Conf-920[illegible]

BNL--47728

Receiv

DE92 018117

JUL 2

AIAA

AIAA 92-3697

NSPWG-RECOMMENDED SAFETY REQUIREMENTS AND GUIDELINES FOR SEI NUCLEAR PROPULSION

ALBERT C. MARSHALL
SANDIA NATIONAL LABORATORIES
ALBUQUERQUE, NM

J. CHARLES SAWYER, JR.
NASA HEADQUARTERS
WASHINGTON, DC

ROBERT A. BARI
BROOKHAVEN NATIONAL LABORATORY
UPTON, NY

NEIL W. BROWN
GENERAL ELECTRIC
SAN JOSE, CA

HATICE S. CULLINGFORD
NASA JOHNSON SPACE CENTER
HOUSTON, TX

ALVA C. HARDY
NASA JOHNSON SPACE CENTER
HOUSTON, TX

JAMES H. LEE
SANDIA NATIONAL LABORATORIES
ALBUQUERQUE, NM

WILLIAM H. MCCULLOCH
SANDIA NATIONAL LABORATORIES
ALBUQUERQUE, NM

GEORGE F. NIEDERAUER
LOS ALAMOS NATIONAL LABORATORY
LOS ALAMOS, NM

KERRY REMP
NASA LEWIS RESEARCH CENTER
CLEVELAND, OH

JOHN W. RICE
IDAHO NATIONAL ENGINEERING LABORATORY
IDAHO FALLS, ID

JOSEPH A. SHOLTIS
UNITED STATES AIR FORCE
KIRTLAND AIR FORCE BASE
ALBUQUERQUE, NM

AIAA/SAE/ASME/ASEE
28th Joint Propulsion Conference and Exhibit
July 6-8, 1992 / Nashville, TN

MASTER

For permission to copy or republish, contact the American Institute of Aeronautics and Astronautics
370 L'Enfant Promenade, S.W., Washington, D.C. 20024

DISCLAIMER

NSPWG-RECOMMENDED SAFETY REQUIREMENTS AND GUIDELINES FOR SEI NUCLEAR PROPULSION

Albert C. Marshall
Sandia National Laboratories
Albuquerque, NM

J. Charles Sawyer, Jr.
NASA Headquarters
Washington, DC

Robert A. Bari*
Brookhaven National Laboratory
Upton, NY

Neil W. Brown
General Electric
San Jose, CA

Hatice S. Cullingford
NASA Johnson Space Center
Houston, TX

Alva C. Hardy
NASA Johnson Space Center
Houston, TX

James H. Lee
Sandia National Laboratories
Albuquerque, NM

William H. McCulloch
Sandia National Laboratories
Albuquerque, NM

George F. Niederauer
Los Alamos National Laboratory
Los Alamos, NM

Kerry Remp
NASA Lewis Research Center
Cleveland, OH

John W. Rice
Idaho National Engineering Laboratory
Idaho Falls, ID

Joseph A. Sholtis
United States Air Force
Kirtland Air Force Base
Albuquerque, NM

Abstract

An Interagency Nuclear Safety Policy Working Group (NSPWG) was chartered to recommend nuclear safety policy, requirements, and guidelines for the Space Exploration Initiative (SEI) nuclear propulsion program to facilitate the implementation of mission planning and conceptual design studies. The NSPWG developed a top-level policy to provide the guiding principles for the development and implementation of the nuclear propulsion safety program and the development of Safety Functional Requirements. In addition, the NSPWG reviewed safety issues for nuclear propulsion and recommended top-level safety requirements and guidelines to address these issues. Safety requirements were developed for reactor start-up, inadvertent criticality, radiological release and exposure, disposal, entry, and safeguards. Guidelines were recommended for risk/reliability, operational safety, flight trajectory and mission abort, space debris and meteoroids, and ground test safety. In this paper the specific requirements and guidelines will be discussed.

Background

President Bush, in his speech on July 20, 1989, announced his plan to initiate the most ambitious exploration endeavor in history. This

---

*Deputy Chairman, Department of Nuclear Energy.

