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Nuclear Safety Policy Working Group Recommendations on Nuclear Propulsion Safety for the Space Exploration Initiative

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September 27, 1991

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This report represents a consensus opinion of the Nuclear Safety Policy Working Group and does not necessarily represent the official views of NASA, DOD, or DOE. No inferences should be drawn from this report regarding official funding commitments or policy decisions.

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. These recommendations, which are contained in this report, should facilitate the implementation of mission planning and conceptual design studies. The NSPWG has recommended a top-level policy to provide the guiding principles for the development and implementation of the SEI nuclear propulsion safety program. In addition, the NSPWG has reviewed safety issues for nuclear propulsion and recommended top-level safety requirements and guidelines to address these issues. These recommendations should be useful for the development of the program's top-level requirements for safety functions (referred to as Safety Functional Requirements). The safety requirements and guidelines address the following topics: reactor start-up, inadvertent criticality, radiological release and exposure, disposal, entry, safeguards, risk/reliability, operational safety, ground testing, and other considerations.

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List of Acronyms

AEC—Atomic Energy Commission
AFISC—Air Force Inspection and Safety Center
ALARA—as low as reasonably achievable
ANP—Aircraft Nuclear Propulsion
ANS—American Nuclear Society or American National Standard
ASME—American Society of Mechanical Engineers
BPV Code—Boiler and Pressure Vessel Code
BNL—Brookhaven National Laboratory
CFR—Code of Federal Regulations
DOD—Department of Defense
DOE—Department of Energy
DOT—Department of Transportation
EIS—Environmental Impact Statement
EPA—Environmental Protection Agency
ERDA—Energy Research and Development Administration
EVA—extra-vehicular activity
FEMA—Failure Mode and Effects Analysis
FSAR—final safety analysis report
FTA—fault tree analysis
FY—fiscal year
GCR—galactic cosmic radiation
GE—General Electric Company
HQ—Headquarters
IAEA—International Atomic Energy Agency
IEEE—Institute of Electrical and Electronics Engineers, Inc.
INEL—Idaho National Engineering Laboratory
INSRP—Interagency Nuclear Safety Review Panel
JSC—Johnson Space Center
LANL—Los Alamos National Laboratory
LeRC—Lewis Research Center
LMEPO—Lunar Mars Exploration Program Office
MRA—mission risk assessment
NASA—National Aeronautics and Space Administration
NCRP—National Commission on Radiological Protection and Measurements
NEP—nuclear electric propulsion
NERVA—Nuclear Engine for Rocket Vehicle Application
NPS—nuclear power/propulsion system
NRC—Nuclear Regulatory Commission
NSPWG—Nuclear Safety Policy Working Group
NTP—nuclear thermal propulsion
OECD—Organization for Economic Cooperation and Development
OSHA—Occupational Safety and Health Administration
PRA—probabilistic risk assessment
PSAR—preliminary safety analysis report
RLA—request for launch approval

RTG—radioisotope thermoelectric generator
SAR—safety analysis report
SDIO—Strategic Defense Initiative Organization
SEI—Space Exploration Initiative
SER—safety evaluation report
SIP—safety implementation plan
SNAP—System(s) for Nuclear Auxiliary Power
SNAP-10A—A 500-W(e) space reactor power system developed under the SNAP program and flight tested in 1965.
SNL—Sandia National Laboratories
SNM—special nuclear material
SST—Safe Secure Trailer
US—United States
USAF—United States Air Force
USAR—updated safety analysis report

Executive Summary

Nuclear propulsion has been identified as an essential technology for the successful implementation of the Space Exploration Initiative (SEI). Interagency (NASA, DOE, and DOD) workshops were held in the summer of 1990 to explore the options, issues, and requirements for the development of nuclear propulsion systems in support of SEI. The workshop participants recognized the vital importance of safety to a nuclear propulsion program and recommended the formation of an interagency working group to formulate a sound safety policy for SEI nuclear propulsion. Such a group, named the Nuclear Safety Policy Working Group (NSWPG), was chartered in the fall of 1990 to develop and recommend a top-level nuclear safety policy. This working group was also asked to develop recommendations for a number of specific nuclear propulsion safety topics. The recommendations of the working group are presented in this document. The NSPWG recommendations apply only to the present scope of planned SEI nuclear propulsion activities. Consistent and thorough application of these recommendations should provide reasonable assurance that launch approval can be obtained.

E.1 Recommended Safety Policy

The safety policy recommended by the NSPWG establishes the importance and priority that must be placed on safety and establishes the broad framework and overall guiding principles for the development and implementation of an effective nuclear propulsion safety program. The recommended policy statement is provided below and is discussed in Subsection 2.2.

> *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.*

E.2 Requirements and Guidelines Recommended for Flight Safety

In addition to this safety policy, the NSPWG has recommended top-level flight safety requirements and guidelines. These recommended requirements and guidelines should be used by SEI program safety management to develop the program's top-level requirements for safety functions, referred to as Safety Functional Requirements. The recommended requirements and guidelines should be useful for the purpose of conceptual design and program planning. In comparison with the safety requirements, the safety guidelines are more in the nature of suggestions or specific programmatic guidance; they are more tentative than the safety requirements. These guidelines may be used to help formulate Safety Functional Requirements as more information becomes available.

E.2.1 Recommended Safety Requirements

Recommended safety requirements were developed for reactor start-up, inadvertent criticality, radiological release and exposure, disposal, entry, and safeguards. Both quantitative and qualitative requirements were recommended. Quantitative requirements for radiological exposures were recommended only when applicable established guidance could be cited. (Qualitative terms are defined in the report's glossary and are discussed in the text.) More specific and quantitative design requirements must be developed as the program matures and specific concepts are selected.

The policy philosophy of reducing risk to as low as reasonably achievable couples the development and revision of all safety requirements to the effect on risk. This approach allows the development of stringent requirements that are reasonable in the context of their application. A different set of stringent requirements will be needed for other space nuclear programs.

The recommendations for SEI nuclear propulsion flight safety requirements are provided in the following list. These flight safety requirements are discussed in Section 3. Guidance for ground test safety is given in Subsection E.3 and Section 5.

E.2.1.1 Reactor Start-Up.

- *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.*

A "planned orbit" is an Earth orbit condition, prior to insertion into an interplanetary or Earth-Lunar trajectory, that has been predetermined to be safe for reactor start-up operations.

E.2.1.2 Inadvertent Criticality.

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

E.2.1.3 Radiological Release and Exposure. The following requirements apply only to radiological releases and exposures from reactor systems operating in space. Potential radiological releases on Earth are implicitly addressed under reactor start-up, inadvertent criticality, disposal, and entry. 29 CFR 1910.96 (U.S. OSHA, 1989), cited below, is equivalent to 10 CFR 20 (U.S. NRC, 1991a) for radiation workers and includes a 5 rem/year whole body dose limit to astronauts from on-board radiation sources.

I. 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.*

II. 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 the effect on Earth of a radiological release in space 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."

E.2.1.4 Disposal. (See entry also.)

- *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.*

E.2.1.5 Entry. Entry refers to an event in which a reactor system enters the atmosphere or impacts the surface of Earth or another celestial body.

- *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.*
- *For inadvertent entry through an atmosphere, the reactor shall be essentially intact, or, alternatively, shall 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.*

E.2.1.6 Safeguards.

- *Positive measures shall be provided to control and protect the nuclear system and its special nuclear materials (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.*

E.2.2 Recommended Safety Guidelines

Safety guidelines are recommended for risk/reliability, operational safety, flight trajectory and mission abort, as well as space debris and meteoroid safety considerations. These guidelines are presented in Section 4 and are briefly discussed below.

E.2.2.1 Risk/Reliability. The design and development activities directed toward assuring high reliability in system features and functions should receive major emphasis in any nuclear program. The reliability of the safety functions, in particular, is critically important to reducing risk. Demonstration of the achievement of the high-reliability and low-risk goals for SEI nuclear propulsion systems must be accomplished through analysis supported by feature, component, and subsystem testing. The analyses can be both quantitative and qualitative as well as deterministic and statistical. An extensive set of data must be evaluated and integrated to produce acceptable results. These efforts must also be inherently imbedded in the design and development engineering activities. Careful management attention to the planning and conduct of activities contributing to the achievement of the low-risk and high-reliability goals is required.

E.2.2.2 **Operational Safety.** Operational safety is focused on activities associated with operation of the space nuclear propulsion system that are important to safety. It includes all phases of a mission, from pre-launch checkout through disposal of the spent nuclear system. Unique operational aspects important to design and development of a nuclear propulsion system have been identified and discussed in Section 4 with the objective of providing guidance for the SEI nuclear propulsion mission planning, design, and development efforts. Issues important to safety of both piloted and unpiloted missions are addressed. Issues unique to piloted missions have important implications for crew safety and can affect propulsion system requirements. Subsection 4.2.2 describes eight candidate operational issues.

E.2.2.3 **Flight Trajectory and Mission Abort.** In addition to the considerations 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 abort principles should be developed with systematic risk analysis and should include provisions for addressing the recommended safety requirements.

E.2.2.4 **Space Debris and Meteoroids.** Meteoroids and space debris are a part of the space environment and need to be considered in development of safety and reliability requirements. Nuclear propulsion system designers must also address the need to minimize the potential for adding debris to the orbital environment surrounding Earth.

E.3 Ground Test Safety Recommendations

The NSPWG also recommended the general type of safety validation testing that could be required for nuclear propulsion systems and provided guidelines for ground facility and equipment safety.

E.3.1 Ground Test Needs for Flight Safety Validation

Control of hazards associated with space nuclear propulsion systems will require safety test information to validate analysis and to support demonstration of compliance with safety requirements. Early guidance on safety validation testing requirements is needed to permit identification of the scope of test facility needs.

The ground test element of the safety program should focus on data required to assure safety objectives for flight systems will be achieved. These data are necessary to obtain flight approval. Some of the data identified will also be useful to other major tasks, such as ground testing of propulsion reactors.

The flight safety tasks have been logically separated into four groupings: launch and deployment safety, operational safety, disposal safety, and inadvertent entry safety. Potential safety testing that should be considered during facility planning has been delineated Subsection 5.1.2.

E.3.2 Ground Facility and Equipment Safety

The testing of space nuclear propulsion reactors will be conducted on government sites in accordance with DOE orders. The DOE orders provide requirements and guidance that are consistent with the recommended policy statement. The DOE orders will require some interpretation in applying them to specific testing. Interpretation of specific details should be done as part of the design development and independent safety review process.

Requirements for the control of radioactive material during normal, off-normal, and credible accident conditions have been developed for many types of ground test reactors. These generally can be applied to the testing of nuclear thermal propulsion (NTP) and nuclear electric propulsion (NEP) reactors. However, the necessity to exhaust the reactor coolant in the NTP presents a unique area of requirements that have only been considered during the Nuclear Engine for Rocket Vehicle Application (NERVA) program and the Aircraft Nuclear Propulsion (ANP) program.

The issue of beyond-design-basis accidents also requires special attention and may have a strong influence on the approach selected for containment or confinement. The inherent capabilities of the nuclear thermal propulsion fuel to retain fission products may also influence the selection of technology development activities and safety features. Safety design activities must evaluate the value of risk-reducing design approaches and the practicality of implementing the approaches. Ground facility testing is discussed further in Subsection 5.2.2.

Transportation safety and launch facility safety must also be addressed. A certified shipping container which meets DOT and DOE/NRC regulations must be used for the transport of fissile material (e.g., fuel, fuel rods, or a complete reactor assembly) between the ground test facility and the launch site. Safety procedures must be established and facility provisions must be available at the launch site to ensure that activities associated with the nuclear system will not pose a safety hazard. These considerations are discussed Subsections 5.2.3 and 5.2.4.

