senior Consultant to the New Production Reactor Program. Mr. Brodsky was a member of the DOE Naval Reactors Program for over 26 years and served as Assistant Director of Reactor Safety and Computation for the last six years. He is a graduate of the Massachusetts Institute of Technology.

Neil E. Todreas

Dr. Todreas is Korea Electric Power Corporation (KEPCO) Professor of Nuclear Engineering at the Department of Nuclear Engineering at the Massachusetts Institute of Technology (MIT). He joined MIT in 1970, becoming Professor of Nuclear Engineering in 1975 and Head of the Department from 1981 to 1989. Dr. Todreas has done extensive consulting work in the areas of reactor thermalhydraulics and heat transfer, including participation in the DOE Plutonium Disposition Study as a consultant to the Technical Review Committee; the Public Service Electric and Gas (PSE&G) Nuclear Oversight Committee; the Electric Power Research Institute (EPRI) Accident Management-Design Review Group; the B&W Owner’s Group Independent Safety Review Assessment Committee; and serving as a Senior Consultant to the New Production Reactor Program. His current memberships include the Institute of Nuclear Power Operations (INPO) Advisory Council and the U.S. NRC’s Nuclear Safety Research Review Committee, which he served as first Chair. Dr. Todreas is a graduate of Cornell University and the Massachusetts Institute of Technology.
J. Roger Hilley

Mr. Hilley is an independent consultant to the nuclear industry, government contractors, and the U.S. Government. He has extensive professional experience in high-level radioactive waste management; the special nuclear materials production complex and its operation; reactor core design and reactor operations; and management of nuclear research and development. He was the Laboratory Manager for the Savannah River Laboratory, operated by the DuPont Company for the DOE, and later joined the DOE as Associate Director for Storage and Transportation in the Office of Civilian Radioactive Waste Management. During this time he was responsible for implementation of storage and transportation aspects of the Nuclear Waste Policy Act of 1982. Mr. Hilley was a Senior Consultant to the DOE on the New Production Reactor Program and on the Plutonium Disposition Study. He is a graduate in physics from Emory University in Atlanta.

Henry E. Stone

Mr. Stone is President and Founder of H. E. Stone, Inc., a firm founded to perform consulting work in a variety of engineering disciplines. He was with the General Electric Company for many years, retiring recently from the office of Vice President and Chief Engineer. During his career at General Electric, Mr. Stone held the positions of General Manager of the Knolls Atomic Power Laboratory; General Manager of the Boiling Water Reactor (BWR) Systems Department; and General Manager of the Nuclear Energy Engineering Division, with responsibility for BWR engineering, engineered equipment procurement, and operation of the Vallecitos Nuclear Center. Mr. Stone consults with electric utilities and has served on the Nuclear Safety Review Boards of the Sequoyah, Browns Ferry, and Pilgrim nuclear plants. In addition, he served as a Senior Consultant to DOE on the New Production Reactor Program. He is a licensed professional engineer in New York and California and a member of the National Academy of Engineering.

George E. Apostolakis

Dr. Apostolakis is a Professor in the Mechanical, Aerospace, and Nuclear Engineering Department at the University of California, Los Angeles. His research interests include mathematical methods for risk and reliability assessment of complex technological systems; uncertainty analysis; applications of probabilistic models to safety and reliability analyses of nuclear reactors and space systems; and control of hazardous substances. He has consulted extensively for the DOE, the NRC, EPRI, the Jet Propulsion Laboratory, the Lawrence Livermore National Laboratory, the International Atomic Energy Agency, and the State of California. He is the author or editor of numerous books and articles dealing with reliability engineering and risk analysis. Dr. Apostolakis served as a Senior Consultant to the DOE New Production Reactor Program. He is a graduate of the California Institute of Technology.
Joseph A. Sholtis, Jr.
Lieutenant Colonel, USAF (retired)