This work was performed under the auspices of the U.S. Department of Energy, Contract No. DE-ACO2-76CH00016.

new program, the Space Exploration Initiative (SEI), would include a return to the moon and a manned mission to Mars by the year 2019. Nuclear propulsion has been identified as a key enabling technology to meet the objectives of the SEI program (Stafford, 1991).[1]

Nuclear thermal propulsion and nuclear electric propulsion are the two basic types of nuclear propulsion systems that could support the SEI program within the 2019 time frame:

- Nuclear thermal propulsion (NTP) systems produce thrust by heating a propellant (usually hydrogen) passing through a nuclear reactor and expanding the hot gases through a nozzle. The very high temperature capability provided by a reactor and the use of a low molecular weight propellant provides a high specific impulse and high levels of thrust for a relatively low propellant and system mass. At these high thrust levels relatively brief reactor operational times (hours) are required for a voyage to Mars and back. A variety of solid, liquid, and gaseous core reactor concepts have been proposed for NTP systems. NTP solid core concepts have been proposed as the baseline technology for propulsion from Earth orbit to Mars orbit and back (Stafford, 1991).

- Nuclear electric propulsion (NEP) concepts use reactor thermal power with a power conversion system to produce electrical power. The electrical power is then used to accelerate an ionized propellant through an electric thruster. NEP systems produce a very high specific impulse and very low thrust. NEP concepts require very little propellant and could entail relatively low propulsion system mass. A variety of reactors, power conversion devices, and electric thrusters have been proposed for NEP systems. NEP systems have been proposed as a follow-on propulsion technology for Mars cargo missions (Stafford, 1991) and is also under consideration for piloted missions.

Nuclear propulsion is not a new concept. In fact, from the late 1950s through the early 1970s, space nuclear propulsion systems were aggressively pursued by the United States. The Nuclear Engine for Rocket Vehicle Application (NERVA) was developed as part of the ROVER nuclear thermal rocket program. Twenty propulsion reactors were designed, built and tested. Although the NERVA program established a viable capability, the program was terminated in 1973 due to changing national priorities. Nuclear electric propulsion systems were also designed and a variety of propulsion elements were tested, including arc jet and ion engines. The US flight-tested the SNAP-10A reactor power system in 1965. Electricity produced by the reactor power system was used to power an ion engine as part of an experimental package.

When nuclear propulsion was identified as a necessity for SEI, the National Aeronautics and Space Administration (NASA) held joint agency workshops, in June and July 1990, to explore options and requirements to initiate a new space nuclear propulsion program. The agencies represented included the Department of Energy (DOE) and the Department of Defense (DoD), as well as NASA. Based on these workshops, a joint agency Nuclear Safety Policy Working Group (NSPWG) was chartered to recommend a top level nuclear safety policy for the SEI nuclear propulsion program. The working group was comprised of the authors of this paper with Marshall as chair and Sawyer as vice chair. The NSPWG was also asked to recommend safety requirements and guidelines for a number of specific nuclear propulsion safety issues. In this paper, the emphasis will be placed upon the requirements and guidelines. Previous papers on this subject summarized the safety issues and resulting top level policy[2] and the recommendations.[3] The full report[4] of the NSPWG is also available.

Scope

The NSPWG scope of activities can be understood in terms of the proposed safety program hierarchical structure. At the top (Tier 1) of the hierarchy are the policies and mandatory requirements that are set by the existing agencies (DOE, NASA, and so on). Below this level is the SEI Nuclear Safety Policy (Tier 2) that provides the guiding principles for the development and implementation of the safety program and safety requirements. The Safety Functional Requirements (Tier 3) delineate the specific safety functions required of the system or program. The development of these policies is the responsibility of the government agencies. The contractors' responsibilities include the design specifications (Tier 4) and system design and research (Tier 5).

It is expected that the recommended NSPWG Safety Policy will be adopted or adapted at Tier 2 to formulate the Joint Agency Space Nuclear Safety Policy for the SEI space nuclear propulsion program. The NSPWG also recommended Safety Requirements and Guidelines for important safety issues and considerations. It is anticipated that the NSPWG-recommended Safety Requirements and Guidelines will be used at Tier 3 to develop the Safety Functional Requirements for SEI nuclear propulsion.