E.4 Suggested Future Activities

Suggested future activities for the program office to consider include the development of a safety, quality, and reliability plan (Subsection 6.1) and the development of a plan for public participation in the SEI nuclear propulsion program. The importance of a plan for public communication and participation and plan objectives are discussed in Subsection 6.2.

1. Introduction

1.1 Background

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

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.

In the summer of 1990, the National Aeronautics and Space Administration (NASA) held joint agency (NASA, DOE, and DOD) workshops to explore options, issues, and requirements to initiate a new nuclear propulsion program. A joint agency steering committee was formed during the workshops to guide the workshop activities. The workshop participants recognized the vital importance of safety to the successful application of nuclear propulsion for the Space Exploration Initiative. They also recognized the necessity of establishing nuclear safety policy during the conceptual stage to integrate safety into the program from its inception. As a consequence, one of the recommendations from the workshop was the formation of a joint agency working group to develop nuclear safety policy for space nuclear propulsion in support of the SEI program. The steering committee chartered the Nuclear Safety Policy Working Group (NSPWG) to develop and recommend a top level nuclear safety policy and to recommend safety requirements and guidelines for a number of specific nuclear propulsion safety topics. The NSPWG charter is provided in Appendix A. Five other working groups that interface with the NSPWG were also chartered. These other working groups address missions, nuclear thermal propulsion technology, nuclear electric propulsion technology, fuels/materials, and facilities.

The NSPWG includes representatives from all three participating agencies. One industry representative was also appointed as an advisor. The NSPWG members and their affiliations are listed below:

NSPWG Member	Representing	From
Albert C. Marshall - Chairman	DOE	SNL
J. Charles Sawyer, Jr. - Vice Chair.	NASA	HQ
Robert A. Bari	DOE	BNL
Hatice S. Cullingford	NASA	JSC*
Alva C. Hardy	NASA	JSC
James H. Lee	SDIO/DOD	SNL
William H. McCulloch	DOE	SNL
George F. Niederauer	DOE	LANL
Kerry Remp	NASA	LeRC
John W. Rice	DOE	INEL
Joseph A. Sholtis	DOD	USAF
Neil W. Brown - Advisor	Industry	GE

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* Representing the Lunar and Mars Exploration Program Office

Brief biographical sketches are provided for each member of the NSPWG in Appendix B.

1.2 Scope

Figure 1-1 illustrates the hierarchical structure for the development of SEI nuclear propulsion safety policy and requirements as visualized by the NSPWG. At the top of the hierarchy are the existing agency (DOE, NASA, DOD, EPA, etc.) policies and mandatory requirements. At the next level is a Joint Agency Space Nuclear Propulsion Safety Policy. The safety policy establishes the importance and priority placed on safety and provides the overall guiding principles for the development and implementation of an effective nuclear propulsion safety program. The Safety Functional Requirements delineate the specific safety functions required of the system or program (e.g., preclude inadvertent criticality). Top-level agency policies, mandatory requirements, the joint agency Space Nuclear Propulsion Safety Policy and Safety Functional Requirements are the responsibility of the cognizant agencies. The contractors' responsibility begins at the level of system-specific design specifications. Design specifications guide system design and research.

The scope of the NSPWG activities is illustrated on the left side of Figure 1-1. The NSPWG-recommended safety policy should be used to formulate the joint agency Space Nuclear Propulsion Safety Policy for SEI. The NSPWG also has recommended safety requirements and guidelines for important safety issues and considerations. These recommended requirements and guidelines should be used by SEI management and program safety management to develop the program Safety Functional Requirements. Safety requirements and guidelines should be useful for the purpose of conceptual design and program planning. In comparison with the safety requirements, the safety guidelines are more in the nature of suggestions or specific programmatic guidance; they are more tentative than the safety requirements. These guidelines may be used to help formulate Safety Functional Requirements as more information becomes available.

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 described in Section 6 as 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.)

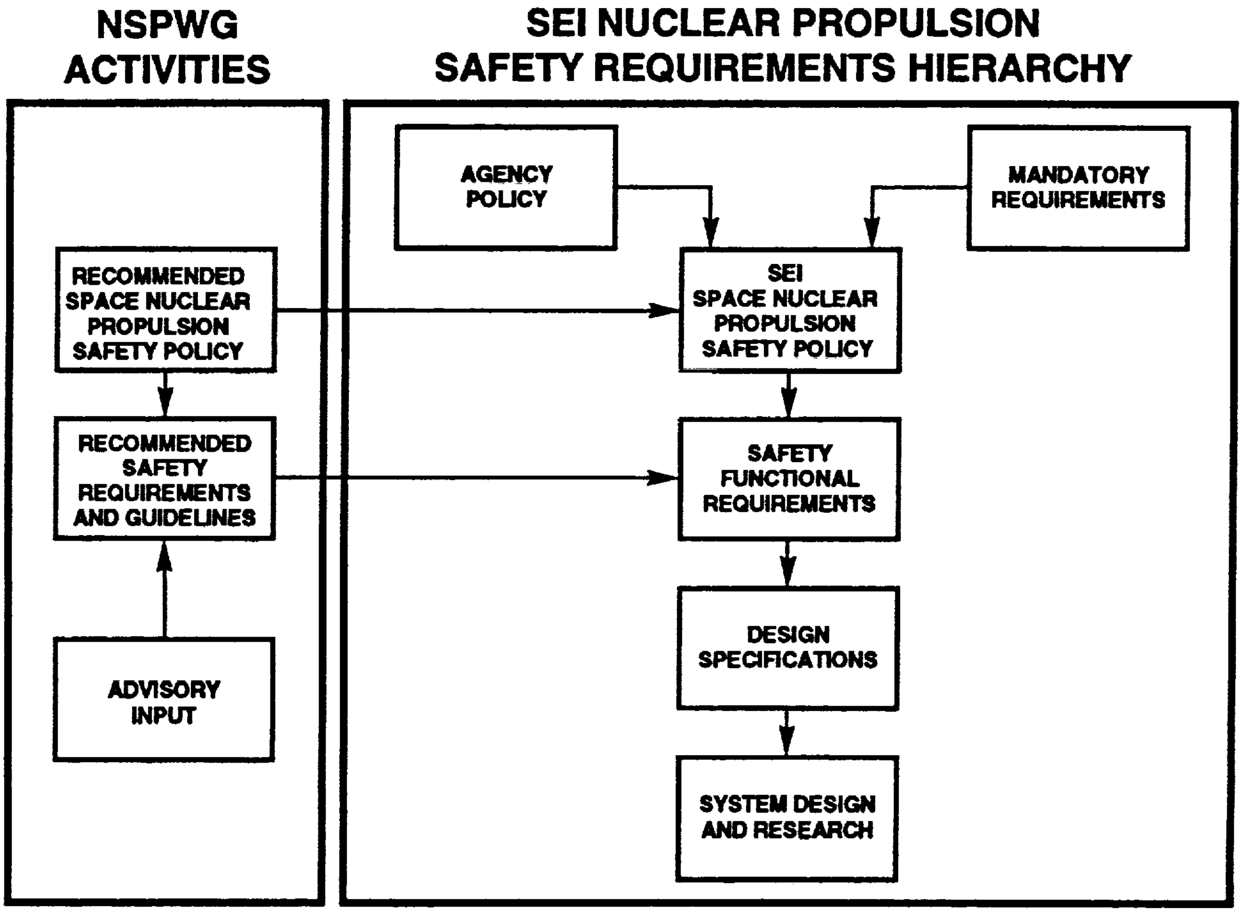

Figure 1-1. Development of Safety Policy and Requirements

1.3 Approach

The development of the NSPWG recommendations took place during a series of ten meetings between November 1990 and September 1991. Three meetings were held in Albuquerque, New Mexico, two in Washington, D.C., one in Houston, Texas; the remaining meetings were conducted by teleconference. To allow for input from the community, NSPWG meeting minutes were mailed to a wide distribution. Participation by observers and guest speakers at meetings was permitted by special request. In addition, two open sessions were held in Washington, D.C. for all interested parties. Presentations of the NSPWG interim findings were also given at a Steering Committee meeting in Cleveland, Ohio in April 1991, at the 1991 annual meeting of the American Nuclear Society in Orlando, Florida in June 1991, and at an American Institute of Aeronautics and Astronautics conference in Cleveland, Ohio, in September 1991 (Marshall and Sawyer, 1991).

The schedule of NSPWG activities is provided by Figure 1-2. The NSPWG first established its scope, objectives, approach, and schedule and defined its terminology. Existing national and international safety requirements were reviewed (e.g., U.S. DOE, 1984). In addition, pertinent previously developed safety policies were also reviewed (e.g., Wahlquist, 1990). A top-level safety policy was formulated and distributed to the individuals on the minutes distribution list for comments. Comments received were then used to make appropriate modifications to provide the recommended safety policy presented in this document.

Members were assigned principal responsibility for one or more of the safety issues identified in the charter or other safety issues identified by the NSPWG. The responsible NSPWG member for each safety topic presented a discussion of the topic to the group using a standard format. The format included the following subjects:

- Scope
- Issues
- Discussion
    - information available
    - considerations, impact and implications
    - justification of requirements and guidelines
    - additional work needed, and safety testing
    - NTP versus NEP considerations
    - manned versus unmanned considerations
    - reusability considerations.

Discussions on each topic continued until consensus was reached on draft recommendations.

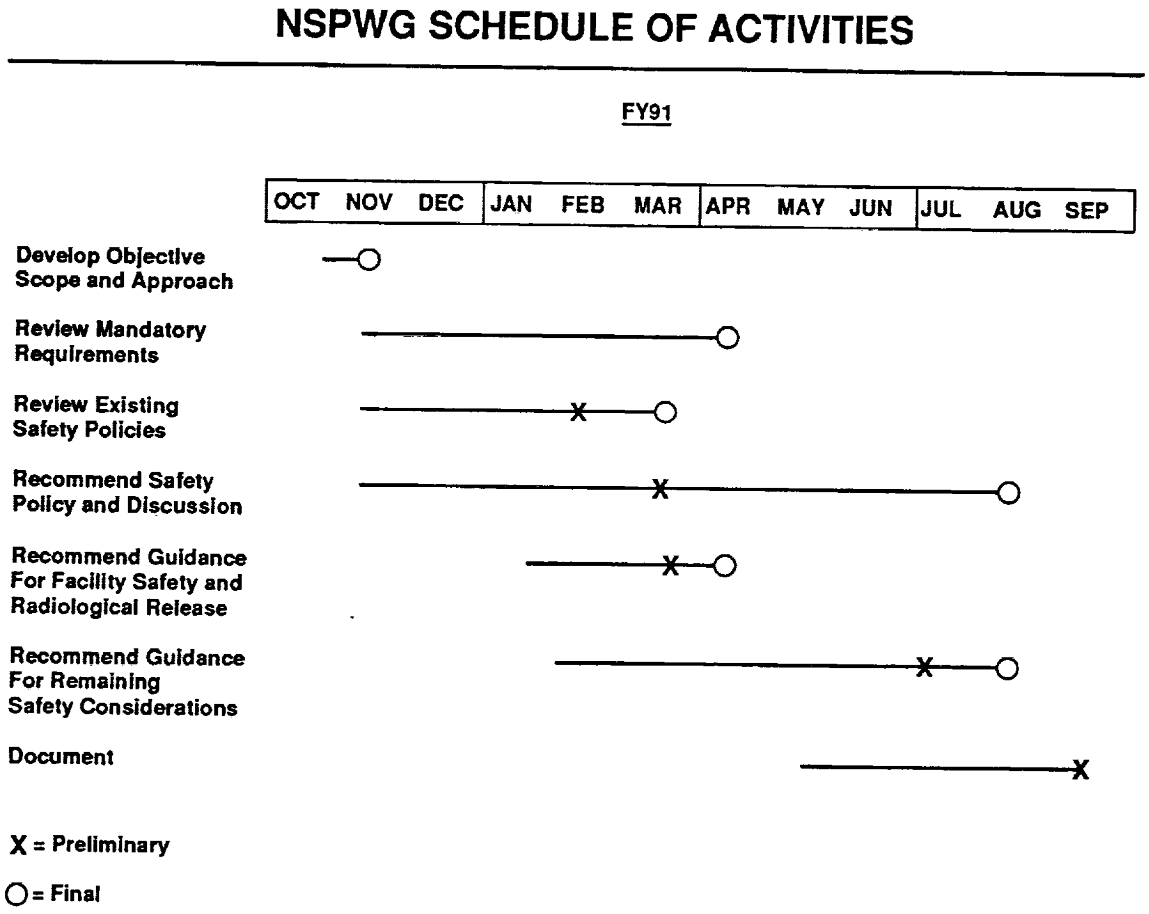

Figure 1-2. NSPWG Activity Schedule

1.4 Report Organization

The remainder of this report is organized as follows:

- The recommended safety policy for the SEI nuclear propulsion program is presented in Section 2. Subsection 2.1 provides the text of the recommended safety policy. The policy is intended to be a clear and concise statement to enhance the visibility, importance, and comprehension of the guiding safety philosophy. An elaboration, interpretation, and discussion of the safety policy is provided in Subsection 2.2.