Colonel Sholtis is Director of Research and Engineering and General Manager of New Mexico Operations for Oakton International Corporation, a small engineering firm specializing in aerospace and nuclear projects. He also provides private engineering consultation services to the nuclear and aerospace communities. Formerly, he was Chief of Nuclear Energy Systems at the Air Force Safety Agency's Directorate of Nuclear Surety at Kirtland AFB, Albuquerque, NM. In that position he was responsible for establishing, implementing, and maintaining Air Force safety policy, guidance, criteria, and programs for the safe space, missile, and terrestrial applications of nuclear energy systems and radioactive sources. During a prior assignment to DOE, he served as Program Manager of the DOD/DOE/NASA SP-100 Space Reactor Power System Technology Development Program. He is a former NRC-licensed Senior Reactor Operator, a position acquired while Head of the Radiation Sources Division and Reactor Facility Directorate at the Armed Forces Radiobiology Research Institute in Bethesda, MD. During his most recent Air Force assignments, he chaired the Power System Subpanel and served as Coordinator for the Interagency Nuclear Safety Review Panel (INSRP), an agency which evaluated the safety/risk of the recent U.S. nuclear-powered Galileo and Ulysses space missions for the Office of the President. Col. Sholtis has authored or co-authored two textbooks, one handbook, and more than seventy-five publications. He is a graduate of Pennsylvania State University and the University of New Mexico.

Richard A. Moore

Dr. Moore serves as the DOE task leader for the Independent Safety Assessment panel reviewing the TOPAZ-II safety design. He is currently Operations Manager for the Office of Defense Energy Projects in the Office of Nuclear Energy, Department of Energy. Prior to this assignment Dr. Moore served in the New Production Reactor Program as Branch Manager for Reactor Systems, Modular High Temperature Gas Reactor (MHTGR). He has convened and chaired other DOE review teams in MHTGR Reactor System Design, Heat Transfer, Severe Accident Mitigation, and Reactor Physics. Earlier work experiences included serving as Vice President and Co-Founder of an Atlanta company which makes radioactive implants for cancer treatment and working for twenty-one years with General Atomic Company in various capacities including Physicist-In-Charge of the Thermionic Critical Experiment and Director of HTGR Program Development. Dr. Moore is a registered professional engineer in California and graduated from the University of Kansas and the Oak Ridge School of Reactor Technology.
APPENDIX B

Speakers Appearing before the Panel, Consultants, and Support Personnel

Alan Newhouse
Deputy Assistant Secretary
Space and Defense Power Systems
U.S. Department of Energy

Neil Brown
Manager
Quality, Safety, and Reliability
DOE SP-100 Reactor Program
Martin Marietta Energy Systems

Wade P. Carroll
Director
Office of Defense Energy Projects
U.S. Department of Energy

Al Marshall
Sandia National Laboratory
TOPAZ-II Project Nuclear Safety
Task Manager

Richard A. Moore, Chair
Manager of Operations
Office of Defense Energy Projects
U.S. Department of Energy

Susan Voss
Los Alamos National Laboratory
TOPAZ-II Safety Project Office
Russian Data Liaison and
Modification Task Leader

Beverly Cook, Co-Chair
Manager of Operations
Office of Special Applications
U.S. Department of Energy

Don Beard
Independent Consultant
Halliburton NUS Corporation
Former Thermonics Program Manager
U.S. Atomic Energy Commission

Ernest D. Herrera
Lieutenant Colonel, USAF
Chief, Power and Thermal
Management Division
Phillips Laboratory (PL/VTP)
Manager, TOPAZ-II Program Office.

Wally Boggs
Research Triangle Institute
Member, Launch Abort Subpanel, INSRP
Consultant on launch accident conditions

Frank Thome
Manager, TOPAZ-II Project
Sandia National Laboratory
(on loan to the USAF)

Frank Wyatt
USAF Phillips Laboratory
Kirtland AFB, NM
TOPAZ-II System Design
Task Leader for U.S. Control System
Modifications

Joseph Sholtis
Lieutenant Colonel, USAF (Ret.)
Former USAF Coordinator for INSRP

Joseph Sapir
Los Alamos National Laboratory
Physics design of TOPAZ-II Neutronics
Subtask Leader for Physics Analyses

Kenneth Kaisler
45th Space Wing, Patrick AFB
Chairman, Launch Abort Subpanel INSRP