In the course of its deliberations, the NSPWG made several assumptions pertaining to the scope of its work. Although the working group's efforts and the development of the policy included the consideration of non-nuclear safety issues, the development of requirements and guidelines focused on nuclear safety issues. Public involvement, the development of an overall safety program plan, and recommendations for a safety review process were identified as activities that should follow the establishment of the safety policy and are suggested future activities. Based on the proposed SEI mission architectures (e.g., Stafford, 1991), the NSPWG assumed that SEI would use nuclear propulsion beginning from orbits about Earth and other celestial bodies, on trajectories between celestial bodies and into deep space, and to and from the surfaces of any celestial body except Earth. All mission phases were included in the scope of the NSPWG activities. (The mission phases are divided into the prelaunch, launch and deployment, operational, and disposal phases.)

Approach

The development of the NSPWG recommendations took place in a series of ten meetings between November 1990 and September 1991. Existing national and international guidelines and regulations were reviewed (see, for example, U.S. Department of Energy[5], 1984). In addition, pertinent previously developed safety policies were reviewed (see, for example, Wahlquist[6], 1990). The NSPWG discussed and developed a top level safety policy. Each member was assigned principal responsibility for one or more of the safety issues to be addressed. The responsible member for each safety issue presented a discussion of the topic to the group. Discussions on each topic continued until a consensus was reached on the draft recommendations. Meeting minutes were mailed to a broad distribution, and several open sessions and presentations were given to obtain feedback from the technical community.

NSPWG Safety Policy

In order to provide the context in which to develop safety requirements and guidelines, the NSPWG developed a top level safety policy which is presented here.

Recommended Space Exploration Initiative Nuclear Propulsion Safety Policy

Ensuring safety is a paramount objective of the Space Exploration Initiative nuclear propulsion program; all program activities shall be conducted in a manner to achieve this objective. The fundamental program safety philosophy shall be to reduce risk 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 nuclear propulsion program.*

In this context, safety is meant to include the health and safety of the public, program personnel, and mission crew, in addition to protection of the terrestrial and nonterrestrial environments. Safety also includes safeguarding nuclear systems and special nuclear materials from unauthorized use or diversion, and protection of property against accidental loss or damage. Although unstated in the policy, it is important to communicate openly with the public on both the benefits and the risks associated with the SEI program. The specific emphasis the program places on safety and the progress made toward achieving safety objectives must also be communicated.

To ensure the protection of individuals and the environment, the fundamental program safety philosophy shall be to reduce risk to as low as reasonably achievable. Economic and social factors and technology maturity must be taken into account to guide the judgment of what is reasonably achievable. This philosophy couples the development and revision of all safety requirements to their effect on risk. Risk is a measure of potential harm or damage, incorporating both the probabilities of undesirable consequences and the magnitude of the consequences, such as number of exposed individuals, number of injuries and fatalities, and the level of environmental contamination. Reduction of risk implies a reduction in both the probability and consequences of potential adverse events.

The development of stringent design and operational safety requirements is essential to implement the fundamental safety philosophy of reducing risk to as low as reasonably achievable. Safety requirements must also accommodate aversion to severe accidents of extremely low probability. These safety requirements must be established and met for all program activities and must be based on applicable regulations and standards and incorporate relevant developments from research activities. These requirements ensure compliance with all applicable national and international regulations. These requirements and supporting guidelines are discussed in the following section.

Recommended Requirements and Guidelines

Recommended safety requirements were developed for reactor start-up, inadvertent criticality, radiological release and exposure, disposal, entry, and safeguards. Both quantitative and qualitative requirements have been recommended. Quantitative requirements for radiological exposures were recommended only when applicable established guidance could be cited. More specific and quantitative design requirements must be developed as the program matures and specific concepts and missions are defined. The development of all recommended requirements (and any subsequent modifications) must be compatible with the fundamental philosophy of reducing risk to as low as reasonably achievable.

Safety Guidelines are recommended for use by the program to establish program plans as well as design and operational requirements for the development of nuclear propulsion systems for SEI. Some of these guidelines may be useful for formulating additional Safety Functional Requirements. Safety guidelines are recommended for risk/reliability, operational safety, flight trajectory and mission abort, and space debris and meteoroid safety considerations.

The NSPWG also recommended the general type of safety validation that may be required for nuclear propulsion systems and provided guidelines for ground facility and equipment safety. A discussion of this topic can be found in References 3 and 4.

NSPWG Requirements

The following safety requirements are recommended for use by SEI management and program safety to develop Safety Functional Requirements.