- Recommended flight safety requirements are presented in Section 3. Subsection 3.1 provides guidance for the use of the requirements. Concise statements of the recommended requirements and a discussion of the requirements are given in Subsection 3.2.

- Section 4 presents recommended safety guidelines for flight systems.

- Recommended guidelines for ground testing are provided in Section 5. Candidate safety validation tests are briefly discussed in Subsection 5.1 for the purpose of facility planning. Safety considerations for ground test facilities, ground transportation of nuclear systems, and nuclear safety at the launch site are discussed in Subsection 5.2.

- A preliminary discussion of suggested future safety activities is presented in Section 6.

- Appendixes A and B provide the NSPWG charter and the background of the working group members.

2. Recommended Safety Policy

2.1 Statement

The following is the NSPWG-recommended policy statement.

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.

2.2 Discussion

The following expansion of the safety policy statement discusses the implications of each of the principles embodied in the safety policy.

The Space Exploration Initiative nuclear propulsion program will develop propulsion systems to support human and robotic exploration of the solar system. Ensuring safety during the execution of the nuclear propulsion program is a paramount objective; all program activities shall be conducted in a manner to achieve this objective. This policy reflects the commitment at the highest levels of program management to safety.

Safety is defined here as a condition judged to be of sufficiently low risk. In the context of this policy, safety is meant to include the health and safety of the public, program personnel, and mission crew as well as the protection of terrestrial and non-terrestrial environments. Safety also includes safeguarding nuclear systems and special nuclear materials against unauthorized use or diversion and protecting facilities and equipment from damage or loss. Safety must be a primary consideration in all phases of the nuclear propulsion program, including design, development, fabrication, transportation, ground testing, system integration and prelaunch activities, launch, deployment, flight testing, operation, and disposal. Safety should be integrated into the design from conception and must be a key consideration in all design, operational, and programmatic decisions.

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.

For any space mission involving significant quantities of radioactive or fissile material, launch approval must be given by the Executive Office of the President of the United States, based on comparison of the projected benefits and the risks for the mission. The decision is based on an established and proven review process that includes an independent assessment of mission safety by an Interagency Nuclear Safety Review Panel (INSRP). The commitment of the nuclear propulsion program to keep risks as low as reasonably achievable helps ensure a judgment that the benefits of potential missions will outweigh the risk.

A comprehensive safety program shall be established to cover all program phases. It shall be directed toward making a thorough search for hazards, establishing requirements for eliminating and controlling hazards, executing experimental and analytical evaluations of the associated risks, and providing reasonable assurance that all safety issues have been identified and adequately treated. The program shall include continual monitoring and evaluation of all activities important to safety and shall, in addition to the final INSRP assessment and review described above, provide for periodic, competent, and independent safety oversight. The safety program should include a clear delineation of the safety assurance function and should be coordinated with the quality assurance and reliability functions.

Effective safety administration is an essential element of the nuclear propulsion safety program and must be guided at the policy level to ensure adequate safety implementation. Clear lines of authority and communication for safety shall be established and maintained. Lines of authority for safety must be instituted to ensure safety responsibility and accountability. Effective communication is essential to implement the safety program. As part of the communication process, it is important to foster open communication with program participants and the public regarding both the benefits and risks associated with the SEI nuclear propulsion program. The specific emphasis placed by the program on safety and the progress toward the safety objectives should also be communicated. The predicted system responses and the expected and potential environments for systems interfacing with the nuclear propulsion system must be communicated among all system developers to ensure appropriate mission level safety evaluations. The specific definition of an organizational structure for safety and the assignment of responsibilities within that structure is vital to the realization of the goals and objectives of the safety program, but that function is outside the scope of this policy statement and discussion and is left to the overall management of SEI using the policy as guidance.

Safety is essential to the success of the program. Management should take specific actions to develop and maintain a safety consciousness among all program participants and throughout all aspects of the SEI nuclear propulsion program. This requires that management be committed to the health and safety of its workers and the public and the protection of the environment, that this commitment be communicated to all program participants, and that safety be given explicit consideration in all technical, operational, and programmatic decisions. The goal is for the commitment to safety to so pervade the program that all participants recognize their safety responsibilities and automatically consider the safety implications of their work.

3. Recommended Safety Requirements for Flight Systems

3.1 Intended Use of Recommended Requirements

The requirements presented in this section and the guidelines given in Section 4 are recommended for use by SEI program safety management to develop program Safety Functional Requirements. A different set of Safety Functional Requirements will be needed for other space nuclear programs and applications. The recommended safety requirements, and the recommended guidelines provided in Section 4, should also be useful for the purpose of conceptual design and program planning.

As the nuclear propulsion program progresses and systems designs mature, the Safety Functional Requirements may need to be modified to maintain the intent of the Safety Policy. Nuclear systems designers and developers should be allowed to propose modifications to the requirements to make them more applicable to the developing systems. The justification for such changes should include the demonstration that the replacement maintains or improves the level of compliance with the program Safety Policy. Any modifications to Safety Functional Requirements will require formal approval by program safety and cognizant agencies through an established review and approval process. Approval of revised safety requirements must be based on an assessment that revisions are consistent with the philosophy of reducing risk to as low as reasonably achievable. This process of proposing revised or supplementary safety requirements allows the requirements to be adapted to the developing program. This process can also stimulate innovation and the creation of systems designs that will lead to improved safety and system performance. When establishing or modifying Safety Functional Requirements, preference should be given to inherent or passive safety measures over the incorporation of active safety features. Revisions to design specifications affecting safety should be based on this philosophy as well.

3.2 Recommended Requirements

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.

The recommended requirements are presented and discussed below.

3.2.1 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 remains securely subcritical. The recommended requirement for 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.*

A "planned orbit" is an Earth orbit condition, prior to insertion into an interplanetary or Earth-Lunar trajectory, that has been predetermined to be safe for reactor start-up operations.

3.2.2 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 (see Subsection 3.2.1) 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 and credible accident conditions.*

3.2.3 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 3.2.1, 3.2.2, and 3.2.5. 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]). 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), NASA has adopted the recommendations of the National Commission on Radiological Protection and Measurements (NCRP, 1989) 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:

I. 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.*

II. 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. This environment includes other space enterprises.*

- *The consequence on Earth of a radiological release from an accident in space shall be insignificant.*

The term "insignificant" as used here for the effect on Earth of a radiological release in space 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.

3.2.4 Disposal

Disposal plans for space reactor systems and associated spacecraft components should be established well 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 (see Subsection 3.2.5). The reactor system integrity must be protected for all normal conditions and credible accident conditions, including collisons with meteroids and orbital debris, that could compromise the user's ability to dispose of the reactor system safely. The potential for contamination of the space environment should also be assessed. For example, destructive collisions with space debris or meteoroids could contaminate large regions of space.

After considering a number of disposal options, the NSPWG concluded that approaches using disposal out of Earth orbit are preferred. Other disposal options should be evaluated and compared to determine the approach in which risk is reduced to as low as reasonably achievable. Based on these considerations, the requirements for disposal are as follows:

- *Safe disposal of spent reactor 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 and degradation that could preclude safe disposal.*

3.2.5 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.

Precluding planned Earth entry is recommended as a prudent means to reduce risk to as low as reasonably achievable. Landing nuclear propulsion systems on celestial bodies other than Earth is permitted, provided that the requirements for radiological release and exposure are met. Furthermore, planned Earth entry refers to mission planning and does not include planning following unforeseen events. For example, a mission terminated prior to the reactor generating a significant radioactive inventory is an unforeseen event. The return of the reactor system to Earth for this situation would not be precluded if it can be shown that the operation can be carried out safely.

The reactor system could enter inadvertently because of a misdirected thrust, fragmentation in orbit and subsequent decay, or from other causes. Inadvertent entry could occur during the launch, operation, or disposal phases. Once deployed, the potential for inadvertent entry can be largely prevented by proper choice of orbits and trajectories and careful maneuvering of the spacecraft when making trajectory adjustments. Should inadvertent entry occur, significant radioactive contamination or exposure can be prevented by ensuring that the reactor remains intact following entry and impact. Alternatively, risk can be reduced by ensuring essentially full high-altitude dispersal of radioactivity. A reactor is essentially intact if it retains sufficient integrity to maintain subcriticality and to keep radioactive fuel, solid fission products, and structures together collectively. (Inadvertent criticality from an inadvertent entry is covered in Subsection 3.2.2 as an accident condition). "Essentially full dispersal" means that radioactive material is widely dispersed in the atmosphere as an aerosol such that the consequences on Earth's environment are insignificant (much less than for terrestrial guidelines). The consequences of other entry modes (e.g., partial disruption) are expected to be greater than for either intact entry or full dispersal.

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 consequences of an inadvertent entry shall be made as low as reasonably achievable.*

- *For an inadvertent entry through an atmosphere, the reactor shall be essentially intact, or, alternatively, shall 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.*

3.2.6 Safeguards

The safeguards topic encompasses all measures provided to control and protect the nuclear system and special nuclear materials (SNMs). The theft, diversion, loss, or sabotage of special nuclear materials must be prevented during all phases of the program. If special nuclear materials fall into unauthorized hands, national or subnational entities may utilize the materials for a nuclear weapon. The likelihood of successful unauthorized use can be reduced by early detection and maximizing the available response time. Prior to launch, successful theft, diversion, or sabotage can be made extremely unlikely through the application of standard, proven physical security and safeguard methods and procedures. Subsequent to launch, potential unauthorized use is generally limited to selected abort or accident situations where opportunity and accessibility exist.

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 special nuclear materials (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.*

4. Recommended Guidelines for Flight Systems

4.1 Intended Use of Guidelines

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, as well as space debris and meteoroid safety considerations.

4.2 Recommended Guidelines

4.2.1 Risk/Reliability

Considerations, discussion, and recommendations related to risk and reliability evaluations have been combined because of their common need to evaluate failure mechanisms and the probability of their occurrence. The design and development activities directed toward assuring high reliability in system features and functions should receive major emphasis in any nuclear program. The reliability of the safety functions, in particular, are critically important to reducing risks both during ground testing and for the flight mission.

4.2.1.1 **Reliability Program.** 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.