B-1
David Trujillo  
Los Alamos National Laboratory  
Subtask Leader for Mechanical Design of Anti-Criticality Device

Mehdi Eliassi  
Advanced Sciences, Inc.  
Consultant on analysis of inadvertent criticality and fresh fuel dispersal by fire, impact, and explosion

Glen Cameron  
Applied Physics Laboratory  
Johns Hopkins University  
Manager, Mission-Level System Engineering, NEPSTP

Leonard W. Connell  
Sandia National Laboratory  
NEPSTP Re-entry Safety and Re-entry Configuration Scenarios

John A. Landshof  
Applied Physics Laboratory  
Johns Hopkins University  
Manager, Mission Operations, NEPSTP

SUPPORT STAFF:

Eric Haskin  
Faculty, University of New Mexico  
Subtask Leader for NEPSTP  
Probabilistic Risk Analysis

Robert Waterfield  
Scribe  
Jupiter Corporation  
Former safety specialist with U.S. Nuclear Regulatory Commission

Arthur C. Payne, Jr.  
Sandia National Laboratory  
Probabilistic Risk Analysis of TOPAZ-II Reactor Design

Clyde Jupiter  
Alternate Scribe  
President, Jupiter Corporation  
Formerly with U.S. Nuclear Regulatory Commission

James Hipp  
Sandia National Laboratory  
Probabilistic Risk Analysis of NEPSTP

Steve E. Mixon  
Technical Writer  
Safety and Licensing Division  
Halliburton NUS Corporation

Glen Schmidt  
New Mexico Engineering Research Laboratory  
Systems Testing & Reactor Qualification

Gary Polansky  
USAF Phillips Laboratory  
PL/VTN, Kirtland AFB  
TOPAZ-II System Flight Engineering Integration

William Ailor  
Aerospace Corporation  
Chairman, INSRP Re-entry Subpanel  
Consultant on re-entry phenomenology
APPENDIX C

List of References Transmitted to Panelists

References transmitted on May 3, 1993:

- SNAP Reactor Overview, August 1984.
- Final Snapshot Safeguards Report, (excerpts), March 1965.
- Radiological Risk Analysis of Potential SP-100 Space Missions, August 1988.
- Various Symposia Reprints, January 1993.

References transmitted on June 10-11, 1993:

References transmitted on June 24, 1993:


• Thermionic System Evaluation Test Briefing, viewgraph presentation, June 10-11, 1993.

References transmitted on July 15, 1993:


• Summary Document: Recommendations and Technical Justification for an SP-100 Reentry Guideline, (LA-UR-86-14), C. Bell, et al.

• Planning Option Study for an Integrated Space Nuclear Reactor Power System Program (excerpts), March 1993, [Prepared for the Office of Management and Budget].

APPENDIX D

Design of TOPAZ-II Space Nuclear Power System

The TOPAZ-II Space Nuclear Power System

TOPAZ-II is a 6 kW(e) space nuclear power system based on direct conversion of heat into electricity by in-core thermionic fuel elements. System parameters are listed in Table 1 for reference. An illustration of the TOPAZ-II reactor system is provided in Figure 1. Major subsystems constituting the complete TOPAZ-II space power reactor system are:

- Nuclear Reactor
- Radiation Shield
- Coolant System
- Cesium Supply System
- Instrumentation and Control (I&C) System
- Anti-Criticality Device (ACD)

Nuclear Reactor

The nuclear reactor contains 37 single-cell thermionic fuel elements (TFEs), which are fueled by uranium dioxide (UO₂) fuel pellets that are 96 percent enriched in U²³⁵. Three of the TFEs are used to drive the electromagnetic (EM) pump, and the remaining 34 provide power to operate the TOPAZ-II reactor and the satellite payload. The single-cell TFE design allows the reactor to be loaded with fuel from the top after the entire system has been constructed. The TFEs are set within channels in blocks of ZrH₁.₈₅ 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 nine control drums. Each drum contains a section of boron carbide (B₄C) neutron poison on its periphery, which is used to control the nuclear reaction by drum rotation. During operation, the nuclear fuel heats the TFE emitters to 1527°C to 1827°C (1800 to 2100K). The waste heat is removed by the coolant system, which flows past the outer surface of the collector of the thermionic unit and maintains the collector at 627°C (900K) during operation.