1. Reactor Start-Up

Safety issues concerning reactor start-up and operation during the prelaunch, launch, and deployment phases are included under the heading of reactor start-up.

A reactor fueled by uranium 235 that has never been operated has a very small radioactive inventory. This inventory is limited to the natural radioactivity of the fuel. Very low-power operation, which may be employed for ground testing, produces a negligible increase in the radioactivity of the reactor system. During power operation, significant neutron and gamma radiation emanates from the reactor. If the reactor operates at an appreciable power level for a sufficient length of time, the reactor will accumulate a significant radioactive inventory that can remain after reactor shutdown. Thus, radiation from an operating reactor or a reactor that has been operated at an appreciable power level could cause a significant exposure to ground operations crews and to launch crews. For a pre-launch, launch, or deployment accident with an operating reactor or a reactor that has been operated at significant power levels, additional issues are raised concerning the potential for radiation exposure to the public and the release of radioactive materials into the environment.

The current NASA mission planning documents for SEI (e.g., Stafford 1991) do not include suborbital reactor operations in their mission planning options; consequently, scenarios requiring suborbital start-up were considered to be beyond the NSPWG scope. Considering this scope, a simple and prudent approach to address the issues under discussion would be to require that the reactor not be operated and remain shutdown until an acceptable orbit is achieved. Very low-power testing of the reactor on the ground should be excluded from this requirement, provided that the fission and activation product inventory from testing is negligible at the time of launch. Reactor shutdown, as used in this discussion, is defined as being subcritical by an adequate margin and incorporating positive measures to ensure that the reactor start-up is 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 its planned orbit.

These recommendations ensure that no hazard is presented from either direct radiation from a critical core or from the accidental release of fission products from power operation of a reactor prior to achieving orbit.

2. Inadvertent Criticality

When shut down, a reactor is subcritical; that is, it cannot support a neutron chain reaction. In this state the reactor is producing no fission power and no additional radioactive inventory. A reactor accident could cause the reactor to become critical by causing changes in the configuration of reactor materials or by changing the material environment of the reactor. Fuel compaction and water immersion from a launch or inadvertent entry accident are examples of these potential accident-caused changes. An inadvertent criticality event can produce significant radiation and can increase the radioactive inventory of the reactor. When additional accident conditions are postulated, criticality could pose a potential hazard to the crew, the public, and the environment. If sufficient power is produced during an inadvertent criticality event, disruption of the reactor system could occur, with the potential for release of radioactive materials to the environment. The potential for inadvertent criticality can be essentially precluded by incorporating features to assure a secure shutdown during launch and assuring highly reliable shutdown features for accidents. The recommended requirement for inadvertent criticality is as follows:

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

3. Radiological Release and Exposure

Guidance on radiological releases and exposures to radiation from reactor propulsion systems deployed in space are needed to protect the mission crew, space environment, and Earth environment. The protection of other space enterprises, such as other space missions involving astronauts, is encompassed by protection of space environments. In addition, the mission spacecraft must be protected from any adverse effects that could result from radiological releases. This guidance pertains to routine operation and potential accidents in space. Space, in this context, includes all regions beyond Earth's biosphere, including other celestial bodies. Radiological release and exposure prior to intended operation or in the event of inadvertent Earth entry are covered in Subsections 1, 2, and 5. Principal reactor sources of radiation include neutrons and gamma radiation that have not been stopped by radiation shielding, potential fission product release, and positron and electrons produced from gamma interactions with the system. Charged fission products, positrons, and electrons can be trapped in Earth's magnetosphere and remain a source of radiation for a period of time. Trapped radiation can contribute to the crew dose and can adversely affect other space enterprises, such as satellite gamma ray observations.

For routine operation and expected occurrences, allowable doses can be preestablished. For accidents, deterministic requirements are inappropriate and probabilistic guidance is recommended. In all cases the principle of reducing radiological risk to as low as reasonably achievable should be used to enhance safety. Current NASA guidance for total whole body dose is 50 rem/year, of which 5 rem/year may be received from man-made on-board radiation sources (see 29 CFR 1910.96 [U.S. OSHA, 1989]).[7] Since the natural background radiation dose to the crew will be quite high for some proposed SEI missions, the 5 rem/year dose limit from reactor radiation is both reasonable and prudent. Pursuant to 29 CFR 1960.18 (U.S. OSHA, 1991)[8], NASA has adopted the recommendations of the National Commission on Radiological Protection and Measurements (NCRP, 1989)[9] as its supplementary standard for space flight crew radiation exposures. NASA implementation of this standard requires, among other things, that exposure limits for on-board radiation sources comply with 29 CFR 1910.96, except where the NASA mission or objectives cannot be accomplished otherwise.