The reliability program should focus on identifying and eliminating, if possible, mechanisms that can cause failure. Standard methods, such as Failure

Modes and Effects Analysis (FMEA), should be applied to search systematically for failure mechanisms. Identified failure mechanisms that cannot be eliminated should have demonstrated margins relative to the required performance lifetime.

Large subsystem tests and flight system tests should include activities that provide assurance that tests can be conducted with a high probability of being completed as planned. These activities should be integrated with the quality assurance activities and could include elements such as a critical items list. The reliability program should also include activities to support establishing design and procurement specifications of those parts required to achieve the reliability objectives.

4.2.1.2 Risk Analysis. 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. Figure 4-1 illustrates the proposed role of risk and safety analysis in SEI. Several types of risk assessments and analysis will be required to incorporate the nuclear and space technology elements into a common set of methods.

For large, expensive nuclear systems, it is not practical to obtain large samples of system-level failure rates. Nor is it practical to run large-scale tests for severe accident consequences included in risk assessments. These issues can only be addressed through detailed probabilistic analysis using subsystem and piece-part failure-rate data and phenomenological test data on failure mechanisms and accident consequences. Much has been accomplished in the fifteen years since WASH-1400 (Rasmussen, 1975) was published to advance the methods for reliability prediction and risk assessment. The methods, when appropriately applied, focus on assuring that high-quality judgments are derived from test data and validated analyses. These methods have been used in a preliminary fashion to perform a Mission Risk Analysis (MRA) for SP-100. The safety analysis reports (SARs) and safety evaluation reports (SERs) for past RTG-powered space missions also involve extensive use of probabilistic risk assessment methods.

The reliability analysis activities should be coordinated with the risk analysis activities to avoid duplication of effort and potential inconsistency in approach or evaluations. For example, activities such as fault tree analysis required to perform safety/risk assessments should use the same data base as the reliability program activities.

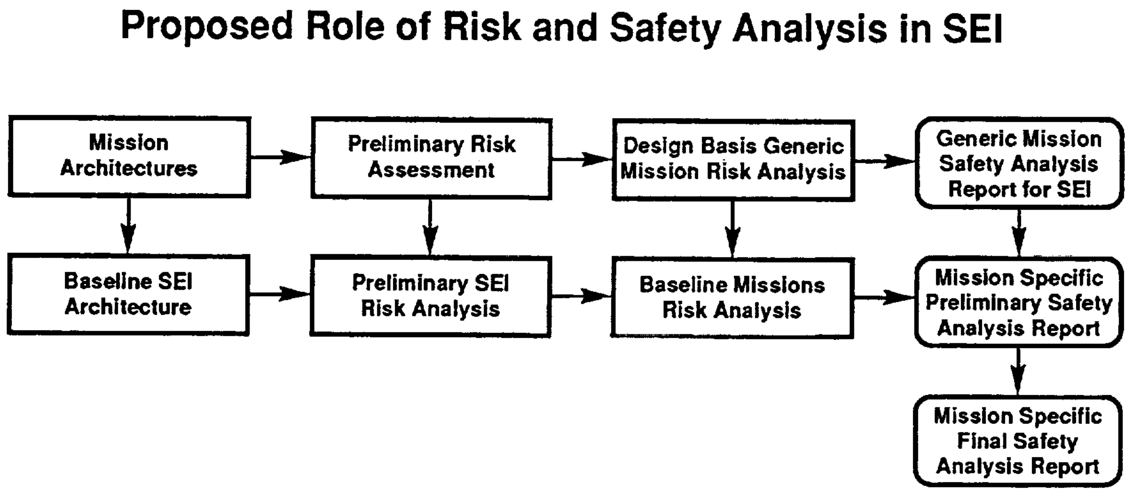

Figure 4-1. Proposed Role of Risk and Safety Analysis in SEI (Simplified)

Risk analyses will require the results of consequence analyses and the testing used to validate consequence models. Consequence analyses and testing provide prediction of potential accident sequences and the uncertainties associated with these predictions. Consequence analysis and testing must be integrated with the risk analyses methods. For example, uncertainties in trajectory analysis for abort sequences should be systematically investigated and factored into the mission risk analysis. Several acceptable ways to structure these types of activities are possible, and it is important to tailor these efforts to the specific organization structures and types of technology. Since this information is not yet available, very specific recommendations concerning these activities cannot be provided at this stage. Risk analysis activities must be integrated sufficiently well to make it possible for the line management and safety technologists to demonstrate jointly the safety adequacy of flight designs and test facility operations.

Figure 4-2 illustrates the activities and interfaces that should be maintained between the reliability and risk analysis activities (top and bottom paths on the figure, respectively). Feedback activities have been omitted to simplify the diagram, but several iterations of the identified activities can be anticipated. Starting at the left of the figure, conceptual designs will be used to plan development activities. Both analytical methods and testing related to failure probability and failure consequences will be required to support the risk analysis. Data bases currently available, as well as those unique to SEI, should be compiled and controlled for common use in the program analysis. Two activity boxes identify the expert judgement processes that need to be developed and commonly applied to both probability and consequence results used in risk analysis. Probabilistic, consequence, and mission event trees all feed into the risk analysis, the output of which is used to develop safety requirements and support safety analysis reports. The reliability analysis activity and the consequence analysis also directly support the development of safety requirements used for system and mission design.

4.2.2 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.

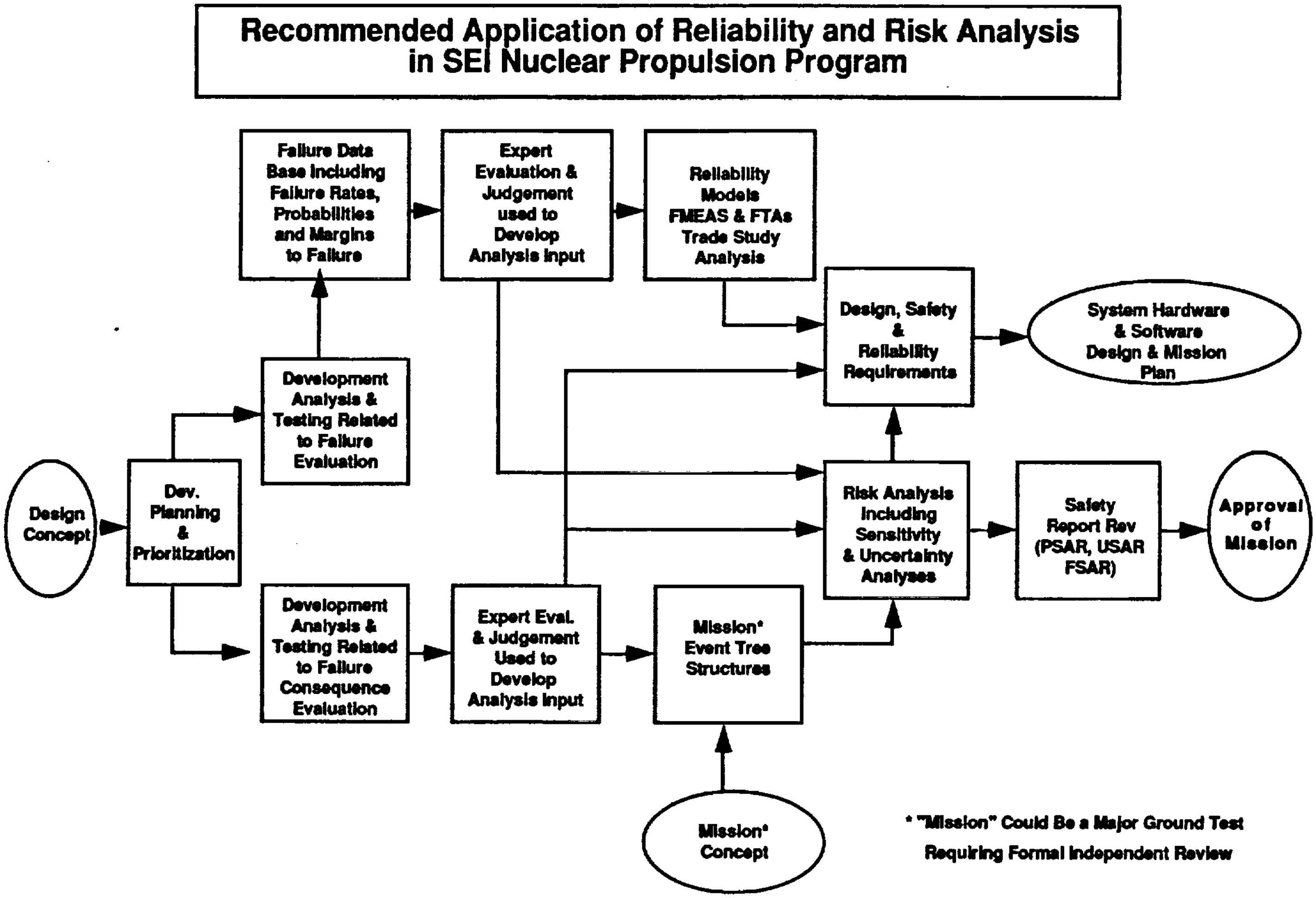

Figure 4-2. Recommended Application of Reliability and Risk Analysis in SEI Nuclear Propulsion Program

Eight issues have been identified in this discussion as potential topics to be addressed by the operational safety activity. Other high-priority issues may be identified that should also be integrated into this effort. Although this effort and the topics addressed also apply to considerations other than safety, the recommendations and discussion provided here place emphasis on operational safety.

4.2.2.1 Integrating Safety Considerations. The first level of safety is provided by sound design and operational practice. This means that it is desirable to have large margins between the operating envelope and the operational states that approach failure. The designer and developer should be aware of the need to identify the margins in the design. When beneficial and practical, the margins should be increased relative to safety limits.

4.2.2.2 Criticality and Control Calibration. As part of the acceptance testing, it will probably be necessary to achieve reactor criticality and calibrate the control devices and instrumentation. This operation may take place at the factory or launch site. The approach to this operation should be considered during the conceptual and preliminary design phases. The pre-operational safety aspects associated with maintaining safe nuclear critical experiments are a part of this activity. Control system design or supplementary features required to assure a very low probability for inadvertent criticality during these operations should be considered.

4.2.2.3 Role of Flight Crew in Nuclear Operation. It is almost certain that even during piloted missions the reactor(s) will automatically start up and restart and will be automatically controlled. However, it is equally certain that on piloted missions the crew will have opportunities to intervene in these automatic actions, if in their judgement this is warranted. The information required to support their making sound decisions will influence instrumentation requirements. Response actions could also have special requirements that merit early consideration so that the system is designed to perform properly in an emergency. Pilot roles and procedures should be identified so that instrumentation and information for pilot emergency actions or intervention, if any, are identified and developed.

4.2.2.4 Instrumentation Requirements and Operational Strategies. Autonomous control will be required for cargo and robotic missions and will probably be used for piloted missions. Diagnostic and fault correction systems will be necessary to achieve the high systems reliability requirements. These strategies must include features to reduce inadvertent or spurious shutdowns. Spurious shutdowns could adversely affect crew safety. These strategies and the equipment to implement them have safety implications that require evaluation as soon as practical in the design cycle. Sensor information reliability and confirmation of the reliability of diagnostic and fault correction strategies will require thorough consideration.

4.2.2.5 Development of the Operational Duty Cycle. The nuclear propulsion system operational duty cycle must be identified to assure adequate margins in the design. Thermal and mechanical cycling can be very important to failure analysis. Early identification of the duty cycles and their relationship to planned mission and abort strategies are needed to allow safety evaluations to influence the establishment of adequate margins in the design duty cycle. This effort would also contribute to identification of features needed for shutdown heat removal.