Radiation Shield

The radiation shield is attached to the lower end of the reactor. The shield is composed of a stainless steel shell that contains lithium hydride (LiH). The shell thickness varies along its top and bottom, and serves both as a container for the LiH and as the gamma ray shield. The LiH is the neutron shield. The radiation shield is designed to reduce the accumulated dose after three years of operation to 10¹¹ neutrons/cm² and 0.05 Mrad gamma at 18.5 meters from the centerline of the reactor core.
Coolant System

The reactor coolant system includes sodium-potassium (NaK) coolant, a single EM pump, stainless steel piping, and a heat rejection radiator. The NaK coolant enters the reactor core through a lower plenum. It passes through the core and is heated from 470°C to 570°C (743 to 843K) by the waste heat from the thermionic conversion process. After passing through the core, the NaK exits through an upper plenum and flows through two stainless steel pipes to the radiator inlet plenum. The radiator consists of inlet and outlet plena that are connected by 78 coolant tubes. Thin copper fins are attached to the outside of the coolant tubes. After flowing through the radiator, the NaK flows through two coolant pipes that divide into three pipes each. The coolant flows through the six pipes and into the EM pump. The EM pump, which is powered by three of the TFEs, pumps the NaK back to the reactor lower plenum.

Cesium Supply System

The cesium supply system provides cesium (Cs) to the TFE interelectrode gap. Cesium favorably modifies the work functions of the emitter and collector and is necessary to suppress the space charge that occurs near the emitters of thermionic converters; suppressing this charge increases the efficiency of the converter. The cesium supply system consists of a cesium reservoir, throttle valves, a cesium plenum, and stainless steel tubing. During operation, the cesium from the reservoir is distributed to all of the TFE interelectrode gaps. The cesium vents to space through a throttle valve at a rate of 0.5 g/day.

Instrumentation and Control System

The Topaz II Instrumentation and Control (I&C) system provides the mechanism for monitoring, controlling, and telemetering power system conditions. Its major functions are: (1) to start up the power system; (2) to maintain operation of the system under nominal operating conditions; (3) to stabilize the voltage supplied to the payload; (4) to perform the commands supplied from the ground control station; (5) to shut down the Topaz II power system; (6) to maintain safety control during land-based operations; (7) to telemeter performance data to the ground; (8) to shunt excess electrical power to ballast resistors; and (9) to charge the storage battery.

Three significant characteristics of the I&C system either require or are under consideration for modification. First, it may be desirable to supplement the existing neutron detectors with self-powered detectors to provide more accurate neutron power level information in the low power range. Second, adding the capability to eject the reflectors on orbit may be required to fulfill some protect functions. Third, the Russian automatic control system (ACS) is not space qualified; consequently, it will be necessary to design and incorporate a new ACS.

Anti-Criticality Device (ACD)

One of the safety functional requirements developed by the BMDO and USAF for Flight TOPAZ was that "inadvertent criticality shall be prevented for both normal conditions and
credible accident conditions." In examining this imposed requirement, the NEPSTP team concluded that an engineered safety feature to prevent inadvertent criticality should be added to the reactor.

Two methods were considered: remotely removable poison, which would initially reside in the center hole of the annular fuel of a number of the thermionic fuel elements; and a fuel-out mechanism, which would maintain the fuel for several elements (presently four) outside the reactor and not insert them until the reactor is in a sufficiently high orbit and a reactor startup is authorized. Currently, the fuel-out approach has been selected, and the design and fabrication of this ACD is underway at LANL.
## TOPAZ-II PARAMETERS

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<td>Height (cm)</td>
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<td>E &gt; .1 MeV(n/cm²)</td>
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<td>Gamma Dose (rad)</td>
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TOPAZ II
Reactor Core

Safety Drums (3)
Control Drums (9)

B₄C Poison
Be Reflector Insets
37 Single-Cell TFEs
Coolant Flow Path
ZrH₁.₈₅ Moderator
SS Cladding
SS Vessel