Radiological release to the space environment may have a significant or insignificant effect depending on where and when it is released and depending on the quantity and type of radiation released. For example, an appreciable release of long-lived radioactive materials on the surface of the moon would be unacceptable and in violation of international treaties. On the other hand, it could be acceptable to allow released radioactive materials in some regions of deep space to decay and dissipate over a period of years. Conditions for releases in space and potential future space enterprises are too numerous to allow quantitative guidance at this stage.

No established guidance was found that would be directly applicable for setting quantitative limits for radiological contamination of Earth's environment from space activities. A conservative requirement for releases in space potentially affecting Earth's environment would be to assure that any radiological contribution to Earth's environment is much less than the radiological guidelines for terrestrial activities. For example, the US Environmental Protection Agency limitations for radiological environmental contamination of US territory could be the most appropriate guideline.

The recommendations presented here recognize that any radioactive releases in space, for both normal and accident conditions, should have an insignificant and probably undetectable effect on Earth's environment. Based on these considerations the requirements for radiological release and exposure are as follows:

Routine Operations and Expected Occurrences

- Use 29 CFR 1910.96 dose limits for on-board radiological sources.
- Radiological releases from the spacecraft shall not impair its use.
- Radiological release from the spacecraft shall not contribute significantly, over an extended period of time, to any local space environment.
- Radiological release from the spacecraft shall have an insignificant effect on Earth.

Accidents

- The probability of accidents involving radiological release affecting the immediate or long term health of the crew shall be extremely low.
- For those accidents involving radiological release for which the crew is expected to survive, the radiological release shall not render the spacecraft unusable.

- The probability of a significant radiological effect from an accident on any local space environment over an extended period of time shall be extremely low.
- The consequence on Earth of a radiological release from an accident in space shall be insignificant.

The term "insignificant" as used here for radiological release means "much less than the value specified for terrestrial guidelines." An extremely low probability event is one that is not expected to ever occur during the execution of the SEI program. "Significant" means "greater than the most appropriate guideline or norm." An "extended period of time" is understood to mean "encompassing the time period of potential future space enterprises in the region of space under consideration."

The requirement presented above for radiological effects from accidents on the spacecraft apply only to radiological effects. Reactor failures or accidents might render the spacecraft unusable from factors other than radiological effects. These other factors must be addressed as reliability considerations, and their management must be consistent with the philosophy of reducing risk to as low as reasonably achievable.

4. Disposal

Disposal plans for space reactor systems and associated spacecraft components should be established before the propulsion system is deployed. Furthermore, the method of disposal must be safe; that is, the radioactive materials of the disposed reactor system must not endanger the public or the environment. Strategies for disposal must preclude entry by orbital decay in order to comply with the requirement for no planned Earth entry (next topic). The reactor system integrity must be protected for all normal conditions and credible accident conditions, including collisions with meteoroids and orbital debris, that could compromise the user's ability to dispose of the reactor system safely.

The recommended disposal requirements are as follows:

- Safe disposal of spent nuclear systems shall be explicitly included in Space Exploration Initiative mission planning.
- Adequate and reliable cooling, control, and protection for the reactor system shall be provided for all normal and credible accident conditions to prevent reactor system disruption or degradation that could preclude safe disposal.

5. Entry

Entry refers to an event in which a reactor system enters the atmosphere or impacts the surface of Earth or another celestial body. Entry issues include the potential for the release of fission products and activation products into Earth's or another planet's environment and the potential for exposure from direct radiation from the reactor. Radioactive release due to entry can result from the effects of passing through a planetary atmosphere or from reactor disruption from impact.