4.2.2.6 Extra Vehicular Activity (EVA). The system developer and mission designer should avoid EVA (planned or contingency) during all mission phases because of the significant hazard and complication associated with an EVA. If in-flight EVA is absolutely required, reactor shielding and EVA protected zone (shielded) constraints and requirements must be established. For nuclear propulsion systems that release toxic or radioactive material during operation, the system developer and mission designer must consider provisions for on-board procedures and facilities for post-EVA radiation detection, containment, and, if necessary, decontamination. Specific guidelines, procedures, constraints, and requirements addressing these and other possible EVA nuclear propulsion issues should be established by the system developer and mission designer.

4.2.2.7 Proximity Operations. Proximity operations during SEI missions include orbit and interplanetary flight activities involving vehicle rendezvous, docking, and station keeping. After reactor start-up, exposure to reactor radiation will be a major concern for these activities. The nuclear propulsion system developer and the SEI mission designer must consider reactor shielding, protected zone (shielded) and distance constraints and requirements for all proximity operations planning. Guidelines, constraints, and requirements should be established to address these issues.

4.2.2.8 Testing and Surveillance. It will be necessary to conduct both testing and surveillance of various nuclear propulsion subsystems and their interfaces with other subsystems at times during flight. The need to conduct such tests is related to the mission profile and the variation in the operational state of subsystems. For example, each period of reactor operation and thrusting could be followed by a long period of shutdown and coasting. Prior to powered restart it will be necessary to identify the instrumentation and control actuators that are still operational and, if some have failed, to identify the level of redundancy and associated operational strategy. To assure that the testing and surveillance activities can be completed, it is first necessary to identify them and the procedures for testing and verifying their operation.

4.2.3 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 report. The sections that discuss these nuclear safety issues are referenced below:

- Reactor Start-Up Requirements—Subsection 3.2.1
- Inadvertent Criticality—Subsection 3.2.2
- Radiological Release and Exposure Requirements—Subsection 3.2.3
- Disposal Requirements—Subsection 3.2.4
- Entry Requirements—Subsection 3.2.5
- Risk/Reliability Guidelines—Subsection 4.2.1

- Operational Safety Guidelines—Subsection 4.2.2.

Specific mission-abort principles should be developed with systematic risk analysis, and where practical, should include provisions for addressing the nuclear safety requirements listed above. 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.

4.2.4 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 meteroids 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.

Mission trajectories for most candidate SEI missions require relatively short time periods in the space debris environment; consequently, the probability of debris impacts is relatively low and substantial protective features might not be required. NEP-powered missions will have longer periods of exposure to space debris but exposures will be still relatively short compared to spacecraft that continually orbit Earth.

A second issue related to space debris is the potential that SEI spacecraft and power systems have for adding debris to the environment. Of greatest concern is addition of debris to the orbital environment surrounding Earth, but more generally to include the orbits of other planetary environments visited by the spacecraft. The National Space Policy requires,

> " . . . All space sectors will seek to minimize the creation of space debris. Design and operations of space tests, experiments and systems will strive to minimize or reduce accumulation of space debris consistent with mission requirements and cost effectiveness. The U.S. Government will encourage other space-faring nations to adopt policies and practices aimed at debris minimization . . ."

The nuclear propulsion system designers need to be made aware of these requirements and take measures to control release of debris material. These requirements may have greater implications for any NTP systems that release some particulate in the coolant flow. Even though these particles may be extremely small, the potentially large numbers of them will influence requirements for limiting erosion of the fuel surface.

5. Recommended Guidelines for Ground Activities

Safety requirements for ground testing nuclear propulsion reactors are needed to establish facility designs. Requirements are needed in two broad categories: (1) requirements for testing that will assure flight systems achieve the program safety objectives and support launch approval, and (2) requirements to assure that ground testing will be conducted safely. Subsection 5.1 addresses the first category and Subsection 5.2 addresses the second category. Much of the work identified in Subsection 5.1 supports ground test safety objectives as well as flight test safety objectives.

5.1 Ground Test Needs for Safety Validation

5.1.1 Background

Control of hazards associated with space nuclear propulsion systems will require safety test information to validate analysis and to support both establishing and demonstrating compliance with safety requirements. Early guidance is needed to identify the scope of testing needed to support flight system safety and test facility safety requirements. Care should be taken not to confuse safety requirements for ground testing with those for the flight system.

Nuclear propulsion systems technology varies over a broad range and the design options for many candidate concepts are also quite varied. Options based on advanced NERVA technology solid fuel designs are reasonably definitive in their features, while other designs employing innovative liquid and gaseous fuel forms are only conceptual with little design and performance data available. Recommendations based on available information are of necessity based heavily on solid core design and the NERVA/Rover program experience. Although preliminary recommendations are useful for the innovative designs, further development of the design concepts must proceed before safety testing requirements unique to their characteristics can be developed. As the innovative concepts become more developed, the facility plans and safety testing issues must be reviewed to identify any additional safety testing requirements.

5.1.2 Recommendations

The safety program should include a task to define and assure completion of the testing required for flight system safety. This element of the safety program should focus on data required to assure the safety objectives, as they apply to the flight systems, will be achieved. These data are necessary to obtain flight approval. Some of the data identified will also be useful to other major tasks, such as ground testing of propulsion reactors.

Flight safety tasks can be logically separated into four groupings: launch phase, operation phase, disposal phase, and inadvertent entry. The list represents candidate testing that should be considered for the purpose of planning test facilities only. This does not represent a recommendation that the testing will actually be needed for flight approval. Specific designs are required to establish the actual safety testing requirements.

Candidate Testing to Support Safety Evaluation

A. Launch Phase Safety

1. Critical experiments for accident-caused geometries or introduction of moderator or reflective material.
2. Core material behavior for solid booster fire environments.
3. Exposure of safety features to launch pad explosion and fire environments.

B. Operational Phase Safety

1. Measurement of inherent core reactivity mechanisms for assuring stable control.
2. Reliability of control, shutdown, and shutdown cooling features.
3. Demonstration of adequacy of flight system operator interfaces and operating procedures.
4. Adequacy of instrumentation calibration, reliability and lifetime data.
5. Measurement of fission product release or fission product retention.
6. Transient testing of fuel under design-basis accident conditions.
7. Demonstration of shielding performance including margin to lifetime.

C. Disposal Phase Safety

1. Obtain performance and reliability data on features employed to implement the disposal plan. Features could include systems for separation of disposable items or attachment of disposal devices.
2. Reliability of reactor systems required to prepare the core for disposal.

D. Inadvertent Entry

1. Dynamic impact testing of core elements required to retain the function of assuring subcriticality, acceptable retention of radioactivity, and to assure functioning for appropriate emergency actions. This would include features that assure subcriticality on ground or water impact.
2. Testing of features required to assure success of the planned response mode for inadvertent entry.
3. Testing of features for location and recovery of debris.

5.2 Ground Facility and Equipment Safety

5.2.1 Background

The discussion and recommendations presented here are based on the intended application of the safety policy to the nuclear propulsion reactor test facilities, recent SP-100 Nuclear Assembly Test experience, and experience with ground testing nuclear power and propulsion reactors. Two basic issues have been identified: (1) What requirements exist and what requirements should be developed and applied to assure safety in ground testing of space nuclear propulsion reactors? and (2) What process should be assumed to be applied in planning safety reviews of ground testing of nuclear propulsion reactors?

Many types of nuclear reactors are being evaluated for potential use in space nuclear propulsion. NTP reactor concepts include the use of solid, liquid, or gaseous nuclear fuel. As previously stated, the solid core concepts are the most developed, in part, because of the extensive experience from the NERVA/Rover program. The discussion and recommendations that follow are based on the issues as they relate to ground testing of solid-fueled nuclear thermal rocket engines. The recommendations could be applicable to the gaseous- and liquid-fueled NTP concepts, but issues and recommendations unique to these concepts could be critical and must wait for more specific design detail. The recommendations also apply to the NEP reactors except for the effect of using the open cycle in the NTP. NEP system concepts have closed reactor coolant systems while the NTP systems use the reactor coolant to produce thrust and, consequently have open reactor coolant systems. From a ground test safety standpoint, the open and closed cooling approach is the singularly significant difference between the NTP and the NEP reactor concepts. Otherwise the generic safety issues are common to ground testing of both these propulsion reactor types.

A fundamental safety issue is exposure of people and the environment to sources of ionizing radiation. Control of the exposure to toxic materials is also important but does not present a unique safety challenge for the more developed nuclear propulsion reactor concepts. Safety issues associated with storage and handling of large quantities of hydrogen reactor coolant will also need attention but should not present new or unmanagable safety issues. Use of other reactor coolants may introduce different safety requirements.

Requirements for the control and release of radioactive material during normal and credible accident conditions have been developed for many types of ground test reactors. These generally can be applied to the testing of NTP and NEP reactors. These requirements focus on providing inherent safety design characteristics that permit control of the reactor with highly reliable sensors and actuator mechanisms. Features are also provided that assure control of fission products even if the highly reliable control systems fail. The usual response to such a postulated failure is to shut down the reactor and cool the nuclear fuel and structural support so that the reactor remains shutdown and the radioactivity remains contained or confined. In the US, large commercial power reactors provide containment that is intended to function in the event of postulated failure of inherent and engineered safety features. The containment retains the radioactivity postulated to be released as the result of damage to the reactor core. The established requirements to implement this approach could generally be applied to the ground test reactors for NEP application. They could also be applied to the ground testing of the solid core NTP test reactors; however, the necessity to exhaust the reactor coolant in an NTP reactor engine presents a unique area for requirements that have only been considered during the NERVA/Rover and Aircraft Nuclear Propulsion programs. In the case of the NEP reactor concepts employing refractory metals that require the vacuum conditions of space during operation, a unique requirement exists for vacuum enclosure of the reactor and its coolant boundary.

Requirements for features to address these unique characteristics must be developed based on reducing the risk to as low as reasonably achievable. Thus, the safety design activities must include design efforts that evaluate risk-reducing design approaches and the practicality of implementing the approaches. These approaches could feature inherent reactor characteristics, such as nuclear fuel with a substantial capability for retention of fission products, or they could use special test facility features such as a shutdown system not intended for use in the flight system.

The operating duty cycle of nuclear propulsion reactors must be considered in the safety evaluations. The duty cycle could consist of very short full power operating times. This duty cycle may allow safety approaches that achieve both high reliability in safety features and reduced sources of radioactivity and decay heat.

Testing of space nuclear propulsion reactors will be conducted on government sites in accordance with DOE orders. The DOE orders provide requirements and guidance that are generally consistent with the recommended policy statement. The DOE orders will require some interpretation in applying them to specific testing. Interpretation of specific details should be done as part of the process of design development and independent safety review. Recommendations relative to the more general elements of the DOE orders are provided in the following sections. (DOE orders regulating safety and environmental protection are currently being revised and codified.)

5.2.2 Ground Test Facility Recommendations

Safety testing to support safety of ground tests of reactor propulsion systems should focus on three key functions:

- reliability of safe reactor shutdown
- reliability of safe shutdown heat removal
- control and confinement of radioactive materials during operation and postulated accidents.

Demonstration of reliability of safety functions could be demanding, depending on the extent to which components with demonstrated reliability are used. The reliability demonstration cannot be accomplished on the basis of large sample statistics. It will require reliability modeling and systematic evaluation and demonstration of margins relative to identified degradation and failure mechanisms.