Drawing Courtesy of New Mexico Engineering Research Institute (NMERI)
## APPENDIX E

### List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ACD</td>
<td>Anti-Criticality Device</td>
</tr>
<tr>
<td>ACS</td>
<td>Automatic Control System</td>
</tr>
<tr>
<td>AEC</td>
<td>Atomic Energy Commission</td>
</tr>
<tr>
<td>AFB</td>
<td>Air Force Base</td>
</tr>
<tr>
<td>AIAA</td>
<td>American Institute of Aeronautics and Astronautics</td>
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<tr>
<td>ALARA</td>
<td>As Low As Reasonably Achievable</td>
</tr>
<tr>
<td>BMDO</td>
<td>Ballistic Missile Defense Organization</td>
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<tr>
<td>BOL</td>
<td>Beginning of Life</td>
</tr>
<tr>
<td>B&amp;W</td>
<td>Babcock and Wilcox</td>
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<tr>
<td>BWR</td>
<td>Boiling Water Reactor</td>
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<tr>
<td>cm²</td>
<td>Square Centimeter</td>
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<td>DOE</td>
<td>Department of Energy</td>
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<tr>
<td>DOD</td>
<td>Department of Defense</td>
</tr>
<tr>
<td>EM</td>
<td>Electromagnetic</td>
</tr>
<tr>
<td>EOL</td>
<td>End of Life</td>
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<tr>
<td>EPRI</td>
<td>Electric Power Research Institute</td>
</tr>
<tr>
<td>FSAR</td>
<td>Final Safety Analysis Report</td>
</tr>
<tr>
<td>INSRP</td>
<td>Interagency Nuclear Safety Review Panel</td>
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<tr>
<td>ISA</td>
<td>Independent Safety Assessment</td>
</tr>
<tr>
<td>KEPCO</td>
<td>Korea Electric Power Corporation</td>
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<tr>
<td>km</td>
<td>Kilometers</td>
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<tr>
<td>kW(e)</td>
<td>Kilowatts electric</td>
</tr>
<tr>
<td>kW(th)</td>
<td>Kilowatts thermal</td>
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<tr>
<td>LANL</td>
<td>Los Alamos National Laboratory</td>
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<tr>
<td>m²</td>
<td>Square Meter</td>
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<tr>
<td>MeV</td>
<td>Million Electron Volts</td>
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<tr>
<td>MHTGR</td>
<td>Modular High Temperature Gas-cooled Reactor</td>
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<tr>
<td>MIT</td>
<td>Massachusetts Institute of Technology</td>
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<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<td>NEP</td>
<td>Nuclear Electric Propulsion</td>
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<tr>
<td>NEPSTP</td>
<td>Nuclear Electric Propulsion Space Test Program</td>
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<td>NMERI</td>
<td>New Mexico Engineering Research Institute</td>
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<td>NRC</td>
<td>Nuclear Regulatory Commission</td>
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<tr>
<td>NSC</td>
<td>National Security Council</td>
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<tr>
<td>NSDM</td>
<td>National Security Decision Memorandum</td>
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<td>PL</td>
<td>Phillips Laboratory</td>
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<tr>
<td>PRA</td>
<td>Probabilistic Risk Assessment</td>
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<tr>
<td>PSA</td>
<td>Preliminary (Nuclear) Safety Assessment</td>
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<tr>
<td>PSAR</td>
<td>Preliminary Safety Analysis Report</td>
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<tr>
<td>PSE&amp;G</td>
<td>Public Service Electric and Gas</td>
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<tr>
<td>SHO</td>
<td>Sufficiently High Orbit</td>
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<tr>
<td>SNAP</td>
<td>Space Nuclear Auxiliary Power</td>
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<td>TFE</td>
<td>Thermionic Fuel Element</td>
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<tr>
<td>TMI</td>
<td>Three-Mile Island</td>
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<td>TSET</td>
<td>Thermionic System Evaluation Test</td>
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<tr>
<td>UO₂</td>
<td>Uranium Dioxide</td>
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<td>USAF</td>
<td>United States Air Force</td>
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END

4/30/94

FILED

DATE