Should inadvertent entry and impact occur, emergency response measures will be more effective for small areas of distribution of system debris. The location and cleanup of system debris is simpler for debris confined to small areas than for widely scattered debris. Recommended requirements for entry are as follows:

- Planned Earth entry shall be precluded from mission profiles.
- Both the probability and the consequences of an inadvertent entry shall be made as low as reasonably achievable.
- Inadvertent entry through an atmosphere shall be essentially intact, or, alternatively, result in essentially full dispersal of radioactivity at high altitude.
- For an impact, radioactivity shall be confined to a local area to limit radiological consequences.
- The reactor shall remain subcritical throughout an inadvertent entry and impact.

6. Safeguards

Safeguards encompass all measures used to control and protect special nuclear materials (SNM).

Proven safeguards approaches developed for terrestrial use are applicable to the protection of nuclear propulsion system hardware and SNM prior to launch. It is important to ensure, to the extent practicable, that this existing safeguards technology is not precluded or compromised by the nuclear propulsion system design. Also, design options exist which can enhance safeguards of nuclear propulsion system hardware. This is particularly true with respect to the nuclear fuel, especially its composition and material form. In assessing such options, consideration should be given to preserving the direct applicability of existing safeguards technology. Based on these considerations, the recommended safeguards requirements are:

- Positive measures shall be provided to control and protect the nuclear system and its SNM from theft, diversion, loss, or sabotage.
- To the extent practicable, the design of the nuclear system shall incorporate features that enhance safeguards and permit proven safeguards methods to be employed.
- Positive measures or features shall be provided to facilitate timely identification of the status as well as the location and, if necessary, recovery of the nuclear system or its SNM.

NSPWG Guidelines

The following safety guidelines are recommended for use by the program to establish program plans as well as design and operational requirements for the development of nuclear propulsion systems for SEI.

1. Risk/Reliability

All activities in the SEI program, including the nuclear propulsion activities should be guided by a formal reliability program based on a common technical approach. The reliability program should focus on the generic problem of demonstrating high reliability at the system level based on feature and component testing and a few subsystem-level tests. The reliability program should be integral with the engineering design and development activities to maximize the usefulness of test data. This means that reliability technologists should support definition of the design and development testing, and these efforts should include margin testing and test-to-failure activities necessary to support demonstration of reliability.

The reliability program should include analytical activities to relate empirical data to systems-level performance objectives and support definition of data requirements. These analytical activities should also be used to support the establishment of priorities for the data requirements. Highest priority should be given to the design and data requirements that support evaluation and demonstration of the reliability of safety functions. For example, demonstration of the reliability of the control system to perform the shutdown function is very important to safety. Shutdown heat removal and its role in retaining radioactive materials is also an important safety function, especially in ground testing.

All program elements should support the safety policy objective of assuring that risks are as low as reasonably achievable. Design-basis mission risk analysis should be initiated as soon as possible to serve as the foundation of the future baseline mission risk analyses. The risk analysis tasks should provide analytical evaluation of the risk to individuals and the environment associated with each major task. This information should be compiled and reported to the responsible line management for use in the decision making process. The risk analysis information should also be used to guide safety design requirements and safety testing and analysis development activities. Several types of risk assessments and analysis will be required to incorporate the nuclear and space technology elements into a common set of methods.

2. Operational Safety

All missions planned in SEI, whether piloted, cargo, or robotic, require long operational sequences that include a large number of varied operations. Consideration of these operations and the design strategy to assure that they can all be accomplished safely should be completed as early as practical. Early objectives include: (1) incorporation of adequate safety margins and operational safety features in the design, (2) identification of all developmental equipment required to support safe operations, and (3) identification of the design duty cycles and environmental conditions that this equipment must accommodate to assure its reliability for all mission phases. Normal, abort, and credible accident sequences must be included. A high level of computer simulation is recommended. Candidate human-machine interface equipment should be integrated with nuclear system simulators. It is important that these tasks be given priority and visibility so requirements that will lead to acceptable levels of mission safety can be established.

Eight issues have been identified for consideration by the operational safety activity. These are discussed in detail in Reference 4 and are:

- Integrating Safety Considerations.
- Criticality and Control Calibration.
- Role of Flight Crew in Nuclear Operation.
- Instrumentation Requirements and Operational Strategies.
- Development of the Operational Duty Cycle.
- Extra Vehicular Activity (EVA).
- Proximity Operations.
- Testing and Surveillance.