The issue of radiological containment or confinement for postulated severe accidents requires early attention and must be closely coupled to program schedule and strategy. Large safety margins potentially provided by containment for severe accidents can be used to simplify and accelerate safety evaluations and reviews; however, containment structures can be very expensive. Although the program must evaluate severe accident events, the short operating time and the durability of the fuels used in nuclear propulsion reactors may not demand accident mitigation to achieve the safety objectives. If the physics of the postulated severe accidents permit demonstration through experimentation and analysis of adequate radiological confinement, expensive containment structures may be unnecessary. Nonetheless, regulators could place emphasis on the issue of radiological confinement for postulated accidents involving severe core damage. Developers should give careful consideration to potential mitigative approaches for postulated severe accidents. The selected approach can only be determined with the knowledge of system design specifics.

Specific test needs will be dependent on the details of the design features in each system. For the NTP system tests it will be necessary to have data on fission product release as a function of operating temperature and time. The safety and environmental constraints on ground testing these reactors may demand greater retention of radioactivity than for a space flight mission. Fuel testing for NEP systems will also be required but it is expected to be focused more on lifetime and functional reliability concerns than on safety validation. Much of the testing will have to be completed for NEP systems based on SP-100 fuel. The safety program must provide early focus on demonstration of the reliability of shutdown and shutdown heat removal functions to support nuclear system level ground testing.

Ground testing of space nuclear propulsion systems that include nuclear fuel and the potential for release of radioactive materials or exposure of personnel to direct radiation should, as a minimum, adhere to existing DOE orders related to siting and establishment of safety design requirements (DOE Order 5480.6 [U.S. DOE, 1986] and DOE Order 5480.4 [U.S. DOE, 1984]).

The required application of 10 CFR 50 (U.S. NRC, 1991b), Appendix A (General Design Criteria for Nuclear Power Plants), in DOE Order 5480.6, should be interpreted in terms of the more general requirement of 10 CFR 50.34(a)(3)(i): that principal design criteria be provided for the facility using 10 CFR 50, Appendix A as guidance. The mandatory requirement for IEEE279, IEEE308, IEEE603, ANS 15.1 and the ASME BPV Code in DOE Order 5480.4 will also need interpretation when applied to unique equipment associated with nuclear propulsion test facilities. The exemption provided for space-based nuclear reactors in DOE Order 5480.6, 8.c. should be interpreted to be applicable only to flight systems; the exemption should not apply to ground test reactor facilities for these systems.

The requirement in DOE Order 5480.6 for preparation of safety analysis reports using NRC guidelines on standard format and content will require interpretation. Nonetheless, the concept of identifying design-basis accidents and analyzing these to assure adequate safety margins are implemented in the design should be retained. The concept should be extended as has been the practice with most recent safety reviews of power reactors to include analysis of severe accidents that are lower in probability than the design-basis accidents. The evaluation of this latter category of accident can be included in a formal risk analysis and also used in the establishment of a site suitability source term used in conjunction with meeting the siting requirements of 10 CFR 100 (U.S. NRC, 1991c) called for in DOE Order 5480.6. The results of these analyses will have an important role in establishing the extent of the safety features required to assure safe reactor shutdown, shutdown cooling, and control of the release of radioactivity.

Siting requirements and specific facility design requirements should be established to maintain radiation exposure dose consequence for normal operations, including anticipated operational occurrence, to levels consistent with 10 CFR 20 (U.S. NRC, 1991a). Although this is not a mandatory standard in DOE Order 5480.4, it has been generally adhered to and implements the NCRP recommendations for occupational and public exposures to radiation. Application of this guidance to the NTP reactor exhaust may require special filtering holdup, or location of the exhaust release point.

The requirements for formal review of the Safety Analysis Reports specified in DOE Order 5481.1B should be applied. Organizations and staff assigned to complete independent reviews should be identified as soon as possible so that a competent and comprehensive review can be completed.

5.2.3 Transportation Equipment

A certified shipping container which meets DOT and DOE/NRC regulations will normally be required for the transport of fissile material (e.g., fuel, fuel rods, or a complete reactor assembly) between the ground test facility and the launch site. Although DOE's Safe Secure Trailer (SST) provides adequate physical security for the transport of fissile materials, it is not certified to meet the expected requirements for nuclear propulsion reactors and there are no plans to obtain SST certification as a shipping container. Thus, although the SST can be used as a carrier, a certified shipping container will normally be required to ensure its contents will remain subcritical, shielded, and adequately contained under normal and specified accident conditions.

Certified shipping containers exist that may accommodate the fuel and fuel forms likely to be used for the spectrum of SEI nuclear propulsion systems under consideration. Certified shipping containers capable of meeting the expected transportation safety requirements and capable of accommodating a full SEI nuclear reactor propulsion assembly have not been identified. Therefore, unless assembly occurs at the ground test facility and at the launch site, a container will probably have to be designed and built and then analyzed and successfully tested to obtain certification before actual use.

Based on this information, the following recommendations are made:

- Verify the adequacy and availability of existing certified shipping containers for the transport of fuel and fuel forms envisioned for SEI nuclear propulsion systems.
- Because of the demanding certification requirement for nuclear fuel shipping containers, the program should, as early as practical, evaluate fuel transportation and loading options to determine shipping container requirements.

By focusing appropriate, timely attention on the requirements for a specially-designed and appropriately certified shipping container, the program office can ensure that this vital equipment will be available for use when needed.

5.2.4 Launch Facility

Safety procedures must be established, and facility provisions must be available, at the launch site to ensure that assembly, storage, checkout, testing, and integration of nuclear propulsion system flight hardware will not pose a hazard to the public, workers, property, or the environment. Prior to launch, nuclear propulsion flight hardware must be handled safely and proper shielding must be provided. Adequate physical security and safeguards must be provided during the prelaunch phase. As a minimum, storage, checkout, and integration will be required at the launch site; thus, an adequate facility must be available at the launch site. The program should focus attention on the requirements for a special facility at the projected launch site and initiate appropriate actions to ensure its adequacy and availability for use when needed.

6. Suggested Future Activities

This section suggests future activities related to safety that should be considered by the SEI program office. Subsection 6.1 addresses the need for a safety, quality and reliability program plan and the necessary features of the plan. In Subsection 6.2, communication with and participation of the public are discussed with some thoughts on how these activities might be pursued.

6.1 Safety, Quality, and Reliability Program Plans

As one of its first tasks the SEI nuclear propulsion program, in conjunction with the SEI program office, must develop program plans for safety, quality assurance, and reliability. These program plans will establish the framework for implementation of activities important to safety. Program plans for the overall SEI program should also be developed.

The Safety Program Plan should: (1) establish the scope and importance of safety to the success of the program, (2) include a concise statement of safety policy for the program, (3) identify specifically how safety will be managed within the organizational structure of the program, (4) identify how safety assessment within the program and independent safety oversight will be conducted, (5) provide technical safety guidance to permit activities to move forward and continuously progress, and (6) task the program participants to develop a Safety Implementation Plan (SIP) for each functional area or activity.

Information provided in this report is directly applicable to items (1), (2), and (5) identified above; thus, no further discussion of these items is necessary.

Item (3) addresses the mainline safety program. It will involve technical and safety analysis and reviews routinely conducted by management and staff as a distinct function. The Safety Program Plan should establish an effective safety review process within the program for ensuring safety and the ultimate success of the program. Doing so will help management to focus and maintain appropriate attention continually on safety throughout the duration of the program. More specifically, it will provide management with an indispensable means of obtaining timely, objective programmatic and technical safety performance assessments. These assessments can serve to verify safety performance and may guide the redirection of program activities, when necessary, to achieve safety objectives.

Item (4) identifies two additional safety review functions internal to the program but outside the mainline structure, namely independent safety assessment and independent safety oversight. The former primarily involves technical assessments of mainline safety performance, while the latter is broader, encompassing both technical and programmatic safety appraisals, including management performance. Both functions demand objective reporting of findings and recommendations directly to management. Top management must put both of these functions in place specifically for itself while also authorizing establishment of these functions at lower levels of management.

Well established procedures for independent safety oversight and environmental review and approval of terrestrial nuclear reactors as well as the launch of space nuclear systems are in place in the US. These are embodied in DOE orders for terrestrial reactors and in the Interagency Nuclear Safety Review Panel process for launch approval of nuclear systems (Sholtis, 1991). These procedures appear applicable and appropriate for the SEI nuclear propulsion program. Thus, planning for the independent reviews should be initiated on the basis of these existing procedures. The objectives of this early planning should be to confirm the adequacy of these procedures for the SEI nuclear propulsion program and provide preliminary schedules for the development work needed to support the safety and environmental approval.

Item (6) involves the development of SIPs. These SIPs are intended to ensure proper safety focus throughout the SEI Nuclear Propulsion Program. In particular, they must specify how the program participants are going to execute their functional activities, and conform with the Safety Program Plan.

6.2 Public Participation

The SEI nuclear propulsion program, in conjunction with the overall SEI program, should place high priority on the establishment of a plan for public participation in the nuclear propulsion program. The plan should emphasize two-way communication between the program and the public on the safety aspects of nuclear propulsion. Planning should address formal participation processes, such as public participation in environmental impact statement activities, as well as informal processes.

Planning for formal communication processes with the public should be initiated based on use of existing procedures. The objectives of initial planning should be to confirm or modify these procedures, as appropriate, for the SEI nuclear propulsion program. Schedules should be established to integrate formal communication processes with the activities needed to support safety and environmental approvals.

The initial planning effort for public participation should develop a process that addresses the need for meaningful public involvement in that the process:

- contributes to safety
- provides a forum for two-way communication between the public and the program
- allows public concerns to be addressed
- improves public understanding of SEI safety
- serves SEI program goals

Glossary of Terms

Accident—an unplanned event with adverse or potentially adverse consequences.
As Low as Reasonably Achievable (Exposure)—to control or manage exposures and releases of radioactive material to the environment as low as social, technical, economic, practical, and public policy considerations permit. A process to attain dose levels as far below acceptable limits as possible.
As Low as Reasonably Achievable (Risk)—to reduce risks to levels as low as social, technical, economic, practical, and public policy considerations permit.
Credible (Events or Accidents)—those events or accidents that must be considered for the system design basis.
Criticality—the operating state of a nuclear reactor where the neutron population in the reactor remains constant over time.
Critical Items List—a list of component items or technical issues used to focus program management attention on items that are most important to the control of safety and reliability risks.
Entry—the event in which a reactor system enters the atmosphere or impacts the surface of Earth or another celestial body.
Essentially Intact—the state in which a reactor retains sufficient integrity to maintain subcriticality and keep radioactive fuel, fission products, and structures together.
Extended Period of Time—encompassing the time period of potential future space enterprises in the local region of space under consideration.
Extremely Low Probability Event—an event that is not expected to ever occur during the execution of the SEI program.
Full Dispersal—the wide-spread scattering of a radioactive material in the atmosphere as an aerosol such that the consequences on Earth's environment are insignificant.
Insignificant (radiological consequence on Earth)—much less than the maximum allowed by terrestrial guidelines.
Local Space Environment—the region of space under consideration.
Low Power Testing—critical operation of a reactor at a sufficiently low power level to assure generation of only a negligible quantity of radioactive materials.
Piloted Mission—A space mission carried out with a human crew.
Planned Orbit—an Earth orbit condition, prior to insertion into a interplanetary or Earth-Lunar trajectory, that has been predetermined to be safe for reactor start-up operations.
Probabilistic Risk Assessment (PRA)—the systematic and quantitative application of logic models (e.g., fault trees and event trees) and analytical techniques to estimate the probabilities and consequences of undesirable events.
Risk—a quantitative or qualitative expression of potential harm or damage that considers both the probability that events will cause harm or damage and the consequences of those events.

Rover—U.S. nuclear thermal rocket program pursued from the late 1950s through the early 1970s, including development of the NERVA reactor concept.

Safeguards—those measures or features used to protect nuclear systems and special nuclear materials from theft, diversion, loss, or sabotage.

Safe—judged to be of sufficiently low risk.

Safety Analysis Report (SAR)—a report that characterizes the level of safety associated with the use of a reactor system.

Safety Evaluation Report (SER)—report that provides an independent safety evaluation of a reactor system based, in part, on a review of the SAR.

Safety Functional Requirements—requirements delineating specific safety functions.

Safety Guidelines—suggestions and programmatic guidance for safety.

Safety Policy—a policy that establishes the importance and priority that must be placed on safety and establishes the broad framework and overall guiding principles for the development and implementation of an effective nuclear propulsion safety program.

Shutdown—subcritical by an adequate margin and incorporating positive measures to ensure that the reactor remains securely subcritical.

Significant—greater than an appropriate guideline or norm.

Space Enterprises—all human-directed activities within or dependent upon the space environment, including satellites, piloted, cargo and robotic space missions, and other endeavors.

Space Environment—all regions of space beyond of Earth's biosphere, including other celestial bodies.

Special Nuclear Material (SNM)—plutonium, uranium 233, or uranium enriched in the isotopes 233 or 235 excluding source material.

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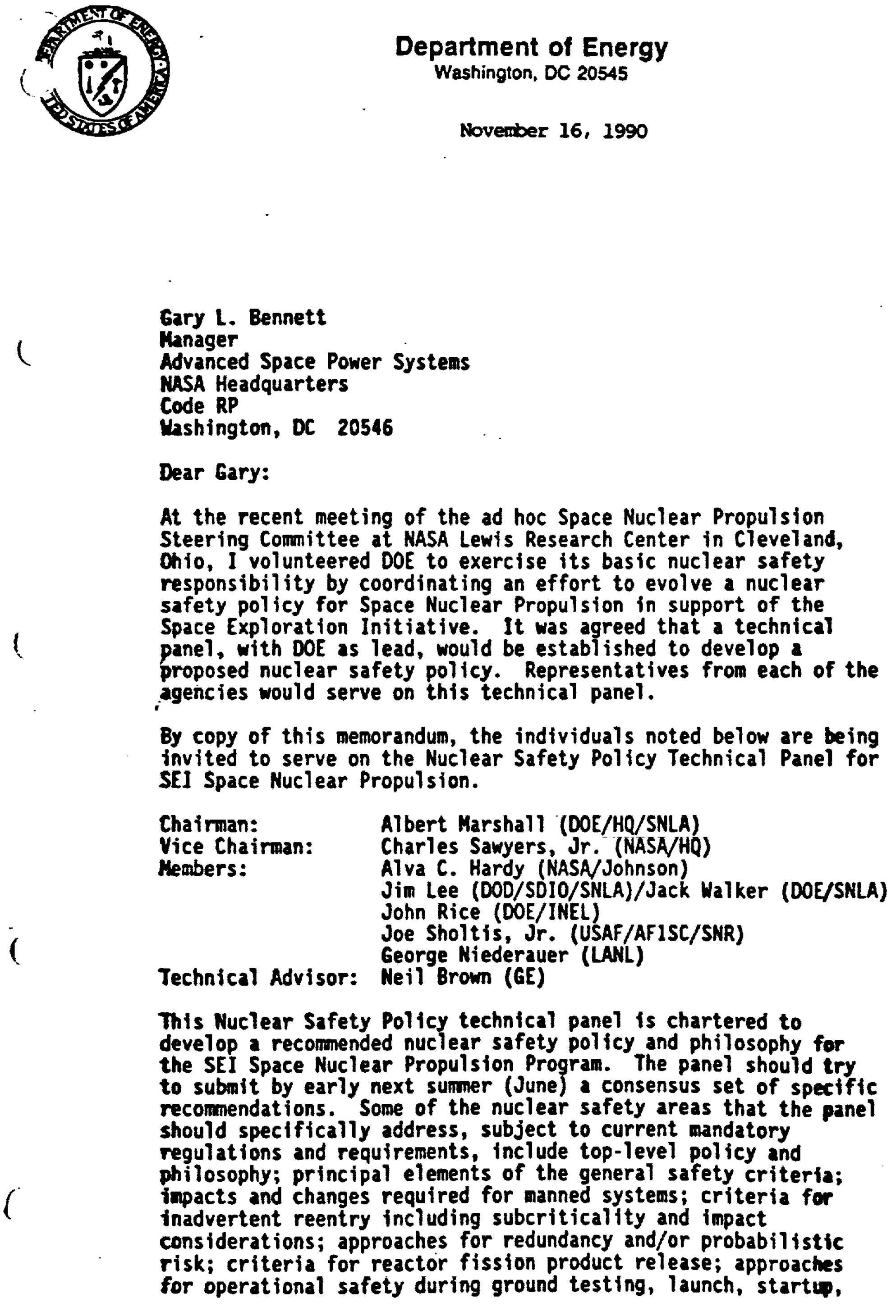
Appendix A. Charter

Nuclear Safety Policy Working Group Charter

NOTE: The NSPWG Panel Membership was changed, with Steering Committee approval, to include the individuals on the title page of this report. Also, a draft report on the NSPWG was requested for September 1991. Both of these changes followed the issuance of the NSPWG charter.



Department of Energy
Washington, DC 20545

November 16, 1990

Gary L. Bennett
Manager
Advanced Space Power Systems
NASA Headquarters
Code RP
Washington, DC 20546

Dear Gary:

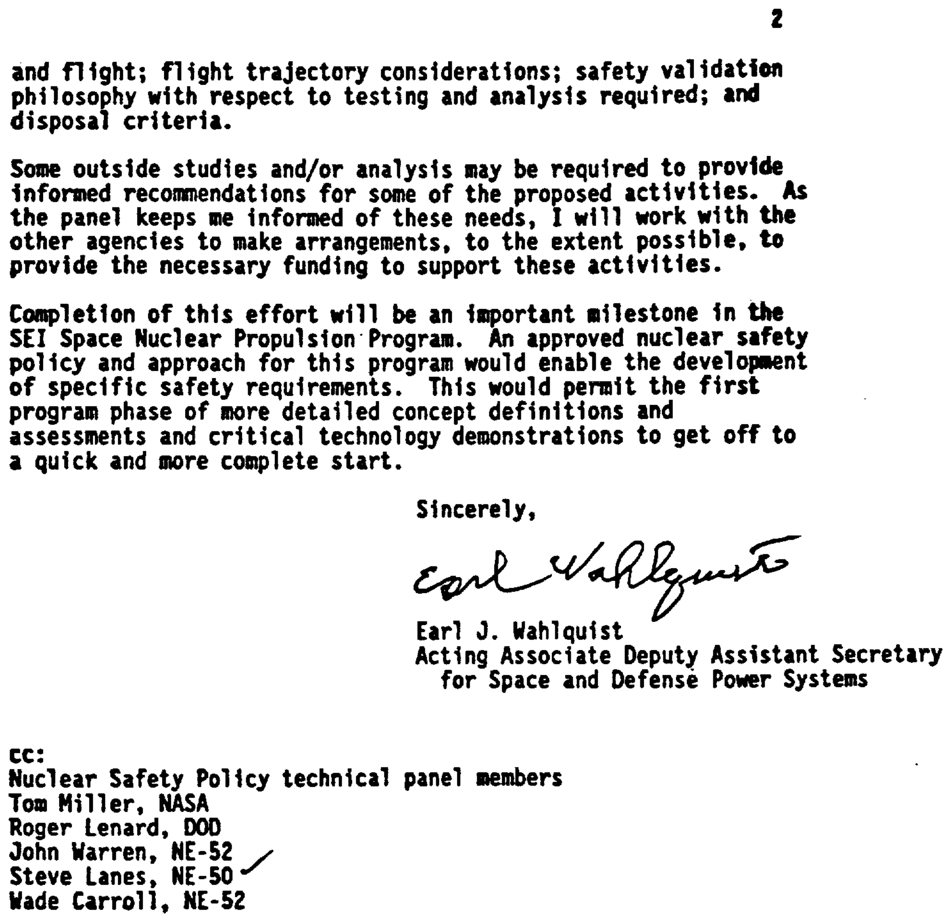
At the recent meeting of the ad hoc Space Nuclear Propulsion Steering Committee at NASA Lewis Research Center in Cleveland, Ohio, I volunteered DOE to exercise its basic nuclear safety responsibility by coordinating an effort to evolve a nuclear safety policy for Space Nuclear Propulsion in support of the Space Exploration Initiative. It was agreed that a technical panel, with DOE as lead, would be established to develop a proposed nuclear safety policy. Representatives from each of the agencies would serve on this technical panel.

By copy of this memorandum, the individuals noted below are being invited to serve on the Nuclear Safety Policy Technical Panel for SEI Space Nuclear Propulsion.

Chairman:	Albert Marshall (DOE/HQ/SNLA)
Vice Chairman:	Charles Sawyers, Jr. (NASA/HQ)
Members:	Alva C. Hardy (NASA/Johnson)
	Jim Lee (DOD/SDIO/SNLA)/Jack Walker (DOE/SNLA)
	John Rice (DOE/INEL)
	Joe Sholtis, Jr. (USAF/AFISC/SNR)
	George Niederauer (LANL)
Technical Advisor:	Neil Brown (GE)

This Nuclear Safety Policy technical panel is chartered to develop a recommended nuclear safety policy and philosophy for the SEI Space Nuclear Propulsion Program. The panel should try to submit by early next summer (June) a consensus set of specific recommendations. Some of the nuclear safety areas that the panel should specifically address, subject to current mandatory regulations and requirements, include top-level policy and philosophy; principal elements of the general safety criteria; impacts and changes required for manned systems; criteria for inadvertent reentry including subcriticality and impact considerations; approaches for redundancy and/or probabilistic risk; criteria for reactor fission product release; approaches for operational safety during ground testing, launch, startup,

Figure A-1. Letter from Earl J. Wahlquist, Acting Associate Deputy Assistant Secretary for Space and Defense Power Systems



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and flight; flight trajectory considerations; safety validation philosophy with respect to testing and analysis required; and disposal criteria.

Some outside studies and/or analysis may be required to provide informed recommendations for some of the proposed activities. As the panel keeps me informed of these needs, I will work with the other agencies to make arrangements, to the extent possible, to provide the necessary funding to support these activities.

Completion of this effort will be an important milestone in the SEI Space Nuclear Propulsion Program. An approved nuclear safety policy and approach for this program would enable the development of specific safety requirements. This would permit the first program phase of more detailed concept definitions and assessments and critical technology demonstrations to get off to a quick and more complete start.

Sincerely,

Earl Wahlquist

Earl J. Wahlquist
Acting Associate Deputy Assistant Secretary
for Space and Defense Power Systems

cc:
Nuclear Safety Policy technical panel members
Tom Miller, NASA
Roger Lenard, DOD
John Warren, NE-52 ✓
Steve Lanes, NE-50 ✓
Wade Carroll, NE-52

Figure A-1. Letter from Earl J. Wahlquist, Acting Associate Deputy Assistant Secretary for Space and Defense Power Systems (Continued)

Appendix B. Panel Background

Robert A. Bari

Dr. Robert A. Bari is presently Deputy Chairman, Department of Nuclear Energy, Brookhaven National Lab. Dr. Bari received his AB in physics in 1965 from Rutgers University and his Ph.D. in physics in 1970 from Brandeis University. Currently, he is responsible for programs on reactor safety, nuclear safeguards, radiation protection, waste management, nuclear data center, and advanced nuclear concepts. Since 1974 he has been involved in safety assessment of commercial, research, and test reactors and other complex facilities. Previous assignments in nuclear safety at Brookhaven include: Group Leader (1975-1981); Division Head, 1981; and Associate Department Chairman, 1982-1988. Numerous publications and presentations on probabilistic risk assessments, severe accident analysis, and safety goals have been published. He has participated in several international programs on nuclear safety through OECD, IAEA, and various bilateral agreements. Dr. Bari is a fellow of the American Nuclear Society and currently Chairman of its Nuclear Reactor Safety Division.