3. Flight Trajectory and Mission Abort

In addition to the many and varied inputs, constraints, and requirements necessary for chemical thrust mission trajectory planning, the designers of SEI missions using nuclear propulsion must address the nuclear safety issues during the process of trajectory design, analysis, and selection. Specific nuclear safety issues that should be addressed are discussed elsewhere in this paper.

Specific mission-abort principles should be developed with systematic risk analysis, and where practical, should include provisions for addressing the nuclear safety requirements. In the event of mission abort after nuclear system operation, flight elements should have sufficient alternate (nuclear or non-nuclear) propulsion capability to return the crew safely and place the nuclear reactor in the planned or alternate disposal trajectory.

4. Space Debris and Meteoroids

Meteoroids and space debris are a part of the space environment and need to be considered in the development of safety and reliability requirements. The technology required to quantify this environment and provide protection for spacecraft is ongoing. Unique features associated with nuclear propulsion systems requiring special development attention have not been identified. The ongoing development efforts for sensors and protective materials to address debris and meteoroids concerns may need to be supplemented to support the SEI programs. Improved measurement and modeling of the environment could be of benefit to the spacecraft and propulsion system designers. Because of their large radiator areas, NEP systems are likely to require more attention to protection from space debris and meteoroids than NTP systems would. The need to accommodate particle impacts may be the limiting factor for minimizing the mass of large NEP radiators. For NTP systems, pressure requirements and structural requirements result in relatively thick fuel tanks and other large surfaces of potential concern. These thicker components for NTP systems reduce their potential vulnerability to particle impacts.

Conclusions

The Safety Policy, Requirements, and Guidelines, and other recommendations have been provided to guide the design and development of nuclear propulsion systems for SEI. The Safety Requirements and Guidelines are intended to provide initial direction for early trade studies and should be expected to be expanded and refined as a result of development work and design evolution. Timely adoption or adaptation of these recommendations should greatly facilitate the implementation of the nuclear propulsion program and will assure the safety of the public, mission staff, and the environment during all program activities.

Acknowledgments

This work was a joint agency, multi-laboratory effort supported by the Department of Energy (DOE), the National Aeronautics and Space Administration (NASA), and the Department of Defense (DoD). This paper was prepared by the author employed by Brookhaven National Laboratory, which is operated for the U.S. Department of Energy under contract DE-AC02-76CH00-016. Although this effort was led by the DOE, the funding and execution of this work was provided by the participating laboratories and agencies.

References

1. Stafford, T. P. (1991) "America's Space Exploration Initiative," U.S. Government Printing Office, May, 1991.

2. Marshall, A. C. and J. C. Sawyer, Jr. (1991) "A Recommended Interagency Nuclear Propulsion Safety Policy," presentation at AIAA/-NASA/OAI Conference on Advanced SEI Technology, Cleveland, OH, 4-6 September 1991.

3. Marshall, A. C. and J. C. Sawyer, Jr. (1992) "Nuclear Safety Policy Working Group Recommendations for SEI Nuclear Propulsion Safety," Proceedings of the 9th Symposium on Space Nuclear Power, Albuquerque, January, 1992, CONF920104, American Institute of Physics, pp. 806-811.

4. Marshall, A. C., et al. (1991) Nuclear Safety Policy Working Group Recommendations on Nuclear Propulsion Safety for the Space Exploration Initiative, NSPWG-1, September 1991.

5. U.S. Department of Energy (1984) DOE Order 5480.4: Environmental Protection, Safety, and Health Protection Standards, 15 May 1984.

6. Wahlquist, E. J. (1990) "U.S. Space Reactor Programs," The Anniversary Specialist Conference on Nuclear Power Engineering in Space, Transactions Part 2, Papers of International Specialist, Obninsk, U.S.S.R., 15-19 May 1990.

7. U.S. Occupational Safety and Health Administration, Department of Labor (1989) U.S. Code of Federal Regulations, 29 CFR 1910.96, Chapter VII: Ionizing Radiation, Office of the Federal Register, National Archives and Records, 1 July 1989.

8. U.S. Occupational Safety and Health Administration, Department of Labor, 1991. U.S. Code of Federal Regulations, 29 CFR 1960.18: Supplementary Standards, July 1, 1991, Office of the Federal Register, National Archives and Records, Chapter XVII.

9. National Council on Radiation Protection and Measurements, 1989. Guidance on Radiation Received in Space Activities, NCRP Report Number 098, 1989.