Mr. Neil W. Brown

Mr. Brown is presently Manager of Safety and Reliability for the SP-100 space reactor project at General Electric. Mr. Brown received his B.S. in Mechanical Engineering from the University of Washington in 1960 and his M.S. in Mechanical Engineering from the University of Santa Clara in 1968. He has been employed by General Electric for more than 30 years and has worked in both the aerospace and terrestrial nuclear power areas. His work in the nuclear area has focused primarily on advanced nuclear systems. Mr. Brown participated in safety review and NRC licensing of the Southwest Experimental Fast Oxide Reactor and the Clinch River Breeder Reactor. He has also contributed safety assessments of both General Electric and DOE studies of the safety of advanced reactor concepts including liquid metal cooled, gas cooled, and water and steam cooled reactors. He is a licensed Professional Mechanical Engineer in the State of California.

Dr. Hatice S. Cullingford

Dr. Hatice S. Cullingford works as a senior engineer at NASA's Lunar and Mars Exploration Program Office (LMEPO) located at Johnson Space Center. Since her Ph.D. and B.S., both in chemical engineering from North Carolina State University, Dr. Cullingford has worked in space, nuclear, and environmental systems at NASA, Los Alamos, and the AEC/ERDA/DOE. She is a registered professional engineer in the state of Texas. Dr. Cullingford's work began with the Liquid Metal Fast Breeder Reactor Program (Clinch River Breeder Reactor Project) in reactor system thermal hydraulics, then continued with plasma engineering and technology development for magnetically confined fusion energy and system design studies for laser fusion and hybrid reactors. She has also been responsible for analysis of hydrogen systems, pressurized water reactor safety, and alternative concepts for replacement production reactors. Dr. Cullingford has been active at NASA in both project and program management. Her contributions include technology development and demonstration, conceptual designs, and simulation models of environmental control and life support for the space station and missions to the Moon and Mars. Dr. Cullingford's current responsibilities include risk management and system engineering for SEI. Hatice has been recognized for her long-term and strategic planning achievements at both ERDA and JSC. She has produced three (one pending) patents and authored about 50 papers and reports.

Mr. Alva C. Hardy

Mr. Hardy is employed at NASA/JSC/Space and Life Sciences/Solar System Exploration Division/Space Science Branch. He serves as Radiation Subsystem Manager for Space Shuttle dosimetry and technical manager of the NASA Johnson Space Center efforts in Space Shuttle and Space Station ionizing radiation analysis for crew safety. He received his B.S. in physics and mathematics in 1962 from Southwestern Oklahoma State University. Mr. Hardy has been with NASA Houston since 1962, with twenty-six years experience involved with ionizing radiation analysis and dosimetry activities for NASA manned space programs, primarily dealing with radiation issues related to flight crew safety. Mr. Hardy provides a basic understanding of the NASA Astronaut Ionizing Radiation Risk Limitation System for Space Activities, including regulatory/legal requirements, current ground rules and constraints and concerns for advanced program applications.

Mr. Albert C. Marshall

Mr. Marshall is presently employed at Sandia National Laboratories and serves as the Safety Advisor for Space Reactor Systems for the Department of Energy. His current responsibilities also include a part-time faculty assignment at the University of New Mexico in the Department of Chemical and Nuclear Engineering and space reactor work for Sandia National Laboratories. Mr. Marshall received a B.S. in Physics in 1965 and an M.S. in Nuclear Engineering in 1967, both from the Pennsylvania State University. He has twenty-two years work experience in the area of nuclear reactor systems at Sandia National Laboratories, General Atomics, and Bettis Atomic Power Laboratory. He has worked primarily in the areas of reactor physics, reactor design and analysis, and reactor safety for a broad variety of reactor types and applications. He was project leader for two large and complex in-core experimental programs to explore both light-water-cooled reactor and liquid-metal-cooled reactor severe core damage accident phenomenology. Mr Marshall was the lead staff member for a comparative assessment of space reactors and has eight years of work experience in the area of space reactors.

Dr. William H. McCulloch

Dr. McCulloch is presently a distinguished member of the technical staff at Sandia National Laboratories. He currently is responsible for reactor safety for advanced nuclear power systems. Dr. McCulloch received a B.S. in Engineering

Physics in 1963, an M.S. in Mechanical Engineering in 1964, and a Ph.D. in Mechanical Engineering from Texas Tech University in 1964. He is also a registered professional engineer in the state of New Mexico and has received numerous recognitions for outstanding achievements. He has worked at Sandia National Laboratories since 1967 primarily in the areas of Heat Transfer and Systems Analysis, Solar Energy Projects, Light Water Reactor Safety and Space Nuclear Systems. In 1975, he was assigned from Sandia to the ERDA (now the DOE) Division of Solar Energy. He served on the Interagency Nuclear Safety Review Panel Power Systems Subpanel of the Galileo mssion and chaired the subpanel for the Ulysses mission. Dr. McCulloch has authored or co-authored more than 30 technical publications.

Dr. George F. Niederauer

Dr. Niederauer is currently SP-100 Project Safety Manager at Los Alamos National Laboratory. Dr. Niederauer received his B.S. in 1964 in Mathematics and his M.S. in Nuclear Engineering in 1966 from the South Dakota School of Mines and Technology. In 1967 he received his Ph.D. in Nuclear Engineering from Iowa State University. He has experience with computer code development and analysis of light water reactors and liquid metal cooled reactors in the areas of reactor physics, kinetics, thermal hydraulics, and heat transfer. Management responsibilities included groups involved in computer code development for safety analysis, reactor simulators and real time monitoring, safety analysis of reactor systems and containment, and risk assessment. He has also been employed at Bettis Atomic Power Laboratory, NASA Lewis Research Center, Aerojet Nuclear Company, and Energy Incorporated.

Mr. Kerry Remp

Mr. Remp is currently the Deputy Chief of the Safety Assurance Office, NASA Lewis Research Center. Responsibilities include management of systems safety activities for all NASA Lewis Research Center spaceflight, terrestrial and facility programs, including nuclear propulsion, Space Station Freedom power system and numerous satellite and experimental programs. Mr. Remp received his B.S. in Marine Engineering, with a minor in Nuclear Engineering in 1982 from the U.S. Merchant Marine Academy. Some of his achievements to date include: Development and review of safety requirements for the NASA/DOE/DOD joint Space Exploration Initiative (SEI) program; review of construction and operational aspects of numerous U.S. nuclear power generation plants, including extensive experience at Perry Nuclear Power Plant; member of hydrostatic testing team for the H.B. Robinson nuclear power plant; and development of safety and quality assurance training programs for numerous nuclear power plants managed by the Yankee Atomic Electric Company.

Mr. John W. Rice

Mr. Rice is currently the Nuclear Safety Support Program Specialist at Idaho National Engineering Laboratory. Mr. Rice received his M.S. in Nuclear Engineering from the Air Force Institute of Technology in 1975. During his Air Force career he was Nuclear Weapon Safety Officer at the Air Force Weapons Laboratory, Nuclear Weapon Safety Officer at HQ Strategic Air

Command, and Space Nuclear Safety Officer at the Air Force's Inspection and Safety Center's Directorate of Nuclear Surety (AFISC/SN). While at AFISC/SN, he was also responsible for nuclear safety approval for Air Force launches of minor radioactive sources and Executive Secretary for the Interagency Nuclear Safety Review Panel for NASA's Galileo space mission. More recently, Mr. Rice was the Nuclear Safety Program Specialist at INEL for the Multimegawatt Space Reactor Project Integration Support Office.

Mr. J. Charles Sawyer, Jr.

Mr. Sawyer is presently assigned to the NASA Headquarters Safety Division in the Office of Safety and Mission Quality (Code Q) as the NASA Headquarters Level I Safety Manager for the Space Station Freedom Program, for the Space Exploration Initiatives and for the Nuclear Propulsion Program. Previously he was the Level I Payload Safety Manager, dealing with the payload safety aspects of payloads such as Galileo, Ulysses, Hubble Space Telescope, Telemetery Date Relay Satellite, and Magellan. In previous assignments Mr. Sawyer was the Director of Range Safety at the USAF Armament Division at Eglin Air Force Base, Florida where he was responsible for the development of range safety policies and criteria for approximately 600 test and evaluation programs, which included the US Navy Tomahawk, the US Army Hellfire, the USAF Advanced Medium Range Air to Air Missile (AMRAAM), the AGM-13C, and several types of laser- and television-guided bombs. Prior to accepting the position as Director of Range Safety, Mr. Sawyer was a Range Safety Analyst at the Armament Division and at the Pacific Missile Test Center at Point Mugu, CA, where he developed range safety criteria for many of the early tactical and strategic weapons systems, scientific sounding rockets and participated in several of the Nuclear Readiness-to-Test Exercises at Johnston Atoll as a member of Joint Test Force 8. Mr. Sawyer holds a B.S. in Mechanical Engineering (aerospace option) from the University of California, Berkeley, and a M.S. in Systems Management from the University of Southern California. He is a graduate of the USAF Air War College.

Lt Col Joseph A. Sholtis, Jr.

Lt Col Joseph A. Sholtis, Jr., is Chief of the Analysis and Evaluation Branch, Nuclear Power and Sources Division, Directorate of Nuclear Surety, Air Force Safety Agency, Kirtland AFB, New Mexico, overseeing Air Force terrestrial and U. S. aerospace nuclear power projects from a safety standpoint. From March 1984 to August 1987, while assigned to Air Force Element, U.S. Department of Energy, Lt Col Sholtis served as the Program Manger of the joint DOD/DOE/NASA SP-100 Space Reactor Power System Development Program. From August 1980 to March 1984, he served as Chief, Radiation Sources Division and Reactor Facility Director at the Armed Forces Radiobiology Research Institute in Bethesda, Maryland. He has supported Interagency Nuclear Safety Review Panel (INSRP) evaluations of the Viking, LES 8/9, and Voyager missions employing Radioisotope Thermoelectric Generators (RTGs), chaired the INSRP Power System Subpanel for the RTG-powered Galileo and Ulysses space missions, served as the DOD INSRP Coordinator for the Ulysses mission, and served as a technical expert on the United Nations Working Group on Nuclear Power Sources in Outer Space. He has also followed development of the Soviet Romashka and Topaz space reactors. He holds a B.S. from the Pennsylvania State University and an M.S. from the University of New Mexico in Nuclear Engineering. He is a member of the faculty of the Uniformed Services University of Health Sciences and has authored/co-authored one textbook, one handbook, and more than sixty technical publications.

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13. ABSTRACT ***(Maximum 200 words)***

An interagency Nuclear Safety Working Group (NSPWG) was chartered to recommend nuclear safety policy, requirements, and guidelines for the Space Exploration Initiative (SEI) nuclear propulsion program. These recommendations, which are contained in this report, should facilitate the implementation of mission planning and conceptual design studies. The NSPWG has recommended a top-level policy to provide the guiding principles for the development and implementation of the SEI nuclear propulsion safety program. In addition, the NSPWG has reviewed safety issues for nuclear propulsion and recommended top-level safety requirements and guidelines to address these issues. These recommendations should be useful for the development of the program's top-level requirements for safety functions (referred to as Safety Functional Requirements). The safety requirements and guidelines address the following topics: reactor start-up, inadvertent criticality, radiological release and exposure, disposal, entry, safeguards, risk/reliability, operational safety, ground testing, and other considerations.

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